FULL REMOTE ALIGNMENT SYSTEM FOR THE HIGH-LUMINOSITY LARGE HADRON COLLIDER HL-LHC

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Abstract

The High Luminosity Large Hadron Collider (HL-LHC) is an upgrade of the LHC to achieve instantaneous luminosities, a factor five larger than the LHC nominal values. During the Long Shutdown 3, scheduled between 2026 and 2028, nearly 1.2 km of accelerator components will be replaced by new ones, relying on key innovative technologies. The Full Remote Alignment System (FRAS) is being developed to perform the remote alignment of these new HL-LHC components. FRAS will enhance the accelerator performance, decrease the required orbit corrector strengths, all of this while limiting the radiation doses for surveyors working in the tunnel, therefore allowing for more frequent alignment campaigns. Innovative solutions for the remote adjustment and position determination of the components are being qualified, including the internal monitoring of the position of cold mass and crab cavities inside their cryostat. This paper will provide a status of the systems under development and qualification, from the sensors and motor assemblies to the low level / high level acquisition and control/command systems and their corresponding software.

INTRODUCTION

The Full Remote Alignment System (FRAS) for the HL-LHC project [1][2] will perform the remote alignment of components located on both sides of the Interaction Points (IP) 1 and 5 of the LHC within ± 2.5 mm. Initially it will be used to correct the machine misalignment with respect to the center of the Inner Tracker of the two detectors, once the first beams have circulated. On a more standard operational basis it will be employed to correct for the continuous ground motion without the need of interventions in the tunnel. We can distinguish two types of components over the 220 m on each side of the IP. The first category of components will be equipped with alignment sensors to determine their position and will be supported by motorized supports to perform their remote adjustment. In total, 32 components per IP will be continuously monitored. The second category of components will be “FRAS compatible”, i.e., not equipped with such sensors and motors, but being able to comply with the remote displacements of their adjacent components, considering their large aperture margin with respect to the expected ground motion [3] and the possible beam configurations. This paper will focus on the first type of components and will present the overall alignment strategy, from the solutions to perform the remote position determination and their motorized adjustment to the acquisition and control/command systems and associated software. It will conclude with the qualification plan of this new alignment concept.

SOLUTIONS FOR REMOTE POSITION DETERMINATION

The remote determination of the components position will be performed by a redundant configuration of different types of sensors, using diverse technologies, namely: Wire Positioning Sensors (WPS) based on a capacitive technology, Hydrostatic Levelling Sensors (HLS), based on Frequency Scanning Interferometry (FSI) technology [4] and inclinometers, based on both FSI and capacitive technologies.

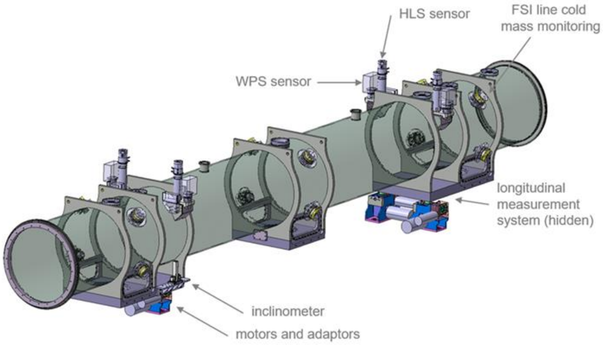

Figure 1: Solutions for remote position determination

Capacitive WPS sensors

Capacitive WPS sensors are under development and qualification at CERN, including:

- A new WPS sensor based on a flexible polyimide Printed Circuit Board, with electrodes printed on the surface and coated with gold [5].
- A new type of cables transferring the signals over more than 110 m to their remote electronics with very limited noise (peak to peak noise below 5 µm), keeping the accuracy of the measurement within 15 µm [6].
- A new sensor electronics, based on an Analogue to Digital Converter and digital data processing to provide remote diagnostics and to perform remote parameters tuning (for example of the sensor frequency). It will be housed in a Distributed I/O Tier (DI/OT) crate, with digital output directly transferred via the WorldFIP field bus interface [7].

These new developments answer the specific requirements for FRAS within the HL-LHC project: the possibility to stretch one single wire over more than 220 m directly through the WPS sensors and the wire protection, without opening them, via an “optical fiber type” blowing process. By developing sensors in-house, the chosen electronics components and their radiation hardness are known and can be accurately chosen and mastered [5, 7].

FSI based HLS sensors

The FSI technology performs absolute distance measurements within a micrometric accuracy [4]. In the case of an HLS sensor, the FSI optical ferrule is inserted into the measurement head and measures contact free the absolute distance to the water surface in the vessel [4]. It has the great advantage to use optical fibers as they are far less expensive to buy and install in the tunnel than standard cables for capacitive measurements. On the other hand, this technology could be more sensitive to water vibrations as measuring with respect to the water surface. Dedicated studies are in preparation at CERN to study such an impact of vibrations.

Specific vessels with an isostatic mechanical interface based on three reference spheres are under design to allow a micrometric repeatability between the sensor head and the vessel, combined with a perfect tightness.

Inclinometers

Three different generations of inclinometers have been developed, all based on the same initial concept: the offset measurement of a suspended pendulum w.r.t the mechanical frame of the sensor. The bottom of the pendulum is equipped either with a glass sphere to perform FSI measurements from both sides of the sensor frame w.r.t. to the glass sphere, or with a reference surface to measure these offsets by a capacitive technology.

First tests performed on the third FSI prototype have demonstrated a repeatability below 10 µrad and an accuracy of the order of 150 µrad [4].

Qualification strategy

As all these sensors are developed in-house, a thorough qualification plan has been put in place. First, each type of sensor has undergone specific tests, using dedicated test benches and a climatic chamber, to assess their repeatability, their accuracy, their long-term stability, and the impact of humidity, temperature, and vibrations on the measurements.

Once the sensors, including their cables and remote electronics, are validated, they will be qualified on a 140 m test facility through cross-comparison measurements. In that case, it is not only the sensor that is validated but also its associated alignment system: a wire stretched under a specific protection for the WPS, or a given hydraulic network for the HLS. Irradiation tests aiming at a Total Ionizing Dose (TID) of up to 2 MGy are also in preparation.

Sensor configuration

Combinations of different types of sensors are under study. They must fulfill the following parameters:

- Integration and allow access (in case of maintenance) in the very crowded environment of the LHC tunnel, including the optimization of the number of cables,
- Alignment requirements received from beam physicists [8, 9],
- Minimization of the alignment cost,
- Improvement of the reliability: the redundancy of sensors allows the control of each degree of freedom and the identification of possible errors. The different technologies used to determine the degrees of freedom will provide independent layers of protection during the alignment process (see the ”Risk and Safety Assessment” section).

Internal monitoring

The alignment sensors are located on the cryostats, e.g., the external envelopes of the components. For two types of specific components: the Inner Triplet (IT) quadrupoles (focusing the beam before the collision points) and the crab cavities (rotating the beam to improve the overlap of bunches at the collision point), a new system will be added for a better knowledge of the position of the beam through the thermal cycles of the components. It will monitor continuously the position of the cold masses of the IT quadrupoles and the crab cavities with respect to their cryostat within an accuracy of ± 0.1 mm and within a micrometric resolution

Such an internal monitoring is achieved by welding specific targets onto the cold masses of the IT quadrupoles and onto the bellows of the crab cavities, and by measuring contact free the absolute distances between optical heads located on the cryostats (at ambient temperature) and these targets (at 1.9 K), using FSI technology. Dedicated targets [10] to avoid cryo-condensation and in-house feedthroughs have been designed and successfully validated through a series of test-setups [11] and in a tunnel environment on the first prototype of crab cavities [12].

SOLUTIONS FOR REMOTE ADJUSTMENT

Two solutions to perform the remote adjustment of components are proposed: one solution based on a Universal Adjustment Platform (UAP) for components with a weight below 2 tons, and a second solution based on HL-LHC jacks for components above 2 tons. In both cases, each adjustment axis (except the longitudinal one) is equipped with a motorized assembly to provide a remote adjustment stroke of ±2.5 mm.

UAP platform

This development is derived from a specific request from surveyors who are often in charge of the adjustment of components without having been involved in the design of the adjustment solution. In some of the cases, the design is not adapted to the limited access and harsh environmental conditions in tunnels. The proposed UAP is based on “universal block type” standardized units (jigs and joints linking a bottom and an upper plate), that can be adapted very easily by the team in charge of the design of the platform [13]. This platform fulfills very important functionalities:

- Having all the adjustment knobs on the same side (typically on the transport side) to ease the access.
- Providing intuitive and fast displacements, along 5 to 6 Degrees Of Freedom (DOF).

Two versions of the UAP have been developed: one for light components (with a weight below 300 kg), and another for heavier components (with a weight between 300 kg and 2 tons). The tests performed on a prototype of the large version confirmed the ergonomics and functionality of the platform with [14]:

- A non negligeable reduction of the time of alignment (gain of time by a factor 4 with respect to a standard type of platform).
- 3D adjustment accuracy better than 50 µm and 100 µrad.
- An installation repeatability within ± 40 µm.
- A micrometric resolution per axis over the whole stroke.

Three different modes of the UAP platform will be possible:

- A manual mode: an operator acting directly on the adjustment knobs in the tunnel,
- A hybrid mode: plugging temporarily motors and their mobile displacement unit on the adjustment knobs,
- A remote mode: equipping each adjustment knob with a permanently installed motor assembly.

HL-LHC jacks

Jacks developed for the LHC have been upgraded to fulfil the HL-LHC integration requirements and to integrate motor assemblies. The mechanical concept of the LHC jacks relies on a piston that is lifted (vertical displacement) or pushed (for a transverse displacement: either radial or longitudinal, depending on the orientation of the jack). Each jack allows displacements along 1 or 2 DOFs and will follow the configuration shown in Figure 2. Components at the extremities will be equipped with a fixed longitudinal anchor to withstand vacuum forces.

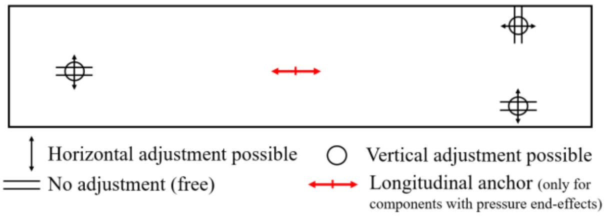

Figure 2: Adjustment configuration

The main functional requirements of the motorized jacks are summarized in Table 1 below.

Table 1: Motorized jacks’ requirements

Requirements	**Value**
Nominal forces on jacks: Vertical Radial Longitudinal	 > 172 kN > 21 kN > 27 kN
Long term stability of position	< 0.1 mm / year
Nominal operating torque on radial motor adjustment shaft	< 60 N.m
Minimum gap between cryostat and floor	340 mm
Possibility to insert/remove easily and quickly a motor assembly	Less than 3 minutes
Radiation hardness	2 MGy
Adjustable range: In horizontal directions In vertical direction	 > ± 10 mm > ± 20 mm
Motorized stroke:	± 5 mm

Specific mechanical adapters are under design, for both the vertical and the radial axes [15], that will allow the motorized operation of the jack (Figure 3). Concerning the radial adapter, a spline axis interface with an Allen key socket was selected as it provides a fast and ergonomic interconnexion between the adapter coupling and the jack axis. The 2-screw mounting and positioning process using two pins decreases the assembly and disassembly duration to less than 1 minute. Concerning the vertical adapter, several requirements had to be considered: the nominal load of 172 kN, the nominal movement speed of 20 µm/s at the output piston and its compatibility with the hydraulic jack used for the manual alignment. Two prototypes of vertical adapters were designed and tested: one based on a vertical level concept, the other one based on a hydrostatic elastomer (Polyurethane PU block, currently in use for the motorized jacks of the LHC low beta quadrupoles [16]). After satisfactory qualification tests for both prototypes, the second one (PU type) has been retained as simpler and smaller.

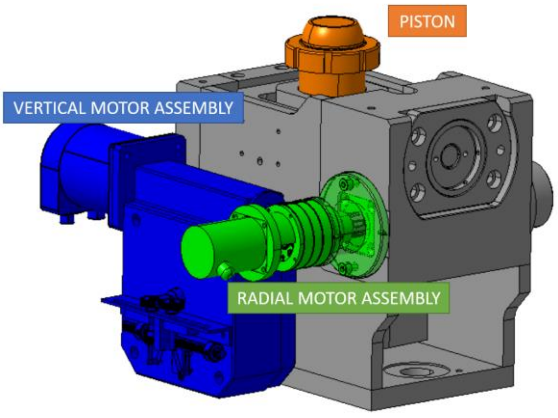

Figure 3: Motorized jack design

Motor assemblies

The motor assemblies, for both the UAP and HL-LHC jacks will consist of a mechanical interface adapter, a gearbox, a stepper motor, limit switches and a resolver integrated in such a way that it will provide an absolute position of the motor assembly. To ease the maintenance and limit the number of spares, the same stepper motors will be used for the UAP platform and for the radial axis of the HL-LHC jacks.

Each motor assembly will first be qualified on dedicated benches to control their main parameters (torque, backlash, hysteresis). The functionalities of the motor assemblies will be controlled first on a dedicated setup: a specific jack under load to control their resolution and range along 1 DOF, then on the single component test setup along 5 DOF and on the IT String test under real operating conditions.

ACQUISITION AND CONTROL/COMMAND SOLUTIONS

Figure 4 presents the layout of the acquisition and control/command solutions for the FRAS. To detect the position of components, two different types of acquisition and data processing systems are under development: one for FSI measurements with more than 1000 channels, the other one for capacitive measurements with more than 200 channels. The final number of sensors will be frozen after the qualification of the alignment strategy on the IT String setup.

A new FSI architecture has been proposed to optimize the design effort and the final cost. To deliver laser beams and acquire measurement signals from all the FSI sensors, the system consists of 4 racks. Each rack (providing 256 measurement channels) will be equipped with a photodetector data acquisition electronics, an FSI data processing GPU servers and 4 interferometer optical modules.

A high-performance field Sensors Acquisition and Motion Control system (SAMbuCa) system will provide a flexible and modular driving solution for the 400 motors with their corresponding resolvers [17]. It is an open hardware solution to maintain complete control on the source code and used hardware. SAMbuCa is based on high availability PXIe front ends and aims to complement the offer of the DIOT project [18].

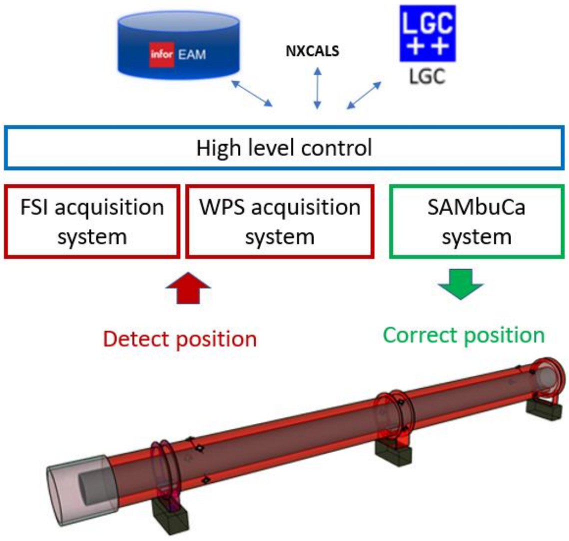

Figure 4: Acquisition and control/command layout

High Level Controls

The overall controls design follows a similar approach as the one used already in the alignment of the LHC low beta quadrupoles at CERN [19].

The CERN UNified Industrial COntrol System (UNICOS) [20] with SIEMENS WinCC OA SCADA (Supervisory Control And Data Acquisition) underneath will be used for the FRAS supervision layer. The control layer will be developed on top of the CERN Front-End System Architecture (FESA) framework [21]. It will be deployed in several type of front-ends running a real-time Linux operating system.

The supervision layer will ensure a graphical user interface for the operators, a data logging functionality in the CERN long-term database, the Next Accelerator Logging Service (NXCALS), storing and presenting Controls/Infrastructure related data gathered from thousands of devices in the whole accelerator complex, and the communication with other databases for the management of operational data.

The control layer will deploy an application running on Linux Front End Computers [22].

The front-end software will provide two distinct functionalities:

- A layer delivering the abstractions of the various sensors and actuators in an object-oriented design. It will perform real-time interactions with the hardware systems (FSI acquisition, WPS acquisition, SAMbuCa motion control, etc.) and implement their logic to provide engineering values as well as diagnostics capabilities to ensure integrity.
- A second layer including the algorithms to compute the required 3D positions via the least square adjustment software LGC++ developed by CERN [23] and the control of the motors to reach the nominal position.

RISK AND SAFETY ASSESSMENT

As FRAS will allow the remote alignment of components over more than 220 m on each side of the IP, it was mandatory to demonstrate that it can be operated and maintained without putting the LHC components or the persons intervening in the tunnel at risk, e.g., that risk control measures can reduce the risk to an acceptable level [24].

Hazard and risk analysis

The Failure Mode and Effect Analysis (FMECA) method was used to identify single equipment and system failure modes and their potential consequences. Four operational phases for FRAS were considered for such an analysis: a remote alignment mode (displacement of the components from the CERN Control Centre (CCC) with no personnel in the tunnel), a maintenance mode (FRAS experts in the tunnel), a pilot beam mode (displacements performed remotely while there is a low intensity particle beam circulating in the tunnel) and a high intensity beam (during which the alignment of components is not allowed and the FRAS corresponding motors are disabled). Different potential failure causes were identified in parallel: a FRAS power cut, a mechanical issue with a jack causing the magnet to drop and exceed the bellow limits, resulting in a damage to the interconnecting bellows.

Once the failure modes are identified, their criticality can be analyzed according to two parameters: the consequence as LHC downtime (in months or years) and the estimated risk frequency. These estimations are based on the LHC operational experience and recommendations from IEC 61511-3 standards. The necessary risk reduction for machine protection is then deduced from the acceptable risk established by the organization.

Two main risks were identified during FRAS operation:

- A damage at the level of an interconnection bellow, for which there would be a downtime of the LHC between 1 month and 1 year, with a frequency estimation bigger than 1 failure every 10 years and smaller or equal than 1 failure every year, requiring a risk reduction by a factor 100.
- A damage of the HL-LHC components (only during high intensity beam), with an estimated downtime of the LHC higher than 1 year and an estimated initial frequency bigger than 1 failure every 100 years and smaller or equal than 1 failure every 10 years, requiring a risk reduction as well by a factor 100.

Concerning personnel protection, the risk analysis demonstrated that the risk for personnel is less critical than for the LHC machine due to the limited exposure time of workers in the tunnel and all the other means put in place to avoid the hazard: safety procedures, escape routes, oxygen deficiency hazard detectors, etc.

Mitigation of hazard and risk

The hazard identification and risk assessment showed that a risk reduction for the machine protection by a factor 100 is needed. According to the IEC 61511-3, this can be achieved by the design and development of a SIL1 (Safety Instrumented System) with certified devices and very strict safety requirements, or by applying at least two independent Protection Layers (PL). The second solution was chosen as SIL certified radiation tolerant hardware for FRAS would be both, a technical and a cost challenge. According to IEC 61511-3 Annex C and F, a risk reduction of 10 can be claimed by each of the PLs, if they meet the following criteria: specificity, independence, dependability, diversity, and auditability. In our case, in addition to operational procedures and operator alarms, two instrumented PLs should be installed since total independence and diversity between these instrumented PLs will be very hard to achieve.

For FRAS, two to three instrumented PLs will be implemented to mitigate the risk of bellow damage during the relative displacement between two adjacent components. They will allow stopping immediately the displacement before a safety limit is reached. These PLs will be based on three different technologies to determine the 3D position of components and therefore the position of the bellows:

- Capacitive technology,
- FSI technology (not available for all degrees of freedom),
- Motor resolvers used as absolute position sensors.

To avoid any damage of components because of its misalignment when a high-intensive beam is circulating, the correct alignment of the entire equipment chain will be checked before each beam injection. On top of this, a mechanical key located at the CCC will allow disabling the FRAS motors.

Both statuses will be integrated into the CERN Beam Interlock System [24].

The hazard identification and risk assessment as well as the design of the protection layers [25] has been endorsed by the CERN Machine Protection Panel and the concerned equipment owners. The next milestone will be the finalization of the FRAS control system layout and software architecture towards the preparation of the final FRAS system.

OVERALL QUALIFICATION STRATEGY

As it will be the first time that the FRAS is installed on such a scale and given that the system integrates different technologies, at different levels of development readiness, an overall qualification strategy has been put in place, in different stages:

- 1st stage: individual qualification of all types of sensors and motor assemblies,
- 2nd stage: validation of the full strategy: from the sensors and motor assemblies to the acquisition and control/command systems and software on one single component, at warm,
- 3rd stage: validation on the IT String Test facility, consisting of six full-scale HL-LHC magnets

interconnected and cooled down at 1.9K during two thermal cycles [26].

1st stage: individual qualification

As introduced before, all sensors and motor assemblies, their acquisition and control/command systems will undergo an individual qualification process.

2nd stage: validation on a single component

The whole FRAS strategy from hardware to software will be validated on one single component: an LHC prototype dipole with an approximated weight of 20 tons named Twice Aperture Prototype (TAP). The TAP will be equipped with a redundant configuration of sensors to compare and qualify the different types of alignment sensors: capacitive WPS, FSI-based HLS and inclinometers. It will be supported by HL-LHC motorized jacks. The layout is shown on Figure 5.

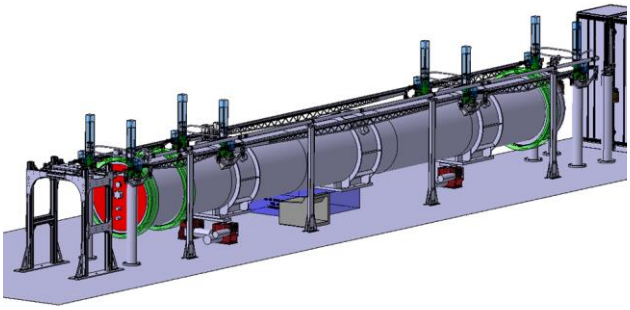

Figure 5: Layout of the single component test-setup.

The objectives of this test-setup are, firstly, to define and prepare all the installation procedures for all the components: from the jacks to the sensors and motor assemblies. Secondly, to implement the whole acquisition and control/command chain on one component. We will check that the interfaces between front-end software layers are correctly defined and implemented. Thirdly, we will test the position adjustment algorithms and the compliance of the PL interlock logic to finalize the software strategy and prepare the IT String test.

3rd stage: validation on the IT String test

This facility will allow the full-scale integration and operational qualification of the superconducting magnets from the IT quadrupoles up the first separation dipole. These 6 interconnected components will be operated at nominal conditions under vacuum and at a temperature of 1.9 K. The FRAS will be deployed in a more redundant configuration than foreseen in the tunnel to perform cross-comparisons between the different alignment systems. 28 WPS, 28 HLS, 4 inclinometers and 6 FSI sensors for the longitudinal position, with their associated wire stretching devices, wire protection, hydraulic network will be installed and commissioned. The internal position of the cold masses of the IT quadrupoles will be monitored for the first time on interconnected cryo-magnets using the FSI. This complete configuration will allow a better understanding of the cold masses position inside their cryostat during a full thermal cycle.

All jacks will be equipped with their motor assemblies and the whole process of remote alignment will be qualified, including the risk mitigation measures.

Some components that will be part of the FRAS in the LHC tunnel (such as collimators) are not part of this IT string test. Specific parameters like adjustment algorithms will be qualified on a dedicated facility that will consist of two collimators (with a representation of their adjacent main components).

CONCLUSION

For the first time, the Full Remote Alignment System will allow the remote alignment of components over more than 220 m on both sides of IP1 and IP5, within a stroke of ± 2.5 mm and an accuracy of ±150 µm. The remote position of the components will be determined by alignment sensors: a redundant configuration of WPS, HLS and inclinometers, while the adjustment will be performed by motorized adapters plugged on jacks or Universal Adjustment Platforms.

A clear and thorough qualification procedure has been put in place, ranging from individual tests on the sensors and motor assemblies to an overall system qualification as part of the IT string test scheduled to start in 2024. An intermediate qualification on the single component test-setup is being put in place to converge on the last design details.

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