Chapter 15

Integration, (de-)installation and alignment

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15 Integration, (de-)installation and alignment

15.1 Overview

The HL-LHC will require modifying the machine and infrastructure installations of the LHC in several points along the Accelerator Ring, in particular: P1, P2, P4, P5, P6, P7 and P8.

Part of the modifications and improvement in P2, P4, P7 and P8 shall be completed during Long Shutdown 2 (LS2) and be operational for LHC Run 3, while the largest part of the interventions will take place in Long Shutdown 3 (LS3) and they will affect primarily P1, P4, P5, P6 and P7. The activities required point by point will be therefore listed and analysed here below.

The Project evolution has allowed and obliged to revise and refine the previous integration plan. Here below the main changes are singled out

- Point 1 and Point 5
  - The LHC Machine layout has been made compliant with the optics version 1.4 that integrates the deployment of the Full Remote Alignment and the results of the matching section optimization. The present layout is based on updated and refined equipment designs considering the progress of the engineering design of each system. This includes in particular: magnet cryostats, DFX, Crab Cavity cryo-modules, collimators that have all seen important evolution in their design.
  - The system optimization implied a revision of the localization of some of the equipment, i.e. the power converters feeding the circuits of the Higher Order correctors magnets that are in the Corrector Package have been moved from the new HL-LHC underground infrastructures to the service alcoves of the LHC tunnel.
  - Following the refinement of the services design and the machine equipment requirements, the full integration in the new HL-LHC underground infrastructures has been reviewed. The integration activity in this area is strictly linked to the finalization of the construction design of the caverns that are being built during LS2.
  - In a similar way, and for the same reasons, the integration of the new surface buildings and the connecting technical galleries has been revisited in detail, leading to an optimization in the gallery topology and refinement in the building design.
- Point 4:
  - The cryogenic system upgrade at Point 4 has been reviewed. In order to support the operation in Sector 3-4 (that is fed by a refrigerator unit inherited from the LEP machine) the refrigerator will be upgraded, but without impacting the cryogenic distribution network. The previously foreseen mobile

refrigerator that was foreseen to cool the LHC RF accelerating cavities for testing and conditioning purposes has been abandoned.

  - o The conceptual design of the Hollow-Electron Lenses has been integrated in the tunnel together with their services validating the design choices.

- Point 6
  - o The previous foreseen upgrade of the Q5 units has been abandoned. The presently installed units will be operated in the HL-LHC configuration as they currently are in the existing LHC configuration.
  - o The horizontal beam dump dilution kicker system is planned to be upgraded with the installation of 1 additional kicker module for each beam.
  - o The Beam Dump block will be upgraded already in LS2 with new upstream windows. Additionally, the dump block will be mechanically separated from the beam dump line and its support system modified to allow for an improved absorption of the shock waves during beam impact.
  - o The entire Beam Dump block is planned to be replaced during LS3 in preparation for the HL-LHC exploitation.

15.2 Point 1 and Point 5

The largest part of the new equipment required to meet the HL-LHC performance objectives will be installed at P1 and P5. The items to be installed and actions to be carried out are listed below and are applicable to both points, if not otherwise specified. The list is organized by geographical areas.

15.2.1 LHC machine tunnel

De-installation:

- All the accelerator equipment from the interface with the experimental cavern (TAS included) until the Q6 (excluded) needs to be removed from the Interaction region on the Right and Left side of the IP (so defining a "Q6L-Q6R" zone).
- In a similar way, all the cabling in the Q6L-Q6R region has to be removed. The present cables and optical fibres will be of three families:
  - o Cabling linked to LHC equipment in this area and that has therefore to be de-installed and to be replaced with the new HL-LHC equipment (ex. triplets, D1, D2 magnets and their ancillary equipment).
  - o Cabling linked to the machine equipment not affected by the HL-LHC modifications, but that are passing through the Q6L-Q6R region and that need to be de-installed to permit the execution of the Civil Engineering (CE) activities in the area.
  - o General services and safety systems cabling passing through the Q6L-Q6R region.
- In the same area, the present QRL will also have to be removed. A new return module will be installed in the region between the Crab Cavities and the Q4. This element will allow separation of the coolant flows coming from the LHC QRL and the one of the new HL-LHC QXL. The HL QXL will feed the part of the machine from Q1 to the Crab Cavities included. This return module should also provide the possibility, if required, to connect the LHC QRL with the HL QXL, ensuring an increased level of redundancy in the system. The LHC QRL between the Crab Cavities and the Q6 will be reassembled re-using as much as possible the previous QRL elements but re-installed in order to cope with the different optical positions of the Q4 and Q5 magnets.
- It will be necessary to remove all the services linked to the above mentioned equipment that will be de-installed, and also all the services that could obstruct the opening of the vertical cores that will link the

HL-LHC new infrastructures with the LHC tunnel (e.g. cables trays, cooling pipes, ventilation ducts, part of monorail system, etc.).

- Opening of the vertical cores linking the HL-LHC new infrastructures with the LHC tunnel: these cores will be not excavated when the new main HL-LHC cavern will be created, but only later at the start of LS3 and therefore after the completion of LHC Run 3. The activity will take place well after the completion of the underground HL-LHC complex.

Preparation for re-installation:

- Minor works could be necessary in order to prepare the tunnel floor and wall to receive the installation of the new equipment (for larger and dedicated CE activities see the next paragraphs).
- Re-install the general services and safety system cables with their needed supports and ancillaries.
- Re-install general services equipment previously dismounted (e.g. cooling pipes, ventilation ducts, part of monorail system, safety equipment, etc.).

Installation of the new equipment, probably in the following sequence:

- TAXS (the installation of the TAXS will take place from the experimental caverns of P1 and P5 and the therefore this activity is strictly linked with the upgrade program of the experiments);
- QXL with related valve and service modules;
- Magnets, Crab Cavities, TAXN and collimators support systems;
- Magnets, Crab Cavities and TAXN;
- distribution feedboxes (DFX) for the Q1 to D1 magnet system and distribution feedboxes (DFM) for the D2 magnet;
- Super Conducting (SC) link section from the DFM till the D2;
- Collimators.

The sequence of installation of the vertical SC links (DSHX and DSHM) to be connected to the DFX and DFM still needs to be assessed according to the options retained for their routing.

Figure 15-1: 3D integration model of the high-luminosity insertion regions of IR1 and IR5 of the HL-LHC machine. From left to right: Q1, Q2, Q3, D1, Corrector Package, DFX, DFM, TAXN and collimators, D2, 2 Crab Cavities cryo modules, Q4.

15.2.2 Existing LHC tunnel service areas

The caverns hosting the Matching section power converters (named with code RR) on both sides of IP1 and IP5 will need to be re-organized, and in particular the following actions will be necessary:

- De-install the power converters and other related systems (e.g. the quench detection system) linked to the powering of the removed LHC D2 magnet as it will be fed via a new SC link (DSHM) and the related DFM.

- Re-organize the remaining equipment in order to have the most efficient space occupation, increase if necessary and possible the radiation shielding, and place the most radiation-sensitive equipment in the most protected areas. Possible replacement of equipment with new, radiation-tolerant designs can be envisaged.

In the bypass caverns around the experiments of Point 1 and Point 5 (named USC55, UL14 and UL16) the presently installed power converters (dedicated to feed the LHC final focus quadrupoles) will be removed. Racks belonging to the magnet protection system and low current power converters (120 A and 200 A) will be installed at those locations.

At present, no CE work interventions are foreseen in the RRs areas.

15.2.3 The new HL-LHC underground service areas

15.2.3.1 General concepts

The installation of the new cryogenic plants in points 1 and 5 provide independent cooling capacity to feed the final focus and the part of the matching section till the D2 including the Crab Cavities.

The lower corresponding cold boxes will be installed in new underground caverns. The maximum difference in level between the lower cold box outlet and the new QXL distribution line shall be less than 20 m. Points that need to be considered:

- The above-mentioned maximum allowed height difference of 20 m.
- The need to build connection galleries to distribute the cryogenic fluids from the cold box to the left and right of the IP.
- The advantage for the Crab Cavities to have the RF equipment installed in the proximity, providing easier exploitation, and simplifying the equipment installation.
- The possible synergy with the magnet power converter system installation.
- The lack of space to integrate the RF waveguides or coaxial lines in the LHC tunnel.

For the construction of the new underground caverns and galleries, the HL-LHC project has identified the following list of systems that need to be integrated:

- The cold boxes and the connection to the QXL.
- The RF ancillaries (powering and control, space will be reserved for a possibly doubling of the HL-LHC baseline Crab Cavities system at a later moment of the HL-LHC operation).
- The magnet power converters.
- The systems required for connecting the power converters to the magnets (distribution boxes and superconducting links).
- The related technical services (cooling and ventilation, electrical supply, access control systems, technical networks, etc.).
- The necessary safety related equipment (smoke extraction, firefighting equipment safety room, etc.).
- Main part of the magnet protection system, of the survey electronics and of the beam instrumentation electronics.

The installation approach shall guarantee the access to the power converters, the relevant part of the RF ancillaries and to the survey and beam instrumentation electronics also during periods with beam present in the machine (‘beam-on’). The underground cavern location/design and the equipment installation implies that none or only very limited amounts of radiation will come from the LHC to the new areas and that there will be no risk of oxygen deficiency in case of He release from the cryogenic system installed in the LHC machine.

The proposed solution has been identified with the nick name of "double decker" (See Figure 15-2 and Figure 15-3). Superconducting links and the RF ancillaries will be installed in the UAs that extend from the UR gallery (located parallel to the LHC machine tunnel at a distance of about 40 m) to the top of the LHC machine in a vertical point as close as possible to the equipment that needs to be connected. In this connection point, the rock layer between the LHC tunnel vault and the UL galleries will be about 7 m. Vertical cores will provide the path through which the cryogenic lines, the SC links and the RF powering will descend towards the LHC tunnel. To guarantee escape paths to safe areas for all the envisaged incident scenarios it has been decided to build two escape ways (UPR) joining the UA extremities to the LHC tunnel.

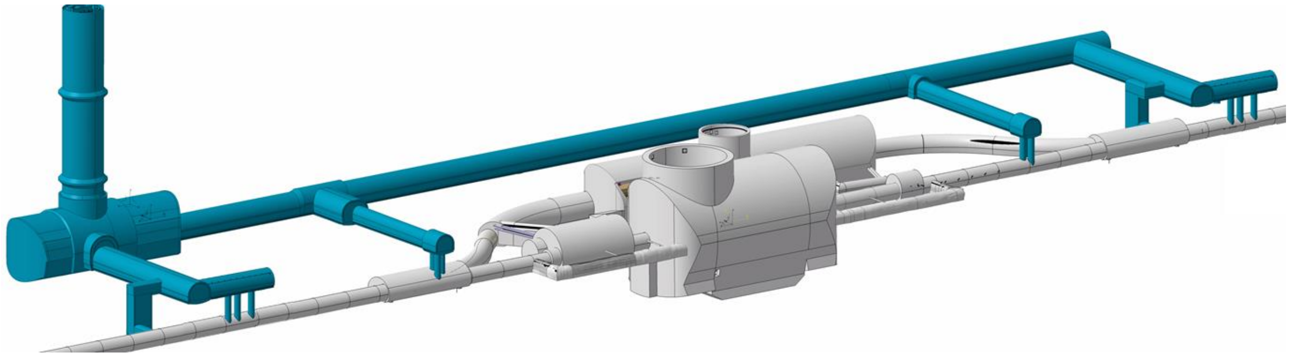

Figure 15-2: Axonometric view of the HL-LHC underground Civil Engineering infrastructures as it would appear in IP5.

The main elements of the new underground structures and their code names are visible in Figure 15-3:

- PM: shaft joining the surface to the underground structure.
- US: cavern for the installation of the cryogenic cold box.
- UW: physically part of the US caverns, but separated from it by a fire-resistant wall, the UW will house cooling and ventilation equipment.
- UR: gallery parallel to the LHC tunnel, about 40 m away, and extending from the location of the Crab Cavities system on the right of the IP to the point where the Crab Cavities are installed on the left of the IP. Approximately 300 m long.
- UA: two galleries per LHC point, distributed symmetrically with respect to the IP and joining the URs to a position on top of the Crab Cavities installed in the LHC tunnel.
- UL: two galleries per LHC point, distributed symmetrically with respect to the IP and joining the URs to a position on top of the DFX (near the D1 magnet) installed in the LHC tunnel.
- UPRs: safety exists joining the UAs with the LHC tunnel and providing a second escape way towards the main LHC tunnel in case the PM could not be reachable.

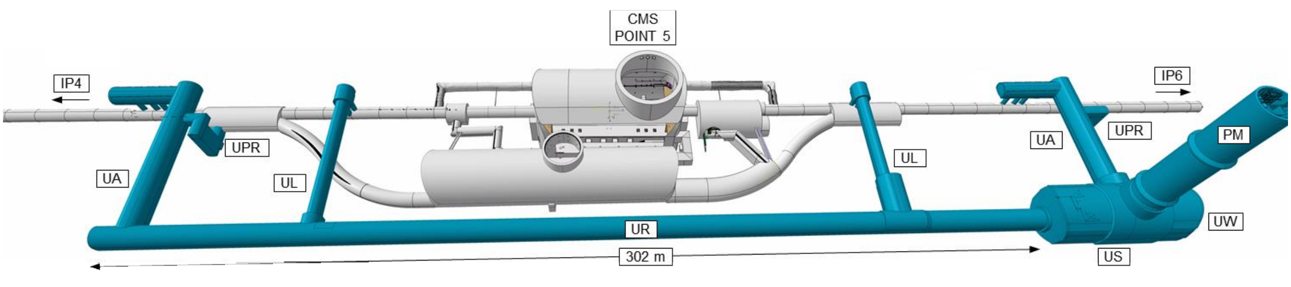

Figure 15-3: Top view of the HL-LHC underground Civil Engineering infrastructures as it would appear in IP5 with the relevant underground code names.

In the following paragraph the installation approach for the many equipment will be discussed.

15.2.3.1 The cryogenic installation

The HL-LHC lower cold box cryo-line (see Figure 15-4) will join the distribution box in the alcove of the nearest UL. From this distribution box, two cryo-lines will exit feeding the QXLs left and right of the IP. The first one would run along the UL and connect into the LHC tunnel via a vertical core. The second will run through the UR length and then (as for the first one) will join the other UL and will descend down through the core to be connected to the LHC QXL.

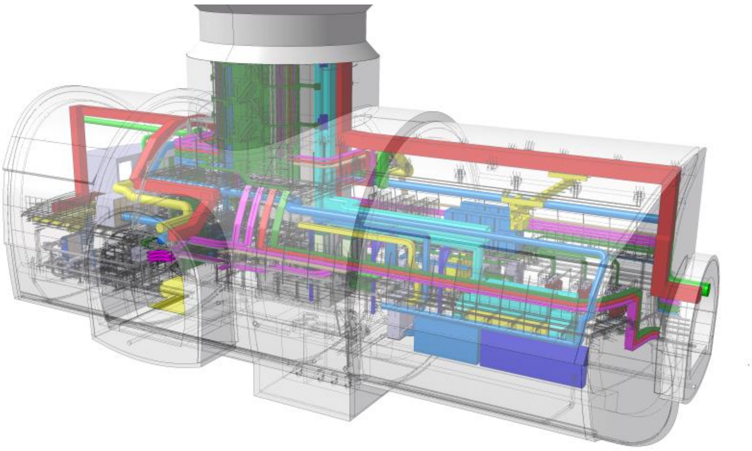

Figure 15-4: The cavern (US) hosting the cold box (in the image in light blue on the front right) with other technical services.

15.2.3.2 The superconducting links

There are four Superconducting links per IP, two per IP side. The largest in section (code name DSHX) will connect the dedicated current leads system (code name DFHX) to the distribution feed box in the LHC tunnel (code name DFX) in order to feed the superconducting magnets installed from Q1 to D1. The second one, smaller in section, but longer, (code name DSHM) will connect the current leads (installed in the DFHM) to the distribution feed box DFM dedicated to feed the D2 magnet along with its correctors.

The DFHX and DFHM will be installed in the URs near the power converters that will feed them and as close as possible to the ULs (Figure 15-5). The Superconducting links will reach, through the UL and together with the cryo-lines, the vertical crossing of the LHC and then will descend down through cores to be connected to the DFX and DFM that will be installed in the LHC tunnel on top of the beam line for the DFX and on top of the D2 for the DFM (Figure 15-6).

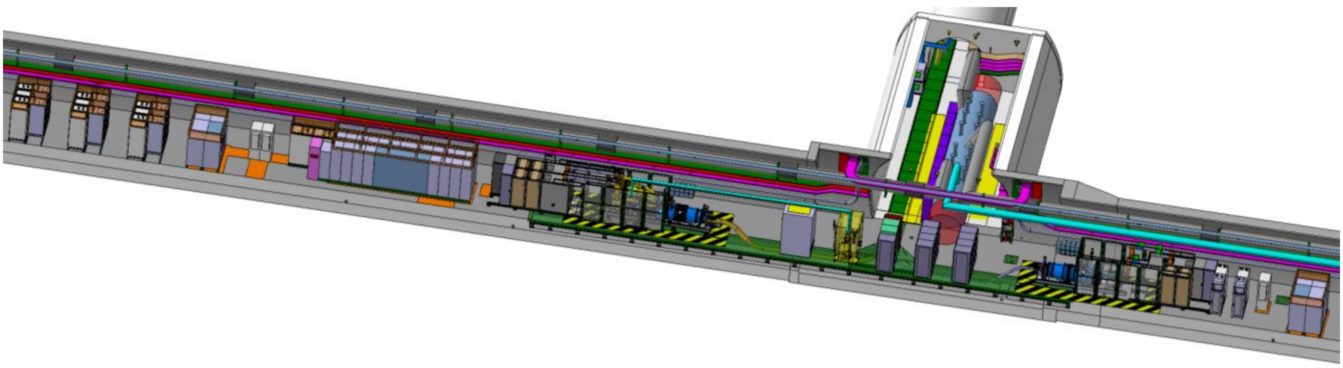

Figure 15-5: Installation of the DFHX and DFHM in the UR and routing of the SC links towards the UL. Externally, with respect to the two feed boxes, the Power Converters connected to the relevant circuits are installed. The related Energy Extraction units, when present, share the same locations.

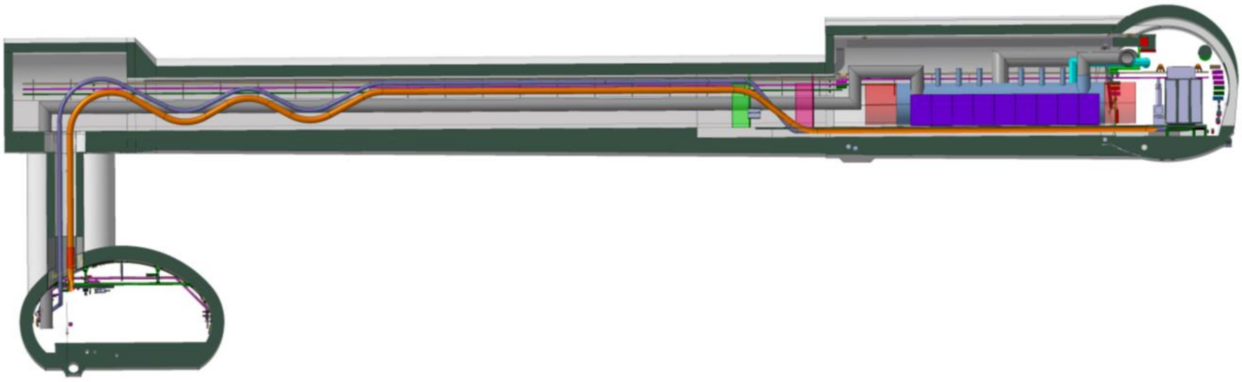

Figure 15-6: The UL gallery with the routing of the cryogenic and Superconducting link towards their vertical connection with the LHC machine tunnel.

15.2.3.3 The Power converters

The power converters connected to the DFHX and DFHM will be installed in the URs (8) in the vicinity of these two units and connected via a network of warm cables, water cooled cables, solid copper bus bar and switches (CDBs) assuring personnel safety via through an electrical separation of the magnet string during interventions and ELQA campaigns. The power converters are the main source of space requirement and of ventilation cooling capacity requirement in the URs. Therefore, any possible optimisation on the electrical scheme (reduction of the number of circuits or of the circuit current) will have a relevant impact on the underground space requirement and on the required ventilation cooling capacity to be installed in the URs.

15.2.3.4 The RF ancillaries

The waveguides joining the RF superconducting cavities to the circulator will require two large cores per IP side (Figure 15-7). The two safety escape ways (UPR) to the LHC tunnel will represent the two paths through which radiation could propagate from the LHC machine into the UA and therefore to the UR. The foreseen layout is:

- Vertically to the position of the Crab Cavities in the LHC tunnel, three large cores will be drilled: two for the Crab Cavity feeding (each one housing two waveguides), one for the instrumentation and control cables. The latter will also house some recently added small piping (warm cryogenic piping, water, and compress air)
- Opposite to the Crab Cavities, the waveguides will exit inside the UA tunnels, running parallel and on the top of the LHC tunnel and separated from it by about 7 m of rock.
- In the UA tunnels the waveguides will be connected to the respective loads and circulators. These elements are not radiation sensitive and therefore they will be installed just at the exit of the cores or further inside the UAs. Such arrangement will allow reducing the waveguide length, facilitating the installation of the maze required for radiation attenuation.

A maze will be installed at the junction of the gallery and the UAs in order to reduce the influx of radiation to a level allowing access during beam operation also in case of accidental beam loss scenarios (defined by the Radio Protection as the theoretical loss of the full beam intensity on a massive block placed under the entrance of the cores along the LHC beam trajectory). Solid-state amplifiers and RF power supplies will be installed in the UAs, between the maze and the junction between the UAs and the URs, and they will be connected to the circulator by coaxial cables. The RF control racks will be placed in a shielded Faraday cage. The safety escape ways (UPRs) have been designed in order to fulfil the same radiological requirements.

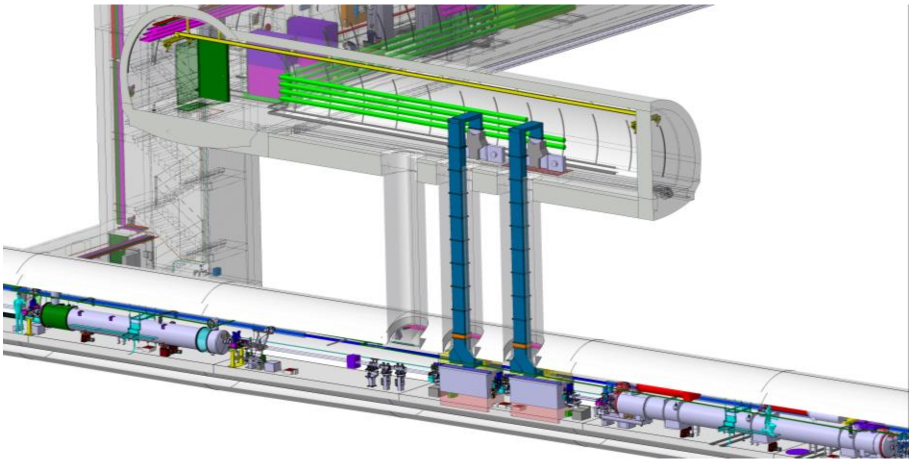

Figure 15-7: The axonometric view of the UA with the waveguides providing RF powering to the Crab Cavities installed in the LHC and the tetrodes installed along the UA.

15.2.4 New surface installation

With the adoption of the double decker solution, all the systems directly linked with the HL-LHC machine equipment will be installed underground with the exception of the warm compressors of the cryogenic plants. On the surface it will be necessary to construct, both at Point 1 and Point 5, new buildings to host the general services. Detailed descriptions of these buildings and of the equipment to be installed there are not the objective of this Chapter, and therefore the description will be limited to the list of the required buildings and their main functions:

- SD: access to the PM shaft connecting the surface to the new underground US-UR complex;
- SU: ventilation service building;
- SE: electrical service building;
- SHM: compressor building;
- SF: cooling towers.

In addition, various technical galleries and concrete platforms for equipment support to be installed in open air will be required.

The layouts for the Point 1 and Point 5 are depicted in Figure 15-8 and Figure 15-9.

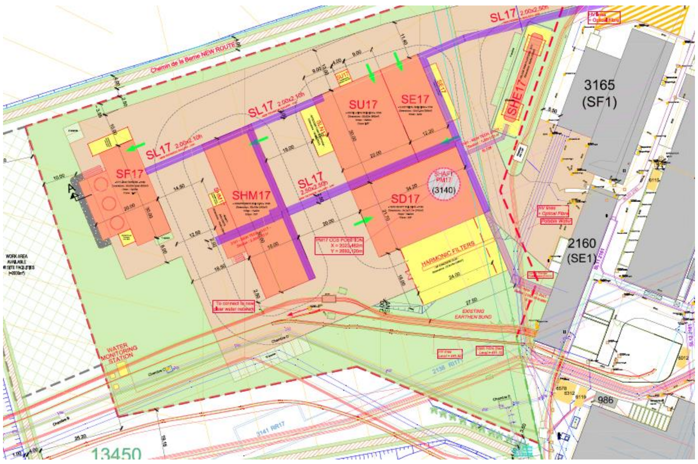

Figure 15-8: The LHC Point 1 with the new HL-LHC surface buildings in orange. Simple concrete slabs are highlighted in yellow.

Figure 15-9: The LHC Point 5 with the new HL-LHC surface buildings in orange. Simple concrete slabs are highlighted in yellow.

15.2.4.1 Activity sequence considerations

Concerning the execution of the underground works, vibration propagation studies and LHC optics studies have revealed the elevated risk to perturb LHC beam operation if the activities of excavation would be performed during LHC Runs. Consequently, the project has anticipated the majority of excavation during the LS2 in order to avoid any risk for LHC operations. In order to avoid interference of the main HL-LHC CE activities with the LHC tunnel in the LS2, the completion (opening) of the vertical cores between the new underground infrastructures and the LHC tunnel will be dug and finished only during LS3.

For what concerns the installation, while the sequence of interventions on the underground LHC installed equipment (in LHC and RR Tunnels) is quite clear and linked to the end of the LHC Run 3, the sequence for the other installation and surface CE activities is still under evaluation.

15.3 Point 2

In order to limit the heat deposition from secondary beams on the superconducting magnets during the ion run, TCLD collimators in the dispersion suppressor will also be installed in P2 (Chapter 5). The installation will take place only in one slot on each side of the IP (presently occupied by the interconnection cryostat LECL.11L2 and LECL.11R2, in the regions from 419 m to 432 m from the IP on each side). The initially proposed strategy relying on the installation of two 11 T units with the related by-pass and TCLD collimators has been changed in replacing the interconnection cryostat with a modified version of the by-pass cryostat developed for the TCLD collimator installation in P7 (chap.11). This approach is much more cost effective, and it has been made possible thanks to the study and tests performed during Run 2 that have confirmed the possibility to steer the secondary ion beam to be intercepted by the TCLDs installed in these locations.

In Point 2 it will be also necessary to upgrade the primary injection absorbers (TDIS). The new TDIS will be at the same position as the present TDI as it needs to be at 90° betatron phase advance relative to the MKIs. To equip the two injection regions, two TDISs units are required. They will be installed in the Long Straight Sections (LSS) in IP2 left side (82 m from the IP) and the other in IP8 right side (78 m from the IP). The intervention at Point 2 will be completed by the movement of the TCLIA by 2.2 meters towards the IP (auxiliary collimator). This change is performed to increase the acceptance of the Zero-Degree Calorimeter of ALICE.

All installation in IP2 will take place and be completed during LS2.

15.4 Point 4

15.4.1 Cryogenic system upgrade

P4 will receive an upgrade of the cryogenic system to address the additional cryogenic load from the new installations.

15.4.2 New beam line elements

The following elements are foreseen to be installed in the long straight section at Point 4 for the HL-LHC. Their installation will take place in LS2 and LS3:

- **Synchrotron light diagnostics:** New synchrotron light diagnostics, looking at photon emission from the D4 bending magnet. It will be installed on the beam heading to IP4 and it will also include a new extraction mirror located ~20 m from D4 toward D3 and an optical path to bring the synchrotron light to a light detector located in a hutch in the UA gallery. The optical line will be installed through a duct to be drilled in the shielding wall. This installation is foreseen on both beams, one on each side of IP4.
- **Synchrotron light monitors**: The present synchrotron light monitor's undulator magnet, installed on the beams heading away from IP4, will be upgraded and optical hutches will be installed in in the UA's galleries. This will require to install an optical path and drilling the corresponding ducts in the RA-UA shielding walls.
- **High Bandwidth BPM:** To support the Crab Cavity operation in Pt1 and Pt5, two High Bandwidth BPMs will be installed on each beam and on each side of IR4, substituting the current head-tail monitors.
- **Hollow Electron lenses**: They will complete the collimation system by providing an active control of the beam halo population and therefore the beam loss rate in the collimation regions of IR3 and IR7. The Hollow Electron lenses will be equipped with BGC (Beam Gas Curtain) monitors to visualize the position of the beams and their overlap inside the equipment. A prototype of the BGC will be already installed in LS2 for development purpose.

The Hollow Electron lenses require transverse space that is only available in the central region of the long straight section at IP4, between D3 Left and D3 Right, where the beam separation is 420 millimetres.

15.5 Point 6

Quench tests and optics optimization have led to reconsider the necessity to increase the nominal field of the two Q5 units installed left and right of IP6. Therefore, there is no more necessity to intervene on the cryogenic distribution line and on the Q5 assemblies to lower their operating temperatures to 1.9 K.

The horizontal beam dump dilution kicker system is planned to be upgraded with the installation of two additional kicker modules. The Beam Dump block will be upgraded already in LS2 with new upstream vacuum windows. The entire Beam Dump block is planned to be replaced during LS3 in preparation for the HL-LHC exploitation. The impact on integration and installation of these activities planned for LS3 is object of ongoing studies.

15.6 Point 7

In order to protect the superconducting magnets (by excessive heat deposition from off-momentum proton leakage from the main collimator system itself), some special collimators (TCLD) must be installed in the dispersion suppression region, i.e. in the continuous arc cryostat. The installation of these collimators will take place during LS2.

In order to cope with the proton losses in the dispersion suppressor area it has been decided to install two TCLD collimators on each side of the IP. In order to do so it will be necessary to:

- Remove MB.A9L7 and the symmetric MB.A9R7.
- Substitute each removed dipole with a unit composed of two 11 T dipoles (Chapter 11) separated by a cryogenic bypass.
- Install the TCLD collimator on top of the cryogenic bypass (Chapter 5).

The magnet installation will also require a new dedicated quench protection system and a trim circuit with its own power converter. The 600 A power converter for the trim circuit will be installed in the nearby RRs.

15.7 Point 8

As mentioned in the Point 2 activity description, a new primary injection absorbers (TDIS) will be installed also in Point 8 in the LSS.

In addition, as LHCb will see the delivered luminosity increased after the Long Shutdown 2, two absorbers of neutral debris are necessary to protect the D2 magnets. The two masks denominated TANB will be installed at ±119 meters symmetrically with respect to IP8. In order to increase their efficiency, it is necessary to displace the horizontal and vertical tertiary collimator installed in the zone in order to create the space as near as possible to the magnet to be protected.

All equipment in P8 will be installed during LS2.

15.8 Alignment and internal metrology

15.8.1 General objectives, requirements, and constraints

The HL-LHC performance heavily relies on precise and accurate alignment of the magnets, RF systems and beam diagnostics components. The alignment and internal metrology of these components can be divided into three steps: the fiducialisation, the absolute alignment of the components w.r.t. the underground geodetic network (“standard alignment”) and the relative alignment (“smoothing”) of the components using sensors and actuators to determine their position and re-adjust them remotely.

In the HL-LHC, the monitoring of cold masses inside each cryostat of the inner triplet combined with the continuous determination of the position of each cryostat, will considerably improve the alignment of the inner triplet compared to the LHC era. This new instrumentation will allow monitoring the cold mass displacements occurring after cool-down, due to mechanical stresses. The mechanical axes of the magnets from Q1 to Q5 shall be included in a cylinder with a radius of 0.10 mm. The fitting of all mechanical axes of these magnets located on the right side of the IP shall be included in a cylinder with a radius of 0.15 mm w.r.t. magnets located on the left side of the IP (Figure 15-10) [1].

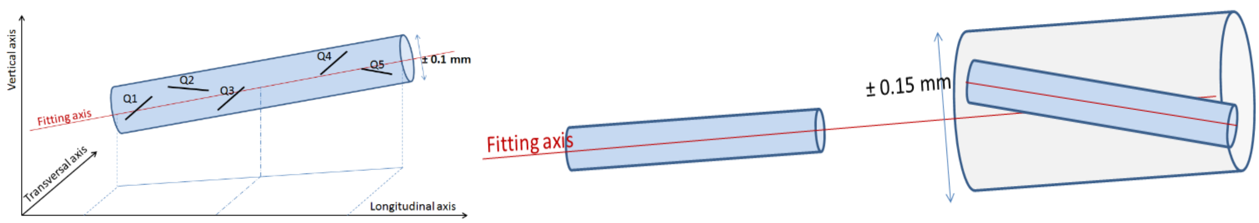

Figure 15-10: The HL-LHC alignment requirements

The Full Remote Alignment (FRA) of all the components from Q1 to Q5 will provide the capability to perform a complete and rigid remote alignment from the CCC of all the components of ±2.5 mm, if the machine components are misaligned w.r.t. the detector inner tracker [2]. Such correction will be applied after having circulated a first pilot beam that will provide a unique and efficient reference. The FRA will also allow correcting ground motions remotely during one year of operation to another. A thorough study performed on all the intermediary components has classified the machine components as capable to accept misalignments of ±2.5 mm (“ remote alignment compatible”) w.r.t their adjacent components (e.g. vacuum components with sufficient aperture) or needing to be equipped, as the main components, with remote adjustment and position determination capabilities [3].

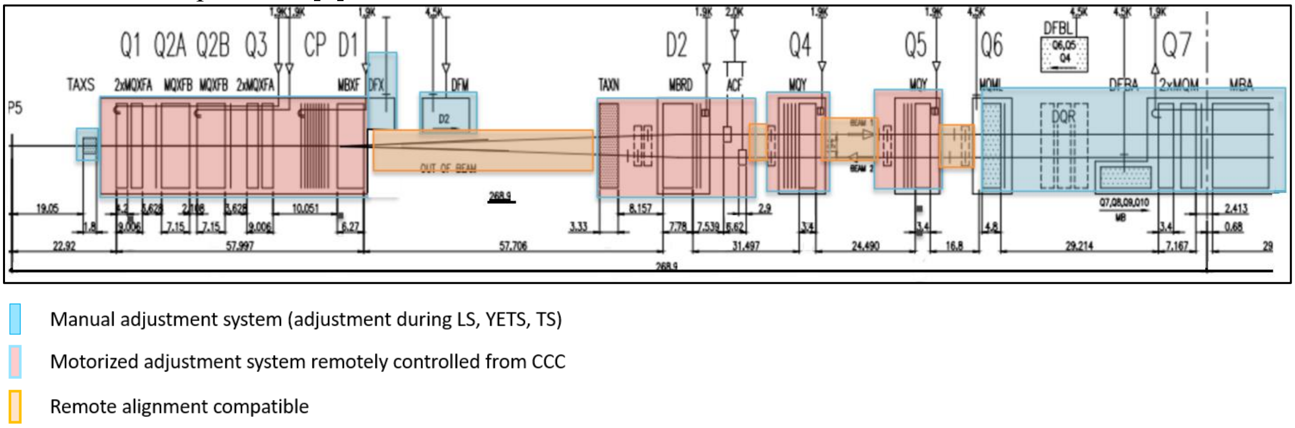

Figure 15-11: Full Remote Alignment system applied to the HL-LHC 1.4 optics

On top of the increase of the window for machine operation, the FRA will allow a reduction of radiation doses taken by surveyors. It will decrease the required strength of orbit correctors and will provide an increased level of machine flexibility. In addition, the derived equipment simplification has opened up the possibility to re-optimize the matching sections leading to the present HL-LHC optics v1.4.

15.8.2 Internal metrology

The determination of the coordinates of the fiducials (or alignment targets), located on the vacuum vessel of the cryo-assembly magnets, w.r.t. the as-built mechanical and magnetic axis of the quadrupoles and dipoles, is the basic information necessary for all further alignment actions and it is the object of the fiducialisation process [3][4]. Each cryostat will be equipped with redundant 1.5-inch fiducials. Considering the lessons learnt from the LHC, the following improvements of the internal metrology will be implemented:

- The straightness of the cold mass and the position of the vacuum pipe will be controlled during the manufacturing phase of the cold masses.
- The position of the cold mass inside the cryostat will be controlled after the manufacturing phase within an uncertainty of measurement of ±0.1 mm.
- Additional reference points on the cold mass extremities will increase redundancy and allow to re-fiducialise the magnets in-situ if needed and to perform additional geometrical controls of the interconnection areas.
- The positions of the fiducial targets on the cryostats and of the interface points with the jacks will be measured and re-adjusted if needed after magnet assembly to allow for the full range of the alignment system.
- The same procedure as in the LHC will be carried out to determine the mechanical position of the BPM, the beam screens and the cartography at the ends of each cryo-assembly [5].

15.8.3 Internal monitoring of cold masses and crab cavities inside their cryostat.

As described in Ref. [1], the position of the mechanical axis of each Inner Triplet magnet, w.r.t. the fiducials installed on top of the cryostat, will have to be known within ±0.1 mm (1σ). Such budget of error includes the error of fiducialisation and the error of the cold mass monitoring.

To fulfil such requirements, it is proposed to use Fourier analysis-based Frequency Scanning Interferometry (FSI) [6]. This system performs absolute distance measurements between the ferule of one optical fiber and multiple targets. This CERN designed FSI has the advantage of being less sensitive to the variations of intensity of the reflected optical signal.

The position of the cold mass inside its cryostat will be monitored at three sections by four distance measurements (Figure 15-12). The optical fiber is inserted in a feedthrough on the cryostat; the mechanical reference of the optical fiber has been determined during the calibration process w.r.t. external targets placed on the feedthrough. Once the cryostat is installed in the accelerator tunnel, the position of these targets will be determined in the machine reference frame by laser tracker measurements, and consequently it will provide the position of the "zero" for the optical fibers in such a frame. Each section of the cold mass is equipped with four targets, installed on a specific support developed to avoid cryo-condensation and designed to keep each target at a temperature above 200 K. Validation tests conducted with such a configuration demonstrated that the center of each section could be determined within a standard deviation of 0.1 mm (1σ) in the referential frame of the cryostat [7].

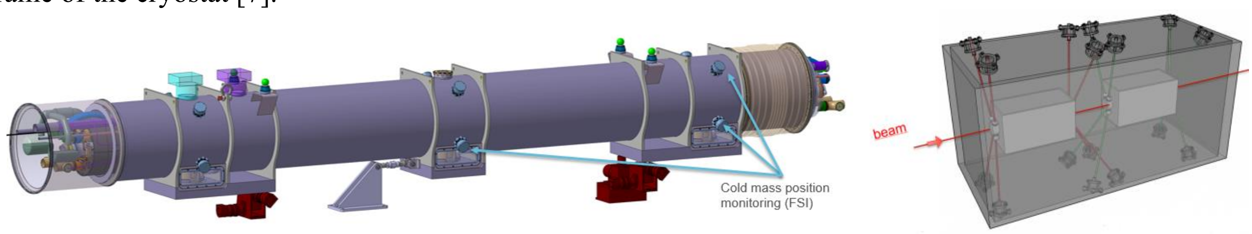

Figure 15-12: FSI lines of sight in Inner Triplet quadrupoles (left) and crab cavities (right)

The position of each crab cavity inside its cryostat will be monitored through two sections performing four distance measurements between the cryostat and targets installed on the flange of the dressed cavity (Figure 15-12). Tests performed in real conditions in the SPS tunnel demonstrated that the relative position of the cavities could be monitored within a few micrometers and their absolute position in the tunnel reference frame could be determined within an accuracy of 50 μm [7].

15.8.4 Standard alignment

In order to assure similar beam geometry for the HL-LHC as during the LHC era the underground network will be re-determined in the area where new components will be installed. The network will be derived from the old components prior to their dismounting as their position is known in the context of beam operation / performance. Later, this re-determined underground network will be used for the preparatory works, once the old components are removed from the tunnel. Initially, the marking on the floor of the position of the new elements will take place, following the strategy used in the LHC [8] and then, the heads of jacks will be positioned within ±2 mm w.r.t. their theoretical position with the adjustment screws in their middle range. Once the jacks are at their nominal position, they will be sealed on the floor [9].

Traditionally, in accelerators, the alignment of the cryo-assembly magnets is carried out in two steps: the initial alignment and the smoothing (relative alignment of cryo-assembly magnets w.r.t. each other, not considering the underground geodetic network any more as reference). In the case of HL-LHC, only the first step will be carried out using standard alignment measurements [10]. The second step will be performed using sensors and actuators.

The initial alignment will take place once the magnets have been installed on their jacks before the interconnection and cool-down operations are completed. Each cryostat will be aligned independently w.r.t.

the underground geodetic network using its external fiducials within ±0.25 mm (1σ). Once the initial alignment completed, the interconnection phase will start.

15.8.5 Alignment sensors and actuators

To determine remotely the position of each cryo-magnet assembly or intermediary components (as collimators), each component will be equipped with two capacitive Wire Positioning Sensors (WPS). The two WPS provide four degrees of freedom by measuring the transverse (horizontal and vertical) offsets with respect to a stretched wire: pitch and yaw rotations, vertical and radial translations, within a micrometric accuracy. The roll angle will be determined either by Hydrostatic Levelling Sensors (HLS) (three HLS sensors in that case will determine the vertical distance to a water surface within a micrometric accuracy providing redundancy in the vertical translation and pitch rotation), or by a radiation hard inclinometer when space is limited on the component. The longitudinal position of each component will be determined by FSI measurements between a reference point fixed to the floor and the cryostat interface. On the triplets, an inclinometer will be added to provide redundancy in the roll determination.

Diagnostic devices associated with each alignment system will carry out the remote validation of the sensors. Prototypes are already in place in the LHC.

To link radially the tunnel on both sides of experimental areas, a wire will be stretched in a gallery parallel to the LHC tunnel around IP1 and IP5 [11]. A combination of WPS sensors and FSI measurements will provide the six distance measurements between tunnel and parallel gallery wires. Left and right sides will be linked vertically by HLS sensors as can be seen in Figure 15-13 [12].

The WPS and HLS sensors installed in the experimental area will provide machine references in the experimental areas, to align the TAXS using standard instrumentation.

The remote adjustment of the components according to 5 degrees of freedom will be achieved dependent on the component, either by motorized jacks or by a standardized adjustment platform equipped with permanent motors. In both cases, the motorization solution shall fulfil the following requirements: a resolution of displacement below 10 µm, over a stroke of ±5 mm. The remote adjustment system shall provide a high stiffness to the cryostat support, with the first Eigenfrequencies as high as possible.

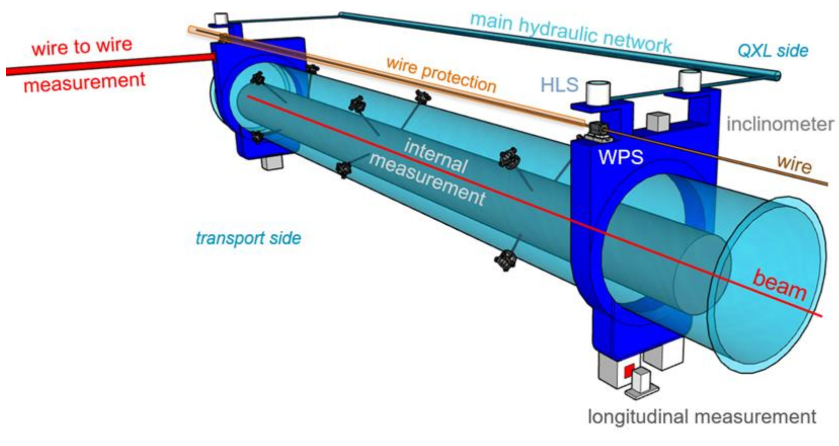

Figure 15-13: Alignment sensor configuration

The standardized adjustment platform is a CERN universal solution for the alignment of light weight components: the knobs interfaces of all adjustment axes will be located towards the transport area, with a simplified and intuitive kinematics allowing performing its adjustment without complicated algorithms [13]. The platform can be configured in three versions: manual (adjustment acting on knobs), semi manual (adjustment by plugging motors temporarily) or automatized (equipped with permanent motors). The objective of using the same platforms below all the components is to limit the doses taken by the surveyors [14].

During the Long Shutdowns, the components with no remote adjustment capability will have their position controlled, using laser trackers in an automatize mode.

15.9 References

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