Chapter 3

The HL-LHC Machine*

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This chapter summarizes the baseline parameters and layout for the HL-LHC machine, discusses options for alternatives to the baseline configurations, comments on the integration issues and describes the overall planning for the HL-LHC upgrade.

1. HL-LHC Baseline Parameters

The performance of the HL-LHC machine is boxed in between the request for a high integrated luminosity (ca. 3000 fb^{-1} by the end of the HL-LHC exploitation over ca. 10 years of operation and translating to an annual integrated luminosity of ca. 250 fb^{-1} assuming scheduled 160 days for proton physics production per year and that the HL-LHC exploitation starts with an integrated luminosity of ca. 300 fb^{-1} at the end of the LHC Run III in 2022) and a maximum number of 140 events per bunch crossing. While the request for maximum integrated luminosity asks for the largest possible peak luminosity, the request for limited number of events per bunch crossing limits the peak luminosity to a maximum value of ca. $5\cdot10^{34}$ $cm^{-2}s^{-1}$. Operating the HL-LHC with the maximum number of bunches and utilizing luminosity leveling provides the best compromise for satisfying both requests. Table 1 shows the resulting baseline parameters approved by the HL-LHC Layout and Parameter Committee [1] for the standard 25 ns bunch spacing configuration together with the parameters for the nominal LHC configuration and two alternative scenarios which might become interesting in case the LHC operation during Run II reveals problems either related to the

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emittance preservation along the LHC cycle for high intensity operation (the so-called BCMS filling scheme allows the preparation of small emittance beams at the price of a reduced number of bunches) or the electron-cloud effect. The fall back solution for the latter scenario is a 50 ns bunch separation scheme at which electron cloud effects are not expected to be an issue, but where the peak luminosity needs to be leveled at a lower value in order to keep the number of events per bunch crossing below 140. The luminosity leveling time is of the order of 8 hours and an efficient operation of the HL-LHC machine hence requires an average physics fill length that is slightly larger than the leveling time (e.g. ca. 10 hours). The required HL-LHC average fill length is approximately 50% larger than the average fill length of the LHC Run I period (ca. 6 hours).

The baseline parameters are based on a β^* value of 15 cm at the IP and the operation with Crab Cavities for compensating the geometric luminosity loss factor that becomes significant when operating with such small β^* values and a large crossing angle. These parameters coupled together imply larger aperture insertion magnets (triplet magnets, D1, D2 and Q4, Q5 magnets), lower operating temperatures for some of the insertion magnets (e.g. Q4 and Q5) and the exploitation of a novel optics matching scheme ATS [2] that utilizes the neighboring arcs for matching the insertion optics to the rest of the machine, requiring some upgrades in the non-experimental insertions (e.g. additional Q5 in IR6). The larger aperture triplet magnets of the HL-LHC insertion increases the peak fields at the coils for constant magnet gradients and implies for the HL-LHC the use of novel Nb_3Sn magnet technology and a reduction of the triplet magnet gradients with respect to the nominal LHC configuration. The use of lower quadrupole gradients implies in turn longer triplet magnets (the functional quantity is given by the integrated magnet gradients) and an increase in length of the common beam pipe region next to the IP. The use of superconducting recombination dipole magnets in IR1 and IR5 allows to a large extend a compensation of the length increase of the common vacuum beam pipe region and it limits the increase in unwanted parasitic collision points of the two beams at an acceptable level.

Figure 1 shows the HL-LHC baseline insertion layout (top) together with the layout of the present nominal LHC machine (bottom) [3].

The installation of additional collimators in the dispersion suppressors (DS) next to IR2, the insertion for the ion-physics detector ALICE, is also part of the HL-LHC baseline. In the DS of IR7 two collimators per side are foreseen to be installed to cope with diffractive proton losses, while additional collimators in the DS of IR1 and IR5 are considered as options for the HL-LHC upgrade pending further results from the LHC operation experience in Run II. Figure 2 shows the

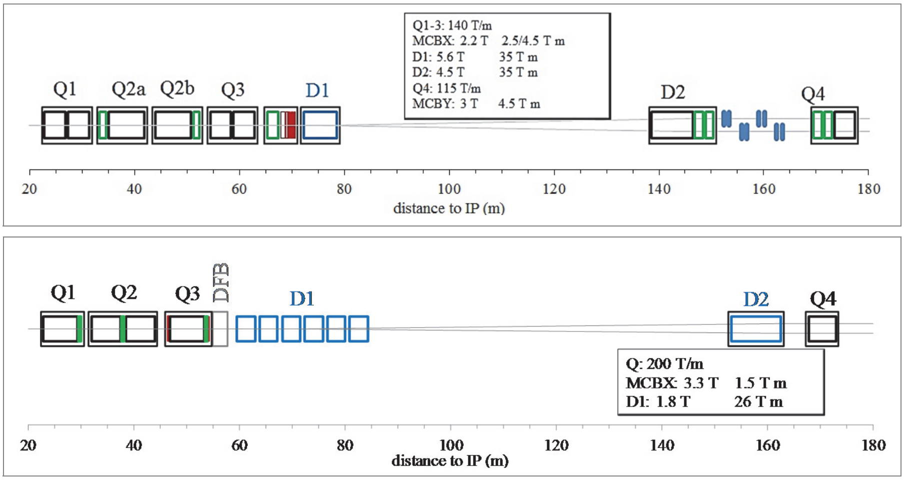

Fig. 1. Comparison of the LHC nominal (bottom) and the HL-LHC baseline layout for the high luminosity insertions (top).

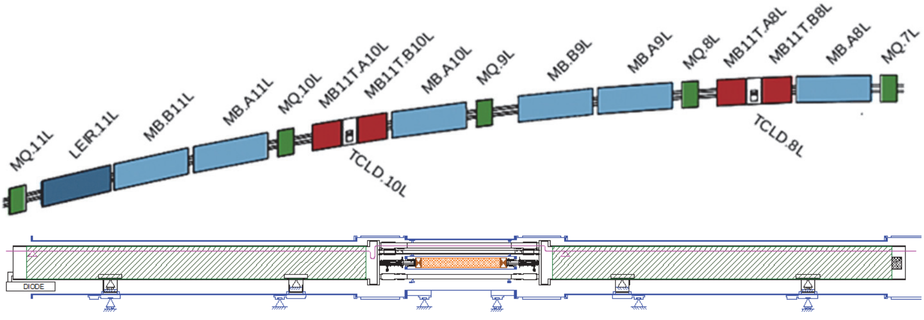

Fig. 2. Design for P7 11 T cryo-assembly per side.

schematic illustration of the required modifications in the Dispersion Suppressor of IR7, which features two collimators per DS instead of the only one collimator per DS between Q9 and Q10 in IR2.

Additional layout modifications are still being examined (e.g. the installation of higher or lower harmonic RF systems and a hollow electron lens for beam halo cleaning in IR4). However, these layout modifications are not yet part of the HL-LHC baseline configuration.

Other layout modifications, like the removal of the power converters from the tunnel area and the change of the feed-boxes for powering the insertion magnets via a superconducting link have no direct impact on the optics and parameter choice for the HL-LHC baseline and will not be deeply discussed here. However, they are vital for improving the LHC efficiency and for achieving the required increase in the average physics fill length for the HL-LHC exploitation.

Table 1. High Luminosity LHC parameters (LHC nominal ones for comparison).

Parameter	**Nominal LHC (design report)**	**HL-LHC 25ns (standard)**	**HL-LHC 25ns (BCMS)**	**HL-LHC 50ns**
Beam energy in collision [TeV]	7	7	7	7
N_b	1.15E+11	2.2E+11	2.2E+11	3.5E+11
n_b	2808	2748	2604	1404
Number of collisions in IP1 and IP5	2808	2736 [1]	2592	1404
N_{tot}	3.2E+14	6.0E+14	5.7E+14	4.9E+14
beam current [A]	0.58	1.09	1.03	0.89
x-ing angle [μrad]	285	590	590	590
beam separation [σ]	9.4	12.5	12.5	11.4
β^* [m]	0.55	0.15	0.15	0.15
ε_n [μm]	3.75	2.50	2.50	3
ε_L [eVs]	2.50	2.50	2.50	2.50
r.m.s. energy spread	1.13E-04	1.13E-04	1.13E-04	1.13E-04
r.m.s. bunch length [m]	7.55E-02	7.55E-02	7.55E-02	7.55E-02
IBS horizontal [h]	80 -> 106	18.5	18.5	17.2
IBS longitudinal [h]	61 -> 60	20.4	20.4	16.1
Piwinski parameter	0.65	3.14	3.14	2.87
Geometric loss factor R0 without crab-cavity	0.836	0.305	0.305	0.331
Geometric loss factor R1 with crab-cavity	(0.981)	0.829	0.829	0.838
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03	3.3E-03	4.7E-03
beam-beam / IP with Crab cavity	3.8E-03	1.1E-02	1.1E-02	1.4E-02
Peak Luminosity without crab-cavity [cm^{-2} s^{-1}]	1.00E+34	7.18E+34	6.80E+34	8.44E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm^{-2} s^{-1}]	(1.18E+34)	19.54E+34	18.52E+34	21.38E+34
Events / crossing without levelling and without crab-cavity	27	198	198	454
Leveled Luminosity [cm^{-2} s^{-1}]	-	5.00E+34 [5]	5.00E+34	2.50E+34
Events / crossing (with leveling and crab-cavities for HL-LHC)	27	138	146	135
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.25	1.31	1.20
Leveling time [h] (assuming no emittance growth)	-	8.3	7.6	18.0
Number of collisions in IP2/IP8	2808	2452/2524 [7]	2288/2396	0[4]/1404
N_b at SPS extraction [2]	1.20E+11	2.30E+11	2.30E+11	3.68E+11
n_b / injection	288	288	288	144
N_{tot} / injection	3.46E+13	6.62E+13	6.62E+13	5.30E+13
ε_n at SPS extraction [μm] [3]	3.40	2.00	< 2.00 [6]	2.30

[1] Assuming one less batch from the PS for machine protection (pilot injection, TL steering with 12 nominal bunches) and non-colliding bunches for experiments (background studies…). Note that due to RF beam loading the abort gap length must not exceed the 3 μs design value.

[2] An intensity loss of 5% distributed along the cycle is assumed from SPS extraction to collisions in the LHC.

[3] A transverse emittance blow-up of 10 to 15% on the average H/V emittance in addition to the 15% to 20% expected from intra-beam scattering (IBS) is assumed (to reach the 2.5 μm/3.0 μm of emittance in collision for 25 ns/50 ns operation).

[4] As of 2012 ALICE collided main bunches against low intensity. satellite bunches (few per-mill of main bunch) produced during the generation of the 50 ns beam in the injectors rather than two main bunches, hence the number of collisions is given as zero.

[5] For the design of the HL-LHC systems (collimators, triplet magnets,…), a design margin of 50% on the stated peak luminosity was agreed upon.

[6] For the BCMS scheme emittances well below 2.0 μm have already been achieved at LHC injection.

[7] The lower number of collisions in IR2/8 wrt to the general purpose detectors is a result of the agreed filling scheme, aiming as much as possible at a democratic sharing of collisions between the experiments.

2. Alternative Options

As mentioned in the above, HL-LHC project aims at achieving unprecedented peak luminosity and event pile-up per crossing by reducing the IP beta functions, increasing the bunch population and providing crab collisions with crab cavities. In the following three failure scenarios are described together with the possible alternatives to the baseline HL-LHC configuration that, implemented, would allow reaching the desired performance:

2.1. Performance limitations by longitudinal multi-bunch instabilities: These might be mitigated either with a higher harmonic 800 MHz RF system in addition to the nominal 400 MHz LHC RF system or a 200 MHz RF system as a new main RF system [4] and using the existing LHC 400 MHz system as a higher harmonic system. In both cases the RF systems should be operated in bunch shortening mode as this has been experimentally demonstrated in the SPS to be the robust approach for mitigating multi-bunch instabilities. This is in conflict with using the 800 MHz system for bunch lengthening as a means for reducing the peak pile-up density.

2.2. Performance limitations due to the electron cloud effect producing too large heat-load: This might be mitigated by using the 8b+4e filling scheme [5] or longer bunches with a 200 MHz main RF system. The 8b+4e scheme provides larger bunch charge with about 30% fewer bunches. The 200 MHz system might allow to provide bunches as long as 20 cm. Both options show in simulations a suppression of the electron-cloud in the dipoles throughout the full LHC cycle.

2.3. Crab cavities demonstrating not to be operational for hadron beams: SPS tests, machine protection issues, crab cavity impedance, or emittance growth due to RF phase noise might eventually suggest that crab cavities cannot be operated in the HL-LHC. In this scenario it is mandatory to resort to flat optics at the IP. Magnetic or electromagnetic wires [6] might be placed near the separation dipoles in order to compensate for the long-range interactions allowing for a reduction of the crossing angle and therefore increasing the luminous region. A 200 MHz RF system might also help if it allows increasing the bunch intensity. This is expected for single bunch limitations, however multi-bunch instabilities might dominate the performance limitations.

Another set of alternatives to the HL-LHC baseline configuration offer a better luminosity quality by reducing the pile-up density. It has been proposed that lowering the pile-up density might allow for a larger total pile-up and therefore larger luminosity [7]. Three alternatives in this direction follow:

- Peak pile-up leveling with β^*. This alternative does not require any extra hardware and only slows down the baseline β^* leveling to ensure a peak pile-up density below a target value. Since the largest peak pile-up is reached in the baseline only for a short time at the end of the β^* leveling process, it is possible to reduce this largest peak pile-up with little or negligible impact in the integrated luminosity [8].
- Longitudinal bunch profile flattening. Either the use of a lower harmonic 200 MHz or a higher harmonic RF system might be used in conjunction with the existing LHC 400 MHz RF system to lengthen and flatten the longitudinal bunch profile. However it has been remarked that this operational mode implies a substantial hardware upgrade and might be operationally challenging. Alternatively, RF phase modulation has already been successfully used to slightly flatten the longitudinal bunch profile [9] in the LHC. Further studies of longitudinal bunch profile flattening are required to assess its potential for the HL-LHC. Combining this last option with peak pile-up leveling with β^* offers the lowest possible peak pile-up without significant impact on performance and without any hardware modification to the current baseline.
- Crab kissing [7]. This alternative can be realized in various ways. The initial proposal uses flat bunches, a magnetic or electromagnetic wire to reduce the crossing angle (to lower the crab cavity voltage) and crab cavities in the separation plane to maximize the luminous region. The compensating wire might not be needed if the each crab cavity achieves 5 MV (while the nominal voltage is 3.3 MV). The possibility of doing crab kissing in the crossing plane has also been explored.

Simulations of the fill evolution have been performed taking into account luminosity burn-off, intra-beam scattering and synchrotron radiation. The assumed event pile-up and the expected integrated luminosity per year are shown in Fig. 3 for all the mentioned alternatives. A 50% efficiency over one year of operation (160 days) is assumed. This means that the time in physics plus the time to come back to physics (turn-around time) is 80 days. A turn-around time of three hours has been used in simulations. Beam parameters and further details can be found at [10, 11].

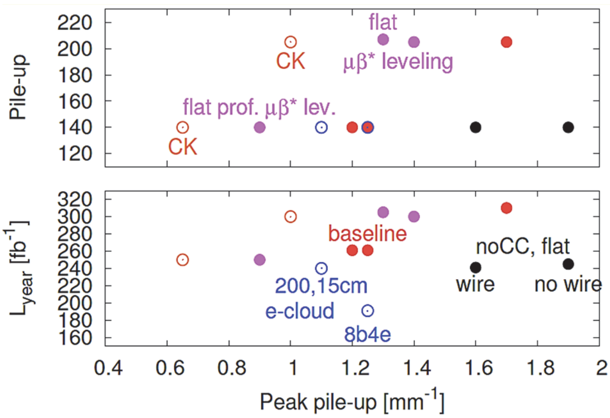

Fig. 3. Performance expectation of different alternatives. The red markers represent the baseline scenarios for different target of total pile-up (140 and 200 event per crossing). Flat optics (no crab cavities) with and without the wire compensator are shown in black. Crab kissing scheme is represented with orange markers. Peak pile-up density leveling with β^* is shown on magenta. In case e-cloud effects need to be mitigated, 200 MHz RF system or the 8b+4e filling scheme (green and blue markers) could be deployed.

3. HL-LHC the Geographical Distribution of the Upgrade Interventions

HL-LHC will require modifying the machine and infrastructure installations of the LHC in several points along the ring. In particular:

- Point 4
- Point 7
- Point 2
- Point 6
- Point 1
- Point 5

Points are listed according to the chronological order foreseen presently for the HL-LHC system installation.

3.1. *Point 4*

Point 4 will be equipped with a new cryogenic plant dedicated to the RF systems (and other cryogenic equipment that might be installed in IR4). The installation will require a warm compressor system on surface and a junction from the surface to the underground installation where a new cold box will be placed. The cold box will then feed a RF dedicated cryogenic distribution line.

3.2. *Point 7*

3.2.1. *The horizontal superconducting links*

In Point 7 two horizontal SC links will be installed in order to electrically feed the 600 A circuits connected to the 2 DFBAs (DFBAM and DFBAN). The related power converters will be installed in the TZ76 and will be connected to the superconducting link via short warm cables. The two superconducting links will then run for about 220 meters in the TZ76 and then enter into the LHC machine tunnel via the UJ76. They will then be routed for about 250 m in the LHC tunnel in order to be connected to the DFBAM and DFBAN (Fig. 4).

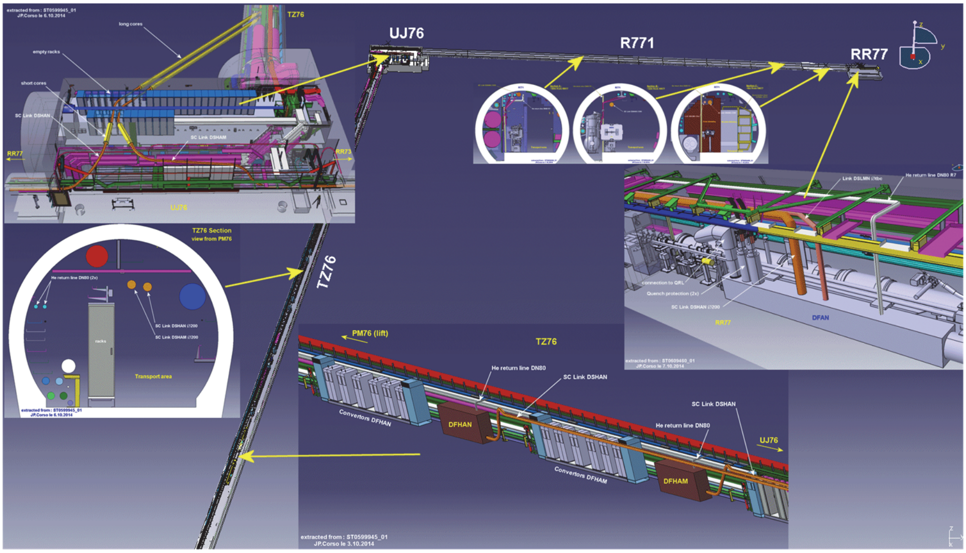

Fig. 4. View of the foreseen installation of the superconducting link system at Point 7. Power converters in the TZ76, routing of the link from the TZ76, via the UJ76 till the RR 77.

3.2.2. *New collimators in the dispersion suppressor*

In order to protect the superconducting magnets (excess heat deposition) from off-momentum proton leakage from the main collimator system itself, some special collimators must be installed in the Dispersion Suppression region, i.e. in the continuous cryostat. The evaluation of the real need of this modification will be completed on the base of the first results of the LHC Run II.

In order to cope with the proton losses in the Dispersion Suppressor area it has been decided to install two collimators on each side of the IP in the slots presently occupied by the Main Bending Magnets MB.B8L7 plus the MB.B10L7 and the symmetric MB.B8R7 plus the MB.B10R7. Each removed dipole will be replaced by a unit composed of two 11 T dipoles separated by a cryogenic by-pass. The collimator will be positioned on the top of the cryogenic by-pass.

3.3. *Point 2*

In order to limit the heat deposition from collision debris in the superconducting magnets during the ion run, collimators in the dispersion suppressor will also be installed in Point 2. In this case the installation will take place only in one slot on each side of the IP replacing the MB.A10L2 and MB.A10R2 main bends.

3.4. *Point 6*

In Point 6 the two quadrupole magnets Q5 will be modified in order to fulfil the needs of the new HL-LHC ATS optics. Two options presently under evaluation lead both to the exchange of the present Q5 with a new and higher gradient Q5.

3.5. *Point 1 and Point 5*

The largest part of the new equipment, required by the HL-LHC performance objectives, will be installed in Point 1 and Point 5. 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.

3.5.1. *LHC machine tunnel*

De-installation:

All the machine equipment from the interface with the experimental cavern, starting with the TAS, up to the DFBA (included) need to be removed. The present QRL will be also removed in the same area and a new return module will be installed to allow separating the flows of the coolant coming from the LHC QRL and the one from the new HL-LHC QRL Installation.

- Installation of the new equipment probably in the following sequence:
  - TAXS
  - Services
  - QRL with related valve and service modules
  - Horizontal superconducting links from the DFM to the magnets
  - Magnets and crab cavity support system
  - Magnets and crab cavity

- TAXN
- Distribution feed boxes for the Q1 to D1 magnet system (DFX) and for the D2 to Q6 magnet system (DFM)

The sequence of installation of the vertical superconducting links to be connected to the DFX and DFM still need to be assessed according to the options retained for its routing.

3.5.2. *Existing LHC tunnel service areas*

The RRs on both sides of Point 1 and Point 5 will need to be re-organized and in particular it will be necessary to: de-install the power converter and other related systems linked to the powering of the removed LHC matching section and then to re-organize the remaining equipment in order to, increase if necessary the radiation shielding.

3.5.3. *New HL-LHC tunnel service areas*

The installation of the new cryogenic plant in Point 1 and Point 5 will have two objectives:

- Provide independent and redundant cooling capacity to feed the final focus and matching sections left and right of each of the two High Luminosity insertions of the LHC.
- Provide redundancy to the cryogenic plant installed to cool the experimental systems.

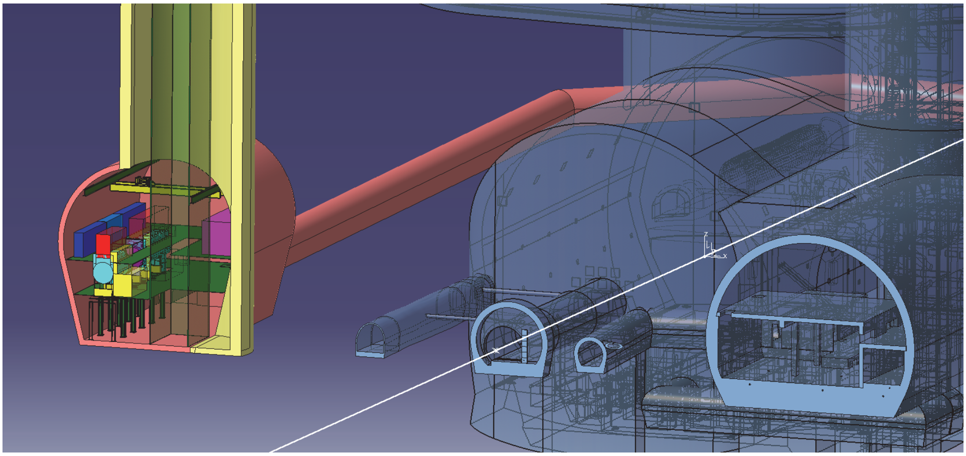

Fig. 5. Possible option for underground installation of the cryogenic cold box in Point 5.

The cold box shall be installed in underground areas (Fig. 5). Presently the required volume does not exist. Therefore conceptual studies have started in order to identify the best options for building new underground caverns to install this equipment and the related service and control system. Two possible approaches are under study: the baseline corresponds to solutions with magnet power converters on surface, and a second one with power converters in the underground areas.

3.5.4. *New connection from the LHC tunnel and HL-LHC service areas to the surface*

The following connections between the surface and the underground installation shall be made available:

- LHC tunnel, crab cavity area, to the surface. The crab cavities need to be connected to the dedicated RF power system and their control system. The present preferred choice is to install these services in dedicated surface buildings.
- New HL-LHC service area to the surface. These connections are necessary to link the surface part of the cryogenic plant with the cold box installed in the new underground HL-LHC service areas.
- Vertical routing of the superconducting links. In each point at least four superconducting links will need to be routed from the surface to the underground areas.

3.5.5. *New surface installation*

The following installations shall find space on surface in Point 1 and Point 5 and in their proximities:

- Crab cavity RF power and services hosted in two ad hoc surface buildings. They shall be positioned on the surface, vertically directly above the tunnel position where the crab cavities will be installed. There will be two surface buildings for each point, one on the left part of the machine and one on the right part. The surface extremities of the ducts/shaft for the crab cavity coax or shaft shall be housed inside this building.
- Cryogenic installation. On surface the warm compressors and the other part of the cryogenic plant shall be installed.
- Power converters, upper extremities of the superconducting links, protection systems and energy extraction system related to the circuits fed via the

superconducting link. This area shall be possibly located near the surface part of the cryogenic plant and in any case on the top of the surface extremity of the routing of the vertical superconducting link.

4. Schedule

The HL-LHC schedule aims at the installation of the main HL-LHC hardware during LS3, together with the final upgrade of the experimental detectors (so-called upgrade Phase-II). However, a few items like the new cryogenic plant for P4, the 11 T dipole for DS collimation in P2 (for ions), the SC links in P7 and several prototypes for the collimation, beam instrumentation and injection and beam dump systems are already foreseen for LS2.

The HL-LHC schedule is based on the following milestones:

2014: Preliminary Design Report (PDR)
2015: End of Design Phase, release of the Technical Design Report (TDR)
2016: Proof of main hardware components on test benches
2017: Testing of prototypes (including crab cavity test in SPS) and release of TDR_v2
2017–2021: Construction and test of long lead hardware components (e.g. magnets, crab cavities, SC links, collimators)
2018–2019: LS2 — Installation of Cryo-plant P4, DS collimators (11 T) in P2, SC link in P7
2021–2022: String test of inner triplet
2023–2025: LS3 — Main installation (new magnets, crab cavities, cryo-plants, collimators, absorbers, etc.) and commissioning

The present schedule is based on the Project Product Breakdown structure and the HL-LHC lifecycle (Fig. 6). For each one of the components identified there is a simplified schedule that contains the time foreseen for the processes (see Fig. 7):

- Requirements definition
- Functional specification
- Engineering specification
- Acquisition
- Fabrication, assembly and verification
- Installation and commissioning

And the already identified time constrains and dependencies:

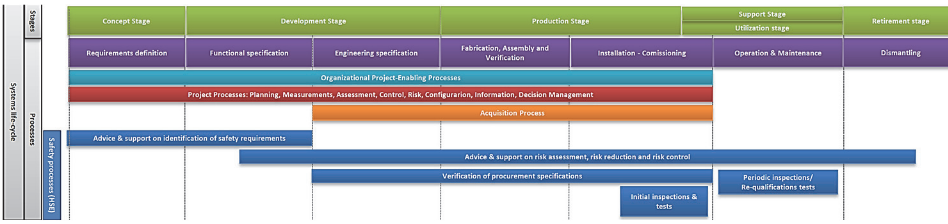

Fig. 6. HL-LHC life cycle processes.

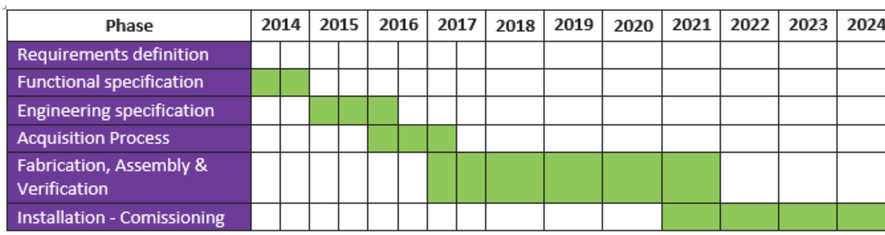

Fig. 7. HL-LHC simplified process schedule for a PBS element.

The schedule also takes in account other general principles such as the reduction of doses taken by the workers during the dismantling of the LHC components maximizing the cold down periods.

The baseline schedule manages also the variants. We call variants the present design alternatives inside the baseline. A variant is for example the installation in surface or underground of the new series of power convertors for the insertion magnets. The variants affect in most cases several components.

The schedule also contains the tasks linked to non-baseline components and their decision parameters.

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