Chapter 16

IT string and hardware commissioning

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16 IT string and hardware commissioning

16.1 The HL-LHC IT string layout

16.1.1 Introduction and goal of the HL-LHC IT string

The HL-LHC IT string (IT string) is a test stand for the HL-LHC, whose goal is to validate the collective behaviour of the IT magnets and circuits in conditions as near as possible to the operational ones. Each individual magnet circuit will be powered through a SC link and its associated current leads up to the ultimate operational current while cooled to 1.9 K in liquid helium. The test stand will be installed in the building 2173 (SM18) and will use magnets, superconducting (SC) link, current leads, power converters and protection equipment designed for the HL-LHC with their final design, and usable for the HL-LHC. The test bench will allow a real size training for the installation and alignment, the validation of the electrical circuits, the protection scheme of the magnets, and the SC link. At this occasion, all subsystem owners will be able to fine-tune their set up and to complement or change when necessary, before they are finally installed into the HL-LHC. The powering procedures will be written and validated during the tests. These tests will also improve our knowledge of every single component and will give us the opportunity to optimize the installation and hardware commissioning procedures.

16.1.2 Description of the HL-LHC IT string

The HL-LHC IT string will be composed of the cryo-magnet assemblies called Q1, Q2a, Q2b, Q3, CP and D1 (Figure 16-1). In total, 21 superconducting magnets using Nb-Ti or Nb_3Sn technology will be required to set-up the HL-LHC IT String.

In the IT string, as for the HL-LHC, the magnets will be powered via a SC link (DSH) by standard HL-LHC power converters. The circuit will also include the current leads and the water-, air- cables or bus bars between the power converter and the leads passing through the so called disconnector boxes (DCB).The DCBs are placed in the vicinity of the power converters allowing the safe separation of the electrical circuits while necessary. The SC link will be connected to the bus bars of the magnets via a dedicated equipment called DFX.

Cold diodes will provide decoupling between cold and warm parts of the circuit and limit the over-currents in the superconducting bus bars and link conductors. The diode assembly will be located in between D1 and the DFX, in order to be accessible for maintenance and replacement. For this reason, a dedicated box, as a part of the so-called D1-DFX Connection Module, operating at 1.9 K, will be installed into the IT string.

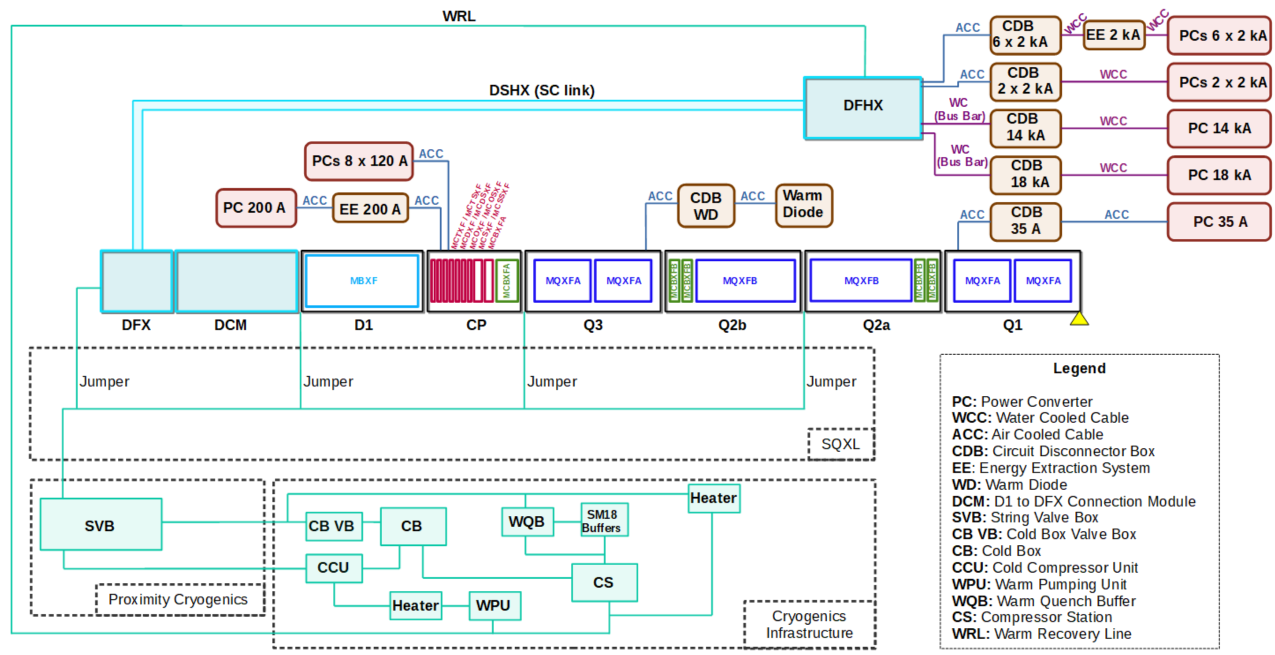

Figure 16-1: Schematic view of the IT string.

The cooling of the magnets will be done via a dedicated cryogenic valve box and will be a new additional “client” for the SM18 cryogenic installations sharing the cooling and pumping capacity with the RF and magnet testing. As such, the cryogenic equipment cannot be re-used in the HL-LHC.

16.1.3 Location of the IT tring test stand

For practical reasons, the IT string will be installed in SM18 that is housing the cryogenic powering test facility of the RF cavities and SC magnets for both the LHC and the HL-LHC. The integration of the test stand in the SM18 is shown in Figure 16-2.

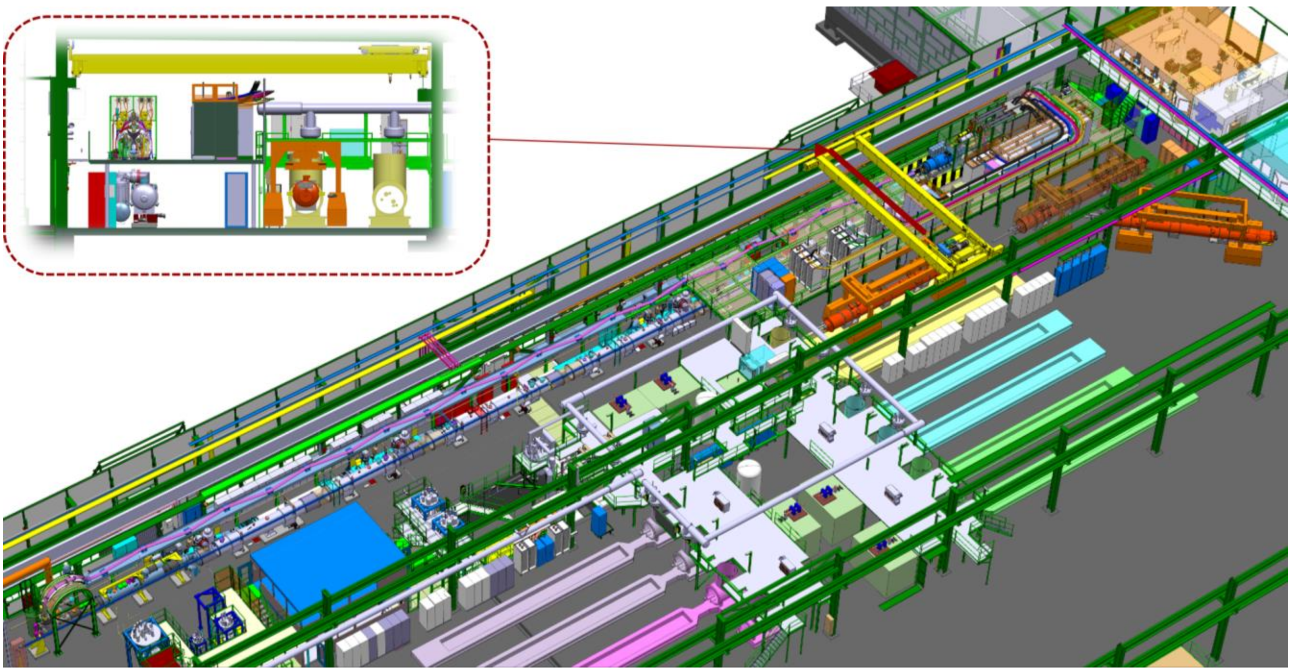

Figure 16-2: Integration of the IT string. Top left picture: cross-section view. Bottom: top view of the string assembly.

The powering system is centralised on a metallic bridge between the wall and the present structure holding the electrical racks of the horizontal magnet test benches.

16.1.4 Time scale of the IT string test stand

One of the main goals of the IT string is to test and confirm the nominal operational conditions and the collective behaviour of the entire IT setup, before the installation of the magnets and main components into the LHC tunnel. The delivery schedule of the cold masses is the key element defining the starting date for the installation fixed for the end of 2021. The IT string will be active until October 2023 as it is shown in Figure 16-3. During this extended period under study, the string will not be in operation, but will stay available in case of new tests are required.

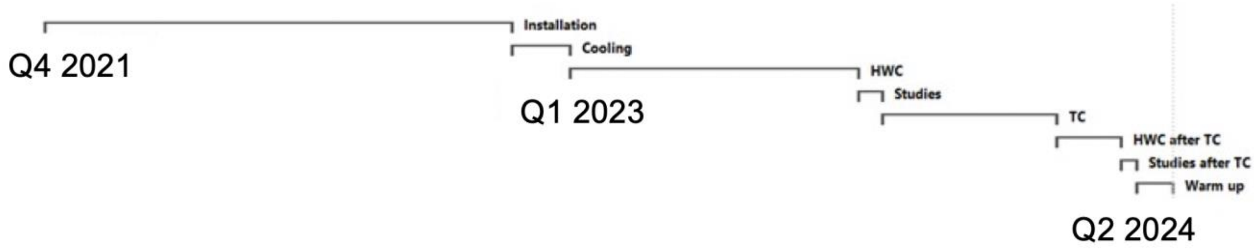

Figure 16-3: Delivery schedule of the cryo-magnet assemblies for the IT string.

16.1.5 Technical infrastructure for the IT string test stand

The main components of the IT string technical infrastructure are:

- The cryogenic cooling system.
- The water-cooling system.
- The electrical powering system from the general network.

The SM18 test hall area is equipped with technical infrastructure that will serve the IT string test. Its capacity however is not sufficient when shared between the other activities: the RF cavity and SC magnet tests. The HL-LHC SC magnets and links production qualification will require approximately 100 tests for magnets and 20 for SC links in the period between 2019 and 2025. The test stands should also assure the testing of the spare LHC magnets (estimated to 50 tests) during the same period. In view of these activities, the existing infrastructure has to be upgraded.

16.1.5.1 Cryogenic cooling system upgrade

The estimated needs of cryogenic cooling of the IT string are 12 g/s for cooling and 6 g/s for pumping. The cryogenic powering tests of the LHC and the HL-LHC magnets are scheduled at the same time. These considerations implied the need of an upgrade in the liquid helium (LHe) production system from the present 27 g/s to 60 g/s. Using the present installations and combining the two warm pumping units, the total of 12 g/s capacity is used for magnet and/or IT string testing at 1.9 K operation. The upgrade started in 2019.

16.1.5.2 Water cooling system upgrade

16.1.5.2.1 Demineralised water system

The HL-LHC magnets are powered with currents higher than those of the present LHC magnets. Therefore, the power converters and associated installations needing water cooling require a higher quantity of demineralised water. Consequently, the demineralised water production was upgraded to a system that is able to deliver 138 m^3/h. The upgrade of the demineralised water system was successfully completed in 2016.

16.1.5.2.2 Primary water system

With the increased need of demineralised water and upgraded cryogenic cooling system, the need for primary water also increases. The SRF, the SC magnets and the IT string cooling capacity will be double of the present 1.6 MW, while the cryogenic upgrade will require an increased capacity from 2.5 MW to 6 MW. The primary water system was upgraded in 2019.

16.1.5.3 Electrical powering system upgrade

The IT string consumption is estimated to 1 MVA. It is going to be connected, together with the new Cluster F 20 kA power converter to the new transformer of 3 MVA capacity leaving approximately 1 MVA free power for future needs. The installation of the new 3 MVA transformer was completed in 2019.

16.1.6 Installation and dismounting of the IT string

The heaviest and largest objects will be installed, positioned, and aligned with dedicated equipment. The option to handle the cryo-assemblies with the specific handling tools (different from those used for the LHC magnet installations) is under study. The slope of the tunnel will not be reproduced for the string as none of the main users have requested it.

16.2 Preliminary test program for the IT string

16.2.1.1 Performance test of components before installation into the IT string

Each individual component will be tested before its installation in the IT string. The responsible institute will test magnets at their premises and/or at CERN at nominal operational condition (or equivalent). The individual magnets will be powered up to their ultimate current and at each step of the test, their electrical integrity will be checked. Voltage test procedure will follow exactly the one applied in the accelerator according to the table defined in Chapter 6.

16.2.1.2 Electrical circuit integrity test

The typical High Voltage Qualification (ElQA) test will be performed at the specified level of voltage for each step and each circuit. The continuity of the instrumentation and protection system wiring will be verified. The IT string will allow the testing of the revised and adapted ELQA procedures for the HL-LHC.

16.2.1.3 Cryogenic system test

The cryogenic system test will focus on the cool-down of the magnet chain and the thermal behaviour after the quench of the cold and warm powering systems, composed by magnets, bus bars, cold diodes, SC links, cold boxes, current leads, warm cables and power converters.

16.2.1.4 Vacuum system test

The IT string will not be equipped with beam screen and therefore there is no test planned to verify heat deposition. Those verifications will be done offline. The insulation vacuum will be qualified with leak tests and tests of different sealing options. Also, there will be no separation between beam and cryostat vacuum. Lack of beam screen and vacuum separations are maybe the most important deviations from the operational configuration. The decision was taken to limit the cost and in view of the experience accumulated with LHC, which is still very relevant for the vacuum system of the IT triplet.

16.2.1.5 Powering of the IT magnets

The HL-LHC will require the development of new power converters, a high precision 20 kA 2-quadrant power converter, and the magnets will be powered singularly (for the independent magnets) or in series (for the Q1 to Q3 assembly), adjusted with 3 trim circuits. The IT string will be the first and unique occasion for testing the series powering before the real powering in the tunnel.

The cold powering system is composed mainly of the HTS current leads and the SC link, which relies on cooling with helium gas. The gas has a temperature range from 4.2 K up to 35 K - 50 K. The use of MgB_2 and HTS materials enables safe operation of the superconducting components, for which a temperature margin of at least 10 K is guaranteed. Although the SC link will go through qualification test before the IT string tests, the complete warm and cold powering circuit will be only tested in the IT string before their installation into the LHC tunnel.

The most critical aspects that the IT string will address are the cooling performance of the cold part of the circuits, the electro-magnetic cross talk between circuits inside the SC link, and the protection of the circuits while using the new protection scheme that includes the CLIQ system for the magnets. The IT string will also allow the qualification of the individual splices of the interconnections between magnets and cold powering system.

16.2.1.6 Magnet protection system test

The protection system of the magnets is relying on quench heaters and/or the Coupling Loss Induced Quench (CLIQ) system. A careful protection system test has to be performed before powering the magnets at low and intermediate current. Specifically, for Nb_3Sn magnets, it was found that flux jumps appear in the low and medium current range, with amplitudes ranging from 10 mV up to 2 V, and characteristic times of 10 to 20 ms. The quench detection will be done with the universal QPS (uQPS) as planned for the HL-LHC. This system will be only tested on a complete circuit in the IT string.

16.2.1.7 Interlock test

The interlock system validation will be one of the most critical tests. The HL-LHC interlock system will integrate and handle, with a given logic, signals from all subsystems. The overall system test will be only possible in the IT string, as the interlock system used on the benches for the test of individual cryo-magnet assemblies is a dedicated one, not necessarily working in the same conditions as in the tunnel.

16.2.1.8 DAQ test

As for the interlock system, the DAQ of the IT string will be the one associated to the uQPS.

16.2.1.9 Performance tests

During the performance tests, we will investigate the capability of the different subsystems to work together and within the specified conditions.

16.2.1.10 Quality assurance

The IT string will give the opportunity to validate and test all Quality Control (QC) steps and installation and test procedures.

16.3 Hardware commissioning in the tunnel after LS3

16.3.1 Commissioning of the superconducting circuits

16.3.1.1 Electrical Quality Assurance tests

As stated in Ref. [1], the objective of the ElQA tests is to release each individual superconducting circuit for powering, to gather all the necessary electrical parameters for operation, and to track all data acquired and to manage the related non-conformities.

16.3.1.1.1 ElQA at warm

At the end of the installation and connection of all magnets, resistance measurements and a high voltage qualification of all circuits will be performed: to check whether the circuit is closed; to determine a reference resistance value at warm; and to validate the galvanic insulation versus ground. The values of voltages to be applied and the maximum acceptable leakage current values are reported in the Chapter 6 and may dynamically evolve according to experience gained with prototypes and IT string commissioning.

16.3.1.1.2 ElQA at cold

Similar tests will be performed at cold, with larger test voltages applied. The circuits and the corresponding link will be cooled down to their nominal temperature. For the high voltage qualification of all lines, the tests will be performed to validate the galvanic insulation versus ground and the capacity of all lines to withstand the mutual high voltages developed during a fast change of current in the different circuits (typically during a fast abort or quench).

The high voltage qualification also includes testing of all the elements that are electrically connected to the tested circuit. Such elements are:

- the instrumentation and feedthrough systems.
- the magnet protection units.
- the temperature sensors with the related tunnel cabling and electronics.
- the tunnel cabling for routing the voltage taps used for the protection of the superconducting circuits.

In addition, transfer function measurements will be performed, with the aim of determining the impedance as a function of the frequency. The results of these measurements are used to spot possible inter-turn shorts, and for the power converter team to adjust the regulation of the power converters.

16.3.1.2 Powering tests

The HL-LHC magnets present several peculiarities [2] that have to be kept in mind for their commissioning. The most relevant are: the fact that the vast majority of magnets will be cooled down to 1.9 K (with only a small number of matching section magnets at 4.5 K); that Nb_3Sn will be used extensively for the first time; that the current of the inner triplet will be the highest in the machine (18 kA); and, importantly, that some of the high current magnets will be protected only via energy extraction in a dump resistor without quench heaters. In addition, the powering scheme of the inner triplet will be different from the present one with implications in case of a quench of one of the magnets (see Chapter 3). There will be 11-T magnets in the DS where NbTi and Nb_3Sn magnets will be powered in series with the difference of a trim power converter locally feeding the 11 T (to compensate for the different transfer functions) through resistive current leads, identical to those used to power the arc 60 A circuits.

The powering of all circuits up to nominal current will be done in steps. At the end of each step, online and offline analyses are performed by equipment owners and protection experts to assess the performance of all hardware in the circuit. In particular, for the powering of individual circuits, several cycles at different current levels will be performed to study the performance of the magnets, the efficiency of the protection mechanisms (by provoking fast aborts and even quenches), and to check all functionalities of the powering interlocks and of the power converters (via provoked powering failures).

A typical series of tests includes:

- at minimum operational current, testing of the full interlock chain, with the verification of cryogenic signals, power permit, powering failure, circuit quench transmission, and fast power abort requests.
- at low current, a check of the power converter performance and verification of all protection functionalities, by means of provoked slow and fast power aborts, with energy extraction.

- repetition of a series of power aborts and simulation of quenches from progressively higher current levels, with more and more energy stored (e.g. 25%, 50%, and 100% of the nominal stored energy).

Before starting a new powering test, all previous tests must have been validated. The validation includes approval by power converter and powering interlock experts, magnet owners, and protection experts. Cryogenics experts should also confirm the correct operation of their installations and instrumentation. The criteria for approval, the parameters, and the relevant information to be stored will be discussed in due time.

After the individual test of all circuits up to the design current, the common powering of a set of circuits will be done for magnets that are in the same cryogenic envelope and are powered from the same link (usually referred to as the powering of a group of circuits). The objective of this simultaneous powering is to validate operation of all magnets in nominal conditions; current cycles similar to those applied in normal operation should be used for the powering of a group of circuits. Important at this stage is the behaviour with combined powering in critical conditions, such as the fast power abort of a circuit when the others are at full current. For the inner triplets, in particular, quenching in a triplet quadrupole might induce a quench in a nearby quadrupole or corrector if the current in this related circuit is not extracted fast enough. These tests should be performed on all the magnets and could well trigger the change of detection thresholds and protection configurations. Once more, all tests should be approved by a group of experts and recorded for future reference.

Particular attention also has to be paid to those circuits that are not equipped with heaters and are protected by energy extraction on a dump resistor. For such circuits, a precise estimate of the energy deposited during a quench has to be made, not only in the case of bench tests, but also in the more severe conditions of combined powering in the tunnel. Eventually, the protection threshold should be adapted to reduce energy deposition and improve magnet safety during powering.

16.3.1.3 Magnet training

Operations at 7 TeV will hopefully be established during Run 3. In the process, extensive experience will be gained with the required dipole training to get to the requisite current level. The effects of a full thermal cycle will also be given by commissioning following LS2. A sound estimate of the number of quenches required following LS3 will thus be possible and well optimized procedures will be in place to assure an effective retraining campaign. Sufficient time should be foreseen in the schedule for this phase.

16.3.2 Hardware commissioning of the HL collimation system

At the HL-LHC, the requirements for hardware commissioning of mechanics and controls of the collimation system will be essentially equivalent to those of Run 2 and Run 3. Required tools are expected to be well debugged and validated by the time of the HL-LHC. The collimator settings, controls, and operational sequences should be extensively re-tested during the hardware commissioning and cold-checkout phases [3]. A dedicated test to address the reproducibility of collimator movements during critical operational sequences (such as the ramp) will be performed. At this stage, the collimators should have been fully installed and the local collimator controls in the tunnel fully validated. Unlike other hardware commissioning tests (such as the magnets), most of the collimation commissioning can be done parasitically, the main exception being the testing of the interlock system where the beam interlock system (BIS needs to be available.

Before beam is injected into the machine, the machine protection (MP) functionality of the collimation system must be guaranteed. Each collimator is connected to the BIS and has more than 20 interlocks that will need to be verified. The jaw positions and collimator gaps are monitored via six linear variable differential transformer (LVDT) sensors. These signals are interlocked with inner and outer limit values, making a total of 12 interlocks per collimator. In addition, there are a total of six energy-dependent and β^*-dependent limit functions and an interlock to protect from 'local' mode collimation control. The temperature of the collimators is also monitored and interlocked with minimum and maximum adjustable thresholds independently for five sensors per collimator. After successful results from these tests, the system will be ready to allow beam into the machine.

The new design of the TCLD collimator to be installed between two short 11-T dipoles and the connection cryostats around IR2 has been finalized. These collimators feature the latest design improvements, including embedded BPMs for fast alignment, and will be commissioned for the first time in LS2. New hardware will have to be part of the hardware commissioning as well. In particular, crystal primary collimators and the hollow electron beams. At this stage, the final implementation of interlocking aspects for these devices is not yet finalized.

16.3.3 Commissioning of the cryogenic systems

The HL-LHC foresees numerous modifications of the cryogenic system [4]. The operation of the resultant system, together with the time needed to qualify and tune the system, will be detailed once the design is definitive. Provisionally, an approximate time of three weeks is considered to be mandatory to commission the system for the superconducting magnets.

16.3.4 Commissioning of the crab cavities

As for all elements in the LHC, the crab cavities will be tested on the surface at the SM18 facility to nominal specification prior to its installation in the tunnel. One such prototype was installed in the SPS for a complete qualification of the standard two-cavity module with LHC-type beams in 2018 [4] and the installation of the other complete prototype is planned for beam tests in the SPS during Run 3.

The commissioning of the crab cavity system is differentiated into two main phases: cavity conditioning up to nominal operating voltage including the associated ancillary system (high power RF, cryogenics, vacuum) followed by RF commissioning with beam. Once the cryomodules are stable at 2 K, the RF conditioning is expected to take several weeks and is assumed to be within the hardware commissioning period.

Concerning the commissioning of the cryogenics, the correct operation of the cooling loops and the capacity will be verified, together with the expected behaviour of the instrumentation; proper verification criteria and sequence will be defined at later time with input from the qualification of the cryogenic-module on the surface tests. The vacuum integrity and the vacuum interlocks will be tested as well, which should cut the RF power in case of issues and during cavity conditioning.

The conditioning of the cavities will first be performed on the surface, but the commissioning of the low-level RF system (the tuning control, the regulation loop around the amplifier, plus the RF feedback) was validated in the SPS for the first time in its nominal configuration. A detailed procedure for the verification of all functionalities and the summary of issues and performance is available at Ref. [4].

All possible RF manipulations and synchronization with the main RF system in P4 is foreseen for the LHC operation cycle will first be performed without beam. An important verification concerns the efficiency of the fast feedback of the cavity field. The delay loops in the SPS between the two cavities was arranged to mimic the cavity setup in the LHC to both ensure the fast and independent control of the cavity set point voltage and phase, and the slower loop to regulate the cavities on either side of the IP. This is essential to ensure machine protection in the event of an abrupt failure of one of the cavities.

16.4 Commissioning with beam

Beam commissioning is not formally part of the HL-LHC construction project. After HWC the machine will be handed over to the HL-LHC operations team (BE department). A skeleton plan is shown in Table 16-1.

The initial commissioning phase should evolve through initial set-up, system commissioning through the nominal cycle, standard measurement and correction, set-up of protection devices, and validation. It is a relatively complex phase with necessary interplay between the various teams to allow beam-based commissioning of systems such as tune and orbit feedbacks, transverse dampers, RF, etc. under appropriate conditions at the various phases of the operational cycle.

Table 16-1: Outline of initial commissioning following LS3.

Phase	Key objectives
Injection and first turn	Injection region aperture, injection kicker timing
Circulating beam	RF capture, beam instrumentation, initial parameter checks
450 GeV initial commissioning	Transfer line and injection set-up, orbit,
450 GeV measurements and setup	Beam instrumentation, optics, aperture, collimation, LBDS
450 GeV two-beam operation	Separation bump checks, beam instrumentation
Ramp	Snapback, chromaticity control, orbit, and tune feedbacks
Flat-top checks	Collimation, optics, orbit, decay
Squeeze	Optics, collimation set-up
Validation	Loss maps, asynchronous dumps
Collide	First stable beam with a low number of bunches

The aims of the initial commissioning phase are as follows.

- Establish nominal cycle with a robust set of operating parameters. This will include commissioning of the squeeze to an appropriate β^* with measurement and correction of the optics and key beam parameters at each stage. One should not expect to probe the limits of the HL-LHC parameter space at this stage.
- Measure and correct the optics. Measure the aperture.
- Set-up injection, beam dump, and collimation, and validate set-up with beam.
- Commission beam-based systems: transverse feedback, RF, injection, beam dump systems, beam instrumentation, and orbit and tune feedbacks.
- Commission and test machine protection backbone with beam.
- Check the understanding of magnet model and higher order optics.

The initial commissioning phase is performed at low intensity, with a low number of bunches, and a generally safe beam. The output of this phase is taken to be first collisions in stable beams with a small number of bunches. Following this, pilot physics can be delivered with up to 100 widely spaced bunches. Scrubbing will then be required before entering the intensity ramp-up phase. Scrubbing could well follow the two-stage approach deployed following LS1. This approach is outlined below.

- Initial scrubbing with 25 ns beam following initial commissioning opening the way for a period of 25 ns operation with non-nominal batch spacing.
- Initial intensity ramp-up with 25 ns is then foreseen. During this stage, system commissioning with higher intensity continues (instrumentation, RF, injection, beam dumps, machine protection, vacuum, etc.). Variables at this stage include bunch intensity, batch structure, number of bunches and emittance. Physics fills can be kept reasonably short. The intensity ramp-up is performed in a number of clearly defined steps with associated machine protection and other checks. This phase will be used to characterize vacuum, heat load, electron cloud, losses, instabilities, UFOs, and impedance.
- Thereafter a further scrubbing period with 25 ns and possibly the doublet beam is foreseen.
- This is followed by an intensity ramp-up with 25 ns dictated by electron cloud conditions, with further scrubbing as required. Past experience indicates that a sustained period of physics in the presence of electron cloud will be needed.

Important beam-related characteristics such as lifetime, beam loss through the cycle, stability, quench levels, and UFO rates will only become fully accessible with an increase in bunch intensity and number of bunches during the intensity ramp-up phase.

16.5 References

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