Commissioning and optimization of the injector complex after LS2

1 General considerations

The objective of the LHC Injectors Upgrade (LIU) project is to deliver beams with adequate characteristics for reaching the goal of the High Luminosity LHC project (see chapters 1 and 2). The actions foreseen in the context of LIU consist of installing new equipment, renovating/upgrading existing equipment and implementing new schemes of beam production. Most tasks will take place during the next long LHC shutdown period, Long Shutdown 2 (LS2). They can be divided into two main categories:

- operation critical,
- non-critical.

The operation critical modifications concern systems that have to perform according to specification in order to be able to produce presently operational beams in the PS, requiring a full commissioning before beam delivery for physics can start. The non-critical modifications can be fully commissioned in a later stage when the "basic" machine is operational, e.g. during parallel or if necessary dedicated machine development sessions. It is essential that the equipment concerned by the non-critical modifications does not degrade beam performance of the "basic" machine. Prior to the commissioning a complete list will be drawn up attributing each modification to one of the two categories.

Regardless, the commissioning of each equipment and process shall take place in a well-organized and staged manner according to a detailed planning with clear hand-over milestones. The following successive phases can be distinguished which generally require the full availability of general services such as electricity, cooling water and ventilation:

- Training of the operations team,
- Hardware commissioning,
- Dry runs,
- Commissioning with beam,
- Validation up to the former operational beam characteristics,
- Study and optimization up to the LIU goals in terms of beam characteristics (see chapter 1).

These phases are described in the following sections.

1.1 Training

Although members of the operations team are frequently involved in the tasks of the equipment groups, a formal training on the new or upgraded systems and processes is required in order to ensure efficient and safe exploitation. This training shall be given by specialists during dedicated training sessions towards the end of the long shut down period, during which the upgrade will take place. A detailed planning of these training sessions has to be setup in due time.

1.2 Hardware commissioning

For the hardware commissioning phase it is assumed that all equipment are fully installed and connected, in the tunnel and in the equipment rooms. It is also assumed that the general services, such as electricity, cooling water and ventilation are fully operational. The hardware commissioning, which will take place in the last part of the long shutdown, has the aim of checking that equipment is functional and properly interconnected. The absence of beam during this period will allow relatively easy access to the tunnel in case interventions are required. These tests, where applicable, shall cover:

– electrical connections (quality, heating, etc.);
– equipment cooling (hydraulic pressure, flow, etc.);
– equipment heating when powered at specified rms power (thermography);
– verification of the polarity (connections, magnetic field, etc);
– signal transmission;
– failure scenarios (actions following interlocks etc.).

These tests shall be done locally and shall not rely on the full availability of controls and timing system, as in this phase of the commissioning they might not be fully operational yet.

The responsibility of the hardware commissioning lies with the equipment specialists. However, the coordination of the hardware tests shall be ensured by the machine technical coordinator. Each equipment for which the hardware commissioning has been completed and validated by the equipment specialists shall be declared as available for dry-runs.

1.3 Dry-runs

For this phase, the entire infrastructure including controls and timing system has to be operational and all equipment and application software has to be available. The aim of the dry run is to test and validate entire equipment chains and processes without having beam in the machine, nonetheless involving all means of control and diagnostics.

The responsibility of the dry-runs lies with the operations team that will need close collaboration with the equipment specialists and members of the controls group. Each equipment or process that passed the dry-run, perhaps after several iterations, shall be declared available for commissioning with beam.

1.4 Commissioning with beam

Once the dry-run phase has been completed the theoretical settings will be loaded for each equipment and/or process after which a beam with reduced intensity and beam size (e.g. pencil beam) will be used to commission the machine. The good functioning of the diagnostics systems will play a vital role in the optimization of the settings, hence in obtaining the required beam performance.

As previously mentioned, the operation critical systems and processes will need to be commissioned with beam from the start (e.g. the upgraded injection). The non-critical systems and processes, however, can be commissioned at a later stage, possibly during parallel or dedicated machine development sessions (e.g. longitudinal damper).

The responsibility for the commissioning with beam lies with the operations team in close collaboration with machine supervisors, beam physicists and RF specialists.

1.5 Validation

The operational commissioning process ends with the validation phase, where the goal is to reach and possibly exceed the beam characteristics available before the shutdown. Each equipment or process for which the required performance has been reached shall officially be declared operational.

1.6 Optimization

The LIU goals in terms of beam characteristics are, by definition, inside unknown territory. Reaching them will require fine optimization and extensive beam physics studies in all the accelerators. Progress in performance has to propagate along the cascade of accelerators, from the lowest up to the highest energy. In other terms, the SPS will only be confronted with the most challenging beams once Linac4, PSB and PS will have reached their own LIU goals.

In case the desired performance cannot be obtained it should be clarified if this is related to a technical or to a beam physics limitation requiring more profound studies. Time might be needed during shutdowns and/or technical stops to modify installed equipment.

2 PSB

2.1 Scope

The main modifications taking place in the PSB during LS2 are listed in Table 1. They are meant for:

- charge exchange injection of the Linac4 beam at 160 MeV kinetic, with the possibility of painting in all phase planes,
- bringing the transfer energy to the PS up to 2 GeV kinetic,
- increasing the accelerated beam intensity by a factor of ~2.

Table 1: Main modifications to the PSB during LS2, with estimated hardware commissioning durations

Upgrade activity	Hardware commissioning and dry-runs [months]
Replacement of all equipment in the injection region	
Replacement of the power supply of the main dipoles	
Upgrade or replacement of ejection/recombination/transfer equipment	
Upgrade/replacement of RF systems	
Upgrade of beam instrumentation	

2.2 Preparation phase before LS2

According to the present planning, Linac4 will be fully commissioned at the end of 2015, and it will be subject to a reliability run during most of 2016.

The opportunity of having the 160 MeV H- beam available will be used to test as much as possible of the PSB injection equipment. For that purpose, half of a PSB injection section will be installed at the end of 2015 in the Linac4 to PSB transfer line and tested with beam during the first half of 2016 ("half sector test"). That will allow gaining valuable experience with the new hardware, controls, application software and in general with the new injection principle. This phase will help correct potential design flaws and accelerate the setting-up of the PSB at the end of LS2.

2.3 Hardware commissioning and dry-runs following LS2

During hardware commissioning the equipment experts have to check in detail the newly installed equipment as well as all equipment under their responsibility. In particular the cable removal and cable installation campaign, but also the numerous installation activities inside the tunnel and in the equipment galleries justify this precaution. The hardware commissioning period follows the installation phase and is individually timed for each equipment. Test should proceed as soon as all the boundary conditions are fulfilled, i.e. the equipment cabled, ready to be powered and controlled, vacuum, cooling etc. available if needed and the different testing steps permitted by the machine/access conditions. One major lesson from SNS Ring commissioning was that the equipment set the pace for the overall duration of the commissioning phase [2].

Dry-runs will be organised as soon as equipment becomes available. An essential pre-requisite is for the control infrastructure to be in an operational state with all applications ready and tested from the CCC.

2.4 Beam commissioning up to validation

After the successful completion of dry-runs on all systems (RF, beam instrumentation, power supplies etc.), beam commissioning will begin, provided that the following additional conditions are met:

- Linac4 beam fully characterised in the LBE line and requested commissioning beam ready,
- Correct operation of Linac4 pre-chopper and chopper as main actors for the beam interlock system, to avoid beam being sent to head- and tail dumps of the distributor as well as losses during distributor kicker switching between rings and finally to provide an adequate beam structure for injection into the PSB.

- Linac4 beam synchronised with all PSB injection systems (distributor, vertical septum, beam instrumentation, magnets, chicane and painting bump, PSB RF etc.),
- Magnets polarity checked (quadrupoles and corrector magnets in the BI line),
- Beam interlock system validated,
- New magnetic cycle prepared,
- Extensive support from equipment and controls specialists especially during the first phase of beam commissioning,
- Availability of optics models for the injection region and the PSB rings with extensive support from beam physicists present in the control centre (optics checks, injection process, re-matching of the injection line, issues with orbit closure etc.).

A very low intensity beam from Linac4 of 0.5 μs length should first be used with software interlocks (SIS) in place to guarantee the intensity limit. This beam will be injected successively in the 4 rings and it will serve to check/calibrate beam interlock and test injection systems with their beam instrumentation. This phase is expected to take 1-2 weeks.

Once beam will have been centred on H0/H- dumps and with all ring equipment available (especially RF and beam instrumentation) the setting-up will continue with preliminary adjustment of trajectories/orbit and transverse tunes in the PSB. When the beam will circulate for ~10-20 turns with an orbit around ~±5 mm, the RF will be switched on and RF adjustment will begin. Tune measurement will then be possible, allowing refinement of the working point and adjustment of BSW and KSW bump closure to minimize injection oscillations. Four weeks are estimated necessary to complete this work programme.

The next step will be to adjust beta-beating compensation, measure transverse emittances and check apertures in all rings. Commissioning of the matching monitor will begin. The duration of this phase is estimated as 1 week.

Acceleration up to 2 GeV will then be set up, involving completely new main power supply (MPS) and High Power RF equipment. All RF loops have to be functional as well as synchronisation of ejection timings to the external dump. Resonance compensation will be necessary, starting with pre-loaded functions for the multipole correctors. The energy of the different rings will be equalized using the Bdl trim power supplies. After adjustment of extraction and recombination systems, aperture scans will be performed at the septa location. This phase will take 3 weeks.

Preparation of the LHCPROBE beam will be the logical next step, both because it is low intensity (5.10^9 p) and because it is probably the first one required by the downstream machines. Properly working beam instrumentation and fine control of RF and magnetic elements will be essential for tailoring intensity and emittances in all phase planes. A total of 3 days should be sufficient for achieving the LHCPROBE nominal parameters and adjusting the BTP beam line to make it available to the PS.

The setting-up of the multiple operational beams will then take place (STFPRO, LHC production beams, ISOLDE, AD…) by progressively increasing the injected beam intensity and optimizing painting at injection and in general the adjustments in all phase planes. Given the highest priority, the LHC production beam could be available after 2 more weeks. Afterwards, it will take 3 more months to prepare and adjust the multiple operational beams in parallel with the delivery of beams to the PS.

and PSB work reliably according to its specifications. Requirements on beam instrumentation are especially stringent from the very beginning of that phase.

2.5 Summary of beam commissioning planning

The different beam commissioning and validation phases and their respective durations are summarized in Table 2. No contingency is included for dealing with unplanned difficulties (e.g. foil breakage etc.).

Table 2: Successive beam commissioning and validation phases and their estimated durations

Milestone	Phase	Duration [weeks]
	First injections	2
	First turn and closed orbit	4
	Optics and aperture	1
	Accelerate and extract	3
	Produce the LHCPROBE beam	0.5
Availability of LHCPROBE beam		**10.5 weeks**
	Setting-up of LHC production beam	2
Availability of LHC production beam with pre-LS2 beam characteristics		**12.5 weeks**
	Setting-up of other operational beams in parallel with delivery of beam to the PS	13
Validation of all operational beams at pre-LS2 performance level		**25.5 weeks**

Approximately 10.5 weeks of beam commissioning are needed before delivering the first beam (LHCPROBE) to the PS. If absolutely necessary, a low intensity/higher emittance beam could be delivered earlier to the PS (after ~6 weeks), by preparing only ring 3. The completion of beam commissioning of the other rings in parallel with the regular delivery of beam to the PS would however require 4 more weeks. In any case, the total time required with beam until the pre-LS2 beam characteristics are available for all operational beams adds up to ~6 months.

2.6 Optimization

Many Machine Development sessions will be needed for checking how far the beam characteristics can be improved, understanding potential new limitations and finding means to circumvent them. Additional methods like longitudinal painting will be tested and optimized in view of reaching the LIU goals in terms of beam characteristics from the PSB.

This phase will take place in parallel with the physics run. Its successful completion will only be possible if adequate MD time is made available and if all equipment in Linac4, transfer lines and PSB are reliably working according to their specifications. Beam instrumentation in particular should be fully operational from the beginning. Duration will depend on the amount of allocated beam time and on the availability of adequate specialists.

3 PS

3.1 Scope

Although some of the PS upgrades are implemented during LS1, the main and most critical ones will be done during LS2. This is summarized in Table 3.

The main performance improving changes after LS2 will be:

- the increase of the injection energy into the PS up to 2 GeV kinetic,
- the reduced beam loading effects on RF cavities and the increased RF voltages at 40 and 80 MHz.

Table 3: Overview of the equipment and processes concerned by the upgrade

Item	Commissioning	Criticality
Beam production scheme (BCMS)	after LS1	Non-critical
Resonance compensation	after LS1	Non-critical
Transverse damper	after LS1	Non-critical
Longitudinal damper	after LS1	Non critical
Working point control	after LS1	Non critical
Injection energy	after LS2	Operation critical
Low energy correctors	after LS2	Operation critical
Internal dump	after LS2	Operation critical
RF upgrades	after LS2	Operation critical

The other upgrades (Low energy correctors, internal dump …) will improve safety, ease of operation and reliability.

3.2 Preparation before LS2

The "Batch Compression, Merging and Splittings" scheme which was only demonstrated during test periods at the end of run 1, will have to be set-up for reliably operating at high luminosity with 25 ns bunch spacing in LHC during run 2.

The equipment installed during LS1 will be tested during Machine Development sessions and progressively put in operation during run 2.

Combined with an improved modelling and control of the working point using the Pole Face Windings, the compensation of resonances permitted by the new sextupoles will help handle beams with large space charge induced tune shift. That should improve performance of operational high intensity beams (e.g. AD, nToF) as well as accelerate setting-up after LS2 with the higher brightness beams from the PSB.

Once equipped with the required amplifiers and low level RF, at the beginning of 2015, a new longitudinal damping systems will start being tested. Before the beginning of LS2 it should be operational at suppressing longitudinal coupled bunch instabilities, improving the quality of beam gymnastics and reproducibility of beam characteristics especially for LHC.

3.3 Hardware commissioning and dry-runs following LS2

The injection energy increase from 1.4 GeV to 2 GeV kinetic will be obtained with upgraded or new equipment that need dedicated and extensive commissioning before the first beam.

The renovated power converters of the low energy correctors should be exercised and demonstrate adequate and identical rise times.

The upgraded RF systems should be conditioned up to their new and higher nominal voltages.

The upgraded or newly installed diagnostics for the injection will need to be commissioned too.

3.4 Beam commissioning up to validation

After the successful completion of dry-runs on all systems, beam commissioning will begin. The estimated duration of the successive phases is given in Table 4.

Table 4: Successive beam commissioning and validation phases and their estimated durations

Milestone	Phase	Duration [weeks]
	First injections	2
	First turn and closed orbit	4
	Optics and aperture	1
	Accelerate and extract	3
	Produce the LHCPROBE beam	0.5
Availability of LHCPROBE beam		**10.5 weeks**
	Setting-up of LHC production beam	2
Availability of LHC production beam with pre-LS2 beam characteristics		**12.5 weeks**
	Setting-up of other operational beams in parallel with delivery of beam to the PS	13
Validation of all operational beams at pre-LS2 performance level		**25.5 weeks**

3.5 Optimization

Machine Development …

4 SPS

In terms of schedule the LS2 upgrade activities in the SPS are dominated by two tasks:

- 200 MHz RF upgrade,
- aC-coating of 6 sectors.

However, many other systems are also being upgraded and the re-commissioning with beam will be extremely challenging in view of the need to deliver beam immediately to the LHC for luminosity production. The end of the injector upgrade work in LS2 will therefore require a very well-organised and complete set of commissioning tests to prepare for nominal operation with beam, the scope of which will include individual system tests and powering, controls system integration tests, dry-runs from the CCC, machine cold check out and beam commissioning.

The main boundary conditions are the length and timing of LS2, at 18 months from Q3 2018 onwards, the scope of the work to be done, summarised below, and the planning for the beams to be delivered to the LHC. Clearly, manpower and expert availability for the commissioning phases is also a key factor but this will not be discussed here, under the assumption that the CERN groups involved take the necessary steps to ensure that adequate qualified support is available.

In the following sections the scope of the LS2 work in the SPS is recalled, and the main commissioning steps outlined, together with the presently estimated durations and known dependencies. The expected performance evolution after LS2 is also described, in terms of reasonable assumptions on the available beam characteristics, together with a proposed overall strategy for the commissioning of the full LIU beams.

4.1 Scope

For the LIU project, the main SPS upgrades implemented during LS2 are listed in Table 5, together with the estimated time for hardware commissioning/dry-runs. To note that these preliminary estimates do not take into account any co-activities.

The tunnel work on the 200 MHz RF systems during LS2 involves 6 months of cavity rearrangement in LSS3: 18 existing cavity sections with their services have to be displaced and re-installed, 2 new cavity sections added as well as 6 new couplers.

Electron cloud is one of the major limiting factors for 25ns beam operation. One promising mitigation consists of coating vacuum chambers with a thin film of amorphous carbon. Over the years a technology was developed for treating the chambers in the magnets without the need of dismantlement. Nevertheless this has to be done in a special workshop on the surface. After LS1, 4 SPS half-cells will be coated and their performance will be evaluated with beam. The aim for LS2 will be to coat 90% of the SPS: >700 dipoles, the main quadrupoles, long straight sections, pumping port shields and maybe as well the short straight sections. A first planning of the magnet flow between tunnel and surface workshop has been presented. The maximum estimated flow consists of 6 magnets in and 6 magnets out per day, yielding 12 months in total including commissioning for this activity.

A new external beam dump will have to be installed. Although the definitive solution will only be defined at the end of 2014, it will in any case necessitate underground civil engineering and completing this task during LS2 will be challenging.

Among the many other activities, a major one is the modification of the injection system to reduce the injection kicker rise-time to 100 ns for ions.

Table 5: main SPS upgrade items in LS2, with estimated commissioning time

Upgrade activity	Hardware commissioning and dry-runs [months]
200 MHz RF system (high power and low-level)	6.5
aC-coating of 6 sectors	
Improve ZS pumping and impedance	1
Reduce the impedance of kickers	2
Upgrade the extraction protection system	1
Install new external high-energy beam dump	3
Exchange TIDVG dump core	2
Add a new wide-band transverse damper	3
Renew/improve beam instrumentation	3
Improve vacuum sectorisation of the arcs	1
Upgrade the injection damper for ions	3
New injection system with 100 ns rise-time kicker for ions	4

4.2 Preparation before LS2

Several systems will already have been installed or upgraded and commissioned before LS2, including the transverse damper and the 800 MHz RF system with new high power and low level RF systems.

The 200 MHz upgrade activity has already started, and the new building will be handed over end of 2015. The amplifiers will be installed inside and tested on dummy loads before the beginning of LS2.

4.3 Hardware commissioning and dry-runs following LS2

The time required for hardware commissioning and dry-runs of the different newly installed equipment is given in Table 5.

6.5 months will be necessary for commissioning the 200 MHz RF systems immediately after installation. From the logistics point of view, transport through LSS3 will be prohibited during a total of 12.5 months.

Commissioning of the new injection system for ions is the next most time-consuming (4 months) activity.

4.4 Beam commissioning up to validation

According to this analysis, 16.5 months will be necessary for the SPS to be ready to receive beam from the PS. Beam commissioning will be very challenging due to the modified RF hardware combined with a new RF beam control, therefore a minimum of 1.5 months have to be reserved. Depending on the electron cloud situation in the SPS and the required scrubbing (machine has been at atmosphere over many months), it is expected that at least another 1.5 months have to be added to be ready to send the present nominal LHC production beam to the LHC (1.15×10^{11} p+/bunch at 25 ns, around 2.5 μm transverse emittance). This is summarized in Table 6.

Table 6: Successive beam commissioning and validation phases and their estimated durations

Milestone	Phase	Duration [months]
	Injection and acceleration of low intensity beam	1.5
Availability of LHCPROBE beam		**1.5 months**
	Setting-up of LHC production beam (including scrubbing)	1.5
Availability of LHC production beam with pre-LS2 beam characteristics		**3 months**
	Setting-up of other operational beams in parallel with delivery of beam to the PS	?
Validation of all operational beams at pre-LS2 performance level		**?**

4.5 Optimization

The commissioning of the final HL-LHC beams with double the brightness is expected to take around 2 years of parallel machine development and dedicated tests. Many new systems and functionalities must be commissioned across the complex, including a completely new type of injection in the PSB (160 MeV H-) with brand-new hardware, and it is expected that much of Run 3 will be needed to learn how to operate and optimize the adjustment of the newly installed equipment and to routinely produce the new beams.

The necessary studies and Machine Development can tentatively be scheduled as follows:

a. 1 day per week until the end of 2020: establish high intensity 25 ns (2.5×10^{11} p+/bunch) beam with few bunches, working on the following subjects:
   - Damper,
   - Longitudinal transfer,
   - Longitudinal stability,
   - Transverse stability,
   - Beam losses,
   - Instrumentation,
   - Beam characterisation.
b. 1 day per week during 2021: establish high intensity 25 ns (2.5×10^{11} p+/bunch) beam with 72 - 288 bunches, acting mostly on:
   - Longitudinal transfer,
   - Electron cloud,
   - Longitudinal stability,
   - Transverse stability,
   - Beam losses,
   - Instrumentation,
   - Beam characterisation,
   - Conditioning of beam dumps.

Clearly, many details remain to be worked out, including the time sharing between machines and the exact order of different steps, as well as the split with physics beams. However, it is clear that significant dedicated commissioning time will need to be planned across the injector complex throughout 2020 and 2021 at least, with the likelihood of continuing in 2022 and even of having more dedicated blocks during 2023 when the LHC is scheduled to be off for LS3. It should be noted that in addition to the proton beam, ion beams and associated equipment also need commissioning, including the slip-stacking in the SPS and the new faster rise-time ion injection system.

If this commissioning strategy is adopted, and assuming 12 h per week can be dedicated to the LIU beam commissioning through 2020 and 2021, then a total of about 18 days per year integrated commissioning time would be available. This is not particularly long, given the amount of upgrades made in all the machines, and the ambitious beam performance target, and it may be that more dedicated time will need to be made available. A few longer 3-4 day periods may anyway be useful and should be planned in, probably to coincide with LHC technical stops – the need for any extra dedicated time can be judged sometime in 2020, and should possibly already be planned as a review or checkpoint midway through 2020, where the progress can be examined and the strategy adjusted if needed. Clearly, to ensure that these important beam time requests are met will need a general and high-level agreement on the beam time sharing between LIU beam commissioning, other SPS MD and the SPS physics program.

5 Integrated LS2 planning

The above analysis of the estimated time required for recovering pre-LS2 performance from the different accelerators of the injector complex is summarized in Figure 1. The main conclusion is that, to fit within the allocated slot of 18 months of beam stop in LHC, beam commissioning in the PSB, PS and SPS have to begin respectively after no more than 13.5, 15 and 16.5 months. A first estimate prepared for the "Review of LHC and Injectors Upgrade Plans" [6] in October 2013 showed that this will not be easy, especially in the PSB where the extensive amount of cabling work is on the critical path. A detailed schedule remains to be prepared, making the optimum use of the access time during the machine stops before LS2 and taking properly into account all the activities (e.g. SPS external dump and 100 ns rise time kickers).

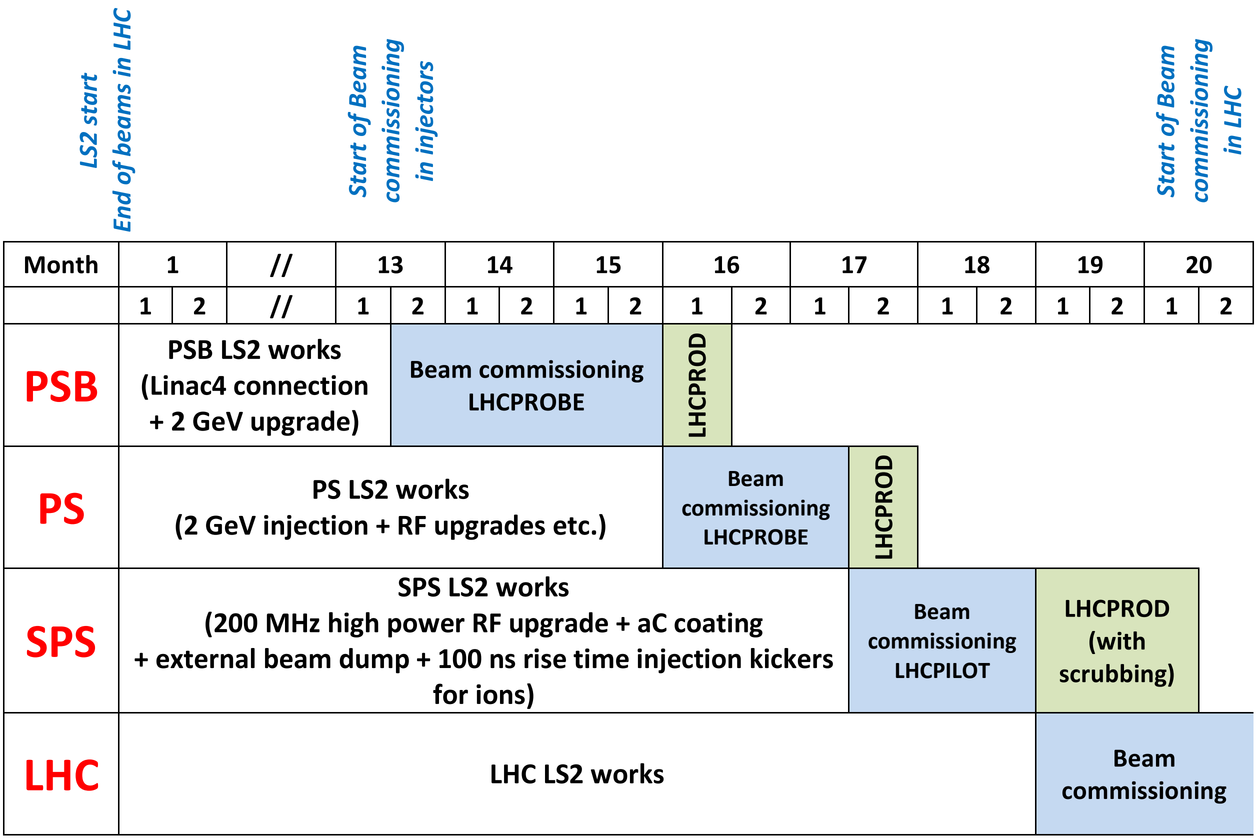

Figure 1: Preliminary estimates of shutdown time required for the LHC injectors during LS2 [6].

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