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WORK EFFORT IN THE LHC INJECTOR COMPLEX FOR THE UPGRADE SCENARIOS

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Abstract

This document describes the work in the PSB, PS and SPS that is required for upgrade scenario 1. It will be shown that the requirements on the hardware work needed for upgrade scenario 1 are identical to the ones of the upgrade scenario 2 [1]. The various activities are detailed as well as their dependencies and an estimate given for the duration of the necessary shutdowns and recommissioning periods with beam. It is mentioned whether some decisions are still to be taken and are related to information to be obtained after LS1. Another important aspect is the evaluation of the risks related to the upgrade interventions and operational complexity, which concern schedule, beam characteristics as well as reliability and overall performance. It has been studied if part of the activities could be spread out over several machine stops, and as conclusion the preferred scenario will be presented.

LINAC4 STATUS

Linac4, presently under construction, will replace the present 50 MeV Linac2 as injector of the CERN proton complex. The commissioning of the linac, which started with the 3 MeV test stand early 2013, will be divided into 5 different stages corresponding to the different accelerating sections and will be completed by the end of 2015. A one year reliability run is foreseen in 2016, after which the linac will be ready to be connected to the injector complex. From that date, any postponement of the connection will entail some major drawbacks:

- The risk of a Linac2 breakdown remains for more years, mitigated only by an emergency connection with 50 MeV protons at reduced performance.
- Linac4 will need to be maintained operational in parallel with Linac2, with a related cost and use of resources.
- Key experts (retirements, staff on limited duration contracts and fellows) will leave the project before 2018.
- Possible uncontrolled shift of the commissioning schedule due to demotivation of the team and redefinition of priorities in case of a delayed connection during LS2.

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CONNECTING LINAC4

The required connection work on the linac side will take place in two different areas: at the Linac2-Linac4 interface and at the present location of the LBE/LBS measurement lines. These areas are surrounded with dashed lines in Fig. 1.

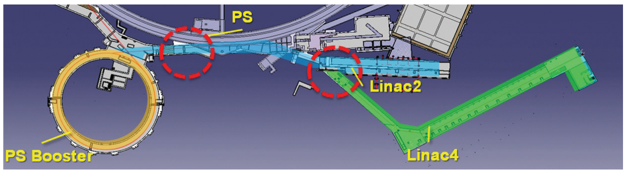

Figure 1: Linac4 connection working areas.

Linac2-Linac4 Interface

Linac4 will be connected to the existing Linac2 transfer line to the PSB at the location of the LT.BHZ20 bending magnet. On top of the line installation, some civil engineering work is required: drill a new DC cable path, build a shielding wall to protect the Linac2 surface building, add some shielding around the beam pipe at the transition, drill a new emergency exit in the Linac2 wall and assemble a chicane of concrete blocks in the Linac2 tunnel. Given the relatively small area where all these tasks need to be done, the work has to be sequenced. Before starting any work in this area, it is required to wait for a 4 weeks cool-down time after the Linac2 beam stop; 8 more weeks will then be needed to complete the connection. This results in a total duration of 12 weeks starting from the Linac2 beam stop until the completion of the work at the Linac2/Linac4 interface.

LBE and LBS Measurement Lines

Two measurement lines are presently used to characterise the beam from Linac2 before PSB injection: The LBE line for transverse emittance and the LBS line for energy and energy spread measurements. These two lines having been designed for an energy of 50 MeV and need to be upgraded for use at 160 MeV with Linac4.
A recent analysis indicated that because of the limited space available and of the difficult access an upgrade of the LBS line would have induced heavy civil engineering work in the direct vicinity of the PS tunnel with many complications and interference in terms of planning for the PSB and the PS upgrade tasks. The working time in the LBS area

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was estimated to 5 months. It was therefore decided to develop a new measurement technique based on longitudinal emittance reconstruction with some additional diagnostics installed in the Linac4 transfer-line [2]. This new measurement technique provides a better resolution for a drastically lower cost than the LBS upgrade, and on top of that does not interfere with the PSB and PS planning. The present LBS line can be kept as is for ion beams from Linac3.
The LBE line instead will be completely upgraded installing 2 quadrupoles, 3 profile monitors and a beam dump. After 6 weeks of cool-down in the PS tunnel (no beam or ion run) before accessing the LBE area, it will take 2 weeks for removing the existing line and 4 weeks to assemble to new one (cabling done in parallel). This results in 12 weeks in total (including cool-down).

Linac4 Operational

Following the 12 weeks needed both for the Linac2-Linac4 interface and for the LBE measurement line, 3 additional weeks have to be added for hardware and beam commissioning. The overall planning is shown in Fig. 2.
15 weeks after the last proton in Linac2, Linac4 could be ready to send a fully characterised beam to the PSB.

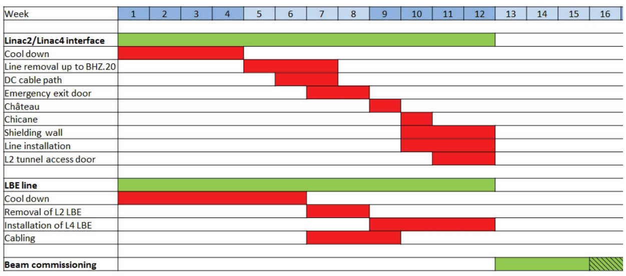

Figure 2: Linac4 connection planning.

Ion Run in Parallel to Linac4 Connection

The only constraint for having an ion run in parallel to the Linac4 connection is given by the time needed on the LBE line upgrade (6 weeks). In fact, the LBE being located in the direct vicinity of the PS tunnel, no work can be done in the area while an ion beam is circulating in the PS. An ion run could take place before the LBE upgrade (and being therefore considered as cool-down time) or after the LBE upgrade. The PSB injection upgrade work can safely take place in parallel to an ion run, the booster being shielded from the PS by a 6 meter thick wall.

WORK EFFORT IN THE PSB

The LIU upgrade activities for the PSB comprise two main parts: Modifications due to the Linac4 connection and the upgrade to 2 GeV extraction energy. The baseline plan foresees that both parts will take place in parallel during LS2, but due to the significant amount of changes affecting major systems of the PSB, this would imply risks for the restart after LS2 and could lead to delays for the whole accelerator chain. Therefore it was also studied if these two distinct parts could be separated by connecting Linac4 to the PSB in an intermediate shorter shutdown.

Connection of Linac4 to the PSB in an Intermediate Shutdown

The connection of Linac4 to the PSB implies an increase in injection energy from 50 to 160 MeV injecting an H^- instead of a proton beam. This requires the following changes:

- Replace certain magnets and power supplies in the PSB injection line due to the increased beam rigidity
- Install new beam instruments adapted to the Linac4 beam and/or specific for the H^- injection process
- Change the vertical beam distribution system to inject the Linac4 beam into the 4 superposed PSB rings (new distributor, vertical septum)
- Exchange the complete PSB injection section: New injection chicane with 4 magnets per ring, charge-exchange stripping foil unit, H^0/H^- dump, horizontal phase-space painting bump using 4 kicker magnets, novel beam instrumentation
- Modify vacuum sectorisation and vacuum chambers in 2 main bending magnets
- Install new beam interlock system.

Fig. 3 shows a simplified 3D-model of the future PSB injection section.

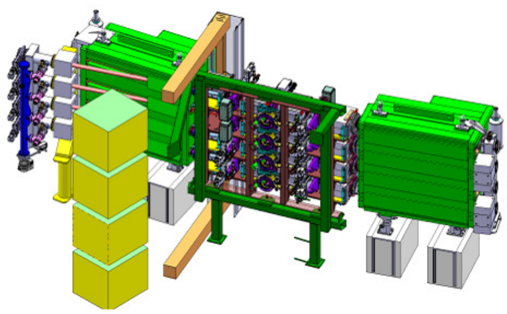

Figure 3: 3D view of the future PSB injection section without services (PSB tunnel wall also not shown). The 4 injection lines are visible at the left behind a transformer stack.

The required cool-down time of 1-1.5 months was assumed to take place in parallel with the end-of-year LHC ion run and the 2 weeks of Christmas break. During this time preparatory work like installation of new racks can take place. Due to the saturation of many cable trays and ducts the necessary cabling and uncabling campaign has been estimated to 5 months by EN-EL, assuming 3 shifts per day. Dismantling and installation of the new equipment will take 4.5 months; for the new injection section a detailed work plan has been elaborated to have confidence in this estimate. This period will be followed by 1 month of high-voltage conditioning of the injection kickers and parallel cold check-out of the machine. The PSB will then be able to send the low-intensity LHCPROBE beam to the PS after 8 weeks of beam commissioning followed by the LHC production beam 2 weeks later. An overview of the work effort for the Linac4 connection to the PSB is given in Table 1.

Table 1: Work breakdown for the connection work.

Activity	duration
Radiation cool-down and preparatory work	1.5 months
Dismantling, installation and cabling campaign	4.5 months
HV testing and cold check-out	1 month
Running in PSB to provide LHC production beam	2 months
Total	**9 months**

In order to virtually shorten this period of 9 months for the LHC, it has been proposed to extend the LHC proton run in 2016 until beginning of December for additional integrated luminosity. Ion commissioning of the LHC ion injector chain would be performed in the last quarter of 2016 in parallel to the proton run and until the Christmas break. Beginning of January an extended LHC ion run of 3.5 months could take place, from which other ion users in the North Area could also profit. This long ion run period would then be followed by 4.5 months of CMS pixel detector installation, which would fill up the 9-month period.

PSB Upgrade - Baseline Work Effort

In the baseline scenario, Linac4 will be connected to the PSB during LS2, and in parallel the 2 GeV PSB upgrade will take place. In addition to the activities mentioned in the previous paragraph, the following work needs to be carried out:

- Replace main power supply; new PSB MPS will be installed in a new building
- Modify main magnet cooling circuits + shimming
- Renovate PSB cooling and ventilation systems (consolidation)
- Upgrade the PSB RF systems
- Exchange certain magnets and/or power supplies in the extraction lines
- New extraction and recombination kickers, new recombination septa
- Add or modify beam instrumentation
- Install new beam interlock system
- Renovate electrical services (consolidation).

During the first 1.5 months of radiation cool-down, the new MPS will be tested, connecting one main magnet circuit. In parallel, the renovation of the PSB cooling system (7 months total duration) and of the ventilation system (12 months) can start. An impressive cabling campaign of 9 months in total (3 shifts per day) needs to be undertaken. The dismantling and installation efforts for the new equipment amount to 5.5 months, which results in the uncomfortable situation that during 3 months equipment testing has to wait for the cabling to be finished.
The PSB can therefore be closed only 10 months after the stop of the run preceding LS2. From this point on, hardware tests can continue in parallel: tests of the MPS with the final load (2 months), running in of the new RF system (5 months), HV DC conditioning of the new extraction kickers and equipment tests (5 months).
Beam commissioning in this case will be extremely complex with the new injection hardware, new instrumentation, new MPS, new RF system plus new extraction equipment with 4 rings to be set up. It is estimated that the LHCPROBE beam can be sent to the downstream machine 2.5 months after beam commissioning start, followed by the LHC production beam 2 weeks later. Additional beams should follow at an approximate rate of 2 per week at best. In summary, the LHC production beam is expected to be available to the PS after **18 months**.

WORK EFFORT IN THE PS

Despite a multitude of LIU-related work has already been carried out during LS1, many LIU-PS activities remain to be undertaken during LS2, but they are not representing a bottleneck for the LS2 duration. The main ones are the following:

- Replace vertical correctors and normal/skew quadrupoles due to increased injection energy of 2 GeV - 5 months
- Exchange PFW (pole face windings) of the main magnets (consolidation) - 11 months
- Install new injection kicker, bumper and septum - 4 months
- Upgrade of 10 MHz RF system
- Install 2 new internal dumps
- Exchange certain magnets and/or power supplies in the extraction lines - in the shadow of other activities
- New beam instrumentation (wire scanners, BLMs, injection SEM grid etc.) - not time-critical
- Upgrade electrical services, vacuum systems etc.

For the PS, no detailed study is yet available concerning potentially needed cabling campaigns. Nevertheless it has been stated by EN-EL that with the current information the expected work load would be less substantial than for the PSB, which would mean that the campaign would not be a bottleneck in the PS.
Counting 1 month of radiation cool-down, general access can be given after 2 months to perform all the above-mentioned tasks. Four weeks of hardware test and 2 weeks of cold check-out will follow the installation period, which means that the PS would be ready to receive beam from the PSB after **14.5 months**.

For beam commissioning and to provide the LHCPROBE beam to the SPS, 5 weeks should be reserved (2 weeks for OP and 3 weeks for RF) under the assumption that the PS will restart with the old beam control and that there will be a switch-over possibility implemented between old and new beam control. Two additional weeks are required to set up the LHC production beam.

WORK EFFORT IN THE SPS

The upgrade activities in the SPS are dominated by 2 tasks: The 200 MHz RF upgrade and the aC-coating of 6 sectors. It has been assumed for the cabling campaign that it would last less than 10 months, but this needs to be confirmed with a more detailed study. In order to reach the beam performance required for the LHC within Upgrade Scenario 1, electron cloud mitigation means need to be adopted already during LS2. This means that Upgrade Scenarios 1 and 2 involve identical hardware modifications for the SPS. The main SPS upgrade items are:

- Upgrade 200 MHz RF system (power and low-level) - 12.5 months
- Perform aC-coating of 6 sectors - 12 months
- Improve ZS and work to reduce the impedance of other kickers
- Install new external high-energy beam dump and exchange TIDVG dump core
- Upgrade the extraction protection system
- Add a new wide-band transverse damper (intra-bunch damping in the vertical plane)
- Renew/improve beam instrumentation
- Improve vacuum sectorisation of the arcs
- Ions: upgrade the injection damper for ions and add new short rise-time kickers (100 ns).

The 200 MHz upgrade activity has already started, and a new building that will house the amplifiers will be handed over end of 2015. The tunnel work 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. The remaining 6.5 months will be used for system commissioning. This activity cannot be split up; once started it has to be completed. From the logistics point of view it will also prohibit transport activities passing through LSS3.

Electron cloud is one of the major limiting factors for 25ns beam operation. One 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 can 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 [3]. The max. estimated flow consists of 6 magnets in and 6 magnets out per day, yielding 12 months in total including commissioning for this activity.

A first LS2 planning for the SPS has been elaborated and is summarised in Table 2.

Table 2: LS2 work overview for the SPS.

Activity	**duration**
Radiation cool-down and preparatory work	2 months
Upgrade activities	12.5 months
Patrols, DSO tests	1.5 weeks
Magnet + power supply tests	6 weeks
Cold check-out	4 weeks
Commissioning with beam	1.5 months
Total	**≈18 months**

After this planning, the SPS will be ready to receive beam from the PS after **16.5 months**.
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 LHC production beam to the LHC.

LS2 FOR THE INJECTORS

The required LS2 duration from the point of view of the LHC injectors follows from the previous chapters with the constraint that the manpower availability for the work in the different machines has not yet been studied in detail (service groups, interventions for both upgrade and consolidation). According to this planning the LHC would receive first beam from the injectors **20.5 months** after the end of run before LS2 (see Figure 4), or the LHC production beam after **22 months**. This is longer than the 18 months generally assumed as LS2 duration because of the complexity of the cabling campaigns, especially in the PSB. If the cabling campaign in the PSB could be reduced by 3 months, the PSB could send beam 3 months earlier to the PS, which would exactly match the time when the PS would be ready to receive beam from the PSB. The LS2 injector schedules would then align quite well, and the LHC would receive the LHCPILOT after **18 months** and the LHC production beam after **19.5 months**.

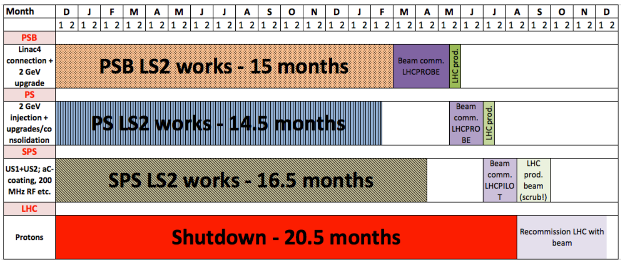

Figure 4: Required duration in the different LHC injectors for modifications during LS2.

RISK MITIGATION

The primary risk resulting from the injector upgrades is related to the schedule, although the technical risks due to the extensive amount of new equipment installed in all of the accelerators is also significant. To minimise these risks, the following points should be considered:

- Identify and advance certain interventions to earlier short shutdowns if possible; in this context a connection of Linac4 to the PSB in an intermediate shutdown should be mentioned
- Perform detailed integration studies that include as well CV and EL equipment (cooling pipes, cable trays etc.) to avoid mechanical conflicts during installation
- Construct mechanical mock-ups for complex installation items
- Produce a more detailed planning of the interventions including manpower resource planning to identify potential co-activity issues; take into account the integrated dose per worker
- Organise test stands or beam tests where possible to reduce technical risks (for example installation of half of the PSB injection chicane in the Linac4 transfer line)
- Prepare new applications/controls well ahead of the deadline and well tested to be ready for the commissioning
- Develop a detailed beam commissioning planning with clear check lists.

CONCLUSIONS

It is necessary to identify solutions to gain 3 months for the PSB cabling campaign in the PSB to align the injector upgrade schedules for LS2. This requires detailed studies of the present cabling situation, identification of obsolete cables to provide space as well as future cabling and rack installation requests. Only under the assumption that such a solution can be found, the LHC can expect to receive an LHCPILOT beam after 18 months of shutdown. The delivery of the LHC production beam is then depending on the required scrubbing after LS2.
From the machine side it would be advantageous to connect Linac4 to the PSB in an intermediate shutdown, which could be an option in case the experiments would be interested in an extended ion run period in addition to the CMS pixel detector exchange.

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