

WHAT WILL LP-SPL AND PS2 PROVIDE FOR THE LHC

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Abstract

The construction of LP-SPL and PS2 is proposed as upgrade for the injection chain of the LHC. The motivation and the benefits for the LHC and the operation of the complete accelerator complex are discussed. The beam parameter space for LHC operation is outlined. A realistic schedule for construction of the new machines is presented, including timeline and strategy for commissioning until at least the present ultimate beam can be delivered. Reliability issues as well as the cost of construction are also addressed.

INTRODUCTION

The Low-Power version of the Superconducting Proton Linac (LP-SPL) and the PS2 synchrotron are proposed to replace PS-Booster and PS in the chain of LHC injectors, within the framework of the CERN accelerator complex upgrade programme [1], to fully exploit the LHC potential.

The first stage of the injector upgrade started in 2008 with the construction of Linac4 [2], which will supply an H⁺ beam at 160 MeV to the existing chain Booster-PS-SPS from 2013 onwards, replacing Linac2 and removing the space bottleneck at 50 MeV Booster injection.

The second stage is planned to start in 2013 and will see the construction of the 50 GeV PS2 and its injector, the LP-SPL, replacing the 25 GeV PS and the 1.4 GeV Booster. The LP-SPL [3] will use Linac4 as front-end and deliver a 4 GeV H⁺ beam to the PS2 [4]. The SPS will also have to undergo a substantial upgrade programme [5] to be able to digest the beams with higher brightness and intensity delivered by the new complex at up to 50 GeV injection energy. An overview on the two-stage injector upgrade programme for protons is shown in Figure 1.

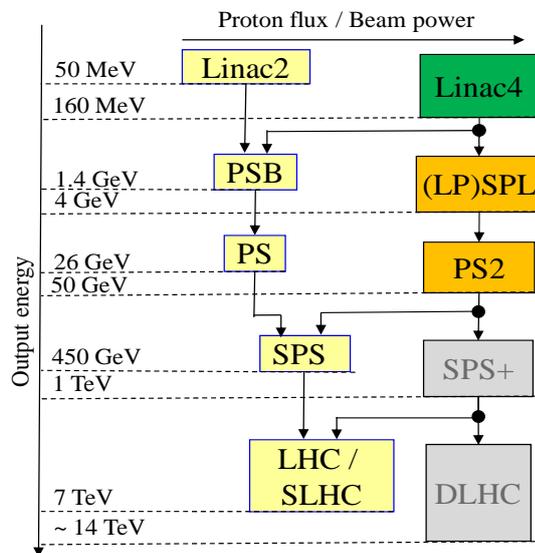


Figure 1: Overview of the CERN proton injector complex upgrade programme: stage 1 (green), stage 2 (orange).

For operation with ions from Linac3/LEIR, the PS2 will replace the PS, as shown in Figure 2.

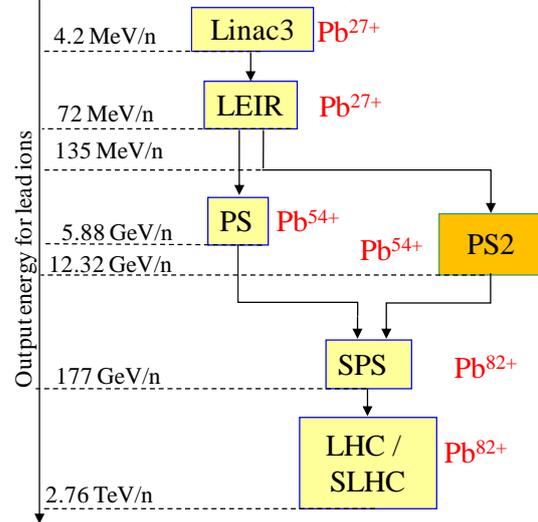


Figure 2: Overview on the CERN ion injector complex with PS2 upgrade.

DESIGN GOALS, OPERATION ASPECTS AND MAIN PARAMETERS

The present injector complex, with the ageing PS in its centre, is operating far beyond initial parameters and stretched to the limit for reaching ultimate performance for the LHC. This performance could only be established with complex operation modes (e.g. LHC bunch train production in the PS) requiring manpower intense tuning, a large diversity of specific hardware and the related expert knowledge for setting-up and maintenance.

The new injector complex aims at simplified operation procedures and will be based on state-of-the-art hardware with a high multiplicity, to reduce tuning needs and to minimize specialist manpower requirements for operation and maintenance. LP-SPL and PS2 will also provide sufficient performance margin for a safe and efficient exploitation of the higher energy machines and in particular the LHC.

The LHC luminosity upgrade [6] defines the overall requirements on LP-SPL and PS2 and thus the main parameters and design choices.

The main design goals for LHC operation are:

- Significantly increased beam brightness.
- Flexibility for generating bunch patterns and spacing.
- Sufficient operation margin for full exploitation of the LHC.

General design goals are:

- High reliability and availability.
- Simplification of operation schemes.
- Reduced beam losses for operation.
- Potential for future upgrades of the complex.
- Potential for future non-LHC physics programmes.

Beam brightness

The target figure for beam brightness has been set at twice that of the so-called “ultimate” LHC beam [7]. This corresponds to 4×10^{11} protons per LHC bunch at PS2 ejection and incorporates an intensity reserve of 20%. Limiting the vertical incoherent space charge tune spread at PS2 injection to below 0.2 requires a transfer energy LP-SPL to PS2 of 4 GeV [8]. Doubling the available beam brightness has several beneficial aspects:

- The new injector complex will have a reasonable margin for LHC operation, in contrast to the present complex, where the ageing machines all have to be stretched up to their limits, to provide the “ultimate” beam. This will be an important asset for full exploitation of the LHC.
- The increased brightness opens up the way for LHC operation with so-called low-emittance schemes [9], where the higher brightness is not used to increase the intensity within constant emittances but rather to reduce the transverse emittances while keeping the intensity unchanged. This might become particularly important for luminosity upgrades, if it turns out that the LHC is intensity limited.
- With the increased brightness the new injectors will also have the potential for supplying higher intensity beams with smaller losses and less activation than today. It will provide CERN with the capability to address a competitive fixed-target physics programme either directly or through the SPS.

Generation of LHC beams

The flexible generation of any proton bunch train for LHC operation is an inherent feature of the new injector complex. The LP-SPL will provide a beam with a micro structure of 352 MHz and a macro structure of up to 40 MHz that can be adjusted with the 3 MeV chopper [10]. The PS2 will feature a tuneable 40 MHz RF system as main accelerating system [11]. Consequently, bunch trains of any spacing (multiples of 25 ns) and pattern can be “painted” directly into the PS2 40 MHz RF buckets using the LP-SPL chopper.

This straightforward and flexible method does not only ease operation significantly but also avoids the additional RF systems required for splitting in the present PS [12]. The main benefits are:

- Minimisation of RF systems and correspondingly reduced manpower needs.
- Minimisation of machine impedance.
- Simplification of operation since no longitudinal splitting and gymnastics are required.

For ion operation, the beam production scheme with the PS2 is identical to the nominal ion beam in the PS [13].

General operation aspects

With extraction energy at 50 GeV from the PS2, the new injector complex will provide beams at significantly higher energy than the present complex. This will lead, via adiabatic damping, to smaller beam sizes and reduced

losses when transferring to the SPS. SPS injection will take place significantly above the transition energy of 22 GeV, which is expected to reduce the impact of instabilities and collective effects. The higher transfer energy also opens the way for an SPS upgrade at a later stage, aiming at an LHC injection energy around 1 TeV.

Doubling the top energy compared to the PS entails a larger PS2 circumference of around twice the PS, or about one fifth of the SPS, which represents an optimum since it halves the number of PS2 pulses to fill the SPS for the LHC. Assuming an LHC filling scheme similar to the present nominal scheme [14], the SPS will receive two batches each of 168 bunches with 25 ns bunch spacing and 2.4 s between injections. This is to be compared with four batches today from the PS with 3.6 s between batches. This represents an important shortening of the SPS injection plateau from 10.8 s to ~ 2.4 s nearly halving the SPS cycle for the LHC, as shown in Figure 3.

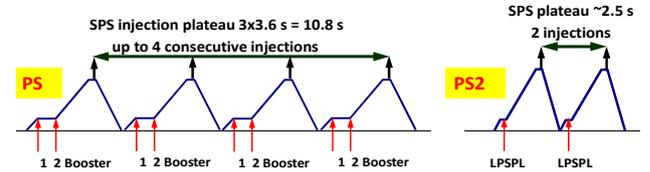


Figure 3: LHC cycle in SPS with present (PSB – PS) and new (LP-SPL – PS2) injector complex.

The circumference ratio PS2 – SPS will also allow filling the SPS circumference completely, for fixed target operation, with a single five-turn extraction from the PS2. Presently this is achieved with two consecutive ejections from the PS, forcing the SPS to wait 1.2 s with a high intensity beam at low energy for the second batch.

The new injector complex will supply all proton beams for the SPS with a 40 MHz structure with bunches shortened to 4 ns total length to fit the SPS 200 MHz system. Presently this is done for the LHC [12] but not for the Fixed-Target (FT) beam, where instead a debunched beam with a 200 MHz pre-structure is transferred. Because of the clean bunch-to-bucket transfer, a reduction of injection losses for the FT beam is expected in the SPS.

Operation of the PS2 will also be simplified as compared to the PS, by avoiding transition crossing, which will also be beneficial for reduction of beam losses. The magnet and power systems of the PS2 will be designed for a cycle length of around 2.4 s for 50 GeV, so that the overall cycling scheme of the new injector complex will be similar to today’s operation.

The main parameters of the new injector complex are summarized in Table 1 for LP-SPL and Table 2 for PS2.

Table 1: Main parameters of LP-SPL.

| Parameter (maximum) | Unit | LP-SPL |
|-----------------------------------|------|--------|
| Beam energy (kinetic) | GeV | 4.0 |
| Average beam current during pulse | mA | 20 |
| Pulsing rate | Hz | 2 |
| Pulse duration | ms | 0.9 |
| Beam power | kW | 140 |

Table 2: Main parameters of PS2, compared to PS.

| Parameter | Unit | PS2 | PS |
|-------------------------------|------|----------------------|----------------------|
| p injection energy (kinetic) | GeV | 4.0 | 1.4 |
| p extraction energy (kinetic) | GeV | 20-50 | 13-25 |
| Circumference | m | 1346.4 | 628.3 |
| LHC bunch intensity (max.) | ppb | 4.0×10^{11} | 1.7×10^{11} |
| LHC pulse intensity (max.) | ppp | 6.7×10^{13} | 1.2×10^{13} |
| FT pulse intensity (max.) | ppp | 1.0×10^{14} | 3.2×10^{13} |
| Cycle time | s | ~2.4 | 1.2 / 2.4 |
| Energy per pulse (max.) | kJ | 800 | 70 |
| Beam power (max.) | kW | 320 | 60 |

IMPLEMENTATION AND COMMISSIONING STRATEGY

Layout and implementation aspects

Figure 4 shows the layout of the new injectors and the implementation in the existing complex.

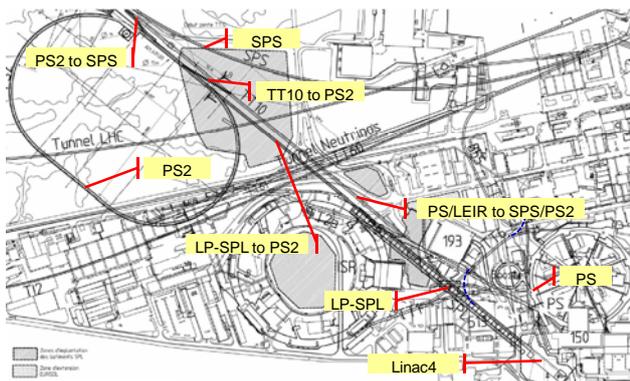


Figure 4: Layout of LP-SPL and PS2 and implementation in the existing CERN accelerator complex.

The LP-SPL follows Linac4 in straight prolongation. The transfer line from LP-SPL to PS2 is also in the same direction but descends to the level of the SPS. The PS2 is positioned tangentially to the end of the existing TT10 transfer line that links PS and SPS. This layout is considered the optimum choice and has the following advantages:

- Avoiding large bending radii in the H^- injection line from LP-SPL to minimise Lorentz stripping losses.
- Minimum length of high-energy transfer line PS2 to SPS and use of existing SPS injection channel.
- Minimum length of the injection line from existing TT10 line for ions from LEIR.

As a consequence, all PS2 injection and extraction systems can be concentrated in a single straight section suggesting a racetrack shape of the machine.

Civil engineering work

The excavation and civil engineering work for most of the tunnels for the new injector complex can take place in parallel to machine operation with the present complex,

without impact on the LHC schedule. This concerns the following underground areas:

- LP-SPL tunnel
- LP-SPL to PS2 transfer line
- PS2 ring tunnel and access shafts
- PS2 injection/extraction cavern

The requirements of a later connection of Linac4 to the LP-SPL are already being taken into account in the presently ongoing construction of the Linac4 building so that only minor civil engineering work will be needed.

The civil engineering connections from the PS2 to the existing TT10 transfer line (for the ion injection line and the extraction line towards the SPS) can however only be established while the TT10 transfer tunnel is accessible and the SPS is in shut-down. The estimated time for establishing the two connections is about 4 months during which the following activities will take place:

- Dismantling and protection of around 100 m of TT10 equipment in each of the two regions concerned.
- Establishing the tunnel connections and related civil engineering and technical infrastructure work.
- Installation of removable radiation shielding in the tunnel connections.
- Reinstallation of (old) TT10 equipment.

After this work, beam operation with the present injector complex can resume, while installation work of the new injectors can take place independently. The only exceptions are the short beam line segments between Linac4 and LP-SPL and the two connections between TT10 and PS2 that are blocked with removable radiation shielding.

Commissioning strategy

Once the new injectors are installed, commissioning of LP-SPL and PS2 will be done in a staged way, without interference with the physics operation of the present injector complex.

In a first stage, the shielding between Linac4 and the LP-SPL will be removed and the transfer line equipment will be installed. This will take a few weeks and it can easily fit within a regular accelerators' shutdown. The transfer line Linac4 – LP-SPL will be equipped with a switching dipole that will either deflect the Linac4 beam to the PS-Booster, for physics operation, or let it pass straight through, for commissioning of the LP-SPL, as indicated in Figure 5. This way, every second Linac4 pulse will be used for LP-SPL commissioning while the PSB will be served with a beam for physics operation at a repetition rate of 1 Hz.

In a second stage, once LP-SPL commissioning has reached a satisfactory level, the beam from the LP-SPL will be passed further on, via the transfer line LP-SPL – PS2, towards the PS2. PS2 commissioning will then take place, again completely independent of and without any impact on physics operation.

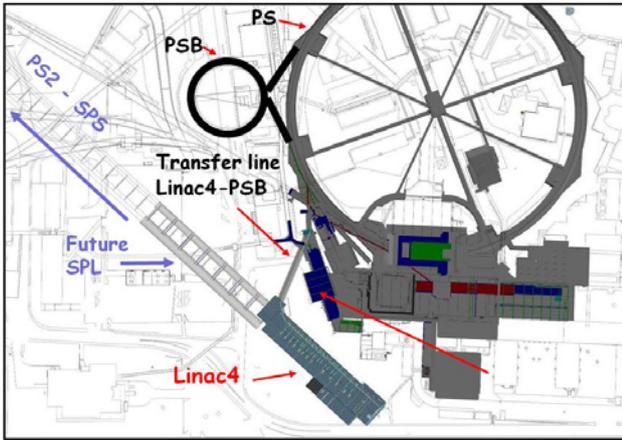


Figure 5: Layout and connection of Linac4 to PS-Booster and LP-SPL.

Putting the new injectors in operation

When the performance of the new injectors in standalone mode will have reached the desired level, i.e. at least identical to the top performance of the existing complex, the switch over from existing to new injector complex for physics operation will be prepared. It is assumed that at this stage most of the SPS upgrades will have already been implemented, in particular electron cloud mitigation measures, RF system upgrades and possibly even new injection system. The remaining modifications in the TT10 transfer line and the SPS will then be:

- Removal of radiation shielding in the two transfer tunnels between TT10 and PS2.

- TT10 beam line rearrangement and installation of new beam line elements for the connections with PS2.
- Replacement of the SPS injection system with a new 50 GeV injection system, if not already done.

A regular shutdown of at least 4 months duration is considered compatible with the above modifications.

Once the last part of the TT10 transfer line will have been rearranged to guide the PS2 beam towards the SPS, it will no longer be possible to send a beam from the PS to the SPS and the new injectors will provide the beams for physics. The beam commissioning phase is expected to be rather short and similar to an ordinary setting-up, since it concerns only transfer line modifications and the new SPS injection system. Once in physics operation, the further increase of LP-SPL, PS2 and SPS performance to the expected final level will take place in parasitic mode in parallel to physics operation.

PROJECT SCHEDULE

The preliminary project schedule for the construction of LP-SPL and PS2 is shown in Figure 6. The schedule assumes project approval by end 2012 and start of civil engineering work in 2013. Most of the time critical items in the preparatory phase are civil engineering related and substantial activities will have to take place even before full project approval, e.g. preparation of the large civil engineering tenders. Another important and time critical item is the environmental impact study. A total period of about 6 years is estimated for construction and commissioning of the new injectors, so that operation for physics could start in 2020.

| | 2009 | | 2010 | | 2011 | | 2012 | | 2013 | | 2014 | | 2015 | | 2016 | | 2017 | | 2018 | | 2019 | | 2020 | | | | |
|---|------|---|------|---|------|---|------|---|------|---|------|---|------|---|------|---|------|---|------|---|------|---|------|---|---|---|---|
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 |
| 1 All SPL and PS2 Parameters defined | ★ | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 Integration layout (sufficient staff number) | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 Definition of main parameters for all tunnels and buildings | | | | ★ | | | | | | | | | | | | | | | | | | | | | | | |
| 4 Call for tender for CE Consultancy | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5 CE preliminary study and geological investigations | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6 Design CE totally frozen | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 Environmental impact study | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8 Preparation of tender drawings and cost estimation | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9 Cost Estimate / Project Proposal | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10 Call for tender for CE works | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 11 Civil Engineering works - underground | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 12 Civil Engineering works - surface | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 13 CV, EL, Handling & lifting, access syste, safety systems | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 14 Delivery of the infrastructure and equipment | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 15 SPL and PS2 machine installation | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 16 SPL and PS2 commissioning | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 15 Installation TL PS2 - TT10 and SPS 50 MeV injection system | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 16 SPS and TT10 commissioning with PS2 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 17 Start operation for physics | | | | | | | | | | | | | | | | | | | | | | | | | | | ★ |

Figure 6: Provisional project schedule for construction and commissioning of the new injectors LP-SPL and PS2.

COST ESTIMATE

Even though the study of the new injector chain is well-engaged [3, 4, 5], prototypes and tests have hardly started. Hence the design of the future accelerators is not completed and not all families of equipment have been

specified. The construction cost estimate made in November 2009 [15] shall therefore be considered as preliminary, with a significant uncertainty margin (~20%). A total material budget of 890 MCHF was estimated necessary for the new accelerators during a

6-7 years construction period, resulting explicitly from 481 MCHF for the LP-SPL and 410 MCHF for PS2. In addition, the necessary upgrades of the SPS are estimated at 66 MCHF.

The following comments have to be taken into account:

- Cost figures are given in CHF for 2009.
- The R&D until the end of 2012 and the corresponding resources are not included in the estimated cost of construction.
- CERN manpower has not been estimated (although industrial support personnel is included).
- The cost of dismantling the present and future accelerators has not been analyzed and is not included.

LP-SPL construction cost estimate

The main SPL cost items are quoted in Table 3.

Table 3: LP-SPL main cost items

| Item | Cost MCHF | Rel. % |
|--|--------------|-------------|
| RF equipment (80 klystrons for 160 b=1 cavities + 66 IOTs for 66 b=0.65 cavities + power supplies, waveguides, LLRF, interlocks & controls, etc.) and 2 test places for cryomodules. | 219 | 45.6% |
| Civil Engineering (underground & surface buildings) + cooling/ventilation & electrical infrastructure. | 113 | 23.5% |
| Cryomodules (20 cryomodules with 8 b=1 cavities + 11 cryomodules with 6 b=0.65 cavities + 226 tuners & couplers + 80 quadrupoles + 30 BPMs). | 79 | 16.4% |
| Cryogenics (6.4 kW at 4.5 K + distribution). | 17 | 3.5% |
| Dumps (~1.4 and 4 GeV) and ejection system to ISOLDE (20 ms rise/fall time deflection system + stripping foil and H0 dump). | 15 | 3.1% |
| Beam instrumentation (transformers, beam loss monitors, laser wire profile monitors, screens). | 15 | 3.1% |
| Controls (including machine interlocks). | 10 | 2.1% |
| Accelerator vacuum (including isolation vacuum in cryomodules) | 8.5 | 1.8% |
| Safety & access (monitors, alarms, access doors with control system). | 3 | 0.6% |
| Magnets (normal conducting in the transfer line + power supplies). | 1.3 | 0.3% |
| TOTAL | 481 | 100% |

Using information from the SNS project [16, 17, 18], a comparison has been made for RF, cryomodules and cryogenics, which contribute to approximate two thirds of the SPL cost. These three subjects add up to 304 MCHF or 63% of the estimated total cost of the LP-SPL. Extrapolation of the SNS figures gives a total of 371 M\$ (or ~378 MCHF at the current exchange rate). This number is somewhat larger than the CERN estimate, but it includes manpower and it assumes an RF system capable of 6 % duty factor instead of 0.04 % for the LP-SPL.

This comparison underlines the credibility of the LP-SPL estimate.

PS2 construction cost estimate

The main PS2 cost items are quoted in Table 4.

Table 4: PS2 main cost items

| Item | Cost MCHF | Rel. % |
|--|--------------|-------------|
| Civil Engineering (underground buildings for PS2 and related transfer lines & surface buildings, environment shaping). | 90 | 22.0% |
| Main magnets (dipoles, quadrupoles, linear and non-linear corrector magnets). | 70 | 17.1% |
| RF equipment (40 MHz: cavities + power supplies, waveguides, LLRF, transv.damper). | 58 | 14.1% |
| Injection and extraction elements (H-injection, fast injection, fast ejection, slow extraction, tune kickers, internal dump kickers and beam dump, dump line and beam dump, PFNs for fast kickers and bumpers, electronics and controls, cabling). | 45 | 10.9% |
| Technical infrastructure (electrical distribution, cabling, cooling and ventilation, piping, plants, access, safety, heavy handling). | 43 | 10.5% |
| Transfer lines (SPL to PS2 (H-), existing TT10 to PS2 (ions from LEIR), PS2 to SPS and PS2 to and injection dump); all equipment included (scaled from CNGS transfer line). | 36 | 8.8% |
| Power converters (main dipole & quadrupole converters, auxiliary and correction magnets converters, septa converters). | 29 | 7.1% |
| Vacuum system (coated vacuum chambers, gauges, valves, pumping modules, ion and NEG pumps, cabling, bakeout equipment). | 13 | 3.2% |
| Beam instrumentation (110 beam position monitors, 250 fast beam loss monitors, wire scanner, dc and fast beam current transformers, wall current monitors, tune measurement, controls & electronics, cabling). | 10 | 2.4% |
| Control system (control HW and software, racks, interlock & timing systems, cabling). | 10 | 2.4% |
| Collimation and machine protection (primary and secondary collimators for TLs and PS2 betatron and momentum collimation, masks) | 6 | 1.5% |
| TOTAL | 410 | 100% |

CONCLUSIONS

The injector upgrade with LP-SPL and PS2 has been designed to provide a large flexibility and sufficient operational margin for full exploitation of the LHC and a large potential for upgrades.

The total material budget for the construction of both machines and the associated transfer lines is estimated at 900 MCHF. With a project approval in 2012, the new injectors could be available for physics operation by 2020. Construction and commissioning of the new injectors can be done without impact on LHC operation. .

The new injectors will not only bring large flexibility but also significant simplification of operation processes, e.g. straightforward generation of LHC bunch patterns or absence of transition crossing, hereby reducing beam losses and minimizing breakdowns, beam quality fluctuations and experts intervention and tuning needs.

The use of reliable and state-of-the-art equipment with high multiplicity will have a positive impact on hardware and machine availability and will also result in an efficient spare part policy and a reduction of manpower needs for exploitation.

Moreover, the new injector complex will have one circular machine less than the present one which will further simplify operation reduce the exploitation workload.

The new injector complex will be a solid basis for future proton operation at CERN, offering a large potential for the LHC during its lifetime, and allowing for other applications and future upgrades long after the LHC is stopped.

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