LHC INJECTORS UPGRADE (LIU) PROJECT AT CERN

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Abstract

A massive improvement program of the LHC injector chain is presently being conducted under the LHC Injectors Upgrade (LIU) project. For the proton chain, this includes the replacement of Linac2 with Linac4 as well as all necessary upgrades to the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) and Super Proton Synchrotron (SPS), aimed at producing beams with the challenging High Luminosity LHC (HL-LHC) parameters. Regarding the heavy ions, plans to improve the performance of Linac3 and the Low Energy Ion Ring (LEIR) are also pursued under the general LIU program. The full LHC injection chain returned to operation after Long Shutdown 1 (LS1), with extended beam studies taking place in Run 2. A general project Cost and Schedule Review also took place in March 2015, and several dedicated LIU project reviews were held to address issues awaiting pending decisions. In view of these developments, 2014 and 2015 have been key years to define a number of important aspects of the final LIU path. This paper will describe the reviewed LIU roadmap and revised performance objectives of the main upgrades, including the work status and outlook in terms of the required installation and commissioning stages.

INTRODUCTION

The LIU project aims at increasing the intensity/brightness in the injectors in order to match the HL-LHC requirements [1, 2], while ensuring high availability and reliable operation of the injector complex up to the end of the HL-LHC era (ca. 2035) in synergy with the Consolidation (CONS) project [3].

The timeline of the LIU project is sketched in Fig. 1, reflecting the 2016 update from the management decisions taken for the CERN Medium Term Planning. Differently from the previous version [4], Long Shutdown 2 (LS2) has been moved ahead by six months and extended by another six months, resulting in an overall duration of two years (2019-2020). Beam commissioning in the injectors is now scheduled to start in Q2 of 2020 (Linac4), with the PSB commissioning its first post-LS2 probe beam in Q4 of 2020. Since LIU is now in its execution phase, numerous project related activities are taking place, and will continue, during the Run 2 until the beginning of LS2 in 2019, and specifically:

- A variety of beam simulation studies and machine measurement campaigns are being carried out to validate the assumptions made for the beam parameters as well as to explore the performance boundaries of the different machines and define strategies to cope with the various performance limitations (e.g. space charge, electron cloud, machine impedance);
- Important equipment like protection devices, RF cavities, beam instrumentation is being designed, built or procured and, where possible, tested with beam;
- Installation and cabling work for some of the LIU upgrades is advanced to the (Extended) Year-End-Technical-Stops - (E)YETS's - compatibly with all the other maintenance activities foreseen during these stops in terms of time and resources;
- All the work on the surface, like civil engineering and infrastructure for the new buildings, installation of racks, etc. can take place independently of the running machines and is steadily advancing;
- Linac4 commissioning and Half Sector Test to qualify the new injection scheme into the PSB will be finalised and ready by beginning of 2017. This will make the connection to Linac4 possible in the unlikely case that LHC has to stop for an extended time before LS2.

All major LIU installations and hardware works, including for instance the Linac4 connection, the PSB energy upgrade and the SPS RF power upgrade will then be impleneted during LS2. Commissioning of LIU beams will take place in 2020-21 for the Pb ion beams, as the full beam performance is already required for the 2021 ion run. The proton beam commissioning up to the LIU beam parameters will gradually be performed during Run 3 to be ready after Long Shutdown 3 (LS3). This strategy would as well allow performing any further hardware corrective actions during the Run 3 technical stops or LS3, if needed.

LIU-ions

The target HL-LHC integrated luminosity with Pb-Pb in the post-LS2 era (2.85 fb^{-1}/year over four runs until 2029) can be met if the parameters of the Pb beam at the SPS extraction match the values in Table 1, top row [2].

Table 1: Ion beam parameters at LHC injection

	N (10^8 ions/b)	$\epsilon_{x,y}$ (μm)	Bunches
HL-LHC	2.1	1.3	1248
Achieved	2.2	1.4	518
LIU	1.7	1.3	1152

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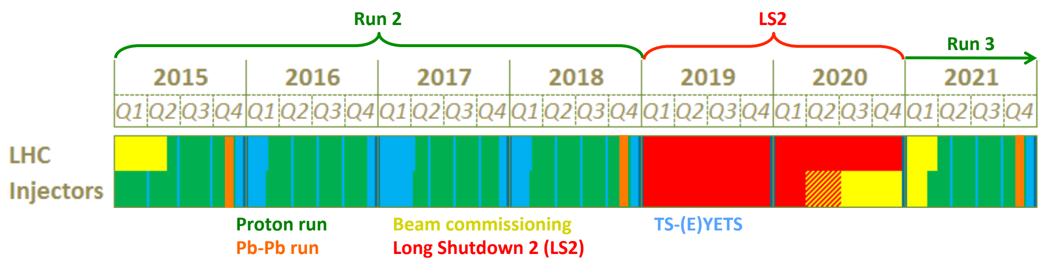

Figure 1: LHC (upper row) and Injectors (lower row) operation schedule.

Following an intensive campaign of machine studies in 2015, it was possible to achieve a significant improvement of the overall performance of the injection chain with respect to previous years, in particular by means of:

- Identifying space charge as responsible for the large beam losses in LEIR at RF capture. This led to a significant improvement of beam transmission thanks to reduction of the peak density while bunching (see Fig. 2, which shows how the losses at RF capture decrease by applying more dilution in the longitudinal phase space) and resonance compensation using sextupoles;
- Reducing flat bottom losses and transition losses in the SPS, as well as changing the spacing between subsequent injected bunch trains from the PS to 150 ns.

The achieved parameters at the SPS extraction are shown in Table 1, middle row. While these values prove that the HL-LHC desired single bunch parameters are in principle in reach, the beam filling pattern still needs to be optimised in order to allow for a larger number of bunches in LHC.

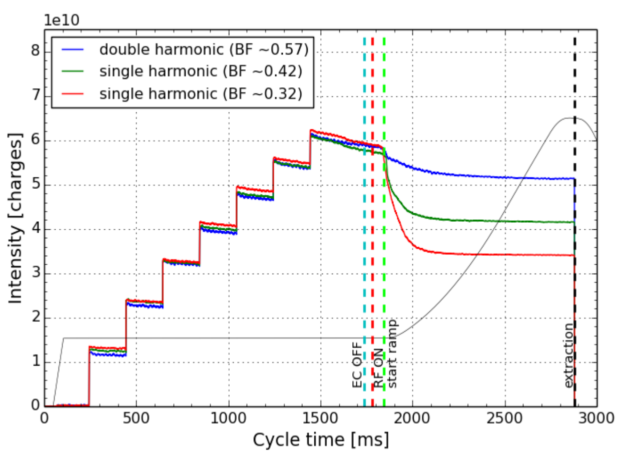

Figure 2: Beam intensity along the LEIR magnetic cycle (B field in gray) for three different values of bunching factor (BF).

The following set of LIU baseline upgrades are aimed at matching the achievable Pb ion beam parameters at the SPS extraction with those requested by HL-LHC, as well as improving the availability of the ion injector chain:

- **Source and Linac3**: Improvement of the Low Energy Beam Transport (LEBT); Increase of the injection rate from Linac3 into the Low Energy Ion Ring (LEIR) from 5 to 10 Hz; Renovation of the spectrometer line (LBS) for energy measurements; Upgrade of beam intensity and emittance measurement devices;
- **LEIR**: Beam loss reduction; Installation of an external dump; Instrumentation improvements;
- **PS**: Bunch splitting and transfer of four bunches spaced by 100 ns to the SPS;
- **SPS**: Momentum slip stacking to reduce the length of the bunch trains into LHC and to allow for a larger number of bunches in LHC; Reduction of injection kicker rise time from 225 to 150 ns; Mitigation of losses at injection energy and during the energy ramp.

After the implementation of all the LIU upgrades, the parameters shown in Table 1, bottom row, will be achieved [5]. Compared to the HL-LHC request, the baseline LIU-ions scenario gives 20% lower bunch intensities at the SPS extraction and 8% fewer bunches in LHC, leading to 15% lower integrated luminosity [6].

BASELINE UPDATE FOR LIU-protons

To fulfil the HL-LHC requirement of integrated luminosity, the proton injectors are expected to produce 25 ns proton beams with about double intensity and 2.4 larger brightness [1] (Table 2, top row).

Table 2: Proton beam parameters at LHC injection

	N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	Bunches
HL-LHC	2.3	2.1	2760
Achieved	1.2	2.5	2244
LIU	2.0	1.9	2760

During Run 2, beams with 25 ns bunch spacing are being used for luminosity production in LHC, with parameters displayed in Table 2, middle row. Apart from the number of bunches, limited in 2015 by the electron cloud in the LHC and with a perspective of increase from machine scrubbing [7], there is no margin to improve further the beam characteristics in the injectors. To reach the HL-LHC goal, the LIU baseline foresees the following improvements [8]:

- Replace Linac2 with Linac4. The H^- charge exchange injection into the four rings of the PSB at 160 MeV will allow the production of beams with twice higher brightness than presently (see measured and simulated brightness lines displayed in Fig. 3 [9]);
- Raise the injection energy in the PS to 2 GeV to allow for higher beam brightness at the same space charge tune spread. This requires an increase of the PSB magnetic field and the replacement of its main power supply and RF systems. The intensity out of the PS can also be increased thanks to the newly installed longitudinal feedback against the longitudinal coupled bunch instabilities and the transverse feedback to gain a higher margin against transverse instabilities;
- Increase the beam intensity accelerated in the SPS. This relies mainly on the following actions. First, the RF power will be upgraded by adding a new 200 MHz power plant, rearranging the 200 MHz cavities, increasing the power and installing a new low-level RF for the 200 and the 800 MHz RF systems. Second, the electron cloud, one of the main limitations of the SPS with 25 ns beams, will be mitigated following the strategy outlined below. Third, the SPS dumps and protection devices will have to be adapted for the larger beam intensity and brightness. A new main dump system has been designed and will be installed during LS2. The extraction protection, transfer line stoppers and collimators will be upgraded, or new interlocking systems added.

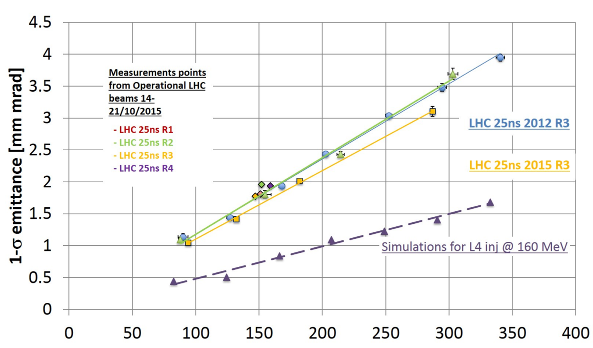

Figure 3: Transverse emittance vs. beam intensity at PSB extraction measured in the four rings and simulated (with Linac4).

The beam parameters expected at LHC injection after implementing all the improvements for the LIU program outlined above are reported in Table 2, bottom row (tagged LIU). It must be noted that, projecting from present knowledge, the bunch intensity achievable at LHC injection after the full injector upgrade will still be about 15% below the HL-LHC specification. Following the outcome of the Cost & Schedule Review that took place in March 2015 [10] and the reviewers' recommendations from the SPS scrubbing vs. coating review [11], it was decided to:

- Include the SPS longitudinal impedance reduction in the LIU baseline: shielding the horizontally focusing quadrupole (QF-type) flanges and increasing High Order Mode (HOM) damping in the 200 MHz cavities;
- Rely on beam induced scrubbing and stage the amorphous-Carbon coating of the SPS, with partial coating of the machine in LS2 (i.e. complete coating of the QF chambers, in synergy with impedance reduction; one arc coating of dipole chambers of MBB type, to debug full-scale logistics and quality control; replacement of remaining large radius drifts with coated chambers).

Because of the a-C coating staging, there will be a risk that the LHC beams during Run3 could exhibit lower brightness and higher losses in the SPS than the target values. If this will be the case and if scrubbing does not suffice as mitigation in this new parameter regime, the desired performance could still be recovered by completing the a-C coating of the SPS during LS3. On the other hand, the inclusion of the SPS impedance reduction in the LIU baseline offers the potential to achieve higher intensities per bunch at the exit of the SPS and possibly reach the 2.3×10^{11} p/b required by HL-LHC. To confirm this LIU intensity reach, however, a few pending items are still being carefully analysed, e.g. intensity limitations from the pre-injectors, compatibility with dump systems and protection devices, and SPS kicker heating.

OPTIONS

Some other options are under consideration to push further the injector performance in an effort to match the HL-LHC needs in terms of integrated luminosity:

- **Protons**:
  1) Provide more margin for higher bunch current out of the SPS (larger longitudinal emittance at flat top) through the following means: 1) using an intermediate optics (Q22) in the SPS, which would provide a trade-off between margin in Transverse Mode Coupling Instability threshold and constraint on RF power; 2) reducing the ramp rate and performing bunch rotation at 450 GeV to help the coupled-bunch instability limitation on the ramp and the constraint on the bunch length at the SPS extraction, respectively.
  2) Produce longer trains from the PS (80 bunches instead of 72) or higher brightness beams by means of the BCMS production scheme [12]. This, however, adds significant damage risk for the protection devices in the SPS, LHC and transfer lines between the two;
- **Ions**: Use batch compression to 50 ns at top energy in the PS, which leads to 25 ns spacing in LHC after slip stacking in the SPS and requires the installation of a new broad-band cavity in the PS. This scheme, whose feasibility is under study, has the potential to fully meet the HL-LHC requirements [5].

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