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PERFORMANCE WITH THE UPGRADED LHC INJECTORS

M. Meddahi* and G. Rumolo, for the LIU project
CERN, Geneva, Switzerland

Abstract

The upgrade project for the Large Hadron Collider (LHC) injectors is described in detail, highlighting the major improvements implemented in the injector chain. Lessons in technical progress, project management and planning are presented. The performance of the upgraded systems in intensity, average particle flux and beam brightness is described and compared to the upgrade goals and LHC's original design parameters. The LHC performance with the upgraded injection chain and the luminosity achieved are presented. A future outlook to future developments is given. This paper focuses on proton beams.

LIU PROJECT GOALS AND PHASES

The LHC Injectors Upgrade (LIU) project was conceived to increase the intensity/brightness across the LHC injectors chain (i.e., the new Linac4, the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS), the Super Proton Synchrotron (SPS) and the ion PS injectors, i.e. the Linac3 and the Low Energy Ion Ring (LEIR)) in order to match the High Luminosity LHC (HL-LHC) requirements for both protons and lead (Pb) ions [1]. While defining and implementing the means to reach the above goal, the project also had to ensure high availability and reliable operation of the injector complex up to the end of the HL-LHC era (ca. 2040) in synergy with the accelerator consolidation activities, coordinated under the CONS project [2]. The scope of the project included a series of major upgrades in all accelerators of the LHC injectors chain, which are detailed in [3, 4]. The main items relevant to the achievement of the desired beam performance will be listed separately in one of the next sections.

Table 1 summarises the main target parameters at the SPS extraction for both protons and Pb ions, as well as the values achieved until 2018, i.e., before the full implementation of the LIU upgrades. For protons, the main challenge lies in reaching the target single bunch parameters (double intensity and roughly double brightness). For Pb ions, the single bunch parameters have been already demonstrated and only the LIU upgrades will allow achieving the required total number of bunches in the LHC thanks to a novel production scheme in the SPS, the so-called momentum slip stacking. Slip stacked beams were successfully injected into the LHC in October 2022 for a short test ion run [5] and the full performance is expected in fall 2023. In the remaining part of this paper we will solely focus on proton beams.

The LIU project was launched in 2010 and its baseline items were refined thanks to extensive beam studies that took place in Run 1 (2009 – 2013) and Run 2 (2014 – 2018). The first upgrade items were already installed during the Long Shutdown 1 (LS1: March 2013 – June 2014 for the injectors) or, when possible, during the Year-End Technical Stops (YETS), to allow tests with beam and/or advance installations to spread the workload over a longer period. In fact, the peak of the LIU execution phase took place during the Long Shutdown 2 (LS2: 2019 to 2020 for the injectors), when the largest part of the equipment conceived in the project baseline were installed (see below).

* Malika.Meddahi@cern.ch

Table 1: Beam parameters at LHC injection for protons and Pb ions, HL-LHC target and achieved in Run 2.

	N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	Bunches
HL-LHC	2.3	2.1	2760
Pre-LIU	1.15	2.5	2760
	N (10^{8} ions/b)	$\epsilon_{x,y}$ (μm)	Bunches
HL-LHC	1.9	1.5	1248
Pre-LIU	2.0	1.5	648

At the end of the equipment installation phase, standalone beam commissioning in the new or upgraded injectors started in July 2020 for Linac4, December 2020 in the PSB, March 2021 in the PS and May 2021 in the SPS. The restart of the injectors chain was only slightly delayed with respect to the original plans, because of a slow-down of the activities in spring 2020 caused by the Covid-19 pandemic and the consequent lockdown.

The ramp-up of the LHC beams to the LIU performance [6] began in 2021 and is advancing at the expected pace to be ready to reliably deliver the desired beams to LHC after Long Shutdown 3 (LS3: 2026 – 2028 for the LHC). Although the beam commissioning progress has mostly been smooth in these first two years, the ramp-up is revealing additional limitations, mainly concerning SPS hardware, which may require future actions. Therefore, the option is being kept open to perform further hardware corrective interventions during the Run 3 technical stops or LS3, if needed.

EXECUTION OF THE LIU BASELINE ITEMS

To fulfil the HL-LHC requirement of integrated luminosity, by the end of Run 3 (2021 – 2025) the proton injectors are expected to produce trains of 288 bunches (4x72) with 25 ns bunch spacing and with about double bunch intensity and 2.4 times larger brightness at the SPS extraction with respect to the values achieved before LS2 (Table 1, top two rows).

To reach this goal, the LIU project implemented the following baseline items [3]:

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- Linac2, which accelerated protons to 50 MeV, was replaced by Linac4, which accelerates H^- ions to 160 MeV. The H^- charge exchange injection into the four rings of the PSB at the increased energy was the key upgrade for the production of beams out of the PSB with twice higher brightness compared to what was achieved with Linac2 for the same space charge tune shift at PSB injection [7];

- The beam kinetic energy for the PSB-PS transfer was raised from 1.4 to 2 GeV and longitudinal beam parameters at the PSB-PS transfer were optimised. The combination of these upgrades was projected to allow reaching the LIU beam brightness target at unchanged space charge tune spread [8]. Achieving a higher PSB extraction energy required the replacement of the PSB main power supply and RF systems;

- A series of measures were taken to extend the intensity range of longitudinal stability in the PS and meet the LIU specifications, namely the installation of a new broad-band cavity as kicker for the longitudinal feedback, the reduction of the impedance of the 10 MHz RF system and the implementation of the multi-harmonic feedback systems on the high frequency RF systems [9];

- The SPS 200 MHz RF system was upgraded in power and controls. The peak RF power increase was achieved by operating two new 200 MHz power plants, changing to a pulsed operation mode, and rearranging the 200 MHz traveling wave structures to reduce their impedance, and consequently the beam loading effect with LHC-type beams. A further reduction by a factor three of the High Order Modes (HOM) of these cavities was achieved through installation of specially designed couplers. A new low-level RF for the 200 MHz RF system was also installed and commissioned, which allows for more flexibility, beam loss reduction and new RF beam manipulations;

- The SPS focusing quadrupole (QF) flanges have been shielded and a-C coating was applied to the attached vacuum chambers in the quadrupoles. These combined actions were aimed at increasing the threshold for longitudinal beam instabilities as well as to mitigate the electron cloud induced transverse instabilities. Due to the limited a-C coating, however, the production of the target LIU beams was expected to still have to rely on beam induced scrubbing in the future operation [10];

- Several protection devices along the injectors chain (e.g., beam stoppers and intercepting devices) and a new SPS main beam dump were installed to cope with the larger beam intensity and brightness. The SPS extraction protection, transfer line absorbers and collimators were either exchanged, or new interlocking systems have been added to ensure their function;

- An important fraction of the beam measurement monitors, vacuum systems, and general services have been upgraded to comply with the performance and reliability targets;

The LIU baseline was carefully constructed such that the limiting beam performance factors could be lifted and the beam parameters expected at LHC injection will match the HL-LHC target values reported in Table 1 for the LHC standard beam (trains of 72 bunches at the PS extraction). This can be illustrated visually in a so-called *limitation diagram*, as shown in Fig. 1. In the beam parameter space of transverse emittance versus bunch intensity at SPS extraction, all the boundaries for intensity and brightness limitations in the PSB, PS and SPS, based on the most advanced machine and beam dynamics models, are plotted. Inaccessible regions are shaded. The best achievable parameter set corresponds to the point with the highest intensity and lowest emittance in the non-shaded area. As can be seen, the achievable beam parameters for the LHC standard beam match exactly the HL-LHC target values. The measured points from Run 2 are plotted for reference, highlighting the important challenge for the LIU project [11].

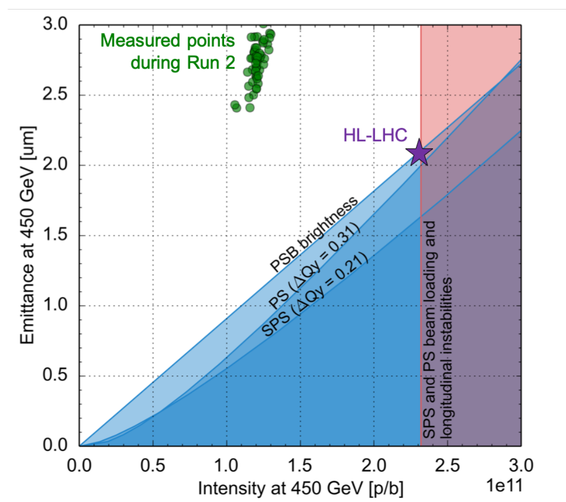

Figure 1: Limitation diagram for standard LHC 25 ns beam. The best achievable LIU parameters match the HL-LHC target (purple star). Measured points from Run 2 are also displayed (green).

It should be mentioned that the standard beam remains the type targeted by HL-LHC to fulfil its integrated luminosity goal during the high luminosity run [1]. Due to the LIU improvements, other LHC beam types will also accordingly improve their performance in post-LS2 operation. For example, both the Batch Compression Merging and Splitting scheme (BCMS) [12], which results in trains of 48 bunches from the PS, and the 8b4e beam, consisting of trains of 56 bunches from the PS arranged in alternating sequences of eight bunches and four empty bunch positions [13, 14], could be potentially produced with about 20% higher brightness with respect to the standard beam, at the expense of lower numbers of bunches in the LHC. These beams (pure

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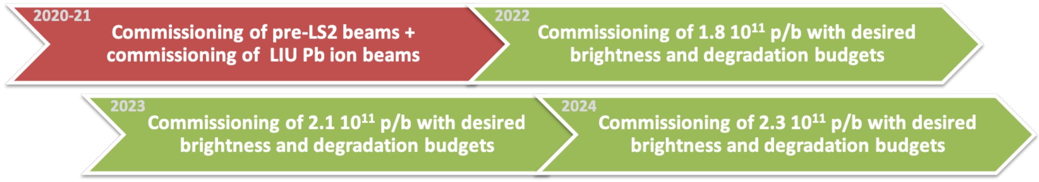

Figure 2: Gradual intensity ramp up to the LIU beam intensity over Run 3.

or mixed) are considered by HL-LHC as alternatives in case mitigation is needed against unwanted emittance blow up and/or electron cloud effects in the LHC, as the early experience of Run 3 might already suggest [15].

LIU BEAM PARAMETERS RAMP-UP THROUGHOUT RUN 3

The timeline for the ramp-up of the LHC beams to the LIU specifications along Run 3 was conceived in the final part of the project and is sketched in Fig. 2. It is based on the idea that the progress will be gradual and the foreseen milestones will be achieved during dedicated machine development time allocated in the operational years. Each intensity and brightness step will rely on mastering operationally unprecedented beam parameters and will require accelerator conditioning in terms of vacuum and electron cloud, especially for the SPS. Possible hardware interventions can be identified and applied in the YETS's, or even in LS3 (2026 – 2027 for the injectors), should any further limitation emerge during the learning curve. In the course of the LIU project, a list of post-LIU upgrade items, with Run 3 checkpoints, has been prepared to mitigate possible shortcomings in performance revealed in operation [16].

Recommissioning the Injectors Chain with Beam after LS2

To adequately prepare the restart of the injectors in 2020 – 2021, extensive individual system tests took place during the shutdown period, followed by periods of hardware commissioning, which included also the newly installed LIU equipment and dedicated full integration tests (so-called dry runs) with operational software. After the hardware commissioning, blocks of variable length for stand-alone beam commissioning were allocated to each accelerator of the injection chain. The details of the recommissioning schedule were all carefully planned and included in the general LS2 master plan [17], which was eventually adjusted to take into account the 2.5-month shift due to the lockdown for covid-19 early 2020.

The start-up strategy, lessons learnt, hardware faults and miscellaneous issues are largely covered in [18]. The main objective of the 2021 run, first one after the upgrades, was to re-establish pre-shutdown parameters for LHC as well as fixed target beams in the CERN accelerators. In fact, Linac4 and PSB were already delivering HL-LHC parameters right from the post-LS2 restart and the PS quickly started its brightness ramp-up. The SPS showed its potential to accelerate beams with higher intensity than pre-LS2, but cavity conditioning for the main RF system as well as outgassing and heating of some of the kicker magnets made a full exploitation only gradually possible over 2022 and 2023. Reproducibility and efficiency turned out to be challenging with beams at the edge of stability. Automation, machine learning and various optimisation techniques started being developed to globally optimise the CERN accelerator complex performance.

Beam Parameter Progress in 2022

Linac4 had an availability well above 95% all through 2021 and 2022, and also stably delivered the required intensity of 27 mA for all LHC-type beams (about 0.3 - 0.6 % flatness of the current during the pulse). Details are given in [20]. Over the 2022-23 YETS, a new H^- source has been installed, with the potential to produce 40 mA at the exit of the Linac4. While this improvement is not expected to impact the achievable brightness of the LHC-type beams (the lower number of injected turns required to produce them will not alleviate space charge at injection), this will however open the door to the accumulation of higher proton intensities in the PSB, which may be of interest for fixed target users.

The brightness curves measured in the PSB were already close to the LIU target early in 2021 and could be further optimised throughout 2021 and 2022. After a campaign of resonance compensation, optimisation of the working point as well as correction of the beta beating introduced by the injection chicane, the brightness could be even further improved (Fig. 3). It can be seen that, while the achieved brightness is clearly above LIU target for high intensity LHC beams, the emittance tends to plateau at lower intensities due to scattering on the injection foil and injection errors. Further techniques for parameter improvement are still under development and hold promise, in particular:

- Injecting the Linac4 rectangular pulses into a triple harmonic bucket results in flatter bunches than those reachable with the operational double harmonic capture and it mitigates the space charge induced emittance blow-up right at injection.
- Injection with a vertical tune above the half-integer is expected to limit the space charge induced emittance blow-up due to the crossing of the integer resonance [19]. It was possible so far to achieve injection above

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the half-integer without degrading the brightness. More effort needs is being made to compensate resonances and obtain a clear gain from this method.

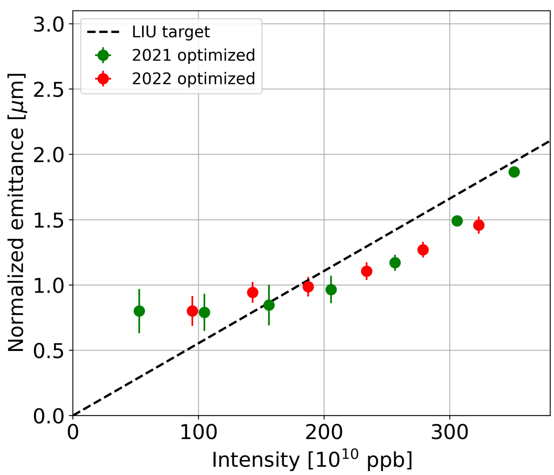

Figure 3: PSB brightness measured after LS2, in 2021 and 2022. The small error bars prove the reproducibility of these measurements, which clearly outperform the LIU target in the high intensity range.

Thanks to the further RF upgrades implemented during LS2, e.g., the impedance reduction of the 10 MHz RF system, the PS comfortably recovered the LIU bunch intensities of 2.6×10^{11} protons per bunch achieved before LS2, and even demonstrated beam stability up to intensities of 2.9×10^{11} protons per bunch with the fixed-frequency 40 MHz RF system as Landau cavity in bunch shortening mode (i.e. with 10 MHz and 40 Mhz RF systems in phase at the bunch centre) in the last part of the acceleration. Above these values, longitudinal parameters tend to become degraded due to quadrupolar coupled-bunch instabilities. However, it was demonstrated that, with the installation and the implementation of appropriate signal processing, the longitudinal feedback system can be successfully extended also against quadrupolar instabilities replacing the Landau system up to 2.9×10^{11} protons per bunch and guaranteeing stability even up to 3.15×10^{11} protons per bunch.
The longitudinal emittance at the transfer from PSB to PS in 2021 was initially chosen to be about 2 eVs and only reached its target value of 3 eVs in spring 2022. The PS brightness, which still followed the “degraded” 2 eVs line in 2021, finally reached its target in 2022, as can be seen in Fig. 4 [21].

During 2021 the SPS operation was affected by a few equipment issues, the mitigation of which could be implemented during the following YETS. They had nevertheless a significant impact on peak and/or integrated performance during this first year of operation after LS2 [18]. For example, the RF voltage with the 200 MHz cavities was still limited due to slow conditioning and arcing in two RF power lines, and the vacuum pressure in one of the vertical dump kickers (MKDV1) of the newly installed SPS beam dump system had to be kept very low to avoid risks of sparking. The reduced RF power and kicker vacuum problems limited the achievable intensity and number of bunches with LHC-type beams in 2021. Stable beam conditions could be established for HiRadMat runs at 4×72 bunches with 1.2×10^{11} protons per bunch. The record bunch intensity of 1.6×10^{11} protons per bunch could be accelerated to flattop but only in a single train of 72 bunches. Subsequently, in the 2021-22 YETS the weak vertical beam dump kicker was exchanged, the 200 MHz RF cavities further conditioned and the two power lines repaired during the time without beam. As a consequence, it was possible to progress with the ramp-up of the LIU beam parameters in the SPS in 2022, as originally planned. In particular, beam intensities up to more than 2×10^{11} p/b could be successfully injected into the SPS in trains of 36, 48 or 72 bunches and kept on the 26 GeV flat bottom without important beam quality degradation. Losses would be kept well below 10% and the emittance growth was within the assigned 10% budget, as well. The brightness measured at the end of the injection energy plateau shows that the LIU target, here represented as a shaded area between the target injection and extraction values (since the emittances have been measured at the end of the 26 GeV plateau instead of flat top) is indeed in close reach, see Fig. 5. The thick blue star marker, which indicates the emittance of five trains of 48 bunches at the end of the injection plateau

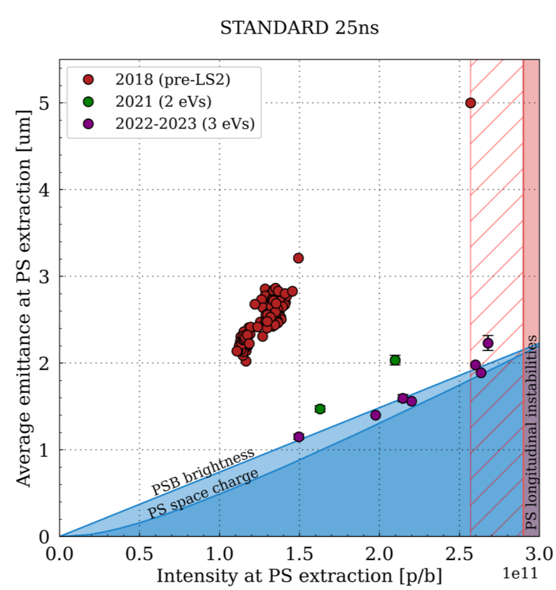

Figure 4: Measured brightness of standard LHC 25 ns beam in the PS plotted on the limitation diagram at the PS extraction for 2018 (red), 2021 with 2 eVs (green) and with the nominal 3 eVs in 2022-2023 (purple). Measurements were carried out in 2022 with 3 eVs bunches transferred from the PSB to the PS. The hatched area, assumed unstable in the definition of the LIU baseline items, represents the additional region of stability observed with beam after LS2.

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as a function of the measured intensity of 2.4×10^{11} p/b at about 150 GeV, confirms that the strategy envisaged for the LIU intensity against transverse instabilities, based on high chromaticity and higher working point [22], is indeed valid.

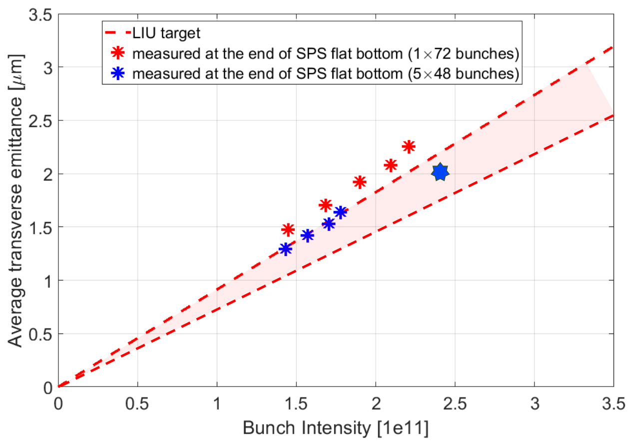

Figure 5: Measured brightness of the LHC 25 ns beam in the SPS for trains of 72 (red marks) or 48 bunches (blue marks).

An intense scrubbing campaign took place at the beginning of the 2022 SPS run to ensure the conditioning of the newly installed vertical dump kicker as well as of the other machine sectors vented during the previous YETS. As was anticipated in the LIU risk register [16], the scrubbing efficiency was strongly affected in 2022 by the beam induced heating of the four modules inside the last injection kicker magnet vacuum tank (MKP-L), which quickly reached a temperature of 70º C and required subsequently long periods of cool-down to not exceed this value. Another limitation that appeared later during the year when accelerating several trains of high intensity LHC beam, was the occurrence of spurious vacuum spikes in the horizontal dump kickers, probably triggered by the short bunch lengths reached towards the end of the accelerating cycle (high peak currents). Due to these pressure spikes, the SPS could actually accelerate in 2022 1.8×10^{11} p/b in only four trains of 36 bunches, or a lower number of trains with more bunches per train.

A Sneak Peek of 2023 Beam Commissioning

A new low-impedance MKP-L was installed during the 2022-23 YETS, designed to reduce the beam induced heating rate by a factor 2 to 10 depending on bunch length [23]. Thanks to this new device, the SPS scrubbing run in 2023 has been very efficient and could benefit from long periods in which an LHC beam could be run on a long 400 GeV plateau cycle. This mode of operation allowed conditioning not only the new devices but also the difficult ones identified during the 2021-22 run (e.g., the horizontal dump kickers) for intensities up to 2.2×10^{11} p/b in one train and 2×10^{11} p/b in four trains of 72 bunches. The brightness preservation of this beam in the SPS will be studied later this year.

LIU BENEFITS FOR FIXED TARGET BEAMS

Thanks to the newly installed LIU equipment, the improvement of the beam characteristics throughout the LHC injectors chain has naturally resulted into the extension of the parameter reach or an improved quality of beams typically used for the fixed target physics production. We only briefly describe here in the following two examples.

Before LS2 the PSB accelerated a maximum of 10^{13} p/ring, but with large losses during injection and RF capture (up to 40%). After the connection to Linac4, the PSB has already shown its potential to produce 30% higher intensities (i.e., up to 1.3×10^{13} p/ring) with losses below 10% seen in the first phase of the acceleration [24].

The production scheme of the beams for the SPS North Area has been improved in the PS thanks to the commissioning of the barrier bucket extraction (to be used together with the Multi Turn Extraction (MTE), already operational for many years), made possible by the same broadband cavity installed in the ring as a part of the feedback system against longitudinal instabilities [25]. The losses at PS extraction of this beam have been thus significantly reduced and so the dummy septum, originally installed to intercept these losses, can now be retracted improving the aperture for fast extracted beams.

CONCLUSIONS

The installation of the LIU hardware was completed during the 2019-20 long shutdown and since 2021 the LHC injectors have been back into operation. A detailed beam parameter ramp-up strategy, established under the LIU project to be put in place during Run 3 and based on a gradual exploitation of the newly installed hardware, is being successfully followed to produce the target LIU beams in their yet unexplored parameter range. The PSB has reached and even surpassed the target brightness for LHC beams. The PS has also demonstrated its capability of extracting LHC beams with the required beam intensity and emittance. The SPS is moving gradually towards the production of LIU beams, having identified and so far successfully mitigated some hardware limitations emerged during the early part of the ramp-up exercise. Presently, the SPS has proven to be able to extract 4 trains of 72 bunches with 2×10^{11} p/b, which is in line with the timeline of the ramp-up, and no absolute showstopper has been identified.

Although risks might still exist for the achievement of the final target beam parameters, the success of the first ramp-up steps as well as the important lessons learnt on the way and the support of the post-LIU mitigation options can make us confident that the injectors will be capable of successfully playing their crucial role for achieving the target luminosity and providing high quality beams for fixed target physics in the HL-LHC era, and beyond.

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