ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-MOA1I1

BEAM PERFORMANCE WITH THE LHC INJECTORS UPGRADE

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Abstract

The LHC Injectors Upgrade (LIU) project was put in place between 2010 and 2021 to increase the intensity and brightness in the LHC injectors to match the challenging requirements of the High-Luminosity LHC (HL-LHC) project, while ensuring reliable operation of the injectors complex up to the end of the HL-LHC era (ca. 2040). During the 2019–2020 CERN accelerators shutdown, extensive hardware modifications were implemented in the entire LHC proton and ion injection chains, involving 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). Since 2021, beams have been recommissioned throughout the injectors chain and the beam parameters are being gradually ramped up to meet the LIU specifications using new beam dynamics solutions adapted to the upgraded injectors. This paper focuses on the proton beams and describes the current state of the art.

A COMPACT RECAP OF THE LIU PROJECT

The main goal of the LIU project was to enable the LHC injectors to reliably produce beams for LHC with intensity and brightness matching the HL-LHC specifications for both protons and lead (Pb) ions [1]. The project had to identify simultaneously, and prioritise, the means to reach the required beam parameters and the interventions that would ensure high availability and reliable operation of the injector complex up to the end of the HL-LHC era (ca. 2040), in close collaboration with the accelerator consolidation (CONS) project [2]. All this translated into the implementation of a series of major upgrades in all accelerators of the LHC injectors chain, which are detailed in [3,4]. The principal items are listed separately in the next section.

Table 1 summarises the main target parameters at 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 single bunch parameters will have to be roughly doubled in both intensity and brightness. The filling pattern assumes four trains of 72 bunches spaced by 25 ns per SPS-to-LHC injection (200 ns between trains). For Pb ions, the single bunch parameters were already demonstrated thanks to a dedicated LIU crash program in 2015–16 as well as subsequent LEIR improvements in 2017-18 and 2021–22 which provided margin on the extracted intensity and excellent operational stability and reproducibility [5–7]. The LIU upgrades are only expected to permit doubling the 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 [8] and the full performance is expected in fall 2023, when 7 trains with 8 bunches spaced by 50 ns (100 ns between trains) will be provided for each SPS-to-LHC injection. The remaining part of this paper will solely focus on proton beams.

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)		
HL-LHC	2.0	1.5	1248
Pre-LIU	2.0	1.5	648

The LIU project lifecycle spanned from 2010 to 2021 and its baseline items were gradually refined thanks to extensive beam studies that took place in Run 1 (2009–2013) and Run 2 (2014–2018). A first subset of upgrade items, mainly in the form of prototypes, 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 to advance installations to alleviate the workload during Long Shutdown 2 (LS2: 2019 to 2020). In fact, the great majority of

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ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-MOA1I1

the LIU items were installed during the LS2, which had to be extended by only two months with respect to the original planning because of a slow-down of the activities in spring 2020 caused by the Covid-19 pandemic and the consequent lockdown.

At the end of the equipment installation phase, 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 LIU project officially ended in June 2021 with the closure of all related work packages and budget codes. The accounting books were closed with about 1.5% saving on the global cost to completion.

The ramp-up of the LHC beams to the LIU performance [9] 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 three years of operation after LS2, the learning curve was not always straightforward and exploring new territory in terms of beam parameters inevitably unveiled some new limitations, which could be so far understood and timely addressed. Should any new limitation emerging during the final part of the ramp-up require it, the option exists to perform possible further hardware interventions in the remaining YETS's or in LS3 (2026–2027 for the injectors). In the course of the LIU project, a list of beyond-LIU upgrade items, with Run 3 checkpoints for implementation, was carefully prepared to mitigate possible shortcomings in performance revealed in operation [10].

LIU BASELINE ITEMS AND EXPECTED BEAM PERFORMANCE

To reach the goal expressed in Table 1, the LIU project implemented in short the following main baseline items [3]:

- Connection of the PSB to the new Linac4, which accelerates H^- ions to 160 MeV in order to alleviate space charge, reduce losses and increase flexibility at PSB injection [11];
- New PSB main power supply and RF systems, renovated PSB-PS transfer line and new PS injection region to allow transferring large longitudinal emittance beams at 2 GeV from PSB to PS and preserve the pre-LIU space charge tune spread for double brightness [12];
- Installation in the PS of a broad-band cavity as kicker for the new longitudinal coupled-bunch feedback, reduction of the impedance of the 10 MHz RF system and implementation of the multi-harmonic feedback systems on the high frequency RF systems to cure PS longitudinal instabilities [13];
- Rearrangement and upgrade of the SPS 200 MHz RF system in power, low-level and High Order Modes (HOM) reduction to increase the beam stability range and allow new RF beam manipulations [14];
- Shielding of the SPS focusing quadrupole (QF) flanges and a-C coating applied to the attached vacuum chambers in the quadrupoles to reduce impedance and mitigate the electron cloud induced transverse instabilities to ease beam induced scrubbing [14];
- Installation and/or replacement of several intercepting devices along the injectors chain and in the transfer to LHC (e.g., beam stoppers, new PSB, PS and SPS beam dumps) to cope with the higher beam intensity and brightness;
- Upgrade of beam measurement monitors, vacuum systems, and general services to comply with the performance and reliability targets;

The LIU baseline was carefully constructed such that the limiting beam performance factors, thoroughly identified through a combination of machine studies and beam physics modeling for all the injector synchrotrons, could be lifted at least to the point that the beam parameters expected at LHC injection will match exactly the HL-LHC target values reported in Table 1 for the LHC standard beam (four trains of 72 bunches at the SPS extraction). This can be seen in the so-called *limitation diagram* 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, mainly determined by space charge at injection and beam instabilities as predicted by machine and beam dynamics models, are plotted. Shaded regions are not accessible. The best achievable parameter set corresponds to the point with the highest intensity and lowest emittance in the non-shaded area. Unsurprisingly, it exactly matches the HL-LHC target values. The measured points from Run 2 (green) highlight the important challenge for the LIU project [15].

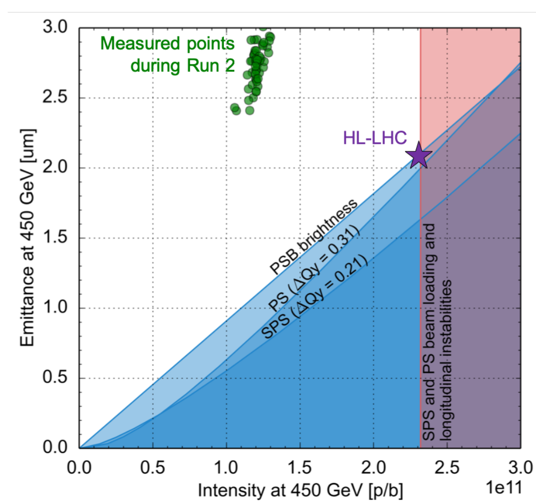

Figure 1: Limitation diagram for standard LHC 25 ns beam. The best achievable LIU parameters match the HL-LHC target (purple star). Measured points from Run 2 are also displayed (green).

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The standard beam remains the type targeted by HL-LHC to fulfil its integrated luminosity goal during the high luminosity run [1]. Thanks to LIU, other LHC beam types also improve their performance in post-LS2 operation. For example, both the Batch Compression Merging and Splitting scheme (BCMS) [16], 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 [17, 18], 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 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 be suggesting [19, 20].

EVOLUTION OF LIU BEAM PARAMETERS THROUGHOUT RUN 3

The LIU Beam Commissioning Plan

The beam parameter milestones plan for the ramp-up of the LHC beams to the LIU specifications during Run 3 was conceived in the final part of the project and is sketched in Fig. 2, with bunch intensity in the top plot and transverse emittance in the bottom one [21, 22]. It was based on the idea that the first goal would be to restore the injector operation as before LS2 and then the beam parameter evolution towards the LIU goal would take place gradually, with the foreseen milestones achieved through dedicated machine development time allocated year after year. Concerning the beam intensity (Fig. 2, top plot), the assumption was that the PS would recover the LIU intensity by the end of 2021 (as was already demonstrated with a longitudinal feedback prototype before LS2), while the intensity extracted from the SPS would be slowly increased towards the LIU parameters over the whole Run 3. This is because each intensity step in the SPS relies on mastering operationally unprecedented beam parameters and requires accelerator conditioning in terms of vacuum and electron cloud. Concerning the brightness (Fig. 2, bottom plot), the assumption was that the new PSB brightness would be comfortably achieved by 2022, while the PS brightness performance would be progressively boosted by intentionally blowing up the longitudinal emittance in the PSB from the "natural" 1.5 eVs (2021) to 2.2 eVs (2022) and finally 3 eVs (2023), target for the achievement of the LIU goal. The transverse emittance out of the SPS would therefore follow from its maximum intensity extracted, assuming the brightness from the PS and allowing for both 10% losses and 10% emittance growth over the SPS cycle.

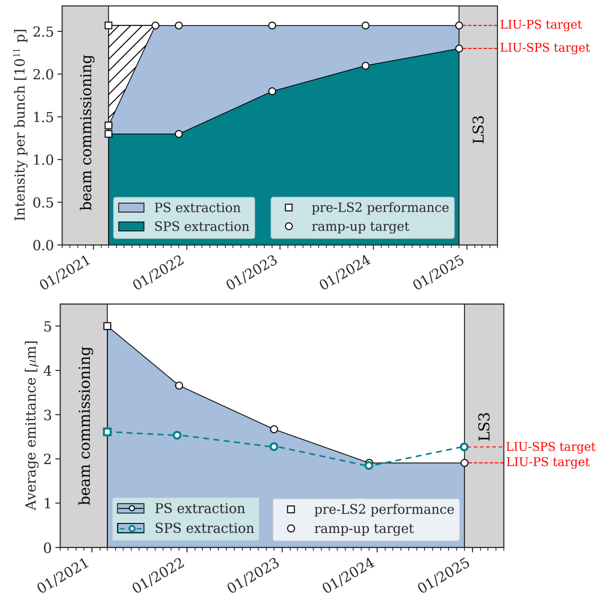

Figure 2: Gradual beam parameter ramp-up to the LIU targets over Run 3, showing the values of intensity (top) and transverse emittance (bottom) expected to be available at the exit of the PS and SPS at the beginning of each operational year.

Recommissioning the Injectors Chain with Beam After LS2

All the injectors returned to operation between July 2020 and May 2021, after individual system tests and hardware commissioning – including the newly installed LIU equipment and dedicated full integration tests with operational software (*dry runs*) – took place. 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 [23], which was eventually adjusted to take into account the 2.5-month shift due to the Covid-19 lockdown in early 2020.

The start-up strategy, lessons learnt, hardware faults and miscellaneous issues are largely covered in [24]. Although the main objective of the 2021 run was to just re-establish pre-LS2 parameters for all beams in the CERN accelerators, Linac4 and PSB turned out to be able to deliver the LIU parameters right from the restart. Therefore, the PS could advance one step of brightness ramp-up (see next subsection). After an extended scrubbing run, which was necessary after the long shutdown to condition uniformly the acccelerator, and especially condition the sensitive elements requiring low pressure values, the SPS was back in production by summer 2021. The progress of the conditioning can be seen for example on the reduction of the pressure rise in the region of the dump kickers, see Fig. 3 [20]. Nevertheless, during 2021 the SPS operation was affected by a few equipment issues, which had a significant impact on peak and integrated performance during this first year of operation after LS2 [24]. 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 kickers (MKDV1), found non-conforming, of a 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 num-

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ber 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, barely fulfilling the post-LS2 ramp-up plan. A record bunch intensity of 1.6×10^{11} protons per bunch could be accelerated to flat top but only in a single train of 72 bunches.

Reproducibility and efficiency appeared 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.

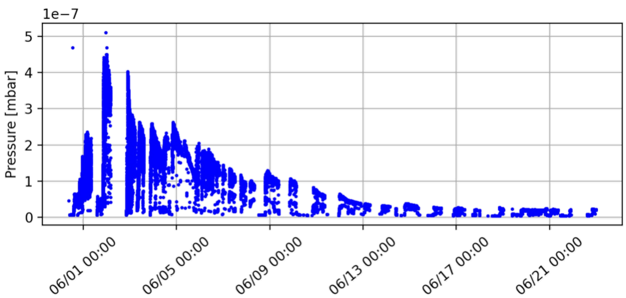

Figure 3: Pressure evolution in the region of the SPS dump kickers over the first 3 weeks of June 2021.

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 sufficient for all LHC-type beams (about 0.3–0.6% flatness of the current during the pulse) as well as for the high intensity beams for the ISOLDE facility [25].

The brightness curves measured in the PSB, already close to the LIU target early in 2021, could be then further optimised throughout 2021 and 2022, following a campaign of resonance compensation, optimisation of the working point as well as correction of the beta beating introduced by the injection chicane (Fig. 4). It can be seen that, while the achieved brightness is better than the 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 improvements are underway, in particular:

- Injection of the Linac4 rectangular pulses into a triple harmonic bucket to flatten bunches at capture and mitigate the space charge induced emittance blow-up.
- Injection with a vertical tune above the half-integer to limit the space charge induced emittance blow-up due to the crossing of the integer resonance [26].

Thanks to the further RF upgrades implemented during LS2, e.g., the impedance reduction of the main 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

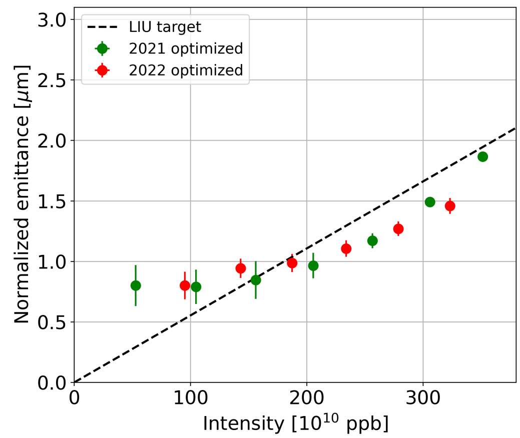

Figure 4: PSB brightness measured in 2021 and 2022.

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. Following the PSB already reaching the LIU brightness after restart, a longitudinal emittance of 2 eVs at the transfer from PSB to PS was implemented in 2021, advancing one brightness ramp-up step in the plan displayed in Fig. 2. The final target value of 3 eVs was then made available in spring 2022, one year earlier than planned. 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. 5 [27].

At the SPS, some of the issues encountered in 2021 operation could be mitigated through interventions in the 2021-22 YETS. For example, the non-conforming 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, trying to stick to the original plan. 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 remain well below 10% and the emittance growth was within the assigned 10% budget. The brightness measured using emittance values at the end of the injection energy plateau and intensities measured in the first phase of acceleration showed that the LIU target was in close reach [28]. A dedicated machine study with five trains of 48 bunches and 2.4×10^{11} p/b (measured at 150 GeV) nicely confirmed that the strategy envisaged for the LIU intensity against transverse instabilities, based on high chromaticity and higher working point [29], is indeed valid. An intense scrubbing campaign took place

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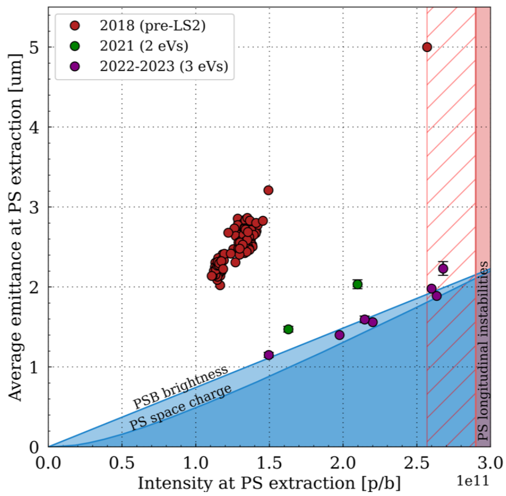

Figure 5: Measured brightness of standard LHC 25 ns beam in the PS plotted on the limitation diagram at the PS extraction for 2018 (red), 2021 with 2 eVs (green) and with the nominal 3 eVs in 2022–2023 (purple). The hatched area, assumed unstable in the definition of the LIU baseline items, represents the additional region of stability observed with beam after LS2.

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 accelerator sectors vented during the previous YETS [20]. As was anticipated in the LIU risk register [10], 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 70^{o} 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, triggered by the high peak currents reached towards the end of the accelerating cycle (high intensities and short bunches). Limited by these pressure spikes, in 2022 the SPS could actually accelerate the target intensity of 1.8×10^{11} p/b only in four trains of 36 bunches, or in a lower number of trains with more bunches per train.

2023 Achievements

Over the 2022-23 YETS, a new H^- source was installed, which has shown its potential to produce 35 mA at the exit of the Linac4 during machine studies in 2023. 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), it opens the door to the accumulation of higher proton intensities in the PSB, which may be of interest for fixed target users. It should be also mentioned here that, during the 2023 run, intensities up to 1.65×10^{13} p/ring (i.e., 70% larger than pre-LIU values) were extracted from the PSB at 1.4 GeV with losses in the 10% range for the highest values [30]. This was achieved with the nominal 27 mA from Linac4 injecting up to 148 turns per ring.

At the SPS, a new low-impedance MKP-L was installed during the 2022-23 YETS [31], designed to reduce the beam induced heating rate by a factor 2 to 10 depending on the bunch length [32]. Figure 6 shows the comparison between the MKP-L heating over the 2022 and 2023 SPS scrubbing runs, highlighting how the impedance reduction program was successful and lifted an important limitation. Thanks to this new device, the SPS scrubbing run in 2023 was very efficient and benefited from long periods in which an LHC beam could even be run in dedicated mode on a cycle featuring a 5 s long 400 GeV plateau [20]. This mode of operation allowed conditioning not only the new devices and vented regions, but also the horizontal dump kickers, which limited the performance in the 2021–22 run. It was therefore possible to reliably produce intensities up to 2.2×10^{11} p/b in four trains of 72 bunches, almost the LIU target (see Fig. 7). Thanks to the available RF power, which has finally matched specifications for four out of the six cavities and reached 80% for the last two; the successful commissioning of the new low-level RF; an optimised voltage program for both the 200 MHz and the 800 MHz RF systems, making use of the new power available; and the deployment of an automatized longitudinal emittance blow-up along the ramp, this beam is longitudinally stable and reaches the specified 1.65 ns average bunch length before extraction [33, 34].

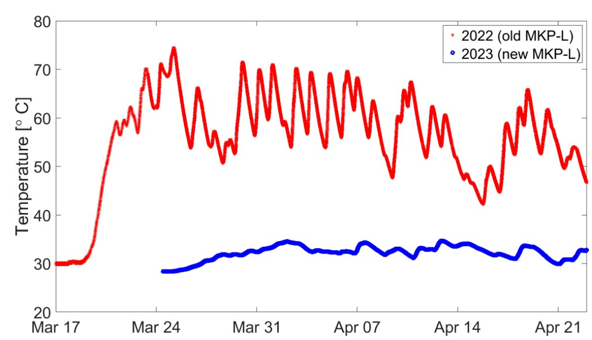

Figure 6: Comparison between the MKP-L heating over the 2022 and 2023 scrubbing runs in the SPS.

The brightness preservation of this beam in the SPS appears comfortably in specifications, as can be seen in Fig. 8. The transverse emittances have been measured at the end of the 11 s long injection plateau (due to a known limitation of the transverse emittance measurement devices – so called *wire scanners* – which cannot measure the full beam at 450 GeV), while the intensity values are taken after the start of acceleration, so that capture losses are included in the picture. The margin seemingly existing with respect to the target line is necessary, as the measured points will actually move higher, once additional losses due to halo scraping before extraction to the LHC and possible further emittance blow-up along the ramp are taken into account.

68th Adv. Beam Dyn. Workshop High-Intensity High-Brightness Hadron Beams HB2023, Geneva, Switzerland JACoW Publishing
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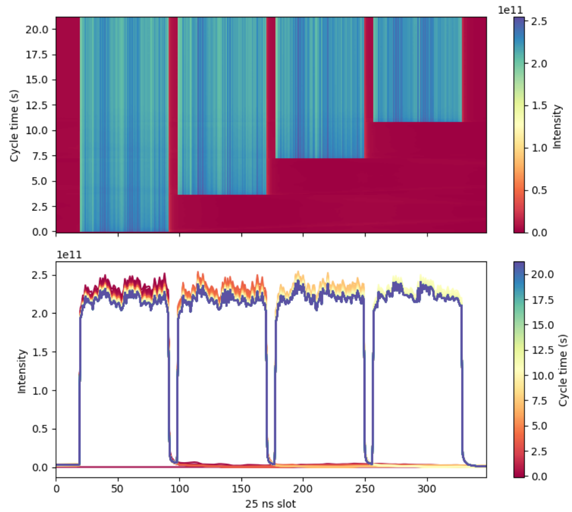

Figure 7: Evolution of bunch-by-bunch intensity of the LHC beam along the full SPS cycle in 2023.

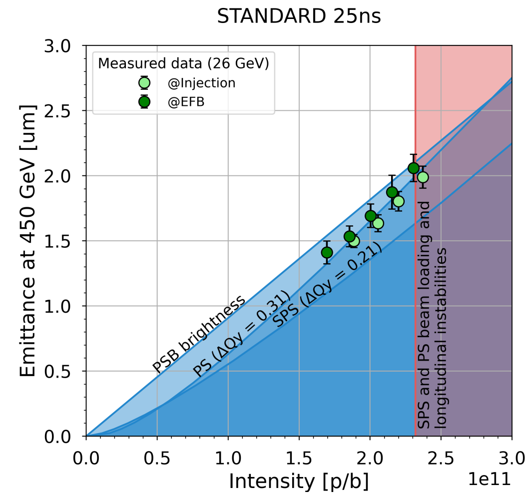

Figure 8: Measured brightness of the LHC beam in the SPS for four trains of 72 bunches. Points measured right after first (Injection) or fourth (EFB) injection are displayed.

It should be mentioned that the achievement of these high intensities and the possibility to run them reliably over long time spans in dedicated mode unexpectedly resulted into the breakage of the carbon wires in all four wire scanners. A careful analysis showed that this was not caused by usage, but rather by the interaction between a peaked line around 800 MHz in the impedance spectrum of the wire scanner device (see Fig. 9) and the broad spectrum of the beam in the last part of the acceleration, leading to excessive wire heating and detachment from the fork [35]. As an outcome of a task force mandated to quickly identify a mitigation action, two new wire scanners were installed in the ring during a technical stop, one equipped with 6 ferrite tiles and another one with 5 ferrite tiles and a coupler connected to a spectrum analyser. As can be seen in Fig. 9, the ferrite tiles induce indeed a strong damping effect on the 800 MHz impedance spectrum line while the coupler shifts and damps also the 160 MHz line, relevant for flat bottom heating. First tests with high peak currents have been successful with no more wire breakage. The outcome of further stress tests planned towards the end of the run will eventually lead to a new design to be implemented in the upcoming YETS.

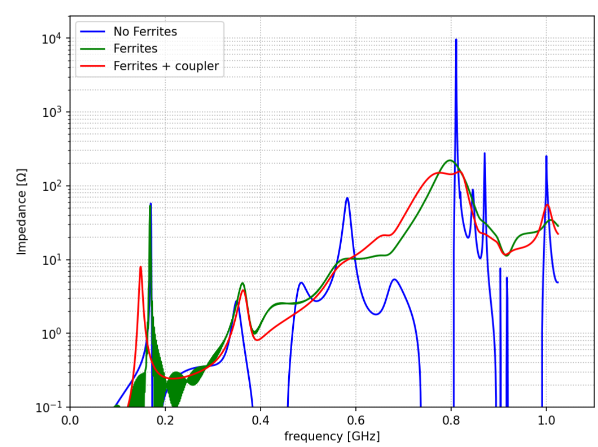

Figure 9: Longitudinal beam coupling impedance of the wire scanner without ferrites, with ferrites and with ferrites + coupler.

CONCLUSIONS

Operating with the new LIU hardware installed during the 2019-20 long shutdown, the LHC injectors are currently following a detailed beam parameter ramp-up plan, based on the gradual exploitation of the newly installed equipment. The PSB has reached and even surpassed the target brightness for LHC beams. The PS can extract LHC beams with the required beam intensity and emittance and has significant margin. After overcoming some limitations that emerged during the ramp-up exercise, the SPS is now ahead of schedule, having proven to be able to extract 4 trains of 72 bunches with 2.2×10^{11} p/b with the target brightness.

The success of the ramp-up plan as well as the important lessons learnt on the way and the support of the post-LIU mitigation options make us confident that the injectors will be capable of successfully playing their crucial role for achieving the target luminosity in the HL-LHC era, and beyond.

ACKNOWLEDGEMENTS

Since the list of co-authors of this paper only represents a subset of all those who contributed to the LIU project and those who are still working on the beam parameter ramp-up in all injectors, the presenting author would like to extend his heartfelt thanks to all those who were/are directly or indirectly involved in these efforts, in particular all CERN operation crews and equipment experts.

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