Chapter III.13

CERN LIU project: beam dynamics aspects and solutions

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The goal of the LHC Injectors Upgrade (LIU) project was to increase the intensity and brightness in the LHC injectors in order to match the challenging requirements of the High-Luminosity LHC (HL-LHC) project, while ensuring high availability and reliable operation of the injectors complex throughout the whole HL-LHC era. Fulfilling this goal required identifying the main performance limitations across all LHC injectors (Linac2, the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS), the Super Proton Synchrotron (SPS)) and then implementing a combination of extensive hardware modifications and new beam dynamics solutions in order to overcome them. The beam dynamics solutions were studied, tested and, where possible, implemented operationally already during the LHC Run 2 (2014–2018). The great majority of the LIU hardware modifications were implemented during the 2019–2020 CERN accelerators shutdown. This chapter describes the rationale behind the main baseline choices of the LIU project and the evolution of the various project phases, before concluding on the expected beam parameter reach and actual commissioning. It will solely address the upgrade of the proton injector chain, which better matches the pedagogical scope of this contribution.

III.13.1 LIU project goals and phases

The LIU project was conceived to increase the intensity/brightness in the injectors and match the HL-LHC requirements for both protons and lead (Pb) ions [1]. While doing so, high availability and reliable operation of the injector complex needed to be ensured up to the end of the HL-LHC era (ca. 2040) in synergy with the accelerator Consolidation (CONS) project [2]. The LIU goal was determined to be achievable through a series of major upgrades in all the accelerators of the LHC injectors chain, which are detailed in [3, 4]. The main items relevant to the desired beam performance as well as the beam physics considerations behind the choices will be addressed only for protons in one of the next sections.

Table III.13.1 summarises the main target parameters at the SPS exit (or equivalently, LHC injection) for both protons and Pb ions, as well as the values that were achieved before the implementation of the LIU project. From this table, it is clear that, while for protons the main challenge lay in reaching the target single bunch parameters (double intensity and roughly double brightness), in the case of the Pb ions the single bunch parameters were already demonstrated well before the end of the project, however the total number of bunches in the LHC would only become accessible through a novel production scheme based on the baseline LIU upgrades.

The LIU project was launched in 2010, with extensive beam studies taking place in Run 1 (2009–2013), leading to the installation of first equipment or prototype systems already during the injectors

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Table III.13.1: 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
Achieved	1.15	2.5	2760
	N (10^{8} ions/b)	$\epsilon_{x,y}$ (µm)	Bunches
HL-LHC	1.9	1.5	1248
Achieved	2.0	1.5	648

Long Shutdown 1 (LS1, March 2013 to June 2014). The final accelerator timeline from 2015 up to the LIU project completion in 2021, is sketched in Fig. III.13.1. LIU saw the peak of its execution phase during Long Shutdown 2 (LS2, 2019 to 2020), with the largest part of its equipment being installed in this time window. The extensive lockdown in Europe due to the pandemic of Covid-19 in the first part of 2020 only engendered a minor delay in the execution of the works, which had to be occasionally reshuffled and reorganised in compliance with the new safety rules enforced by the member states up until well into 2021.

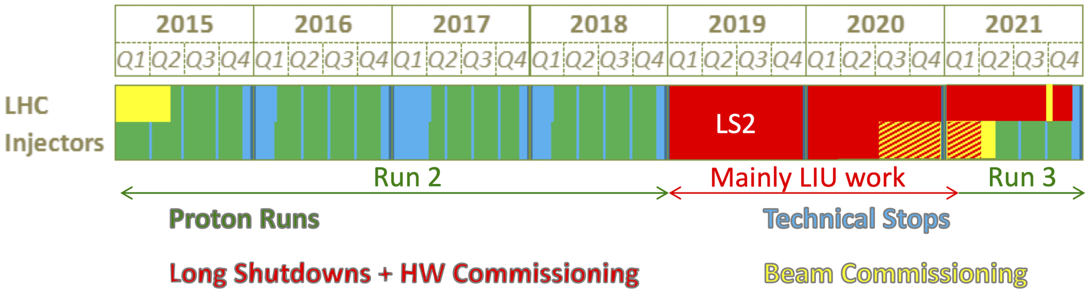

Fig. III.13.1: LHC (upper row) and Injectors (lower row) operation schedule between 2015 and 2021. The meaning of the different colors is explained in the legend below the figure (Courtesy: K. Foraz).

To define and adequately prepare the LS2 installation activities, as well as to ease the related workload, numerous project related activities were successfully carried out already during Run 1, LS1 and Run 2 (2010–2018), specifically:

- Beam simulation studies and machine measurement campaigns necessary 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);
- Design, construction or procurement and, where possible, installation during technical stops and test with beam of RF equipment, injection/extraction/protection devices, power supplies, beam instrumentation, etc.;
- Cabling and decabling work, which could be advanced compatibly with all the other maintenance activities foreseen during the yearly stops in terms of time and resources;

- All the civil engineering and infrastructures for the new buildings, as well as surface installation works, all performed in parallel with the running machines, compatibly with availability of resources;
- Commissioning of Linac4, with subsequent reliability and quality runs from 2016 to 2019 [5]. Tests to qualify the new PSB injection scheme were also performed in 2016–2017 [6, 7].

The LS2 equipment installation and testing phase without beam ended sequentially for the upgraded injector synchrotrons between December 2020 and March 2021, when the different phases of hardware commissioning were completed and each accelerator could move into stand-alone beam commissioning and prepare to provide beam to the next ring in the chain. More precisely, beam commissioning already started in July 2020 for Linac4 (which only had a relatively short technical stop after the 2019 beam quality and reliability run), and continued in December 2020 with the first beam to the PSB, February 2021 to the PS and March 2021 to the SPS.

Commissioning of LIU beams had a head start in 2021 with the recovery of the pre-LIU performance for all accelerators in the injectors chain, and the beginning of the exploitation of the new LIU hardware. The proton beam commissioning up to the LIU beam parameters has been then gradually performed during Run 3 (2021–2024) to be ready after Long Shutdown 3 (LS3). This strategy was put in place to adapt to the expected learning slope in the full exploitation of the newly installed hardware, as well as to allow performing further hardware corrective actions during the Run 3 technical stops or LS3, if needed.

III.13.2 LIU baseline for protons

The bunch intensity and transverse emittance reached at the exit of the SPS before LIU have been plotted in Fig. III.13.2 as green dots in the plane with axes transverse emittance versus bunch intensity at SPS extraction (450 GeV). In the same plane we plot all the boundaries for intensity and brightness limitations in the PSB, PS and SPS. In particular, intensity limitations appear as vertical red lines, making the half-plane $N > N_{\rm lim}$ basically inaccessible. We remark that there were in the injectors two notable intensity limitations both in the PS and SPS, and mainly due to missing RF power and longitudinal instabilities. Brightness limitations are plotted as blue curves and the area below them ($N/\epsilon > b_{\rm lim}$) is also inaccessible. Brightness limitations potentially exist at injection energy in all the injector synchrotrons, however for the LHC standard beams they are actually encountered in the PSB and PS. The brightness limitation in the PSB is plotted empirically based on the best achieved performance after all optimisations and fine tuning. It is also consistent with simulations of multi-turn injection of coasting beam at 50 MeV into the PSB, which represents the situation before LS2. The brightness limitation in the PS is determined by a maximum acceptable space charge tune spread at injection $\Delta Q_{\rm sc}$ of 0.31. This value is also found empirically and can be clearly explained by the need to sandwich the beam tune footprint between the integer resonance and the structural $8Q_y = 50$ resonance line excited by space charge itself. Forbidden regions are shaded. In this so-called *limitation diagram*, the best achievable parameter set corresponds to the point with the highest intensity and lowest emittance in the non-shaded area. That clearly explains the measured values at the SPS extraction.

To fulfil the HL-LHC requirement of integrated luminosity, the proton injectors are expected to

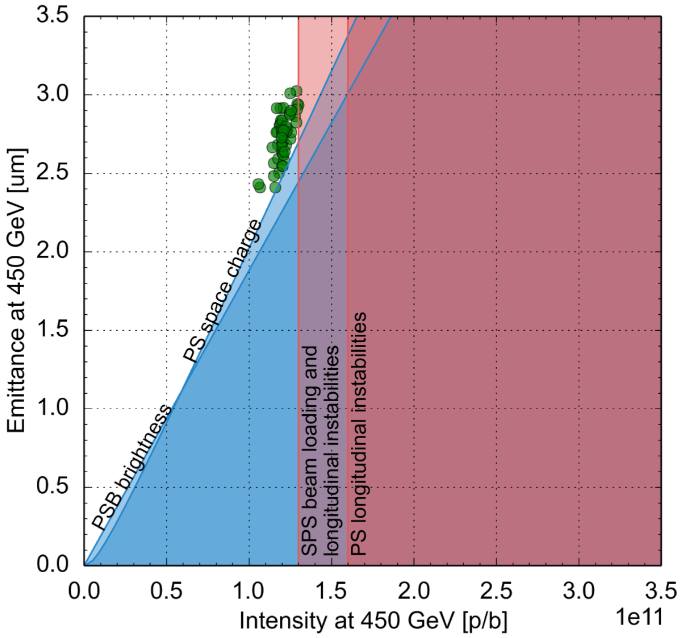

Fig. III.13.2: Limitation diagram for LHC standard 25 ns beam before the implementation of the LIU upgrades. The measured points from Run 2 are displayed as green dots. Brightness and intensity limitations in the chain are also depicted as blue and red shaded areas, respectively.

produce trains of 288 bunches (4×72) with 25 ns bunch spacing and with the values indicated in Table III.13.1, top row. This means that both intensity and brightness at SPS extraction need to be about doubled with respect to present values, quoted in Table III.13.1, second row, and plotted in Fig. III.13.2.

To reach this goal, a solid baseline for the LIU project was built, including the following list of items aimed at lifting the limitations discussed above [3]:

- Replacement of Linac2 (protons, 50 MeV) with Linac4 (H^-, 160 MeV). The H^- charge exchange injection into the four rings of the PSB at 160 MeV was targeted to allow the production of beams with twice higher brightness than presently achieved out of the PSB. The scaling comes from the reduction of the ΔQ_{sc} at PSB injection by a factor 2 based on the higher energy and was proven in detailed simulations [8], see Fig. III.13.3;
- Increase of the kinetic energy at injection into the PS from 1.4 to 2 GeV. In combination with optimized longitudinal beam parameters at the PSB-PS transfer [9], this was expected to allow reaching the LIU beam brightness target at unchanged space charge tune spread. The higher PSB extraction energy required an increase of swing for the PSB magnetic fields as well as the replacement of its main power supply and RF systems;
- Installation of longitudinal feedback against the longitudinal coupled bunch instabilities, reduction of the impedance of the 10 MHz RF system and implementation of the multi-harmonic feedback systems on the high frequency RF systems. These interventions were needed to increase the threshold of the longitudinal coupled bunch instabilities that used to limit LHC beams in the PS. The first and third item were already implemented in the PS even before LS2 and, together with the use of the 40 MHz RF system as Landau RF system over a part of the PS cycle, were enough

to demonstrate that the PS can reliably produce the LIU target intensity. The transverse feedback system in the PS was also made operational to gain margin in machine settings against transverse instabilities;

- Upgrade of the SPS 200 MHz RF system. The RF power was due to increase by adding two new 200 MHz power plants at 1.6 MW, changing to a pulsed operation mode to increase the peak RF power, and rearranging the 200 MHz cavities to reduce their impedance and the beam loading effect with LHC-type beams. A further reduction by a factor of three of the high order modes (HOM) was designed through the installation of specially designed couplers. A new low-level RF for the 200 MHz RF system would be also implemented, which would allow more flexibility, beam loss reduction and new RF beam manipulations [10];
- Shielding of the focusing quadrupole (QF) flanges and amorphous carbon (a-C) coating of the attached vacuum chambers. The goal of these interventions was to increase the threshold for longitudinal beam instabilities and alleviate electron cloud adverse effects, including outgassing and transverse instabilities. Due to the limited scope of the a-C coating campaign, however, beam induced scrubbing was also expected to be required for the production of the target LIU beams;
- Upgrade of injectors protection devices and a new SPS main beam dump to cope with the increased beam intensity and brightness. The SPS extraction protection, transfer line stoppers and collimators were all either exchanged, or new interlocking systems will be added;
- Upgrade of an important fraction of the beam instrumentation, vacuum systems, and general services to comply with the performance and reliability targets.

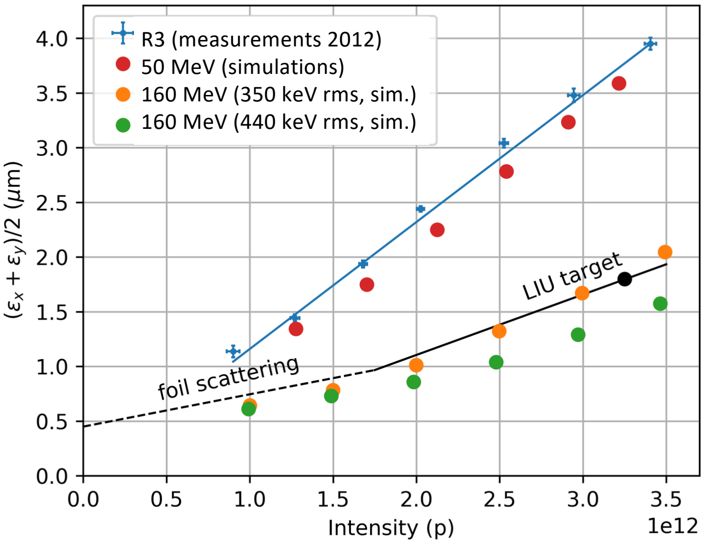

Fig. III.13.3: Simulations and measurements of the PSB brightness with 50 MeV multi-turn proton injection and simulations only with 160 MeV charge exchange H^- injection.

After the implementation of the LIU upgrades, the beam parameters at LHC injection were expected to exactly match the HL-LHC target values reported in Table III.13.1 for the LHC standard beam (trains of 72 bunches at the PS exit). This is illustrated visually in the limitation diagram shown in Fig. III.13.4. After the implementation of the LIU items, all the boundaries for intensity and brightness limitations in the PSB, PS and SPS are expected to move by the needed amount. The best achievable parameter set for the LHC standard beam matches exactly the HL-LHC target values. The measured points from Run 2 are also plotted, highlighting the important challenge for the LIU project [11].

It should be mentioned that the standard beam type is considered as baseline by HL-LHC to fulfil its integrated luminosity goal over the HL-LHC run [1]. Due to the LIU improvements, also other LHC beam types will benefit and see their performance improved in post-LS2 operation. For example, both the batch compression merging and splitting scheme (BCMS) [12], which results in trains of 48 bunches out of the PS, and the 8b+4e beam, made of trains of 56 bunches from the PS arranged in alternating sequences of eight bunches and four gaps [13, 14], have the potential to be produced with about 20% higher brightness with respect to the standard beam, at the expense of lower numbers of bunches in LHC. These beams are considered by HL-LHC as alternatives in case mitigation against unwanted emittance blow up and/or electron cloud effects in the LHC is needed.

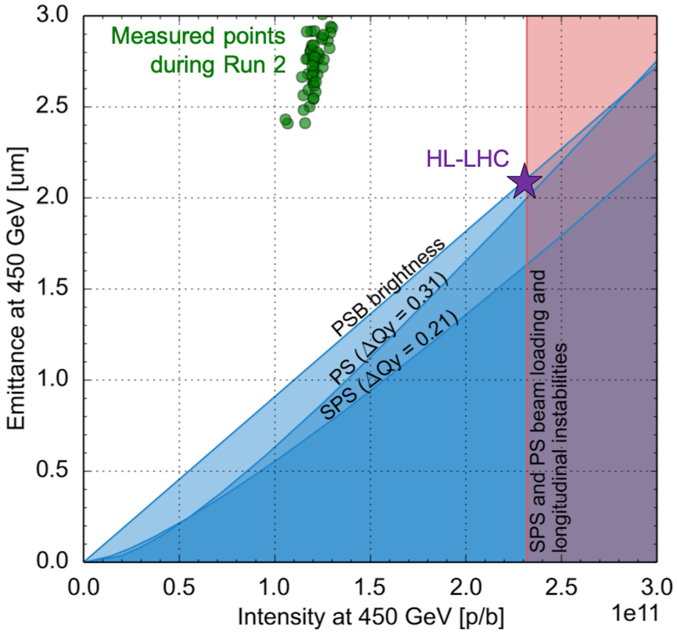

Fig. III.13.4: Limitation diagram for LHC standard 25 ns beam. The HL-LHC target (purple star) matches the best achievable LIU parameters. Measured points from Run 2 are also displayed (green).

On the path to define and implement the means to achieve the target beam parameters, several lessons have been learnt, which have steered and re-prioritized the activities within the LIU project and should be kept in mind for future operation. Two notable examples are described here below.

In 2018, 25 ns standard beams with the desired bunch intensity of $2.6 \cdot 10^{11}$ p/b have been successfully and reproducibly produced at the PS extraction (although the transverse emittance was still more than twice the target value). This achievement has been made possible only thanks to the installation of the broadband Finemet cavity in the PS and its deployment during Run 2. This cavity acts as the kicker for the longitudinal feedback together with other stabilising means to combat longitudinal coupled bunch instabilities on the ramp and at flat top. Figure III.13.5 shows how the bunch intensity at the PS extraction was gradually ramped up from 2015 to 2018 as a combined result of additional RF improvements and operational optimisation [15]. As a mitigation if the target intensity could not be attained, the option of adding a Landau cavity in the PS was also actively pursued in 2017–2018, to be ready for inclusion in the project baseline in case of confirmed need. This experience has clearly shown that 1) learning how to reach unprecedented beam parameters while operating new equipment can take a longer-than-expected commissioning time, especially if this is done in machine development mode; and 2) though eventually not needed in the baseline, having made a preliminary study for a PS Landau cavity still serves the purpose to have laid a robust ground for a possible post-LIU option, if Run 3 operation will call for lower longitudinal emittances from the PS.

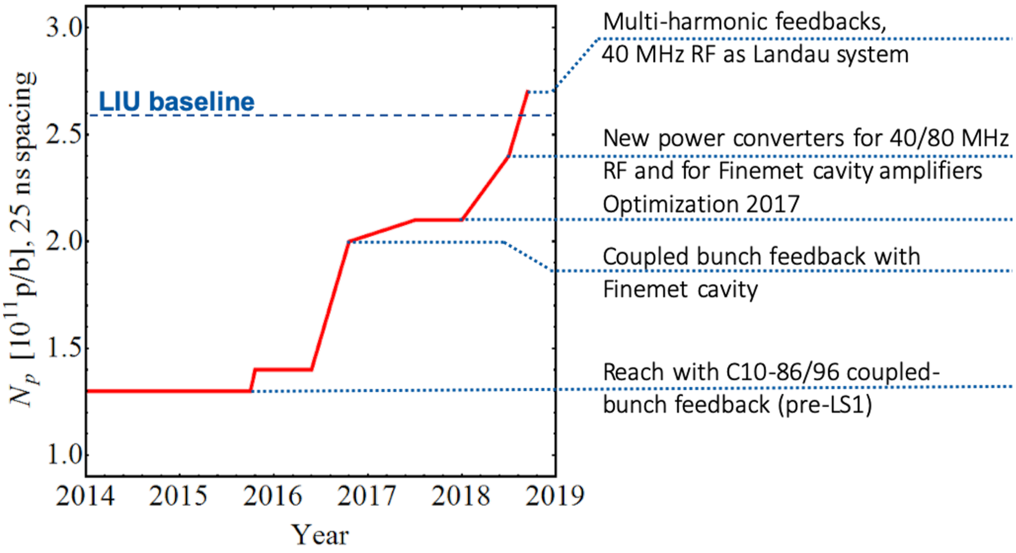

Fig. III.13.5: Evolution of extracted bunch intensity from PS over Run 2. The LIU baseline is also represented as a horizontal dashed line.

The LIU project had originally a-C coating of all the SPS dipole and quadrupole chambers in the baseline in order to suppress a large fraction of the electron cloud inside the machine. However, after the post-LS1 scrubbing experience for nominal LHC beams and the first successful scrubbing runs even with higher intensity LHC beams at 26 GeV/c already in 2015, it was decided to descope the coating to just one machine sextant and mainly rely on beam induced scrubbing also for the target beam parameters. As the scrubbing efficiency was also confirmed in the high intensity runs of 2017–2018, even the a-C coating of one sextant was further descoped in May 2018 during an exercise of budget reduction. Only the a-C coating of the QF chambers and some new drift chambers has been finally retained. Meanwhile, as the longitudinal coupled bunch instabilities along the cycle and at flat top had been clearly identified as responsible for limiting the bunch intensity at extraction to $2 \cdot 10^{11}$ p/b in the SPS, a campaign of impedance identification and reduction was pursued within LIU to extend the intensity reach of the project to its target value. Therefore, the shielding of the QF flanges and re-design of the HOM couplers for the 200 MHz cavities were included in the project baseline in 2016.

III.13.3 LIU commissioning in Run 3

To prepare for the restart of the injectors in 2020–2021, individual system tests took place during the shutdown period, followed by periods of hardware commissioning conducted by the operation teams, which in this case included also the newly installed LIU equipment. After the hardware commissioning and cold check out, blocks of variable length for stand-alone beam commissioning were allocated for each accelerator of the injection chain.

III.13.3.1 LIU plans for beam parameter ramp-up

The envisaged timeline for the commissioning of the LIU beams in Run 3 is shown in Fig. III.13.6.

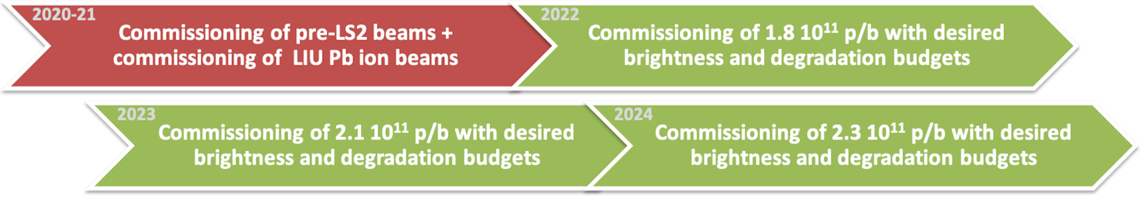

Fig. III.13.6: Gradual intensity ramp-up to the LIU beam parameters over Run 3.

In brief, all the pre-LS2 beams as documented through the existing beam documentation (for both protons and Pb ions) were expected to be recovered by the end of the 2021 run and thus serve their physics users, as they would gradually come online. A progressive improvement of the beam parameters at the SPS extraction was then planned to take place over the following years (2022–24), with the achievement of the LIU target beam parameters anticipated during the last year of Run 3, i.e. 2024. The reason for the gradual ramp-up plan lies in that the general injector operation after LS2 must be re-established with all major new LIU systems to be commissioned with beam and operationally integrated, e.g. the new H^- charge exchange injection into the PSB, the new PSB main power supply and RF system, the PSB-PS transfer at higher energy, the upgraded 200 MHz RF system in the SPS (both for power and LLRF), the new SPS beam dump. Realistically, and also learning from the experience with the PS longitudinal damper during Run 2, full exploitation of the new hardware would take time and experience.

More in detail, during 2022, a combined intensity and brightness ramp-up was expected, with the bunch intensity at the SPS extraction progressively increased from the pre-LS2 $1.3 \cdot 10^{11}$ p/b to the target $1.8 \cdot 10^{11}$ p/b while the transverse emittance was tentatively decreased from the initial 2.5 to 1.7 µm (thanks to simultaneous improvements in the PSB, reaching its best brightness, and the PS after receiving 3 eVs bunches from the PSB). In 2023–2024 the injected intensity into the SPS would have to be further ramped up from 2 to $2.6 \cdot 10^{11}$ p/b at constant brightness, expecting an extracted intensity from 1.8 to $2.3 \cdot 10^{11}$ p/b, possibly in two steps, see Fig. III.13.6.

III.13.3.2 From plans to reality: LIU beam commissioning

The ramp-up that is actually still taking place during Run 3 has turned out to be very close to the plan discussed in the previous subsection. It has been delivering results well ahead of schedule in the PSB and PS, with the LIU objectives already fulfilled by the end of 2022. The SPS suffered a slower start in 2021–22, only marginally fulfilling the 2022 objective due to slow scrubbing of some kicker magnets, which exhibited large outgassing only for short bunches. Thanks to the intervention on one of the injection kickers during the 2022–23 Year End Technical Stop (YETS), the SPS was however able to catch up on the ramp-up schedule in 2023 and even provide in this year LIU beams beyond the ramp-up projections.

In 2021, the PSB came first online and very early in the run proved the new brightness line with beam from Linac4 (half slope with respect to pre-LS2), see Fig.III.13.7. This brightness was later even further optimised by fine tuning the beam parameters from Linac4, correcting beta-beating at injection due too the injection chicane and implementing resonance compensation (see green points in Fig.III.13.7). Further studies are currently underway to gain even more margin. In particular, injection with working point above the half integer and careful compensation of the half integer resonance, as well as injection in triple harmonic bucket are already showing their potential to produce even brighter LHC beams.

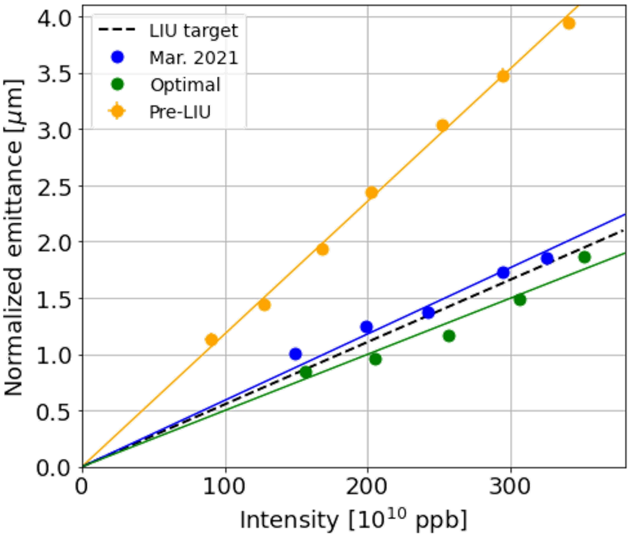

Fig. III.13.7: Measurements of the PSB brightness after LS2, i.e., with 160 MeV charge exchange H^- injection.

The PS also recovered the pre-LS2 performance in 2021 and could already deliver a brightness compatible with 2 eVs bunches from the PSB, since this controlled blow-up was already commissioned in the PSB during 2021. By mid 2022, the PS could already produce the LIU beams with nominal parameters thanks to the final blow-up step applied in the PSB, which allowed injecting 3 eVs bunches into the PS to mitigate the remaining space charge effect. Thanks probably to the impedance reduction of the 10 MHz RF system during LS2, intensities up to $2.9 \cdot 10^{11}$ p/b were successfully extracted from the PS, thus demonstrating an important margin in the deliverable intensity of LHC beams. Furthermore, new development was made on the longitudinal coupled bunch feedback in the PS, and new electronics was installed to make it effective also against quadrupolar instabilities, which helps with stability at high intensity and could even open the door to higher bunch intensities. All the PS achievements have been summarised in the limitation diagram at PS extraction shown in Fig. III.13.8. From 2021 to 2022–23 it is clear that the target brightness is reached after implementing the 3 eVs PSB-to-PS transfer. The intensity reach also appears extended up to $2.9 \cdot 10^{11}$ p/b (striped area).

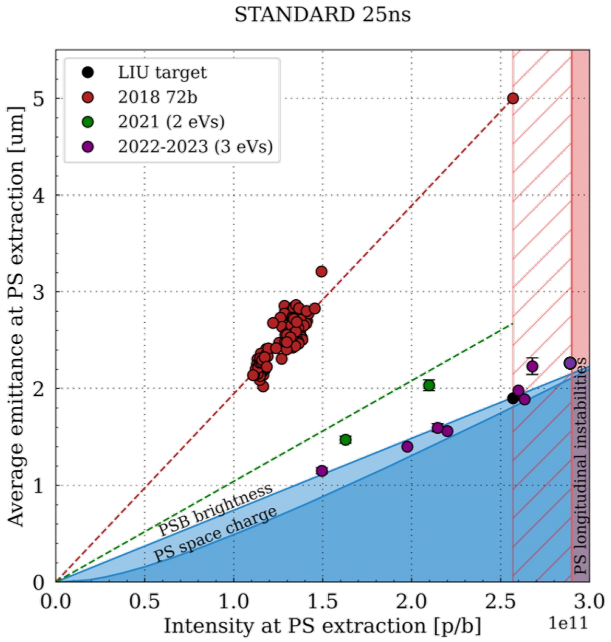

Fig. III.13.8: Limitation diagram for LHC standard 25 ns beam at the PS extraction. Measured points from Run 2 are displayed (dark red), as well as points measured in 2021 (green) and 2022–23 (magenta).

When the SPS restarted operation in 2021, extended conditioning of new equipment and general machine scrubbing was needed to recover the beam quality for pre-LS2 beam intensity. In order to assess the state of the machine after LS2, reference measurements were conducted (e.g. physical aperture, impedance) and compared with the pre-LS2 data. By then end of 2021, the LHC beams were successfully re-established in the SPS with the pre-LS2 bunch intensity and improved emittances. As of 2022, new territory began to be explored in terms of beam parameters. In fact, intensities up to $2.6 \cdot 10^{11}$ p/b were already produced up to PS extraction and even tested at SPS injection during Run 2. However, beams in the intensity range above $1.5 \cdot 10^{11}$ p/b needed the upgraded SPS main RF system to be accelerated in trains longer than 12 bunches. In 2022 the SPS for the first time accelerated several trains of 48 bunches with an intensity per bunch of $1.8 \cdot 10^{11}$ p/b. It was not possible to push further (4 trains of 72 bunches), because the horizontal dump kickers (MKDH) exhibited important pressure spikes when the bunches reached the target 1.65 ns at end of the acceleration cycle. Further scrubbing of these kickers in these beam conditions appeared difficult, due both to the short time of the outgassing (only few milliseconds per LHC production cycle) and the heating of another injection kicker (MKP-L), which would prevent long and uninterrupted scrubbing sessions. Fortunately, in the framework of the implementation of beyond-LIU items [16], the MKP-L was exchanged with a low-impedance version during the 2022–23 YETS, which lifted one of the limitations to further condition the MKDH's. Besides, during the 2023 SPS scrubbing run, a new cycle with an extended flat top was created, which would greatly increase the effective scrubbing time for any element outgassing solely with short bunches. Thanks to all these measures, already in the first half of 2023, the SPS could successfully accelerate 4 trains of 72 bunches with 2.2 · 10^{11} p/b, i.e., ca. 10% above the LIU ramp-up target for 2023. The brightness of this beam was also measured at the SPS (first injection and end of injection plateau) and found consistent with the LIU target projections, as one can see in Fig.III.13.9.

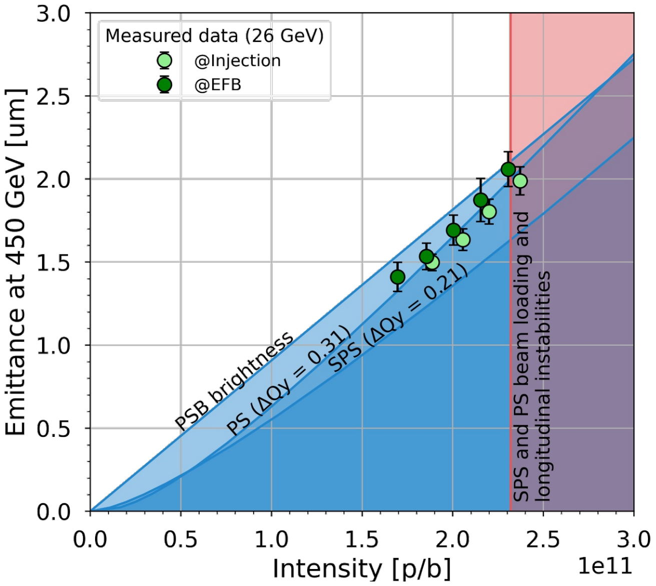

Fig. III.13.9: Limitation diagram for LHC standard 25 ns beam at the SPS extraction. Measured points from 2023 are displayed with measurements taken right at first injection (light green) and end of flat bottom (dark green).

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 newly installed in the SPS under the LIU program. 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 and the broad spectrum of the beam in the last part of the acceleration (see Fig. III.13.10), leading to excessive wire heating and detachment from the fork. 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 six ferrite tiles and another one with 5 ferrite tiles and a coupler connected to a spectrum analyser. As can be seen in Fig. III.13.10, 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 were successful with no more wire breakage. After the final stress tests run at the end of the 2023 run, it was decided to implement the tested modified design for all four wire scanners in the 2023–24 YETS.

III.13.4 Conclusions

The LIU project baseline was built to fulfil the HL-LHC target parameters. An advanced modeling of the LHC injectors and an evolving analysis of their performance limitations constantly guided this ten-year long process and allowed steering possible baseline corrections according to the emerging needs and within the envelope of the project. The main phase of hardware installation lasted almost two years of

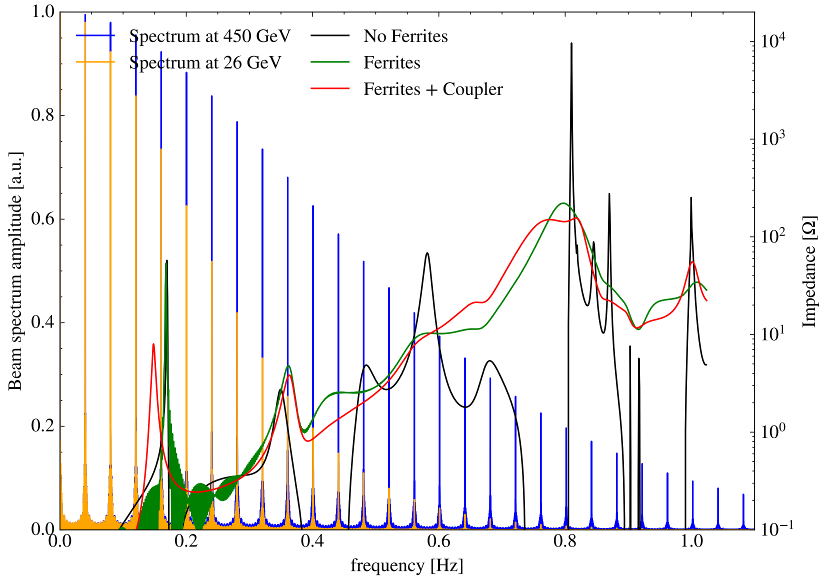

Fig. III.13.10: Longitudinal beam coupling impedance of the wire scanner without ferrites, with ferrites and with ferrites + coupler. The beam spectrum is also plotted both at 26 GeV (3.2 ns) and 450 GeV (1.6 ns), showing how only the beam spectrum at high energy overrlaps with the 800 MHz impedance line.

long shutdown (LS2) and the injectors came back to operation in cascade since July 2020, with the LIU project officially closing on 30 June 2021.

Operating with the new LIU hardware, 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 $2.2 \cdot 10^{11}$ 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.

III.13.5 Acknowledgements

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