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Chapter 21

Beam from Injectors: The LHC Injectors Upgrade (LIU) Project

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The LHC Injectors Upgrade (LIU) project aims at increasing 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 up to the end of the HL-LHC era. Fulfilling this goal requires extensive hardware modifications and new beam dynamics solutions across the entire LHC proton and ion injection chains: the new Linac4, the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS), the Super Proton Synchrotron (SPS), together with Linac3 and the Low Energy Ion Ring (LEIR) as ion PS injectors. The great majority of the LIU hardware modifications have been implemented during the 2019-2020 CERN accelerators shutdown. This chapter describes the various project phases, highlights the past and future challenges, and concludes on the expected beam parameter reach and ramp-up, together with the risks and mitigations.

1. LIU Project Goals and Phases

The LIU project aims at increasing the intensity/brightness in the injectors in order to match the HL-LHC requirements for both protons and lead (Pb) ions [1], 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 accelerator Consolidation (CONS) project [2]. This goal will be achieved 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 will be addressed separately for protons and Pb ions in the next sections.

Table 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 currently achieved. From this table, it is clear that, while for protons the main challenge lies in reaching the target single bunch parameters (double intensity and roughly double brightness), in the case of the Pb ions the single bunch parameters have been already demonstrated, but the total number of bunches in the LHC will only become accessible through a novel production scheme based on the upcoming LIU upgrades.

The LIU project was launched in 2010, with extensive beam studies taking place in Run 1 (2009 – 2013) and its first systems already installed during the injectors Long Shutdown 1 (LS1 – March 2013 to June 2014). The accelerator timeline as from 2015 up to the LIU project completion in 2021, is sketched in Figure 1 (see Ref. [5] and subsequent version updates). LIU had the peak of its execution phase during the Long Shutdown 2 (LS2: 2019 to 2020), with the installation of the largest part of its equipment.

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
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

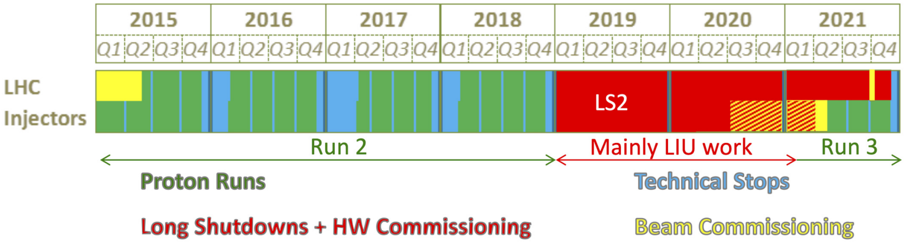

Fig. 1. LHC (upper row) and Injectors (lower row) operation schedule between 2015 and 2021. The meaning of the different colors is explained in the legend below the figure.

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

- Beam simulation studies and machine measurement campaigns have been 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);
- RF equipment, injection/extraction/protection devices, power supplies, beam instrumentation, etc. have been designed, built or procured and, where possible, installed during LS1 or the (Extended) Year-End-Technical-Stops – (E)YETS's – and tested with beam;
- Cabling and decabling work was 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, were performed in parallel with the running machines, compatibly with availability of resources;
- Linac4 was commissioned and underwent reliability and quality runs from 2016 to 2019 [6]. Tests to qualify the new PSB injection scheme were performed in 2016 — 2017 [7, 8].

The LS2 equipment installation and testing phase without beam sequentially ended for each injector synchrotron between December 2020 and March 2021, and stand-alone beam commissioning in the upgraded injectors took place. More precisely, beam commissioning first 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, March 2021 to the PS and April 2021 to the SPS. Linac3 has restarted operation in mid April 2021 after a successful test run, while the first beam to LEIR has been planned for the end of June 2021*.

Commissioning of LIU beams will have a head start in 2021 for the Pb ion beams, in preparation to the achievement of the full beam performance required for the HL-LHC Pb-Pb ion run at the end of 2022. The proton beam commissioning up to the LIU beam parameters will be gradually performed during Run 3 (2021 – 2024) to be ready after Long Shutdown 3 (LS3). This strategy will allow implementing any further hardware corrective actions during the Run 3 technical stops or LS3, if needed, as discussed more in detail further on in this chapter.

2. LIU Baseline for Protons

To fulfil the HL-LHC requirement of integrated luminosity, the proton injectors are expected to produce trains of 288 bunches (4×72) with 25 ns bunch spacing and with about double bunch intensity and 2.4 larger brightness at the SPS exit with respect to present values (Table 1, top two rows).

To reach this goal, the LIU baseline includes [3]:

- Replacement of Linac2 with Linac4. The H^- charge exchange injection into the four rings of the PSB at 160 MeV will produce beams with twice higher brightness than presently achieved out of the PSB [9];
- 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 [10], this will allow reaching the LIU beam brightness target at unchanged space charge tune spread. The higher PSB extraction energy requires an increase of 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

* This chapter reflects the LIU progress as of May 2021

on the high frequency RF systems. These interventions are needed to increase the threshold of the longitudinal coupled bunch instabilities that presently limit LHC beams in the PS. The first and third item have been already implemented in the PS and, together with the use of the 40 MHz RF system as Landau RF system over a part of the PS cycle, have demonstrated that the PS can reliably produce the LIU target intensity. The transverse feedback system in the PS has been also made operational to gain margin in machine settings against transverse instabilities;

- Upgrade of the SPS 200 MHz RF system. The RF power will be increased by adding two new 200 MHz power plants, changing to a pulsed operation mode for increasing 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 3 of the High Order Modes (HOM) will be achieved through the installation of specially designed couplers. A new low-level RF for the 200 MHz RF system will be also implemented, which will allow more flexibility, beam loss reduction and new RF beam manipulations;
- Shielding of the focusing quadrupole (QF) flanges and a-C coating of the attached vacuum chambers. The goal is to increase the threshold for longitudinal beam instabilities and alleviate electron cloud transverse instabilities. Due to the limited scope of the a-C coating campaign, however, beam induced scrubbing is 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 will be 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.

After the implementation of the LIU upgrades, 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 exit). This can be illustrated visually in a so-called *limitation diagram*, as shown in Figure 2: in the beam parameter space of transverse emittance versus bunch

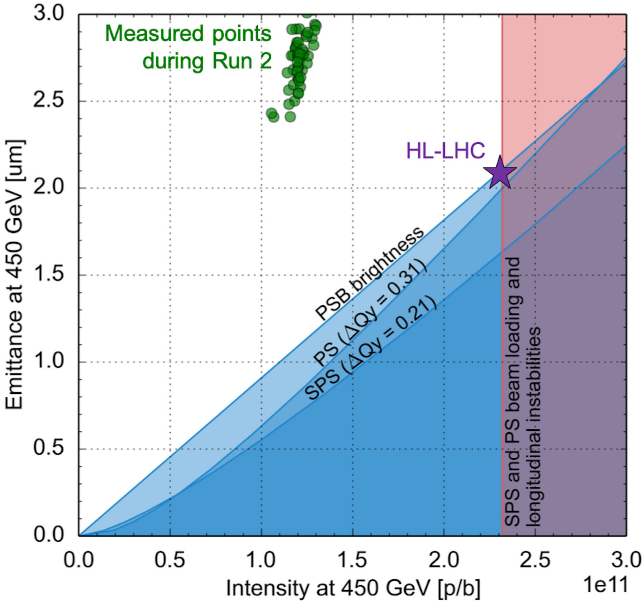

Fig. 2. Limitation diagram for LHC standard 25 ns beam. The HL-LHC target (purple star) matches the best achievable LIU parameters. Measured points from Run 2 are also displayed (green).

intensity at SPS extraction, all the boundaries for intensity and brightness limitations in the PSB, PS and SPS are plotted and the 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 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 8 bunches and 4 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.

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 3 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

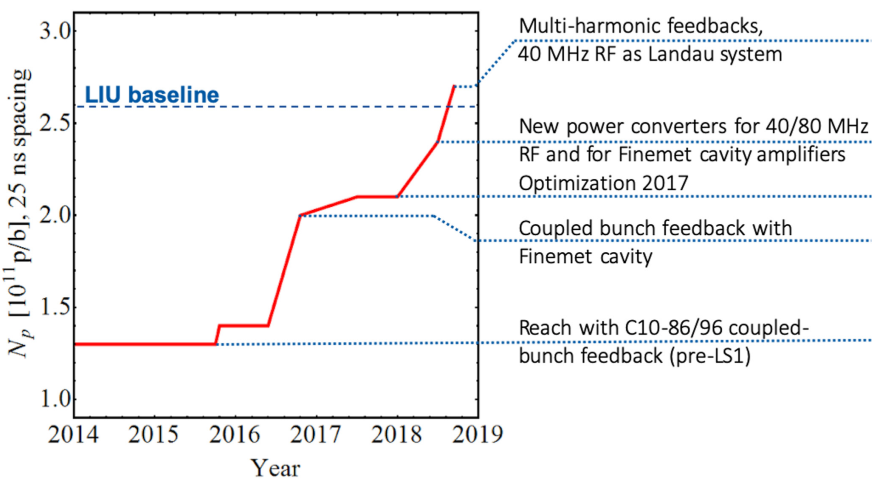

Fig. 3. Evolution of extracted bunch intensity from PS over Run 2. The LIU baseline is also represented as a horizontal dashed line.

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.

The LIU project had originally amorphous carbon (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.

3. LIU Baseline for Ions

The target HL-LHC integrated luminosity with Pb-Pb in the post-LS2 era (ca. 3 nb^{-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.

Thanks to an intensive campaign of machine studies and additional instrumentation installed in Linac3 and LEIR, which required an important temporary refocus of priorities and reshuffle of resources within the LIU project, the

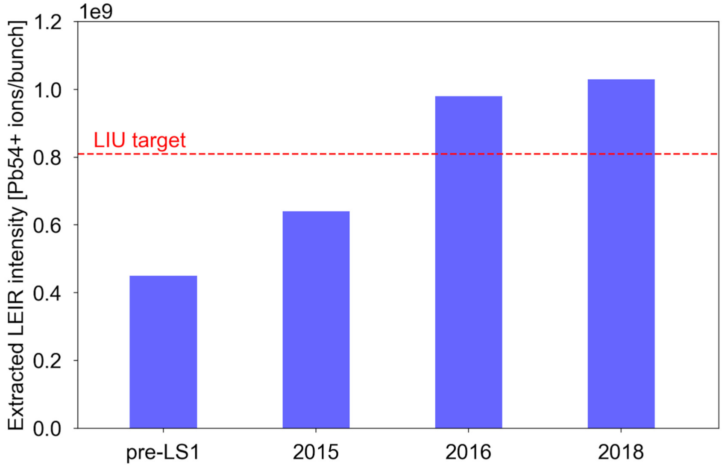

Fig. 4. Evolution of the extracted intensity from LEIR since before LS1 (2013) and over Run 2 (2015-18). The LIU target value is also displayed as a dashed line.

overall performance and reliability of the Pb ion injection chain had already a boost in 2015 [4] and has since further improved during Run 2 with respect to previous runs. As a consequence of the higher current from Linac3 after the removal of an aperture limitation at the source, optimised transfer and injections into LEIR, and mitigation of space charge at RF capture in LEIR, the intensity extracted from LEIR has more than doubled over Run 2, even exceeding the LIU target value by about 20% (see Figure 4). In the SPS the overall transmission has been also improved thanks to working point, RF and transverse feedback optimisation, and the batch spacing at injection has been successfully reduced to 150 ns by optimising the kicker switch settings and deployment of the transverse damper for ions. Globally, as reported in Table 1, the single bunch parameters achieved in 2018 at the SPS extraction already match the HL-LHC desired values, and even include a 5% margin for the additional losses expected with the future RF manipulations.

This is also displayed in Figure 5, in which both the average bunch intensity and total beam intensity per LHC fill are plotted as a function of time, when looking at the first half of the run (light blue, labeled *4 bunch scheme*). During this phase, the nominal Pb ion production scheme was used, leading to the injection into LHC of 9 trains of 4 bunches from the SPS with 100 ns between bunches and 150 ns between trains. From the plot, it is clear that the achieved

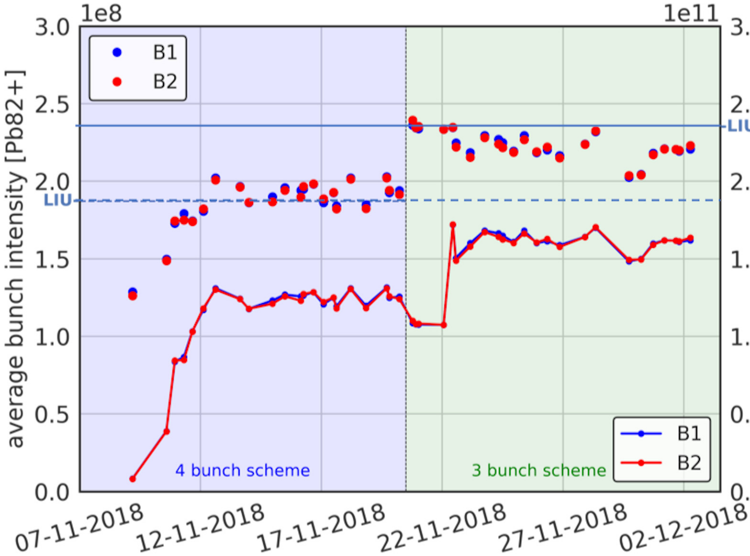

Fig. 5. Average bunch intensity (points and left vertical axis) and total beam intensity (solid lines and right vertical axis) per LHC fill as a function of time during the 2018 Pb-Pb run. The LIU goals for both are also shown as horizontal lines (dashed for bunch intensity and solid for total beam intensity).

bunch intensities at the LHC injection (red and blue dots) were always equal to or larger than the LIU target (dashed line tagged LIU) in regime operation. In addition, and later on during the run, an alternative filling scheme for LHC was set up and operationally used in the 2018 Pb-Pb run, based on the production of three bunches in LEIR and batch compression to 75 ns before the PS extraction. This scheme had the advantage of being able to pack a higher number of bunches in LHC (733 instead of 648), each with 10% higher intensity. To be noted that the potential 33% gain in bunch intensity is partly lost due to strongly nonlinear transmission through the SPS, which exhibits much higher losses for more intense bunches. Both the larger intensity per bunch and the overall larger number of bunches result in larger total numbers of ions in LHC (red and blue lines), as can be seen in Figure 5, second half of the run (light green, labeled *3 bunch scheme*). Assuming that the integrated luminosity in LHC is about proportional to the number of Pb ions that can be injected into LHC, one obtains from the 2018 run the experimental verification that the 3 bunch scheme has the potential to achieve 70% of the HL-LHC integrated luminosity target (solid line tagged LIU), which was estimated beforehand from calculations [16, 17]. The validity of this scheme as a fallback scenario if the momentum slip stacking in the SPS is delayed or underperforms is therefore fully confirmed.

The remaining LIU item to be implemented for post-LS2 ion operation is the momentum slip stacking in the SPS to allow the transfer of 7 trains spaced by 100 ns, each train being made of 8 bunches spaced by 50 ns, to the LHC. In this configuration, 1248 bunches can be injected into the LHC. The momentum slip stacking in the SPS depends on the full deployment of new LLRF capabilities for the 200 MHz RF system, expected to be ready in the last quarter of 2021, and its feasibility has been proved in simulations [18]. In preparation for this mode of operation, dedicated machine studies were conducted in 2018 [19]. It was found that a radial displacement by 20 mm at 300 GeV (energy plateau chosen for slip stacking) does not lead to losses for the ion beam, which suggests that there would be enough momentum aperture to move only one half of the beam during the slip stacking. Unfortunately, longitudinal instabilities were observed after transition crossing and at 300 GeV, which means that stabilisation techniques (i.e. 800 MHz, longitudinal emittance blow up) will have to be studied in simulations during LS2, and then tested and commissioned in 2021 – 2022.

4. LIU Beam 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 have been allocated for each accelerator of the injection chain. The details can be found in the general LS2 master plan [20].

The current timeline for the commissioning of the LIU beams in Run 3 is shown in Figure 6. All the pre-LS2 beams as documented through the existing beam documentation (for both protons and Pb ions) are gradually being recovered in 2021 and will serve their physics users, as they gradually come online. Conditioning of new equipment and general machine scrubbing will be needed in the SPS to recover the beam quality already for pre-LS2 beam intensity. In order to assess the state of the machines after LS2, reference measurements are already being conducted in all machines (e.g. physical aperture, impedance) and compared with the pre-LS2 data. It should not be forgotten that the general injector operation in these two years will be challenging due to the fact that all major new LIU systems have to be commissioned with beam and operationally integrated (though not fully exploited), 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. In addition to all of this, the Pb ion beams will have to be recovered as in 2018 (both 4 and 3 bunch schemes) and commissioning of the momentum slip stacking in the SPS will have to start already in 2021 with the important challenges highlighted in the previous section and in preparation of the 2022 LHC Pb-Pb ion run. As of 2022, the intensity ramp-up of the LHC proton beams can begin. During 2022, one can expect a combined intensity and brightness ramp-up, 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 is tentatively decreased from the initial 2.5 μm to 1.7 μm. New territory will 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 need the upgraded SPS main RF system to be accelerated in trains longer than 12 bunches. The SPS will have to be scrubbed for this new range of intensities and the already encountered horizontal and longitudinal instabilities at 26 GeV/c will have to be overcome in order to ensure beam losses within 10% in the SPS, as required for operational deployment. Therefore, a stabilisation strategy is being developed during LS2, also relying on the search of the instability sources, and will have to be tested and demonstrated. It should be mentioned that additional beam requests from physics (e.g. light ions) may also take significant time and resources, should these requests be approved.

In 2023 – 2024 the injected intensity into the SPS will 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 Figure 6. Apart from the needed additional SPS scrubbing, new and yet unknown limitations might emerge and require additional actions to achieve the target beam param-

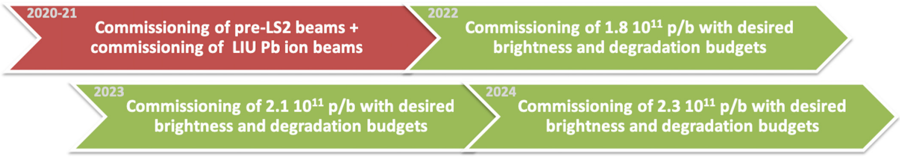

Fig. 6. Gradual intensity ramp-up to the LIU beam parameters over Run 3.

eters. Addressing these limitations and implementing measures to overcome them is part of the scope of the subject treated in the next section.

5. Beyond the LIU baseline

In the course of the LIU project, several additional items were considered at different stages for the achievement of the LIU beam parameters, but were then dropped from the baseline because of low benefit over cost ratio. A complete inventory of these options can be found in [21] with details in the references therein. However, some of them could still be revived in the post-LIU era to respond to some specific failure scenarios. In the following we will report a list of the main items, to be kept in mind during Run 3, should any of the associated failure scenarios indeed occur.

Impedance reduction of the extraction kickers in the PSB. Horizontal instabilities occurring along the PSB cycle are caused by the unmatched terminations of the extraction kickers and are cured by the transverse feedback in routine operation. Future operation might suffer due to the 160 MeV injection, which is a critical energy for the instability, and the acceleration of higher intensity beams for ISOLDE. Although this limitation is expected to be mitigated by the upgraded transverse feedback system, an impedance reduction scheme for the kicker exists and has been proved effective both in electromagnetic and beam dynamics simulations.

Landau RF system in the PS. While the LIU beam intensity has been already proved at the PS extraction, the implementation of a Landau RF system would increase the stability margin and give more potential to decrease the longitudinal emittance out of the PS, which might directly benefit the SPS losses at injection energy if they are too high. A conceptual design of this additional RF system has been performed and its efficiency has been demonstrated in simulations.

a-C coating of the dipole chambers in the SPS. Beam induced scrubbing has been shown to work for high intensity in the SPS, however large tune shifts along the batches and instabilities have been also observed, which might be due to electron cloud and limit future operation. If an active measure to suppress the electron cloud in the most critical elements of the SPS will have to be implemented, the logistics for in-situ a-C coating of selected SPS chambers will be ready and widely tested during YETS and LS2.

Further SPS impedance reduction. In addition to the shielding of the QF flanges and further suppression of the HOMs in the 200 MHz cavities, the SPS might benefit from reducing the impedance of the injection kickers (both for equipment heating and longitudinal stability) as well as from shielding the defocusing quadrupole (QD) transitions and the vacuum valves (mainly for longitudinal stability). The benefit of these measures has been shown in beam dynamics simulations. Concerning the impedance reduction of the MKP-L module of the injection kickers, a solution with longitudinal serigraphy has been found and is planned to be implemented in one of the first YETS after LS2, because it has been calculated that the heating of this element would strongly limit scrubbing and machine development for the LIU intensities during Run 3 and later routine operation in the HL-LHC era.

Wideband feedback system for the SPS. A prototype system was installed in the SPS and proved to work against vertical instabilities both in single and multi-bunch operation. An upgraded version of this system could be used against potential future vertical instabilities caused by persisting electron cloud, or a similar system could be developed ex-novo in the horizontal plane to be used against the horizontal instabilities observed in high intensity operation. In fact, the wideband feedback system in either transverse plane is a powerful means against any type of unpredicted beam instability that could rise in high intensity operation and for which the source cannot be easily suppressed.

Collimation system in the SPS. A two-stage collimation system has been designed for the SPS to intercept large momentum particle losses. Such a system could turn out to be necessary in operation with the LIU parameters and higher loss regime to reduce machine equipment irradiation and activation.

6. Conclusions

The LIU project is currently in its very final phase, with most of the new equipment installation and commissioning taking place during LS2. The project baseline in terms of design and construction of new upgraded equipment was built such that the target LIU beam parameters match the HL-LHC request for both protons and ions. This has been achieved thanks to the constantly improving machine operation and beam modelling for all injectors and to the careful steering of the project priorities towards the most critical items according to the evolving level of understanding, within the given constraints of time, resources and budget. A solid ramp-up strategy has been established for the LIU beam parameters and will be put in place during Run 3, based on a gradual exploitation of the newly installed hardware to produce baseline LIU beams in their yet unexplored parameter range by the end of 2024 for post-LS3 readiness. Although the recommissioning of the whole upgraded injectors chain will be challenging and risks still exist for the achievement of the target beam parameters, mitigation schemes and/or post-LIU options have been prepared within the project, as a pathway for successful luminosity production in the HL-LHC era.

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