WHAT TO EXPECT FROM THE INJECTORS DURING RUN 3

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Abstract

During LS2 the LHC injectors will undergo an important upgrade campaign under the LHC Injectors Upgrade (LIU) project. Linac2 will be replaced by Linac4 and additional hardware will be installed in all the synchrotrons of the LHC injectors chain to enable the production of proton beams of double intensity and brightness to be delivered to LHC in the HL-LHC era (i.e. after LS3). The lead (Pb) ion beams, which have already shown their potential to fulfil the HL-LHC goal in terms of single bunch parameters at the LHC injection, will see their bunch number roughly doubled in the LHC thanks to momentum slip stacking in the SPS. The planned evolution of the beam parameters during Run 3 can be summarised as follows. All pre-LS2 proton beams will be recovered by the end of 2021, while intensity and brightness of the LHC beams will be gradually ramped up to the LIU values throughout 2022- 2024. The commissioning of momentum slip stacking in the SPS for Pb ions is expected to take place in 2021 to allow delivery of LIU ion beams to LHC for the 2021 Pb-Pb run.

INTRODUCTION

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 accelerators of the LHC injectors chain, which are detailed in [3, 4]. The main items relevant to the desired beam performance will be listed separately for protons and Pb ions in the next sections.

Table 1 summarises the main target parameters at the SPS exit 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 become possible with a novel production scheme based on the LS2 LIU upgrades.

The timeline of the LIU project from the end of Long Shutdown 1 (LS1) up to the project completion is sketched in Fig. 1. LIU is currently at the peak of its execution phase, with the largest part of its equipment being installed during the Long Shutdown 2 (LS2).

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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

Numerous project related activities, however, took place already during the Run 2 both in preparation and in anticipation of the LS2 activities, specifically:

- A variety of 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 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 went through reliability and quality runs from 2016 to 2018. The Half Sector Test was also carried out in 2016-17 to qualify the new injection scheme into the PSB.

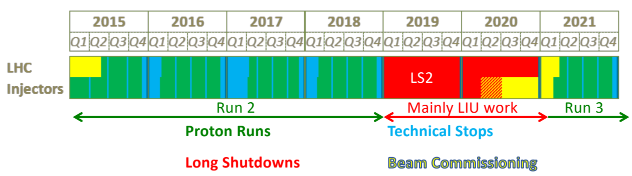

Figure 1: LHC (upper row) and Injectors (lower row) operation schedule between 2015 and 2021.

After LS2, stand-alone beam commissioning in the injectors is scheduled to start in Q2 of 2020 for Linac4, with the PSB commissioning its first post-LS2 beam already in September 2020, the PS in December 2020 and the SPS in January 2021. The detailed schedule of the restart of the ion injectors chain is still being finalised.

Commissioning of LIU beams will take place in 2020-21 for the Pb ion beams, as the full beam performance is already required for the LHC Pb-Pb ion run at the end of 2021. The proton beam commissioning up to the LIU beam parameters will be gradually performed during Run 3 to be ready after Long Shutdown 3 (LS3). This strategy, which will be further outlined in one of the next sections, will allow performing any further hardware corrective actions during the Run 3 technical stops or LS3, if needed. An inventory of beyond baseline LIU items with the associated decision points for implementation during Run 3 and rough cost estimations has been compiled and will be kept as reference for future actions during Run 3 or LS3 [5].

LIU BASELINE AND OTHER BEAM VARIANTS FOR PROTONS

To fulfil the HL-LHC requirement of integrated luminosity, the proton injectors are expected to produce 25 ns proton beams in trains of 288 bunches (4x72b) with about double intensity and 2.4 larger brightness at the SPS exit (Table 1, top two rows).

To reach the HL-LHC goal, the LIU baseline foresees the following improvements [3]:

- Replacement of Linac2 with Linac4. The H^- charge exchange injection into the four rings of the PSB at 160 MeV is expected to result in the production of beams with twice higher brightness than presently achieved out of the PSB [6];
- 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, this will allow reaching the LIU beam brightness target at the same 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 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 40 MHz RF system as Landau RF system over a part of the PS cycle, have demonstrated that PS can reliably produce the LIU target intensity;
- 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 HOMs 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 QF-type 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 reduced a-C coating, however, beam induced scrubbing is also expected to be required for the production of the target LIU beams;
- Upgrade of the SPS dumps and protection devices to make them suitable to the larger beam intensity and brightness. A new main dump system will be installed during LS2. The extraction protection, transfer line stoppers and collimators will be either exchanged, or new interlocking systems will be added.

The beam parameters expected at LHC injection after implementing all the LIU improvements outlined above are found to exactly match the HL-LHC target values reported in Table 1 for the LHC standard beam (trains of 72 bunches at the PS exit). To show that, we use the following procedure. In the plane transverse emittance versus bunch intensity at SPS extraction we plot all the boundaries for intensity and brightness limitations in the PSB, PS and SPS, and shade the forbidden regions. In this diagram, which we call *the limitation diagram*, the best achievable parameter set can be determined, corresponding to the point with the highest intensity and lowest emittance in the non-shaded area. This procedure can be applied to different beam types, each one produced through different RF manipulations in the PS and thus resulting in trains of different lengths sent to the SPS (and eventually different numbers of bunches that can be accumulated in LHC).

Figure 2, left plot, shows the limitation diagram for the LHC standard beam, which creates trains of 72 bunches out of the PS and remains the type targeted by HL-LHC to fulfil its integrated luminosity goal over the HL-LHC run [1]. As said above, in this case the achievable beam parameters match exactly the HL-LHC target values. In addition, due to the LIU improvements, also different LHC beam types will benefit and see their performance improved in post-LS2 operation. The Batch Compression Merging and Splitting scheme (BCMS) [7], which results in trains of 48 bunches out of the PS, will be produced with ca. 20% higher brightness with respect to the standard beam (see Fig. 2, middle plot). Just like the standard 25 ns beams, its bunch intensity reach will be limited by the SPS longitudinal

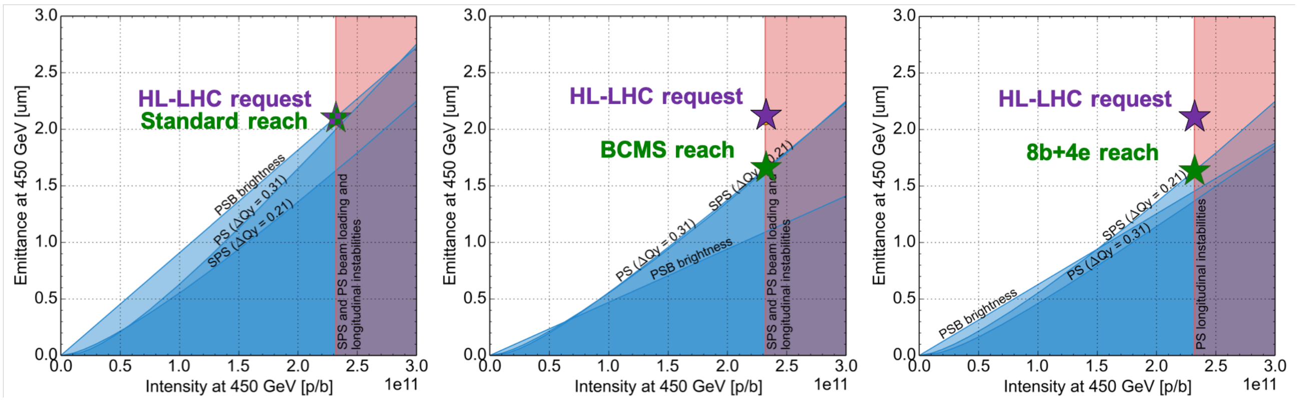

Figure 2: Complete LHC injectors limitation diagrams for LHC standard 25 ns beam (left), BCMS beam (middle) and 8b+4e beam (right). The points with the achievable bunch intensity and transverse emittance are highlighted with a green star for each beam variant, while the HL-LHC target value is displayed with a purple star.

instabilities. Its brightness, instead, will be equally limited by space charge in the PS and in the SPS, which is why this beam will not fulfil its potential of double brightness from the PSB brightness line. Due to the increased brightness, special care had to be taken to validate the robustness of the extraction/transfer/injection protection devices for this beam. The BCMS beam is considered by HL-LHC an interesting alternative in case mitigation against uncontrolled emittance blow up is needed. However, due to its potential to accumulate almost the same number of bunches in LHC as the standard beam, it has been chosen as the baseline beam for Run 3 operation [8]. The 8b+4e beam, made of trains of 56 bunches sent from the PS to the SPS in alternating sequences of 8 bunches and 4 gaps [9], has basically the same performance reach as the BCMS beam, as shown in the limitation diagram at the right side of Fig. 2. SPS space charge and longitudinal instabilities are the limitations for this type of beam. This beam, or any combination of its pattern with a pure 25 ns beam, is considered by HL-LHC an alternative in case mitigation against electron cloud effects (e.g. beam induced heat load in the beam screen of the cold arc) is needed. For the same reason, it could also become the operational beam during Run 3 for physics production.

PRODUCTION OF THE LIU ION BEAMS

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 during Run 2 under LIU, it has been possible to steadily improve the overall performance and reliability of the Pb ion injection chain with respect to previous runs. The intensity out of LEIR has been basically doubled, while in the SPS the overall transmission has been also improved and the batch spacing at injection has been reduced to 150 ns. As a result, as reported in Table 1, the single bunch parameters achieved in 2018 at the SPS extraction already match the HL-LHC desired values, even including a margin for the additional losses expected with the future RF manipulations. This is also displayed in Fig. 3, 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 (labeled *4 bunch scheme*). In addition, 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 packing a higher number of bunches in LHC (733 instead of 648), each with ca. 10% higher intensity. This is visible in Fig. 3, second half of the run (labeled *3 bunch scheme*). Using this scheme operationally for luminosity production in 2018 has thus demonstrated experimentally the potential achievement of 70% of the HL-LHC integrated luminosity target anticipated by calculations [10, 11].

The only remaining LIU item to be implemented for ions 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 by September 2021, and its feasibility has been proved in simulations [12]. In preparation for this mode of operation, dedicated machine studies were conducted in 2018 [13]. 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 at 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.

LIU BEAM COMMISSIONING IN RUN 3

To prepare for the restart of the injectors in 2020-21, Individual System Tests (IST) will take place during the shutdown period, followed by periods of Hardware Commissioning (HWC), which will include also the newly installed LIU equipment. Following the HWC periods, 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 [14]. The steps of beam commissioning during these blocks have been outlined taking into account the interdependency between machines [15] and will be added to the check lists.

For the commissioning of the LIU beams in Run 3, the schedule shown in Fig. 4 will be followed. During 2020-21, all the pre-LS2 beams as documented through the existing beam documentation (for both protons and Pb ions) will have to be recovered 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 will also be 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 will 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 RF system, 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 the momentum slip stacking in the SPS will have to be commissioned between September and November 2021 with the important challenges highlighted in the previous section. As from 2022, the intensity ramp up of the LHC proton beams can begin. Assuming that the BCMS beam will be the operational choice for LHC during Run 3 [8], the focus of the operational deployment will be on this type of beam. 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 1.3e11 p/b to the target 1.8e11 p/b at constant transverse emittance of about 1.3 μm (see Fig. 5). This means that we will start exploring new territory in terms of beam parameters. In fact, while 2e11 p/b were already produced up to PS extraction and even tested at SPS injection during Run 2, this intensity was never received in the SPS with the upgraded main RF system and never accelerated in the SPS 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 will have to be overcome in order to ensure beam losses within 10% in the SPS, as required for operational deployment. That's why a stabilisation strategy is being developed during LS2, also relying on the search of the instability sources, and will then have to be tested and demonstrated. It should be also mentioned that additional beam requests could come from physics (e.g. light ions), which may mean that time and resources will have to be allocated to produce those types of beams, if requests are approved.

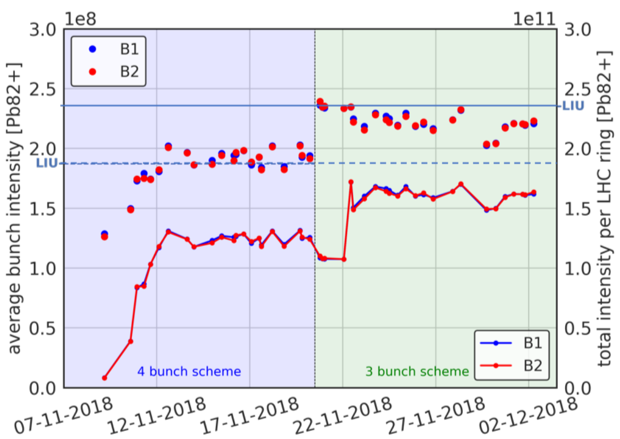

Figure 3: Average bunch intensity (points and left vertical axis) and total beam intensity (solid lines and right vertical axis) per LHC fill as a function of time during the 2018 Pb-Pb run. The LIU goals for both are also shown as horizontal lines (dashed for bunch intensity and solid for total beam intensity).

During 2023-24 the injected intensity into the SPS will have to be ramped from 2 to 2.6e11 p/b at constant brightness, expecting an extracted intensity from 1.8 to 2.3e11 p/b, see Figs. 4 and 5. Apart from the additional scrubbing inevitably needed in the SPS in this new beam parameter range, new and yet unknown limitations might emerge and require additional actions to achieve ultimately the target beam parameters, e.g. reduce the impedance of the PSB extraction kicker, install an additional RF system in the PS to improve PS-SPS transfer, extend the a-C coating and deploy an operational high bandwidth transverse feedback system in either plane in the SPS. Some of these scenarios have been already analysed within LIU but then discarded from the project baseline for budget constraints due to estimated low risk. A complete inventory of these options can be found in [5].

CONCLUSIONS

The LIU project is in its final phase, with most of the new equipment installation, IST and HWC taking place during LS2. The expected LIU beam parameters match the HL-LHC request within the present project baseline for both protons and ions. Different flavours of the proton beams, namely BCMS and 8b+4e have been shown to also benefit from the LIU upgrades. Their parameter reach is of interest, because the BCMS beam has been chosen for baseline physics operation in Run 3, while the 8b+4e variant remains an important back-up in case of electron cloud issues. A mitigation scenario for the Pb ion beams, based on 3 bunches with 75 ns bunch spacing out of the PS, has been already

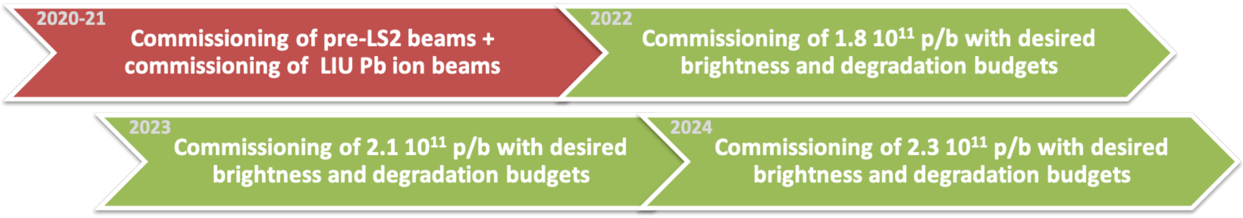

Figure 4: Gradual intensity ramp up to the LIU beam intensity over Run 3.

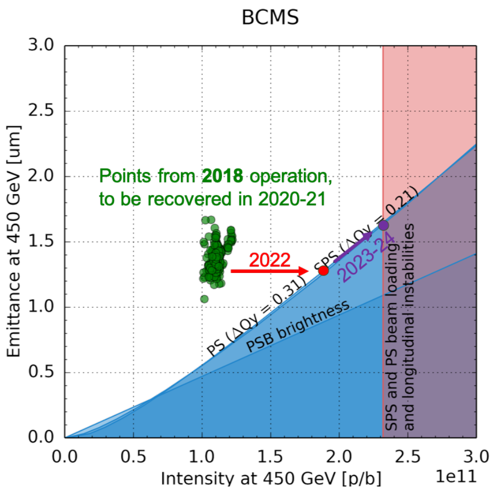

Figure 5: Limitation diagram for BCMS beams with points from 2018 operation and ramp up paths during 2022 and then 2023-24.

demonstrated to potentially provide about 70% of the target HL-LHC integrated luminosity.

The beam parameter ramp up strategy for the LIU beams during Run 3 has been solidly established and will be put in place according to the following principal milestones:

- Recovery of all pre-LS2 beams and production of the HL-LHC Pb ion beams by the end of 2021;
- LHC beams with 1.8e11 p/b out of the SPS available by the end of 2022 with the desired brightness (according to the variant) and beam loss/emittance growth budgets;
- Full performance of LIU beams reached by the end of 2024 for post-LS3 readiness.

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