LHC INJECTORS UPGRADE (LIU) PROJECT AT CERN

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Abstract

CERN is currently carrying out an ambitious improvement programme of the full LHC Injectors chain in order to enable the delivery of beams with the challenging HL-LHC parameters. The LHC Injectors Upgrade project coordinates this massive upgrade program, and covers a new linac (Linac4 project) as well as upgrades to the Proton Synchrotron Booster, the Proton Synchrotron and Super Proton Synchrotron. The heavy ion injector chain is also included, adding the Linac3 and Low Energy Ion Ring to the list of accelerators concerned. The performance objectives and roadmap of the main upgrades will be presented, including the work status and outlook. The machine studies and milestones during LHC Run 2 will be discussed and a preliminary Long Shutdown 2 installation planning given. Finally, for the LHC Run 3, the beam performance across the full injector chain after all the upgrades will be estimated and the required commissioning stages outlined.

INTRODUCTION

The goal of the LHC Injectors Upgrade project (LIU) is to increase the intensity/brightness in the injectors in order to match the High Luminosity LHC (HL-LHC) requirements [1]. For protons, the Linac4/PSB/PS/SPS chain will be enabled to produce higher intensity beams (based on efficient production schemes, space charge and electron cloud mitigation, impedance reduction, feedback systems, hardware upgrade and improvement). For heavy ions, an important upgrade of the injector chain (Linac3, LEIR, PS, SPS) is planned to reach the beam parameters at the LHC injection that can meet the luminosity goal. In addition, the LIU project should ensure the increased injectors reliability and lifetime to cover the HL-LHC era (until 2035). This part, closely related to the CONSolidation, project [2], concerns the upgrade/replacement of ageing equipment (power supplies, magnets, RF) and the improvement of radioprotection measures (shielding, ventilation).

The timeline of the LIU project is sketched in Fig. 1. The simulation studies, beam measurements and equipment procurement will take place during Run 2 until the start of Long Shutdown 2 (LS2). During this time, key dates for pending decisions have been set in order to define the baseline program of all the interventions by end of 2016. All LIU installations and hardware works will then take place during LS2. For some of these installation activities, it is checked if they could be anticipated to Year-End-Technical-Stop (YETS) or Extended-Year-End-Technical-Stop (EYETS). Commissioning of LIU beams will take place in 2020 for the Pb ion beams, as the full beam performances are already needed for the 2020 ion run. The proton beam commissioning up to the LIU beam parameters will gradually be performed during Run 3 to be ready after LS3. This strategy would as well allow performing any further hardware corrective actions during the Run 3 technical stops or LS3, if needed.

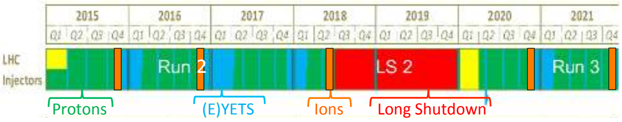

Figure 1: LHC (upper row) and Injectors (lower row) operation schedule (green: proton operation, blue: technical stops, orange: ion operation, red: long shutdown -LS).

LIU IONS

The main target of the LIU-IONS can be described in a simplified form as reaching 7 times the design peak luminosity [3]. This also translates into multiplying by about a factor 3 the peak luminosity extrapolated from beam parameters achieved during the 2013 p-Pb run. Table 1 summarises the desired versus achieved ion performance. The bunch intensity was already at the limit on the SPS flat bottom during the 2013 p-Pb run in terms of acceptable intra-beam scattering and space-charge effects. It is therefore needed to accumulate a larger number of bunches in LHC.

Table 1: Ion Beam Parameters at LHC Injection

	N (10^8 ions/b)	$\epsilon_{x,y}$ (μm)	Bunches
Achieved	1.4	1.2	358
HL-LHC (tbc)	1.4	1.2	960

The means to achieve the LIU-IONS target luminosity are the following:

- Increase the beam current from the source and Linac3 by improving both source and Low Energy Beam Transport (LEBT). This requires identifying and removing bottlenecks with the aid of beam dynamics simulations and beam measurements, and by installing new diagnostics. The increase of the injection rate from 5 to 10 Hz will allow injecting more intensity into LEIR, while keeping the same magnetic cycle duration;
- Increase the beam current out of LEIR by both increasing the amount of injected beam (compatibly with the electron cooling capabilities) and mitigating

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the large beam losses at RF capture. For that, more advanced machine modelling and Machine Developments are needed;

- Use bunch splitting in the PS to produce 4 bunches with 100 ns bunch spacing;
- Increase the number of bunches in the SPS and apply longitudinal slip-stacking, allowing the production of trains with 50 ns bunch spacing. Furthermore, mitigation of the beam degradation at flat bottom will rely on the reduction of the RF noise. The use of Q20 optics will be kept, as it proved efficient during the 2013 p-Pb run. For the post-LIU future, it has been also studied how to further increase the number of bunches transferred to the LHC by upgrading the injection system into the SPS to provide 100 ns rise time and producing longer bunch trains from the SPS.

LIU PROTONS

The injectors are expected to produce 25 ns proton beams with about double intensity and higher brightness than nowadays. Table 2 summarises the achieved beam parameters at LHC injection, those estimated achievable with the current baseline LIU upgrades and finally the ultimate HL-LHC target parameters.

Table 2: Proton Beam Parameters at LHC Injection

	N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	Bunches
Achieved	1.2	2.6	≈ 2700
LIU	2.0	1.9	2760
HL-LHC	2.3	2.1	2760

To reach this goal, a cascade of improvements is needed across the whole injectors chain [4]. The main items are listed below and briefly described:

- Replace Linac2 with Linac4. This will allow injecting H- into the PSB at 160 MeV. It requires a complete re-design of the injection into the PSB;
- Raise the injection energy in the PS to 2 GeV to allow for higher beam brightness at the same space charge tune spread. This relies upon increasing the PSB maximum magnetic field, replacing its main power supply, upgrading its main RF systems, changing the PSB-PS transfer equipment and re-designing the PS injection. The intensity out of the PS can also be increased thanks to the newly installed longitudinal feedbacks to suppress coupled-bunch instabilities and transient beam loading;
- Increase the beam intensity accelerated in the SPS by means of the following actions. First, the RF power will be upgraded by adding two new 200 MHz power plants, rearranging the 200 MHz cavities, increasing the power and installing a new low-level RF for both the 200 and the 800 MHz RF systems. Second, the electron cloud, one of the main limitations of the SPS for operation with 25 ns beams, should be actively suppressed by coating with amorphous-Carbon the fraction of the SPS vacuum chambers that have been identified as the most dangerous to the beam and/or easier to handle. The final decision on this item will be taken in mid-2015, after all the data about the achievable SPS performance with scrubbing will be available and analysed. Third, about 500 vacuum flanges, identified as the main SPS impedance source responsible for longitudinal instabilities, should be either shielded or completely/partially exchanged with new ones based on a design providing minimum impedance. In possible synergy with the a-C coating campaign, it is planned to decide by the second half of 2015 how the impedance reduction campaign will be finally conducted, and consequently define the baseline actions. Finally, the removal of other limits on intensity/brightness through the upgrade of beam intercepting devices and dumps is also a major part of the SPS upgrade work.

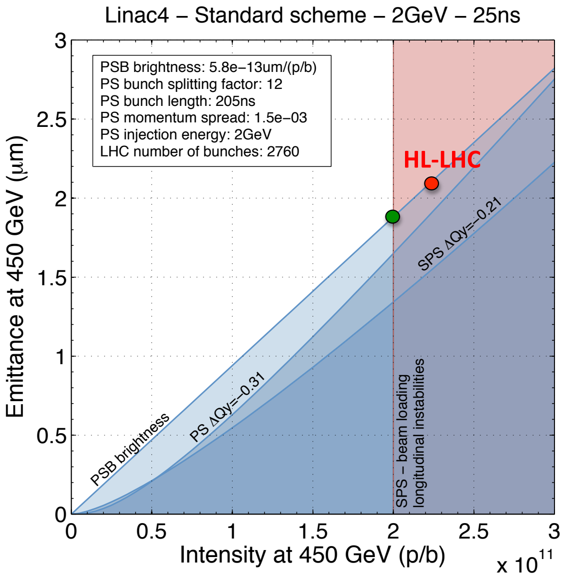

Figure 2: Proton performance reach after implementation of all the Injectors upgrades.

After connecting the PSB to Linac4 and implementing all the improvements for the LIU program, as outlined above, the beam performance at the LHC injection as reported in Table 2 can be reached. These values are limited by longitudinal instabilities/beam loading in the SPS and PSB brightness, as illustrated in Fig. 2. The implementation of the longitudinal impedance reduction in the SPS could potentially allow the value of the maximum intensity out of the SPS to increase towards the HL-LHC goal, however a better quantification of this improvement can be provided only once the baseline of this activity will be frozen.

POTENTIAL FURTHER IMPROVEMENTS

Some other options have been under consideration to further improve the injector performance in an effort to match the HL-LHC needs (not necessarily in terms of beam parameters, but in terms of the integrated luminosity):

- Provide more margin for higher bunch current out of the SPS (larger longitudinal emittance at flat top) through the following means: 1) using for the SPS a new optics (Q22), which would provide a trade-off between margin in Transverse Mode Coupling Instability threshold and constraint on RF power; 2) reducing the ramp rate and performing bunch rotation at 450 GeV to help the beam loading limitation on the ramp and the constraint on the bunch length at the SPS extraction, respectively. It is worth noting that the LHC could also ease this optimisation process, if it becomes able to receive longer bunches from the SPS with a 200 MHz RF system. This is as well being investigated within the HL-LHC project.
- Fill the LHC with a higher number of bunches by injecting trains of 80 bunches into the SPS, instead of the nominal 72 bunches. The scheme is based on injecting 4+3 bunches from the PSB into the PS, with the removal of one out of 21 bunches after the triple splitting at 2.5 GeV. The use of the transverse feedback to kick out a single bunch from the PS was already validated in Machine Development.
- Produce higher brightness beams in the injectors by means of the BCMS production scheme [4]. This results however in injecting trains of 48 bunches from the PS into SPS and eventually a lower number of bunches in the LHC (2592). It requires a careful study of the potential high damage for beam intercepting devices in the SPS, transfer lines and LHC. The performance reach of the BCMS beams is of high interest (2.0×10^{11} p/b in 1.4 μm at 450 GeV), as shown in Fig. 3. In this case, the brightness limitation comes from space charge in both the PS and the SPS.

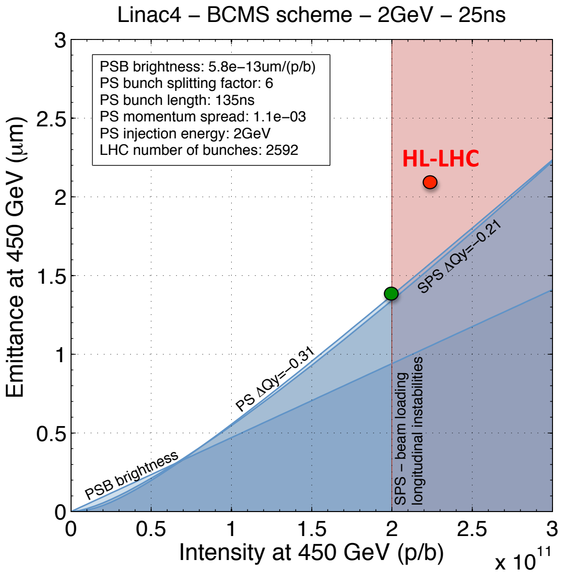

Figure 3: Proton performance reach with BCMS beams.

High brightness beams come with larger Intra Beam Scattering rates in LHC, challenges for emittance measurement devices, fewer bunches in LHC (5%), and decreased efficiency of the LHC octupoles to stabilize the beam. The added high damage risk of the protection devices in the SPS, the SPS-to-LHC transfer lines and the LHC also needs to be taken into account. The energy deposition depends on the total intensity as well as on the spot size. It was demonstrated that the protection devices for Run 2 BCMS beams and LIU beams, might need to attenuate 100-200% more than with the present design. The choice of material is challenging, as the stresses in case of impact of high brightness beams are estimated to be beyond the strength of materials presently used in passive protection absorbers (even the HL-LHC beam may pose problems). R&D is needed to possibly find suitable materials for new absorbers in the post LS2 run. Beam tests in the HiRadMat facility with 440 GeV SPS beam are essential to check the material properties used as input for simulations, the robustness against simulated future beams and to test new promising materials (e.g. 3D Carbon-Carbon).

CONCLUSIONS

Concerning the protons, the LIU baseline program is established to ensure production of LHC proton beams with parameters close to HL-LHC request (right brightness, and for the moment ca. 15% lower intensity per bunch than requested). A very dense machine and simulation study program is being carried out until 2016 to further improve our parameter estimates and take decisions at the latest during 2015 for few remaining pending items. In parallel, hardware specification, design and procurement activities are being conducted and should be completed to meet the LS2 installation target. Promising options have been also identified and are under study to increase the intensity and/or brightness of the LIU beams delivered to LHC. Additional studies are planned to validate these options, after which action planning and cost estimates will be defined.
Concerning the ions, a list of actions has been identified to maximize the luminosity in the LHC immediately after LS2. Big challenges lie ahead to increase the beam current out of LEIR and to reduce the beam degradation along the chain. As the LIU ion beam is the first to be required for physics production after LS2, much effort is presently being put to solve all the related issues.

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