CAN THE PROTON INJECTORS MEET THE HL-LHC REQUIREMENTS AFTER LS2?

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Abstract

The LIU project has as mandate the upgrade of the LHC injector chain to match the requirements of HL-LHC. The present planning assumes that the upgrade work will be completed in LS2, for commissioning in the following operational year. The known limitations in the different injectors are described, together with the various upgrades planned to improve the performance. The expected performance reach after the upgrade with 25 and 50 ns beams is examined. The project planning is discussed in view of the present LS1 and LS2 planning. The main unresolved questions and associated decision points are presented, and the key issues to be addressed by the end of 2012 are detailed in the context of the machine development programs and hardware construction activities.

HL-LHC REQUIREMENTS AFTER LS2

The stated performance objective of HL-LHC is to accumulate 3000 fb^{-1} of integrated p-p luminosity at 14 TeV centre of mass collision energy [1]. In order to achieve this, an annual figure of 250-300 fb^{-1} has been posited, requiring instantaneous luminosity capability of around $7–8\times10^{34}$ $cm^{-2}s^{-1}$, levelling to 5×10^{34} $cm^{-2}s^{-1}$ and high machine efficiency [2]. The present paper covers the first of these challenging requirements: how to deliver the beam from the injector complex for these luminosities almost an order of magnitude above LHC design.

The HL-LHC project has previously outlined possible parameter sets[†] for 25 and 50 ns spacing which give the required luminosity, summarised in Tab. 1, adapted from [2]. Strictly speaking the HL-LHC needs the specified beams from the SPS after LS3, when the major work for the HL-LHC project is planned. The LIU work will take place largely in LS2, so that the period LS2 to LS3 will be an important one in terms of achieving the maximum performance from the injector chain.

The figures quoted are for beams at the start of the collision process at 7 TeV – any beam loss or emittance dilution after extraction from the SPS is not included. The assumptions on the beam loss and emittance dilution for all machines are given in Tab. 2, where it can be seen that the total assumed beamloss $-\Delta I/I_0$ is 27%, and the emittance growth $\Delta\varepsilon/\varepsilon_0$ is 33%, corresponding to a brightness which is reduced to 55% of the original value.

[†]The parameters and performance described in the paper represent the snapshot of the situation at the time of the Chamonix workshop, early February 2012. Changes since this time are not described.

Table 1: Parameters and requirements from HL-LHC

Parameter	Nom.	HL 25 ns	HL 50 ns
N [e11 p+]	1.15	2.0	3.3
n_b	2808	2808	1404
Beam current [A]	0.58	1.02	0.84
X-ing angle [μrad]	300	475	520
Beam sep. [σ]	10	10	10
β* [m]	0.55	0.15	0.15
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.5	2.5	2.5
Δp/p	1×10^{-4}	1×10^{-4}	1×10^{-4}
Bunch length [mm]	75	75	75
IBS horiz. [h]	80-106	25	17
IBS long. [h]	61-60	21	16
Piwinski param.	0.68	2.5	2.5
Geom. reduct.	0.83	0.37	0.37
Beam-beam / IP	3×10^{-3}	4×10^{-3}	5×10^{-3}
Peak lumi. [$cm^{-2}s^{-1}$]	1.0×10^{34}	7.4×10^{34}	8.4×10^{34}
Events/crossing	19	141	257

Table 2: Assumed beam loss and emittance growth through the LHC proton chain

Machine	$-\Delta I/I_0$ %	$\Delta\varepsilon/\varepsilon_0$ %
PSB flat-bottom to extraction	5	5
PS injection to extraction	5	5
SPS injection to extraction	10	10
LHC injection to flat-top	10	10
Total	**27**	**33**

It is also of note that the parameter space for LHC is rather limited – the parameters cannot deviate far from the specified targets, due to various limitations in the LHC machine [3], even for equivalent peak luminosity.

Tables 3 and 4 summarise the parameters in the different machines for the standard bunch splitting scheme.

Table 3: Required 25 ns beam parameters through the LHC proton chain, including losses and emittance growth

25 ns	PSB inj	PSB extr/PS inj	PS extr/SPS inj	SPS extr/LHC inj	LHC top
Energy [GeV]	0.16	2	26	450	7000
n_b	1	6	72	288	2808
N [e11 p+]	32.0	30.5	2.4	2.2	2.0
N in LHC [e11 p+]	2.7	2.5	2.4	2.2	2.0
ε_{xyn} [μm]	1.9	2.0	2.1	2.3	2.5

Table 4: Required 50 ns beam parameters through the LHC proton chain, including losses and emittance growth

50 ns	PSB inj	PSB extr/PS inj	PS extr/SPS inj	SPS extr/LHC inj	LHC top
Energy [GeV]	0.16	2	26	450	7000
n_b	1	6	36	144	1404
N [e11 p+]	26.4	25.2	4.0	3.6	3.3
N in LHC [e11 p+]	4.4	4.2	4.0	3.6	3.3
ε_{xyn} [μm]	2.2	2.4	2.5	2.7	3.0

PRESENT INJECTOR CHAIN PERFORMANCE

The present (2011) performance of the proton injector chain has been detailed in [4]. Concerning losses and blow up, 2011 operation saw 13% beamloss from PS injection to LHC flat-top, with emittance growth of around 0.4-0.5 μm to SPS extraction, and a further 0.5-0.6 μm in the LHC, from an initial value of about 1.6 μm at PS injection, or a total of about 66%.

For 50 ns, around 1.6×10^{11} p+ per bunch with emittances of 2.0 μm were extracted from SPS, while for 25 ns the figures were 1.1×10^{11} p+ and 2.8 μm. These references are plotted in Fig. 1, where the present limitations in the injector complex are also indicated, together with the target value required for HL-LHC. (These plots will be widely used – the lines and regions are indicative, rather than exact mathematical functions: many limits are of course not hard-edged or known with exact precision.)

INJECTOR CHAIN LIMITATIONS AND MITIGATIONS

Space charge and brightness limits

In the PSB, a direct space charge tune spread of -0.3 is considered as comfortably feasible, with higher values not excluded [5]. At the new injection energy of 160 MeV this translates to a transverse emittance of about 0.42 μm per 10^{12} p+. The resulting brightness is 2.4×10^{12} p+/μm.

In the PS, with 2 GeV injection, h=7 with no compression, bunch length 160 ns, and $\delta p/p = 0.0013$, the presently assumed space charge limit is -0.26, which gives approximately 0.8 μm per 10^{12} p+, or a brightness of about 1.2×10^{12} p+/μm. It is apparent that the PS cannot digest fully the beam that the PSB can provide.

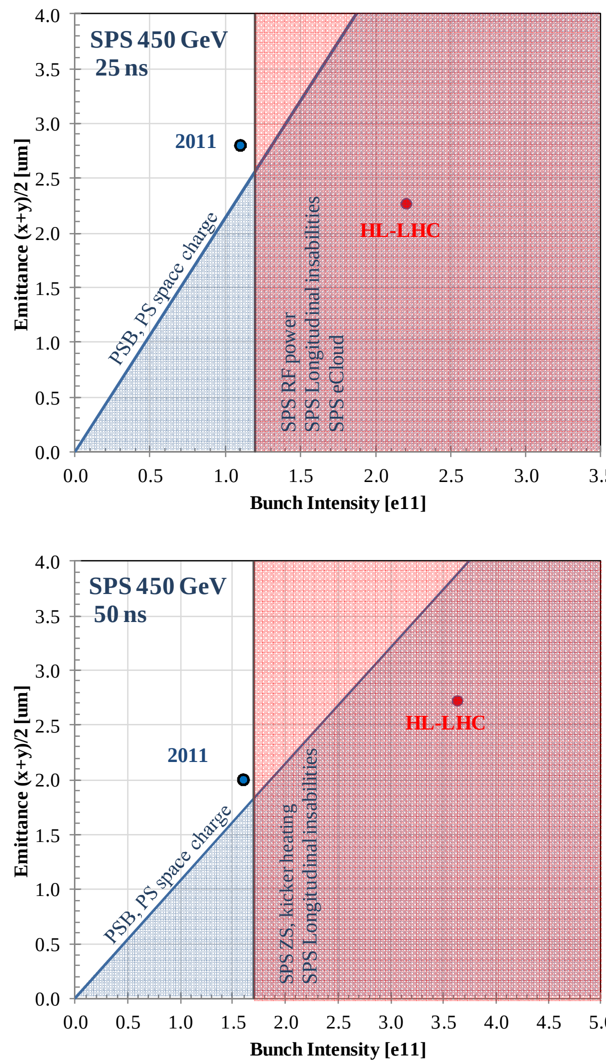

Figure 1: 2011 injector complex performance at SPS extraction, indicating main limitations and HL-LHC requirements, for 25 ns (top) and 50 ns (bottom) spacing.

In the SPS, there is hope to run with a space charge tune shift of -0.15, using the Q20 optics. This gives a brightness of 1.2×10^{11} p+/µm, which is a limitation for 50 ns, but not 25 ns, given the respective splitting factors in the PS of 6 and 12. It must be noted that, unlike the other machines, this tune shift has not yet been confirmed operationally on a regular basis with multi-bunch beams.

The different space charge tune-shift or brightness limits for the three machines are shown in Fig. 2, with for the PSB and PS the present limits also indicated corresponding to 50 MeV and 1.4 GeV injection energies.

Longitudinal limitations

In the PSB no limitations are expected in the longitudinal plane [6].

In the PS, the PS longitudinal coupled bunch instability presently limits the bunch intensity to about 1.7×10^{11} p+, for both 25 and 50 ns beams [7]. The addition of a new coupled-bunch feedback system with a dedicated kicker cavity should increase this limit to about 3×10^{11} p+ per bunch. This is clearly much more of an issue for performance reach with 50 ns, since the 25 ns requirements are well within reach after the upgrade.

Also in the PS, transient beam loading in the 10, 20 and 40 MHz RF systems is an issue through their relative phases along the batch during the splittings. This is not a hard limit but will adversely affect bunch-to-bunch quality via the splitting, and is more critical for 50 ns. The limit with upgraded longitudinal feedbacks is expected to be around 3×10^{11} p+ for both 25 and 50 ns, depending on the acceptable bunch-to-bunch intensity fluctuations.

The longitudinal beam parameters for the PS to SPS transfer are being studied with a view to improving the stability margin in the PS, while not increasing capture losses in the SPS with larger emittances [8].

In the SPS, a major upgrade of the 200 MHz system is planned, to double the RF power in order to cope with the very high beam loading with the target beam parameters. The upgrade requires complete reorganisation of the existing cavities into 6 assemblies, and the addition of two new 1.6 MW RF power plants. This will allow 10 MV at extraction for an RF current of 3 A, twice the present limit. For this the existing power plants will need to operate in pulsed mode at 1.05 MW peak power.

Regarding longitudinal beam stability in the SPS, the 25 ns beam is already unstable for a bunch intensity of around 3×10^{10} p+ [9]. This is presently mitigated with a longitudinal emittance blow up to 0.6 eVs, and use of the 800 MHz system in bunch-shortening mode. To reach the target of 2.3×10^{11} p+ per bunch at 25 ns will need longitudinal emittances of about 0.9 eVs, for the Q26 optics. There might also be some slight gain from the expected lower impedances of the 200 MHz RF system and MKE kickers, and the planned doubling of the available 800 MHz voltage. For the Q20 optics the instability thresholds are higher, scaling with the slippage factor η, but essentially in terms of RF voltage V_{RF} this is balanced by the fact that a smaller longitudinal emittance is needed to obtain the same bunch length for a given V_{RF}.

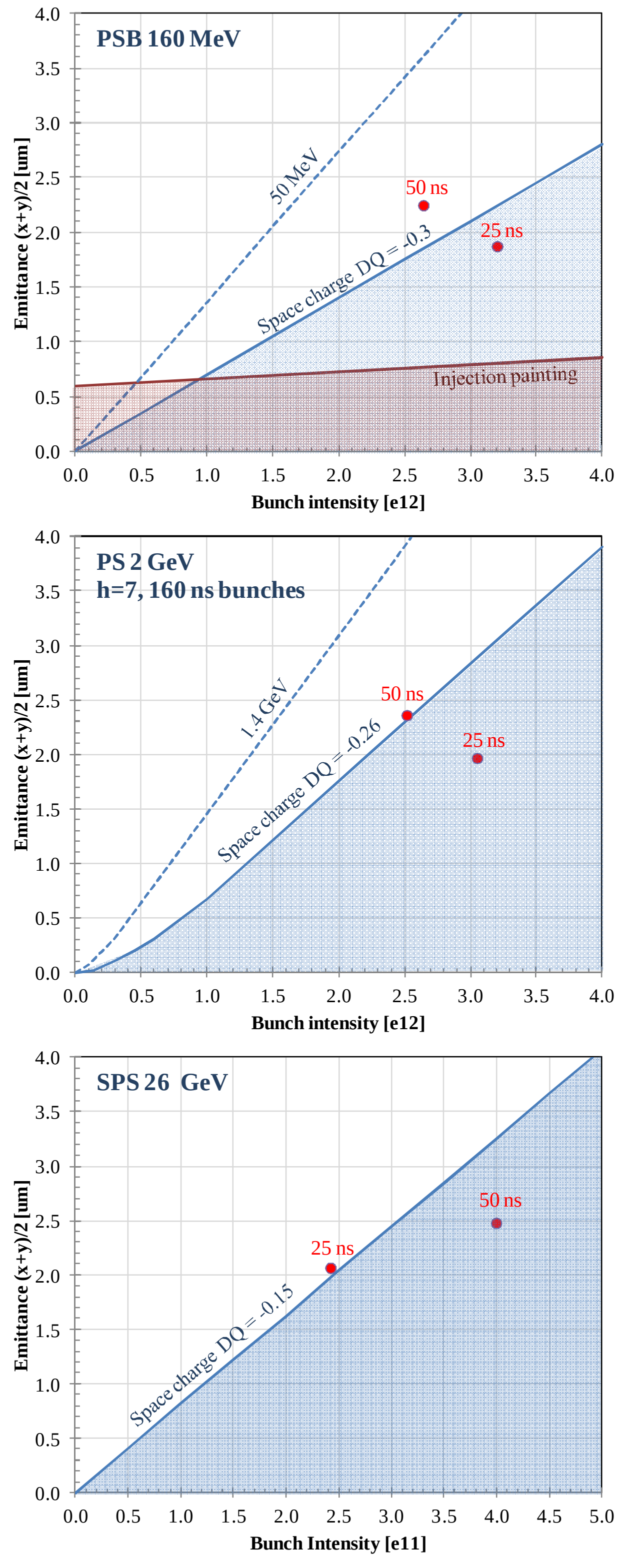

Figure 2. Expected space charge/brightness limits for the LHC injector chain (at injection), after the LIU upgrades. HL-LHC target parameters are shown as red dots.

After the planned upgrades of the 200 and 800 MHz SPS RF systems, it is expected that a factor two in intensity reach will be possible with respect to 2011, meaning 2.3×10^{11} p+ per bunch at 25 ns and $\geq3.5\times10^{11}$ p+ per bunch at 50 ns. The main unknown is the beam stability with high intensity, with the combination of single- and coupled-bunch effects. It would certainly be very beneficial to transfer longer (1.6 – 1.8 ns) bunches to the LHC, but studies are needed on mitigation of capture losses in LHC and injection related beam loss [10].

Transverse Mode Coupling Instability

The single bunch TMC instability is an issue for the SPS with the Q26 optics, where the predicted and measured thresholds (for ~zero chromaticity) are around 1.6×10^{11} p+ [11]. This can be increased with higher chromaticity, at the cost of increased losses and significant transverse emittance blow up. For the Q20 optics this threshold is much higher due to the increased slippage factor η – in measurement no TMCI has been observed for bunch intensities of up to 3.5×10^{11} p+ [12].

Operational limitations

Other limitations also exist, to date mainly in SPS. These are basically limitations on total beam power, either in a single cycle or over several hours.

The heating of the SPS extraction kickers should be solved with the installation of the final shielded kickers during LS1. No beam heating issues have been seen with the other kickers equipped with serigraphed ferrites, and the observed power deposition is about a factor 5 less than in the unshielded kickers.

Sparking in the electrostatic ZS septa has been an issue with very high intensity 50 ns beam in 2011, and has interfered with slow extracted beams. Mitigations such as fast modulation of the main and auxiliary voltages are being studied. In the last resort, the ZS could be switched off and retracted during LHC beam operation, but this would strongly impact the way in which the SPS is run, and reduce the number of protons sent to the North Area.

Also in the SPS, outgassing of the beam dump degrades the vacuum of the injection kickers. Differential pumping and sectorisation has been studied, and more drastic options like moving the dump to another SPS insertion, or designing a new external dump. The effect is, however, mainly a limitation for high duty factor scrubbing and setting up after any local vacuum interventions, rather than directly affecting performance for LHC filling.

Beam instrumentation

Wide-ranging upgrades of the different instrumentation systems across the complex are planned in order to be able to commission, set-up, characterise and monitor the new beams. The higher beam brightness means extending the dynamic range of many systems, and the new H^- injection system in the PSB requires new loss monitors, H^-/H^0 current monitoring, new BTV screens. The very ambitious targets for beam loss and blow up control also require an improvement in the resolution and performance of many distributed and specific systems, such as beam orbit, beam loss, matching monitors and tune meters. Following the increasingly demanding tolerances of LHC operation the beam size measurement systems are also being upgraded to improve the measurement accuracy and reliability, with the development of new wire scanners for PS and SPS, and an ionisation rest gas monitor for the SPS.

Machine protection and beam loss control

The beam extracted from the SPS is well above the damage limit for normal accelerator components, and already passive beam intercepting protection devices are installed in critical locations to avoid damage in case of mis-steered beam during the transfer from SPS to LHC. The increased beam intensity and reduced beam size mean that several of these devices will need upgrading. The collimators at the ends of the TI2 and TI8 transfer lines will need replacing by more robust, more absorbing units, and will also be moved to avoid the issues seen at present with cross-talk with the LHC beam loss system.

Electron cloud limitations

In the PS, electron cloud is observed for a few milliseconds just before extraction [13]. Presently this has only perturbed acquisitions from some pickups, and is not a limitation in terms of beam related performance. A simulation effort is planned to investigate the expected effects with the upgraded beam parameters, to evaluate whether instabilities, losses or emittance growth may occur. Possible mitigation measures include double bunch rotation shortly before ejection and vacuum chamber coating.

In the SPS electron cloud has been a major concern for 25 ns beams, and is also present with 50 ns [14]. Effects observed have included vacuum pressure rise, beam losses, instabilities and incoherent emittance growth. A major effort on mitigation methods has been made, with scrubbing runs, clearing electrodes and the development and testing of surface treatments to reduce the secondary electron yield coefficient. Scrubbing is still being evaluated as an alternative, but it appears that the stainless steel surfaces cannot reach the required SEY yields. The baseline for LIU is the coating of the main magnet vacuum chambers with an amorphous carbon layer [15], which will need to be done without removing the chambers from the magnets. The coating has been found to suppress electron cloud, and to date shows good aging behaviour. The assumption for the SPS is that electron cloud limitations will be completely removed after the LIU upgrades. In case this strategy would not work, or to supplement scrubbing should the baseline change, a high bandwidth transverse feedback system is also being developed [16], which will be able to damp the single bunch vertical electron cloud instability.

EXPECTED PERFORMANCE AFTER LS2

Baseline performance expectations

The performance after LS2 will be dictated by the success of the mitigation measures listed above. Under the assumption that the limits and improvement factors are as expected, the performance reach in terms of beam characteristics at extraction from the SPS are shown in Fig.3, for 25 and 50 ns bunch spacing. The achievable characteristics are expected to be 2.3×10^{11} p+ in 3.5 μm transverse emittance for 25 ns, and 2.7×10^{11} p+ in 2.7 μm for 50 ns, as delivered from the SPS at extraction. It can be seen that for 25 ns the emittance is about 50% larger than the target, while for 50 ns the intensity is about 25% lower than the target.

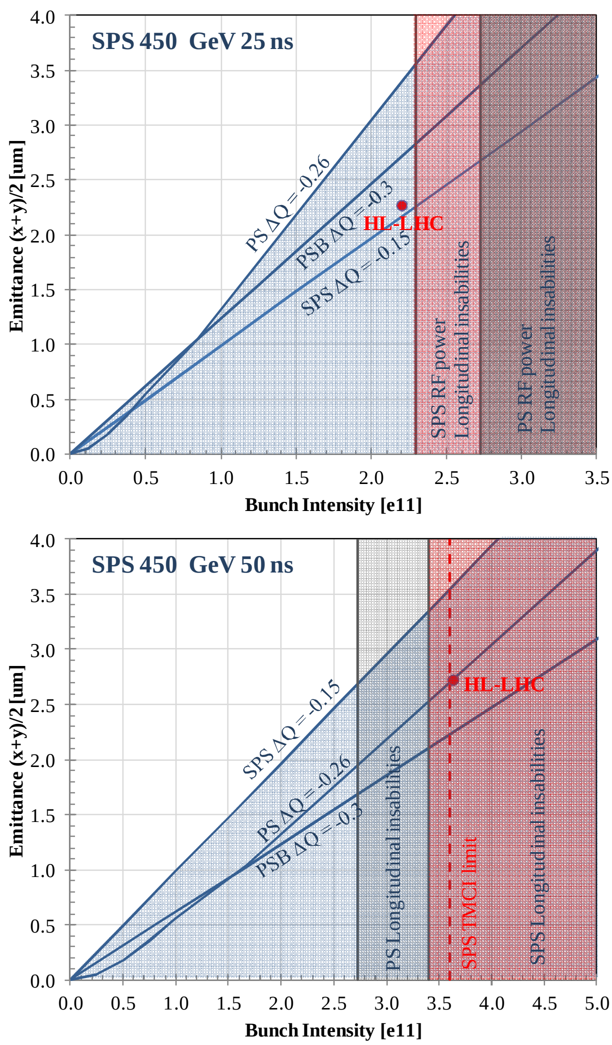

Figure 3. Expected performance reach at SPS extraction, after the baseline LIU upgrades.

"Stretched" performance

To approach the requirements set by HL-LHC, the assumed baseline LIU upgrades described above are not sufficient. There will need to be further improvements in the performance reach of the injector complex. An improvement target is in the control of beam loss and emittance dilution, both in the injectors and in the LHC ring. Table 3 shows "stretched" goals for beam loss and emittance growth. The values in red have changed.

Table 3: "Stretched" beam loss and emittance growth goals through the LHC proton chain

Machine	$-\Delta I/I_0$ %	$\Delta\varepsilon/\varepsilon_0$ %
PSB flat-bottom to extraction	5	5
PS injection to extraction	3	5
SPS injection to extraction	8	5
LHC injection to flat-top	3	10
Total	**18**	**27**

The overall brightness to LHC collision would then be reduced to about 65% of the maximum value, compared to 55% from the values listed in Table 2. The values given in Table 3 are not completely unreasonable. In the PS, the beam loss would need to be controlled to 3%, which seems feasible. In the SPS, 8% beam loss including scraping may also be possible once the transfer line collimators have been relocated to reduce the sensitivity of the LHC to beam losses from transverse tails. In the LHC, the beam loss observed in 2011 was already below the 3% level – the difficulty will be rather to keep the emittance growth at 10%.

With the assumptions listed in Table 3, the achievable beam characteristics are improved slightly, with 2.3×10^{11} p+ in 3.2 μm transverse emittance (previously 3.5μm) for 25 ns, and 2.8×10^{11} p+ in 2.6 μm transverse emittance (previously 2.7×10^{11} p+ in 2.7 μm) for 50 ns.

For 25 ns, with the dilution figures from Table 3, the remaining limitation is then the space charge tune shift in the PS. This would need to increase from -0.26 to -0.32, always assuming 160 ns bunch length, and would then give the potential for meeting the HL-LHC requirement of 2.1×10^{11} p+ in 2.3 μm extracted from the SPS, Fig. 4. For the PS there is reasonable optimism that this could be feasible, since a bunch length of 180 ns is possible, which would already bring a 12% increase in intensity, and the machine would then need to operate at a tune shift of -0.3.

For 50 ns, the remaining limitations are different, associated with the high single bunch intensities in the PS and SPS. With the losses and blow up according to the stretched goals, the SPS tune shift would need to increase to about -0.17, which means multibunch running at the single bunch intensity limit. In addition, the limitation for stability in the PS in the longitudinal plane would need to be increased to about 3.7×10^{11} p+, which is another 20% beyond the assumed upgrade reach, and 150% higher than presently obtained. In the event that these very challenging obstacles could be overcome, while maintaining the very low beam loss and emittance growth targets, the injectors would then be able to deliver 3.4×10^{11} p+ in 2.7 μm, Figure 5, which would correspond to the HL-LHC requirement.

Summary of performance reach evaluation

The various performance reach figures are shown in Tables 4 and 5, including the present performance, LIU baseline, stretched beam loss and emittance growth, and the pushed space charge limits and PS longitudinal stability. As a figure of merit, the value of I_b^2/ε_{xy} at LHC collision is quoted, taking account of the brightness dilution, as a measure of the attainable peak luminosity and scaled to the Hl-LHC requirement. The present injector performance reaches about 20-25% of the HL-LHC requirement, with the LIU baseline at about 70% for 25 ns and 55% for 50 ns. The 25 ns beam appears to be less challenging, given the present state of knowledge of the machines and the planned improvements.

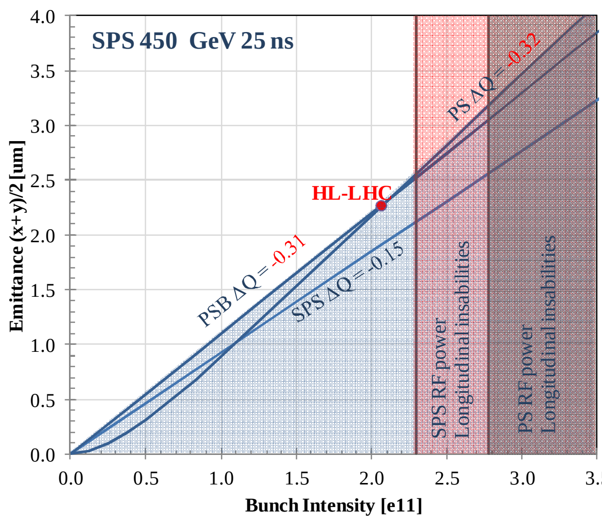

Figure 4. "Stretched" performance at 25 ns at SPS extraction, requiring reduced beam loss and emittance growth (Tab. 3), and operating with a direct space charge tune shift of -0.32 in the PS, with 160 ns bunches.

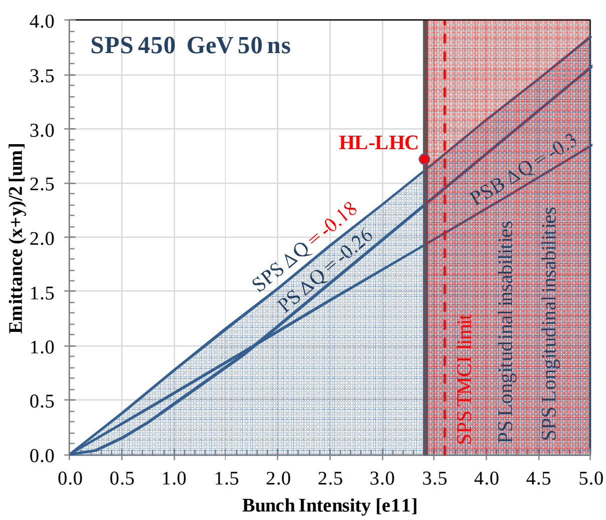

Figure 5. "Stretched" performance at 50 ns at SPS extraction, requiring reduced beam loss and emittance growth (Tab. 3), and operating with a direct space charge tune shift of -0.18 in the SPS, and requiring bunches to be longitudinally stable at 3.7×10^{11} p+ in the PS.

Table 4: Comparison of performance reach for different injector upgrade hypotheses, for 25 ns bunch spacing.

25 ns	I_b [10^{11}]	ε_{xy} [μm]	k [I_b^2/ε_{xy}]
HL-LHC target	2.0	2.5	1.00
2011 performance	1.1	2.8	0.20
LIU baseline	2.3	3.5	0.70
+ stretch loss/blowup	2.3	3.2	0.76
+ PS ΔQ = -0.32	2.3	2.5	1.00

Table 5: Comparison of performance reach for different injector upgrade hypotheses, for 50 ns bunch spacing.

50 ns	I_b [10^{11}]	ε_{xy} [μm]	k [I_b^2/ε_{xy}]
HL-LHC target	3.3	3.0	1.00
2011 performance	1.6	2.0	0.26
LIU baseline	2.7	2.7	0.55
+ stretch loss/blowup	2.8	2.6	0.61
+ SPS ΔQ = -0.18	2.8	2.1	0.76
+ PS long. stable 3.7e11	3.4	2.6	1.05

UNKNOWNS, RISKS AND ISSUES

The discussion on the performance reach assumes that all of the planned upgrades will work as foreseen. To stretch the performance to approach the HL-LHC requirements, further improvements will be necessary, beyond the present project baseline. There are several risk areas and uncertainties.

For the electron cloud, the mitigation baseline in the SPS is aC coating, but the option of scrubbing (plus high bandwidth damper) is still open. Information is needed in 2012 on the measured and simulated performance reach with scrubbing, for the actual technical stainless steel surfaces in the machine. In addition, the aC coating also has a potential issue with the as-yet unexplained high vacuum pressures seen in the coated regions. In the PS, simulation and measurement are needed to decide whether mitigation is required against ecloud with the LIU beam parameters – mitigation would be complicated, if a solution like chamber coating were needed.

For the SPS, the deployment of the Q20 optics will be required. Deployment of this optics for operation after LS1 would be preferable – there are still a number of issues to solve, including the non-closure of the injection chicane and the rematching of the extraction and transfer lines, as well as the performance with full intensity multibunch beams.

The longitudinal stability in the PS will be the key issue for the injector complex performance with 50 ns. Here the effectiveness of the planned longitudinal feedback system in overcoming the longitudinal coupled bunch instability remains to be demonstrated – and the factor 2 improvement required for the LIU baseline is already very challenging. Pushing beyond this to the HL-LHC requirement will need another 50% compared to today's performance, and this has to be considered as very speculative. The increase of the SPS space charge tune shift to -0.18 is also far from certain, since the baseline value of -0.15 is an assumption based on single bunch measurements rather than the operational experience used for the PSB and PS.

The attainable space charge tune shift in the PS will be another key issue for the complex performance with 25 ns. Here the outlook is rather optimistic, as the bunch length can certainly be increased to 180 ns, and measurements are ongoing to investigate whether ΔQ_y of -0.3 will be possible [17]. A programme of study for 2012 will include probing the space charge limit, working point optimisation and resonance compensation studies.

Another particular concern is the ZS septum in the SPS, which suffers greatly from the high intensity LHC beams. In case the performance in cohabitation cannot be improved, the drastic option of switching off the extraction to the North Area whenever LHC beam is in the SPS will need to be taken.

The re-commissioning of the injector complex after LS2 will be particularly onerous. There will certainly be a large effort and significant time needed to recover the pre-LS2 performance, as there will be essentially three 'new' injectors to start up, together. The PSB will have a new ramp to 2 GeV, probably together with a new H^- injection at 160 MeV, with new RF systems, new instrumentation, and new beam transfer systems. The PS will have a new 2 GeV injection, new longitudinal feedback systems and new instrumentation. The SPS will be newly rebuilt after complete ecloud coating, will have an essentially new main RF system, new high bandwidth feedback, new orbit and loss monitoring systems, and various other devices. The normal startup time of one or two weeks per machine will not be possible – months of beam commissioning must be counted for each machine to recover the pre-LS2 performance. It is expected that it will certainly take the full operational period between LS2 and LS3 for the injectors to reach the baseline LIU goals.

Finally, there will almost certainly arise as-yet unforeseen effects and limitations, either associated with, or independent from, the foreseen upgrades. Clearly there is a risk that these will delay or limit the level of the final performance of the complex.

CONCLUSIONS

For the HL-LHC era, the requirements placed on the LHC machine and the injector complex are very challenging. The LHC will need to make dramatic improvements in current, peak luminosity and efficiency. The injector complex will need to provide 25 ns beams with twice the present intensity in the present emittance, and 50 ns beams with a factor of 2.5 higher intensity and a brightness increase of 50%.

The baseline LIU upgrades do not allow the complex to reach the HL-LHC requirements after LS2, which do not themselves have much margin for relaxation. For the complex to come close to the parameters requested by HL-LHC, all of the planned upgrades will need to be fully effective, and the machines will need to approach single bunch limits with multi-bunch operation. A better than originally assumed control of beam loss and emittance blow up will need to be maintained with these very high brightness beams.

The limitations after the LIU upgrades are in place are expected to be different for the 25 and 50 ns beams. The PSB performance should be adequate for both bunch spacings, but for 25 ns the limitations will be the attainable space charge tune shift in the PS, while for 50 ns space charge in the SPS together with longitudinal beam stability in the PS will be the major issues.

Overall, the HL-LHC requirements are not totally out of reach, although there are many unknowns and many risks. In any event, it is clear that it will take several, if not many, years of operation to hope to exceed the LIU baseline performance and to dream of approaching the specified parameters.

ACKNOWLEDGMENT

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