PROTONS: BASELINE AND ALTERNATIVES, STUDIES PLAN

G. Rumolo, H. Bartosik, T. Bohl, H. Damerau, A. Findlay, R. Garoby, S. Gilardoni, B. Goddard, S. Hancock, K. Hanke, G. Iadarola, M. Meddahi, B. Mikulec, Y. Papaphilippou, E. Shaposhnikova

CERN, Geneva, Switzerland

Abstract

This paper focuses on the injector improvements and upgrades foreseen within the LHC Injectors Upgrade (LIU) project as well as the expected benefits in terms of proton beam characteristics resulting from their implementation. The roadmap of the main upgrades will be illustrated, with special emphasis on the machine studies and milestones during Run 2 that will have an impact on it. In this framework, a strategy to choose between scrubbing and a–C coating of the SPS will be also presented and discussed. Concerning the beams in Run 2, we will not review here the possible physics production beams, which are the subject of [1], but rather some special LIU beams, like: 1) beams needed for electron cloud enhancement and efficient LHC scrubbing (doublets); 2) extra–bright 25 ns beams produced with the pure batch compression scheme; 3) 8b+4e beams, which have the advantage of allowing for higher bunch current while potentially reducing the electron cloud build up. Finally, the beam performances across the full injector chain will be estimated for the operation after Long Shutdown 2 (LS2).

INTRODUCTION

The main goal of the LIU project is to boost the performance of the LHC injectors in order to match the HL-LHC requirements [2]. For this purpose, brightness and intensity of the physics production beams must be increased by:

- Replacing Linac2 with Linac4 and using H^- charge exchange injection into the PSB at 160 MeV;
- Raising the injection energy into the PS from the present 1.4 GeV to 2 GeV;
- Doubling the RF power and mitigating the electron cloud in SPS;
- Putting in place all the other necessary upgrades across PSB, PS and SPS to make them capable of accelerating and manipulating higher intensity beams (e.g., impedance reduction, feedback systems, resonance compensation, improved instrumentation);
- Upgrading the injectors of the ion chain (Linac3, LEIR, PS, SPS) to produce beam parameters at the LHC injection that can meet the post-LS2 luminosity goal [3] compatibly with the achievement of the goals for proton beams in the common injectors.

At the same time, complementary to what is being already put in place within the CONS (consolidation) project [4], LIU also needs to take actions to guarantee the injectors reliable operation and lifetime into the HL-LHC era (i.e. until 2035), such as upgrade or replace all ageing equipment (e.g. power supplies, magnets, RF) and improve radioprotection measures (e.g., shielding, ventilation).

The baseline, and optional items, of the works to be done within the LIU project has been already solidly established, with only a few remaining items for which a final decision still needs to be taken (mainly based on ongoing studies). In terms of timelines, all critical LIU related (both machine and simulation) studies need to be carried out during Run 2 and finished well before the beginning of LS2, in order to provide all the necessary information to take the final decisions and launch the necessary actions. Presently, all key dates to define the pending items have been set no later than end 2015. All LIU hardware modifications and installations will then mainly take place during LS2, although some works could be advanced to the previous Year-End Technical Stops (YETS), whenever this is possible. The final part of the LIU project will include the commissioning of the new LIU beams during Run 3. The LIU goals in terms of beam characteristics are, by definition, new territory. Reaching them will require fine optimization and extensive beam physics and machine development studies in all the accelerators. To achieve the desired performance either technical or beam physics issues might have to be sorted out after LS2 and it could be envisaged to modify the installed equipment over the following YETS periods, if necessary. However, we should also bear in mind that, while the proton beams can be carefully prepared and tuned during Run 3 in order to be ready after Long Shutdown 3 (LS3), the Pb ion beams will need to be already available for physics production by the ion run scheduled at the end of 2020,

This paper will only focus on the protons beams. Before discussing all upgrades planned within the LIU project and the performance reach of the injector complex after their implementation, it is useful to briefly review the operational beam characteristics achieved in 2012. Using the standard production scheme with 72 bunches per PS batch, the injectors delivered the 25 ns beam with $N \approx 1.2 \times 10^{11}$ p/b and transverse emittances of $\varepsilon_n \approx 2.6\,\mu$m for the LHC Scrubbing Run. The successful implementation of the Batch Compression bunch Merging and Splitting (BCMS) scheme [5, 6] in the PS allowed the number of splittings of each PSB bunch to be reduced by a factor two at the expense of reducing the number of bunches per PS batch from 72 to 48. With this scheme a high brightness 25 ns beam with similar intensity per bunch but a transverse emittance $\varepsilon_n \approx 1.4\,\mu$m at SPS extraction was provided to the LHC for the 25 ns pilot physics run. For both beam types, the achievable beam brightness is determined by the multi-turn injection in the PSB and space charge in the PS. The main intensity limitations for the 25 ns beams in the injector complex are due to electron cloud effects and longitudinal instabilities in the SPS. Stable beam conditions with four PS batches and bunch lengths at SPS extraction compatible with injection into the LHC were achieved for a maximum intensity of about $N \approx 1.3\times10^{11}$ p/b, while injecting higher intensity values only resulted in an increase of the losses along the cycle and a visible deterioration of the beam quality at 450 GeV.

All upgrades for the PSB, PS and SPS foreseen by the LIU project as well as the resulting parameter reach for proton beams will be described in the following sections. For the estimation of the achievable beam parameters out of the LHC injectors in the future, it is assumed that emittance growth and losses amount to 5 % in the PSB and in the PS, respectively, and to 10 % in the SPS, as summarized in Table 1. These budgets have been found to be consistent with the optimized performance of LHC beams across the injector chain in 2012 and are thus considered as LIU targets.

Table 1: Beam loss and emittance growth budgets.

Machine	$-\Delta N/N_0$	$\Delta\varepsilon/\varepsilon_0$
PSB injection to extraction	5 %	5 %
PS injection to extraction	5 %	5 %
SPS injection to extraction	10 %	10 %
End-to-end	19 %	21 %

PS COMPLEX

Brightness limitations for 25 ns beams

In the present configuration with Linac2, the LHC beams are produced in the PSB at a constant beam brightness [7], which is mainly determined by the efficiency of the multi-turn injection process and space charge effects in the low energy part of the cycle. Extrapolating from the original target to obtain twice the intensity within the same transverse emittance as today's LHC beams, it is assumed that the connection of Linac4 and the H^- charge exchange injection at 160 MeV will allow doubling the beam brightness out of the PSB for LHC beams [8]. This is illustrated in the limitation diagrams for the standard and the BCMS beam production schemes shown in Fig. 1, where the shaded areas correspond to beam parameters not accessible after the LIU upgrade. Note that the normalized transverse emittance is plotted as a function of the intensity per bunch at LHC injection (450 GeV) including already the budgets for emittance growth and losses through the injector chain as defined in Table 1. Recently, a working group devoted to studies of injection from Linac4 into the PSB has been set up to define via simulations: 1) the future PSB brightness curve, and 2) the intensity reach of future ISOLDE beams. Studies are based on the assumption that Linac4 will be able to provide 40 mA within 0.35 μm rms emittance [9]. Chopping to 650 ns per injected turn will then lower the average beam current injected into the PSB to 26 mA. As a consequence, injection of HL-LHC beams [2] will require about 20 turns, while injecting 100 turns could result into beam intensities of about 1.5×10^{13} p/ring with a few percent loss in the injection process.

In order to mitigate space charge effects on the PS injection plateau with the higher beam brightness available with Linac4, the PSB-PS transfer energy will be increased from the present 1.4 GeV to 2 GeV as part of the baseline LIU PSB and PS upgrades. This will require some important upgrades in the PSB (increase of the magnetic field in the magnets, new main power supply, upgrade of the existing main C02 and C04 RF systems – or their replacement by a Finemet cavity based RF system – redesign of the beam extraction and subsequent transfer) as well as a redesign of the injection into the PS. Based on measurements with single bunch beams [10] and the operational experience with the high brightness 25 ns BCMS beam at 1.4 GeV, a maximum vertical space charge tune shift of $\Delta Q_y \approx -0.31$ on the PS injection plateau can be considered acceptable with respect to blow-up and losses [8]. The corresponding transverse emittance as a function of intensity per LHC bunch for this tune shift is shown in Fig. 1 together with the beam parameters at LHC injection achieved in 2012. The highest beam brightness in the PS achievable with the 2 GeV upgrade is then estimated assuming the maximum bunch length compatible with the PSB recombination kicker rise time, i.e. $\tau = 205$ ns for the standard production scheme (6 PSB bunches injected on harmonic number $h=7$ in the PS) and $\tau = 135$ ns for the BCMS beams (8 PSB bunches injected on $h = 9$), and the largest longitudinal emittance compatible with the RF gymnastics. Note that after the implementation of the LIU upgrades, i.e. the connection of Linac4 and the 2 GeV PSB-PS transfer, the PS complex is expected routinely to deliver 25 ns beams with twice higher brightness as compared to the present performance.

Intensity limitations for 25 ns beams

Considering the operational experience with other high intensity beams, no intensity limitations from coherent beam instabilities are to be expected in the PSB within the parameter range of interest for HL-LHC.

In the PS, longitudinal coupled-bunch instabilities during acceleration and at flat top presently limit the intensity of LHC beams to about $N \approx 2.0\times10^{11}$ p/b at extraction. Furthermore, transient beam loading induces asymmetries of the various bunch splittings and thus a bunch-to-bunch intensity variation along the bunch train. However, within

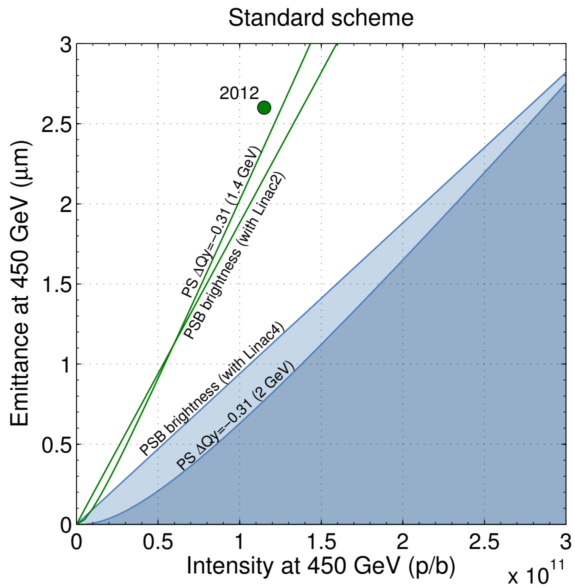

Figure 1: Beam brightness limitations in the PS complex for the standard 25 ns beam production scheme (left) and the 25 ns BCMS scheme (right) after the LIU upgrades (blue curves) and at present (green curves) together with the beam performance achieved in 2012 (green dots).

the LIU project a new coupled-bunch feedback system with a dedicated wide-band Finemet cavity as a kicker and new 1-turn delay feedback boards for beam loading compensation on the main 10 MHz RF system have been installed during LS1 and are ready for testing during Run 2. They are expected to push the intensity limit to values around $N = 3.0 \times 10^{11}$ p/b, i.e. well beyond the requirement for the 25 ns HL-LHC beam.

Various instabilities in the transverse plane can be observed with LHC beams in the PS. Horizontal head-tail instabilities are encountered at flat bottom [11], which are presently cured by introducing linear coupling between the transverse planes and operating close to the coupling resonance. It was demonstrated in Machine Development (MD) studies that these head-tail instabilities at 1.4 GeV can be suppressed also by the PS transverse feedback system commissioned in 2012 [12], which has the advantage of providing additional flexibility for optimizing the machine working point for the space charge dominated LHC beams. The power amplifiers of this feedback have been upgraded in the frame of the LIU project in preparation for the future injection at 2 GeV. Another important use of the transverse feedback that has recently emerged is its potential capability of kicking out one out of 21 bunches at low energy after triple splitting (obtained from a 4+3 bunch injection from the PSB) in order to produce trains of 80 bunches instead of the usual 72 [13].

The fast vertical instability observed in the PS during transition crossing with high intensity (TOF-like) beams is not expected to be a limitation for the HL-LHC beams [14]. However, a similar instability discovered recently with single bunch beams of small longitudinal emittance needs to be analyzed further in future MD studies, as it could not be cured with the aforementioned PS transverse feedback system due to its limited bandwidth [12].

After the final bunch splittings at the PS top energy resulting in the 25 ns bunch spacing, an electron cloud develops during the bunch shortening and bunch rotation before extraction to the SPS [15]. Nevertheless, no beam degradation has been observed so far in operational conditions as the time of interaction between the beam and the electron cloud is restricted to a few tens of milliseconds. It was observed in dedicated MD studies that the electron cloud drives a horizontal coupled bunch instability if the 25 ns beam is stored at top energy [16]. The onset time of this instability could be efficiently delayed by the PS transverse feedback system [12]. The electron cloud is therefore not likely to become a limitation for the HL-LHC beams. Nevertheless, future machine studies with HL-LHC-like bunch intensities (hopefully available thanks to the new wide-band longitudinal feedback system) will be conducted during Run 2 to measure the possible beam degradation driven by electron cloud in that parameter range.

SPS

The main challenges for future high intensity 25 ns LHC beams in the SPS are instabilities in the transverse and longitudinal planes, beam loading and RF power, electron cloud and space charge effects on the long injection plateau. Since the end of 2010, extensive machine studies have been performed with a low gamma transition optics. In comparison to the Q26 optics used in the past, which has 26 as the integer part of the betatron tunes and a gamma transition of $\gamma_t = 22.8$, the working point is lowered by 6 integer units in both planes in the Q20 optics [17] such that the transition energy is reduced to $\gamma_t = 18$. Consequently, the phase slip factor $\eta \equiv 1/\gamma_t^2 - 1/\gamma^2$ is increased throughout the acceleration cycle with the largest relative gain of a factor 3 at injection energy. As the intensity thresholds for all instabilities observed in the SPS scale with the slip factor η, a significant improvement of beam stability is achieved with the Q20 optics as discussed in more detail below. The Q20 optics is being used successfully in routine operation for LHC filling since September 2012 [18] and will be the default machine configuration for LHC beams in the SPS in the future.

Transverse plane

The vertical single bunch Transverse Mode Coupling Instability (TMCI) at injection was identified as one of the main intensity limitations in the Q26 optics. For bunches injected with the nominal longitudinal emittance $\varepsilon_l = 0.35$ eVs, the corresponding instability threshold is around $N_{th} \approx 1.6 \times 10^{11}$ p/b (with vertical chromaticity close to zero) [19]. The instability manifests itself through emittance blow-up and fast losses. Slightly higher intensities can be reached when increasing the chromaticity, however at the expense of enhanced incoherent emittance growth and losses on the flat bottom. Analytical models based on a broadband impedance predict that the instability threshold with zero chromaticity scales like $N_{th} \propto |\eta|\varepsilon_l/\beta_y$ [20], where β_y denotes the vertical beta function averaged over the locations of the impedance source. Thus, the instability threshold can be raised by injecting bunches with larger longitudinal emittance. However, the beam transmission between PS and SPS is degrading for larger longitudinal emittances, unless an additional 40 (or 80) MHz cavity is installed in the PS for improving the bunch shape at extraction [21] (which will be studied in MDs during Run 2). On the other hand, a significant increase of the instability threshold is expected in the Q20 optics even with the nominal longitudinal emittance, since the product of the slip factor and the vertical beta function at important impedance sources ($\eta\,\beta_y$) is about 2.5 times higher compared to the Q26 optics. An extensive measurement campaign with high intensity single bunch beams has confirmed this expectation. The instability threshold in the Q20 optics for chromaticity close to zero and nominal longitudinal emittance was found at around $N_{th} \approx 4.5 \times 10^{11}$ p/b in excellent agreement with numerical simulations using the latest SPS impedance model [22, 23]. With the Q20 optics the TMCI is not of concern for the beam parameters envisaged by the HL-LHC, even for the 50 ns "back-up" scenario [24], which requires significantly higher intensities per bunch compared to the 25 ns beams. However, the factor two margin in terms of bunch intensity with respect to the HL-LHC target value provided by the Q20 optics can be partly traded off choosing an intermediate γ_t optics (e.g. Q22), which can still provide enough stability against TMCI to fulfil the HL-LHC target, but puts less constraint on the required voltage at extraction. This will be briefly addressed in the next subsection, and is discussed in detail in [13].

To determine the brightness that can be swallowed by the SPS, a working point scan was performed with the Q20 optics using a beam with a large estimated vertical tune spread (about $\Delta Q_y = -0.20$). The goal was to check experimentally how much space in the tune diagram is needed to accommodate the incoherent space charge tune spread and thus to minimize emittance blow-up on the long injection plateau. The results of this MD are described in detail in [25]. Based on these results and considering the budgets for emittance blow-up and losses defined in Table 1, which permit slightly larger blow-up in the SPS than observed in the measurements, the presently maximum acceptable space charge tune shift in the SPS for an optimized working point is set to $\Delta Q_y = -0.21$.

Longitudinal instabilities and RF power

The longitudinal instabilities observed with LHC beams in the SPS are a combination of single bunch and coupled bunch effects [26]. The beam is stabilized in routine operation by increasing the synchrotron frequency spread using the 4th harmonic (800 MHz) RF system in bunch-shortening mode in combination with controlled longitudinal emittance blow-up along the ramp, which is performed with band-limited phase noise in the main 200 MHz RF system.

For a given longitudinal emittance and matched RF voltage the thresholds of the longitudinal coupled bunch instability and the single bunch instability due to loss of Landau damping scale proportional to the slip factor η [27]. Improved longitudinal beam stability was therefore observed in measurements with the Q20 optics at injection and during the ramp [28], where sufficient RF voltage is available to restore the same bucket area as with the Q26 optics. In fact, the Q20 optics provides significant margin for increasing the beam intensity at injection energy, where the attainable longitudinal emittance is limited by capture losses and the transfer efficiency between the PS and SPS. The situation is different at flat top. The maximum voltage is applied in both optics in order to shorten the bunches for the transfer into the 400 MHz buckets of the LHC. Better beam stability would still be achieved in the Q20 optics for a given longitudinal emittance, however, in this case the bunches would be longer. In order to have the same bunch length in the two optics, the longitudinal emittance has to be smaller in the Q20 optics. From the scaling of the instability threshold for loss of Landau damping (LD) [27] it follows that the same beam stability is obtained in both optics for the same bunch length at extraction.

At the end of 2012, a series of MD sessions were devoted to the study of high intensity 25 ns beams in the Q20 optics. The larger longitudinal emittance of beams with $N > 1.2 \times 10^{11}$ p/b already at injection and the controlled longitudinal emittance blow-up in the SPS required for their stabilization result in an average bunch length at extraction close to the limit $\tau \approx 1.7$ ns, acceptable for transfer into LHC. Presently, $N \approx 1.35 \times 10^{11}$ p/b is considered to be the maximum intensity reachable with the current RF system in the SPS that can be stably accelerated and extracted with bunch lengths within specification. Using the scaling law for single bunch instability due to loss of Landau damping, the RF voltage needs to be increased proportionally to the intensity to keep the bunch length constant [29].

The 200 MHz main RF system of the SPS consists of four travelling wave cavities, of which two are made of four sections and the other two are made of five sections [30]. The maximum RF power presently available in continuous mode is about 0.75 MW per cavity, which corresponds to a maximum total RF voltage of about 7.5 MV at nominal intensity of the 25 ns beam. However, less RF voltage is available for higher beam intensity due to the effect of beam loading and the limited RF power [31]. This voltage reduction is larger for longer cavities, i.e., it is increasing with the number of cavity sections. The LIU baseline upgrades for the SPS include an upgrade of the low-level RF and a major upgrade of the 200 MHz RF system [32]. Upgrading the low-level RF alone will allow pulsing the RF amplifiers with the revolution frequency (the LHC beam occupies less than a half of the SPS circumference), leading to an increase of the peak RF power up to about 1.05 MW per cavity. Furthermore, the LIU upgrade foresees the rearrangement of the four existing cavities and two spare sections into two 4-section cavities and four 3-section cavities, and the construction of two additional power plants providing 1.6 MW each. This will entail a reduction of the beam loading per cavity, an increase of the available RF voltage and a reduction of the beam coupling impedance (its peak value at the fundamental frequency).

Figure 2 shows the maximum total RF voltage of the SPS 200 MHz system as a function of the beam current with and without the RF upgrades. The RF voltage required for keeping the bunch length constant with increasing intensity taking into account the compensation of potential well distortion (PWD) and the required longitudinal emittance blow-up for stabilizing the beam against the single bunch instability (loss of Landau damping) is indicated in the same graph. The presently maximum achieved intensity of $N \approx 1.35 \times 10^{11}$ p/b (corresponding to 1.7 A beam current) together with the corresponding maximum RF voltage of 7 MV serves as reference point. It follows that a maximum beam current of 1.9 A will be in reach after the low-level upgrade (4 times 1.05 MW pulsed) and 2.7 A after the full RF upgrade (cavities rearranged into six with 4×1.05 MW and 2×1.6 MW) [29]. These values correspond to maximum intensities at extraction of about $N \approx 1.45 \times 10^{11}$ p/b and $N \approx 2.0 \times 10^{11}$ p/b, respectively, when taking into account 3% intensity reduction due to scraping before extraction for cleaning transverse beam tails. However, it should be emphasized that this estimation is based on simplified scaling laws and that slightly longer bunches, if accepted by the LHC, are significantly more stable ($\sim \tau^5$).

If the major impedance source determining the red line in the above plot is found and mitigated, the slope of the line could be reduced and, therefore, the intensity reach of the 25 ns beams at SPS extraction could be significantly extended and cover the HL-LHC range (see, for example, green line in Fig. 2). In 2013-14, two dedicated studies were conducted in parallel, aiming at identifying the cause of the longitudinal instabilities: on one hand, the longitudinal impedance model of the SPS was progressively refined adding the contributions of all vacuum flanges and other elements, while, on the other hand, the impedance measurement data from the 2012-13 machine development sessions were fitted with macroparticle simulations based on the updated impedance model. The main result of these studies seemed to point to the impedance of the vacuum flanges as responsible for halving the value of the intensity threshold for longitudinal instabilities. Reducing, or even suppressing, this source of impedance by means of shielding or redesigning of the flanges would be a possible key to accessing larger beam currents out of the SPS [33]. If the finding is confirmed and the related mitigating action is clearly identified and endorsed by LIU by end 2015 (in order to be able to prepare for LS2), this would become a major extra activity to be added to the baseline with its time requirements and additional budget implications.

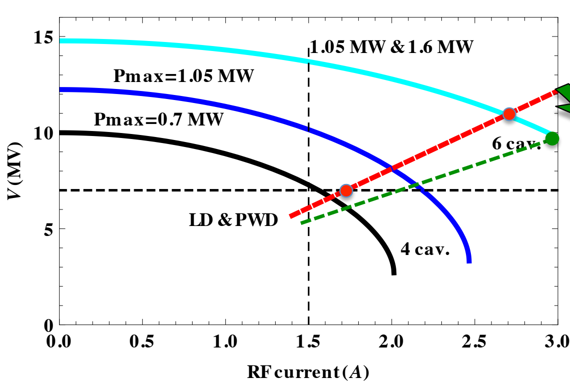

Figure 2: Maximum total RF voltage as a function of the beam current for different cases: present situation (black line), after the low-level RF upgrade to operate in pulsed mode (blue line) and after the cavity rearrangement and the construction of two additional power plants of 1.6 MW each (light blue line). The voltage required to maintain constant bunch length at extraction taking into account the single bunch longitudinal instability and the voltage reduction due to potential well distortion is also shown as a red line together with the present and future points (red dots). A possible line after impedance reduction is also shown (green) together with the achievable point (green dot).

Electron cloud

The electron cloud effect has been identified as a possible performance limitation for the SPS since LHC type beams with 25 ns spacing were injected into the machine for the first time in the early years of 2000. At that time a severe pressure rise was observed all around the machine together with transverse beam instabilities, significant losses and emittance blow-up on the trailing bunches of the train [34]. Since 2002, Scrubbing Runs with 25 ns beams were carried out almost every year of operation in order to condition the inner surfaces of the vacuum chambers and therefore mitigate the electron cloud. This allowed achieving a good conditioning state of the SPS up to 2012, both in terms of dynamic pressure rise and beam quality. During the Scrubbing Run of the LHC at the end of 2012, the 25 ns beam was regularly extracted from the SPS Q20 optics with four batches of 72 bunches with $N \approx 1.2 \times 10^{11}$ p/b and normalized transverse emittances of about 2.6 μm [18]. Extensive machine studies showed that for this beam intensity the 2012 conditioning state of the SPS was sufficient to suppress any possible beam degradation due to electron cloud on the cycle timescale [35].

Further experiments performed with the Q20 optics showed that it was possible to inject the full train of the 25 ns beam with up to $N \approx 1.35 \times 10^{11}$ p/b without transverse emittance blow-up and preserve the beam quality up to extraction energy, as shown in Fig. 3 (top). For higher intensities ($N \approx 1.45 \times 10^{11}$ p/b injected) a transverse instability was observed after the injection of the third and the fourth batch, leading to emittance blow up as shown in Fig. 3 (bottom) and particle losses on the trailing bunches of the injected trains. The observed pattern on the bunch-by-bunch emittance is typical of electron cloud effects. Since the SPS was never scrubbed with such high beam intensities, an additional scrubbing step might be required for suppressing these effects.

Several studies have been devoted in 2012 to the optimization of the scrubbing process and in particular to the definition and test of a possible "scrubbing beam", i.e., a beam able to produce a higher electron cloud density in the beam chambers and, therefore, a higher scrubbing efficiency compared to the standard LHC type 25 ns beam. A 25 ns spaced train of "doublets", each of which consisting of two 5 ns spaced bunches, has been proposed [36]. As shown in simulations, this beam has indeed a lower multipacting threshold compared to the standard 25 ns beam due to the shorter empty gap between subsequent doublets, which enhances the accumulation of electrons in the vacuum chamber. For producing this beam with the existing RF systems of the injectors, long bunches from the PS ($\tau \approx 10$ ns full length) have to be injected into the SPS on the unstable phase of the 200 MHz RF system and captured in two neighboring buckets by raising the voltage within the first few milliseconds. Very good capture efficiency (above 90%) could be achieved in machine studies for intensities up to 1.7×10^{11} p/doublet.

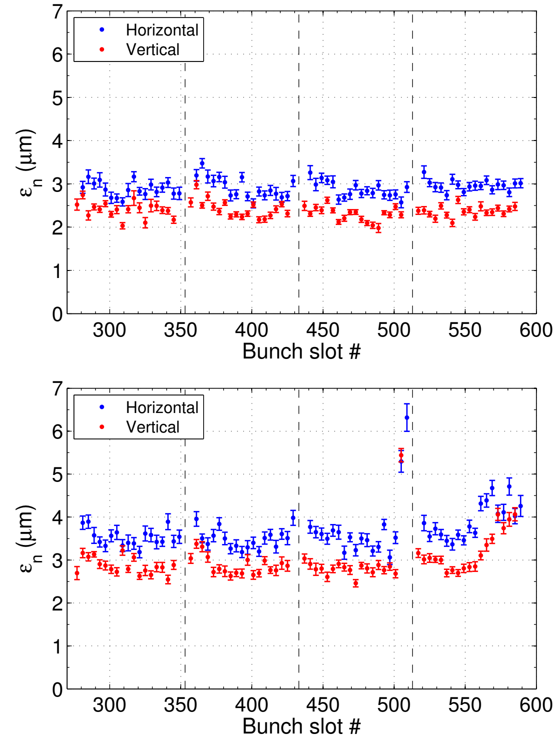

Figure 3: Bunch by bunch emittances measured at the SPS flat top for 4×72 bunches of the 25 ns LHC beam with intensities at injection of $N \approx 1.35 \times 10^{11}$ p/b (top) and $N \approx 1.45 \times 10^{11}$ p/b (bottom).

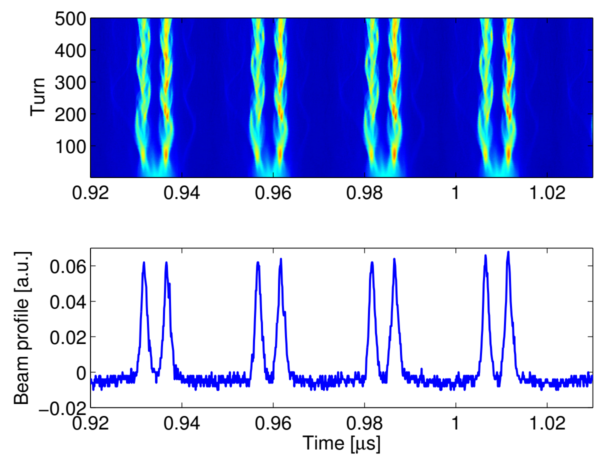

Figure 4: Evolution of the longitudinal beam profile in the SPS during the splitting at injection for the production of the doublet beam (top) and longitudinal bunch profiles of the doublet beam measured 1 s after injection (bottom).

Figure 4 (top) shows the evolution of the longitudinal profile of the beam during the "splitting" right after the injection in the SPS. Figure 4 (bottom) shows the "final" beam profile, measured one second after injection. It was also verified that it is possible to rapidly lower the RF voltage and inject a second train from the PS without any im-

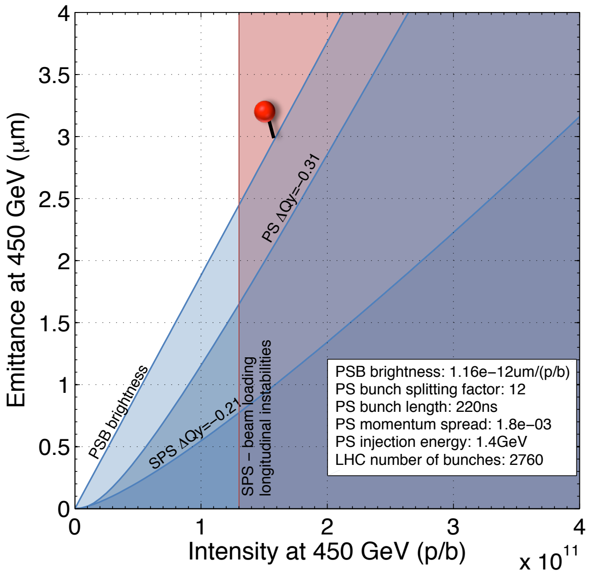

Figure 5: Limitation diagram for the doublet beam

portant degradation of the circulating beam. Observations on the dynamic pressure rise in the SPS arcs confirmed the enhancement of the electron cloud activity as expected from simulations. The enhancement was also observed with the dedicated SPS strip detectors.

Although successfully produced at 26 GeV/c in the SPS, this beam was never accelerated during the 2012-13 tests. In order to permit acceleration of intensities larger than 1.3×10^{11} p/(25 ns slot), it is planned to accelerate the doublet beam on a slower ramp (possibly up to three times slower), which will require dedicated machine time for setting up and development. The achievable quality at 450 GeV/c is widely unknown, as slow acceleration, longitudinal instability and, not least, the effects from the enhanced electron cloud could contribute to beam degradation. However, the best achievable parameters for the doublet beam at SPS top energy can be found from the post-LS1 limitation diagram for LHC beams, as discussed in [8]. Figure 5 shows the desired point for the doublet beam placed in the plane intensity – emittance, in which the areas corresponding to regions in the parameter space not accessible in standard operational conditions, due to brightness or intensity limitations in the different accelerators, have been shaded. The point lies in the "forbidden" zone due to its high intensity (however considered achievable thanks to the slow ramp, as discussed above) and is expected to be produced with transverse emittances of at best 3 μm, but very likely above this value due to reasons already mentioned.

A high bandwidth (intra-bunch) transverse feedback system is being developed for the SPS as part of the LIU project in collaboration with the LHC Accelerator Research Program (LARP), with the goal of fighting electron cloud instabilities and improving the beam quality during the scrubbing for making it more efficient. In 2013, experimental studies with prototype hardware already demonstrated the successful suppression of slow headtail instabilities of mode 0 (dipole mode) with single bunches. Further studies with improved hardware will follow in 2014 and 2015.

In case scrubbing is not sufficient for suppressing the electron cloud effect with the high beam intensity and small transverse emittance required for HL-LHC, or in case the reconditioning process is very slow after large parts of the machine are vented (like during a long shutdown), the inner surface of the SPS vacuum chambers has to be coated with a low Secondary Electron Yield (SEY) material. The solution developed at CERN is to produce a thin film of amorphous Carbon (a-C) using DC Hollow Cathode sputtering directly inside the vacuum chamber [37]. The suppression of electron cloud in coated prototype vacuum chambers has been fully validated with beam in the SPS [35]. An additional four SPS half cells (including quadrupoles) have been coated with a-C during LS1 for further testing in Run 2.

The coating of the entire machine circumference of the SPS with a-C is a major task, which requires careful preparation and planning of resources (as all magnets need to be transported to a workshop). The decision whether the SPS needs to be coated or scrubbing alone can guarantee enough electron cloud mitigation has therefore to be taken not later than mid-2015. After the long shutdown, a Scrubbing Run of one week plus three days will take place by the end of 2014 with the goal of recovering the operational performance, as it is expected that the good conditioning state of the SPS will be degraded due to the long period without beam operation and the related interventions on the machine. Another Scrubbing Run, split into two weeks, will be performed in the first half of 2015 in order to scrub the machine for high intensity 25 ns beams. After collecting all the additional experience from post-LS1 operation and the important information from the extensive experimental scrubbing and high intensity studies with 25 ns beams (and doublets), the final choice between coating and scrubbing will be made in mid-2015.

SPECIAL BEAMS

Both to increase the accessible area in the beam parameter space and to create beams that could be useful for future MD studies and/or physics operation, new beams with alternative filling patterns are planned to be produced in MDs during Run 2. Two examples, for which we will briefly review here the parameter reach, are the Pure Batch Compression (PBC) scheme and the 8b+4e scheme.

The PBC scheme is based on the direct compression in the PS of an eight bunch train – injected in two consecutive batches from the PSB – from $h = 9$ into $h = 21$ at 2.5 GeV, and eventually the application of two subsequent double splittings at 26 GeV/c. The result of this gymnastics is a train of 32 bunches for the SPS (instead of the nominal 72, which translates into a decrease by 11% of the number

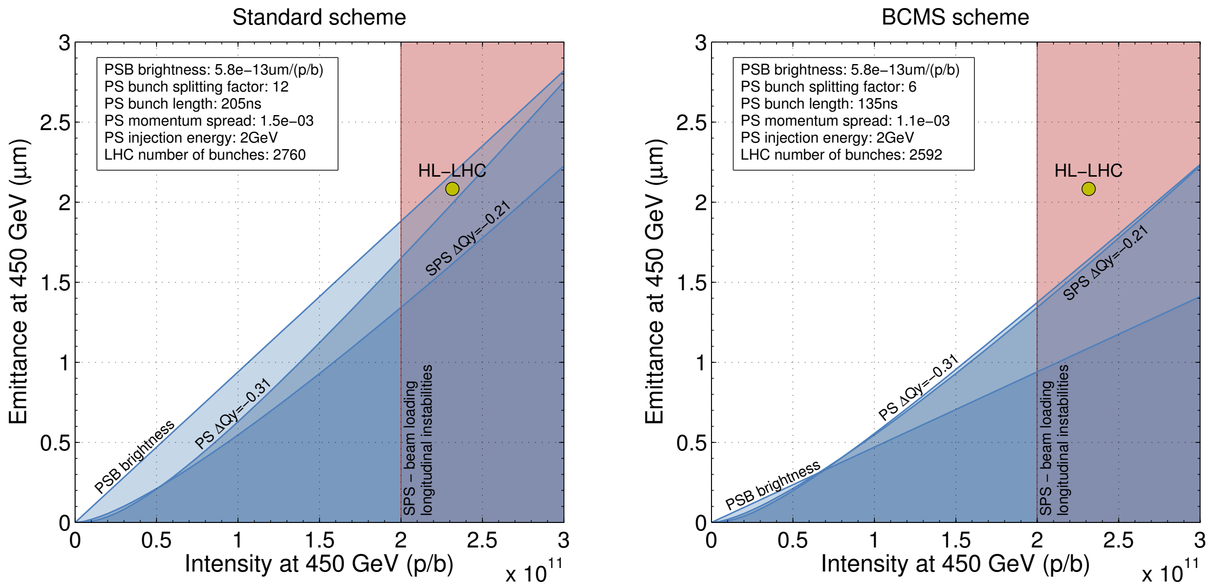

Figure 6: Limitation diagrams for 25 ns beams produced with the standard scheme (left) and the BCMS scheme (right) after implementation of the LIU upgrades.

of bunches in LHC). These bunches can be, however, very bright, as they could potentially pack $N = 1.3 \times 10^{11}$ p/b within $\varepsilon_n \approx 0.9\,\mu$m at the SPS extraction. These beams could be interesting to study transport of sub-μm emittance beams through the LHC injector chain (still widely unexplored) as well as to conduct advanced space charge studies in the SPS (especially in their 50 ns variant, which is based on only one double splitting at the flat top in the PS and can result in even brighter bunches).

The 8b+4e scheme is basically the same as the standard production scheme, but uses 7 bunches (instead of 6) from the PSB injected into $h = 7$ and then converts the first triple splitting from $h = 7$ to $h = 21$ into a double splitting with an empty bucket. By doing that, the train obtained at 26 GeV/c after the two double splittings will be made of 7 sequences of 8 bunches and 4 empty gaps (hence the name 8b+4e). Since both beam loading and longitudinal instabilities in the SPS could be somewhat relaxed by the batch structure with micro-trains shorter than the RF cavity filling time, the intensity reach of this beam should be almost 50% larger than the standard 25 ns beam. This means that $N = 1.8 \times 10^{11}$ p/b can be obtained within a transverse emittance slightly lower than the standard 25 ns beam, $\varepsilon_n \approx 2.3\,\mu$m. The interest in this beam lies in that it could be envisaged as a future candidate for luminosity production in LHC, as it might relax electron cloud formation in the arc dipoles (having a significantly higher multipacting threshold) and can pack higher bunch current. Because of the filling pattern however, it will result in a lower number of bunches in LHC (about 1900). It is worth mentioning, finally, that the 8b+4e beam can also be produced in its BCMS variant. In this case, it is necessary to suppress bunch merging and subsequent triple splitting and end up with pairs of bunches separated by an empty bucket at 2.5 GeV. In this case, only 4 sequences of 8 bunches and 4 empty gaps can be sent to the SPS, but the transverse emittance achievable for $N = 1.8 \times 10^{11}$ p/b would be as low as $\varepsilon_n \approx 1.4\,\mu$m.

INJECTORS PERFORMANCE REACH

The expected performance reach of the entire LHC injector chain after implementation of the LIU upgrades is shown in Fig. 6 for the standard and the BCMS scheme. The beam parameters are given at LHC injection taking into account the emittance growth and loss budgets from Table 1. The best beam parameters correspond to an intensity of $N = 2.0 \times 10^{11}$ p/b (limited by longitudinal instabilities and RF power in the SPS) within transverse emittances of $\varepsilon_n = 1.9\,\mu$m for the standard scheme (limited by the PSB brightness). Although the bunch intensity is about 15% lower than the value requested by HL-LHC, the target brightness is found to be achievable. If methods to extend the intensity reach of the SPS are successfully implemented (e.g. impedance reduction, slow ramp and bunch rotation or intermediate optics, [33]), the HL-LHC parameter values can be achieved. Alternatively, the missing intensity could be compensated by a larger brightness. The BCMS beam, with $N = 2.0 \times 10^{11}$ p/b within $\varepsilon_n = 1.4\,\mu$m (limited by space charge in the PS and SPS) as displayed in Fig. 6, right plot, has this potential. However, high brightness beams also come with larger IntraBeam Scattering (IBS) rates and fewer bunches (5%) in the LHC, are less effectively stabilized by the octupoles, if necessary, and can be a challenge for the emittance measurement devices. Besides, they hold a high damage risk for protection devices in SPS, transfer lines and LHC [38]. A complete overview on the beam

Table 2: Achievable beam parameters after implementation of LIU upgrades in comparison with HL-LHC request.

PSB								
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU	Standard	29.55	1.55	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.55, 0.66)
	BCMS	14.77	1.13	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.35, 0.44)
HL-LHC		34.21	1.72	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.58, 0.69)

PS (double injection)								
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU	Standard	28.07	1.63	2.0	3.00	205	$1.5 \cdot 10^{-3}$	(0.16, 0.28)
	BCMS	14.04	1.19	2.0	1.48	135	$1.1 \cdot 10^{-3}$	(0.19, 0.31)
HL-LHC		32.50	1.80	2.0	3.00	205	$1.5 \cdot 10^{-3}$	(0.18, 0.30)

SPS (several injections)								
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU	Standard	2.22	1.71	26	0.37	3.0	$1.5 \cdot 10^{-3}$	(0.09, 0.16)
	BCMS	2.22	1.25	26	0.37	3.0	$1.5 \cdot 10^{-3}$	(0.12, 0.21)
HL-LHC		2.57	1.89	26	0.37	3.0	$1.5 \cdot 10^{-3}$	(0.10, 0.17)

LHC							
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	bunches/train
LIU	Standard	2.00	1.88	450	0.60	1.65	72
	BCMS	2.00	1.37	450	0.60	1.65	48
HL-LHC		2.32	2.08	450	0.65	1.65	72

parameters throughout the LHC injector chain is given in Table 2.

SUMMARY AND CONCLUSIONS

The connection of Linac4 is anticipated to double the beam brightness out of the PSB compared to the present operation, thanks to the H^- charge exchange injection and the higher injection energy of 160 MeV. Raising the PS injection energy to 2 GeV will mitigate space charge effects on the injection plateau and match the performance of the PS to the higher brightness available with Linac4. The upgrades of the transverse and longitudinal feedbacks in the PS together with the RF upgrades will push present intensity limits beyond the requirements for HL-HLC. With the SPS Q20 optics the TMCI at injection is not an issue. The major SPS RF upgrade with two new power plants and rearranged RF cavities will push the achievable intensity from the present $N = 1.3{\times}10^{11}$ p/b to $N = 2.0{\times}10^{11}$ p/b. The possibility to extend this intensity limit depends on the success in reducing the main sources of longitudinal impedance, presently identified in the vacuum flanges. Alternatively, the use of of a slower acceleration rate combined with bunch rotation before extraction (or intermediate gamma transition optics or a 200 MHz RF system installed in LHC for capture) might also serve the purpose. Additional studies and a definition of the action planning and cost estimates are needed to decide whether an impedance reduction strategy should eventually be pursued. The other point on which the future SPS performance critically depends is electron cloud mitigation. The decision if the SPS vacuum chambers all around the machine will be coated with a-C in order to completely suppress the electron cloud will be taken in mid 2015 based on the experience and experimental studies from two Scrubbing Runs to be performed in 2014 and 2015. The main questions to be addressed are whether 1) scrubbing (for example with the doublet scrubbing beam), instead of coating, can be proved to be a viable path for recovering the operational performance after a long shutdown, and 2) scrubbing can suppress the electron cloud also for the future high intensity beams.

The overall performance of the LHC injectors after the implementation of all baseline LIU upgrades, i.e. an intensity of $N = 2.0 \times 10^{11}$ p/b and a transverse emittance of $\varepsilon_n = 1.9\,\mu$m for the 25 ns beam with 72 bunches per PS batch (standard scheme), nearly matches the parameters needed by HL-LHC with the presently assumed pile-up limit and machine physics efficiency. The possible use of BCMS beams in the future, which, in spite of the lower number of bunches, could compensate with a larger brightness the 15% lower intensity given by the SPS, may be hindered by its high damage potential for protection devices. For achieving the anticipated performance, all upgrades must be effective, including those not explicitly mentioned in this paper but important for overcoming operational limitations or assuring reliability of the complex. Finally, a very dense program of machine and simulation studies has been established until end of 2015 in order to further improve our parameter estimates and steer decisions on the few remaining pending items.

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