PERFORMANCE POTENTIAL OF THE INJECTORS AFTER LS1

H. Bartosik, C. Carli, H. Damerau*, R. Garoby, S. Gilardoni, B. Goddard, S. Hancock, K. Hanke, A. Lombardi, B. Mikulec, V. Raginel, G. Rumolo, E. Shaposhnikova, M. Vretenar, CERN, Geneva, Switzerland

Abstract

The main upgrades of the injector chain in the framework of the LIU Project will only be implemented in the second long shutdown (LS2), in particular the increase of the PSB-PS transfer energy to 2 GeV or the implementation of cures/solutions against instabilities/e-cloud effects etc. in the SPS. On the other hand, Linac4 will become available by the end of 2014. Until the end of 2015 it may replace Linac2 at short notice, taking 50 MeV protons into the PSB via the existing injection system but with reduced performance. Afterwards, the H^- injection equipment will be ready and Linac4 could be connected for 160 MeV H^- injection into the PSB during a prolonged winter shutdown before LS2. The anticipated beam performance of the LHC injectors after LS1 in these different cases is presented. Space charge on the PS flat-bottom will remain a limitation because the PSB-PS transfer energy will stay at 1.4 GeV. As a mitigation measure new RF manipulations are presented which can improve brightness for 25 ns bunch spacing, allowing for more than nominal luminosity in the LHC.

INTRODUCTION

The performance reach of the LHC depends on the beam parameters, respectively the beam brightness from its injectors. To overcome today's limitations of the injector chain, a significant upgrade program, the LHC Injectors Upgrade (LIU) Project, has been launched at the end of 2010 [1]. All major upgrades of the injector complex, including the replacement of the proton injector Linac2 by Linac4 [2], a new PSB injection for H^-, the increase of the PSB-PS transfer energy from 1.4 GeV to 2 GeV [3], as well as a major RF upgrade and coating of the beam pipe to suppress electron clouds in the SPS, are coordinated within the LIU Project. These upgrades will however only be ready for implementation during the second long shutdown (LS2) in 2018. According to the present baseline planning, Linac4 will become available by the end of 2014 and the equipment for the new H^- injection into the PSB will be ready for installation at the end of 2015.

LINAC AND PSB PERFORMANCE

Linac4 connection to the PSB

Assuming that Linac4 will be fully commissioned and will have successfully completed its reliability run by the third quarter of 2015, two main options for the connection to the PSB could be pursued [2]. Firstly, as the present baseline scenario, Linac4 could be connected to the PSB with H^- at 160 MeV during LS2 in 2018/2019. Unfortunately, this implies that the new Linac will remain unused for about three years and must be kept in stand-by during this period. Secondly, the connection of Linac4 could be advanced to an intermediate stretched winter shutdown, so-called LS1.5 [4]. This option would imply about 7 (+1) months without protons from the injectors (the first month of PSB cool-down could be in the shadow of an ion run in LHC).

A third, emergency option only becomes interesting in case of a major unrepairable failure of the aging Linac2. In the case of such an unlikely event, Linac4 could be operated as a 50 MeV proton accelerator. The existing proton injection could then be used to transfer the beam into the PSB. After less than two months, protons could be delivered by the injectors, but with reduced performance. It is important to point out that the emergency connection of Linac4 with protons does not save any installation or commissioning time later, when switching to H^- at 160 MeV, as the duration is dominated by the installation of the PSB H^- injection elements.

Performance of Linac2/PSB

The brightness of the PSB with Linac2 delivering protons at 50 MeV for LHC-type beams has been explored during the 2011 run (Fig. 1). The average transverse emittance increases approximately linearly with the intensity per bunch at extraction. At equal intensity, the transverse emittance of the best performing ring 3 is about 17 % below the emittance of ring 1, shown in Fig. 1. Further investigations during the 2012 run will focus on these differences between rings.

Connection of Linac4 with protons or H^-

In case of an unrepairable fault of Linac2, Linac4 could replace it delivering 50 MeV protons after less than two months of modification, which would include

- converting the ion source from H^- to protons,
- detuning of all RF structures above 50 MeV,
- turning a bending magnet (BHZ20, which selects between proton beam from Linac2 or Linac4) towards the transfer line from Linac4,

* heiko.damerau@cern.ch

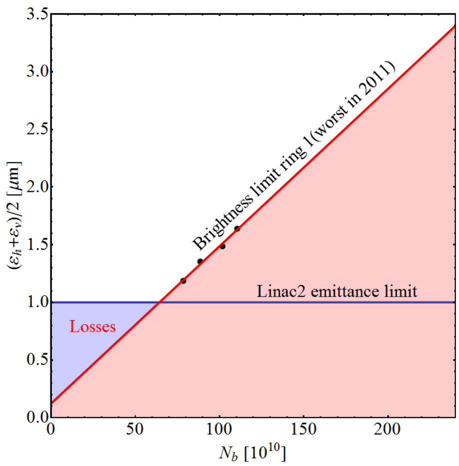

Figure 1: Average emittance versus intensity per bunch of the worst PSB ring 1 [5]. The lossy region (shaded in purple) of very small transverse emittances below 1 μm only becomes accessible by controlled transverse shaving after injection in the PSB. With Linac4 the slope of the brightness limit line will be halved. Emittances are quoted as 1σ normalized.

- closing the vacuum,
- commissioning of the transfer line from Linac4 to BHZ20 and re-commissioning up to PSB injection.

Table 1: Comparison of Linac2 and Linac4 with protons.

	Linac2	**Linac4**
Kinetic energy at exit	50 MeV	
Pulse current	160 mA	40 mA
Transverse emittance	1 μm	0.4 μm
Maximum beam pulse length	100 μs	400 μs
Bunch frequency	202.56 MHz	352.2 MHz
Relative brightness	1	0.625

Table 1 compares the beam parameters of Linac2 and Linac4, assuming that the achievable current in Linac4 will be the same for protons and H^-. The peak current in Linac4 is mainly limited by space charge at low energy and RF beam loading, but the beam pulses can be longer than in Linac2. The new charge-exchange injection into the PSB will allow for these longer beam pulses to be injected (up to 100 turns/ring at 160 MeV compared to the present 15 turns/ring at 50 MeV) and painted within small emittances, limited by space charge in the PSB.With proton injection betatron stacking has to be used so that the maximum pulse length remains limited by PSB acceptance and distributor pulse length (100 μs).

Simulation studies have been performed to compare the brightness of proton beams from Linac2 and Linac4 after injection into the PSB [6]. They indicate that only 75 % of today's brightness for LHC-type beams could be reached with protons from Linac4, which would translate (brightness times bunch intensity) into about half the luminosity in the LHC.

The connection of Linac4 with H^- at 160 MeV could either take place early during a prolonged winter stop (LS1.5) or during LS2. An early connection would allow commissioning of the PSB injection separately from the extra complexity of an increased PSB extraction energy. Additionally the PSB would profit from the full brightness of Linac4 for LHC-type beams. However, at least when using the present double-batch injection, the performance of the PS will only marginally benefit because of the space charge limitation at 1.4 GeV. In case of a connection during LS2, the PSB with its injection, ejection and RF systems changed at the same time will have to be commissioned as a new machine. Since the major upgrades of PS and SPS will also be implemented during LS2, the whole injector chain will profit significantly from the improved performance of Linac4 and PSB.

PS AND SPS PERFORMANCE

The bunch intensity as delivered from the PSB within a given transverse emittance is distributed over several bunches at PS extraction. This splitting ratio transforms the intensity axis of Fig. 1 into intensity per bunch transferred to the SPS. For the nominal RF manipulation, with triple splitting on the flat-bottom and two bunch pair splittings on the flat-top, each incoming bunch is split into 12 bunches for LHC in the PS. A reduction of this splitting ratio by new RF manipulations allows the injection of less intensity per bunch from the PSB for the same bunch intensity at PS extraction, hence reducing transverse emittance and increasing brightness. However, the smaller splitting factor implies shorter batches, longer filling time and fewer bunches in LHC compared with the nominal production scheme.

Space charge and coupled-bunch instabilities in the PS

The main limitations in the PS are space charge on the flat-bottom (1.4 GeV) and longitudinal coupled-bunch instabilities after transition crossing. To improve understanding of the former, an extensive measurement campaign has been pursued in 2011, confirming that the vertical tune spread of the nominal 25 ns beam for LHC ($1.6 \cdot 10^{12}$ ppb at injection corresponding to $1.3 \cdot 10^{11}$ ppb at ejection) is already close to the maximum permissible tune spread. Studies with larger space charge will continue in 2012, but $\Delta Q_y = -0.26$ computed using Eq. (1) is assumed throughout as a conservative limit for beams injected in double-batch [7]. In case of single-batch injection, as could become possible with Linac4 as a pre-injector and immediate acceleration in the PS, space charge will cause less emittance blow-up and a slightly higher brightness might be obtained [8].

Since the beam size increase due to momentum spread and non-zero dispersion introduces a non-negligible contribution for small transverse emittance beams, the integration formula [9]

$$\Delta Q_y = \frac{r_p N_b}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z}\frac{1}{\sqrt{\epsilon_y}} \oint_C \frac{\sqrt{\beta_y(s)}}{\sqrt{\beta_y(s)\epsilon_y}+\sqrt{\beta_x(s)\epsilon_x+\sigma^2_{\Delta p/p}D^2_x(s)}}\,ds \qquad (1)$$

has been applied for the tune spread calculations, where $\beta_{x/y}(s)$ and $D_x(s)$ are the beta and dispersion functions. The physical emittances $\epsilon_{x/y}$ in the equation are related via $\epsilon_{x/y} = \varepsilon_{x,y}/(\beta\gamma)$ to the normalized emittances $\varepsilon_{x,y}$.

The space charge limit, together with the Linac2/PSB brightness limitation, are shown in Fig. 2 (for double-batch injection on $h = 7$) and Fig. 3 (for double-batch injection on $h = 9$). In both cases maximum brightness from the PSB and the allowable space charge tune spread at PS injection pose similar limitations. Hence at 1.4 GeV, Linac2/PSB and the PS are well matched. This also implies that double-batch in the PS can only profit marginally from higher brightness from the PSB connected to Linac4 without an upgrade of the PSB-PS transfer energy to 2 GeV. Experience with other than LHC-type single-batch beams (e.g. the TOF beam) in the PS shows that $|\Delta Q| > 0.3$ could be possible, but for high-brightness beams this will be subject to further studies during the 2012 run.

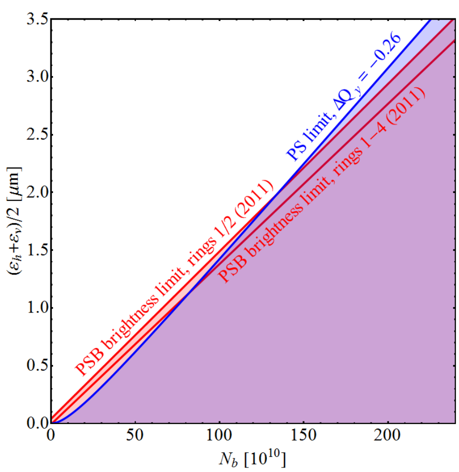

Figure 2: Linac2/PSB brightness limit together with the PS space charge tune spread limitation of $\Delta Q_y = -0.26$ for injection of LHC-type beams on $h = 7$.

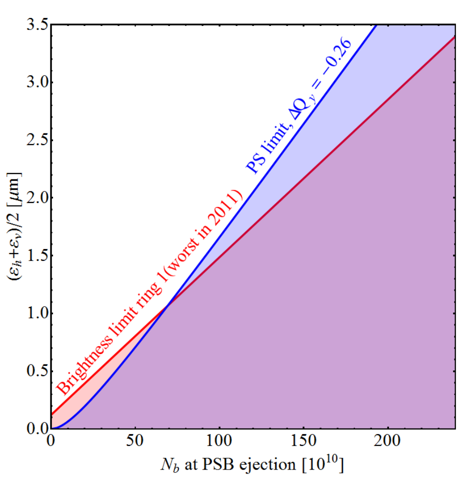

Figure 3: Same plot as Fig. 2, but for injection on $h = 9$.

Coupled-bunch oscillations that develop after transition are the main longitudinal limitation. A feedback system for these instabilities has already been installed in 2005 [10], but its capabilities are limited since two 10 MHz accelerating cavities are operated as longitudinal kickers rather than a broadband device. The attainable bunch intensity versus longitudinal emittance (per bunch at extraction) is plotted in Fig. 4. For the beam with 50 ns bunch spacing, half

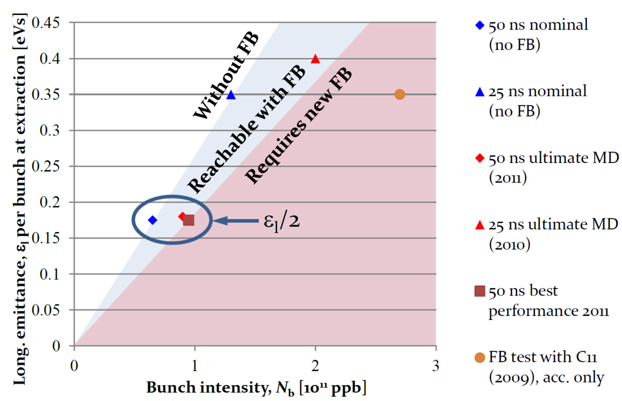

Figure 4: Maximum bunch intensity versus longitudinal emittance accelerated stably for final bunch spacings of 25 ns and 50 ns.

the particles per bunch within half the longitudinal emittance are accelerated in the PS; hence the 50 ns cases in Fig. 4 appear as 25 ns cases at half emittance and intensity. The measurements suggest an empirical scaling of the coupled-bunch instability threshold proportional to the average longitudinal bunch density N_b/ε_l and impose an absolute intensity limit of $1.9 \cdot 10^{11}$ ppb (for $\varepsilon_l = 0.35$ eVs), independent from the bunch spacing. The development of a longitudinal Finemet-based wide-band kicker cavity to cover all possible oscillation modes has started in collaboration with KEK. Assuming that the kicker cavity will be installed during LS1, the new feedback could be commissioned in 2014/2015.

Limitations and improvements in the SPS

The major upgrades within the LIU Project in the SPS, such as coating the vacuum chamber with amorphous carbon to eliminate e-could effects and the major 200 MHz RF upgrade from 4 to 6 cavities, can also only take place during LS2 [11, 12]. Improvements during the period between LS1 and LS2 are nonetheless expected from [13]:

- the new Q20 optics for LHC-type beams which has been extensively studied in 2011 and which requires only minor hardware changes;
- the upgrade of the low-level and feedback systems of the 800 MHz RF system, as well as more voltage from the second cavity equipped with a new amplifier;
- reduced impedance due to shielding of the last MKE kicker.

The brightness reach at SPS extraction for the Q20 optics has been explored with single bunches during machine developments (MDs) in 2011 and the emittances versus intensity are illustrated in Fig. 5. With these improvements

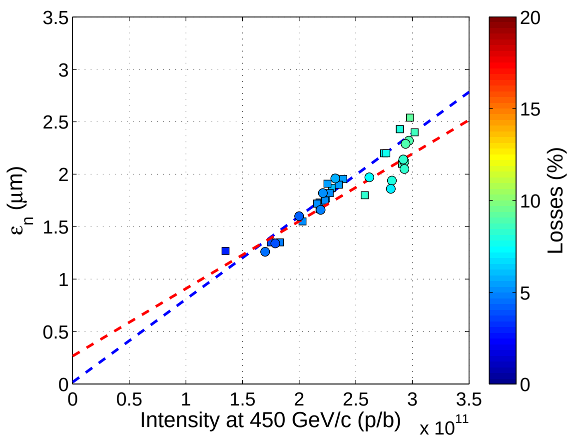

Figure 5: Transverse normalized emittances at flat-top in the SPS with the Q20 optics measured with single bunches [14].

after LS1, and potential further optimizations during MDs with the Q20 optics in 2012, this brightness reach could be assumed as an optimistic limit also for multi-bunch beams.

Performance with 25 ns bunch trains will however be limited by e-cloud effects and possible beam characteristics will depend on the degree of scrubbing of the SPS vacuum chamber after LS1.

RF MANIPULATIONS IN THE PS

In the transverse planes the PS is expected to preserve emittances. In the longitudinal plane RF manipulations are required to produce short bunches spaced by 25 ns or 50 ns. In the nominal scheme, each bunch from the PSB is split in 12 parts for 25 ns spacing, requiring $12 \cdot 1.3 \cdot 10^{11} \simeq 1.6 \cdot 10^{12}$ ppb at injection. Reducing the splitting factor by new RF manipulations [15] increases the brightness per bunch at the cost of a shorter batch at extraction from the PS.

Performance with present production scheme

The nominal production scheme of LHC-type beams in the PS consists of double-batch injection of $4 + 2$ bunches from the PSB into $h = 7$ buckets, leaving a gap of $1/7$ of the circumference for the extraction kicker. After the second injection, the bunches are split in three on the flat-bottom, resulting in 18 bunches at $h = 21$. Following acceleration to 26 GeV, one (50 ns bunch spacing) or two (25 ns) bunch pair splittings result in finally 36 (50 ns, each PSB bunch split in 6) or 72 (25 ns, splitting ratio 12) bunches at $h = 84$, the only RF harmonic on which, together with $h = 168$, sufficient RF voltage is available to produce short bunches for the bunch-to-bucket transfer to the SPS.

Given the various limitations of the injector chain, the expected performance is summarized in Table 2.

The observed performance of the injectors agrees well with the expected figures. The last two rows indicate relative intensity and luminosity in the LHC (simple scaling without taking the total number of bunches per LHC ring into account). The coupled-bunch limited 50 ns beam is chosen as reference, since its parameters are close to those of the beam delivered to the LHC at the very end of the 2011 run. Although reducing the event pile-up in the experiments, the luminosity with 25 ns bunch spacing would only be two thirds of what has already been achieved with 50 ns.

Batch Compression schemes

With the operational $4 + 2$-bunch double-batch transfer, the PSB accelerates only two bunches for the second injection, while the other two rings remain empty. Hence only half of the possible brightness from the PSB is deployed with the beam accelerated for the second injection into the PS. Additionally, the large splitting ratio requires high intensity at injection from the PSB with the corresponding emittance (Fig. 1). Alternative schemes to reach $h = 21$, the canonical harmonic for acceleration of 25 ns and 50 ns beams, have therefore been proposed [16, 17].

To profit from the full PSB brightness, $4+4$ bunches can be injected into $h = 9$ buckets [18]. Following a harmonic number change (batch compression) from $h = 9 \rightarrow 10$, a bunch pair splitting $10 \rightarrow 20$ and a further batch compression step to $h = 21$, the splitting ratio becomes 8 in the 25 ns case, respectively 4 for 50 ns spacing. First beam tests in 2011, injecting two bunches from each PSB ring (Fig. 6), have demonstrated the feasibility of the RF manipulation scheme at 2 GeV. Its full implementation, including beam tests in SPS and LHC, is foreseen during the second half of the 2012 run. Table 3 gives an overview of the expected performance. Thanks to the reduced splitting ratio, beams with smaller transverse emittance can be produced. While the 50 ns variant could become interesting to push luminosity in the LHC, the 25 ns beam will allow the exploration of the regime of small transverse emittance beams in the injector chain and tentatively also in the LHC.

More evolved RF manipulation schemes in the PS could further increase brightness, once transverse emittance conservation has been demonstrated up to the flat-top in the SPS. Assuming sufficient longitudinal emittance margin,

Table 2: Performance reach of the injectors with the present bunch splitting scheme in the PS. For the PS 5 % losses and 5 % emittance blow-up are assumed while the SPS causes 10 % losses and 10 % blow-up.

		50 ns early 2011	**25 ns** ∼nominal	**50 ns** CBI-limit
PS injection	Bunch intensity	$0.8 \cdot 10^{12}$ ppb	$1.6 \cdot 10^{12}$ ppb	$1.2 \cdot 10^{12}$ ppb
	Normalized emittance, ε	$1.2\,\mu$m	$2.4\,\mu$m	$1.8\,\mu$m
	Vertical tune spread, ΔQ_y	-0.24	-0.26	-0.25
PS ejection	Bunch intensity	$1.27 \cdot 10^{11}$ ppb	$1.27 \cdot 10^{11}$ ppb	$1.90 \cdot 10^{11}$ ppb
	Normalized emittance, ε	$1.3\,\mu$m	$2.5\,\mu$m	$1.9\,\mu$m
	Bunches per batch	36	72	72
SPS ejection	Bunch intensity	$1.15 \cdot 10^{11}$ ppb	$1.15 \cdot 10^{11}$ ppb	$1.71 \cdot 10^{11}$ ppb
	Normalized emittance, ε	$1.4\,\mu$m	$2.8\,\mu$m	$2.1\,\mu$m
	Brightness limit PSB	X	X	X
	Space charge limit PS	X	X	X
	Coupled-bunch limit PS	-	-	X
	RF power limit SPS	-	X	-
	Relative intensity in LHC	0.67	1.33	1.0
	Relative luminosity in LHC	0.67	0.67	1.0

Table 3: Performance reach of the injectors with $h = 9 \to 10 \to 20 \to 21$ batch compression and splitting scheme.

		50 ns high intens.	**25 ns** high intens.	**25 ns** low $\varepsilon_h/\varepsilon_v$
PS injection	Bunch intensity	$0.8 \cdot 10^{12}$ ppb	$1.07 \cdot 10^{12}$ ppb	$0.64 \cdot 10^{12}$ ppb
	Normalized emittance, ε	$1.3\,\mu$m	$1.8\,\mu$m	$1.0\,\mu$m
	Vertical tune spread, ΔQ_y	-0.26	-0.26	-0.26
PS ejection	Bunch intensity	$1.90 \cdot 10^{11}$ ppb	$1.27 \cdot 10^{11}$ ppb	$0.76 \cdot 10^{11}$ ppb
	Normalized emittance, ε	$1.3\,\mu$m	$1.9\,\mu$m	$1.0\,\mu$m
	Bunches per batch	32	64	64
SPS ejection	Bunch intensity	$1.71 \cdot 10^{11}$ ppb	$1.15 \cdot 10^{11}$ ppb	$0.68 \cdot 10^{11}$ ppb
	Normalized emittance, ε	$1.5\,\mu$m	$2.1\,\mu$m	$1.1\,\mu$m
	Brightness limit PSB	-	-	X
	Space charge limit PS	X	X	X
	Coupled-bunch limit PS	X	-	-
	RF power limit SPS	-	X	-
	Relative intensity in LHC	1.0	1.3	0.8
	Relative luminosity in LHC	1.4	0.9	0.6

bunch pair merging doubles the intensity per bunch, while keeping transverse parameters unchanged. It has therefore been suggested to inject $4 + 2$ bunches in $h = 7$ buckets and, on an intermediate flat-top, sequentially raise the harmonic number up to $h = 14$ and then merge back to 3 bunches in $h = 7$. The usual triple splitting procedure can then be executed, finally yielding $h = 21$. A simulated mountain range density plot of this manipulation is shown in Fig. 7. Due to the bunch merging, the splitting ratio is halved (25 ns: 6; 50 ns: 3) and the brightness increases accordingly (Table 4, left and center columns), at the cost of half the number of bunches at extraction with respect to the nominal scheme. The same RF manipulations can also be easily adapted to the injection of $4 + 4$ bunches into $h = 9$ buckets (Fig. 8). This not only saves two harmonic number steps during batch compression, but also exploits the full brightness from all PSB rings and yields 30 % longer batches (Table 4). It is important to point out that with these RF manipulations in the PS, nominal luminosity can be reached with 25 ns bunch spacing, without increasing the total intensity circulating per beam in the LHC.

An even further reduction of the splitting ratio and potentially even higher brightness could be reached by a pure batch compression scheme. Injecting $4+4$ buches into $h = 9$ buckets and sequentially changing the harmonic number to $h = 21$ (simulated mountain range density plot in Fig. 9) may push the beam parameters from the PS well beyond what can be digested by the SPS (Table 4, right column). A beam generated with such a scheme could nonetheless be a powerful tool to probe limitations in the SPS.

Table 4: Performance of the injectors with $h = 7$ or $9 \rightarrow \ldots \rightarrow 21$ batch compression, merging and splitting schemes.

		50 ns high intens.	**25 ns** low $\varepsilon_h/\varepsilon_v$	**25 ns** ultra-bright
PS injection	Bunch intensity	$0.6 \cdot 10^{12}$ ppb	$0.8 \cdot 10^{12}$ ppb	$0.65 \cdot 10^{12}$ ppb
	Normalized emittance, ε	$1.0\,\mu$m	$1.2\,\mu$m	$1.0\,\mu$m
	Vertical tune spread, ΔQ_y	-0.21	$-0.24/-0.26$	-0.26
PS ejection	Bunch intensity	$1.90 \cdot 10^{11}$ ppb	$1.27 \cdot 10^{11}$ ppb	$1.54 \cdot 10^{11}$ ppb
	Normalized emittance, ε	$1.1\,\mu$m	$1.3\,\mu$m	$1.1\,\mu$m
	Bunches per batch	$18/24$	$36/48$	32
SPS ejection	Bunch intensity	Beyond SPS	$1.15 \cdot 10^{11}$ ppb	Beyond SPS
	Normalized emittance, ε	reach	$1.4\,\mu$m	reach
	Brightness limit PSB	X	X/-	X
	Space charge limit PS	-	-/X	X
	Coupled-bunch limit PS	X	-	-
	RF power limit SPS	-	X	X
	Relative intensity in LHC	(1.0)	1.3	(1.63)
	Relative luminosity in LHC	(1.8)	1.3	(2.38)

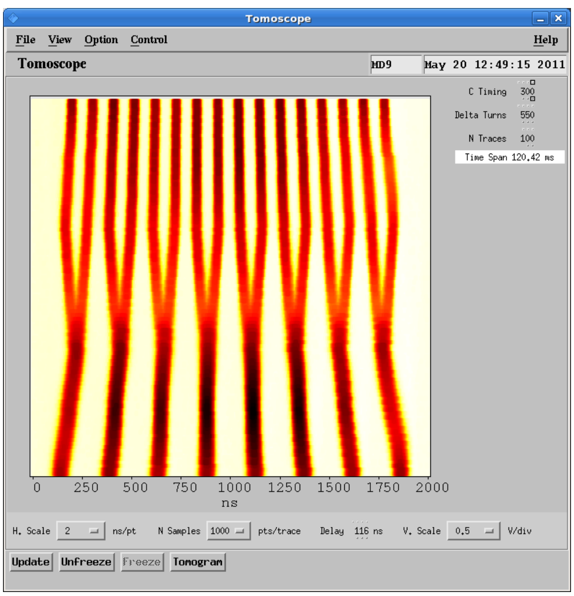

Figure 6: Batch compression and splitting scheme, $h = 9 \rightarrow 10 \rightarrow 20 \rightarrow 21$. The manipulation process (time goes from bottom to top) takes about 120 ms.

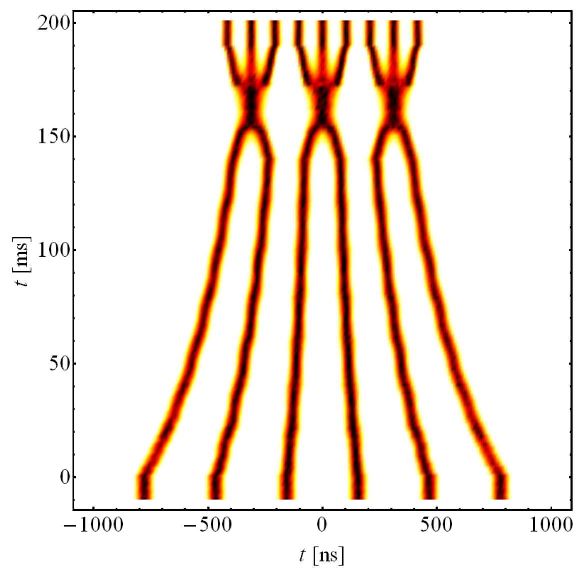

Figure 7: Batch compression, merging and triple splitting scheme, $h = 7 \rightarrow \ldots \rightarrow 14 \rightarrow 7 \rightarrow 21$.

Filling time and bunch numbers in the LHC

The total cycle length of 3.6 s in the PS does not need to be prolonged. More than 450 ms could be exploited without exceeding three basic periods (double-batch injection). This extra time is sufficient to accommodate an intermediate flat-top for the RF manipulations. Fewer bunches due to shorter batches from the PS can partly be compensated by more injections into the SPS. However, the total number of bunches per ring in the LHC is still lower because of the extra kicker gaps and an extended filling time cannot be avoided (Table 5). Depending on the scheme in the PS about 10 % fewer bunches can be injected per LHC ring which may take less than five minutes more than the theoretical minimum dedicated filling time for both LHC rings.

CONCLUSIONS

With the PSB-PS transfer energy remaining at 1.4 GeV until LS2, potential performance improvements in the LHC injector chain after LS1 are expected from low transverse emittance beams produced with batch compression RF manipulations in the PS. Emittance conservation up to the flattop in the PS looks promising, but remains to be demon-

Table 5: Maximum number of bunches per ring and minimum (dedicated) filling time of the LHC [19, 20, 17].

RF manipulation	Transfers PS-SPS	# of bunches abs.	rel.	Minimum filling time
Triple splitting, $h = 7 \to 21$	2/3/4 · 72 bunches	2808	1.0	8 min 38 s
Batch compression, $h = 9 \to 10 \to 20 \to 21$, Fig. 6	up to $4 \cdot 64$ bunches	2688	0.96	$\sim$ 9 min 20 s
Batch comprsn., $h = 7 \to \ldots \to 14 \to 7 \to 21$, Fig. 7	up to $7 \cdot 36$ bunches	2520	0.9	$\sim$ 13 min
Batch comprsn., $h = 9 \to \ldots \to 14 \to 7 \to 21$, Fig. 8	2/4/5/(6)·48 bunches	2592	0.92	10 min 5 s
Pure batch comprsn., $h = 9 \to \ldots \to 19 \to 21$, Fig. 9	up to $8 \cdot 32$ bunches	$\sim$ 2450	$\sim$ 0.87	$\sim$ 14 min 20 s

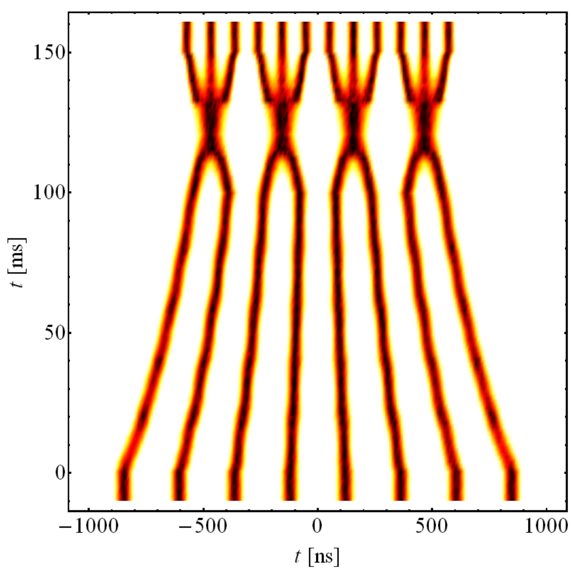

Figure 8: Batch compression, merging and triple splitting scheme, $h = 9 \to \ldots \to 14 \to 7 \to 21$.

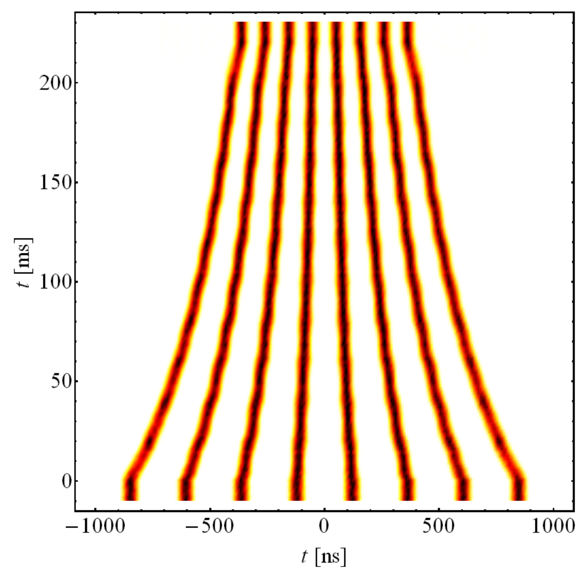

Figure 9: Pure batch compression scheme, $h = 9 \to \ldots \to 20 \to 21$.

strated in the SPS. The feasibility of the $h = 9 \to 10 \to 20 \to 21$ batch compression scheme for LHC-type beams has been shown in the PS. Following its full implementation, a test with SPS and LHC is planned for the second half of 2012. MDs with a more evolved RF manipulation scheme, promising more than today's luminosity with 25 ns bunch spacing in the LHC, will be performed in 2012 to decide on a possible implementation in the RF beam control for the after-LS1 period. In the SPS, improvements before LS2 are expected from the Q20 optics, the 800 MHz RF upgrade and the completion of the MKE shielding. The performance gain with Linac4 alone will be modest, but the filling time of the LHC could be reduced using single-batch injection in to the PS. With double-batch injection with Linac4, the PS could be pushed to its space charge limit. To profit fully from the performance potential of Linac4 injecting H^- into the PSB, the upgrade of the PSB-PS transfer energy to 2 GeV is essential [21].

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