EXPECTED PERFORMANCE IN THE INJECTORS AT 25 ns WITHOUT AND WITH LINAC4

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Abstract

The quality of the 25ns beams that can be delivered at the LHC injection is determined by the injection process into the PSB, as well as by space charge, collective interactions, electron cloud and RF power limitations in the PS and SPS. Using the information available from our present experience, the main goal of this paper is twofold: (1) to assess the intensity and brightness reach of the 25ns beams produced by the LHC injector chain with the two main schemes, before and after the connection of the PSB to Linac 4; and (2) to identify which bottlenecks will be likely to limit the performance with Linac 4. A few options to maximize the potential of the increased brightness provided by Linac 4, based on flattened bunch profiles at the PS injection or the use of alternative optics configurations, will be included in the analysis.

INTRODUCTION

During the 2011 and 2012 runs, the LHC physics production mainly made use of 50 ns beam, while the 25 ns beams were only injected into LHC on few occasions for injection tests, Machine Development (MD) sessions, an extended scrubbing run and a short pilot physics run [1, 2]. Furthermore, several MD sessions making use of 25 ns beams also took place in the SPS, during which the set up of this type of beams was optimized throughout the whole LHC injector chain even prior to their use in LHC [3]. Nowadays, thanks to a vast experience and several important improvements carried out over the years over all the accelerators of the LHC injection chain, the nominal 25 ns beam is produced well within specifications [4] and its transport through the different accelerators hardly exceeds the allocated beam loss and emittance blow up loss budgets (i.e. 5% intensity loss and emittance growth in the PSB and PS, and 10% in the SPS). For example, one of the essential ingredients that contributed to limit the degradation of the 25 ns beams along their transport to the LHC was the accumulated scrubbing of the SPS over the years, which has eventually made the amount of electron cloud in the ring acceptable to produce 25 ns beams within specifications [6]. It is also important to recollect at this stage that in 2012 a new scheme for the production of 25 ns beams was developed and applied. This scheme, called BCMS (Batch Compression and bunch Merging and Splitting), is described in [7, 8]. By reducing the splitting factor in the PS from 12 to 6 (at the expense of producing trains of 48 instead of 72 bunches at the PS exit), these beams can in principle reach double brightness with respect to those produced with the standard scheme.

After Long Shutdown 1 (LS1), the LHC will run with 25 ns beams for physics production. Therefore, the goal of this paper will be to analyze the possible future scenarios with 25 ns beams and provide the beam characteristics that can be expected at the different stages of the LHC injection chain for each scenario. In particular, after summarizing the achieved performance of the injectors with 25 ns beams, Section 1 will focus on the potential improvements that can be implemented after LS1, providing also the achievable beam parameters. Section 2 will describe the expected performance improvement after the connection of Linac 4 to the PSB and how this can translate into an increased brightness of the beam delivered to the LHC even in absence of any other upgrade throughout the injector chain. In this framework, some exotic ideas to beat the space charge limit at the PS injection will be briefly discussed, like the use of hollow bunches at the PSB-PS transfer or the implementation of alternative optics configurations at the PS injection. Finally, the possible advantages of the single batch PSB-PS transfer will be also addressed.

PRE-LINAC4 ERA

Achieved performance

An upper limit for the brightness of the LHC-type beams is determined at the PSB injection, because of the efficiency of the multi-turn injection process as well as the effects of space charge during injection. To obtain bunches with 1.2 eVs longitudinal emittance (resulting in 180 ns total bunch length with the maximum 8 kV voltage on h=1) at the PSB extraction, as required for the following RF manipulations at 1.4 GeV in the PS, the transverse emittance versus extracted intensity curve has been measured at the PSB with careful optimization of the injection settings for all measurement points (lower line in Fig. 1) [9]. The brightness is actually already defined at capture of the beam in the h=1 bucket, because intensity and emittance measurements along the PSB cycle reveal that no significant beam loss or emittance blow up takes place after capture for any of the measured points. In the case of the BCMS beams, due to the injection into h=9 in the PS, the total bunch length at PSB extraction cannot exceed 150 ns, which limits the value of longitudinal emittance for the PSB bunches to 0.9 eVs. To achieve this value of longitudinal emittance at extraction, it is necessary to produce it already at injection by means of longitudinal shaving and conserve it along the cycle. This makes the achievable brightness of the BCMS beams lower than that of standard LHC beams, so that the resulting curve transverse emittance versus extracted intensity moves to the upper line of Fig. 1.

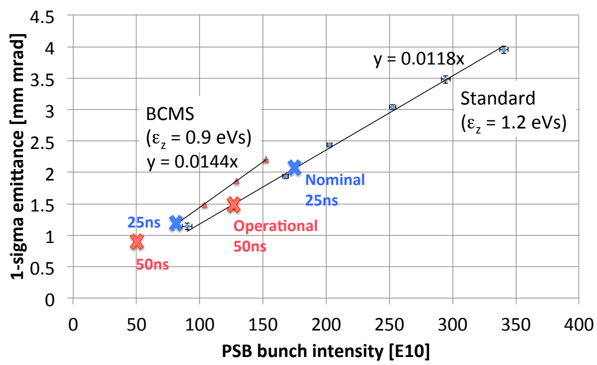

Figure 1: Performance at the PSB extraction with LHC-type beams. The two lines correspond to standard and BCMS production schemes, as labeled.

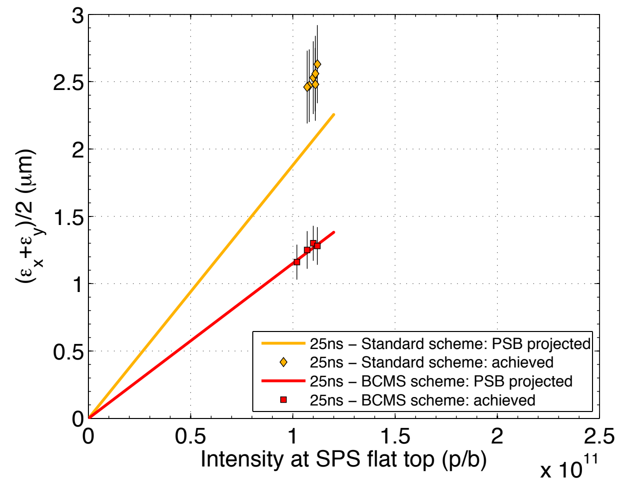

Figure 2: Performance at the SPS extraction with 25 ns beams. The projected lines from the PSB perfomance are also plotted, after applying the expected intensity loss and emittance growth budgets throughout the injector chain.

The measurement points displayed in Fig. 2 refer to 25 ns beams at the SPS extraction and were taken after the low gamma transition optics Q20 became operational in the SPS [10]. The transverse emittances shown in this plot are deduced from combined wire-scans at the end of the SPS flat bottom and the values were cross-checked with measurements in the LHC. The error bars include the spread over several measurements as well as a systematic uncertainty of 10%. The bunch intensity is measured at the SPS flat top after the scraping of the beam tails, as required prior to extraction into LHC. From these measurements, two important considerations can be made. First, the 25 ns beams produced with the standard production scheme are well within the original specifications (i.e. $1.15{\times}10^{11}$ ppb and 3.5 μm transverse emittance [4]) and the BCMS scheme can achieve much higher brightness (in trains of 48 bunches). Second, the same figure shows not only the measurement points but also the projected lines from the PSB brightness (i.e. the measured PSB brigthness lines are translated into protons per SPS bunch applying 5% and 10% intensity loss and emittance growth in the PS and SPS, respectively). Therefore, one can see that the standard 25 ns beam goes through the injector chain with an additional 15% emittance blow up (or intensity loss) compared to the allocated budget, while the BCMS beam performs within the expected budgets. Possible reasons for the worse performance of the standard 25 ns beams could be the slow losses at the SPS flat bottom or space charge effects at the PS injection, which, combined with the larger transverse emittances, may potentially lead to increased fast losses.

The space charge induced tune spread can be evaluated at each stage of the injection chain (relativistic factors β, γ) from the measured values of bunch peak density $\lambda_{\max}$, transverse emittances $\epsilon_{x,y}$, and momentum spread δ as well as from the knowledge of the machine optics (beta functions, $\beta_{x,y}(s)$, and dispersion functions, $D_{x,y}(s)$), using the following formula:

$$\Delta Q_{x,y} = \frac{\lambda_{\max} r_p}{2\pi\beta^2\gamma^3} \oint \frac{\beta_{x,y}(s)ds}{\sigma_{x,y}(s)\left[\sigma_x(s)+\sigma_y(s)\right]} \quad (1)$$

with r_p being the classical proton radius and

$$\sigma_{x,y}(s) = \sqrt{\epsilon_{x,y}\beta_{x,y}(s) + D^2_{x,y}(s)\delta^2} \, .$$

Calculating the tune spread values achieved at the PS and SPS injections for both the 25 ns beams, with parameters reviewed here above, and the 50 ns beams (standard and BCMS) [11], and from the experience accumulated in dedicated space charge MDs throughout 2012 and 2013 [12], the maximum values of ΔQ considered acceptable at the PS and SPS injection have been set to 0.31 and 0.21, respectively.

Expected post-LS1 performance

The 25 ns beams (both standard production and BCMS) in the 2012/13 run were already at the limits of what the LHC injectors can produce. In terms of intensity per bunch, the intensity reached at the exit of the SPS is only 10% lower than what is achievable within the present limitations due to the RF power and the longitudinal instabilities in the SPS [5, 6]. Actually, during one MD session at the end of 2012, an intensity of about 1.35×10^{11} ppb could be successfully accelerated to 450 GeV/c, but the beam was found to be degraded in all planes probably due to a combination of longitudinal instabilities and revived electron cloud effects. In terms of brightness, both the standard production scheme and the BCMS rely on bunches that are already at, or very close to, the limit of space charge at the PS injection ($\Delta Q_y = 0.31$).
The possibility to improve the performance after LS1 rests therefore on the perspectives of increasing the bunch intensity by 10% and improving the brightness by circumventing the space charge limit at the PS injection. To explain then which improvements could be envisioned, we

first need to clarify the reasons limiting the longitudinal parameters of the bunches at the PSB extraction:

- For the standard production scheme (injection into PS h=7), the longitudinal emittance is limited to 1.2–1.3 eVs to ensure the quality of the triple splitting at 1.4 GeV before acceleration in the PS. As a consequence, the bunches cannot be longer than 180 ns, which is the matched value for the required longitudinal emittance in the PSB h=1 bucket with 8 kV at 1.4 GeV. In reality, the acceptable bunch length could have been as much as 220 ns in order to be compatible with the rise time of the recombination kicker in the transfer line (105 ns) and provide the correct bunch spacing to fit into the PS h=7 (327 ns).

- For the BCMS scheme (injection into h=9), the bunch length is limited to 150 ns to allow for the 105 ns rise time of the recombination kicker and obtain the 255 ns spacing of the PS h=9. The maximum longitudinal emittance allowing for this bunch length at the PSB extraction is 0.9 eVs.

The first condition to improve the situation above is to allow for larger longitudinal emittances to be transferred from the PSB to the PS. This is possible if triple splitting in the PS are made at 2.5 GeV instead of the injection energy. Second, the PSB should be able to provide bunches at 1.4 GeV with total length of 220 ns or 150 ns for the standard production scheme or the BCMS, respectively, and longitudinal emittances larger than the matched values on h=1 alone with 8 kV. This is possible with a controlled longitudinal blow up made with C16 along the ramp and with additional 8 kV on h=2 used in phase with h=1 at 1.4 GeV (instead of being reduced to 1 kV as in standard operation). The longitudinal emittance of a bunch at the PS injection should not exceed:

- 3 eVs (h=7)/2 eVs (h=9) due to the acceptance bottleneck at the start of acceleration from 1.4 to 2.5 GeV;

- (Total Split Factor $\times 0.35$ eVs)/1.1, as bunches at the PS extraction must have longitudinal emittance of 0.35 eVs with 10% blow up allowed in the PS;

- Flat Bottom Split Factor $\times 1$ eVs for transition crossing on h=21, as bunches go smoothly through transition if their longitudinal emittance is below 1 eVs;

- The matched value in the PSB with h=1+2 with available voltage and desired bunch length at extraction.

Considering all the constraints, bunches with 2.8 eVs longitudinal emittance can be transferred with the standard scheme, while 1.5 eVs is the maximum tolerable with the BCMS scheme. The overall performance of standard and BCMS 25 ns beams at the SPS extraction is illustrated in Figs. 3.

In these figures, the emittance vs. intensity curves corresponding to the known performance limitations (i.e. PSB brightness, PS and SPS space charge) are plotted at the SPS extraction both without (green curves) and with (blue curves) the relaxed longitudinal parameters at the PSB-PS transfer. The intensity limitation of 1.3×10^{11} ppb due to the SPS RF power and longitudinal instabilities limitation is also displayed as a vertical red line. Since these curves also represent the borders between areas of reachable and unreachable parameter ranges, the latter ones have been shown as shaded regions. Obviously, the larger longitudinal emittances at the PSB injection result in longer bunches and/or larger momentum spreads, which reduce

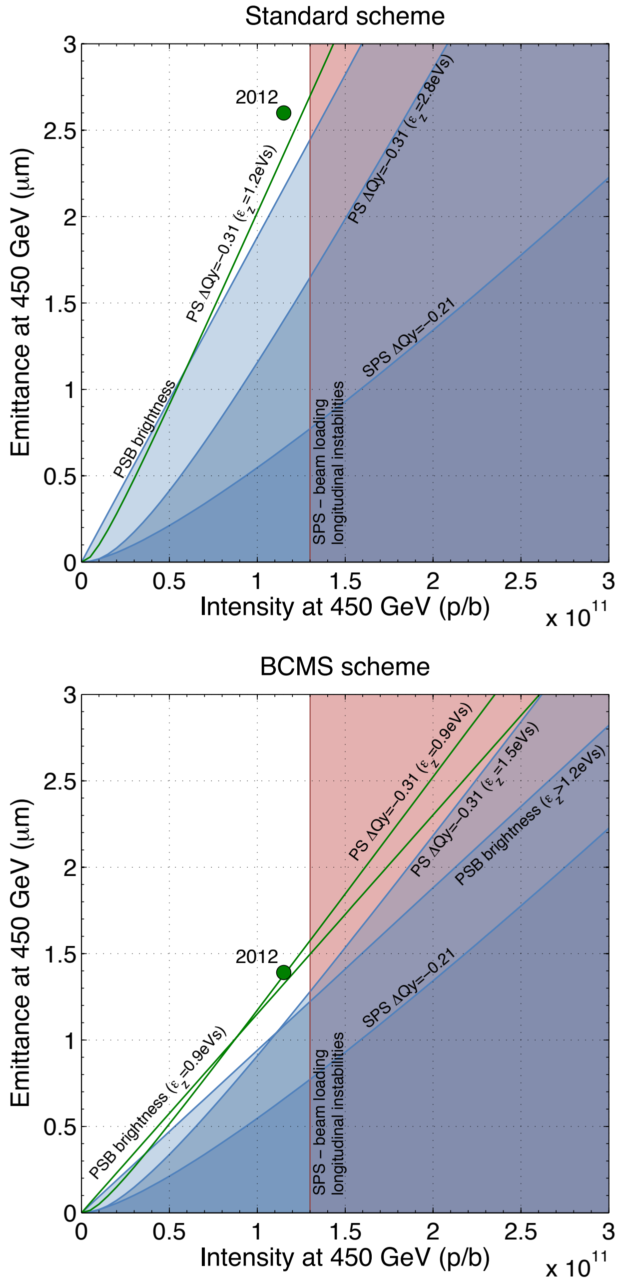

Figure 3: Limitation diagrams for the standard production (top) and BCMS scheme (bottom).

		PSB						
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Post-LS1	Standard	19.21	2.02	0.05	1.0	1100	$2.4 \cdot 10^{-3}$	(0.58, 0.67)
	BCMS	9.60	1.06	0.05	1.0	1100	$2.4 \cdot 10^{-3}$	(0.48, 0.61)
	PBC	6.40	0.78	0.05	1.0	1100	$2.4 \cdot 10^{-3}$	(0.40, 0.53)
	8b⊕4e	17.73	1.86	0.05	1.0	1100	$2.4 \cdot 10^{-3}$	(0.57, 0.67)

		PS (double injection)						
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Post LS1	Standard	18.25	2.12	1.4	2.79	220	$1.8 \cdot 10^{-3}$	(0.14, 0.23)
	BCMS	9.12	1.11	1.4	1.48	150	$1.4 \cdot 10^{-3}$	(0.18, 0.31)
	PBC	6.08	0.72	1.4	1.0	150	$0.9 \cdot 10^{-3}$	(0.21, 0.31)
	8b⊕4e	16.84	1.96	1.4	2.0	220	$1.3 \cdot 10^{-3}$	(0.18, 0.25)

		SPS (several injections)						
					after filamentation (ϵ_z=0.35 eVs, B_l=4 ns @inj)			
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Post-LS1	Standard	1.44	2.22	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.05, 0.08)
	BCMS	1.44	1.16	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.08, 0.14)
	PBC	1.44	0.86	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.10, 0.18)
	8b⊕4e	2.00	2.05	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.08, 0.13)

		LHC					
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	bunches/train
Post-LS1	Standard	1.30	2.44	450	0.47	1.63	4×(72b+8e)
	BCMS	1.30	1.28	450	0.47	1.63	6×(48b+8e)
	PBC	1.30	0.95	450	0.47	1.63	6×(32b+8e)
	8b⊕4e	1.80	2.26	450	0.60	1.67	4×(7×(8b+4e))

Table 1: This table summarizes all achievable parameters with 25 ns beams after LS1. The performances of two new schemes with Pure Batch Compressions (PBC) and production of "standard" trains alternating 8 bunches and 4 gaps (8b⊕4e) are also included.

the slope of the curve $\Delta Q_y = 0.31$ in the emittance vs. intensity plane. It is clear that the possibility to transfer bunches with larger longitudinal emittance from the PSB to the PS results into a higher achievable brightness, only limited by the PSB brightness for the standard production scheme and by the PS space charge for the BMCS scheme. It should be noted that relaxing the longitudinal parameters at the PSB extraction also results into a more favorable PSB brightness line for BCMS beams, because the 1.2 eVs line of Fig. 1 can also be assumed for this type of beams.

Table 1 summarizes all the achievable parameters after LS1. For sake of completeness, it includes not only the 25 ns beams produced with the standard and BCMS schemes, discussed above, but also the Pure Batch Compression (PBC) scheme [13] and the (8b⊕4e) scheme described in references [13, 14]. To be noticed that the sub-μm emittance values of the PBC scheme are in principle achievable in the PSB by means of transverse shaving, although the emittance preservation all through the injection chain has not yet been demonstrated for this type of beams and could prove not to be trivial.

PERFORMANCE WITH LINAC 4

After the connection to Linac 4, the main assumption is that beams out of the PSB will have double brightness with respect to the value achieved currently with Linac 2. In practice, the PSB performance with Linac 4 can be assumed to be represented by two lines with half slope compared to those shown in Fig. 1. In Fig. 4 the limitation diagrams with Linac 4 (as described in the previous section) are diplayed. Beams produced with the standard scheme can reach 1.3×10^{11} ppb within 1.65 μm, which is a significant improvement compared with the 2.44 μm achievable with Linac 2 (see Fig. 1). This improvement basically relies on the margin on the PS space charge provided by the new longitudinal parameters in the PSB-PS transfer (see Fig. 3, top plot). Beams produced with the BCMS scheme will have 1.3×10^{11} ppb within 1.28 μm, which equals the achievable performance with Linac 2. This is not surprising, because the BCMS beams, even with the new longitudinal parameters for the PSB-PS transfer, will be still limited by the space charge in the PS. As a consequence, with no other upgrades downstream, this type of beam will not be able to benefit from the increased brightness from the Linac 4.

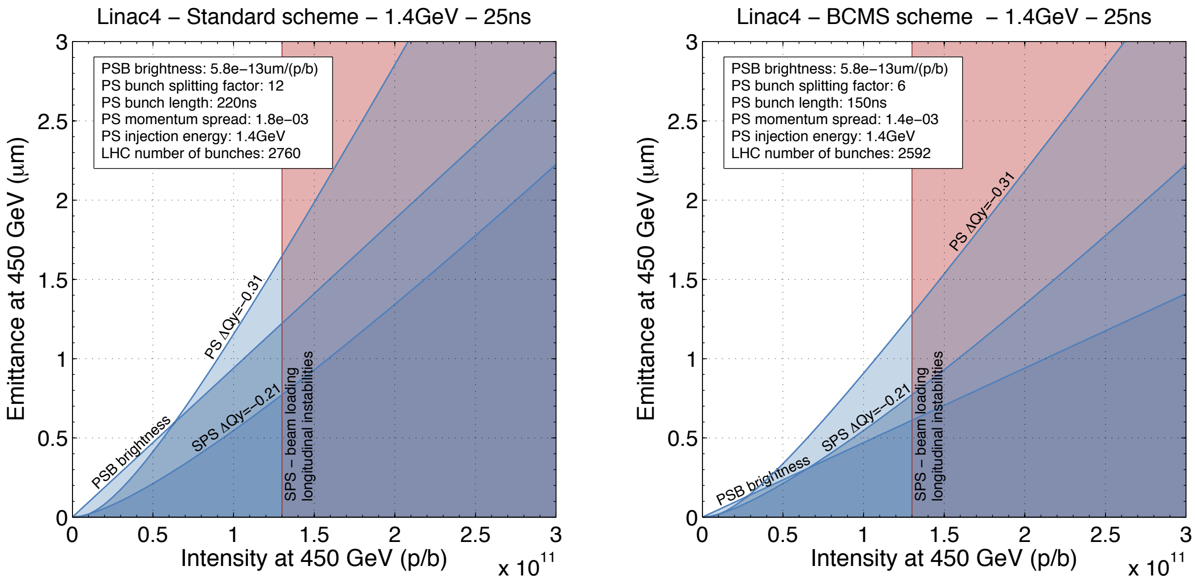

Figure 4: Limitation diagrams for the 25 ns beam (standard and BCMS production scheme) after the connection to Linac 4.

Figure 4 also reveals that, if we could find a means to lower the curve of the PS space charge below the one of the PSB brightness, Linac 4 would provide the potential to increase the brightness of both the standard and the BCMS beams by as much as 20–30%. From the tune spread formula Eq. (1), it is clear that, assuming that the PSB-PS transfer energy will remain 1.4 GeV, the only knobs to achieve this brightness gain lie in either decreasing the bunch peak density (i.e. flattening the bunch), or increasing the momentum spread, or both. Some ideas are presented in the following subsections.

Hollow bunches

To flatten the bunch profile, the first option is to use the second harmonic in counterphase with the main harmonic in both the PSB and the PS, and then transfer matched flat bunches. This manipulation only distributes the core particles over a larger longitudinal phase space area, but the core remains the most highly populated region. However, this solution does not offer a large gain potential and would also pose technical problems of synchronization between the two accelerators. Consequently, we will mainly focus on another option to flatten the bunch profile, i.e. creating a hollow bunch in the longitudinal phase space. Unlike the first option, in this case the bunch distribution in the longitudinal phase space is changed and the core is depleted, with most particles being moved to large synchrotron amplitudes. Hollow bunches can be produced in several different manners:

1. By using a second harmonic with tailor-made voltage and phase programs on both main and second harmonic. This allows redistributing the particles in the longitudinal phase space and folding the highly populated core into a large synchrotron amplitude ring. Two possible techniques are considered, which were already proposed and discussed in [15]. The overall manipulation needs a few synchrotron periods and would require an extended flat top of few tens of milliseconds in the PSB.
2. By shaking the beam by means of an RF phase modulation close to the synchrotron frequency and then applying a higher harmonic sweeping excitation to smear the particles into a ring-like distribution. First tests were already successfully conducted at both the PSB and PS [16, 17]. This technique can be applied in the PSB while accelerating.
3. By injecting the hollow distribution directly in the PSB by means of longitudinal painting and controlled chopping (after the connection of the PSB to Linac 4). Since one full cycle for longitudinal painting needs 40 injected turns, while the 25 ns beam only needs the injection of about 7 turns, a large fraction of the beam will have to be chopped out. With this scheme, the hollow bunch will then have to be stably accelerated through all the PSB cycle, preserving its longitudinal structure.

The phase space distributions before and after the hollow bunch creation (compatible with the transfer constraint of a full bunch length below 220 ns) using the technique 1) are sketched in Fig. 5. Comparing the top and bottom plots, a depression of peak density by about 40% as well as a broadening of the momentum spread, both potentially contributing to a relaxation of the space charge, are visible. In this case, the estimated gain also depends on the larger bunch length allowed for the hollow bunch compared to the initial bunch.

Techniques 1) and 2) have been already experimentally tested (as shown in the relative references), but they have

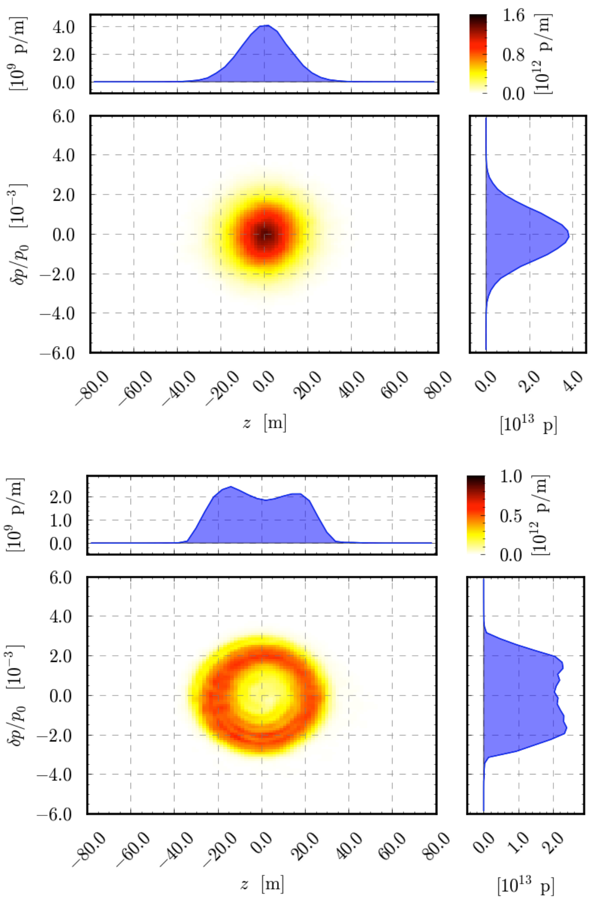

Figure 5: Longitudinal phase space density plots before and after the RF gymnastics to create a hollow bunch. Beside, the projections in the two dimensions are also plotted.

never been used for the production of operational beams. Although promising because of the potential space charge reduction they offer, stability and operational reliability of hollow bunches is yet to be demonstrated. For example, a possible practical problem could be encountered with the triple splitting, because this type of manipulation applied to a hollow bunch could lead to daughter bunches unbalanced in intensity. Another issue could be linked to the different location and density of the tune footprint of a hollow bunch, which is being investigated via long term tracking simulations including space charge.

Alternative optics configurations

Another idea that is currently under investigation to ease space charge at the PS injection is the possible change of the injection optics to enhance the horizontal dispersion or to create vertical dispersion via coupling [18]. Both possibilities are in principle viable thanks to the horizontal and vertical acceptances of the PS, which are sufficient to accommodate the low emittance LHC beams, even with enlarged transverse sizes. The option of distorting the optics to enhance the horizontal dispersion could potentially lead to a reduction of the tune spread by 10–15% and was already tested on a few Machine Development (MD) sessions during the 2012-13 run, although no conclusion on its efficiency can be drawn yet. The option of creating vertical dispersion is based on the use of the existing skew quadrupoles and could yield a 30% reduction of the space charge tune spread with the existing magnets, while new hardware should be installed to increase its efficiency. MDs aiming at testing the coupled optics are planned to take place after LS1.

Single batch PSB-PS transfer

The last point we want to discuss in this analysis is the production of LHC beams with single batch PSB-PS transfer and which advantages this might entail. For all the schemes discussed so far in this paper, we have always implicitly assumed two consecutive injections from the PSB to the PS, i.e. 4+2 bunches for the standard scheme and 4+4 bunches for the BCMS (in the so-called double batch PSB-PS transfer). The reason is that this way of producing LHC beams naturally allows increasing their brightness (as prescribed by the PSB brightness line, Fig. 1). An alternative scheme, already used operationally in the past for the production of 50 ns beams, relies on one single PSB-PS transfer by extracting two bunches per ring from the PSB. This would make the LHC injection process shorter at the expense of a net loss of initial brightness related to the higher intensity per ring that needs to be injected.

In a simplified view, as it provides LHC beams with double brightness compared to the present, Linac 4 would in principle also enable the production of all the present LHC beams with a single batch PSB-PS transfer. In practice, since the bunches should be transferred from h=2 in the PSB, they would be shorter (about 140 ns) and consequently feel more space charge for the same brightness in the PS (defined as intensity over transverse emittance ratio). On the positive side, these beams would be accelerated immediately after injection and the 1.2 s flat bottom, deleterious for long term space charge effects, would be removed. As a consequence, a larger tune spread than $\Delta Q = 0.31$ at the PS injection could be probably acceptable for beams transferred in single batch. However, due to lack of experience, it is difficult to estimate to which extent this value can be exceeded. Table 2 summarizes the parameters achieved in the past with the 50 ns beams (the only ones to have been produced and used operationally for LHC physics using this scheme) [19] as well as the parameters achievable in the future with Linac 4 in both the standard and the BCMS production schemes. It is clear that the beams produced with the standard scheme would need to stand a tune spread at PS injection that is 25% beyond the limit from last year's operational experience.

By allowing four injections into the SPS in 7.2 s instead of the present 10.8 s, the length of the SPS flat bottom could be reduced by 33%, which results in an overall reduction of the SPS filling cycle by 17% (half of the cycle is taken

		PSB (1 b after capture, c=285 ms)						
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Achieved	50 ns	17.47	2.19	0.05	—	—	—	—
	25 ns	—	—	—	—	—	—	—
Linac4 (25 ns)	Standard	38.41	2.22	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.54, 0.62)
	BCMS	19.21	1.37	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.40, 0.48)

		PS (6 – 8 b/inj)						
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Achieved	50 ns	8.30	2.30	1.4	1.0	145	$1.07 \cdot 10^{-3}$	(0.14, 0.17)
	25 ns	—	—	—	—	—	—	—
Linac4 (25 ns)	Standard	18.25	2.34	1.4	0.9	140	10^{-3}	(0.32, 0.39)
	BCMS	9.12	1.44	1.4	0.9	140	10^{-3}	(0.23, 0.31)

		SPS (4 – 6 × 36-72 b/inj)						
					after filamentation (ϵ_z=0.35 eVs, B_l=4 ns @inj)			
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
Achieved	50 ns	1.32	2.42	26	0.42	3	$1.5 \cdot 10^{-3}$	(0.04, 0.06)
	25 ns	—	—	—	—	—	—	—
Linac4 (25 ns)	Standard	1.44	2.45	26	0.42	3	$1.5 \cdot 10^{-3}$	(0.04, 0.07)
	BCMS	1.44	1.51	26	0.42	3	$1.5 \cdot 10^{-3}$	(0.06, 0.11)

		LHC (n ×144-288 b/inj)				
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)
Achieved	50 ns	1.20	2.70	450	0.60	1.65
	25 ns	—	—	—	—	—
Linac4 (25 ns)	Standard	1.30	2.70	450	0.45	1.55
	BCMS	1.30	1.66	450	0.45	1.55

Table 2: Table showing the achieved beam parameters for 50 ns beams and parameters in reach with 25 ns beams using a single batch transfer scheme between PSB and PS.

by acceleration and flat top, whose lengths do not change with single or double batch beams). In the best case of dedicated LHC filling, this would translate into a reduction of the minimum waiting time of the LHC beams at 450 GeV by 17%. Given the emittance growth measured in the LHC between injection and collision, this potential reduction of the time at injection could have a beneficial impact on the attainable luminosity (especially in the case of strong electron cloud degradation of the 25 ns beams at 450 GeV), although it is very unlikely to lead to a better performance than the twice brighter double batch variants discussed in the previous part of this paper.

CONCLUSIONS

In summary, the present 25 ns beams can be delivered to the LHC well within specifications. The BCMS beams perform within emittance growth and intensity loss budgets throughout the injector chain, while the standard ones exhibit 15% larger emittance values at the exit of the SPS. These beams were successfully used at the end of 2012 for the LHC scrubbing run and a short pilot physics run. After LS1, due to the RF power limitations in the SPS, the intensity per bunch of the 25 ns beam can only be increased up to 1.3×10^{11} ppb out of the SPS. The possibility to further improve the performance reach of the injectors will then mainly rely on the potential brightness increase attainable from the relaxation of the longitudinal parameters at the PSB-PS transfer. This will be made possible by making all the RF manipulations in the PS at 2.5 GeV (as opposed to the present 1.4 GeV) and will play a major role in relaxing the space charge constraint at the PS injection thanks to the longer bunches and/or broadened momentum spread. In particular, standard and BCMS beams will be transferred to the PS with longitudinal emittances of up to 2.8 and 1.5 eVs, respectively, (compared to the present 1.2 and 0.9 eVs) leading to potentially 15–20% brighter beams at the SPS extraction.

After the PSB connection to Linac 4, beams with double brightness with respect to present beams will be delivered by the PSB. In absence of any other upgrade within the LHC injection chain, this will entail 33% brighter beams from the standard production scheme (which were originally limited by the PSB brightness), but no gain for the BCMS beams, which were already limited by the PS space charge. The space charge at the PS injection can actually be reduced by either flattening the bunch profile at the PSB-PS transfer (e.g. creating hollow bunches) or by changing the PS injection optics to enhance dispersion. These schemes, though promising and tested in MDs, have never been validated in standard operation. The PSB-PS single batch transfer scheme has the potential to decrease the minumum LHC injection time by 17% for the same initial brightness beams as with Linac 2.

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