POST LS1 25 NS AND 50 NS OPTIONS FROM THE INJECTORS

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Abstract

Pre-LS1, the parameters of the 50 ns and 25 ns LHC-type beams in the LHC injector chain have considerably improved with respect to their initial specifications. In addition significant and rather successful effort has gone into the development and testing of several alternative LHC beam production schemes in the injectors with the aim of providing high brightness beams to the LHC.

These schemes will be outlined together with their performance potential, possible challenges and additional requirements for their use by the LHC in the post-LS1 era.

2012 LHC 50 NS AND 25 NS EVOLUTION

The initial LHC multi-bunch beam characteristics, as given in Table 1 have evolved significantly since they were documented in 2004 [1]. During the Chamonix workshop on LHC performance, in January 2012, the performance reach of the injectors for 2012 was discussed [2] and a set of tentative beam characteristics for the 2012 run was extrapolated from results obtained during the 2011 run, exploring possible margins and taking into account known limitations in the different accelerators of the LHC injector chain. In the final days of the 2011 proton run, the SPS routinely delivered the 50 ns beam with an average transverse emittance of 1.9 μm and a bunch intensity of 1.5×10^{11} protons. All transverse emittances in this publication are the average of the horizontal and vertical emittances and are defined at 1 σ normalised. The tentative beam characteristics for the 2012 LHC run are summarized in Table 2 and foresaw a marginal increase in the average transverse emittance to 2 μm for a bunch intensity increase to 1.6×10^{11} protons, providing roughly the same brightness for a slightly higher intensity.

However, further improvements made during the 2012 run lead to a slightly higher bunch intensity of 1.65×10^{11} and a decrease of the average transverse emittances to 1.65 μm. The beam parameters obtained for the whole LHC injector chain in 2012 are summarised in Table 3.

Although the 25 ns beam was not used by the LHC during the physics run, it was regularly used for machine development studies. It should be noted that also the performance of this beam was enhanced, as for the first time the 25ns beam could be delivered well within specifications, with an average transverse emittance that was decreased from 3.6 μm to 2.6 μm out of the SPS for a nominal bunch intensity of 1.15×10^{11} protons.

Reminder of the classical 25 ns and 50 ns LHC beam production scheme

Both the 25 ns and 50 ns beams in the PS are produced, using the same well-established principles [3] that are based on different variants of longitudinal bunch splitting.

Table 1: Specified beam characteristics for the principal multi-bunch LHC beams in the injectors [1].

	PSB extraction				PS extraction			SPS extraction			
Beam	**Ip/ring [$\times10^{11}$]**	**$\varepsilon_{h/v}$ [μm]**	**nb batch**	**nb bunch**	**Ip/bunch [$\times10^{11}$]**	**$\varepsilon_{h/v}$ [μm]**	**nb bunch**	**Ip/bunch [$\times10^{11}$]**	**$\varepsilon_{h/v}$ [μm]**	**$\varepsilon_{long.}$ [eVs]**	**nb bunch**
25 ns	2.4 – 13.8	≤ 2.5	2	4 + 2	0.2 – 1.15	≤ 3	72	0.2 – 1.15	≤ 3.5	≤ 0.8	1 - 4×72
50 ns	1.2 – 6.9	≤ 2.5	2	4 + 2	0.2 – 1.15	≤ 3	36	0.2 – 1.15	≤ 3.5	≤ 0.8	1 – 4×36

Table 2: Proposed beam characteristics for the principal multi-bunch LHC beams in the injectors for the 2012 run [2].

	PSB extraction				PS extraction			SPS extraction			
Beam	**Ip/ring [$\times10^{11}$]**	**$\varepsilon_{h/v}$ [μm]**	**nb batch**	**nb bunch**	**Ip/bunch [$\times10^{11}$]**	**$\varepsilon_{h/v}$ [μm]**	**nb bunch**	**Ip/bunch [$\times10^{11}$]**	**$\varepsilon_{h/v}$ [μm]**	**$\varepsilon_{long.}$ [eVs]**	**nb bunch**
25 ns	16	2.5	2	4 + 2	1.3	2.5	72	**1.15**	**3.5**	0.7	1 - 4×72
50 ns	8	1.6	2	4 + 2	1.8	1.9	36	**1.6**	**2**	≤ 0.8	1 – 4×36

Table 3: Achieved beam characteristics for principal multi-bunch LHC beams in the injectors at the end of the 2012 run.

	PSB extraction				**PS extraction**			**SPS extraction**			
Beam	**Ip/ring [$\times 10^{11}$]**	**$\varepsilon_{h/v}$ [µm]**	**nb batch**	**nb bunch**	**Ip/bunch [$\times 10^{11}$]**	**$\varepsilon_{h/v}$ [µm]**	**nb bunch**	**Ip/bunch [$\times 10^{11}$]**	**$\varepsilon_{h/v}$ [µm]**	**$\varepsilon_{long.}$ [eVs]**	**nb bunch**
25 ns	16	2	2	4 + 2	1.3	2.4	72	**1.15**	**2.6**	0.7	1 - 4×72
50 ns	12	1.35	2	4 + 2	1.9	1.5	36	**1.65**	**1.65**	≤ 0.8	1 – 4×36

The PS Booster provides the beam in 2 batches of respectively 4 and 2 bunches. Special care is taken to provide the required longitudinal emittance, but also the transverse emittance blow up is kept as low as possible. The SPS will then receive up to 4 batches from the PS with each 36 or 72 bunches per batch for the 50 ns and 25 ns beams respectively.

The detailed PS production scheme for the 50 ns beam is illustrated in Fig 1. The production of the 25 ns bunch spacing beam is identical, apart from an additional longitudinal bunch splitting on the 26 GeV/c flattop. In order to maintain the extracted nominal bunch intensity and longitudinal emittance at PS extraction equal for the 50 ns and the 25 ns versions, the PS Booster bunch intensity for the 25 ns version is twice the intensity of the 50 ns version. In addition the 25 ns beam undergoes a controlled longitudinal blow up at PS injection to increase the longitudinal emittance by nearly a factor 2 in order to compensate for the extra longitudinal splitting.

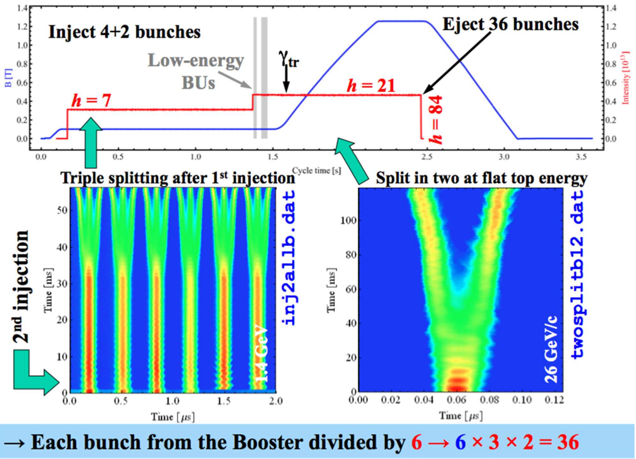

Figure 1: LHC 50 ns double batch beam production scheme.

For the first injection into the PS, the PS Booster provides 4 bunches, 1 bunch per ring. The second PS injection of 2 bunches takes place 1.2 seconds later. As a result 6 bunches are injected in the PS that uses the 7th harmonic, leaving 1 RF bucket unpopulated, to be used as PS extraction kicker gap. Towards the end of the long flat bottom each bunch is split in 3 by changing the RF harmonic of the 10 MHz cavities from h=7 to h=21. This results in 18 bunches that are then accelerated up to the 26 GeV/c flattop, where another harmonic change from h=21 to h=42 takes places, using the 20 MHz cavity. This final splitting provides a beam of 36 bunches followed by 6 empty buckets, all spaced by 50 ns that are handed over to the 40 MHz cavity running at h=84. The final step, just before extracting the beam, consists of shortening the bunch length to the required ~ 4 ns at 4σ, by increasing the 40 MHz cavity voltage, first adiabatically and later non-adiabatically. Once the rotated bunches have become sufficiently short to fit in the 80 MHz bucket, the 80 MHz cavities are added.

The transverse emittance established by the PS Booster multi-turn injection scheme is reasonably well preserved along the remainder of the injector chain and also explains the larger transverse emittance for the 25 ns beam at the extraction of each of the machines, starting at the PS Booster. For the 25 ns beam the bunch intensity per ring needs to be a factor 2 higher than for the 50 ns beam. In the PS Booster the transverse emittance increases linearly with the intensity per ring and thus per bunch.

LHC injectors 2012 performance improvement

During the 2012 run, much emphasis was put on the identification and reduction of transverse blow up sources in the PS Booster, PS and SPS, hence the transverse emittance reduction at SPS extraction from 2 µm in 2011 to 1.65 µm in 2012 for a slight increase in intensity per bunch, as given in Table 2 and Table 3.

In order to monitor the beam brightness evolution in the different machines, systematic measurements and logging of the measurement results was put in place in July. Fig. 2 shows an example of the beam brightness evolution in the PS. The red crosses represent the bunch intensity at PS extraction, while the blue squares represent the brightness of the extracted beam. These plots were regularly updated for the different machines in order to follow the trend and to identify possible beam brightness degradation. For example, early August an improvement on the PS Booster injection matching was identified and implemented. As a result the beam brightness increased and the PS working point had to be adapted in order for the LHC to profit from this improvement. In Fig. 2 this is visible by a step increase of the beam brightness, while the intensity per bunch remained constant.

In September another important improvement was introduced, but this time in the SPS, when the Q26 working point made place for the newly developed Q20 working point, lowering the transition energy and thus moving it away from the injection energy. The aim is to remove or at least ease the intensity limitations in the SPS with minimal cost and no hardware changes [4]. The new optics was thoroughly and successfully tested before being used to fill the LHC.

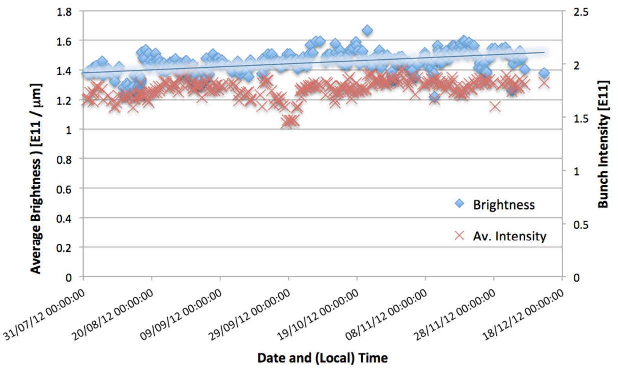

Figure 2: PS flattop beam brightness and bunch intensity evolution from the end of July until the end of the 2012 proton run.

Fig. 3 illustrates this improvement by indicating the beam brightness measurements on the SPS flattop, the LHC flat bottom and the LHC flattop over about 300 fills, during which the Q20 working point was introduced.

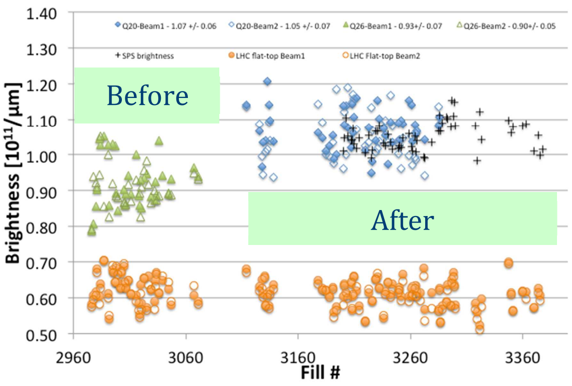

Figure 3: SPS and LHC beam brightness before and after the Q20 deployment.

With the Q26 working point the beam brightness, as measured on the LHC flat bottom, lies around 0.9×10^{11} p/µm with a spread of about 0.12×10^{11} p/µm. After the deployment of the Q20 working point the beam brightness increased by nearly 20% to an average of 1.05×10^{11} p/µm with approximately the same spread of 0.12×10^{11} p/µm. However, as a result of transverse emittance blow up during the LHC ramp and/or squeeze the beam brightness on the flattop in the LHC could not yet benefit from this injector performance improvement.

The continuous optimisation resulted in considerably brighter beams from the LHC injectors. Table 4 summarises the initial beam parameters available to the LHC in April, when the SPS started producing the 50 ns beam in 2012, and the beam parameters at the end of the 2012 run, together with the relative improvements.

Table 4. Summary of beam parameter out of the SPS start and end 2012 run.

	April	November	Relative change
Intensity [×10]	1.4	1.65	+ 18%
$\varepsilon_{h/v}$ [µm]	1.8	1.65	- 10%

Some limitations and difficulties encountered

The reduction of the transverse beam size in the PS Booster also means that beam alignment errors in the recombination process will result in larger relative transverse emittance blow up in the PS, as the injection oscillations of the individual bunches cannot be corrected. The transverse damper, which was tested in 2012 and will be made operational for 2014, will alleviate this situation.

The increase of the beam brightness intensifies the PS injection space charge effects with the danger of transverse emittance blow up, especially during the 1.2 second long flat bottom. In order to avoid this, the working point needs to be controlled precisely.

Another issue encountered does not lie in the production of the high brightness beams, but in measuring its transverse emittance. The PS Booster and the PS do not contain non-dispersive regions. Therefore the dispersion contribution needs to be subtracted from the measured beam size. Errors in the determination of the dp/p and the dispersion value at the wire scanner position will make the precise determination of the transverse emittances more difficult for the low emittance beams. In the SPS the small beam sizes result in only about 15 measurement points per wire scan. Accumulating measurements during multiple cycles enhances the precision of the measurement and thus the fit, but it will also average the difference between the batches. In addition the combination of the beam intensity and brightness on the SPS flattop provides beam conditions that are beyond the breakage limit of the wire, excluding transverse emittance measurements at high energy in the SPS.

THE MENU FOR POST-LS1

The classical 50 ns and 25 ns beams

The classical 25 ns and 50 ns beams should remain available for the LHC after LS1 with the beam characteristics as presented previously. However some of the LS1 activities, in particular the exposure to air of the SPS vacuum chambers, can potentially compromise the performance temporarily as a result of an increase of the secondary emission yield for electrons, possibly resulting in electron cloud issues.

The high-brightness 50 ns and 25 ns beams

In parallel to the continuous optimisation of the classical 50 ns beam the new 50 ns and 25 ns beam production schemes, developed in the framework of the LIU project [5] were tested successfully in the injectors.

These beams were also occasionally provided to the LHC for tests.

The roots for this new scheme reside in the fact that the PS Booster transverse emittance increases linearly with intensity. Therefore, lowering the intensity per ring and making use of all rings, with 1 bunch each, for both batches to the PS, in combination with a longitudinal bunch-merging scheme in the PS, the bunch intensity can be increased while the transverse emittance is preserved, provided space charge effects are managed correctly. As a result the so-called Batch Compression, Merging and Splitting (BCMS) scheme has been developed, which is illustrated in Fig. 4.

The PS Booster will produce two batches of 4 bunches each, still injected 1.2 seconds apart into the PS, which has the 10 MHz RF system working on h=9. On an intermediate flattop of 2.5 GeV, where longitudinal acceptance is increased and space charge effects are reduced, a batch compression will take place, inserting empty buckets along the PS circumference, by increasing the RF harmonic number in steps from h=9 through h=10, h=11, h=12, h=13 to h=14, resulting in 8 bunches and 6 empty buckets. The second stage consists of merging 2 bunches into 1 bucket by changing the harmonic from h=14 to h=7. The merged bunches contain twice the intensity, for the same transverse emittance. The 4 bunches obtained are then each split in 3 going from h=7 to h=21, resulting in 12 bunches and 9 empty buckets. The beam is then accelerated up to the 26 GeV/c flattop, where another harmonic change from h=21 to h=42 takes places, using the 20 MHz cavity and splitting the bunches. A final bunch rotation will then provide 24 bunches spaced a 50 ns. However, for the 25 ns bunch spacing version, before performing the final bunch rotation, an additional bunch splitting, increasing the harmonic from h=42 to h=84, will produce 48 bunches spaced at 25 ns.

The intensity required from the PS Booster per ring for 24 bunches at 50 ns on the BCMS scheme is a factor 2 lower than for the 36 bunch 50 ns classical beam, hence the increase of beam brightness, at the expense of a reduced number of bunches. Optimising the LHC filling scheme can for the major part compensate the later.

Table 5 summarises the performances achieved in 2012 with both the classical and the BCMS production schemes, which will also be the expected performance available after LS1.

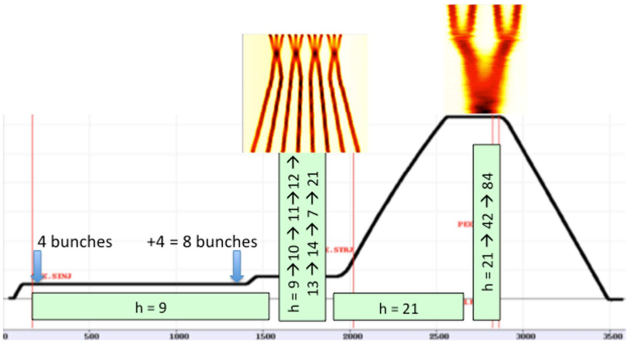

Figure 4: LHC 25 ns BCMS beam production scheme.

The number of bunches per PS batch from the BCMS beams is 50% lower than for the classical scheme. However, injecting 5 batches instead of 4 in the SPS and optimizing the LHC filling scheme will only result in a 10% reduction of the number of bunches in the LHC.

In order to evaluate the potential increase in luminosity for the BCMS scheme the luminosity is calculated using eq. 1, assuming that all geometrical parameters, such as crossing angle etc. remain constant.

$$L \propto \frac{N^2}{\varepsilon} M \tag{1}$$

N represents the number of protons per bunch, M the number of bunches and ε the average transverse emittance.

In Fig. 5 the classical 50 ns beam, as produced at the end of the 2012 proton run is taken as a reference, normalised with the number of bunches that can be stored per beam in the LHC. The other beam variants with each their maximum number of bunches in the LHC per beam are then compared to the classical 50 ns version. From this it is clear that the newly developed BCMS production scheme will provide substantially higher luminosity than the classical scheme.

Table 5: Beam characteristics overview for the classical and batch compression, merging and splitting (BCMS) scheme achieved in 2012 and expected for after LS1.

	PSB extraction				**PS extraction**			**SPS extraction**			
Beam	**Ip/ring $[\times10^{11}]$**	**$\varepsilon_{h/v}$ [μm]**	**nb batch**	**nb bunch**	**Ip/bunch $[\times10^{11}]$**	**$\varepsilon_{h/v}$ [μm]**	**nb bunch**	**Ip/bunch $[\times10^{11}]$**	**$\varepsilon_{h/v}$ [μm]**	**$\varepsilon_{long.}$ [eVs]**	**nb bunch**
25 ns	16	2.3	2	4 + 2	1.3	2.5	72	**1.35**	**~3**	0.7	1 - 4×72
50 ns	12	1.35	2	4 + 2	1.9	1.5	36	**1.65**	**1.65**	≤ 0.8	1 – 4×36
25 ns BCMS	7.5	1	2	4 + 4	1.2	1.2	48	**1.15**	**1.4**	0.7	1 - 4×48
50 ns BCMS	6	0.9	2	4 + 4	1.9	1.1	24	**1.6**	**1.2**	≤ 0.8	1 – 4×24

The 50 ns BCMS beam produces about 20% more luminosity, but will also increase the pile-up in the experiments, which is already considered being high. The 25 ns BCMS provides close to 30% more luminosity than the classical version and about 5% more than the classical 50 ns beam. The latter means that with the 25 ns BCMS a slightly higher luminosity can be produced, but with twice the amount of bunches, therefore reducing the pile-up by 50%.

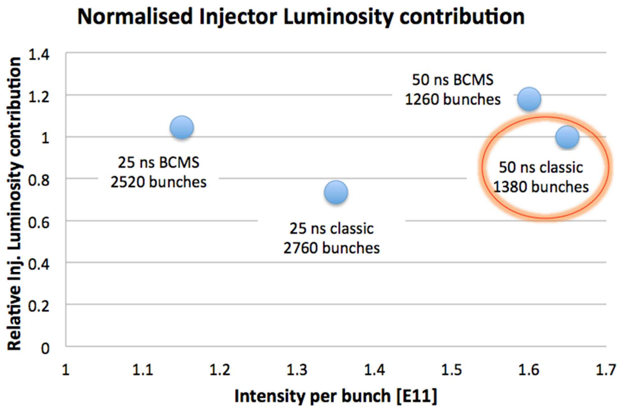

Figure 5: Relative luminosity contribution by the injectors for the different production schemes.

Although the BCMS beams have been successfully tested and have proven to provide good performance, these beams are new and were only commissioned during the autumn of 2012. Since then these beams were produced in a machine development context, providing little, but nevertheless some operational experience. During the 2014 injector run these beams will undergo further development and will need to be made fully operational, while exploring their performance limitations.

LS1 WORK POTENTIALLY IMPACTING THE BEAM PERFORMANCE

During LS1 many machine improvements are foreseen. However some of these can also form potential issues or challenges during the restart in 2014.

In the PS Booster the magnet stacks will be realigned with the aim to improve the uncorrected closed orbit. In addition the orbit correctors will be powered making it possible to correct the closed orbit, using also new beam position monitors. A new transverse damper will also be installed and commissioned, in parallel to the existing transverse feedback.

The PS magnets will be realigned, followed by a beam-based realignment during the 2014 restart. The transverse damper will be made operational in both planes, making the PS less dependent on the residual PS booster recombination errors. The longitudinal beam control will also be upgraded with a new 1-turn delay feedback, an increase of voltage available per 10 MHz cavity tuning group and a new longitudinal feedback kicker, for which no experience exists in the PS.

The SPS machine will also be partly realigned, mainly in sector 6. The ungrounded vacuum chambers that caused orbit perturbation in 2012 will be grounded and the loose shims will be consolidated. The MKE kicker that presently presents a limitation due to heating will be equipped with improved shielding, using serigraphy. The entire 800 MHz RF system will undergo a complete overhaul and the transverse damper will be upgraded and a high bandwidth system will be developed. The beam-based realignment during the 2014 start up will focus on the high-energy orbit for the Q20 optics. The SPS vacuum chambers will be opened in many places, risking an increase in the electron secondary emission yield. This means that substantial scrubbing will be required during the 2014 run in order to retrieved the good conditions of 2012, obtained after “years” of scrubbing.

In addition to these machine-specific changes and consolidation a general and major timing and controls renovation will take place. All these changes need to be commissioned and made operational at start up in 2014.

CONCLUSIONS

The operational beam performance in the LHC injector chain has evolved considerably during the 2012 run, mainly by identifying and reducing transverse emittance blow up sources. The new high-brightness LHC beams have been developed within the LIU project and were tested successfully toward the end of 2012, using a scheme of batch compression, merging and splitting. As a major result the 25 ns BCMS beam will provide a slightly higher luminosity in the LHC than the classical 50 ns beam, with the advantage that the event pileup in the detectors will be reduced by a factor 2.

The LS1 activities will potentially improve the machines status and should contribute to a better beam performance. However, the new and/or consolidated systems will need to be commissioned and made fully operational in order to be able to fully benefit from their potential.

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