PERFORMANCE REACH OF THE INJECTOR COMPLEX IN 2012

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Abstract

At the start of the 2011 physics run, quite some margin in the performance of the injectors was available and identified. Following the fast increase of the performance of the LHC itself during 2011, these margins have very much been exploited and some have even been pushed further.

In view of further increase in the LHC luminosity, the 2012 performance reach of the injectors will be reviewed. One of the arising topics is satellite bunches from the injectors. Until now concerted effort went into supressing satellite bunches to a minimum, but a recent successful test with "controlled" satellites might make their routine production and characterisation an important topic in 2012.

This paper will treat the 2012 performance reach for the protons in the injector chain and mainly concentrates on the beam with 50 ns bunch spacing, as the 25 ns bunch spacing variant does not meet the required integrated luminosity needs for 2012. This paper will not treat LHC Injector Upgrade (LIU) project tasks and will therefore not deal with the performance after the long shutdown, LS1, in 2013/2014.

BRIEF REMINDERS OF LAST YEARS' CHAMONIX WORKSHOP

During the 2011 Chamonix workshop the performance reach of the injectors in 2011 was presented and discussed [1]. The emphasis was on the differences between the beam characteristics as specified [2] and those obtained, both given in Table 1 and 2, respectively.

The injector complex performance profited from the margins that were available in the beams with bunch spacing larger than 25 ns. Beams with larger bunch spacing and thus less bunches, require injecting fewer protons into the PS Booster and result in lower transverse emittances, and thus higher beam brightness.

Further possible sources of increasing beam brightness were addressed: 1) increasing the LINAC2 beam current from 160 mA to the specified 180 mA and 2) applying double batch injection from the PS Booster into the PS.

A test with a LINAC2 beam current of 177 mA was performed, but the increase of beam brightness in the PS Booster was insignificant [3]. The second option, double batch injection from the PSB into the PS, was also followed up and gave results that exceeded expectations.

Table 1: Documented beam specifications for principal multi-bunch LHC beams in the injectors [2].

	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	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: Possible beam characteristics for principal multi-bunch LHC beams in the injectors for 2011.

	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 (DB)	16	2.5	2	4 + 2	1.3	2.5	72	1.15	3.6	0.7	1 - 4×72
50 ns (SB)	24	3.5	1	3 x 2	1.75	3.5	36	1.45	3.5	≤ 0.8	1 – 4×36
50 ns (DB)	8	1.2	2	4 + 2	1.3	1.3	36	1.15 (?)	1.5 (?)	≤ 0.8	1 – 4×36

* Given transverse emittances are 1σ normalized.

THE 2011 INJECTORS PERFORMANCE

The 2011 LHC commissioning and first stable beams were achieved using the single batch injection, 75 ns bunch spacing beam. However, the LHC quickly increased its capability to accept brighter beams and the injector complex needed to anticipate an increase in performance.

Beam Evolution

Following the successful scrubbing run, during the first week of April, the switch to the single batch injection, 50 ns bunch spacing beam was made, increasing the number of bunches per extraction out of the PS from 24 to 36. However, the intensity per bunch and the transverse emittance were initially similar.

On July 14th the single batch injection into the PS was replaced by a double batch injection, reducing considerably the transverse emittances from about 3.5 μm 1σ normalized to about 1.9 μm 1σ normalized, as mentioned in Table 3. Initially a controlled blow up of the transverse emittance was performed in the SPS in order to maintain the same beam conditions and thus brightness as with the single batch injected beam. This blow up was gradually decreased and definitively removed by the end of July, as is illustrated in Fig. 1.

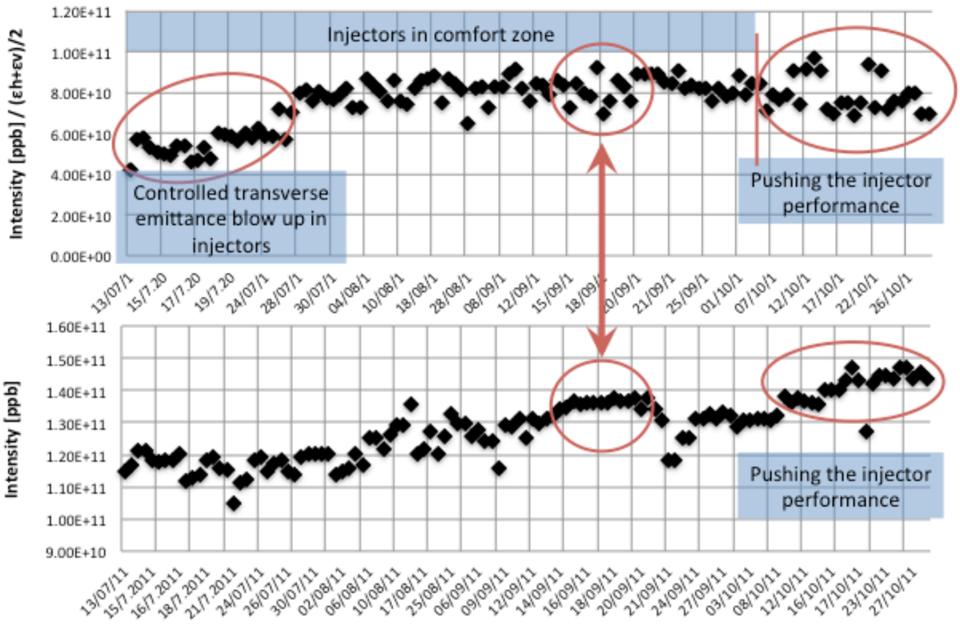

Fig. 1: LHC 50 ns beam brightness and intensity ejected from the SPS as a function of date, based on data extracted from the SPS logbook.

The double batch injected, 50 ns bunch spacing beam has been the workhorse for the remainder of the 2011 run. After the controlled transverse blow up was removed, the performance of this beam was pushed further by gradually increasing the intensity per bunch from 1.2×10^{11} to a maximum 1.5×10^{11} in the second half of October. Due to the nature of the beam production and injection in the PS Booster an increase of intensity also resulted in an increase of the transverse emittances. The intensity was increased by about 30%, while the transverse emittances increased by about 27%, which resulted in a small increase in the beam brightness, as is illustrated in Fig. 1. The final performance that was reached in 2011 for the different beams is summarized in Table 3. It is worth noting that the 25 ns bunch spacing beam was for the first time produced within specification throughout the entire injector chain.

As indicated in Fig. 1 the LHC injectors ran in a kind of comfort zone until the start of October, with beam parameters that were relatively easy to produce and reproduce. However, from October 9th onwards, when the intensity was increased further from 1.3×10^{11} to 1.4×10^{11} and later even briefly to 1.5×10^{11}, the beam brightness was not increasing in a stable manner. Actually the average beam brightness decreased, indicating that the injector complex was performing at or close to a limit and that the beam quality at this intensity needed consolidation.

Improved Operability

The double batch 50 ns beam became actually only operational in 2011. Thanks to the many machine development sessions, but also during normal operation more and more experience was gained and improvements along the injector chain were made, such as the introduction of dedicated users for the 12 bunch and 36 bunch versions, experience in adjusting the longitudinal bunch splitting parameters in the PS, etc.

Table 3: Beam characteristics for principal LHC beams in the injectors as produced in 2011.

Beam	PSB extraction				PS extraction			SPS extraction			
	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 (DB)	16	2.5	2	4 + 2	1.3	2.5	72	1.15	3.5	0.7	1 - 4×72
50 ns (SB)	24	3.5	1	3 x 2	1.75	3.5	36	1.45	3.5	≤ 0.8	1 – 4×36
50 ns (DB)	10	1.4	2	4 + 2	1.6	1.6	36	1.5	1.9	≤ 0.8	1 – 4×36

THE LHC DOUBLE BATCH 50 NS BEAM PRODUCTION

The LHC double batch 50 ns beam is produced in the PS [4, 5], receiving 4 bunches from the PS Booster during the first injection and 2 bunches 1.2 seconds later, during the 2nd injection. This results in a total of 6 bunches in the PS with an RF harmonic h=7, leaving one RF bucket unpopulated, to be used as extraction kicker gap. Fig. 2 illustrates the PS cycle with the long flat bottom, indicating the injection scheme.

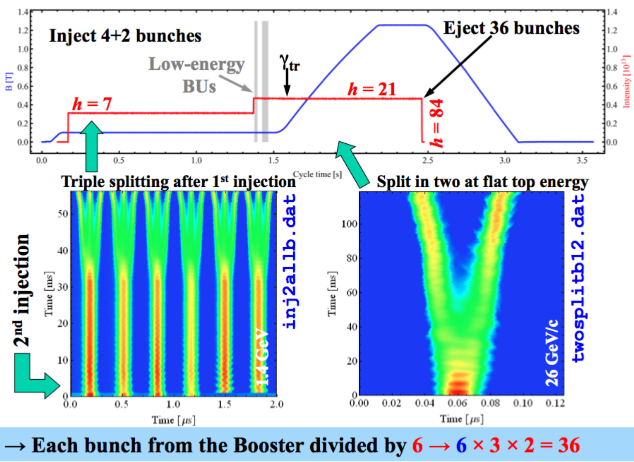

Figure 2: LHC 50 ns double batch beam production scheme.

The 6 injected bunches are each split in 3 by changing the RF harmonic from h=7 to h=21, resulting in 18 bunches as indicated in the waterfall plot in the left bottom corner of Fig. 2. After acceleration to 26 GeV/c on h=21 each bunch is split in 2, increasing the number of bunches to 36 and leaving 6 RF buckets (h=42) empty. The bunches are subsequently handed over to h=84 (40 MHz), keeping their spacing at 50 ns. Before extracting the beam an adiabatic voltage increase, using the 40 MHz cavity, reduces the bunch length to about 13 ns, followed by a bunch rotation, using a non-adiabatic RF voltage increase on the 40 MHz and 80 MHz cavities, in order to obtain bunches of about 4 ns long at 4σ. As a result of the multiple longitudinal bunch splittings, the longitudinal emittance received from the PS Booster would ideally be divided by a factor of 6. However, controlled longitudinal blow-up with a phase modulated 200 MHz RF system is applied to cross transition, to keep the beam stable thereafter and to provide the specific longitudinal emittance of 0.35 eVs per bunch at PS extraction.

The small transverse emittances, of about 1.4 μm 1σ normalized, provided by the PS Booster rings, are reasonably well preserved during acceleration in the PS. Bunches of maximum 1.6×10^{11} protons within 1.6 μm 1σ normalized are then injected into the SPS in up to 4 batches of 36 bunches each. These 144 bunches are accelerated in the SPS and after extraction bunches of up to 1.5×10^{11} protons within 1.9 μm 1σ normalized are delivered to the LHC. Table 3 provides an overview of the different beam characteristics along the LHC injector chain, as obtained in 2011.

Potential issues impacting on the beam quality are space charge in the PSB and the PS that can cause an increase in transverse emittances. Above transition energy, longitudinal coupled-bunch instabilities are damped using a feedback on 2 of the 10 MHz cavities. In case these coupled bunch instabilities cannot be suppressed the longitudinal beam quality might be degraded such as: varying longitudinal emittance and bunch length along the batch, but also bunch-to-bunch intensity variation and significant satelites in-between bunches. Scrubbing in the SPS remains important for this beam, as otherwise e-cloud development could cause instabilities, especially if the intensity would be increased further.

MARGINS LEFT FOR IMPROVEMENT

The aim for the LHC injector chain is to improve on the beam characteristics in order to increase the beam brightness. Without making important hardware changes as proposed by the LIU project [6, 7], the main parameters of focus are the intensity per bunch and the transverse emittances.

Increase of Beam Brightness

Concentrating on the bunch intensity and the transverse beam emittance, the luminosity in the LHC is proportional to the square of the number of particles per bunch and inversely proportional to the transverse emittances, as is shown in Eq. 1, where the contribution from the geometric reduction factor has been neglected.

* Given transverse emittances are 1σ normalized.

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

However, an increase in intensity from the PS Booster also results in an increase of the transverse emittances, as illustrated in Fig. 3.

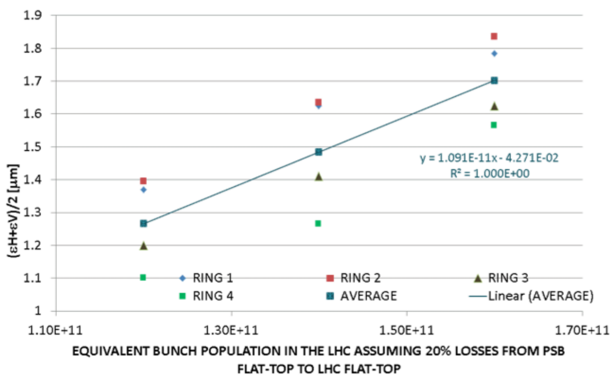

Figure 3: The linear relationship between intensity and transverse emittance per ring in the PS Booster.

Since the relationship between intensity increase and emittance increase is approximately linear, the luminosity in the LHC becomes proportional to the intensity per bunch, as long as any emittance blow-up in the LHC itself can be neglected. Therefore Eq. 1 can be reduced to Eq. 2, provided the whole injector chain can deal with brighter beams without blowing up the transverse emittances further.

$$L \propto N \tag{2}$$

This means that, without implementing major changes in the LHC beam production, as is foreseen within the LIU project, the gain is to be expected from an intensity increase.

However, careful analysis of the graph in Fig. 3 combined with PS double batch filling scheme as explained above, a small improvement could come from optimizing the selection of beam from the PS Booster rings. At present the PS injection scheme injects 4 bunches from the 4 rings during the first batch and 2 bunches from rings 3 and 4 during the second batch. The graph in Fig. 3 shows that the rings 3 and 4 provide higher brightness than the rings 1 and 2. Injecting 3 bunches during each batch, selecting the best rings, could contribute to an increase of the beam brightness. The extreme possibility that could be considered is injecting 3 batches, using ring 3 and 4 only. However, space charge issues during the prolonged flat bottom in the PS might become an issue.

The ultimate solution would be to identify the reason for the increased emittances from the rings 1 and 2 and correct them if possible.

Potential Issues for an Intensity Increase

An intensity increase in the PS Booster needs to be done carefully, taking into account space charge, in order not to degrade the linear relationship between intensity and transverse emittances, as given in Fig. 3.

The long PS flat bottom in combination with higher space charge increases the risk of transverse emittance blow up, especially for the batch injected first. Also transient beam loading in the cavities might increase slightly the spread in longitudinal beam characteristics within the bunch train.

The SPS needs a well-scrubbed machine to avoid issues with e-cloud. Increasing the intensity might also increase the SPS injection losses requiring more intensity to compensate these losses, resulting in higher transverse emittances. For bunch intensities of 1.5×10^{11} and higher, the voltage of the electrostatic septum, used for the slow extraction of the beam towards the SPS North Area (ZS), needs to be lowered to values that are not compatible with beam extraction to the SPS North Area. The build-up of vacuum pressure in the same ZS, when accelerating many LHC cycles in a super cycle, also prevents the SPS from going to shorter LHC filling super cycles, making dedicated filling difficult or even impossible.

A FEW WORDS ON SATELITES

Satellite bunches have long been considered a nuisance by the experiments as they increase the background. However, recently the ALICE experiment expressed interest in using collisions between main and satellite bunches for their proton physics run. A test with enhanced or parasitic satellite bunches was made during the 2011 run and the results have been discussed during the Evian workshop on LHC beam operation. During this workshop it became clear that the experiment would no longer request a beam with enhanced satellite bunches and that the spurious satellite bunches within the beam will be used.

However, enhancing the main-bunch beam performance throughout the injector chain may alter the satellite bunch conditions. The injectors have at present no means to quantify or qualify these satellite bunches. Therefore they should be taken as they come.

CONCLUSIONS

The operational beam performance in the injector chain has evolved considerably since the 2010 run and is much better than ever anticipated. Available margins have been well exploited and leave little room for further performance increases, unless changes as foreseen by the LIU project are implemented.

The best operational performance to the LHC in 2011 was a beam with a bunch intensity of 1.5×10^{11} protons in 1.9 µm 1σ normalized, resulting in a beam brightness of 7.9×10^{10} p/b/µm. After careful adjustments of the beam in the injector chain the anticipated operational performance to the LHC in 2012 is a beam with a bunch intensity of 1.6×10^{11} protons in 2 µm 1σ normalized, resulting in a beam brightness of 8×10^{10} p/b/µm. The beam parameters along the injector chain for this performance are summarized in Table 4.

of beam characteristics and brightness, but also on the North Area physics time, might need to be made.

The injector chain will attempt to increase the performance beyond the values given in Table 4, but this might mean that some compromises on the reproducibility of beam characteristics and brightness, but also on the North Area physics time, might need to be made.

Table 4: Tentative operational beam characteristics for principal LHC beams in the injectors in 2012.

	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**
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