# BEAMS FROM THE INJECTORS

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## *Abstract*

During the LHC proton physics run in 2016 the injectors were regularly providing 25 ns beams, in both the standard and the high brightness, i.e. BCMS, variant. In this paper, the achieved parameters for these two beam production schemes are analysed and compared to the expected performance reach of the LHC injector complex. It is shown that the standard beam could be produced close to the known performance limits, while the high brightness BCMS beams suffered from emittance blow-up especially in the PS. First results from machine development studies addressing this issue are presented, showing the potential for mitigating at least part of the blow-up in the future. An outlook of the expected beam parameters from the injectors in 2017 is given, including also special beam variants like the 8b4e, the 80 bunches and the doublet scrubbing beam.

## INTRODUCTION

The LHC proton physics production run in 2016 was based on beams with the nominal 25 ns bunch spacing [1]. For the first half of the run the LHC was using the 25 ns beam produced with the nominal scheme in the injectors as described in the LHC design report [2]. This beam is nowadays referred to as the “standard” beam. In order to push the luminosity in the LHC experiments, the high brightness variant of the 25 ns beam produced with the Batch Compression bunch Merging and Splitting (BCMS) scheme [3, 4] was used in the second half of the run. In this paper the 2016 achieved performance of these two beam types is analyzed and compared to the expected performance reach of the LHC injector complex at the present stage. In addition to the measures for reducing losses at the PS-to-SPS transfer already implemented in 2016, possibilities for improving the emittance preservation along the injector chain are illustrated through promising results from machine development (MD) studies. Other available beam types such as the 8b4e, the 80 bunch scheme and the doublet scrubbing beam are also briefly discussed. For each of these beam types an outlook of the beam parameters to be expected in 2017 is given in a summary table at the end of this paper.

## 25 ns STANDARD AND BCMS BEAMS

Figure 1 summarizes the achieved beam parameters for the standard 25 ns beam: The graph on the left hand side shows the average transverse emittance measured with the LHC Beam Synchrotron Radiation Telescope (BSRT) right after injection as a function of the average intensity per bunch for the 26 LHC physics fills between June 11 and July 7. The shaded areas indicate beam parameters which are not accessible due to the known performance limitations of the LHC injector chain, taking into account intensity loss and emittance growth budgets of 5% in the PS and 10% in the SPS, respectively. Space charge in the PSB and the PS are expected to limit the achievable beam brightness. The presently available RF power for beam loading compensation in the SPS allows extracting 25 ns beams with up to about $1.3 \times 10^{11}$ p/b. There is quite some spread in the measured beam parameters from fill to fill in particular regarding the transverse emittances. However in some cases the standard beam could be produced very close to the performance limits of the injector chain.

The graphs on the right hand side of Fig. 1 show the horizontal (top) and vertical (bottom) emittances along the injector chain measured with the standard beam during the same period. This data was extracted from the LHC supertable [5], which associates the automatically logged wire scanner measurements of the LHC beams performed routinely by the injectors operation crews with LHC fill numbers. The error bars indicate the spread in the measurements. The measurements in the PSB are performed just before extraction. There are no measurements available for Ring 4 of the PSB, as its wire scanners were out of order. Apart from a short period at the beginning of the run (until end of April, i.e. before the period analyzed here) during which the working points in the PSB rings were not at the optimized values for LHC beams, the transverse emittances out of the PSB basically followed the expected brightness curve imposed by space charge effects at low energy [6]. Only minor emittance degradation is observed along the rest of the injector chain up to the LHC, except for a significant blow-up that appears to occur at the transfer from the PSB to the PS. In fact about 40% larger horizontal and about 15% larger vertical emittances are measured after injection in the PS compared to the values at PSB extraction. Some blow-up is expected due to the known dispersion and optics mismatch between the two machines, which is difficult to avoid with the present transfer line configuration before the LHC Injectors Upgrade in Long Shutdown 2 (LS2). However according to the available optics models this blow-up should be less than 10% for the standard beam [7]. Machine development studies on this subject were not yet conclusive and further investigations need to follow in 2017. It should also be mentioned that the measured beam profiles in the horizontal plane in both the PSB and the PS have large contributions from the beam momentum spread (through dispersion), which has almost a parabolic distribution and is therefore strongly non-Gaussian. The correct

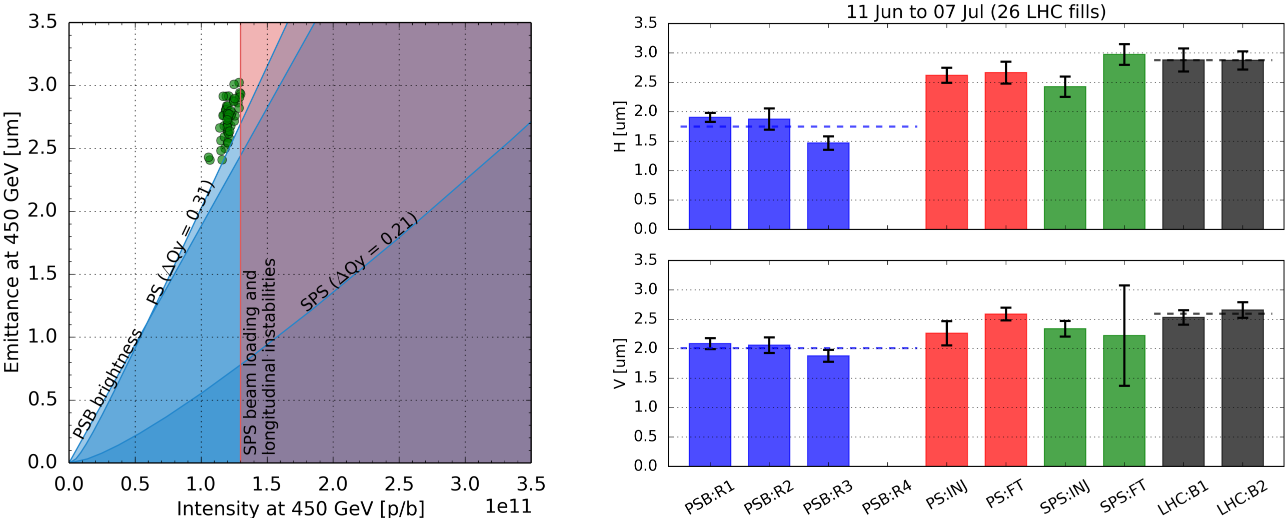

Figure 1: Transverse emittance as function of intensity at LHC injection for the 25 ns standard beam operationally achieved in 2016 (left) and details on the emittance evolution along the injector chain (right).

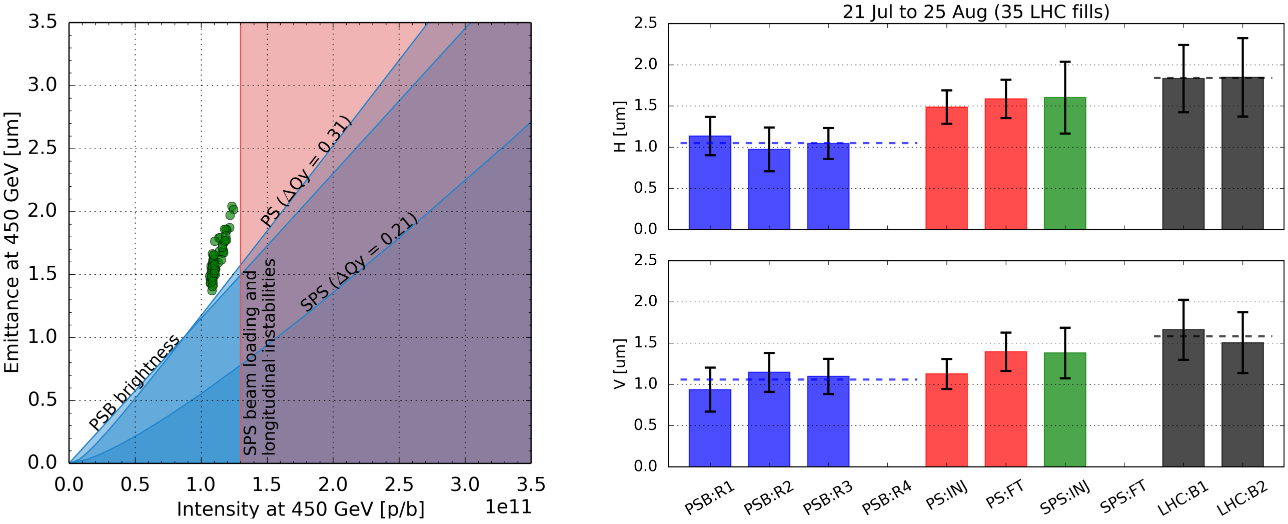

Figure 2: Transverse emittance as function of intensity at LHC injection for the 25 ns BCMS beam operationally achieved in 2016 (left) and details on the emittance evolution along the injector chain (right).

evaluation of the horizontal emittances in these conditions is also being investigated, e.g. performing a deconvolution of the betatronic and the dispersive beam profile contributions using the reconstructed longitudinal distribution from the Tomoscope [8, 9].

Figure 2 shows a similar analysis for the BCMS beam operationally delivered to the LHC: As can be seen on the graph on the left hand side, the expected performance limit of the BCMS beam could not be reached during the period between July 21 and August 25 of the 2016 run[1]. It appears as if the brightness degraded with beam intensity. While the beam brightness extracted from the PSB follows again closely the expected curve [6], there is considerable emittance degradation along the injector chain as shown in the graphs on the right hand side of Fig. 2. As for the standard beam, there is a horizontal blow-up at PS injection which needs to be understood (50% observed in measurements compared to 20% expected from the optics mismatch for BCMS beam parameters [7]). In addition, there is also vertical blow-up along the PS cycle. Before addressing this point in more detail, it should be mentioned that in routine operation no emittance measurements were performed on the SPS flat top for the BCMS beam because the resolution of the existing wire scanners is insufficient for a reliable beam profile reconstruction.

Figure 3 shows measurements of the vertical emittance along the PS cycle for the BCMS beam in operational conditions. The bunches of the first batch suffer from about 10% blow-up along the injection plateau, which can be ex-

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[1] This period corresponds to the time after the voluntary emittance blow-up requested by the LHC in the transition period from standard to BCMS beams and before the BSRT in the LHC was re-calibrated.

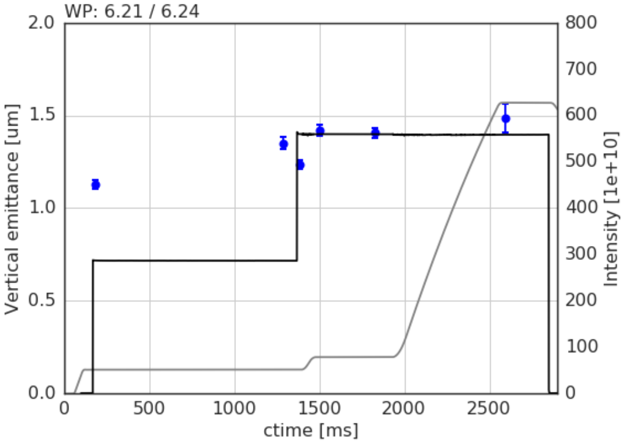

Figure 3: Vertical emittance measured along the PS cycle for a BCMS beam in operational conditions with the working point (6.21/6.24).

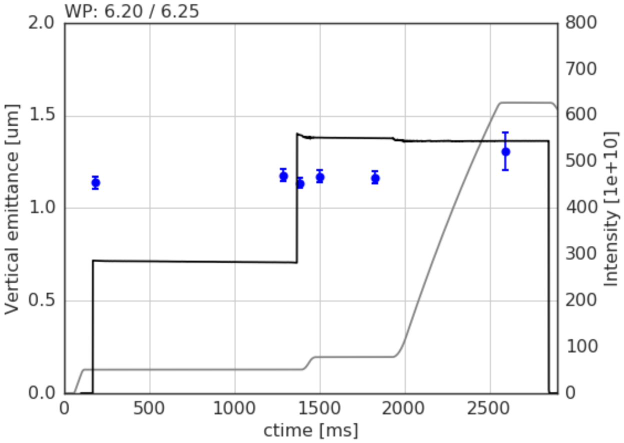

Figure 4: Vertical emittance measured along the PS cycle for a BCMS beam with an optimized low energy working point (6.20/6.25) and a modified RF voltage function to provide constant bucket area during the first acceleration to 2.5 GeV.

plained by the large direct space charge tune spread exceeding the vertical integer resonance. Right after the injection of the second batch the measured emittance is reduced, because the wire scanner measures the average emittance of all bunches. When arriving at the 2.5 GeV intermediate plateau the total emittance growth reaches about 15% compared to the value at injection. During MDs in 2016 it could be shown that this blow-up is due to the bunch shortening caused by the large RF voltage used for acceleration (200 kV), which further enhances the space charge detuning. The vertical blow-up in the PS could be significantly reduced by a) slightly increasing the vertical tune from $Q_y = 6.24$ to $Q_y = 6.25$ in combination with a reduced RF voltage on the injection plateau in between the two injections and b) using an RF voltage function that provides constant bucket area during acceleration in order to avoid as much as possible the bunch shortening. Figure 4 shows the emittance evolution for an MD cycle with these optimizations. Slightly higher losses are encountered during acceleration to 2.5 GeV, which might be avoided by further optimization of the voltage program. These studies give prospect of improved emittance preservation for the high brightness beams in 2017.

Another critical point for the production of LHC beams with 25 ns bunch spacing are losses in the SPS encountered on the flat bottom and during the beginning of the ramp, which reach a total of more than 10% in some cases. MDs in 2016 showed that most of these losses (even the ones on flat bottom) are longitudinal [10]. An important contribution to these losses comes from uncaptured beam directly resulting from the “S” shape of the longitudinal distribution at PS extraction: For injection into the SPS 200 MHz bucket the bunch length needs to be reduced from about 11 ns to 4 ns, which is achieved by bunch rotation at PS extraction using a combination of 40 and 80 MHz cavities. Optimizing the bunch rotation scheme with increased RF voltage at 40 MHz using a second cavity (usually served as hot spare) allowed reducing the losses in the SPS by 40% [11]. This optimized scheme was used in routine operation during the last months of the proton run. Almost as a side product, losses at LHC injection improved by a factor 10 due the reduced population of ghost bunches [12].

Due to a vacuum leak that developed inside the SPS high energy internal beam dump (TIDVG) shielding at the beginning of 2016, the total intensity per LHC injection had to be restricted throughout the run. The standard 25 ns beam was delivered only in single batches, i.e. trains of 72 bunches. For the BCMS beam up to two batches could be transferred per LHC injection, i.e. trains of $2 \times 48 = 96$ bunches. It is planned to install a new SPS high energy beam dump (TIDVG#4) during the EYETS 2016/17. After the TIDVG replacement, all the SPS intercepting devices will be ready for operation with the maximum achievable intensity and brightness, and the only constraint on the maximum intensity at the transfer from SPS to LHC will come from the TCDI transfer line collimators [13]. Based on the present knowledge of the damage thresholds, the TCDIs will limit the operation to 144 BCMS bunches, while up to the nominal 288 bunches of the standard beam can be transferred.

A summary of the beam parameters to be expected in 2017 is given in Table 1. The quoted emittance values are the parameters achieved operationally in 2016, while the values in parenthesis correspond to the expected performance reach of the injectors and should be achievable, e.g. by implementing the optimizations discussed above on the operational cycles. It should be emphasized that the minimum batch spacing (i.e. the SPS injection kicker gap) for 2017 will be 200 ns instead of the nominal 225 ns used in 2016. This reduced batch spacing has been fully validated during proton MDs in 2016 and was already operationally used during the p-Pb run at the end of 2016 [12].

Table 1: Beam parameters to be expected from the LHC injectors in 2017.

| Beam type | Intensity [1e+11 p/b] | Emittance [$\mu$m] | Batch spacing [ns] | Pattern [bunches] |
|---|---|---|---|---|
| 25 ns standard (nom. intensity) | 1.15 | 2.5 (2.4) | 200 | 1-4 x 72 → 288 |
| 25 ns standard (max. intensity) | 1.30 | 2.8 (2.7) | 200 | 1-4 x 72 → 288 |
| 25 ns BCMS (nom. intensity) | 1.15 | 1.7 (1.4) | 200 | 1-3 x 48 → 144 |
| 25 ns BCMS (max. intensity) | 1.30 | 1.9 (1.6) | 200 | 1-3 x 48 → 144 |
| 25 ns 80 bunch (nom. intensity) | 1.15 | 2.6 (2.4) | 200 | 1-3(4) x 80 → 240 |
| 25 ns 80 bunch (max. intensity) | 1.30 | 2.8 (2.7) | 200 | 1-3(4) x 80 → 240 |
| 8b4e (nom. intensity) | 1.20 | 1.8 (1.6) | 200 | 1-3 x 56 →168 |
| 8b4e (max. intensity) | 1.60 | 2.4 (2.1) | 200 | 1-3 x 56 → 168 |

## SPECIAL BEAMS

The 80 bunch scheme has the potential to either increase the total number of bunches in the LHC (using 320 bunches per injection after LS2), or for mitigating total current limits in the SPS for the same LHC performance (using 240 bunches per LHC injection) [14]. In this scheme 4+3 instead of 4+2 bunches are injected into the PS at harmonic h = 7. After the triple splitting one bunch is eliminated using either the transverse damper or the PS extraction kicker. The remaining 20 bunches are accelerated to flat top and twice double split into 80 bunches. All RF gymnastics are identical to the standard production scheme and thus the same brightness as for the standard scheme can be expected. The 80 bunch scheme (using the PS extraction kicker for bunch elimination) was successfully tested in LHC MDs in 2016. Slightly higher losses compared to the operational beams were observed, but this is not unusual for a beam that is not used in routine operation. This might simply be resolved by optimizing the scraper settings in the SPS. It is expected that similar maximum intensity per bunch as compared to the standard 25 ns beam can be achieved as shown in Table 1.

The 8b4e beam is considered as a back-up for the standard 25 ns beam in case the e-cloud remains a limitation for the operation of the LHC during the HL-LHC era [15]. The e-cloud build-up is significantly reduced with this beam thanks to the micro-batch train structure. Starting from 7 bunches from the PSB, the triple splitting in the PS is replaced by a direct h = 7→21 bunch pair splitting, which results in pairs of bunches separated by empty buckets. Each bunch is split in four at PS flat top such that the bunch pattern 6×(8b⊕4e)⊕8b is obtained. This scheme was successfully tested in LHC MDs in 2016: a hybrid filling scheme with 55% of 25 ns BCMS batches combined with 45% of 8b4e batches allowed reducing the heat load in the most critical LHC sector by about 40% while the total number of bunches was only 15% less compared to the equivalent standard filling scheme [16]. As for all LHC type beams in the SPS, the intensity of the 8b4e is limited by the available RF voltage in presence of beam loading. Since the filling time of the SPS RF cavities is about 600 ns and the average line charge density over 300 ns is reduced to 2/3 compared to the normal 25 ns beams, the present intensity limit for the 8b4e is estimated around $1.6 \times 10^{11}$ p/b as summarized in Table 1.

The doublet beam was originally proposed for enhancing the scrubbing efficiency in the SPS at low energy [17], but could also be of interest for scrubbing of the LHC. This beam is produced by injecting a 25 ns beam with enlarged bunch length ($\tau \approx 10$ ns full length) from the PS onto the unstable phase of the 200 MHz RF system in the SPS. By raising the SPS RF voltage within the first few milliseconds after injection, each bunch is captured in two neighboring RF buckets resulting in a train of 25 ns spaced doublets, i.e. pairs of bunches spaced by 5 ns. The doublet beam was sent to the LHC for first tests in 2015, but not in 2016 due to the vacuum leak on the TIDVG in the SPS. It could be made available again for the LHC by mid 2017. There is an interest to use this beam with intensities ranging between 0.6 and $1.6 \times 10^{11}$ p/doublet for assessing its scrubbing potential in the LHC (for lower intensity the stripes of high e-cloud density move to the central region). This would also provide points for an experimental benchmark of the dependence of the e-cloud build up on the bunch (doublet) intensity.

## SUMMARY AND CONCLUSIONS

The 2016 operationally achieved beam parameters of the 25 ns beam produced with the standard scheme was close to the expected performance limit of the LHC injector chain. However the observed blow-up at the PSB-to-PS transfer needs to be studied further. Emittance preservation along the chain is clearly more challenging for the BCMS high brightness variant of the 25 ns beam, for which an additional vertical blow-up along the PS cycle was observed. Based on promising MD results from end 2016, it is expected that the latter can be mitigated mainly by an optimization of the RF voltage program to reduce the space charge tune spread. Losses in the SPS and at injection into the LHC could be improved in the second half of 2016 by deploying an optimized bunch rotation scheme at PS extraction using an additional 40 MHz cavity. Special beams such as the 80 bunch scheme, the 8b4e beam and the doublet beam have been successfully tested in LHC MDs and can be made available if requested by the LHC.

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