OVERVIEW OF THE BEAMS FROM THE INJECTORS

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Abstract

The injectors have delivered different beam types for luminosity production in the LHC during the 2017 run. Besides the nominal beam with 25 ns spacing and 72 bunches at PS extraction, the batch-compression-merging-splitting (BCMS) beam with multiples of 48 bunches at extraction from the SPS has been produced. The reduced number of bunches per batch from the PS is compensated by almost twice as smaller transverse emittance. The vacuum related issues in the LHC (16L2 cell) could be mitigated by switching to the so-called 8b4e beam, where mini-batches of 8 bunches are followed by 4 empty bunch positions in between. Thanks to the flexibility of the injectors, a higher brightness version of the 8b4e has been prepared to quickly react to the needs of the LHC. In this paper, an overview of the beams from the injector complex is given, describing how the beams are produced and summarizing their characteristics, achieved performance and specific limitations. In view of the operation in 2018, the expected beam parameters are presented, as well as a reminder of possible alternative beam types from the injectors.

BEAM PRODUCTION SCHEMES

All the accelerators in the LHC injector chain contribute to the definition of the beam parameters. The transverse emittance is initially defined at injection in the PS Booster (PSB) and increases linearly with the bunch intensity (brightness curve [1]). The beam pattern is then defined in PS, where rf manipulations are performed to split, merge and compress the beam. The versatility of the rf systems in the PS allows to produce various beam patterns and the rf manipulations used during the 2017 run are shown in Fig. 1. At extraction from the PS, the bunch spacing is 25 ns with the longitudinal emittance adjusted to $\varepsilon_L = 0.35$ eVs per bunch as a compromise for low capture losses and beam stability in the SPS. The nominal bunch intensity at PS extraction is $N_b = 1.3 \times 10^{11}$ protons per bunch (p/b). Finally, 1 to 4 batches are extracted from the PS to the SPS to maximize the number of bunches per injection into the LHC.

An important limitation for beam brightness occurs at the transfer from the PSB to the PS. The longitudinal emittance extracted from the PSB should be maximized to reduce space charge effects on the PS flat bottom [2]. However, the maximum bunch length for extraction from the PSB to the PS is limited by the rise time of the recombination kickers [3]. In addition, too large momentum spread leads to transverse emittance blow-up due to a known, and unavoidable with the current optics, dispersion mismatch. Another important limitation is the transfer from the PS to the SPS. The longitudinal emittance should not exceed $\varepsilon_L = 0.35$ eVs to avoid large losses from uncaptured beam on the SPS flat bottom. On the other hand, the longitudinal emittance should not be lower than $\varepsilon_L = 0.35$ eVs to avoid longitudinal instabilities on the SPS flat bottom.

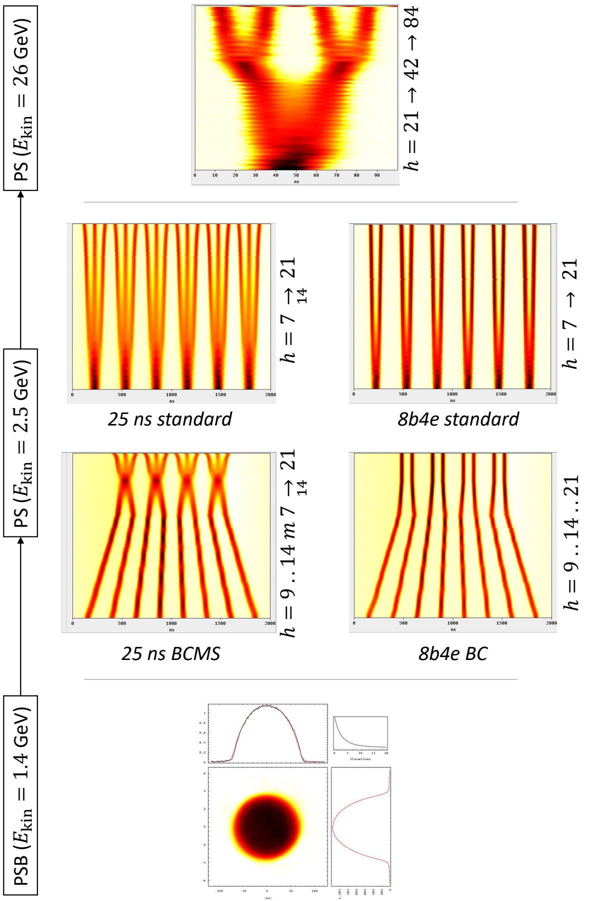

Figure 1: Overview of rf manipulations in PS the beams delivered to the LHC in 2017. The rf harmonics involved and the type of manipulation are displayed with the following signs: '⟶' for splitting, '..' for batch compression and '*m*' for merging. The required number of bunches from PSB together with the bunch parameters are shown in Table 1.

Respecting these requirements and constraints, multiple beam manipulation schemes presented in Fig. 1 are available to reach the nominal bunch parameters at PS extraction. The rf manipulations rely on the numerous rf systems available in the PS. The main rf system consists of 10 (+1 spare)

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Table 1: Beam parameters at extraction from PSB and PS for each beam type (based on 2017 reference measurements).

PSB extraction	**Number of bunches and harmonic at inj. in PS**	**Intensity 10^{11} p/b**	**Longitudinal emittance [eVs]**	**Bunch length] [ns]**	**Number of bunches in PS at PS ext. and splitting factor r**
25 ns standard	6 (h = 7)	16.5	1.27	183	72 (r = 12)
8b4e standard	7 (h = 7)	10.6	1.17	179	56 (r = 8)
25 ns BCMS	8 (h = 9)	7.8	0.92	150	48 (r = 6)
8b4e BC	8 (h = 9)	5.3	0.82	142	32 (r = 4)
PS extraction					
All beam variants	-	1.3	0.35	3.9	-

cavities with a tuning range covering the rf harmonics from $h = 7$ to $h = 21$. These cavities are used to accelerate the beam in the PS, and are separated in three tuning groups allowing to perform rf manipulations on the intermediate plateau (kinetic energy of $E_{\mathrm{kin}} = 2.5$ GeV) with up to three rf harmonics at the same time. At arrival on the flat top, fixed-frequency rf systems at rf harmonics of $h = 42$ and $h = 84$ allow to further split the beam and obtain a bunch spacing of 25 ns. Bunches are then shortened non-adiabatically using cavities at rf harmonics of $h = 168$ before extraction to the SPS.

For each scheme, the splitting factor r indicates how many times bunches are split in the PS, and therefore defines the intensity from the PSB required to reach the nominal intensity of $N_b = 1.3 \times 10^{11}$ p/b at PS extraction. The beam brightness is directly related to the splitting factor: a scheme with high splitting factor requires high intensity from the PSB and will therefore have a large transverse emittance, and hence a lower beam brightness at extraction from the PS. The drawback of a low splitting factor is that fewer bunches are transferred from the PS to the SPS, limiting the total number of bunches filling the LHC and increasing the time needed to fill the LHC. For instance, the standard scheme has a high splitting factor of $r = 12$ leading to moderate beam brightness and the BCMS beam is a variant with higher brightness. The required bunch parameters at PSB and PS extraction as well as the splitting factor for each beam are summarized in Table 1.

The rf manipulations can also be set up to produce "mini-batches", which are used to reduce vacuum related issues due to long batches such as electron cloud build-up in the downstream accelerators. These are known as the "8b4e" variants, since each mini-batch is composed of 8 bunches and 4 empty buckets spaced by 25 ns.

SUMMARY OF PERFORMANCE IN 2017

Various beams were delivered during the 2017 run to cope with the requests of the LHC. The standard 25 ns beam was used in the early stage of the run, mainly for setting up and scrubbing of the LHC. The operation was then quickly switched to the BCMS beam to maximize the beam brightness and produce luminosity during a few months. The LHC operation was then troubled by vacuum issues in the 16L2 cell (more details in [7]). To mitigate this issue, the injectors quickly prepared the standard 8b4e beam. A higher brightness variant of the 8b4e beam using only batch compression at the intermediate plateau (8b4e BC) was then proposed. This beam has the lowest achievable splitting factor for a beam with 25 ns bunch spacing and is hence expected to have the highest brightness per bunch. The main drawback is that only 32 bunches per batch are produced in the PS. The 8b4e BC was put in operation for the first time and allowed to mitigate the vacuum issues in the LHC and keep high luminosity production till the end of the year. The performance of the beams used in 2017 in terms of beam intensity, transverse emittance and number of batches that can be transfered to the LHC is summarized in Table 2.

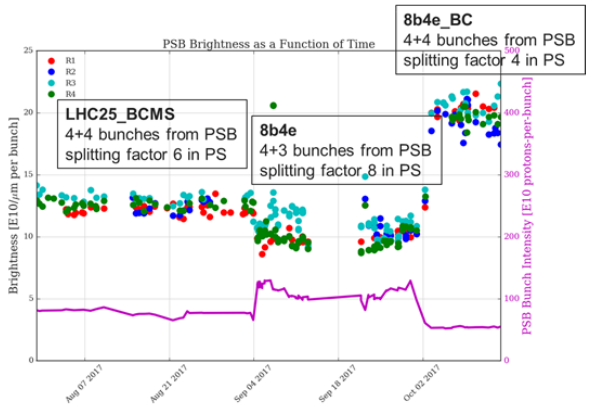

Figure 2: Measured beam brightness in PSB for the beams produced for the LHC 2017 operation.

The beam brightness along the year for beams produced in the PSB is shown in Fig. 2. The displayed beam brightness corresponds to the measured bunch intensity divided by the averaged transverse emittance and by the splitting factor to account for the rf manipulations in PS. Measurements were done at top energy in the PSB. The brightness

Table 2: Summary of beam parameters provided by the injectors. The values in parenthesis correspond to the expected best achievable emittance. See [4] for transverse emittance preservation. See [5] for batch spacing and [6] for hardware limitations defining SPS extraction pattern.

Beam type (menu for 2018)	**Intensity 10^{11} p/b**	**Transverse emittance [μm]**	**SPS extraction pattern**
25 ns BCMS (like 2017)	1.15	1.7 (1.4)	1-3 x 48 → 144
25 ns BCMS (high intensity)	1.30	1.9 (1.6)	1-3 x 48 → 144
25 ns BC (like 2017)	1.25	1.15 (1.0)	1-4 (3) x 32 → 128 (96)
25 ns BC (high intensity)	1.30	1.2 (1.0)	1-4 (3) x 32 → 128 (96)
8b4e BC (like 2017)	1.25	1.15 (1.0)	1-4 (3) x 32 → 128 (96)
8b4e BC (high intensity)	1.60	1.55 (1.2)	1-4 (3) x 32 → 128 (96)
Beam type (backup beams)	**Intensity 10^{11} p/b**	**Transverse emittance [μm]**	**SPS extraction pattern**
25 ns standard (like 2017)	1.15	2.5 (2.4)	1-4 x 72 → 288
25 ns standard (high intensity)	1.30	2.8 (2.7)	1-4 x 72 → 288
8be4 standard (like 2017)	1.20	1.8 (1.6)	1-3 x 56 → 168
8b4e standard (high intensity)	1.60	2.4 (2.1)	1-3 x 56 → 168

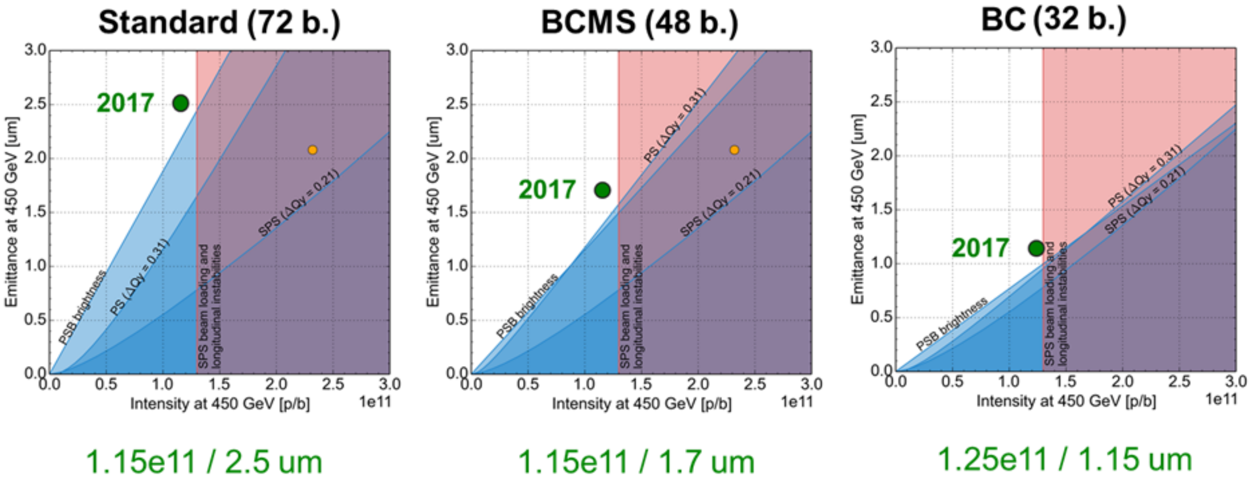

Figure 3: Performance of beams at SPS extraction in 2017 together with the limitations due to space charge and instabilities.

along the year followed the expected curve in the PSB. No show-stopper was found for the 8b4e BC beam which gave excellent performance in PSB. Note that the bunch intensity was varied when the standard 8b4e beam was used to find the ideal compromise between beam intensity and issues in 16L2 in the LHC (intensity scanned in the range 10.5×10^{11} p/b to 13.0×10^{11} at PSB extraction).

The measured transverse emittance at top energy in the SPS for the different beams is shown in Fig. 3. Measurements are displayed together with the expected main limitations in the injector chain in terms of transverse emittance and beam intensity, which are defined by space charge effects, beam loading and instabilities. In general, the performance achieved in 2017 is close to the expected limits. The margin with respect to the best achievable transverse emittance is up to 15-20 % for the beams with high brightness such as BCMS and BC. Most of the transverse emittance blow-up occurs during the transfer from PSB to PS. Details about the transverse emittance preservation along the injector chain can be found in [4].

No further limitations were observed in the PS and in the SPS with the BC beam, which delivered the highest beam brightness as expected from the low splitting factor. Due to the small splitting factor in the PS the space charge limitations in the PSB and PS are reduced and space charge limitations in the SPS becomes relevant. The BC scheme reveals further limitations concerning the transfer from the SPS to the LHC. The maximum number of bunches transfered from the SPS to the LHC is limited by the injection septum protection collimator, which is not designed for beams with high brightness like BC. As a consequence, if the performance of the BC beam was optimized in the future to reach the expected best achievable beam brightness, fewer batches should be extracted from the SPS to the LHC due to hardware limitations (see Table 2). Since the BC beam produces only 32 bunches per batch, the rise time of the SPS and LHC injection kickers need to be pushed to the limits to accommodate a sufficient number of bunches in the LHC to still profit from the high brightness. Details on the acceptable number of bunches for transfer from SPS to LHC depending on the beam brightness are available in [5, 6].

Concerning the maximum achievable beam intensity in the injector chain, the main bottleneck presently comes from beam loading in the SPS. Longitudinal instabilities in the SPS have a threshold in intensity of $N_b \approx 1.2 \times 10^{11}$ p/b in double rf operation and affect the beam quality. During the 2017 operation, the beam intensity could be increased up to $N_b \approx 1.3 \times 10^{11}$ p/b with acceptable beam quality, and up to $N_b \approx 1.4 \times 10^{11}$ p/b during MD sessions with degraded beam quality in the longitudinal plane. The next bottleneck in terms of beam intensity comes from the longitudinal instability in the PS. In 2017, the beam intensity could be increased up to $N_b \approx 2.0 \times 10^{11}$ p/b for all beam schemes with good beam quality using the coupled-bunch feedback.

STUDIES IN 2017 AND EXPECTATIONS FOR 2018

Overall, the beam parameters for 2018 are expected to be comparable to the ones obtained in 2017. There is only small margin for bunch intensity increase. Nevertheless, another beam variant can be proposed which was not yet tested in the LHC. This beam is the 25 ns variant of the BC beam, for which a pure batch compression from the rf harmonic h=9 to h=21 is performed on the intermediate plateau in the PS as shown in Fig. 4 [8]. The principle was first demonstrated in 2014 and tested again during MD sessions in 2017. The beam performance in terms of beam intensity and brightness is expected to be identical to the 8b4e BC beam, as displayed in the Table 2.

The LHC injectors are expected to deliver twice the present nominal intensity per bunch after the Long Shutdown 2 (LS2), thanks to improvements of the machines in the framework of the LHC Injector Upgrade (LIU) project [8]. Nevertheless, operation in 2018 may profit from results of studies performed in 2017 for the LIU project.

Longitudinal emittance control is essential in the PSB for space charge mitigation and transfer to the PS. A dedicated high frequency rf system (C16) is used to perform controlled longitudinal emittance blow-up by applying a phase modulation to the rf voltage. All the presently installed rf systems will be replaced by broad-band Finemet systems during LS2. Although the Finemet systems should cover a range in frequency including the one of the C16 cavity, another mean of controlled longitudinal emittance blow-up is under study in the PSB as an alternative. This can be done by injecting noise into the phase of the main rf system, as presently done in the SPS and the LHC [9]. This method was tested in 2017 and allowed to reach all required longitudinal emittances

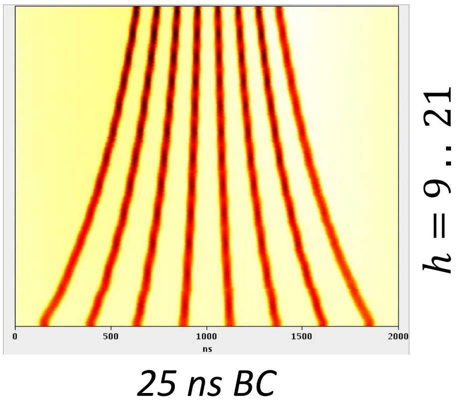

Figure 4: Rf manipulation performed on the $E_{\mathrm{kin}} = 2.5$ GeV plateau for the BC 25 ns beam. A batch compression is applied from the rf harmonic h=9 to h=21.

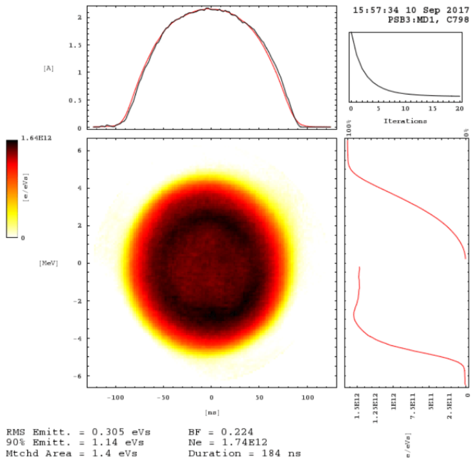

Figure 5: Measured longitudinal distribution for a bunch produced in the PSB using noise injection to the rf phase of the main system for controlled longitudinal emittance blow-up.

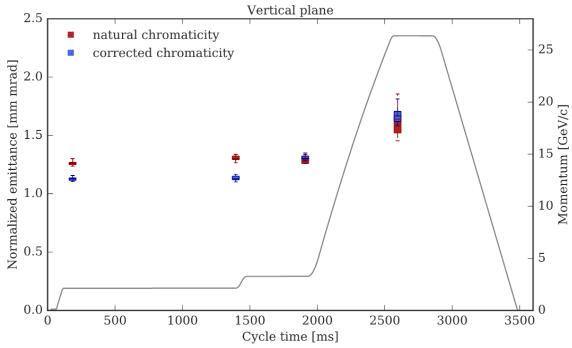

Figure 6: Vertical emittance measured in the PS along the cycle with natural chromaticity and linear coupling (red) and with corrected chromaticity and wide-band transverse feedback enabled (blue).

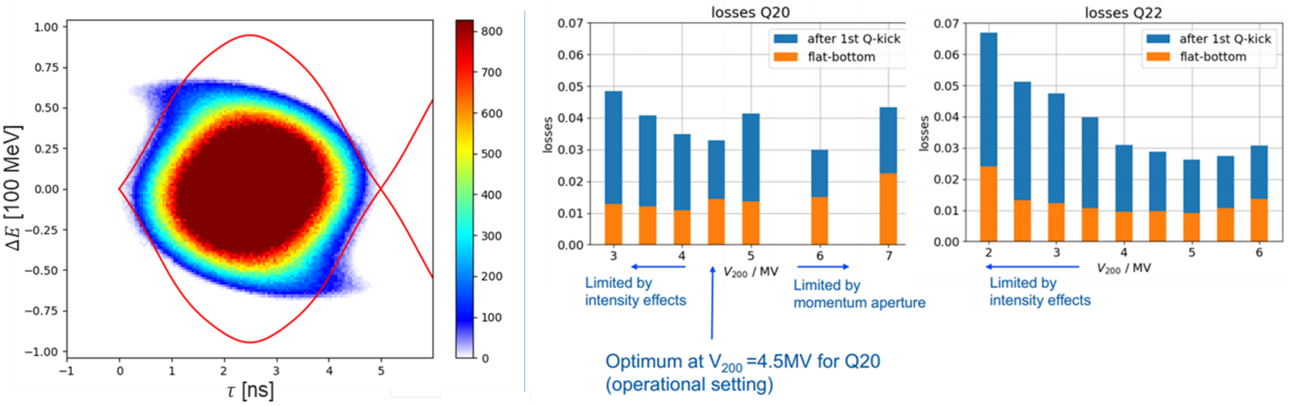

Figure 7: Left: Bunch distribution in the longitudinal phase space at injection in the SPS. Right: Losses on the SPS flat bottom and after clean-up of the uncaptured beam using a tune kicker (Q-kick), as measured from the DC Beam Current Transformer for the Q20 and Q22 optics scanning the injection rf voltage.

with excellent distribution as shown in Fig. 5. Studies will be continued in 2018 to evaluate the reproducibility and reliability of this method in the PSB.

Transverse instabilities on the PS flat bottom are a limitation for the LHC-type beams and are presently mitigated by applying linear coupling between horizontal and vertical planes using skew quadrupoles, together with a high chromaticity. However, the drawback is the large tune footprint of the beam. A wide-band transverse feedback is available to suppress the instabilities in place of the linear coupling, providing more flexibility for the choice of the working point. Tests were performed in 2017 with the BCMS beam. Due to the absence of linear coupling, the vertical emittance could be reduced by 10-15 % on the flat bottom as shown in Fig. 6. There was however no change in the horizontal plane, for which the emittance is mainly defined by the blow-up at injection due to the dispersion mismatch. Studies will be continued in 2018 to improve the handover between low-energy quadrupoles and pole face windings to control the tune and optimize parameters during the ramp.

A bunch compression is performed before extraction from the PS, to fit the long PS bunches (bunch length 16 ns) into the small SPS rf buckets (bucket length 5 ns). The bunch compression consists of a fast increase of the rf voltage of the 40 MHz and 80 MHz cavities, to rotate the bunch in the longitudinal phase space [10]. The non-linearities of the rf voltage are responsible of the "S-shape" of the bunch as shown in Fig. 7 (left). The longitudinal tail population does not fit in SPS rf buckets and is lost at capture. After filamentation, the bunch fills completely the rf bucket and particles with large momentum deviation are lost on the momentum aperture limitations. Studies were conducted in 2017 both in the PS and the SPS to improve the beam transfer. On the PS side, a better characterization of the tail population was achieved by performing a post-acceleration at $h = 84$, which was tested for the first time in the PS. The purpose of the post-acceleration was double: to separate the uncaptured beam from the main beam and to shave the longitudinal tails before bunch rotation to have losses in the PS rather than in the SPS. This demonstrated that the longitudinal tail population, which is difficult to quantify otherwise, is larger than expected and is indeed a main contributor to the losses at injection in the SPS. The rf parameters at injection in the SPS were scanned to evaluate the compromise between transient beam loading effects for low rf voltage and limitations of the aperture due to large momentum spread for high voltage, as shown in Fig. 7 (right). Bottlenecks in terms of transverse aperture were identified and could be attributed to the mechanical design of the vacuum chamber transitions between the QD magnets and the long straight sections. Measurements were also performed using the Q22 optics, which provides more bucket area for the same rf voltage and more momentum acceptance due to the reduced dispersion in comparison with the Q20 optics. Studies will be continued in 2018 to better quantify the tail population of the bunches coming form the PS, to evaluate the impact of transient beam loading and the potential benefits of the Q22 optics.

CONCLUSIONS

Various beams can be produced in the injectors to find a compromise between beam brightness and number of bunches extracted from the SPS. Thanks to the flexibility of the injectors, the requests from the LHC during the 2017 run were fulfilled in (reasonably) short delay, while keeping the beam performance close to the expected limitations. The beam performance is expected to be similar in 2018. The 25 ns BC beam exists as a higher brightness variant of the BCMS beam. The studies performed during 2017 in the framework of the LIU project can slightly improve the injectors performance but may require more studies in 2018 to be applicable in operation.

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