BEAMS IN THE INJECTORS

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Abstract

For the 2015 LHC start up and operation, the injectors will be requested to provide a large variety of beams. Probes and individual LHC-type bunches will be needed at the early commissioning stage. Later on, standard beams with 50 ns bunch spacing, 25 ns bunch spacing and a special doublet beam for electron cloud enhancement will be used for LHC vacuum conditioning and scrubbing. High brightness variants of the 50 and 25 ns beams (BCMS) will also have to be available for the LHC physics operation. The more exotic 8b$\oplus$4e beam could also be considered in some operational post-scrubbing scenarios and should be made ready for that use. The goal of this paper is to provide a realistic estimation of the beam parameters expected from the injectors in 2015 for the aforementioned beam types. Since this estimation will rely on the full recovery of the 2012 performance and the successful implementation of new or optimized production schemes, we will address: 1) The critical milestones to reestablish the 2012 beam conditions (e.g. the scrubbing run of the SPS after the long shutdown); 2) The roadmap of machine studies for testing or improving the beam production schemes in PSB and PS; 3) The necessary experimental tests needed in the SPS for the production of the doublet scrubbing beam, and related issues.

INTRODUCTION

During the LHC Run 1 in 2011 and 2012, the LHC physics production was based on beams with 50 ns bunch spacing, while beams with 25 ns bunch spacing were injected into LHC on few occasions for injection tests, Machine Development (MD) sessions, an extended scrubbing run and a short pilot physics run [1]. After the startup in 2015 the center-of-mass energy at LHC collision will be raised to 13 TeV. It will be crucial to establish physics operation with the nominal 25 ns bunch spacing in order to maximize the integrated luminosity in Run 2 for the limited event pile-up acceptable for the LHC experiments [2]. The LHC will thus request a large variety of beams for the different stages of the machine scrubbing [1], such as standard beams with 50 ns bunch spacing, 25 ns bunch spacing and a special doublet beam for electron cloud enhancement. High brightness variants of the 50 and 25 ns beams (BCMS scheme [3, 4]) will also have to be available for the LHC physics operation.

In this paper the parameters of the LHC physics beams achieved in the injectors until 2012 and the experience gained during the LHC Run 1 will be reviewed. The possibilities for optimizing the beam production schemes, as identified in the course of the RLIUP workshop in 2013 [5], and the beam parameters that should be available from the injectors in 2015 will be presented. The challenges for the production of the doublet beam for scrubbing of the SPS and in particular of the LHC will be summarized together with the necessary machine studies that remain to be done for demonstrating the acceleration of this beam to the SPS flat top to be ready for the LHC scrubbing in 2015. Also the new 8b+4e beam [6], which should allow for a higher intensity per bunch at the expense of a smaller total number of bunches in the LHC, will be discussed, as it could be interesting for the physics production in case the electron cloud effect in the LHC cannot be alleviated by scrubbing. The milestones for re-establishing the 2012 beam conditions as well as the necessary steps for the implementation of the optimized beam production schemes and the new beam types will be outlined.

SINGLE BUNCH BEAMS

In preparation of the LHC p-Pb run in 2013 a new beam production scheme has been developed [7]. With this new scheme single bunch LHC beams can be generated in the PSB with unprecedented reproducibility and control of both intensity and longitudinal emittance. The intensity is thereby controlled by longitudinal blow up with the C16 cavity during the first part of the PSB cycle, which allows preserving the 6D phase space volume for a wide range of intensities. It is therefore expected that after Long Shutdown 1 (LS1) the injectors will be able to deliver LHCPROBE bunches ($5\times10^{9}-2\times10^{10}$ p/b) and LHCINDIV bunches ($2\times10^{10}-3\times10^{11}$ p/b) to the LHC with smaller intensity fluctuations compared to the operation during Run 1.

In October 2012, the injectors were asked to provide single bunch beams with an intensity of about $7\times10^{10}-9\times10^{10}$ p/b and transverse normalized emittances of about $\varepsilon_{x,y}\approx2.5\,\mu$m for the Van der Meer scans. The LHC experiments requested in particular beams with transverse profiles as close to Gaussian as possible. A special single bunch beam was prepared in the PSB using a combination of transverse and longitudinal shaving in order to obtain large transverse emittance but with tails less populated than Gaussian distributions [8]. Because of diffusion in the PS and SPS, these bunches evolved into almost perfect Gaussian shapes at the exit of the SPS and at collision in the LHC as confirmed by the experiments. This beam will need to be ready for the van der Meer scans at the beginning of the 2015 run. Potentially, the production scheme of this beam can be further optimized by adapting the aforementioned new scheme for single bunches.

LHC PHYSICS BEAMS

LHC operation during Run 1 was mainly based on 50 ns beams produced with the standard scheme of bunch splittings in the PS. Beams with the nominal 25 ns bunch spacing have been used in the LHC mainly for the scrubbing run and machine development studies. With the successful implementation of the Batch Compression bunch Merging and Splitting (BCMS) scheme [3, 4] in the PS in 2012 the injectors were able to provide LHC beams with almost twice the brightness compared to the standard production schemes. While the 50 ns BCMS beam was injected into the LHC only for a study of the emittance preservation of a high brightness beam along the LHC ramp, the 25 ns BCMS beam was used for the 25 ns pilot physics run at the end of 2012. It should be emphasized that all these LHC beams were produced close to the performance limits of the injector chain. Figure 1 shows the beam parameters for the two types of 50 ns and the 25 ns beams as achieved in 2012 after the operational deployment of the Q20 low gamma transition optics in the SPS [9]. The transverse emittances

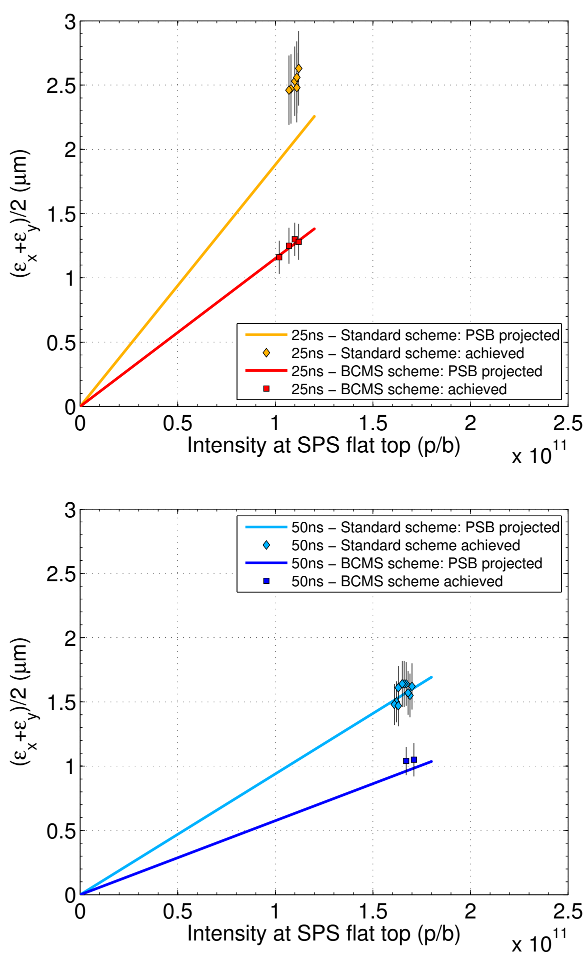

Figure 1: Beam parameters achieved operationally in the SPS in 2012 with the Q20 optics for 50 ns beams (bottom) and 25 ns beams (top) extracted to the LHC.

Table 1: Operational beam parameters in 2012.

Beam type	Intensity	Emittance
Standard (25 ns)	1.20×10^{11} p/b	2.6 μm
BCMS (25 ns)	1.15×10^{11} p/b	1.4 μm
Standard (50 ns)	1.70×10^{11} p/b	1.7 μm
BCMS (50 ns)	1.70×10^{11} p/b	1.1 μm

shown in these plots 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. The solid lines correspond to the PSB brightness curve (i.e. the emittance as a function of intensity measured at PSB extraction) translated into protons per SPS bunch for each beam type assuming intensity loss and emittance growth budgets of 5% in the PS and 10% in the SPS, respectively. All beams were produced within the allocated budgets for beam degradation along the injector chain apart from the standard 25 ns beam, which suffers from slow losses at the SPS flat bottom and maybe also from space charge effects at the PS injection. Nevertheless, the nominal 25 ns beam is well within the original specifications (i.e. 1.15×10^{11} p/b and 3.5 μm transverse emittance [10]). The beam parameters achieved operationally in 2012 are summarized in Table 1.

The first part of the re-commissioning of the LHC beams in the injector chain in 2014 will focus on re-establishing the beam parameters achieved before LS1. This will rely to a large extent on the successful scrubbing of the SPS in order to suppress the electron cloud effect, which is expected to be a performance limitation during the first weeks after the start-up since large parts of the vacuum chambers have been exposed to air. The strategy on the SPS scrubbing run will be addressed in more detail at the end of this paper.

Once the 2012 beam parameters are reproduced, it should be possible to reach slightly higher beam intensity and potentially also higher beam brightness. Already during MDs at the end of 2012 a standard 25 ns beam was accelerated to flat top with an intensity of about 1.3×10^{11} p/b and longitudinal beam parameters compatible with injection into LHC. In addition, high intensity LHC beams will benefit from the upgraded 1-turn delay feedback for the 10 MHz cavities and the upgraded longitudinal coupled-bunch feedback in the PS, which will be commissioned in 2014. It should also be possible to enhance the beam brightness by optimizing the beam production schemes as discussed at the RLIUP workshop [5]: the space charge tune spread in the PS can be reduced by injecting bunches with larger longitudinal emittance, i.e. increasing the bunch length and the momentum spread at PSB extraction. The maximum bunch length at the PSB-to-PS transfer is determined by the recombination kicker rise time. The maxi-

Table 2: Expected performance limits after LS1.

Beam type	Intensity	Emittance
Standard (25 ns)	1.30×10^{11} p/b	2.4 μm
BCMS (25 ns)	1.30×10^{11} p/b	1.3 μm
Standard (50 ns)	1.70×10^{11} p/b	1.6 μm
BCMS (50 ns)	1.70×10^{11} p/b	1.1 μm

mum longitudinal emittance is determined by the RF manipulations and by the momentum acceptance at transition crossing in the PS cycle, but also by the constraint that the final bunches should not exceed 0.35 eVs for injection into the SPS. Optimizing the longitudinal beam parameters at PS injection requires therefore controlled longitudinal blow-up during the PSB cycle with the C16 cavity and the use of the h=1 and h=2 PSB RF harmonics in phase at extraction to keep the larger longitudinal emittance bunches within the recombination kicker gap. Furthermore, the triple splitting in the PS needs to be done at an intermediate plateau of 2.5 GeV instead of the flat bottom for providing sufficient bucket area. Further details are given in Ref. [5]. A summary of the expected performance limits of LHC physics beams for the run in 2015 is given in Table 2.

DOUBLET SCRUBBING BEAM

The doublet beam was originally proposed for enhancing the scrubbing efficiency in the SPS at low energy [11]. 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. Very good capture efficiency (above 90%) for intensities up to 1.7×10^{11} p/doublet could be achieved in first experimental tests in 2012. Figure 2 (top) shows the evolution of the longitudinal profile of the beam during the "splitting" right after the injection in the SPS. Figure 2 (bottom) shows the "final" beam profile, measured one second after injection. It was also verified that it is possible to rapidly lower the RF voltage and inject a second train from the PS without any important degradation of the circulating beam. Observations on the dynamic pressure rise in the SPS arcs confirmed the enhancement of the electron cloud activity as expected from the lower multipacting threshold compared to the standard 25 ns beams predicted by numerical simulations [11]. The experimental studies performed up to now concentrated on SPS injection energy and thus the acceleration of the doublet beam in the SPS has not been tested yet.

Since it is planned to use the doublet beam for the second part of the LHC scrubbing run in 2015 [1], extensive experimental studies in the SPS in 2014 need to be performed for testing and setting up the acceleration of the doublet beam to SPS flat top. The maximum intensity achievable at SPS flat top will be limited by beam loading and the available RF power of the 200 MHz cavities. First MD tests in 2014 will be performed with the normal LHC acceleration cycle, but it is expected that the ramp rate needs to be reduced by up to a factor three in order to reduce the required RF power and thus allow reaching the 1.6×10^{11} p/doublet requested by the LHC [12]. This implies a significant increase of the cycle length in the SPS, even though the flat bottom can be shorter since for the moment a maximum of two batches per SPS extraction are requested for the LHC scrubbing. It should also be mentioned that the doublet beam could suffer from beam quality degradation, such as increased bunch length at SPS extraction, unbalanced doublet intensities and blow-up from e-cloud during the SPS cycle. In the best case the transverse emittance of the doublet beam could be around 3 μm, but significantly larger beam sizes are to be expected in case of instabilities. On the other hand, after its commissioning, the new SPS transverse feedback system will be able to damp the common oscillation mode of doublets throughout the cycle including the time right after injection where the doublets are created.

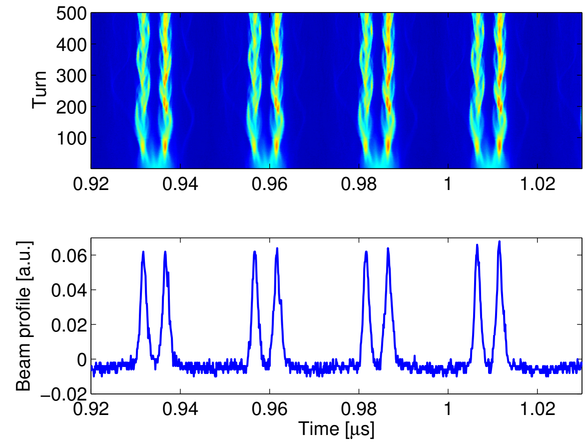

Figure 2: Evolution of the longitudinal beam profile in the SPS during the splitting at injection for the production of the doublet beam (top) and longitudinal bunch profiles of the doublet beam measured 1 s after injection (bottom).

8b⊕4e BEAM

Thanks to its micro-batch train structure, the 8b⊕4e beam was considered as an alternative to the standard 25 ns beam in case the electron cloud remains a limitation for the operation of the LHC during the HL-LHC era [6]. A simulation of the production of the 8b⊕4e beam based on the standard scheme is shown in Fig. 3 (top). 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 pat-

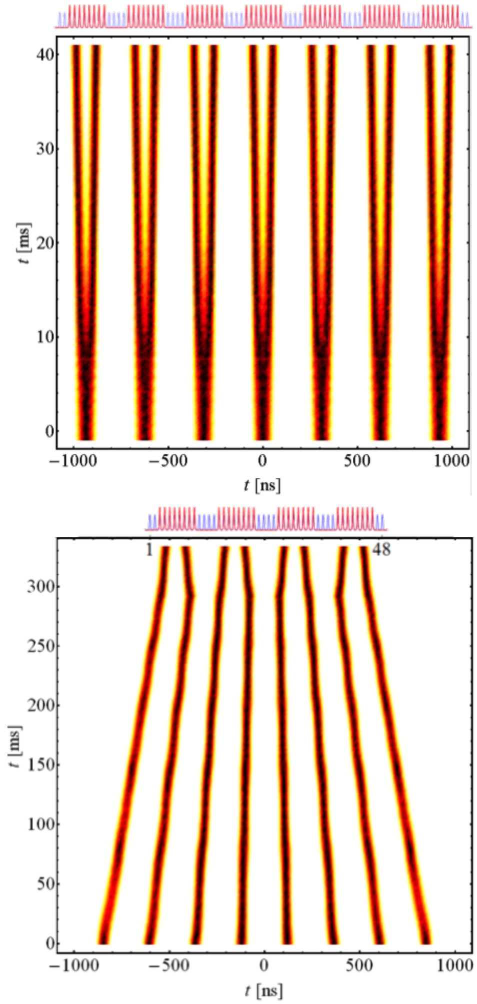

Figure 3: Simulations of the 8b⊕4e beam production in the PS based on the standard scheme (top) and based on the BCMS scheme (bottom). *Courtesy of H. Damerau.*

tern 6×(8b⊕4e)⊕8b is obtained. In this case the bunch train out of the PS is longer than the 72 bunches of the standard scheme, but the remaining gap of 4 empty buckets (about 100 ns) is expected to be sufficiently long for the PS ejection kicker. Without optimization of the LHC filling pattern, the total number of bunches per LHC beam is estimated as 1840. A high brightness version of this beam can be produced by the scheme shown in Fig. 3 (bottom), which is similar to the BCMS scheme but the merging and triple splitting is replaced by a regrouping of bunches during the h = 14→21 batch compression. The resulting bunch pattern in this case is 3×(8b⊕4e)⊕8b and the total number of bunches per LHC beam is approximately 1728.

As for all LHC type beams in the SPS, the intensity of the 8b⊕4e will be limited by longitudinal instabilities and the available RF voltage in presence of beam loading. However, as the average line charge density over 300 ns is being reduced to 2/3 compared to the normal 25 ns beams and the filling time of the SPS RF cavities being about 600 ns, the present intensity limit for the 8b⊕4e is estimated around 1.8×10^{11} p/b. The maximum achievable brightness can be calculated from the known brightness and space charge limitations of the injectors. The estimated beam parameter limitations are summarized in Table 3. Finally it should be emphasized that this beam has not been produced in the injectors so far since it was developed during LS1. First tests of this new beam production scheme will be subject of MD studies in 2014 or at latest in the beginning of 2015, depending on the availability of MD time in the injectors.

Table 3: Expected parameters of the 8b+4e beam.

Beam type	**Intensity**	**Emittance**
Standard (8b⊕4e)	1.80×10^{11} p/b	2.3 μm
BCMS (8b⊕4e)	1.80×10^{11} p/b	1.4 μm

COMMISSIONING AND STUDIES IN 2014

The first weeks of the PSB and the PS startup in the middle of 2014 will be devoted to the setup of the beams needed for physics. The setup of the LHC beams in the PS complex will be done in parallel to physics operation, starting from re-establishing the beam conditions from 2012 (but already with the triple splitting in the PS at 2.5 GeV instead of the flat bottom). Only after that, the longitudinal blow-up along the PSB ramp and the use of h=1 and h=2 at PSB extraction for optimizing the longitudinal parameters at PSB-PS transfer will be tested in MDs and eventually commissioned.

The PS complex has to be ready to deliver the LHC beams at the startup of the SPS in September. As large parts of the SPS have been vented and exposed to air in the course of the works performed during LS1, it is expected that the good conditioning state of the SPS will be degraded. Therefore, two weeks of SPS scrubbing are planned for 2014 with the goal of reconditioning the SPS to the state of before LS1. The success of this scrubbing run is the critical milestone for the preparation of the 25 ns LHC beams for physics in 2015.

The setup of the doublet scrubbing beam for the use in the LHC will be the subject of extensive MD studies in the SPS in 2014. Several dedicated MD blocks will be needed for setting up the acceleration cycle with the reduced ramp rate and for pushing the intensity to the requested 1.6×10^{11} p/doublet. During these MDs, also the behavior of the LHC BPMs in the SPS with the doublet beam need to be tested in preparation of the LHC scrubbing, since an offset of the beam position reading depending on the relative bunch intensity and position of the doublets is expected [13].

Besides the preparation of the doublet beam and the optimization of the LHC physics beams, there are many requests for dedicated MD time in the SPS for 2014 [14]. Careful planning and prioritization of studies will be crucial, as the total amount of requested dedicated MD time exceeds the MD slots available. Therefore tests of the 8b⊕4e beam production scheme will most likely be done in 2015 (although first studies in the PSB and the PS might be possible already in 2014). In general, it should be stressed that 2014 will be a very busy period for the injectors: Besides the physics operation after the beam commissioning with partially new or upgraded hardware, the setup and commissioning of the different LHC beams including the doublet scrubbing beam, the various dedicated and parallel MD studies, substantial amount of beam time will be needed in the PS and SPS for the first-time setup of the Ar-ion beams in preparation for the physics run beginning of 2015.

Finally, it is worth mentioning that there will be another period of dedicated scrubbing of the SPS in 2015. While with the scrubbing run in 2014 the scrubbing efficiency and the time required for achieving acceptable conditioning after a long shutdown will be qualified, the aim of the scrubbing run in 2015 will be to condition the SPS for high intensity 25 ns beams. The outcome of these scrubbing runs will determine if the SPS vacuum chamber really need to be coated with amorphous Carbon [15] as presently part of the baseline of the LIU project for suppressing the electron cloud for the future high intensity LHC beams [16].

SUMMARY AND CONCLUSIONS

Several optimizations of the beam production schemes will be implemented for the LHC Run after LS1. Single bunch beams will benefit from a better control and better reproducibility of intensity and longitudinal emittance. The longitudinal parameters at PSB-to-PS transfer of the 25 ns and 50 ns physics beams will be optimized for allowing even higher beam brightness and, if requested by the LHC, the intensity of the 25 ns beams can also be slightly pushed compared to the 2012 beam parameters. The first step in the beam commissioning of these LHC beams in 2014 will be however to recover their 2012 performance. In this respect, the critical milestone will be the success of the SPS Scrubbing Run, as it is expected that the good conditioning state of the SPS will be degraded due to the long period without beam operation and the venting of machine sectors related to the interventions during LS1.

The setup of the doublet scrubbing beam with acceleration in the SPS in preparation for the LHC scrubbing in 2015 will be one of the main topics of MDs in 2014. Reaching the challenging target intensity of 1.6×10^{11} p/doublet as requested by the LHC will require a reduced ramp rate in order to overcome RF limitations and thus lots of SPS MD time with a long cycle will be needed. Careful planning and prioritization of the dedicated MDs in the SPS will be crucial due to the limited MD time available. First tests of the 8b⊕4e beam will be performed at latest in 2015.

Besides the various physics users, the commissioning of the LHC beams and the MDs related to the new beams requested by the LHC, lots of beam time will be needed in 2014 for the first-time setup of Ar-ion beams.

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