LHC BEAMS FROM THE CERN PS BOOSTER

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Abstract

The CERN PS Booster (PSB) produces a variety of beam flavours for the Large Hadron Collider (LHC). While the nominal LHC physics beams require 6 Booster bunches with intensities up to 1.6×10^{12} protons per bunch, during the LHC commissioning single bunch beams with variable intensities as low as 5×10^{9} protons have to be provided reproducibly. The final transverse and in many cases also the final longitudinal beam characteristics have to be achieved already in the PSB and can be very demanding in terms of beam brightness and stability.

The optimized production schemes for the different LHC beam flavours in the PSB and the achieved machine performance are presented. Experience with the first beams sent to the LHC in September 2008 is discussed. An overview of the first measured results with a new production scheme of the nominal LHC beam using single instead of double-batch beam transfer from the PSB to the PS is also given.

INTRODUCTION

Since the first beam definitions of LHC operational beams were set up in 1994 [1], requirements evolved with the LHC design, needs of the LHC experiments and the injector chain upgrade [2]. A distinction can be made between single- or multi-bunch LHC physics beams and single-bunch LHC commissioning beams. An overview of the current LHC beam requirements at extraction of the Super Proton Synchrotron (SPS) is given in table 1.

Table 1: LHC Beam Specifications at SPS Extraction

LHC Beam Type	Intensity/ bunch [x10^{11}]	Number of bunches	$\varepsilon_{rms, norm.}$ [µm]	$\varepsilon_{long.}$ [eVs]
25 ns physics	0.115-1.15	(1-4)x72	≤3.5	≤0.8
50 ns physics	1.15	(1-4)x36	≤3.5	≤0.8
75 ns physics	0.2-1.15	(1-4)x24	≤3.5	≤0.8
Indiv. physics	0.2-1.15	1, 4 or 16	≤3.5	≤0.8
Pilot beam	0.05	1	≤3.5	≤0.8
Probe beam	0.03-0.2	1	≤1.0	≤0.3

All LHC beams are produced using harmonic one in the PSB. Nevertheless, up to 4 bunches can be sent per batch to the Proton Synchrotron (PS) as the PSB consists of 4 superimposed rings. Until now, the 25, 50 and 75 ns LHC physics beams were produced in a double-batch transfer from PSB to PS using 4+2 rings. To prepare LHC filling, it is also possible to request only 1 PSB ring for these beams resulting in 12, 6 or 4 bunches, respectively. All the other beams use single-batch transfer to the PS with one PSB ring only (except for the individual physics beam with 1 or 4 PSB rings).

Table 2: LHC Beam Specifications at PSB Extraction Assuming 15% Losses [2] until SPS Extraction

LHC Beam Type	Intensity/ bunch [x10^{11}]	Number of bunches (PSB rings)	$\varepsilon_{rms, norm.}$ [µm]	$\varepsilon_{long.}$ [eVs]
25 ns physics	1.62-16.2	6 (4+2)	2.5	1.3
50 ns physics	8.1	6 (4+2)	2.5	1.3
75 ns physics	0.92-5.29	6 (4+2)	2.5	0.9
Indiv. physics	0.24-1.35	1 or 4	2.5	0.3
Pilot beam	0.05	1	2.5	≤0.3
Probe beam	0.05-0.23	1	<1.0	≤0.2

LHC PHYSICS BEAMS IN THE PSB

25 ns LHC Physics Beam

The 25 ns LHC physics beam is referred to as ‘nominal’ LHC beam. It is made of 6 PSB bunches injected in two consecutive cycles into the PS, where it undergoes a triple and then two double splittings for the resulting 72 bunches injected into the SPS. Combinations of up to four PS batches can fill the SPS and later the LHC for the baseline 25 ns bunch filling scheme.

To achieve the nominal LHC intensity while respecting the LHC normalised transverse rms emittance limit of 3.5 µm, bunches of 16.2×10^{11} protons with normalised transverse rms emittances of 2.5 µm have to be produced in the PSB. There is not much margin for a potential intensity increase in the PSB due to space charge limitations, and therefore the 50% intensity increase for the ‘ultimate’ LHC beam would be out of reach for the current injector complex (this led to the start of construction in 2008 of Linac4, a linear accelerator, which will replace the existing Linac2 and will increase the PSB injection energy from 50 MeV to 160 MeV) [3].

It is likely that the LHC will request varying intensities with the nominal bunch separation, down to 1/10th of the nominal intensity. With the constraint of keeping the longitudinal emittance constant, it was decided to compromise on the transverse emittance at PSB extraction. Transverse shaving will be the method used to decrease the bunch intensity in the PSB; the resulting decrease in transverse emittance will be compensated by transverse blow-up in the SPS using the transverse damper system.

50 ns LHC Physics Beam

Only recently the 50 ns LHC physics beam has emerged as one of the first LHC beams to be required. The increased bunch spacing allows tailoring the luminosities to the needs of the four main experiments [4].

For the PSB the 50 ns beam is simply one 25 ns variant with half of the nominal bunch intensity. In the PS the last double splitting is dropped.

75 ns LHC Physics Beam

This beam variant was proposed for early LHC operation to leave out 2 bunches by tripling the bunch separation at PS extraction from 25 to 75 ns. Two double splittings in the PS led to 24 bunches at PS extraction. The longitudinal emittance must be lower in the PSB (0.9 eVs), and the intensity per bunch is decreased by a factor of 3 leaving space for potential brightness increase if required.

Individual Bunch LHC Physics Beam

Large bunch spacing will be needed for the very first collisions during LHC commissioning, which will allow turning off the crossing angle scheme to simplify machine operation. Beam specifications in the LHC are similar to those of the multi-bunch physics beams, with the difference that both transverse and longitudinal characteristics at transfer to the SPS have to already be defined by the PSB as no bunch splitting takes place in the PS. Throughout the full intensity range, emittances have to stay constant. This is assured using the following techniques:

- 2-turn injection
- No transverse shaving; define transverse emittances with position of injected beam on injection bump and vertical injection steering
- Adapt capture efficiency (bucket size) to the desired intensity through longitudinal shaving using only the first harmonic radio-frequency (rf) system
- Adjustment of the final longitudinal emittance to 0.3 eVs by a reduction of the rf bucket size during the first part of the acceleration cycle. Here the rf voltage is kept at ~3 kV so that the bunch occupies the whole bucket area. A tomographic picture (phase space diagram) of the beam at the end this stage is shown in Fig. 1.
- Final adiabatic ramping to the top rf voltage prevents bunch filamentation. Fig. 2 represents the typical rf function during the acceleration cycle.
- Blow-up is used with the C16 cavity to smooth the bunch distribution and increase the longitudinal emittance.

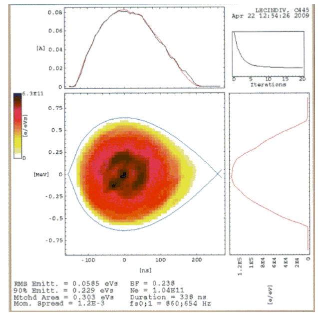

Fig. 1: Tomographic reconstruction of the individual bunch LHC beam in the PSB at the end of step 2 (Fig. 2): intensity $\sim 1\times10^{11}$, longitudinal emittance ~0.3 eVs.

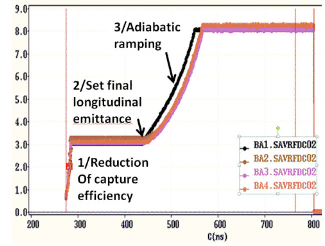

Fig. 2: rf voltage functions of the first harmonic rf system for the individual bunch LHC physics beam for all four PSB rings.

Different combinations of single PSB bunches with a varying number of PS injections into the SPS and specific LHC filling patterns constitute the individual bunch LHC physics beams. One variant of this operation scheme has been developed to meet the LHC TOTEM experiment needs.

LHC COMMISSIONING BEAMS IN THE PSB

Two variants of early LHC commissioning beams exist, the Pilot beam and the Probe beam. Both are single-bunch beams, thus final transverse and longitudinal emittances for SPS injection have to be set by the PSB.

LHC Pilot Beam

The main goal of the Pilot beam is to routinely test the LHC before its filling for physics. It needs to have the same transverse emittances as the LHC multi-bunch physics beams, but with a fixed intensity of 5×10^{9} protons. The strategy for the Pilot beam production in the PSB is identical to the one used for the production of the Individual bunch physics beam.

LHC Probe Beam

The LHC Probe beam production is also based on longitudinal shaving. Beam specifications include a tiny transverse emittance <1 μm and intensities varying by a factor of 5. The lowest intensity has been reduced from 5 to 3×10^{9} protons in the PS through longitudinal shaving, in order to stay within an acceptable security margin below the quench limit of the LHC superconducting magnets.

The Probe beam with an intensity of 3×10^{9} protons was the beam requested for the official LHC start-up day on the 10th of September 2008. A tomographic reconstruction of the LHC Probe beam before PSB extraction is shown in Fig. 3. In Fig. 4 a screen displays the LHC Probe beam after having made its first ever turn in the LHC.

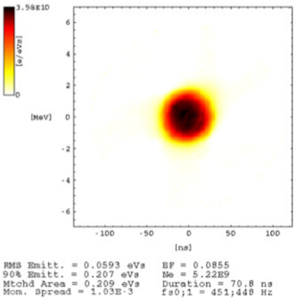

Fig. 3: Tomographic image of the LHC Probe beam in the PSB; intensity 5.2×10^9 protons, momentum spread $\sim10^{-3}$, bunch length ~70 ns and longitudinal emittance ~0.2 eVs.

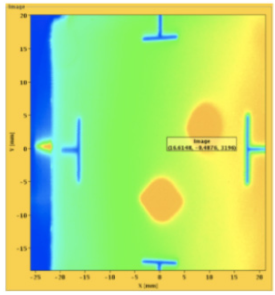

Fig. 4: First ever turn of a LHC Probe beam in the LHC (injected beam and beam after first turn) on September 10th 2008.

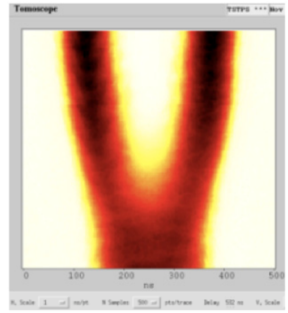

Fig. 5: Bunch splitting of the 50 ns-type LHC beam in PSB ring 3.

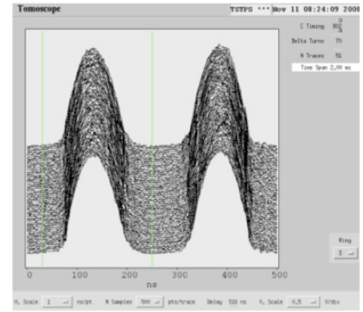

Fig. 6: The 50 ns-type LHC beam 2 ms before PSB extraction showing slight bunch asymmetry. The shorter bunch distance is just sufficient for the extraction kicker rise-time.

SINGLE-BATCH TRANSFER OF THE LHC PHYSICS BEAMS FROM PSB TO PS

A different production scheme has been proposed to achieve a single-batch transfer of the LHC physics beams from PSB to PS [5]. Instead of using two basic periods to inject into the PS four PSB h=1 bunches followed by two more, the method proposes to inject six h=2 bunches (3 rings) at once. The main difficulty for the PSB is to create a bunch separation compatible with the use of harmonic 7 in the PS. The consequence is that the two bunches per PSB ring can no longer be evenly spaced; an h=1 rf component is added to the main PSB h=2 field yielding slightly asymmetric bunches. As the extraction kicker transient needs to occur during the shorter bunch spacing, the 106 ns kicker rise-time therefore limits the maximum bunch length to less than 150 ns.

First beam tests with the PS in 2008 proved the feasibility of this new production scheme. In a first series of experiments, a beam with the longitudinal characteristics (intensity and emittance) needed for 75 ns LHC bunch trains has been generated in the PSB and successfully transferred to the PS.

As a next step, the beam needed for the generation of the 50 ns LHC bunch trains has been demonstrated in the PSB, but not yet injected into the PS. To this end, a typical low energy set-up (double harmonic rf, dynamic working point with resonance compensation) has been applied. Fig. 5 shows the splitting process in PSB ring 3. The bunches at PSB extraction (Fig. 6) had a bunch length just below 150 ns and normalised transverse emittances around the specified 2.5 µm (1 σ) at a bunch intensity of 8.9×10^{11} protons.

For this single batch transfer scheme, the longitudinal emittance must be smaller than the 1.3 eVs in present operation for 25 ns and 50 ns beams. Moreover, the matching between the asymmetric bunches and the buckets is not perfect. The next steps are to apply blow-up in the PS to remove structure from the injection and to adjust the longitudinal emittance to that required for bunch splitting and finally the setting up of the whole PS cycle with single-batch transfer.

The limitations for the 25 ns beam variant have to be studied in detail; in particular problems are expected with excessive direct space charge tune shift at PS injection due to the shorter bunch length; bunch rotation and fast longitudinal blow-up after PS injection could serve as a potential remedy.

CONCLUSIONS

Specifications for the LHC beams in the LHC injector chain have evolved over the years as did the beam production strategies as a consequence. Experience with the LHC will certainly lead to further modifications; in particular bunch intensity and bunch spacing will have to remain flexible from the injector chain. An overview of the different LHC beam variants in the PSB with operational parameters has been given as well as an outlook to potential improvements with respect to single-batch transfer to the PS of the LHC 50 and 75 ns multi-bunch physics beams. After more studies it is planned to use single-batch transfer at least for the 75 ns beam as baseline in 2009 operation.

REFERENCES

[1] K. Schindl, Conversion of the PS complex as LHC proton pre-injector: Project proposal, PS/DI/Note 94-17, Geneva, 1994.

[2] M. Benedikt, LHC Operational Beam Definitions for the Proton Injector Chain, LHC-OP-ES-0002 rev 1.0, CERN AB-OP Note, 2004.

[3] M. Benedikt and R. Garoby, High Brightness Proton Beams for LHC: Needs and Means, Proceedings of the High Energy High Intensity Hadron Beams workshop (HHH 2004), CERN, Geneva, 2004.

[4] M. Ferro-Luzzi, W. Herr, T. Pieloni, LHC bunch filling schemes for commissioning and initial luminosity optimization, LHC-PROJECT-NOTE-415, 19 June 2008

[5] C. Carli, A. Blas, A. Findlay, R. Garoby, S. Hancock, K. Hanke, B. Mikulec, M. Schokker, Studies on Single Batch Transfer of LHC Type Beams Between the CERN PS Booster and the PS, these proceedings.