# LOW-INTENSITY BEAMS FOR LHC COMMISSIONING FROM THE CERN PS-BOOSTER

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*Abstract*

A variety of low-intensity beams will be required for LHC commissioning. In contrast to the nominal LHC physics beam, these single-bunch beams are produced without longitudinal bunch splitting in the injector chain. Consequently, not only the transverse but also the longitudinal beam characteristics have already to be established in the CERN PS-Booster. The required intensities extend down to four orders of magnitude below the typical PS-Booster working range and the transverse emittances must be adjustable to vary the beam brightness over a large range. The different beam variants are briefly summarized and the specific techniques developed for their production, like low-voltage rf capture, and transverse and longitudinal shaving, are described. In particular, the choice of harmonic number and its consequences for operation and beam reproducibility are discussed. Finally, the performance achieved for the different beams is summarized.


## INTRODUCTION

The PS-Booster (PSB) is the first circular machine in the LHC proton injection chain. For production of the nominal LHC beam [1,2] a horizontal three-turn injection is used to accumulate the 50 MeV Linac beam. The multi-turn injection process in the PSB determines the transverse emittances of the beam and therefore the final LHC beam brightness. On the contrary, the longitudinal characteristic of the nominal LHC beam is only fixed at ejection from the PS. Complicated RF gymnastics (triple splitting from harmonics 7 to 21 at injection and two double splittings from harmonics 21 to 42 and 84 before ejection), employing also some controlled longitudinal beam blow-up, are performed in the PS to generate the nominal bunch train for the LHC [3].

The situation is rather different for the first commissioning phase of the LHC, where a variety of low-intensity beams will be required. The production of these beams will follow a completely different scheme, characterized by the fact that there is no longitudinal bunch splitting in the PS. Therefore not only the transverse but also the longitudinal bunch characteristics have to be established already in the PSB. The single bunches coming from the PSB rings are then passed on to the LHC by the injector chain with the major concern being minimization of transverse beam blow-up. The various beams produced with that specific scheme are called “individual bunch” beams [4].

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## OVERVIEW ON BEAM VARIANTS

### Individual bunch physics beam

Depending on the number of PSB bunches (1 or 4) per PS cycle and the number of PS injections per SPS cycle, individual bunch physics beams with a single, 43 or 156 LHC bunches can be obtained. These beams are grouped in the early commissioning filling patterns for the LHC [5]. The bunch intensities required at PSB extraction range from $2.0 \times 10^{10}$ up to $1.3 \times 10^{11}$ protons per bunch, the latter figure corresponding to a nominal bunch in the LHC ($1.15 \times 10^{11}$). The upper limit for the normalised rms transverse emittances is 2.5 μm. For the TOTEM beam, the required transverse emittances are 0.8 μm for an intensity of $4.0 \times 10^{10}$ protons per bunch.

### Pilot beam

The pilot beam consists of a single bunch in PSB, PS, SPS and LHC. The intensity of the pilot beam is $5 \times 10^9$ protons, corresponding to the LHC quench limit at injection energy. The transverse emittances of the pilot beam should be reasonably close to the ones of the physics beam in use at the time which requires a range from 0.8 to 2.5 μm at PSB extraction.

### Probe beam

The probe beam consists of a single, low-emittance bunch in PSB, PS, SPS and LHC. This beam will be used as very first commissioning beam and later on for studies. The beam intensity will be rather low and variable between $5 \times 10^9$ and $2 \times 10^{10}$ protons. The transverse emittances should be smaller than 1 μm.

### Summary

Table 1 summarizes the main parameters of the different individual bunch beams. It should be noted that the longitudinal emittance is identical for all variants at 0.3 eVs (at PSB ejection), which is just slightly below the nominal longitudinal emittance of 0.35 eVs thus allowing for some additional blow up in the injector chain.

Table 1: Main parameters of individual bunch beams for LHC start-up and early operation (at PSB extraction).

| **Beam type** | **intensity per bunch [$\times 10^{10}$]** | **$\varepsilon_{rms, norm.}$ [μm]** | **$\varepsilon_{longit.}$ [eVs]** | **bunches (rings)** |
|---|---|---|---|---|
| **Indiv. physics** | 2.0 – 13.0 | ≤ 2.5 | ≤ 0.3 | 1 or 4 |
| **Pilot beam** | 0.5 | ≤ 2.5 | ≤ 0.3 | 1 |
| **Probe beam** | 0.5 – 2.0 | ≤ 0.8 | ≤ 0.3 | 1 |

## STRATEGY FOR BEAM PRODUCTION

Over the last years many machine development sessions were performed on the PSB to develop a strategy for individual bunch beam production. To cover the whole parameter space, several ingredients were required.

### *Transverse emittances*

Independent horizontal and vertical "shavers" are used for emittance control in the PSB. For each plane the system uses a single correction dipole to deflect the orbit towards an aperture limitation where the beam is shaved in betatron amplitudes. This process is applied directly after rf capture at the beginning of acceleration when there is almost no adiabatic damping and the physical beam size is still large, improving the precision.

### *Longitudinal emittance*

The required value of 0.3 eVs for all beam variants was achieved by longitudinal shaving. For this the rf voltage was reduced to limit the bucket acceptance to 0.3 eVs approximately in the middle of acceleration. Afterwards the rf voltage is again raised to the nominal 8 kV required for a correct longitudinal matching with the PS rf system.

### *Intensity (beam brightness)*

For variation of the beam brightness in the required range a combination of three techniques was used.

- The longitudinal phase space density was controlled in two steps. Firstly the rf voltage during the bunching process was varied hereby changing the part of the unbunched linac beam that is captured and accelerated. Secondly controlled longitudinal blow up was applied during the first part of the acceleration cycle to depopulate the longitudinal phase space. This was done with a higher harmonic rf system [6]. The final longitudinal emittance is then fixed afterwards by shaving with the principal rf system. Applying more or less blow up gives a good control of the longitudinal density and, since there is quasi no coupling between transverse and longitudinal phase spaces in the PSB, the effect is equivalent to a change of the transverse beam brightness.
- The intensity (brightness) of the linac beam can be changed by a sharp factor 5. This was done with the so-called "sieve", a mechanical device that can be moved into the in the injection line and that allows only 20% of the beam to pass through.
- The (transverse) brightness of the beam in the PSB can be influenced by the settings used for the multi-turn injection process. The most effective parameters are the steering and the betatron matching of the injection line, the horizontal and vertical tunes of the machine and the fine timing of the "slow" injection bumpers. A brightness variation of a factor 2 was achieved with the different settings.

The strategy is illustrated in Figure 1, showing the voltages of the principal harmonic (h=2 in this case) and the blow-up rf systems for generation of the $5.0 \times 10^9$ - 0.8 µm probe beam along the acceleration cycle. The effects of capture voltage, beam blow up, transverse and longitudinal shavings on the evolution of the beam current are shown in the lower part.

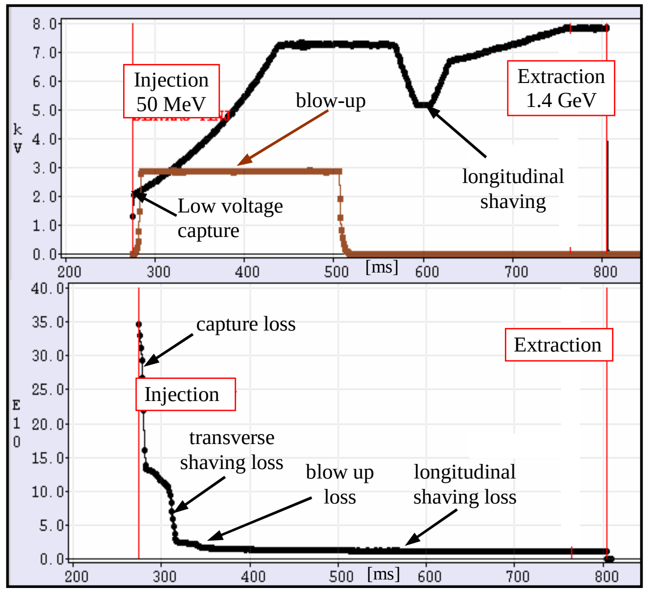


Figure 1: RF voltages and beam intensity along the cycle.

## RESULTS OF BEAM TESTS

### *Machine set up*

A horizontal three-turn injection, similar to the one used for the nominal LHC beam, was used as starting point for the set-up. Resonance compensation and working point optimization are less of an issue because the incoherent space charge tune spreads at injection are significantly smaller than in the case of the nominal beam. All beams were produced in two variants using either h=1 or h=2 as principal rf harmonics. The case of h=1 operation is discussed in more detail below, results from h=2 beam tests are summarised in Reference 7.

### *H=1 operation*

The production of all individual bunch beams with the first harmonic rf system was based on an rf function as shown in Figure 2.

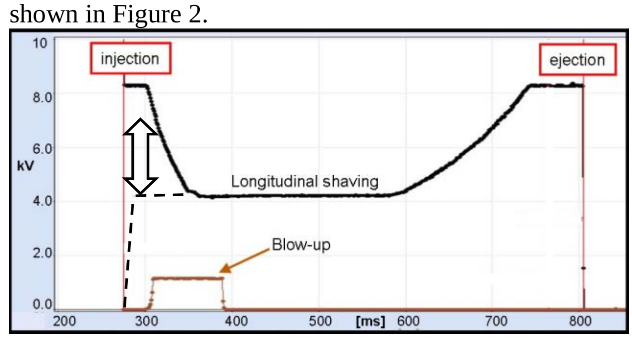


Figure 2: First harmonic and blow-up voltage functions.

The cavity voltage at capture allows a fine tuning of the intensity: the black solid line represents the rf function used for the TOTEM and higher intensity beams, while the dashed line is applied for low-intensity beams like the LHC probe bunch.

Small emittance beams have been produced with intensities ranging from 0.5 to $12\times10^{10}$ protons per bunch. Table 2 summarises the results obtained for three important beam variants, the probe beam, the TOTEM beam and a high-intensity small-emittance individual bunch physics beam. The longitudinal emittance was 0.3 eVs for all beams.

Table 2: Normalized rms emittances obtained with the first harmonic acceleration scheme.

| | Probe beam | Totem | Individual Physics |
|---|---|---|---|
| **Intensity [$\times10^{10}$]** | 0.5 | 4 | 12 |
| $\varepsilon_{h,rms,norm}$ | 0.9 | 0.9 | 0.9 |
| $\varepsilon_{v,rms,norm}$ | 0.8 | 0.8 | 0.8 |

The intensities and emittances were observed to be stable on all bunch variants to better than ±10%, corresponding to LHC demands.

## H1 VERSUS H2 OPERATION

The second harmonic approach was initially preferred for production of individual bunch beams since it was expected to provide better reproducibility for mainly two reasons:

- The second harmonics rf system is naturally better suited to the production of a relatively small longitudinal emittance (first and second harmonics systems have the same nominal voltage of 8 kV).
- By accelerating two bunches, the intensity in the machine is doubled hereby relaxing the demands on the dynamic range of various control loops.

There are however also two important complications from the operation viewpoint:

- Using the second harmonic obviously produces two bunches per ring out of which only one is sent to the PS. “Killing” of the non-useful bunch(es) is achieved with the three vertical recombination kickers of the PSB (recombining the beams from the 4 rings) and the injection kicker of the PS. This does not only require complicated timing set-up but also leads to beam losses in well located spots that should in general be avoided, regardless the relatively low intensity.
- Injection of a non-integer number of turns leads to a strong disruption in the azimuthal intensity distribution along the ring. This can lead to the formation of two unequal bunches in terms of intensity during bunching. Therefore injection set-up and rf phasing are critical processes and need to be continuously monitored and adjusted.

During comparative beam tests over the last years it was shown that the typical reproducibility was around ±10% in intensity and transverse emittances for both the h=1 and the h=2 approach. It was also found that the longitudinal emittance could be controlled relatively easy with both variants. Therefore the final choice was made for the h=1 approach because of its advantages for routine operation.

## CONCLUSIONS

For commissioning and early physics of the LHC so called individual bunch beams will be required. All parameters of these beams have already be defined and fixed at ejection from the PSB in contrast to the nominal LHC physics beam, where all the longitudinal characteristics is established in the PS. An operation strategy for the PSB was developed in order to produce the different beams and to facilitate the switching between them. All beams were produced in two variants using either h=1 or h=2 as principal rf harmonics. The observed stability and reproducibility was in the ±10% range in both cases, corresponding to LHC requirements. The h=1 solution is finally preferred since it offers advantages for operation.

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