CHAPTER 10

PERFORMANCE OF THE PRE-INJECTOR COMPLEX

10.1 GENERAL ISSUES

10.1.1 Transfer Efficiency

Extensive machine experiments during the 2003 operation period have shown that, contrary to original expectations, significant beam losses occur in the LHC injector chain for nominal and ultimate LHC beams. Around 5% of the beam is lost in the PS-complex (starting from capture in the PSB to the TT2 transfer line) and between 10 and 15% is lost in the SPS, mainly at capture. These losses need to be compensated by an increase of the intensity from the pre-injector complex. Since it now seems reasonable to allow for some losses in the LHC as well, the number of protons for the "nominal" and "ultimate" LHC bunches in the PS and also the bunch intensities required from the PSB had to be redefined (see Sec. 2.3).

Since the transverse emittance budget is fixed, any increase in intensity also leads to an increase in beam brightness and thus to a larger space charge tune shift at injection into the PSB which is the limiting factor. The 25 ns bunch train is nearly a factor 3 more demanding on beam brightness in the PSB than the 75 ns train. This lies in the nature of the PS bunch splitting scheme where each PSB bunch is split in 12 LHC bunches for the 25 ns train but only in 4 LHC bunches for the 75 ns train.

For the 25 ns nominal beam an intensity increase of up to 20% is going to be acceptable. On the other hand, for the 25 ns ultimate beam, which is already only feasible in the PSB by using up some of the PS's emittance budget, the required characteristics will become unattainable with present techniques and alternatives have to be considered (see Sec. 10.5).

For the 75 ns bunch trains no problems are anticipated for both nominal and ultimate LHC bunch intensities.

10.1.2 Beam Characteristics

With both 25 ns and 75 ns bunch spacing, the nominal characteristics specified for the LHC have been regularly obtained for the average bunch delivered to the SPS. However, characteristics (intensity, bunch length and transverse emittance) vary along the bunch train. Variations in transverse emittance are due to unequal emittances of the bunches from the four PSB rings, fluctuations in intensity can be caused by unequal intensities from the PSB and hardware imperfections in the PS, which also lead to variations in bunch length.

10.1.3 Uncaptured Beam and Parasitic Bunches

Typically around 1% of particles outside the bunches have been observed before ejection from the PS. They contribute to capture loss in the SPS and to the generation of parasitic bunches.

10.2 THE CASE OF 25ns BUNCH SPACING

At an intensity of 1.3×10^{11} protons per LHC bunch at PS ejection (nominal bunch intensity accounting for ~10% beam losses in the SPS), fluctuations inside the bunch train in intensity, bunch length and transverse emittances are within ±10%, limited by the differences between PSB rings and hardware imperfections in the PS. Fig. 10.1 shows the normalised horizontal and vertical rms emittances measured with wire scanners all along the injector chain. The measurements in the PSB show: the horizontal emittances of the bunches in rings 2 and 4 and the vertical emittances of those in rings 1, 3 and 4; in the PS, they show: at injection all 6 bunches from two PSB batches (PS 1.4GeV) and just before ejection the 72 LHC bunches (PS 26GeV/c); in the SPS, they show: the 72 LHC bunches from one PS batch at injection

(SPS26GeV/c) and at top energy (SPS 450GeV). The emittance budget foresees ($\varepsilon_{n,hor} + \varepsilon_{n,ver}$) ≤ 5 µm at PSB ejection, ε_n ≤ 3 µm for both planes at PS ejection and ε_n ≤ 3.5 µm at SPS top energy.

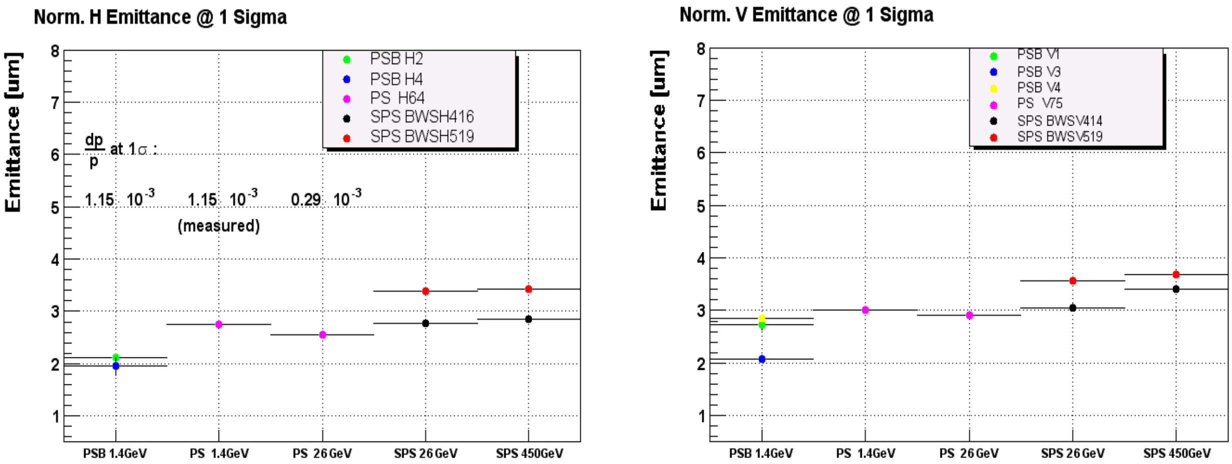

Figure 10.1: Normalised transverse rms emittances for the nominal 25 ns LHC beam along the injector chain (16.5×10^{11} protons per PSB bunch, 1.3×10^{11} protons per LHC bunch at PS ejection, 1.15×10^{11} protons per LHC bunch at SPS top energy).

At higher intensities, the PSB approaches its brightness limit and consequently the transverse emittances start to grow. In the PS, longitudinal coupled bunch oscillations increase the inter-bunch differences by creating different initial conditions for the bunches being split. To improve on this, a longitudinal damper is being prepared which will use the 10 MHz ferrite cavities that are still active during the first splitting at high energy.

10.3 THE CASE OF 75ns BUNCH SPACING

The performance specified for the nominal 75 ns spacing LHC beam has been obtained regularly for the average bunch delivered to the SPS. Bunch characteristics vary along the train. Even at nominal intensity, an asymmetry is observed which is attributed to the drift of the relative phase between harmonics 14 and 28 during the splitting process (see Fig. 10.2).

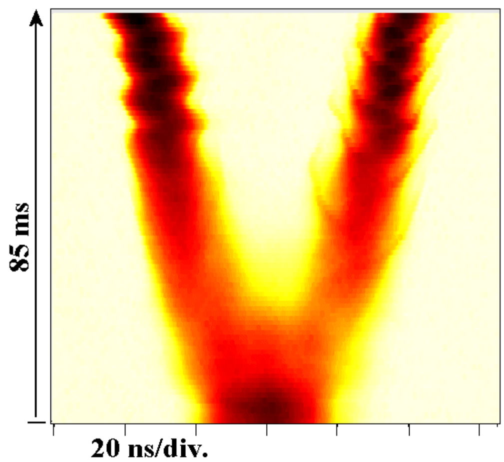

Figure 10.2: 75 ns bunch splitting at nominal intensity (1.15×10^{11} protons per LHC bunch, 25 GeV).

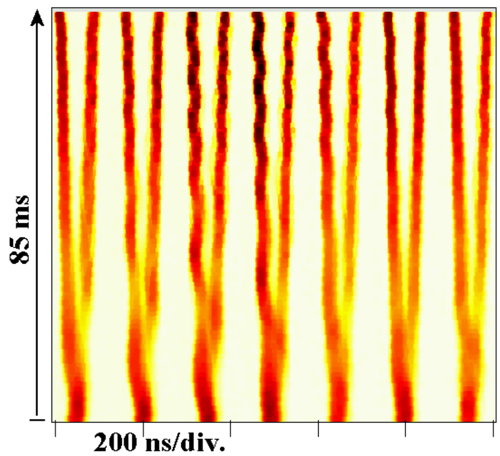

Figure 10.3: Incoherent bunch oscillations before and during 75 ns splitting (1.7×10^{11} protons per LHC bunch).

Because of this phenomenon, it has yet not been possible to equalise the 24 LHC bunches per PS batch simultaneously in intensity and longitudinal emittance.

In contrast to the 25 ns bunch spacing, the PSB operates well below its space charge limit and can therefore easily provide ultimate or even higher intensities within the emittance budget. However, at higher than nominal intensities coupled bunch oscillations appear in the PS, as in the case of the 25 ns bunch train and further increase the discrepancy between the final bunches (see Fig. 10.3). The same longitudinal damper will be employed as a cure.

10.4 PILOT BUNCH BEAMS

The LHC pilot beam consists of a single low-intensity bunch with 0.5×10^{10} protons and a normalised rms emittance of less than 1 μm in the LHC. The production of the pilot beam follows a different scheme than the one of the nominal LHC proton bunch train. Both the transverse and the longitudinal LHC bunch characteristics are already established in the PSB. After ejection from the PSB, the pilot bunch is passed on to the LHC by the downstream machines with the main concerns being to keep the bunch characteristics unchanged and to minimise longitudinal and transverse emittance blow-ups.

During 2002 extensive machine studies were made in the PSB to develop a strategy for pilot bunch production. The aim was to produce not only the low-intensity LHC pilot beam but also single LHC-type bunches with up to nominal intensity, $0.5 \times 10^{10} \leq N_b \leq 11.5 \times 10^{10}$ and with emittances variable between pilot and nominal emittance, $0.85\ \mu m \leq \varepsilon_n \leq 2.5\ \mu m$ at PSB ejection. The longitudinal emittance for all beam variants is kept constant at 0.3 eVs, slightly below the nominal one (0.35 eVs). This parameter space spans a factor 66 in beam brightness, N_b/ε_n.

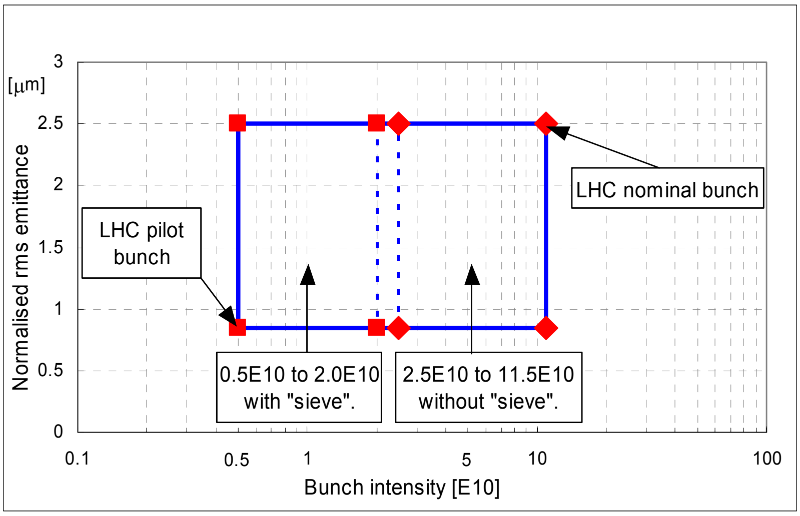

Figure 10.4: Range of PSB bunch characteristics obtained in 2002.

The main ingredients used to cover this large parameter space were:

- Insertion of the “sieve” in the linac transfer line to reduce the beam intensity (transverse density) by a factor 5.
- Controlled longitudinal blow-up (phase modulated RF on h=10) in the PSB to adjust the longitudinal density.
- Transverse shaving to set the transverse emittance.
- Longitudinal shaving (acceptance reduction during ramping) to set the longitudinal emittance.

By properly adjusting the procedures listed above, all the required types of bunches were obtained during 2002 in the PSB [1] as illustrated in Fig. 10.4. The low intensity bunches were obtained using the sieve in the linac to PSB transfer line. During 2003, significant effort was invested to study the acceleration of single bunch pilot-type beams in PS and SPS. Results are very satisfying as the bunch characteristics and especially the small transverse emittances were conserved up to SPS top energy for the pilot beam (0.5×10^{10}, 1 μm). No major difficulties were encountered during tests with a single nominal LHC bunch.

10.5 ULTIMATE BEAM

The level of unavoidable beam loss along the cascade of accelerators makes it impossible to attain the ultimate intensity per circulating bunch in the LHC with the standard schemes (see Sec. 2.3). Two different approaches are feasible to address this shortcoming:

- Increase the beam brightness in the PS, by means of RF gymnastics concentrating the beam in fewer bunches, in a fraction of the PS circumference, at an energy where space-charge is not a limitation. The resulting reduction of the number of bunches delivered per PS pulse will call for changing the LHC filling scheme, with an increase of filling time and a decrease of the filling factor.
- Increase the brightness of the beam in the PSB by injecting at a higher energy with a new linac (Linac4) replacing the 50 MeV Linac2, thus avoiding space charge limitations at injection.

10.5.1 Batch Compression in the PS

By slowly increasing the frequency of the RF holding the bunches, it is possible to reduce the fraction of the ring occupied with particles [2]. This is achieved by successively activating RF systems operating at increasing frequencies. A gap without particles is necessary in the initial beam. The following procedure can be sketched [3]:

- inject 7 (4+3) bunches from two PSB batches into the PS operating on harmonic 9
- accelerate this beam up to an intermediate energy where space charge is sufficiently reduced
- compress the 7 bunches into 7/14 of the PS circumference by adiabatically increasing from h=9 to 10, 11, 12, 13, 14
- accelerate the beam on harmonic 14 up to 25 GeV
- triple split the bunches using RF on h=14, 28 and 42 (similar process as used at 1.4 GeV for the 25 ns bunch train)
- double split the bunches changing the harmonic from 42 to 84 and rotate them before ejection, as in the present 25 ns bunch train scheme.

Finally, a train of 42 bunches spaced by 25 ns is sent to the SPS.

Because of space charge on the 1.2 s long PS flat porch at 1.4 GeV, the total intensity in the PS in that mode is limited to 1.1×10^{13} protons (1.6×10^{12} protons per PSB ring). Neglecting beam loss in the PS, the maximum intensity per bunch sent to the SPS is then 2.65×10^{11} protons. Ultimate intensity in the LHC will therefore be attained if transmission from PS to LHC is better than 64%.

10.5.2 New PSB Injector (Linac4)

Replacing the 50 MeV Linac2 by a 160 MeV Linac4, space charge is reduced by a factor two at injection energy in the PSB. Using the flexibility in painting possible with charge exchange injection, the brightness of the beam delivered by the PSB is expected to double and reach 3.6×10^{12} protons per ring within 2.5 μm rms in both transverse phase planes. With a single batch from the PSB, the following procedure can be applied [4]:

- inject 12 (4×3) bunches into the PS operating on harmonic 14 [1]
- accelerate the beam on harmonic 14 up to 25 GeV
- triple split the bunches using RF on h=14, 28 and 42 (similar process as used at 1.4 GeV for the 25 ns bunch train)
- double split bunches changing the harmonic from 42 to 84 and rotate them before ejection, as in the present 25 ns bunch train scheme.

Finally, a regular train of 72 bunches spaced by 25 ns is sent to the SPS.

Because of the very short time spent at 1.4 GeV, the increase by a factor 14/12 of the space charge induced tune spread in the PS is considered feasible. The total intensity in the PS is then 1.42×10^{13} protons.

[1] Each PSB ring delivers 3 bunches, obtained by triple splitting at 1.4 GeV with the existing RF system. H=1 RF voltage is applied before ejection to reduce the distance between bunches to a period on h=14 in the PS. The recombination kickers in the PSB to PS transfer line have to be modified for faster rise times.

Neglecting beam loss in the PS, the maximum intensity per bunch sent to the SPS is then 1.97×10^{11} protons. Ultimate intensity in the LHC will be attained, with a single batch from the PSB, if transmission from PS to LHC is better than 86%.

If this transmission is not achieved, various batch compression schemes can be envisaged, necessitating the change of the LHC filling scheme, with an increase of the filling time and a decrease of the filling factor.

10.5.3 Comparison between Schemes

Both methods have to be studied in more detail. Their main features are summarised in Tab. 10.1. The new injector for the PSB is a more expensive but very attractive option which would ease operation and reduce the filling time of LHC, leaving more beam time from the PSB and PS available to other users. When combined with batch compression in the PS it has the potential of providing beams of much larger brightness which can be precious for further luminosity upgrades of the LHC.

Table 10.1: Comparison of methods to increase beam brightness.

	Batch compression	New PS injector
Implementation	Limited cost Fast (provided machine time and manpower are available)	Significant cost (~ 70 MCHF) Long (~ 3 years construction)
Exploitation	Complex, delicate & manpower intensive,	Simple & robust
Performance	Increased LHC filling time Reduced LHC filling factor Penalises other beam users	Reduced LHC filling time Usual LHC filling factor Beneficial to other users (more cycles available, with more protons per cycle)
Potential*[2]	Limited at ~ 2.65×10^{11} protons per bunch from the PS	Can go beyond 3×10^{11} protons per bunch from the PS when combined with a batch compression scheme

REFERENCES

[1] M. Benedikt, *LHC pilot bunches from the CERN PS Booster*, Proc. of PAC 2003, Portland, 2003.

[2] R. Garoby, *New RF exercises envisaged in the CERN-PS for the antiprotons production beam of the ACOL machine*, CERN-PS-85-36-RF, Geneva, 1985.

[3] O. Bruning et al., *LHC Luminosity and Energy Upgrade: a Feasibility Study*; LHC Project Report 626, Chapter 11, CERN, Geneva, 2002.

[4] F. Gerigk, M. Vretenar, *Design of a 120 MeV H- Linac for CERN High Intensity Applications*, CERN/PS 2002-069 (RF), Geneva, 2002.

[2] These are preliminary estimates that need to be refined. Upgraded instability damping systems for the PS will be necessary in both longitudinal and transverse phase planes to cope with that intensity.