THE PS COMPLEX PRODUCES THE NOMINAL LHC BEAM

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Abstract

The LHC [1] will be supplied, via the SPS, with protons from the pre-injector chain comprising Linac2, PS Booster (PSB) and PS. These accelerators have undergone a major upgrading programme [2] during the last five years so as to meet the stringent requirements of the LHC. These imply that many high-intensity bunches of small emittance and tight spacing (25 ns) be available at the PS extraction energy (25 GeV). The upgrading project involved an increase of Linac2 current, new RF systems in the PSB and the PS, raising the PSB energy from 1 to 1.4 GeV, two-batch filling of the PS and the installation of high-resolution beam profile measurement devices. With the project entering its final phase and most of the newly installed hardware now being operational, the emphasis switches to producing the nominal LHC beam and tackling the associated beam physics problems. While a beam with transverse characteristics better than nominal has been obtained, the longitudinal density still needs to be increased. An alternative scheme to produce the 25 ns bunch spacing is outlined, together with other promising developments.

1 BEAM REQUIREMENTS

The "nominal" beam required by the LHC features: (i) a small transverse emittance of $\varepsilon^*=3.75\ \mu m$*, needed to fit the tiny LHC dynamic aperture; (ii) an intensity of $N_b = 1.1x10^{11}$ p/LHC-bunch to reach the design luminosity; (iii) a bunch spacing of 25 ns. The combination of (i) and (ii) yields a very high beam brightness N_b/ε^*, which implies severe space charge problems at injection in the PSB and PS. The 25 ns bunch spacing is established at PS ejection.

During the first years of physics, the LHC will operate with the "initial" beam with $N_b = 1.7x10^{10}$ and $\varepsilon^*=1.0\ \mu m$. Although beam brightness is not so much of an issue, the even smaller emittance and its preservation along the chain will be the challenge. However, this paper only deals with the nominal beam.

* Normalised rms emittance $\varepsilon^*_{h,v} = \beta\gamma\cdot\sigma^2_{h,v}/\beta_{h,v}$

1.1 Space charge at PSB injection

The space charge problem at PSB injection (50 MeV) is tackled by filling the PS with two consecutive batches, thus reducing the beam intensity and tune shift by a factor two. This imposes the use of the RF-harmonic number *h*=1 in the PSB (4 rings of 1/4 PS circumference) as can be seen in Figure 1.

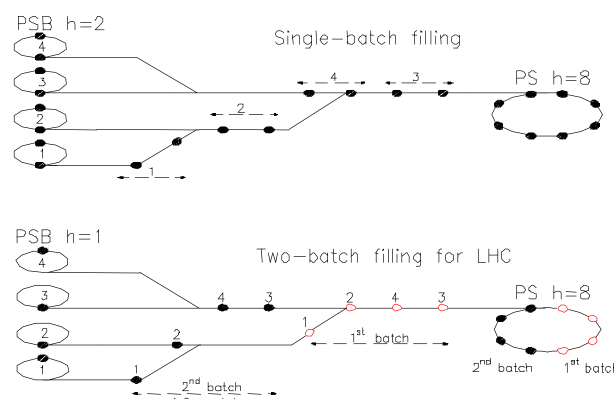

Figure 1: Double batch filling of the PS with *h*=1.

1.2 Space charge at PS injection

The double-batch filling scheme exacerbates the impact of space charge in the PS, as the first injected batch is kept at low energy for one full PSB cycle of 1.2 s. Increasing the PSB-PS transfer energy from 1 to 1.4 GeV reduces the space charge effects by a factor 1.5 (ratio of $\beta\gamma^2$ at these energies). This change of transfer energy implied major upgrading of magnet and power supply systems in the PSB and the transfer line to the PS.

1.3 Providing the LHC bunch spacing

The 25 ns bunch spacing is generated at PS ejection; the bunches have to be shorter than 5 ns to fit the SPS 200 MHz RF-system. This is achieved just before PS ejection at 25 GeV by debunching and rebunching the beam on *h*=84 followed by non-adiabatic bunch rotation. For this, the PS was equipped with 40 MHz (*h*=84) and 80 MHz RF systems.

The main machine and beam parameters of the injector chain (including SPS) are shown in Table 1.

Table 1: LHC proton injector chain, nominal parameters.

	PSB	PS	SPS
kinetic energy [GeV]	1.4	25	450
repetition time [s]	1.2	3.6	16.8
number of pulses to fill downstream machine	2	3	2x12
number of bunches	1/ring	8(16)/84	243
p/pulse nominal [10^{11}]	46	92	267
p/bunch nominal [10^{11}]	11.5	11.5/1.1	1.1
emittance ε* [μm]	2.5	3.0	3.5

2 MAJOR HARDWARE UPGRADES [3]

The major hardware upgrades in the PS Complex are shown in Figure 2. The Canadian contributions (via TRIUMF) to this project are indicated in italics.

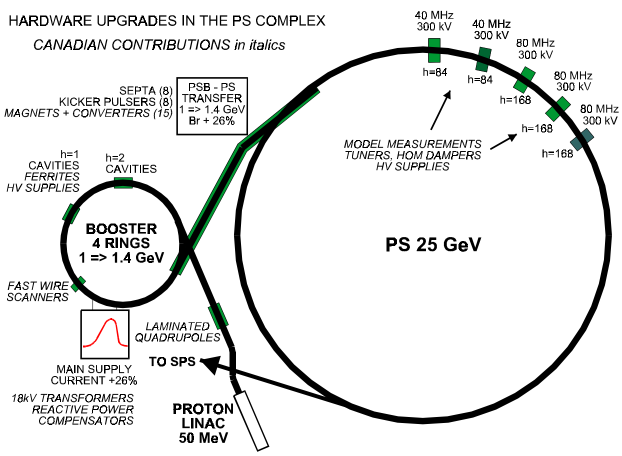

Figure 2: Major hardware upgrades in the PS complex.

- PSB RF systems: (i) new h=1 system to allow double batch injection in the PS and (ii) transformation of the former h=5 to an h=2 system for dual-harmonic operation (bunch flattening to reduce space charge).
- PSB ejection energy to 1.4 GeV: major upgrade of the main power supply to cope with the increase of dipole and quadrupole fields by 26 %.
- PSB-PS transfer energy to 1.4 GeV: (i) 15 new magnets with power converters, (ii) new pulsed septum magnets and power supplies (PSB ejection recombination and PS injection), (iii) refurbishing of fast kickers with more powerful pulsers.
- PS RF systems: (i) modifications to the existing 10 MHz system to allow acceleration on h=8, bunch splitting to h=16 (at 3.5 GeV/c) and acceleration to 25 GeV, (ii) new 40 and 80 MHz systems for rebunching on h=84 and bunch shortening to ~4 ns at 25 GeV.
- PSB and PS instrumentation: new and improved diagnostic devices to measure transverse beam characteristics of small-emittance beams.

3 BEAM TESTS

First beam tests in view of the future role of the PS Complex as LHC injector were performed as long ago as 1993 [4]. These led to the specifications of the PS Complex upgrading project. Now, with all the new hardware available, extensive machine studies [5] have shown that the PS Complex can produce an LHC-type beam, with nominal intensity and transverse emittances staying well below the specified values. Figure 3 shows emittance measurements during different stages of the PS cycle.

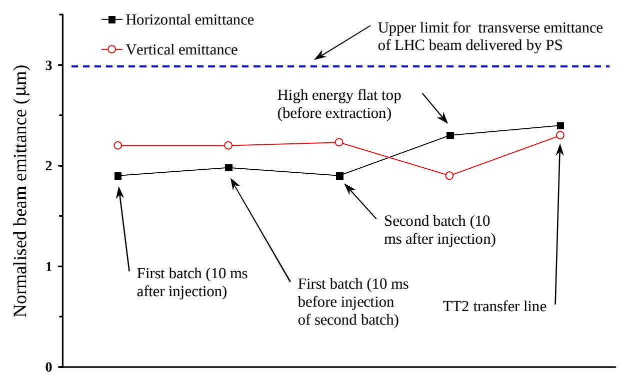

Figure 3: Evolution of normalised emittances $\varepsilon^*_{h,v}$ during the PS cycle for the nominal LHC beam.

However, the 1993 beam test was incomplete for two reasons:

- Only ring 3 out of the four PSB rings was available for acceleration and ejection at 1.4 GeV towards the PS.
- The PS was not equipped with the 40 and 80 MHz RF systems and therefore the debunching-rebunching process at 25 GeV could not be tested.

These limitations have hidden two problems which were only discovered recently: (i) saturation effects in the PSB main bending magnets and (ii) a longitudinal microwave instability in the PS during debunching.

3.1 *Saturation of the PSB bending magnets [6]*

The energy upgrade of the PSB from 1 to 1.4 GeV corresponds to a 26 % increase of the main bending field. Even though the maximum bending magnet field now reaches a moderate 0.86 T, significant saturation effects were observed in the outer gaps of the PSB bending magnets (see Figure 4). As a result, their bending field is nearly 1 % lower than in the inner gaps, perturbing the synchronisation between PSB and PS. Due to the lower bending fields, the beams in the outer rings are synchronised at a positive mean radial position and a higher momentum with respect to the inner rings.

The saturation effect is due to the special four-gap geometry of the PSB bending magnets (Figure 4). The problem was cured by installing a new, dedicated trim power supply on the outer gaps [3].

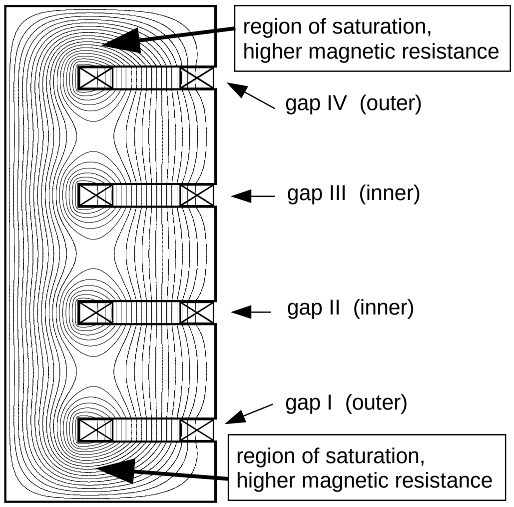

Fig. 4: Flux distribution in PSB main bending magnet at 1.4 GeV beam energy.

3.2 *Longitudinal instability in the PS*

The beam tests have also shown that the longitudinal beam characteristics are degraded at 25 GeV in the PS during the debunching-rebunching process. At nominal intensity, the longitudinal emittance blows up by 40 %, so that the bunches end up 20 % too large in both length and energy spread. An instability, possibly caused by the higher order resonances of the 114 MHz cavities used for lepton acceleration, may be the culprit. Although the removal of these cavities is planned after the year 2000, the debunching-rebunching process will remain sensitive to perturbations.

4 FUTURE DEVELOPMENTS

A possibly more robust procedure avoids the debunching-rebunching process, but rather changes the number of bunches by using multiple splitting operations [7] as represented in Figure 5.

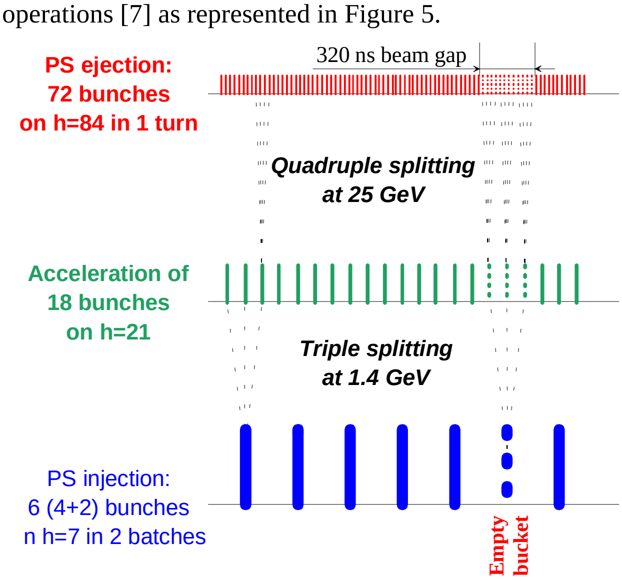

Figure 5: Multiple splitting scheme for the LHC beam.

Captured on *h*=7 in the PS, the bunches are split in three at 1.4 GeV and accelerated on *h*=21. At 25 GeV, each bunch is split twice in two (using a new 20 MHz RF system), so that finally 84 bunches are created if all of the 7 buckets are filled. The multiple splitting scheme was recently proven to preserve longitudinal emittance [8]. Compared to the original scheme, only 7 (instead of 8) PSB bunches are used, and thus 15 % higher intensity and beam brightness are required which may be limiting for the "ultimate" beam. An advantage is the simple generation of a gap in the bunch train (for the PS ejection kicker) by missing out one of the PSB bunches, i.e. injecting only 6 bunches, leaving one bucket empty.

4.1 *"Ultimate" beam*

With $N_b = 1.7\times10^{11}$ and $\varepsilon^*=3.75\ \mu m$, the brightness of the "ultimate" beam and thus its space charge detuning is 1.6 times higher than for the "nominal" one. Promising results were obtained in the PSB on the generation of hollow bunch distributions [9], with a view to improve the bunching factor and thus ease space charge in the PS.

5 CONCLUSIONS

With the major hardware components installed, the upgrading of the PS Complex as LHC proton pre-injector is virtually completed. Indeed, a beam with transverse properties better than nominal has been produced at PS ejection, but its longitudinal density is not yet up to specifications. A novel scheme, based on multiple bunch splitting, potentially produces the dense LHC bunches. First tests are very promising.

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