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PERFORMANCE OF THE LHC PRE-INJECTORS

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The LHC pre-injector complex, comprising Linac 2, the PS Booster (PSB) and the PS, has undergone a major upgrade in order to meet the very stringent requirements of the LHC. Whereas bunches with the nominal spacing and transverse beam brightness were already available from the PS in 1999 [1], their length proved to be outside tolerance due to a debunching procedure plagued by microwave instabilities. An alternative scenario was then proposed, based on a series of bunch-splitting steps in the PS. The entire process has recently been implemented successfully, and beams whose longitudinal characteristics are safely inside LHC specifications are now routinely available. Variants of the method also enable bunch trains with gaps of different lengths to be generated. These are of interest for the study and possible cure of electron cloud effects in both the SPS and LHC. The paper summarizes the beam dynamics issues that had to be addressed to produce beams with all the requisite qualities for the LHC.

1 THE LHC PROTON INJECTOR CHAIN

1.1 Parameters of the LHC proton beams

For LHC collider operation, three different proton beams are required: (i) the "initial" or "commissioning" beam, permitting LHC physics during the first two years at a luminosity of 10^{33} cm^{-2}s^{-1}; (ii) the "nominal" beam for operating the LHC at 10^{34} cm^{-2}s^{-1}; (iii) the "ultimate" beam, which is the foreseeable LHC performance limit at 2.5×10^{34} cm^{-2}s^{-1}.

Table 1: LHC proton injector chain, nominal parameters

	PSB (4 rings)	PS	SPS	LHC
kinet. energy [GeV]	1.4	25	450	7000
repetition time [s]	1.2	3.6	21.6	
nb. of pulses to fill downstr. machine	2 (3 rings)	3 or 4	12 (for one LHC ring)	
bunches/ring	1	6/18/36/72	216/288	2808
RF harmonic nb.	1, 2	7/21/42/84	4620	35640
protons/pulse	4×10^{12}	8×10^{12}	3.2×10^{13}	3.1×10^{14}
protons/ bunch	1.3×10^{12}	1.1×10^{11}	1.1×10^{11}	1.1×10^{11}
ε^*_{rms} [μm]	2.5	3.0	3.5	3.75
ε_L (2σ)/bunch [eVs]	1.5	0.35	1	2.5
4σ bunch length ns	~170	4	1.7	1
Luminosity [cm^{-2}s^{-1}]				1×10^{34}

This paper deals with the nominal beam whose main parameters [2] along the LHC injector chain are compiled in Table 1. At PS extraction, the nominal beam features (i) a small transverse emittance of ε^*_{rms} =3.0 μm (normalized); (ii) an intensity of N_b = 1.1 10^{11} p/bunch; (iii) 72 bunches with a spacing of 25 ns. The ratio N_b/ε^*_{rms}, the beam brightness, is about 1.5 times higher than obtained previously and implies heavy space charge at PSB and PS injection.

1.2 Space charge in PSB and PS

CERN's 50 MeV proton Linac 2 has been upgraded and can now provide pulses of 180 mA during >100 μs. This beam is injected into each of 3 PSB rings by betatron stacking, yielding a beam with an incoherent space-charge tune-spread ΔQ_y ~ 0.6 after RF capture on h=1, when using an h=2 cavity for bunch flattening. Under these conditions, the emittances cannot be kept within the tight specifications; the way out is to fill the PS with two consecutive batches, thus halving the beam intensity per pulse (by stacking only 3 turns per PSB ring) and reducing ΔQ to a more manageable ~0.3.

The double-batch filling scheme exacerbates the impact of space charge in the PS as the first injected batch, occupying about half the PS circumference, dwells at low energy for 1.2 s until the arrival of the second PSB batch. In this time, space charge effects lead to emittance blow-up, which was successfully eliminated by raising the PSB-PS transfer energy from 1 to 1.4 GeV. This reduces ΔQ in the PS and prevents the beam from straddling low-order non-linear resonances.

1.3 Providing the LHC bunch spacing of 25 ns

The 25 ns bunch spacing is generated in the PS just before the beam is sent to the SPS. The bunches must be ~4 ns long to fit the SPS 200 MHz RF system. Originally, this was achieved by debunching, then rebunching the beam on h=84, followed by bunch rotation (that is, the bunches are ejected when they are shortest). For this, the PS was equipped with 40 MHz (h=84) and 80 MHz RF systems. However, when trying the scheme, longitudinal microwave instabilities, generated at nominal intensity by the longitudinal impedance of the PS, blew up the momentum spread during the delicate debunching process: there was no way to make the bunches shorter than 5 ns.

Rather than embarking on a costly impedance reduction programme, the scheme to produce the LHC beam was radically changed. It is now based on the recently invented longitudinal splitting of one bunch into three (triple splitting [3]) and also on the more familiar splitting of one bunch into two (double splitting). In this scheme, 6 PSB bunches (2 batches of 3 bunches, i.e. only using 3 of the 4 PSB rings) are injected into 6 out of 7 PS buckets, thus leaving a void for the PS extraction kicker. The 6 bunches in the 7 buckets are split into 18 by the new method, then accelerated to 25 GeV, split into 36 and finally into 72, so that 12 of the final 84 buckets are empty (Fig. 1).

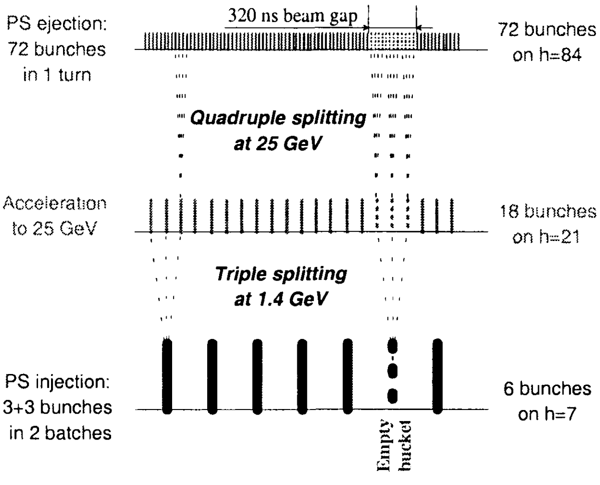

Fig. 1: Multiple splitting scheme for the LHC beam. "Quadruple"splitting means two steps of double splitting.

2 HARDWARE UPGRADES

Major hardware upgrades in the PS Complex [4] are shown in Fig. 2. One quarter of the equipment, indicated in italics, is a contribution of Canada (via TRIUMF).

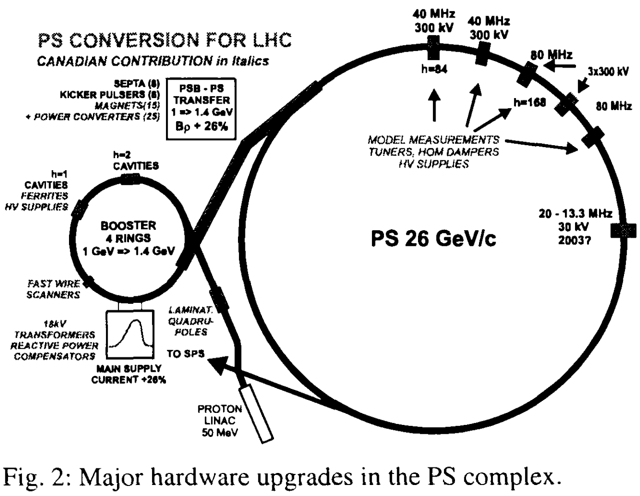

Fig. 2: Major hardware upgrades in the PS complex.

With one bunch per PSB ring (h=1 RF systems), double-batch injection into the PS becomes feasible by appropriate phasing of the bunches in the 3 rings. The PSB energy increase implied 26% higher field levels and thus refurbishing the main magnet supply and replacing most of the PSB-PS transfer line magnets and power converters. At 1.4 GeV (field level ~0.86 T), the PSB top and bottom rings have a weaker magnetic field (by ~1%) than the inner ones due to unequal saturation. A trim supply now equalizes the dipole field in each gap. The 40 MHz and 80 MHz RF systems in the PS are required to generate the bunch spacing and shorten the bunches. Improved diagnostic devices, such as fast wire-scanners, enable transverse beam characteristics of the small-emittance LHC beam to be measured. Finally, a prototype 20 MHz cavity was recently installed in the PS to provide the intermediate bunch harmonic 42 and to allow the new scheme for producing the LHC beam in the pre-injector to be tested.

3 RESULTS OF RECENT BEAM TESTS

3.1 PS Booster [5],[6]

The space-charge detuning is largest (~0.3) at 50 MeV just after RF capture on harmonic 1. Although all second- and third-order stopbands are narrowed by correction lenses, they still increase the emittances. The time during which these resonances are straddled is minimized by appropriate programming of the betatron tunes during the cycle (Fig. 3).

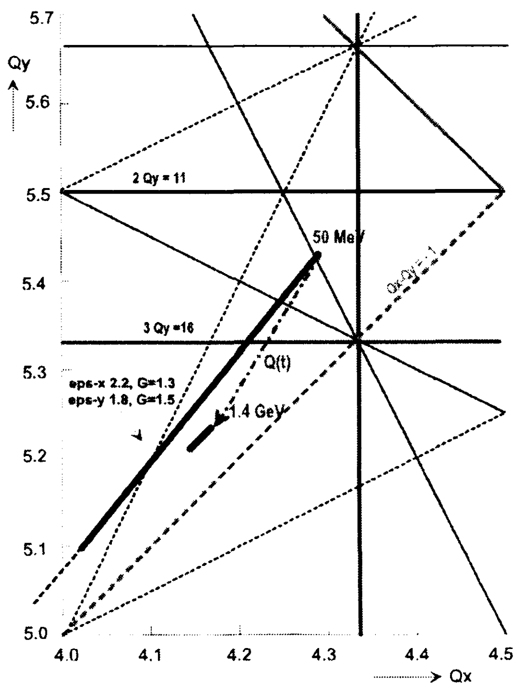

Fig. 3: PS Booster tune diagram with stopbands, time-varying tunes Q(t), and space-charge tune-spread at injection and ejection energies. N=1.4×10^{12} protons/ring, bunching factor 0.55, eps-x,y normalised rms emittances.

Owing to the horizontal 3-turn betatron stacking, $\varepsilon_x > \varepsilon_y$ after injection, but are equalized by deliberate beam "shaving" during acceleration. Before extraction towards the PS, the bunches undergo controlled longitudinal blow-up so as to lengthen them and thus further decrease the space charge detuning in the PS. However, this process is not yet operationally reliable. Beam parameters measured at PSB ejection are compiled in Table 2.

Table 2: Nominal LHC beam, parameters at PSB extraction with one bunch per ring, 3 rings used.

	Achieved	Goal
protons/ring	1.4×10^{12}	1.32×10^{12}
ε_x^* ($=\sigma_x^2\,\beta\gamma/\beta_{TWISS}$) [$\mu$m]	2.2	2.5
ε_y^* ($=\sigma_y^2\,\beta\gamma/\beta_{TWISS}$) [$\mu$m]	1.8	2.5
2-σ long. emittance ε_l [eVs]	0.9[1]	1.5
4-σ bunch length τ_b [ns]	150[1]	190
2-σ momentum spread $\Delta p/p$	2×10^{-3} [1])	2.45×10^{-3}

[1]without controlled blow-up

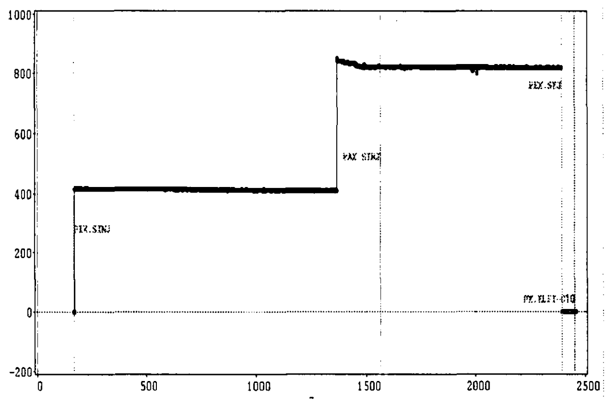

Fig. 4: Intensity of the PS ring (in units of 10^{10} protons) vs. time (in ms).

3.2 PS [5],[6]

Three PSB bunches are injected into the PS, with the RF at h=7, by bunch-to-bucket transfer. They dwell 1.2 seconds on the PS injection plateau until the arrival of the second batch of 3 bunches and are then subjected to several bunch splitting steps, as depicted in Fig. 1. With a working point of (Q_x, Q_y) = (6.22, 6.25), which just accommodates the space-charge detuning of ~0.20, the bunches do not suffer much transverse emittance increase. However, the long bunches are prone to a horizontal high-order (m=6) head-tail mode generated by the resistive wall impedance. This instability is tackled by linear coupling between the horizontal (unstable) and (stable) vertical motion [7]. The chromaticities are set to change sign at transition energy so the beam is kept stable throughout the cycle. Fig. 4 depicts the beam intensity versus time in the PS machine, from injection of the first batch to extraction.

The RF gymnastics in the PS to transform 6 bunches of some 150 ns length into 72 bunches of less than 4 ns length follow the procedure outlined in Fig. 1 [8]. Despite the many steps which do not strictly conserve the longitudinal emittance, the "budget" in the PS is not critical and even larger-emittance and thus longer bunches (190 ns) from the PSB are preferable. The first and most delicate step in the process, bunch triple-splitting at 1.4 GeV, is shown in Fig. 5.

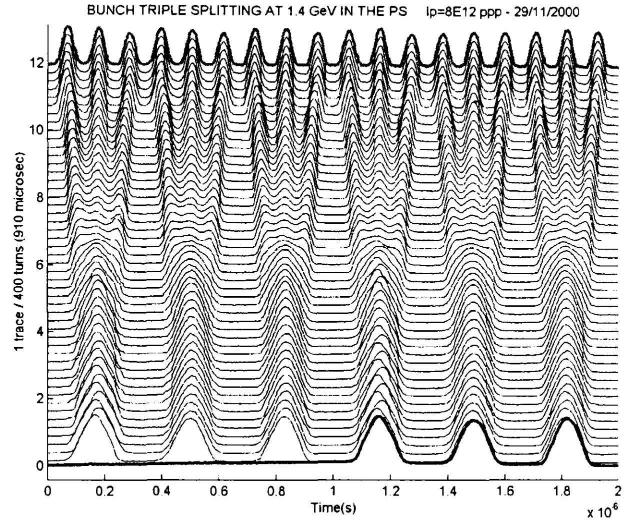

Fig. 5: Bunch triple-splitting of 6 PSB bunches into 18 in the PS at 1.4 GeV. The process takes about 40 ms.

The longitudinal beam structure after shortening of the 72 bunches at the PS ejection flat top is shown in Fig. 6.

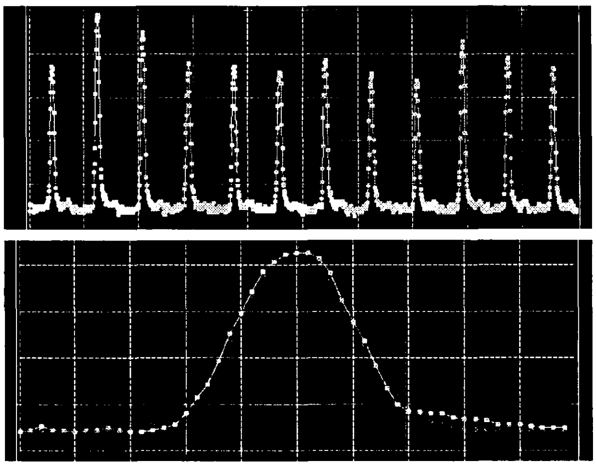

Fig. 6: Twelve out of 72 bunches on the last turn of the PS (top, 30 ns/div); zoom on one bunch (1 ns/div).

Transverse emittance measurements reveal that the normalized emittance does not suffer significant blow-up between PSB and PS ejection, and that it stays comfortably within the allocated emittance budget (Fig. 7). This is what had already been obtained by end 1999.

The characteristic parameters of the LHC beam, as delivered by the PS using the new method, are compiled in Table 3. A comparison with the design figures shows that, indeed, the PS complex can now deliver the nominal beam.

There are indications that an electron cloud builds up during the last turns in the PS (when the bunches, spaced by 25 ns, get compressed to 4 ns) and also in the transfer line TT2 towards the SPS (single-pass). The effect, predicted by numerical simulations [6], appears at the trailing end of the bunch train as a baseline distortion in the TT2 electrostatic pick-up. It can be eliminated by a weak solenoidal field (Fig. 8). Apparently, the beam is not affected by the electron cloud.

Table 3: LHC proton beam parameters at PS extraction

	Achieved	Nominal
protons/bunch	$1.1\text{x}10^{11}$	$1.1\text{x}10^{11}$
ε_x^* $(=\sigma_x^2\ \beta\gamma/\beta_{TWISS})$ [μm]	2.5	3
ε_y^* $(=\sigma_y^2\ \beta\gamma/\beta_{TWISS})$ [μm]	2.5	3
2-σ long. emittance ε_l [eVs]	0.35	0.35
4-σ bunch length τ_b [ns]	3.6	4
2-σ momentum spread $\Delta p/p$	$2.4\text{x}10^{-3}$	$2.2\text{x}10^{-3}$

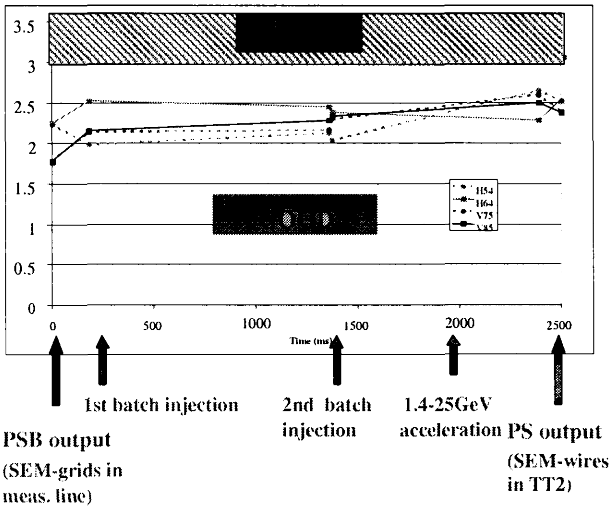

Fig. 7: Evolution of the normalised rms emittances from PSB exit to PS extraction (H=horizontal, V=vertical). Measurements in TT2 were done without bunch compression.

3.3 PS-SPS matching

A well-matched transfer between the PS and SPS (TT2 and TT10) is imperative to comply with the extremely tight emittance budget. After systematic and extensive studies, the optics model now fits the measurements which were performed with Secondary Emission Grids in TT2 and Optical Transition Radiation (OTR) monitors (allowing visualisation of an x-y image of the beam) in TT10. As a result, there is now (i) negligible horizontal and vertical betatron mismatch; (ii) no dispersion mismatch; but (iii) horizontal-vertical coupling (visible on OTR screens as a tilt of the beam ellipse), very likely generated in the PS machine. There is concern about non-linear effects due to the fringe field at PS ejection together with the large momentum spread of the proton beam ($\pm 2.4\text{x}10^{-3}$). This is a potential source of non-linear emittance blow-up at SPS injection and needs further studies.

3.4 Alternative types of bunch trains

Ever since the PS first sent trains of short bunches with 25 ns spacing to the SPS, the latter has suffered from strong transverse instabilities, increasing towards the end of the bunch train, due to electron clouds whose appearance seems to be favoured by the particular features of the bunch train. Electron clouds are expected to be a major issue in the LHC as well. The new way to generate the LHC beam in the PS has a welcome spin-off: the possibility to provide bunch trains different from the nominal ones to study the dynamics of the electron cloud build-up as a function of train parameters. Alternative bunch trains featuring

- holes of 12 (24, 36,..) bunches by omitting 1 (2,3,...) PSB rings, or
- 50 ns spacing, or
- 75 ns spacing

and others are feasible, under study, or envisaged [8].

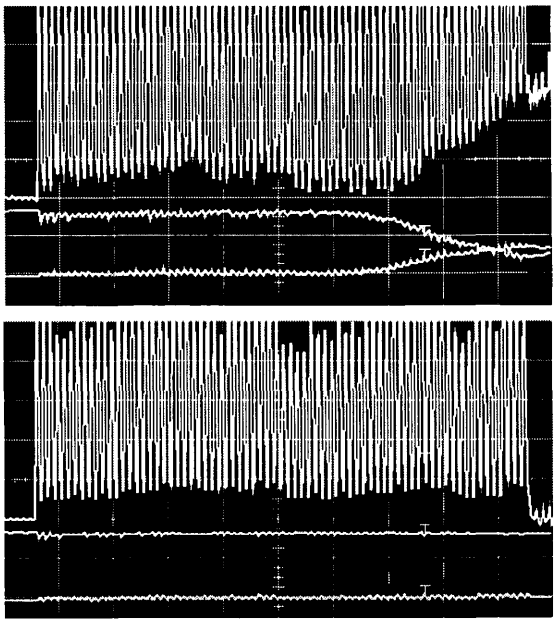

Fig. 8: Baseline drift of the signal from an electrostatic pick-up in the PS-SPS transfer line (TT2) due to electron cloud build-up: (top) solenoid off, (bottom) solenoid (~50 G) on. On each oscillogram, from top to bottom: Sum-signal, Δx, Δy. The beam features 72 bunches, spacing 25 ns, length 4 ns.

4 FUTURE WORK

The successful production of the LHC nominal beam does not mean that the preparation of the PS complex as LHC pre-injector is complete. The following major issues have still to be dealt with:

- Two 20 MHz, 15 kV cavities are required in the PS to provide harmonic 42 in the bunch splitting procedure. It is proposed that they also be tunable to

13.3 MHz, which would enable a bunch spacing of 75 ns.

- New transverse dampers in the PS, with a bandwidth of 20 MHz, to correct injection oscillations and tame transverse instabilities.
- The excessive variation of bunch population (up to ± 20%) will have to be reduced to ± 10% which at first sight appears tolerable for LHC.
- The study of ways to produce the "initial" beam, at ~1/6 of the nominal intensity in ~1/4 of the transverse emittance. While its transverse density is smaller than nominal, the very tight emittance budget is a big challenge.
- There are doubts whether the "ultimate" beam (1.6 times the nominal intensity in the nominal emittance, defined as the LHC performance limit) is feasible with the new scheme, which, compared to the old scheme, requires 15% more intensity per bunch in the PSB and at PS injection. Fortunately, there is no urgency.

5 CONCLUSIONS

The main progress with respect to earlier results with LHC-type beams has been the implementation of the new production scheme based on the recent invention of triple bunch-splitting. The process finally produces bunches of ~ 4 ns length which had not proved feasible with the original scheme based on a debunching-rebunching process, due to microwave instabilities in the PS. In this way, a nominal proton beam comfortably satisfying LHC requirements was achieved for the first time and is available for studies in the SPS. As a fringe benefit, the new pre-injector scheme enables the generation of a variety of alternative bunch trains and spacings which may prove invaluable to investigate electron cloud effects in the SPS. While progress was also very satisfactory on beam dynamics issues, such as matching between the machines, some hardware has still to be installed and future machine studies will deal with the other types of LHC proton beams.

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