Particle Accelerators, 1997, Vol. 58, pp. 63–78
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THE PS BOOSTER AS PRE-INJECTOR FOR LHC

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(Received in final form 25 February 1997)

The LHC will be supplied with protons from the injector chain Linac2–PS Booster–PS–SPS. The beam must have small transverse emittances to fit into the LHC dynamic aperture, but sufficient intensity to assure high-luminosity operation. Such a beam with a brightness twice the one of present beams is feasible with a scheme involving acceleration of one bunch (instead of five) in each of the four PSB rings to a kinetic energy raised from 1 to 1.4 GeV, and two-batch filling of the PS. Beam dynamics aspects such as how to tackle small emittances under high space charge, optimizing the (time-varying) working point and dealing with stop-bands, the advent of new RF harmonics 1 and 2, how to shape the magnet cycle, are discussed, and results of machine experiments reported. Finally, some open issues as well as ideas for future improvements are discussed.

Keywords: Injectors; Space charge; Injection methods; Stop-bands

1 INTRODUCTION

Providing the LHC with protons may appear straightforward for the existing injector chain; however, the LHC is a demanding customer, in particular on "beam brightness" (here defined as the ratio: intensity per bunch/transverse emittance). While the intensity is well within the capabilities of the injectors, the "brightness" will be about twice that of current beams.

In the LHC, 2835 proton bunches per ring with a bunch distance of 25 ns, will collide at 7 TeV per beam.[1] The performance levels have been defined in Table I.

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TABLE I LHC performance levels at collision. "Commissioning": during 1st year of operation for physics. "Ultimate": highest possible performance at the beam–beam limit

	Commissioning	*Nominal*	*Ultimate*
Luminosity [$\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$]	10^{33}	10^{34}	2.5×10^{34}
Protons per bunch	1.6×10^{10}	10^{11}	1.6×10^{11}
Normalized r.m.s. emittance [μm]	1	3.75	3.75

TABLE II The LHC proton injector chain

	Linac2	PSB[†]	PS	SPS
Kinetic energy [GeV]	0.05	1.4	25	450
Cycle repetition time [s]	1.2	1.2	3.6	16.8
Number of pulses to fill downstream machine	1	2	3	2×12
RF harmonic numbers		1	8(16)/84[‡]	4620
Number of bunches		1/ring[¶]	8(16)/84	243
p/pulse "nominal" [10^{11}]		43	84	243
p/pulse "ultimate" [10^{11}]		72	140	405
p/bunch "nominal" [10^{11}]		11	10.5/1.0	1.0
p/bunch "ultimate" [10^{11}]		18	17.5/1.7	1.7
Transv. emittance[§] ε^* [μm]	1.2	2.5	3.0	3.5

[†] 4 rings, each 1/4 of PS circumference; [‡] $h = 84$ for 25 ns bunch spacing at 26 GeV/c; [¶] corresponds to 10.5 LHC bunches; [§] $\varepsilon^* = (\beta\gamma)\sigma^2_{x,y}/\beta_{x,y}$.

The injector chain has to provide a beam quality at least compatible with the "nominal" performance. Experience shows that an injector machine should be capable of "saturating" the client accelerator, therefore a higher performance level ("ultimate") is aimed at, mainly to provide welcome operational margin. Several schemes to satisfy the LHC requirements were proposed;[2] after extensive analysis (including the needs of other users) a scheme emerged whose main characteristics are given in Table II.

2 PSB AND LINAC 2: BASIC CHARACTERISTICS

In order to better understand the options to convert the PSB for the LHC, the main features are briefly presented. The PSB is a slow-cycling (~1 s) synchrotron of four superimposed rings, accelerating protons from 50 MeV to 1 GeV on RF harmonic 5. The lattice consists of 16 strictly regular periods with triplet focusing to maximize transverse acceptances and thus the space charge limit. The design aim was to accelerate 10^{13} p/pulse (2.5×10^{12} p/ring). By fully exploiting the PSB design margins on some of the systems and adding new systems, the PSB peak intensity per ring was eventually raised by a factor 3 to 4 over the design figure.[3] (See Table III for Linac and PSB basic parameters.) Major items are:

(i) Main dipoles (cycling between 0.125 and 0.69 T) and quadrupoles stay far from remanence and saturation effects, thus non-linear field terms stay low and stop-bands manageable;
(ii) The design intensity was based on a direct space charge tune shift of $\Delta Q = 0.25$, a rather conservative figure in hindsight;

TABLE III Linac and PS Booster basic parameters

		Normal	*For LHC (if different)*	
Linac2				
Source p+	Energy	90		keV
RFQ	RF frequency	200		MHz
(4-vane)	Output energy	750		keV
Linac	RF frequency	200		MHz
(Alvarez)	Tanks	3		
	Output energies	10, 30, 50		MeV
	Pulse length	≤ 120	≤ 20	μs
PS Booster				
	Number of rings	4		
	Radius (1/4 PS)	25		m
Lattice	Magnet period	B-F-D-F-B		
	Number of periods	16		
	Tune Q_x (inj. ⇒ ej.)	$4.30 \Rightarrow 4.17$		
	Tune Q_y (inj. ⇒ ej.)	$5.60 \Rightarrow 5.23$	$5.45 \Rightarrow 5.23$	
	γ_t	4.07		
Injection	Energy (momentum)	50 (310.36)		MeV (MeV/c)
	Revolution time	1.67		μs
	Hor. betatron stacking	1–15	2–3	turns
	Acceptances $A_x \times A_y$	300×100		π mm mrad
Acceleration	Bunches per ring	5	1	
	RF systems	$h=5/h=10$	$h=1/h=2$	
	Frequency swing	3–8.5/6–17	0.6–1.8/1.2–4	MHz
	RF voltage per turn	13/6	8/8	kV
Ejection	Energy (momentum)	1 (1.696)	1.4 (2.142)	GeV (GeV/c)
	Dipole field	0.687	0.868	T
	Quadrupole gradient	4.6	5.8	T/m
	Revolution time	599	572	ns
	Pulse repetition time	1.2		s
	PSB pulses/PS cycle	1	2	

(iii) Installation of correction lenses enabled narrowing all 2nd and 3rd order stop-bands covered by the beam which raised the permissible ΔQ to 0.6;

(iv) Linac2, built in the seventies, accelerates 150 mA during 120 μs pulses which are betatron-stacked in each of the PSB rings; more recently, a 750 keV injector RFQ was added, raising Linac2's peak output current to ~170 mA;[4]

(v) The space charge limit was further raised by adding "2nd harmonic" ($h = 10$) cavities which flatten the bunch line density and thus increase the bunching factor (mean/peak line density) early in the acceleration cycle.

(vi) These improvements had to be accompanied by additions to the RF systems in order to keep pace with the increasing intensity: longitudinal coupled-bunch-mode feedback, transverse feedback, beam loading compensation.

The PSB was built for fixed-target physics users who usually ask for high intensity and are hardly bothering about emittances as long as the beam passes through the channels. Colliders, however, need high luminosity whose figure of merit is the beam brightness defined above: the aim for LHC is to provide – for the given bunch spacing of 25 ns – as many protons per LHC bunch as possible within the transverse emittance tailored to LHC needs. Obviously, neither the PSB nor the PS are optimized for this particular target, and that is why a conversion project became necessary.

3 THE PSB AS LHC PRE-INJECTOR: PRINCIPAL CHOICES

The conversion of the PS complex aims at delivering to the SPS the "ultimate" intensity which, according to Table II, is 1.4×10^{13} per PS cycle, within a normalized emittance ε^* (both planes) of 3 μm. The basic features of the scheme which is supposed to enable the PS complex to produce such a beam are presented below.

3.1 Two-Batch Filling of the PS

Usually the PS is filled by sequential transfer of the four PSB rings to the PS, so there is one PSB cycle per PS cycle. For the LHC, each

PSB ring would then have to provide 3.6×10^{12} p/cycle within $\varepsilon^* = 2.5\,\mu\text{m}$, and would suffer from an unmanageable space charge tune shift $\Delta Q \sim 0.8$. Therefore a scheme enabling the PS to be filled with two PSB batches was adopted, reducing the tune shift to $\Delta Q \sim 0.4$; in this scenario, the PSB has to produce 7.2×10^{12} p/pulse (1.8×10^{12} p/ring) in $\varepsilon^* = 2.5\,\mu\text{m}$.

3.2 Injection – Which Method?

The performance parameters of Linac2 are given in Table IV. The particularly high current, which is beyond the specification (150 mA for 120 μs), cannot be tackled by the available RF power. The non-compensated part of the beam loading is taken from the RF energy stored in the tanks which in turn leads to a voltage drop and thus a beam energy drift, which, however, stays acceptable within the short pulse of 20 μs.

On paper, this exceptionally high Linac current should enable the PSB to reach the required intensity by means of *single-turn injection* which is supposed to conserve the small transverse Linac beam emittance. In practice, single-turn injection did not work. After injection and during RF capture, a violent transverse blow-up is observed, with both emittances growing beyond the LHC design figure. Deliberate injection mis-steering – a rudimentary "painting" – did not alter this. The reasons are not fully understood, but there is a conjecture: with 1.8×10^{12} p/ring in $\varepsilon^* = 1.2\,\mu\text{m}$, ΔQ approaches unity in both planes and the incoherent tune spread covers integer stop-bands, resulting in fast emittance increase in either plane (presumably faster than the smear-out time of transverse betatron oscillations which would explain why mis-steering does not help).

In a series of experiments, *betatron stacking of* 2 *to* 3 *turns* proved to be a better way to generate high-brilliance beams. This is astonishing

TABLE IV The performance parameters of Linac2

	Goal	*Achieved*	
Beam current out of Linac2	190	170	mA
Beam current at PSB entry	180	160	mA
During pulse length	20	20	μs
ε^* (both planes) ($=(\beta\gamma)\sigma^2/\beta$)	1.2	1.2	μm
Energy spread ($\pm 2\sigma$)	± 160	± 190	keV

because betatron stacking creates voids in the horizontal phase plane, resulting in a large horizontal emittance. Nevertheless, with all the ingredients routinely employed to generate high-intensity beams, the required performance could (almost) be met. These ingredients are (see Figure 1, showing the time-varying working point with relevant stop-bands, ΔQ):

(i) Enhancement of linear coupling line $Q_x - Q_y = -1$ by means of skew quadrupoles. This has several beneficial effects: first, the horizontal emittance is reduced while the vertical one is increased, rendering the beam rounder as preferred by the LHC; second, the injection efficiency is improved; third, the controllable vertical beam blow-up due to linear coupling is apparently faster than the uncontrolled one due to the integer stop-band $Q_y = 5$.

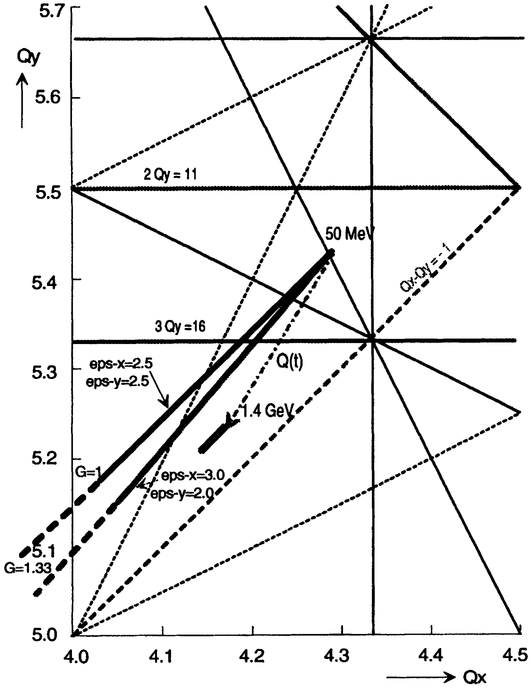

FIGURE 1 PSB tune diagram, stop-bands, time-varying working point $Q(t)$, space-charge tune shifts for an LHC-type beam with 2×10^{12} p/ring.

(ii) Compensation of $3Q_y = 16$ (systematic), $Q_x + 2Q_y = 15$, $2Q_x + Q_y = 14$, $2Q_y = 11$ during the early part of the cycle; providing space in the Q-diagram to accommodate the LHC beam space charge tune spread.

(iii) Time-varying working point: as ΔQ shrinks during acceleration, one profits to move the working point out of the region of harmful stop-bands.

3.3 One Bunch per PSB Ring (Instead of Five)

For two-batch filling of the PS, the beams of the four Booster rings have to be squeezed into one-half of the PS circumference. With 5 bunches per ring, funnelling was used for generating the p-bar production beam which had the same requirement, but this is costly in vertical emittance. The more obvious way is to accelerate one bunch per ring and arranging the 4 bunches – by appropriate positioning of each bunch before extraction and adjustment of the ejection/vertical recombination kicker timings – so as to fill half the PS circumference, thus leaving space for a second PSB batch (Figure 2). This new mode of operating the PS complex requires, amongst other items, four new $h = 1$ variable-frequency RF systems with a voltage of 8 kV, and four

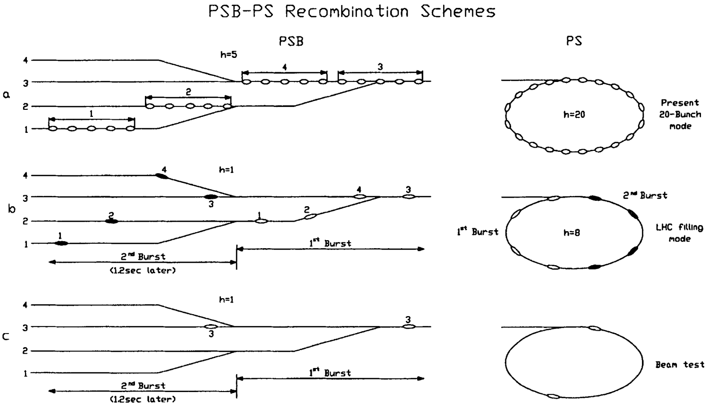

FIGURE 2 PSB – (a) PS recombination schemes with 5 bunches (present); (b) one bunch (LHC filling scheme) per ring; (c) recombination scheme for machine studies in 1993 (one bunch from one ring).

$h=2$ variable-frequency systems, 8 kV, for bunch flattening ($h=5$ cavities modified). With 5 bunches per ring, the PSB is plagued by longitudinal coupled-bunch-mode instabilities which are tamed by elaborate feedback systems which have reached their performance limit. As fringe benefit, beam stability will no doubt be improved by the fact that no longitudinal mode with a non-zero phase shift between consecutive bunches can exist with one bunch in a ring.

3.4 Increase of PSB Energy to 1.4 GeV

At 1 GeV in the PS, the direct space charge of the LHC beam (ultimate) is $\Delta Q \sim 0.4$. Experiments on a 1 GeV injection plateau have revealed that an LHC-type beam dwelling for 1.2 s (the first of the two PSB batches) undergoes excessive transverse emittance increase. As ΔQ scales with $1/\beta\gamma^2$, a factor 1.5 can be gained by increasing the PS injection energy to 1.4 GeV, where $\Delta Q \sim 0.25$ and virtually no blow-up is observed. The beam momentum increases by 26.3% (Table III), so the PSB main dipole field has to be raised to 0.86 T, but stays well within the built-in margins. However, other systems have to undergo major upgrading: the PSB main power supply, the PSB ejection kickers and septa, most magnets (including septa and kickers) of the PSB–PS recombination and transfer line.

3.5 H^- Injection?

With the wealth of positive experience available from most proton accelerators, H^- injection is clearly the choice to obtain highest beam brilliance, in particular because of the superior possibilities of "painting". On the other hand, the highest peak-intensity operational injector proton Linac happens to be available at CERN, and this is why 3-turn betatron stacking is indeed competitive. At present, there is a major obstacle to using H^- injection because for the years to come, the PSB is tied up with accelerating protons and heavy ions in pulse-to-pulse switching mode. Both species pass through the same line whose elements would have to switch polarity between H^- and heavy ions, which is feasible, but costly. Nevertheless, the option of converting Linac2 and the PSB injection to H^- is seriously considered for the time the PSB is not dealing any more with heavy ions.

4 PERFORMANCE AS LHC PRE-INJECTOR: PREDICTIONS, TESTS

Most of the basic choices of the scheme presented in Section 3 were tested in machine study sessions, the most elaborate of which lasted a whole fortnight in late 1993 (Table V).

This test session became possible thanks to extensive preparation work and provided a wealth of results, out of which the most significant ones are discussed below: magnet cycle, RF trapping and acceleration, transverse emittance measurements.

4.1 1.4 GeV Magnet Cycle and RF Bucket Area[6]

The present RF cavities ($h = 5$) operate with a peak RF voltage of 13 kV. If one includes the effect of longitudinal space-charge defocusing (below transition) with $\sim 8 \times 10^{12}$ per ring, a bucket of ~ 0.12 eV s per bunch (~ 0.6 eV s for 5 bunches) is available for adiabatic RF capture (the 200 MHz structure of the Linac beam is not relevant in this context). With 6 kV on the prototype $h = 1$ cavity, almost 1 eV s is available for RF capture (with an almost stationary bucket). This area tends to shrink if the stable phase angle (or $\mathrm{d}B/\mathrm{d}t$) increases too rapidly, so the slower the increase in main magnet field B, the larger the longitudinal acceptance. On the other hand, the lower $\mathrm{d}B/\mathrm{d}t$, the longer the beam has to suffer from a large transverse space-charge tune shift, which exacerbates losses on stop-bands covered by the beam. Thus the strategy for tailoring the magnet cycle is to provide constant bucket area with the maximum RF voltage (note that the $h = 5$ cycle is also programmed in this way).

The resulting cycle features $\mathrm{d}B/\mathrm{d}t$ at injection of 0.4 T/s which is steadily increasing to 2 T/s after 350 ms. The magnet cycle, bucket

TABLE V PSB as LHC pre-injector: final scheme vs. test conditions

Final scheme	*Test conditions*
Linac2 180 mA for 20 μs	160 mA for 20 μs
$h = 1, 2$ cavities in all rings	$h = 1, 2$ prototype cavities in ring 3
PSB to 1.4 GeV, all cycles	PSB to 1.4 GeV, few cycles
PSB–PS line to 1.4 GeV (all levels)	Only level 3 elements to 1.4 GeV
All PSB rings transferred to PS	Only level 3 transferred to PS
Two-batch filling of PS with all rings	Two-batch filling of PS with ring 3 only

area, relative direct space-charge tune shifts for both $h = 5$ and $h = 1$ are shown in Figure 3. With this cycle – computed for an intensity of 7.5×10^{12} p/ring – the LHC beam (1.8×10^{12} p/ring, which means less bucket reduction) was accelerated without beam losses.

To reach 1.4 GeV, the dipole field has to cycle between 0.125 T at 50 MeV and 0.868 T at ejection, and the main quadrupoles up to 5.8 T/m (~0.35 T on pole tip); these figures appear comfortably far from the remanence or saturation regimes. Indeed, measurements with a coil revealed that the main dipole field is strictly proportional to the magnet current between 1 and 1.4 GeV. In the absence of saturation effects in the quadrupoles, their gradients should stay proportional to the excitation current. Under this assumption the quadrupole currents were programmed proportional to the main magnet field with a view to keep tunes constant between 1 and 1.4 GeV. Then tune measurements (by exciting the beam with a dedicated Q-kicker followed by FFT of the resulting oscillation observed by a position monitor) were performed and indeed yielded constant tunes (within 0.01) between 1 and 1.4 GeV. This is an indirect proof that the quadrupole gradients are strictly proportional to the excitation currents in this energy range.

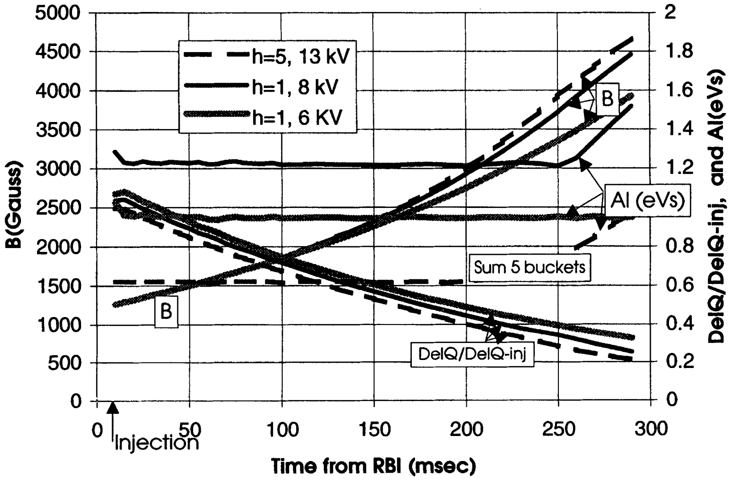

FIGURE 3 Optimized magnet field B, longitudinal acceptance Al, and relative space-charge tune shift vs. time for $h = 5$ and $h = 1$, for 7.5×10^{12} p/ring in the PSB; the LHC beam intensity is 1.8×10^{12} p/ring.

4.2 RF Trapping and Acceleration[7]

The "unbunched" Linac beam, injected into the PSB, occupies a longitudinal phase plane area of ~0.65 eV s, which is adiabatically (with little dilution) captured with an end voltage of 6 kV on the $h=1$ cavity. The stationary bucket size (including space-charge reduction) is about 1 eV s, so there is some margin for dilution and bucket reduction when starting acceleration (Figure 3). The duration of the adiabatic voltage rise (starting from 0.5 kV) is 0.5 ms for $h=5$ (synchrotron frequency f_s at the end of capture ~5 kHz), and was increased to 2 ms for $h=1$ ($f_s \sim 1.7$ kHz), roughly proportional to the synchrotron oscillation period.

For the acceleration, a digital beam control system, where the RF frequency is generated in a processor using the main magnet field as input, was successfully implemented. The RF frequency derived in this way is precise enough to keep the beam near the central horizontal orbit without resorting to a radial feedback loop; a phase loop is, however, still required. The initial bunch area of 1 eV s was fairly well conserved during acceleration.

The $h=5$ cavity in ring 3 was provisionally modified to enable its tuning to $h=2$, but the RF voltage was limited to 3 kV. Nevertheless, flat-topped bunches were created and kept flat during some 100 ms to diminish transverse space charge. However, the phase of the $h=2$ RF system had to be synchronized to the beam phase rather than the $h=1$ cavity RF phase; this trick had been learned in the past when trying to lock the $h=10$ cavity to the $h=5$ system. The largest bunching factor obtained after RF capture was ~0.5, and the trapping efficiency, which includes transverse losses due to suddenly exceeding the space-charge limit after trapping, was better than 90%.

While space charge is efficiently reduced by the $h=2$ system in the PSB, there is as yet not such a possibility in the PS. An interesting alternative is to work on the particle distribution in the phase plane rather than shaping the potential well. A technique to depopulate the bunch centre[8] was tried in the PSB (last part of cycle just before ejection) with the aim to decrease the transverse tune shift on the PS injection plateau. The method involves (i) modulation of the phase between $h=1$ and the beam (modulation frequency near the synchrotron frequency); (ii) application of ~1 kV RF at a much higher harmonic ($h=9$, with a slight offset from the harmonic) to favour smear-out and smoothing of the bunch shape. Flat-topped bunches were indeed observed, but the concomitant bunch lengthening was not compatible with the kicker rise times. Further studies on this technique, including the influence of the $h=2$ system, are planned.

4.3 Transverse Emittances

Transverse emittances of a beam circulating in the PSB are measured with the "BEAMSCOPE"[9] device where the beam is driven against an aperture restriction by a localized, time-varying 3-dipole bump; the amplitude profile is then derived from the loss rate measured with a beam current transformer. The high-intensity proton beams the PSB is routinely producing have emittances ε^* (r.m.s, normalized) at 1 GeV of about 12 (horizontal) and 7.5 (vertical) μm and BEAMSCOPE is adequate. However, for the much smaller LHC beam with $\varepsilon^* \sim 2$ to 3 μm, results are less precise (see point 1 in Figure 4). This also applies to the other type of measurement systems used, based on 3 harps (SEM's) each, one of them in the "Measurement Line" (point 2 in Figure 4), the other one at PS entry (point 3 in Figure 4).

Although there are considerable error bars (which are difficult to evaluate) in the measurements, the results – including the PS[10] where fast wire scanners were used – apparently make sense. First, there is

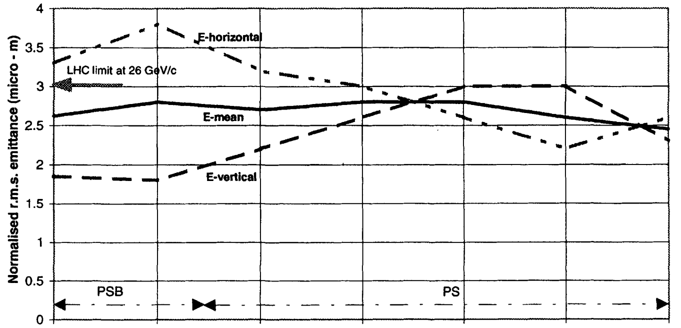

FIGURE 4 Evolution of normalized r.m.s. emittances in PSB and PS,[10] for 1.8×10^{12} p/bunch (equivalent to 1.7×10^{11} p/LHC bunch, "ultimate" intensity).

barely any emittance growth between 50 MeV (after RF capture) and 1.4 GeV (not shown in Figure 4). Second, the beam out of the PSB exhibits $\varepsilon_x^* > \varepsilon_y^*$ as one would expect as a residual from the horizontal betatron stacking (in spite of all the effort to make the difference small). Third, and less obvious, the beam tends to get round ($\varepsilon_x \sim \varepsilon_y$) in the PS, most likely due to linear coupling (the PS is working near the main diagonal in the Q-diagram). Fourth, and even less obvious, the *average* emittance $(\varepsilon_x^* + \varepsilon_y^*)/2$ does not change much between 50 MeV and 26 GeV/c and behaves like an invariant. It is mainly due to the particular way of coupling in the PS that the round LHC beam can be generated by betatron stacking in the PSB.

These measurements were performed on a beam consisting of one bunch from one PSB ring (and also two bunches in the PS obtained by two-batch filling, Figure 2(c)). It is anticipated that the beam in the PS will become larger with bunches from the four PSB rings: there will be unavoidable steering and transverse matching differences between the 4 rings,[11] and the 8 (instead of 2) bunches on the PS injection plateau may suffer from (yet unknown) collective effects.

5 OPEN ISSUES AND POSSIBLE DEVELOPMENTS

5.1 Short and Medium Term

This series of beam tests confirmed most of the design choices for the proposed LHC proton filling scheme in the PS complex. There are, however, quite a few issues which ask for further work on Linac2 and PSB:

(i) How to increase the Linac2 current to 190 mA.
(ii) Why does betatron stacking yield acceptable emittances for the LHC beam. A simulation code, including space charge and linear coupling, is being prepared.
(iii) Evaluation of the potential gain with H^- injection (LHC beam, and the others).
(iv) How to assure longitudinal beam stability in the presence of a second-harmonic system.[12] The difficulties are proportional to intensity, therefore this study predominantly aims at tackling the non-LHC beams.

(v) Refinement of the technique to deplete the bunch centres prior to PSB extraction with the aim to achieve flat-topped bunches on the PS injection plateau.

(vi) How to improve the precision of emittance measurements for the small-sized LHC beam. For the PSB, a fast wire scanner and a monitor based on a fast-moving blade are under scrutiny.

(vii) Evaluate, and possibly cure, the additional mis-steering and (horizontal) mismatch induced by the vertical recombination of the four rings. Whereas the former can largely be cured by slow closed-loop steering corrections (via computer control) and a fast injection oscillation damper in the PS, the latter is more difficult to tackle.

(viii) The "commissioning" beam (see Table I) with its four times smaller transverse emittance deserves special attention: ways to produce it, ways to measure it.

(ix) How to continue to produce beams for users other than the LHC, considering that they ask for 3 to 4 times the LHC intensity, albeit in much larger transverse emittances.

5.2 Longer Term

As already pointed out, the PSB is certainly not the machine optimized as LHC pre-injector, nor is the PS. But the test results have revealed that the nominal LHC beam appears readily attainable and the ultimate not completely out of reach. Therefore a "PS conversion for LHC" project was launched in 1995 and will be finished by 2000.

There are several ideas to further improve the injector chain performance, the boldest of which is the construction of a 2 GeV proton Linac [8], to a large extent re-using the LEP superconducting cavities which will become available by 2001. This Linac would accelerate some 10 mA of H^- to be injected (by charge exchange) directly into the PS. The transverse density (N_b/ε^*) would potentially increase by a factor 3.

A more modest improvement has been put forward during this Workshop, the essence of which is presented below.

The direct space-charge tune shift scales like $\Delta Q \sim 1/(\beta\gamma^2\varepsilon^*)$. The idea is then to further increase the PSB energy from 1.4 to 2 GeV, and

TABLE VI PSB main magnet field and relative direct space-charge tune shift vs. PSB and PS injection energies

	Injection at [GeV]	[GeV/c]	B-PSB [T]	$1/\beta\gamma^2$	$\Delta Q/\Delta Q_{1.4}$	$\Delta Q/\Delta Q_{0.05}$
PS	1	1.696	0.687	0.268	1.52	
	1.4	2.142	0.868	0.176	1	
	2	2.784	1.128	0.108	0.61	
PSB	0.05	0.310	0.125	2.87		1
	0.07	0.369	0.149	2.37		0.83
	0.1	0.446	0.180	1.91		0.66

the Linac2 energy from 50 to 100 MeV (Table VI). These additions would reduce the tune shifts in both PSB and PS and thus potentially increase the permissible transverse density (N_b/ε^*) by a factor 1.5. The price to pay would be (i) two more accelerating tanks for Linac2 to reach 100 MeV, but with much lower current; (ii) changeover to H^- injection into the PSB; (iii) increase of the PSB main dipole field at top energy to 1.13 T (still within reach?); (iv) a new upgrading of the PSB–PS transfer line elements for ~30% more bending power. It remains to be seen whether such an upgrade would indeed be feasible, for example the 30% increase in the PSB–PS line kicker strengths.

6 CONCLUSIONS

The main ingredients of converting the PSB (and Linac2) in view of serving as LHC pre-injector were checked and confirmed in the extensive 1993 beam test sessions. A project to convert the PS complex has been started in 1995 with the aim to produce, at 26 GeV/c, the nominal LHC beam and, if possible, the ultimate one by 2000. LHC-type beams with 25 ns spacing, and 4 ns bunch length will be made available to the SPS for machine study sessions already in 1998. Attaining the ultimate (and the commissioning beam) intensities implies some critical issues, also in the PSB, which have to be addressed. Further improvements of the injector chain performance can be envisaged, ranging from a modest Linac2 and PSB upgrade to the construction of a 2 GeV superconducting linac.

Acknowledgements

I would like to thank R. Cappi, R. Garoby, D. Möhl, H. Schönauer and D.J. Warner for useful comments on the manuscript.

References

[1] The LHC conceptual design, CERN/AC/95-05 (LHC).

[2] R. Cappi, R. Garoby, S. Hancock, M. Martini, J.P. Riunaud, K. Schindl and H. Schönauer, Beams in the PS complex during the LHC era, CERN/PS 93-08.

[3] G. Gelato, L. Magnani, N. Rasmussen, K. Schindl and H. Schönauer, Progress in space-charge limited synchrotrons: four times the design intensity in the CERN PSB, *Proc. 1987 PAC*, Washington, p. 1298.

[4] C.E. Hill, A. Lombardi and M. Vretenar, Setting-up of Linac2 for high intensity, PS/HI/Note 94-02 (MD), PS/RF/Note 94-11 (MD).

[5] R. Cappi, R. Garoby, M. Martini, J.P. Riunaud and K. Schindl, The PS as LHC proton source: results of a two-week beam test in December 1993, *Proc. 4th EPAC*, London, June 1994, p. 500.

[6] The PSB energy increase to 1.4 GeV for the LHC (PSB-MD report on the LHC test 3–15 December 1993), reported by K. Schindl, PS/HI/Note 94-01.

[7] F. Blas, J. Boucheron, R. Garoby, F. Pedersen and G.C. Schneider, Acceleration with $h=1$ and 2 of the LHC test beam in the PSB, MD end 1993, PS/RF/Note 94-03.

[8] R. Garoby, Longitudinal limitations in the PS complex for the generation of the LHC proton beam, these proceedings.

[9] H. Schönauer, BEAMSCOPE – A novel device for measuring emittances and betatron amplitude distributions, *IEEE Trans. Nucl. Sci.* **NS-26**, 3294 (1979).

[10] R. Cappi, The PS in the LHC injection chain, these proceedings.

[11] A. Jansson and M. Lindroos, Mismatch between the PSB and CPS due to the present vertical recombination scheme, these proceedings.

[12] F. Pedersen, Bunched beam longitudinal instabilities in the PSB, these proceedings.