Partial Test of the PS Complex as LHC Proton Injector

The PS Staff, reported by K.Schindl
CERN-PS
CH - 1211 Geneva 23

Abstract

The CERN Large Hadron Collider (LHC) will be supplied with protons from the injector chain Linac 2 - PS Booster (PSB) - PS - SPS. The beam must have small transverse emittances to fit into the tiny LHC dynamic aperture, and sufficient intensity for high-luminosity operation: the required beam brilliance is about twice that of current PS beams. In principle such a beam is feasible by a scheme [1][2] involving acceleration of one bunch in each of the four PSB rings to a kinetic energy raised from 1 to 1.4 GeV, two-batch filling of the PS, and acceleration on new RF harmonics (8 and 16) in the PS to 26 GeV/c. This approach was tested during a 12-day machine development session ("LHC Test") in December 1993 [3], for which hardware had been prepared as prototypes, using only one PSB ring and a low cycle repetition rate. During this LHC Test, virtually all ingredients of the scheme proved to work as anticipated. Comprehensive sets of beam profile measurements under various machine conditions are presented together with consequences for the proposed LHC filling scheme.

1. INTRODUCTION

The main parameters of the LHC proton injector chain are compiled in Table 1. The *nominal* LHC luminosity is 10^{34} cm^{-2}sec^{-1}, and at the *beam-beam limit* 2.5 10^{34} cm^{-2}sec^{-1}.

Table 1: The LHC Proton Injector Chain

	Linac	PSB	PS	SPS
Kinetic energy [GeV]	0.05	1.4	25	450
Repetition time [s]	1.2	1.2	3.6	16.8
number of pulses to fill downstream machine	1	2	3	2 x 12
RF harmonic number		1	8(16)/84	4620
number of bunches		1/ring	8(16)/84	243
p/pulse *nominal* [10^{11}]		43	84	243
beam-beam [10^{11}]		72	140	405
p/bunch *nominal* [10^{11}]		11	10.5/1.0	1.0
beam-beam [10^{11}]		18	17.5/1.7	1.7
Transv. emitt. $\varepsilon*$ [μm]	1.2	2.5	3.0	3.5

$\varepsilon*_{x,y}=(\beta\gamma)\sigma^2/\beta_{x,y}$ throughout the paper.

The ingredients of the final LHC filling scheme are compared with the conditions of the LHC Test in Table 2.

Table 2: Ingredients of the final scheme vs. LHC Test

Final Scheme	LHC Test
Linac 2 180 mA for 20 μs	160 mA for 20 μs
h=1,2 cavities in 4 PSB rings	h=1,2 prototypes in ring 3
PSB to 1.4 GeV, all cycles	PSB to 1.4 GeV, few cycles
PSB-PS line: all to 1.4 GeV	PS level magnets to 1.4 GeV
Two PSB pulses to fill PS	Two PSB pulses to fill PS
PS: Bunch splitting h=8 to 16	Bunch splitting h=8 to 16
Acceleration of 8(16) bunches on h=8 (16) to 26 GeV/c	Acceler. of 1(2) bunches on h=8(16) to 26 GeV/c
Debunching-rebunching to h=84 at 26 GeV/c in PS for LHC bunch spacing of 25 ns	Not tested because no h=84 (40 MHz) cavities in the PS
Ejection of 81 LHC bunches in the line leading to the SPS	Ejection of 1(2) long bunches

2. HARDWARE MODIFICATIONS

The upgrading of the PS complex for the LHC presents a major investment. However, the cost of the LHC Test could be kept very low by using just one PSB ring and pulsing for 2 out of 12 cycles only, with the remaining time serving as a cooling down period for the overheated equipment.

2.1. Linac 2: More Current

The new 750 keV RFQ2 was successfully commissioned in March 1993, with the aim to accelerate 180 mA reliably up to 50 MeV for the LHC. The source current was increased and the RF chains were improved. A beam of 160 mA was obtained, with $\varepsilon* \sim 1.2$ μm, energy spread of $\pm$ 190 keV.

2.2 PSB: Bρ Increased by 26.3 %, New RF Harmonics

Major hardware modifications were: (i) raising of the main power supply current from 3300 to 4000 A, which called for 4 rectifier-inverter groups instead of 3 at 1 GeV; (ii) installation of a prototype h=1 RF system in ring 3, together with a digital beam control system; (iii) modification of the existing h=5 cavity to enable operation at h=2; (iv) some of the PSB-PS transport DC magnets (level 3)

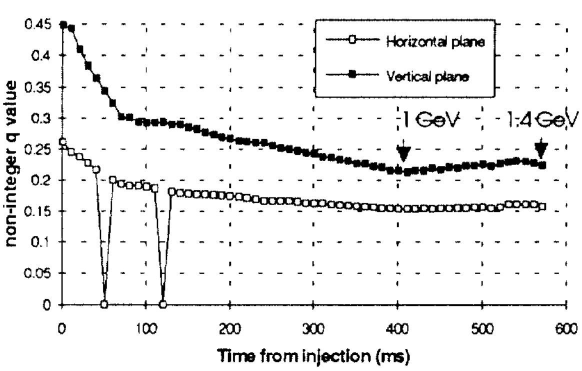

Fig. 1: Q-measurement in PSB along the 1.4 GeV cycle.

had to be operated beyond their ratings, which called for "trapezoidal" ramping of their supplies; (v) the strength of the PSB ring 3 ejection kicker was increased by installing a new pulse generator; (vi) the beam position monitors were adapted to the longer bunches (also in the PS), and an FFT-based Q-measurement facility was implemented.

2.3 PS: New Magnet Cycle, RF Manipulations

The PS magnet cycle features an injection plateau of 1.2 s to enable filling with two PSB pulses, 1.2 s apart. Four kicker magnet modules were simultaneously pulsed to provide more kick strength at PS injection. Modernised fast wire scanners were made available. The unusual longitudinal beam manipulations (acceleration on h=8 and 16, beam splitting, two-batch injection) called for a new prototype low-level RF system.

3. TEST RESULTS

3.1 PSB

The high-brilliance beam is produced by 3-turn horizontal betatron stacking where the round ($\varepsilon_x=\varepsilon_y$) beam from Linac 2 is transformed into a beam with $\varepsilon_x>\varepsilon_y$ although the linear coupling line $Q_x - Q_y = -1$ is enhanced. As the beam tends to become round in the PS, the aim is to minimise $(\varepsilon_x + \varepsilon_y)/2$. The maximum space-charge tune-shift at 50 MeV is $\Delta Q_y \sim 0.4$. (For Q-values vs. time see Fig. 1).

The h=1 system is used to accelerate the beam, while the h=2 system lowers the peak line density of the bunch and reduces space charge at low energy.

The main magnet cycle rise had to be slowed down in its earlier part to avoid shrinking of the h=1 bucket. The dipole field of 0.868 T at 1.4 GeV was obtained by simply raising the magnet current by 26.3%. The currents of the main quadrupoles were kept proportional to the dipole current between 1 and 1.4 GeV, and the Q-values were found to be constant in this energy range (Fig. 1; $Q_x=4+q_x$, $Q_y=5+q_y$). Therefore neither the dipoles, nor the quadrupoles suffer from saturation effects up to 1.4 GeV.

A novel technique of controlled longitudinal blow-up [4] was successfully applied near the PSB top energy. The bunch centre is depleted and thus the bunching factor increased

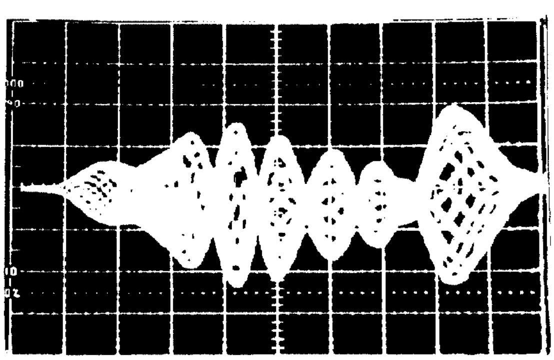

Fig. 2: Horizontal instability in PS; signal shown on several consecutive machine turns. 20 ns/div.

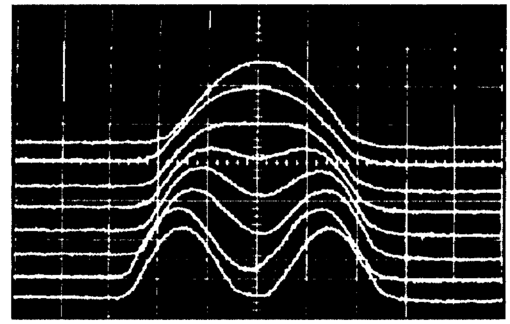

Fig. 3: Mountain range display of bunch splitting(50 ns/div). Sweeps every 800 PS turns. Time from top to bottom.

before ejection, which in turn lowers the space-charge tune shift in the PS.

3.2 PS: Injection Plateau

With the PS injection front porch at 1.4 GeV and a working point of Q_x ~6.22, Q_y ~6.28, the beam was stable and suffered no transverse blow-up; the bunch intensity was 1.8 10^{12} and $\Delta Q_y \sim 0.2$. To assess the benefits of the PSB energy increase, the bunch behaviour was also studied at 1 GeV injection, revealing some 20% emittance blow-up in each plane due to $\Delta Q_y > 0.3$. Moreover, the beam occasionally suffered from horizontal instability, with some 100 ms rise time and beam loss. Although only a single long (200 ns) bunch was circulating, it generated a multi-turn head-tail mode with high mode number (m=6 in Fig. 2) which is attributed to the resistive wall impedance. Head-tail instabilities during PS acceleration were avoided by appropriate programming of the machine chromaticity.

3.3 PS: Longitudinal Beam Handling

The prototype low-level RF system enabled matched beam capture on h=8 of one or two batches from the PSB. Acceleration was carried out on h=8 or 16, depending whether "bunch splitting" was activated or not at the end of the injection plateau: each bunch is split into two parts while the harmonic number of the RF holding the beam is smoothly doubled from h=8 to 16 (Fig. 3). This helps (i) to reduce the peak beam current and thus ΔQ during acceleration, and (ii) to improve the (future) debunching process at 26 GeV/c.

3.4. Double-Batch Filling of the PS

This is indispensable to achieve the required beam brightness: (i) 4 PSB bunches - one per ring - are stored in only one half of the PS circumference; (ii) a second beam is accelerated in the PSB while keeping the four bunches coasting in the PS; (iii) injection of the second pulse of 4 bunches into the remaining half of the PS 1.2 sec after the first one. The azimuthal positions of both injected beams (single bunches during the LHC Test) could be varied in the PS. In this way, the influence of the PS injection kicker rise and fall times on the circulating and newly injected beams

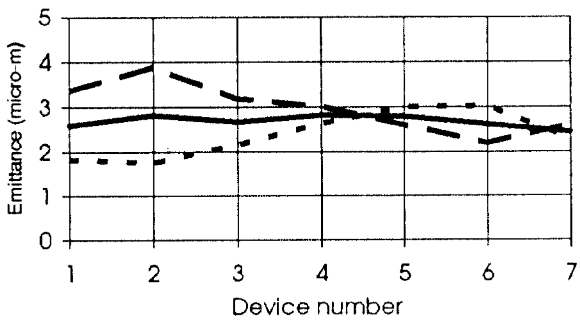

Fig. 4: Normalised emittances (μm) of 1.8 10^{12} p/pulse with PSB at 1.4 GeV. $(\varepsilon_x^*+\varepsilon_y^*)/2$ (full line), ε_x^* (broken line), ε_y^* (dotted line). Device numbering on abscissa: see sect.4. The aim is that $(\varepsilon_x^*+\varepsilon_y^*)/2$ stays below 3 μm at 26 GeV/c.

could be assessed with single bunches: the effect on transverse emittances was barely measurable.

4. TEST RESULTS: TRANSVERSE EMITTANCES

Transverse emittances were determined with several profile monitors along the accelerator chain, for both 1.4 and 1 GeV PSB energies, and for both intensity levels.

All devices listed below measure projected beam densities, except "BEAMSCOPE" which determines betatron amplitude profiles. They are (numbering used in Fig. 4): (1) BEAMSCOPE in the PSB, before ejection; (2) 3 Secondary Emission Monitors (SEM) at PS injection; (3) fast wire scanner in the PS, at injection of first pulse; (4) same, at the end of the injection plateau; (5) same, at 3.5 GeV/c; (6) same, at 26 GeV/c; (7) 3 SEM's in the PS-SPS line. Beam sizes derived from these measurements yield the normalised r.m.s emittances ε^*; in the horizontal plane, beam sizes were corrected for non-zero dispersion.

Of the many sets of emittance measurements recorded, one typical example is given in Fig. 4, which shows the evolution of the emittances with injection at 1.4 GeV. At PSB exit $\varepsilon_x>\varepsilon_y$ (points 1,2), but soon $\varepsilon_x\sim\varepsilon_y$ in the PS (points 3 to 6), probably due to linear coupling, and the beam becomes round at extraction (point 7). In fact, $(\varepsilon_x^*+\varepsilon_y^*)/2$ stays invariant throughout the process.

Emittances obtained at 26 GeV/c for both PSB energies and both intensity levels are summarised in Fig. 5.

5. CONCLUSIONS AND OUTLOOK

This dedicated LHC Test provided a timely opportunity to check the proposed proton acceleration scheme in the PS complex for the LHC with a minimum of modifications. This test was highly successful, because (i) all ingredients of the scheme which were addressed in the test proved to work as anticipated; (ii) with the PSB at 1.4 GeV, the transverse emittances at 26 GeV/c are well within LHC specification for the *beam-beam limit* peformance; (iii) the feasibility of the *nominal* LHC beam with injection into the PS at 1 GeV was demonstrated.

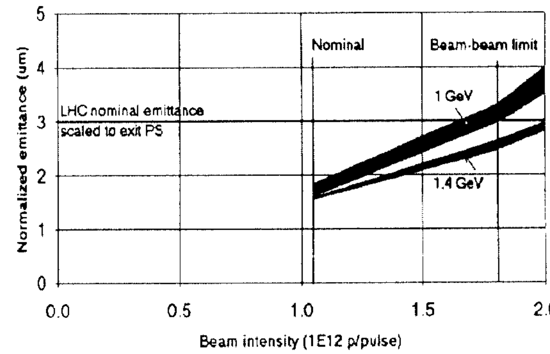

Fig. 5: Average emittance $(\varepsilon_x^*+\varepsilon_y^*)/2$ at 26 GeV/c vs. beam intensity (in 10^{12} p/pulse).

When extrapolating these findings to the final scheme, a safety margin must be provided to cope with the following sources of additional emittance blow-up: (i) vertical recombination of four PSB rings (instead of transferring just one ring); (ii) the presence of 8 bunches (instead of 2) in the PS which are more prone to instabilities; (iii) the debunching - rebunching process at 26 GeV/c.

Most of the present operational beams must be produced during the LHC era, therefore the new hardware of the full scheme has to be compatible with them. Although a first analysis [5] did not reveal any major difficulties, further work and machine studies will be devoted to this issue.

To summarise, the LHC Test has provided evidence that with the features of the proposed filling scheme, in particular the PSB energy increase to 1.4 GeV, a proton beam can be produced in the PS complex which is bright enough to fill the LHC up to the beam-beam limit.

6. REFERENCES

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