

CONVERSION OF THE PS COMPLEX AS LHC PROTON PRE-INJECTOR

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Abstract

CERN's Large Hadron Collider (LHC) [1][2] will be supplied with protons from the injector chain Linac2-PS Booster (PSB)-PS-SPS (Fig. 1). The required transverse beam brilliance (intensity/emittance) is almost twice that of current PS beams and the LHC bunch spacing of 25 ns must be impressed on the beam before its transfer to the SPS. The scheme involves new RF harmonics in the PSB and the PS, an increase of the PSB energy, and two-batch filling of the PS. After a successful test of the main ingredients, a project for converting the PS complex was launched in 1994. Major additions are (i) $h=1$ RF systems in the PSB, (ii) upgrading of the PSB main magnet supply from 1 to 1.4 GeV operation, (iii) new magnets, septa, power supplies, kicker pulsers for the PSB-PS beam transfer, (iv) 40 and 80 MHz systems in the PS, (v) beam profile measurement devices with improved resolution. A significant part of the effort is being provided by TRIUMF under the Canada-CERN co-operation agreement on the LHC.

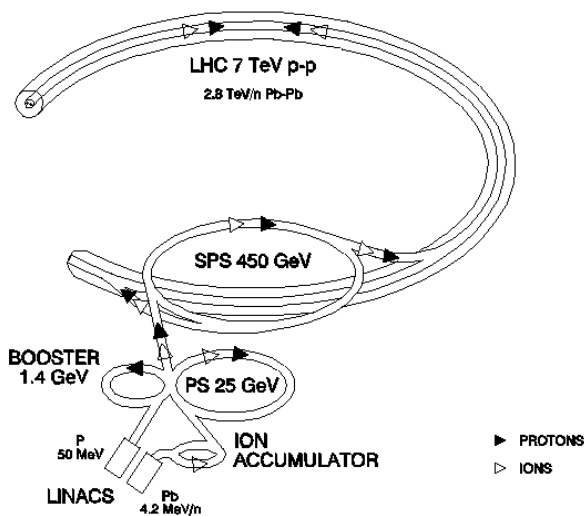


Fig. 1: The LHC injector complex.

1 LHC REQUIREMENTS

Supplying the LHC with protons from the existing chain of injectors may appear straightforward at first sight. However, the beam has to fit into the tiny LHC dynamic aperture, and must also have the brilliance required for

LHC's desired luminosity. While the intensity is well within the capabilities of the PS complex (Linac2, PSB, PS), the beam brilliance requested (here defined as intensity per bunch/normalised rms emittance) needs to be up to twice that of current beams. LHC proton beam parameters at collision (7 TeV per beam) at various stages of operation are summarised in Table 1.

| | Commis- sioning | Nomi- nal | beam-beam limit |
|--|---------------------|--------------|---------------------|
| Luminos. [$\text{cm}^{-2}\text{s}^{-1}$] | 10^{33} | 10^{34} | $2.5 \cdot 10^{34}$ |
| bunch spacing [ns] | 25 | | |
| bunches/beam | 2835 | | |
| protons/bunch | $1.7 \cdot 10^{10}$ | 10^{11} | $1.7 \cdot 10^{11}$ |
| ε^* ($=\beta\gamma\sigma^2/\beta_{x,y}$) [μm] | 1.0 | 3.75 | 3.75 |

Table 1: LHC proton beam parameters at collision. Note that $\varepsilon^* = \varepsilon_x^* = \varepsilon_y^*$.

The injector chain has to produce beams corresponding to the nominal performance; wherever possible, a higher performance level is aimed at, to potentially fill the LHC up to the beam-beam limit and to provide an operational margin.

2 A SCHEME TO REDUCE SPACE CHARGE

With a beam brilliance corresponding to the LHC beam-beam limit, the space-charge tune shifts (ΔQ) are almost twice the present figures at the PSB (50 MeV) and PS (1 GeV) injection energies, leading to unacceptable beam blow-up and loss.

2.1 Double-batch filling of the PS to reduce space charge in the PSB

Usually the four PSB rings (each 1/4 of PS circumference) are transferred sequentially (3-4-2-1), to fill the PS in one pulse. The LHC beam would generate, at PSB injection, a $\Delta Q = 0.9$, far beyond the "hard" limit of 0.55. With two PSB pulses to fill the PS, the intensity per PSB pulse is halved and ΔQ reduced to 0.45.

2.2 RF harmonic 1 in PSB for two-batch filling of the PS

With the RF equal to the PSB revolution frequency, there is just one bunch per ring (5 at present) and two-batch filling of the PS becomes feasible. Appropriate phasing of the bunch in each ring before extraction enables the four

bunches to be lodged in $\frac{1}{2}$ of the PS (Fig. 2), which can then accommodate a second batch.

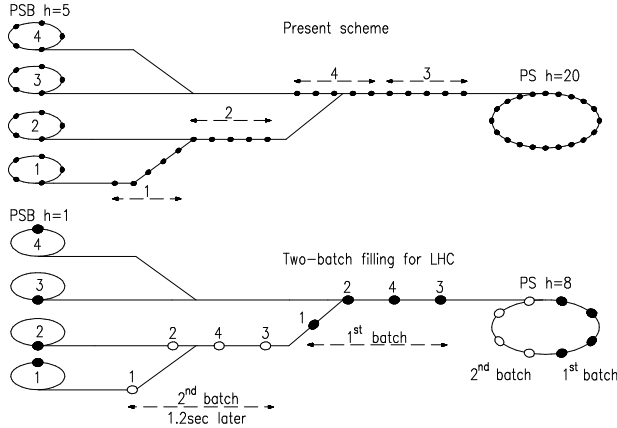


Fig. 2: PSB-PS four-ring transfer schemes.

2.3 PSB energy to 1.4 GeV to reduce tune spread in PS

The first batch from the PSB dwells for 1.2 sec on the PS injection plateau until the second batch arrives and is particularly vulnerable to a large ΔQ . The increase of the PSB energy will reduce the tune shift from 0.3 to a more comfortable 0.2.

For convenience, the main machine parameters of the LHC injector chain (including the SPS [3]) are compiled in Table 2. Note that the RF harmonic number 84 in the PS corresponds to the LHC bunch spacing of 25 ns which is impressed on the beam in the PS on the 25 GeV extraction flat top.

| | 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}] | 43 | 84 | 240 |
| beam-beam | 72 | 140 | 405 |
| p/bunch nominal [10^{11}] | 11 | 10.5/1.0 | 1.0 |
| beam-beam | 18 | 17.5/1.7 | 1.7 |
| emittance ε^* [μm] | 2.5 | 3.0 | 3.5 |

Table 2: The LHC proton injector chain.

3 MAJOR HARDWARE UPGRADES

The 50 MeV proton linac is now equipped with a 750 keV RFQ and produces a beam of unprecedented brightness: 150 mA in $\varepsilon^* = 1.2 \mu\text{m}$ during 120 μs . Ways to increase this intensity to 180 mA (albeit during only 20 μs) are under study.

3.1 New RF systems in PSB

New $h=1$ ferrite-filled RF cavities with a frequency swing of 0.6 to 1.7 MHz, 8 kV, will accelerate one bunch in each ring. Moreover, the present $h=5$ cavities will be modified for a tuning range of 1.2 to 3.9 MHz ($h=2$) to

flatten the bunches and thus reduce the space charge Q -shift in the low-energy part of the cycle.

3.2 Upgrading the PSB to 1.4 GeV

Raising the PSB output energy from 1 to 1.4 GeV implies an increase of the main dipole field by 26% to 0.87 T and of the quadrupole gradient to ~ 5 T/m. Beam measurements at these field levels have shown no sign of saturation. However, the main power supply needs upgrading: putting into service a fourth rectifier-inverter group, renewal of 18 kV transformers, including the reactive power compensation system, and implementing new controls circuitry.

3.3. PSB-PS beam transport to 1.4 GeV

The bending power of most of the magnetic elements of this line cannot be increased by 26%. Eight dc septum magnets are to be replaced by pulsed ones, three vertical bending magnets, six quadrupoles, and a series of correction dipoles are to be rebuilt with laminated yokes [4] and equipped with new power converters. This will permit the change of beam energy from pulse to pulse. The eight kicker magnets are being refurbished with more powerful pulsers [5].

3.4. Acceleration on new RF harmonics in the PS

The PS RF cavities are tuned to $h=8$ so as to accommodate the 8 PSB bunches (Fig. 2). These are then accelerated to 3.5 GeV/c where they are split to 16 bunches, followed by acceleration on $h=16$. New low-level electronics to cope with these harmonics is being built.

3.5. 40 and 80 MHz RF systems in the PS [6]

The LHC bunch spacing of 25 ns as well as bunch length matching (<4 ns) to the SPS are obtained with fixed-frequency RF systems. A 40 MHz cavity (300 kV) bunches the beam on $h=84$, whereas two 80 MHz systems (600 kV) are added to shorten the bunches, to fit into the SPS 200 MHz buckets. The design features a sophisticated mechanical short-circuit, as well as a powerful feedback to prevent high-intensity beams from suffering beam loading effects.

3.6. Beam diagnostics

Several systems are to be improved owing to the small size of the LHC beam, the new RF harmonics, and the intricacies of two-batch filling. Of particular relevance is the resolution of beam profile measurement devices (SEM grids, fast wire scanners) which must be increased by more than a factor 2.

4 BEAM TESTS - PAST AND FUTURE

4.1. Major results obtained so far

A partial test to check the proposed LHC proton filling scheme in the PS complex was carried out in late

1993 [7]. Only PSB ring 3 was used; its hardware was adapted by means of prototypes and pushing some elements beyond their safe limits. It has demonstrated that a proton beam can be produced at 25 GeV that meets the LHC specifications in terms of intensity and ϵ^* and confirmed the main ingredients of the scheme. More recently, the newly installed 40 MHz cavity was successfully used to bunch the beam with 25 ns spacing; the fast feedback system lowers the cavity impedance sufficiently to prevent high-intensity beams from becoming unstable.

4.2 Main beam dynamics issues [8][9]

The last line in Table 2 highlights the tight emittance budget available in the injector chain; every effort has to be made to avoid transverse blow-up. While space-charge detuning sweeps the beam over stop-bands and leads to an unavoidable emittance increase in the synchrotrons, emittance can be conserved in beam transport systems: mis-steering is to be minimized by automatic procedures, and corrected with fast dampers; mismatch is to be tackled by on-line quadrupole correction [10].

The new RF systems and harmonics will need intensive study [11]: (i) keeping the PSB $h=2$ RF in step with the $h=1$ RF even at highest intensity; (ii) bunch splitting from 8 to 16 in the PS; (iii) techniques to depopulate the bunch centre (for lowering space charge); (iv) RF gymnastics in the debunching/recapture process (from $h=16$ to $h=84$) at 25 GeV.

Another issue is to make sure that the proposed modifications do not jeopardize the beams for other users.

| ITEM | STATUS | TRIUMF PART |
|---|--|--|
| PSB $h=1$ RF systems (4) | prototype in one ring | ferrites power supplies |
| PSB $h=2$ RF systems (4) | one cavity commutable $h=5/h=2$ | |
| PSB main supply | control circuitry being tested | transformers (10) var compensator |
| PSB-PS kicker pulsers (7) | prototype tests | study on pulse-flattening [5] |
| PSB-PS septa (8) and supplies | two are operational | |
| PSB-PS line magnets (14) and power supplies | magnets: $\frac{1}{2}$ are ready; supplies: prototype tested | all magnets [4], all power supplies |
| PS 40 MHz cavities (2) | one cavity operational | model studies, tuners, |
| PS 80 MHz cavities (3) | in fabrication | HOM dampers, HV supplies |
| wire scanners (8) 4 rings, H+V | prototype tests in PSB | design + fabrication |
| fast blade profile monitor in PSB | prototype being designed | design and fabrication |

Table 3: Status of major hardware systems, TRIUMF contributions.

5 STATUS OF THE "PS FOR LHC" PROJECT

The project of converting the PS complex for the LHC was launched in 1994 and will be finished by 2000. Right from the start, a fruitful collaboration with TRIUMF has been established, formalised in 1996 by a CERN-TRIUMF cooperation agreement on the LHC. About one quarter of the funds and manpower required are being furnished by TRIUMF (Table 3).

In summary, the aim of the project is to deliver routinely to the SPS a beam of nominal characteristics (81 bunches, each 10^{11} p, $\epsilon^* < 3.0 \mu\text{m}$, $\epsilon_L \sim 0.35$ eVs), and possibly more intensity, by 1999. Presently everything indicates that this goal will be met. This will enable the SPS to assess, in time, its upgrading scheme.

6 ACKNOWLEDGEMENTS

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REFERENCES

- [1] The LHC Study Group, The Large Hadron Collider, Conceptual Design, CERN/AC/95-05 (LHC).
- [2] L. Evans, LHC status and plans, this conference.
- [3] P. Collier (editor), The SPS as injector for LHC, conceptual design, CERN-SL-97-07, March 1997.
- [4] G. Clark, A. Otter, P. Reeve, Magnets for the CERN PS Booster transfer line, this conference.
- [5] G.D. Wait, M.J. Barnes (TRIUMF), K.D. Metzmacher, L. Sermeus (CERN), The application of saturating inductors for improving the performance of the CERN PS kicker systems, this conference.
- [6] R. Garoby, D. Grier, E. Jensen (CERN), A.K. Mitra, R.L. Poirier (TRIUMF), The PS 40 MHz bunching cavity, this conference.
- [7] The PS staff, reported by K. Schindl, Partial test of the PS complex as LHC proton injector, Proc. 4th EPAC, London 1994, p. 500.
- [8] K. Schindl, The PS Booster as pre-injector for LHC, Proc. 3rd Int. Workshop on High Brightness Beams for Large Hadron Colliders ("LHC96"), Montreux, Switzerland, Oct. 1996, to be published in Part. Acc.
- [9] R. Cappel, The PS in the LHC injector chain, LHC96, Montreux, Switzerland, Oct. 1996, to be published in Particle Accelerators.
- [10] B. Autin, L. Giulicchi, A. Jansson, M. Lindroos, A. Lombardi, M. Martini, K. Schindl, Automated emittance preservation in the PS complex, this conference.
- [11] R. Garoby, Longitudinal limitations in the PS complex for the generation of the LHC proton beam, LHC96, Montreux, Switzerland, Oct. 1996, to be published in Particle Accelerators.