Chapter 12

Injection chain

12.1 Introduction

The LHC will be supplied with protons from the injector chain Linac2 — Proton Synchrotron Booster (PSB) — Proton Synchrotron (PS) — Super Proton Synchrotron (SPS), as shown in figure 12.1. These accelerators were upgraded to meet the very stringent needs of the LHC: many high intensity proton bunches (2'808 per LHC ring) with small transverse and well defined longitudinal emittances.

The main challenges for the PS complex are (i) the unprecedented transverse beam brightness (intensity/emittance), almost twice that which the PS produced in the past and (ii) the production of a bunch train with the LHC spacing of 25 ns before extraction from the PS (25 GeV).

Initially, a scheme requiring new Radio Frequency (RF) harmonics of h = 1, 2 in the PSB and h = 8,16, 84 in the PS, an increase of energy from 1 to 1.4 GeV in the PSB, and two-batch filling of the PS was proposed. After a partial test of this scheme in 1993, a project to convert the PS complex for LHC operation was started in 1995 and completed in 2000 [62]. The major parts of

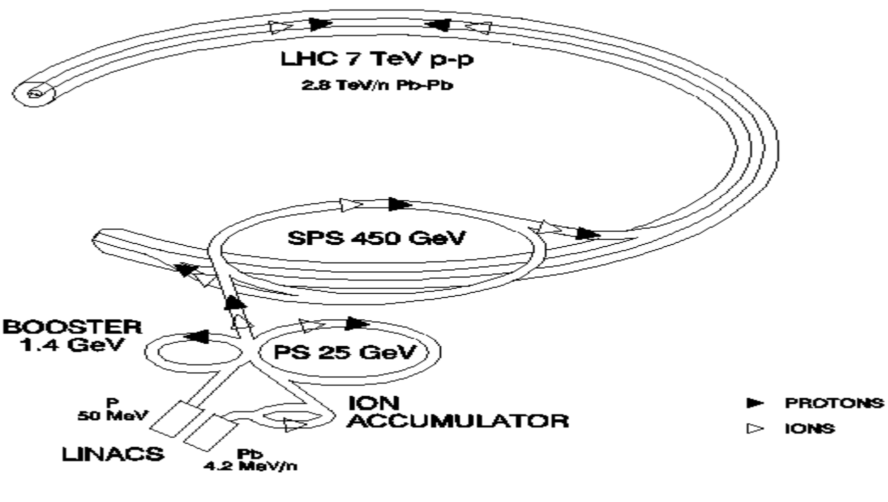

Figure 12.1: The LHC injector complex.

this project were:

i. new $h = 1$ RF systems in the PSB,

ii. upgrading the PSB main magnet supply from 1 GeV operation to 1.4 GeV,

iii. new magnets, septa, power supplies, and kicker pulsers for the PSB-PS beam transfer,

iv. new 40 and 80 MHz RF systems in the PS,

v. beam profile measurement devices with improved resolution.

About one quarter of the project resources (funds and manpower) was provided by TRIUMF under the Canada-CERN Co-operation Agreement on the LHC. During first beam tests with the complete scheme in 1999, difficulties in producing the LHC bunch train at PS extraction were encountered. The problem was an instability in the coasting beam after adiabatic debunching, just before recapture with the new 40 MHz RF system. As a consequence, the final bunch length at extraction was too large (>5 ns) to fit the SPS 200 MHz RF system. A modified scheme, avoiding debunching in the PS while changing the number of bunches by multiple bunch splitting operations, was proposed. This method is based on using RF harmonics $h = 7$, 21, 42 and 84 in the PS and required the installation of an additional 20 MHz RF system in the PS.

The transverse emittances of the LHC beam have to be maintained at their unusually small size throughout the injector chain. Small amounts of mis-steering and mismatch between the accelerators of the chain, virtually negligible for normal operation, become increasingly important and their effect has to be measurable, calling for high-resolution beam profile monitors. Moreover, various position measurement systems were modified to deal with the new harmonics in the circular machines and to allow bunch-by-bunch observation in TT2.

12.2 LHC and SPS requirements

The equation for luminosity given in chapter 2 summarises the "end-point" beam requirements, but this implies many conditions that have to be satisfied, such as,

- the beam emittance must fit the small aperture of the LHC superconducting magnets;
- the beam intensity is limited by the synchrotron radiation that has to be absorbed by the cryogenic system;
- the beam-beam effect causes a spread in betatron tunes ("footprint") when the beams are colliding, and this has to be kept below a certain limit; and
- the space-charge limits in the injectors have to be respected.

There are also conflicting requirements for the longitudinal emittance. It has to be small at injection to ease beam transport from the SPS through the two ∼2.5 km long lines, but larger at collision to avoid transverse emittance blow-up by intra-beam scattering.

An optimisation procedure, taking into account these boundary conditions, has resulted in the LHC beam parameter set compiled in table 12.1. The "ultimate" performance level corresponds

Table 12.1: LHC nominal and ultimate proton beam parameters.

			Injection	Collision	
	Energy	[GeV]	450	7000	
Luminosity	nominal	[$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]		10^{34}	
	ultimate			2.5×10^{34}	
Number of bunches			2808		3564 bunch places
Bunch spacing		[ns]	24.95		
Intensity per bunch	nominal	[p/b]	1.15×10^{11}		
	ultimate	1.70×10^{11}			
Beam current	nominal	[A]	0.58		
	ultimate		0.86		
Transverse emittance (rms, normalized), nominal & ultimate		[μm]	3.5	3.75	Emittances equal in both planes, small blow-up allowed in LHC
Longitudinal emittance, total		[eVs]	1.0	2.5	Controlled blow-up during accel.
Bunch length, total (4σ)		[ns]	1.7	1.0	has to fit into 400 MHz buckets
Energy spread, total (4σ)		[10^{-3}]	1.9	0.45	

to the LHC beam-beam limit, whereas the "nominal" performance combines high luminosity with operational margin. During the first year of physics running, the LHC will be operated at a much lower intensity and luminosity level.

As with the PS complex, the SPS is an "old" machine and is not optimised as an LHC injector. The intensity the SPS is able to accelerate ($\sim 4 \times 10^{13}$ protons per cycle, which is particularly difficult if concentrated on a fraction of its circumference) limits the number of PS pulses per SPS cycle to a maximum of four. The momentum spread acceptance of the PS-SPS line (TT2, TT10) is about $\pm 0.2\%$ in $\Delta p/p$, while the total bunch length has to be below 4 ns to fit into the buckets of the SPS 200 MHz accelerating system, implying a longitudinal emittance of 0.35 eVs per PS bunch. While the longitudinal emittance will be increased from 0.35 to 1 eVs during SPS acceleration, there is little margin for transverse emittance blow-up in this machine. The LHC and SPS requirements define the beam characteristics at PS extraction, summarised in table 12.2 (assuming 100% transmission from PS to LHC). The filling sequence PS-SPS-LHC is sketched in figure 12.2.

12.3 Scheme to produce the LHC proton beam in the PS complex

12.3.1 Space charge issues in PSB and PS

While the intensity required for the LHC is well within the capabilities of the PS complex, the transverse emittance is smaller than usual, yielding a beam brightness about 1.6 times higher than was hitherto achievable. Low-energy synchrotrons suffer from space charge, which can be quantified in terms of the tune shift

$$\Delta Q \propto -\frac{N}{(\beta\gamma^2)_{\mathrm{rel}}\varepsilon_n},$$

where N is the number of protons in the synchrotron. This tune shift would become unmanageable (almost -1) in the PSB at 50 MeV and in the PS at 1 GeV. The measures to overcome this

Table 12.2: Beam characteristics at extraction from the PS.

Proton kinetic energy	[GeV]	25	
Number of PS batches to fill SPS		3 or 4	Limited by SPS peak intensity
PS repetition time	[s]	3.6	PS 2-batch filling from PSB
Number of bunches in PS		72	h=84, 12 empty buckets for extraction kicker
Bunch spacing	[ns]	24.97	
Number of protons/bunch N_b - ultimate - nominal		1.70×10^{11} 1.15×10^{11}	100% transmission assumed from PS to LHC
Transverse normalised rms emittance	[μm]	3.0	
Bunch area (longitudinal emittance)	[eVs]	0.35	
Bunch length (total)	[ns]	4	Limited by SPS 200 MHz buckets
Relative momentum spread $\Delta p/p$ total (4σ)		0.004	Limited by TT2-TT10 acceptance

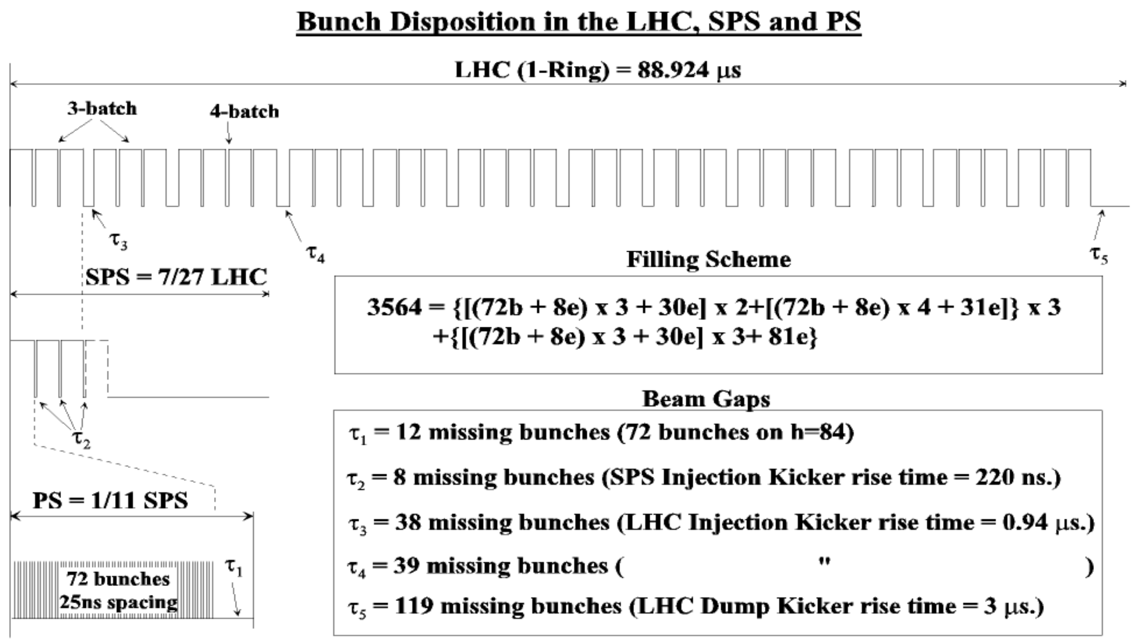

Figure 12.2: Proton bunches in the PS, SPS and one LHC ring. Note the partial filling of the SPS (3/11 or 4/11) and the voids due to kicker rise-time. One LHC ring is filled in ∼3 min.

fundamental limitation are:

- filling the PS with two consecutive PSB pulses, thus significantly reducing the intensity per pulse and thus ΔQat 50 MeV;
- raising the PS injection energy from 1 to 1.4 GeV, thus decreasing ΔQ in the PS by a factor 1.5 from $(1/\beta\gamma^2)_{\mathrm{rel}}$.

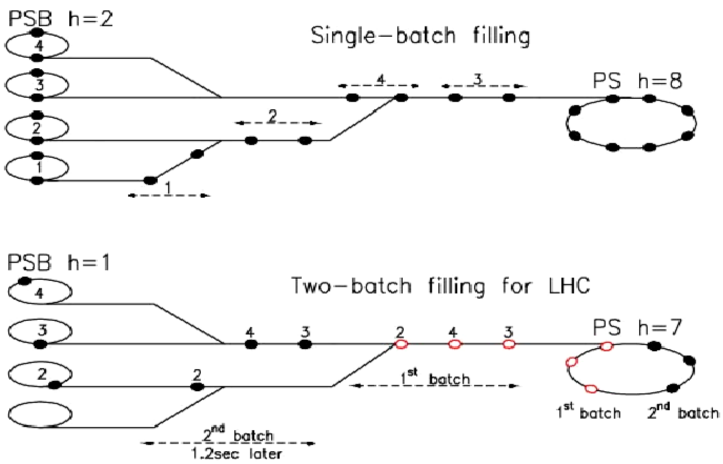

Figure 12.3: PSB-PS transfer: single-batch filling for SPS physics (top), two-batch filling for LHC (bottom).

The four PSB rings, $1/4$ of the PS circumference each, are normally ejected and transferred sequentially to fill the PS in one go, for example, for the SPS physics beam with two bunches per ring (5 bunches per ring until 1997). However, with only one bunch per ring, up to four bunches can be squeezed into $\sim 1/2$ of the PS, thus leaving space for a second PSB batch 1.2 seconds later. Figure 12.3 shows the standard filling scheme for SPS physics, and the LHC two batch filling scheme, in which three and three (or alternatively four and two) bunches from the PSB are transferred to the PS on consecutive PSB cycles.

To operate with RF harmonic $h = 1$ instead of the former harmonic $h = 5$, the PSB is now equipped with new RF cavities, with a frequency range of 0.6 to 1.7 MHz, and the former $h = 5$ systems have been modified to work on $h = 2$. Also, the PS has to cope with new RF harmonics — an opportunity to equip both machines with Digital Beam Control.

To raise the PSB ejection and PS injection energy from 1 to 1.4 GeV (+26.3% in momentum), the PSB main power supply has been upgraded to provide the higher magnet currents. The elements of the PSB-PS beam transport have to provide higher field levels, which meant replacement of most of the magnets (dipoles, quadrupoles, septa, kickers) and their power supplies.

12.3.2 LHC bunch train generation in the PS

12.3.3 Initial debunching-rebunching scheme

The initially proposed scheme injected two times four PSB bunches (two PSB batches) on harmonic $h = 8$ in the PS. The bunches were then split in two and accelerated on harmonic 16 to 25 GeV. The 25 ns bunch spacing was achieved by debunching and rebunching the beam on h=84, followed by bunch rotation with the new 40 MHz (h=84) and 80 MHz RF systems. Out of the 84 bunches, 81 were transferred to the SPS, and three were expected to be lost due to the PS extraction kicker rise-time.

However, when testing the scheme in 1999, microwave instabilities due to the longitudinal impedance of the PS blew up the momentum spread during the delicate debunching process. At nominal intensity, there was no way to make the bunches shorter than 5 ns. The decision was then taken to change to a newly proposed scheme using multiple splitting techniques [63], which avoided this instability, provided a gap without particles for the rise-time of the ejection kicker, and introduced flexibility in the bunch train time structure.

12.3.4 Multiple splitting scheme

For the generation of the LHC bunch train with 25 ns spacing in the PS, a multiple splitting scheme is employed. Six PSB bunches (two PSB batches of 3 + 3 or 4 + 2 bunches) are captured on harmonic h = 7 in the PS. The bunches are then split into three at 1.4 GeV using appropriate amplitude and phase parameters in three groups of cavities operating on harmonics h = 7, 14 and 21. Bunched on harmonic h = 21, the beam is accelerated up to 25 GeV where each bunch is split twice in two using the process which has been demonstrated in regular operation. The new 20 MHz and 40 MHz RF systems are required at that stage. Thus, each of the six original bunches has been split into 12, and 72 bunches have been created on harmonic 84. Finally, the 80 MHz systems shorten the bunches to $\sim$4 ns, so as to fit into the SPS 200 MHz buckets. After injecting only six bunches, the final bunch train contains 72 bunches and 12 consecutive empty buckets, providing a gap of $\sim$ 320 ns (13 $\times$ 25 ns) for the rise-time of the ejection kicker. The change from the debunching-rebunching scheme to the multiple splitting scheme required the installation of a 20 MHz RF system that was not part of the "PS for LHC" conversion project.

The new scheme, though indispensable for longitudinal beam dynamics, has one drawback: There are 72 LHC bunches produced from six PSB bunches, instead of 84 from 8. Thus the intensity per PSB bunch and the beam brightness (due to the fixed emittance) have to be 14% higher than with the debunching-rebunching scheme. The consequence is that the ultimate beam, which is already at the limit of the achievable brightness, can no longer be provided by the PSB. Initially, it was thought that by using up parts of the PS emittance budget and with more experience, one could still achieve the required beam characteristics. This possibility has been ruled out following the observation of beam losses, and alternative RF gymnastics have had to be invoked. A comparison of debunching-rebunching and multiple splitting schemes is given in table 12.3 (the intensities quoted assume 100% transmission from PSB to LHC).

12.4 Overview of hardware changes

The project to convert the PS complex to an LHC pre-injector was launched in 1995. Also in 1995, Canada offered in-kind contributions for the LHC machine (via TRIUMF/Vancouver), which soon developed into an efficient collaboration, with TRIUMF providing $\sim$1/4 of the resources needed for the PS upgrade project. Major systems and their hardware components are listed in table 12.4, together with Canadian contributions and installation dates. The project was essentially finished by 2001.

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Table 12.3: PS complex operation for filling LHC: debunching-rebunching and multiple splitting.

	Debunching-rebunching	**Multiple splitting**
No. of bunches per PSB ring	1	1
No. of PSB cycles per PS cycle	2	2
No. of bunches from PSB per PS cycle	8	6
Harmonic no. at PS injection	8	7
Bunch splitting at 1.4 GeV	1=>2	1=>3
Harmonic no. from 1.4 GeV to 25 GeV	16	21
No. of bunches from 1.4 GeV to 25 GeV	16	18
Gymnastics at 25 GeV	Debunching-rebunching	Double bunch splitting (1=>4)
Harmonic no. at PS extraction	84	84
No. of bunches to SPS per PS cycle	81 (3 bunches lost due to PS extraction kicker rise time)	72 (empty bucket conserved, provides 320 ns for kicker)
PS intensity at 1.4 GeV for 1.15×10^{11} protons per LHC bunch ("nominal")	9.66×10^{12}	8.28×10^{12}
PSB intensity per ring ("nominal")	1.21×10^{12}	1.38×10^{12}
PS intensity at 1.4 GeV for 1.7×10^{11} protons per LHC bunch ("ultimate")	14.28×10^{12}	12.24×10^{12}
PSB intensity per ring ("ultimate")	1.79×10^{12}	2.04×10^{12}

Table 12.4: Major hardware components of the "PS Conversion for LHC" project.

System	Components	Installation	TRIUMF contribution	Comments
Linac	Inter-tank beam shape monitors (2)	1999, 2000		study very high intensities (180 mA)
50 MeV line	laminated quadrupoles	1997	two magnets	correct optics for protons and ions
PSB RFh=1	RF cavities "C02" (4), tune range 0.6-1.7 MHz	1998	ferrites, HV power supplies	one cavity per ring
PSB RFh=2	RF cavities "C04" (4), tune range 1.2-3.9 MHz	1998		bunch flattening and/or splitting
PSB main magnet supply	double-transformers (5), VAR compensator, quadrupole trim supplies, control circuitry	1998	all transformers, VAR compensator	26% increase of magnet current on PSB main magnets
PSB water cooling	closed-circuit demineralised water	2000		copes with more heating at 1.4 GeV
PSB instrumentation	fast wire scanners (4 rings, H+V, + 2 spares)	2001-2003	10 units, design and fabrication.	standard PS beam profile meas. device
	Q-measurement: electronics, kicker pulser	1999/2000		all four beams are kicked
PSB-PS beam transport	ejection/recombination kicker pulsers (6)	1998, 1999		26% more kick to cope with 1.4 GeV
	ejection, recombination, PS injection septa + power supplies (8)	1997, 1998, 1999		half-sine-wave pulses of 3.5 ms
	15 laminated magnets (vertical bending magnets, quadrupoles, correction dipoles)	1997, 1998	all 15 magnets all (+spare) power supplies	allow pulse-to-pulse modulation between 1.4 GeV (PS) and 1 GeV
PS RFh=84	300 kV fixed-frequency (40 MHz) cavities (1+1 spare installed) "C40"	1996, 1999	model studies, tuners, higher-order-mode dampers, HV supplies	for generating LHC bunch spacing of 25 ns at 25 GeV
PS RFh=168	300 kV fixed-frequency (80 MHz) cavities (2+1 spare installed) "C80"	1998, 1999		for shortening the LHC bunches to 4 ns
PS transverse feedback	new amplifiers, deflector, electronics	2003-2005		damping injection oscillations and instabilities
PS instrumentation	wide-band position monitors (2) in line TT2	1998		bunch-by-bunch position measurement
PS RF h=28, 42	15 kV dual frequency 13.3 or 20 MHz cavity, (1+1 spare installed) "C20"	2003-2004		for various bunch splitting operations in the PS