CHAPTER 2

BEAM REQUIREMENTS AND FUNDAMENTAL CHOICES

2.1 LHC AND SPS REQUIREMENTS

The figure of merit for colliders such as the LHC is the luminosity

$$L = \frac{k_b N_b^2 f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} ,$$

with k_b the number of bunches per ring, N_b the number of protons per bunch, f_{rev} the revolution frequency, ε_n the normalised rms transverse beam emittance (same in both planes), β^* the beta-function at the interaction point. L is proportional to the number of events per second and thus has to be maximised. But more conditions are to be satisfied:

(i) the beam emittance has to fit into the small aperture of the superconducting LHC magnets;

(ii) the total intensity $k_b \cdot N_b$ is limited by the thermal energy produced by synchrotron radiation which must be absorbed by the cryogenic system;

(iii) the beam-beam effect – proportional to the transverse beam brightness N_b/ε_n – causing a spread in betatron tunes ("footprint") when the beams are colliding has to be kept below a certain limit;

(iv) the space-charge limit in the injectors, which also scales with N_b/ε_n.

Conflicting requirements also determine the longitudinal emittance ε_L which has to be small at injection (small $\Delta p/p$ 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 elaborate optimisation procedure, taking into account these boundary conditions, has resulted in the LHC beam parameter set [1] compiled in Tab. 2.1. The "ultimate" performance level corresponds to the LHC beam-beam limit, whereas the "nominal" performance combines high luminosity with operational margin. Moreover, during the first year of physics running the LHC will be operated at a much lower intensity and luminosity level.

Table 2.1: LHC nominal and ultimate proton beam parameters.

			Injection	**Collision**	
Energy		[GeV]	450	7000	
Luminosity	nominal	[cm^{-2}s^{-1}]		10^{34}	
	ultimate			2.5×10^{34}	
Number of bunches			2808		3564 bunch places
Bunch spacing		[ns]	24.95		
N_b intensity per bunch	nominal	[p/b]	1.15×10^{11}		
	ultimate		1.70×10^{11}		
Beam current	nominal	[A]	0.58		
	ultimate		0.86		
ε_n (transverse emittance, rms, normalised), 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	

Much like the PS complex, the SPS is an "old" machine and was not optimised for its future function as LHC injector. The intensity the SPS is able to accelerate (~ 4 × 10^{13} protons per cycle, 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 ±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, meaning a longitudinal emittance of 0.35 eVs per PS bunch. While the longitudinal emittance will be increased (hopefully in a controlled way) 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 Tab. 2.2 (assuming 100% transmission from PS to LHC). The filling sequence PS-SPS-LHC is sketched in Fig. 2.1.

Table 2.2: 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 ε_n	[µm]	3.0	
Bunch area (longitudinal emittance) ε_L	[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

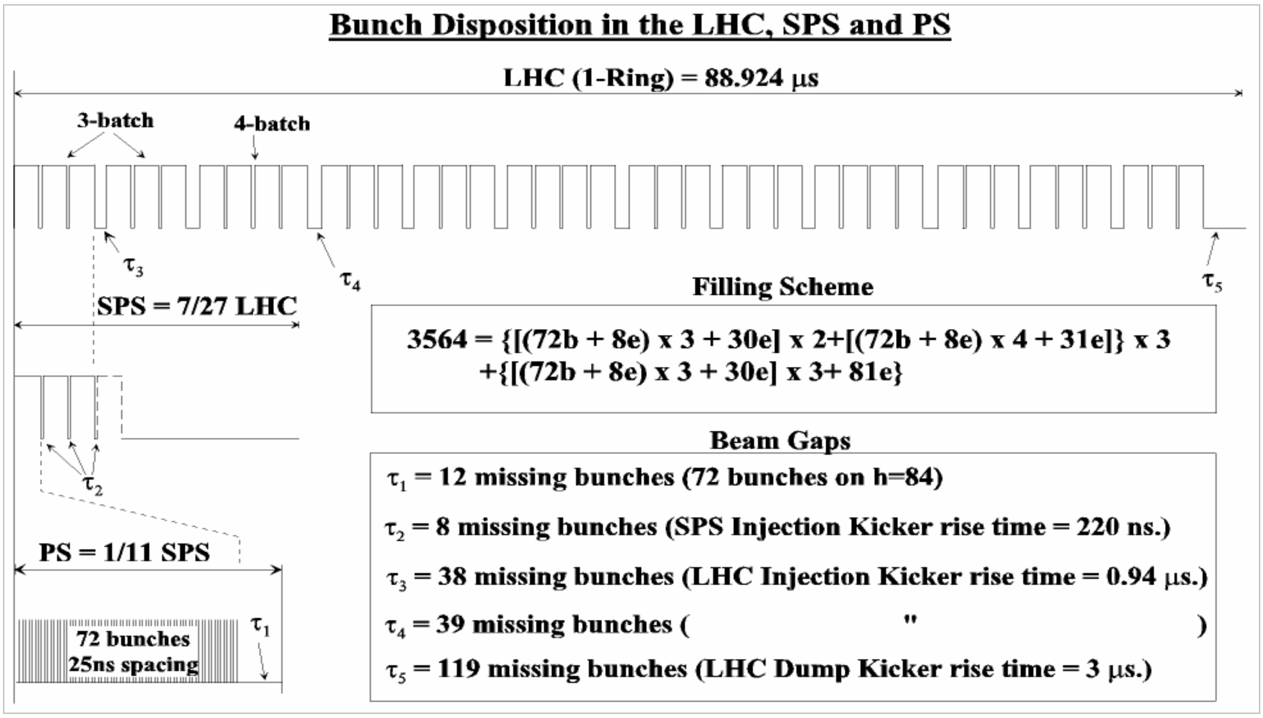

Figure 2.1: Proton bunches in the PS, SPS and one LHC ring. Note the partial filling of the SPS (3/11 or 4/11) and the voids due to kicker rise-time. One LHC ring is filled in ~3 min.

2.2 SCHEME TO PRODUCE THE LHC PROTON BEAM IN THE PS COMPLEX

2.2.1 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 very small, yielding a beam brightness N_b/ε_n about 1.6 times higher than was hitherto achievable. Low-energy synchrotrons suffer from space charge which can be quantified by the tune shift

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

where N is the number of protons in the synchrotron. This tune shift would become unmanageable in the PSB at 50 MeV (almost -1) and in the PS at 1 GeV. The measures to overcome this fundamental limitation are (i) filling the PS with two consecutive PSB pulses, thus significantly reducing the intensity per pulse and thus ΔQ at 50 MeV; (ii) raising the PS injection energy from 1 to 1.4 GeV, thus decreasing ΔQ in the PS by a factor 1.5, $(1/\beta\gamma^2)_{\text{rel}}$.

The four PSB rings, ¼ of the PS circumference each, are normally ejected and transferred sequentially to fill the PS in one go, e.g. 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 ~½ of the PS, thus leaving space for a second PSB batch 1.2 seconds later. Fig. 2.2 shows the standard filling scheme for SPS physics and the LHC two batch filling scheme where three and three (or alternatively four and two) bunches from the PSB are transferred to the PS on consecutive PSB cycles.

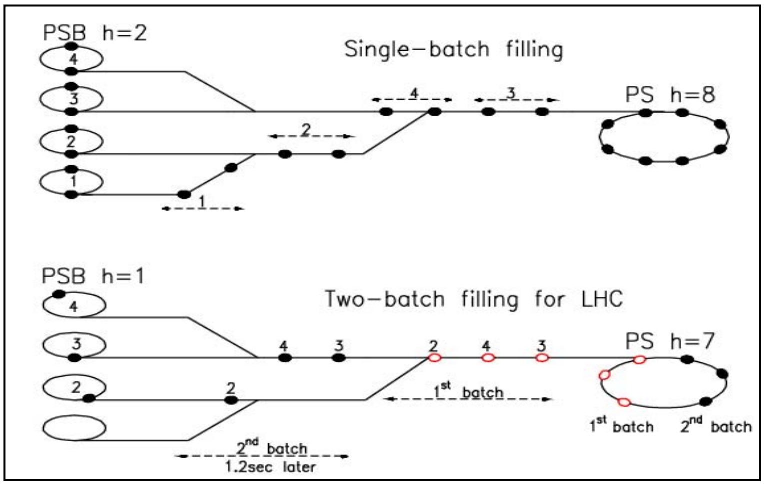

Figure 2.2: PSB-PS transfer: single-batch filling for SPS physics (top), two-batch filling for LHC (bottom).

To operate with RF harmonic 1 instead of the former 5, the PSB is now equipped with new RF cavities featuring 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 cope with the higher magnet currents. The elements of the PSB-PS beam transport have to provide higher field levels, which meant renewal of most of the magnets (dipoles, quadrupoles, septa, kickers) and their power supplies.

2.2.2 LHC Bunch Train Generation in the PS

Initial debunching-rebunching scheme

The initially proposed scheme was for the injection of two times four PSB bunches (two PSB batches) on harmonic 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, 3 were supposed 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 [2] 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.

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 7 in the PS. The bunches are then split in three at 1.4 GeV using appropriate amplitude and phase parameters on three groups of cavities operating on harmonics 7, 14 and 21, respectively [3]. Bunched on harmonic 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. Finally each of the six original bunches has been split in 12 and 72 bunches are created on harmonic 84. The 80 MHz systems finally shorten the bunches to ~4 ns so as to fit into the SPS 200 MHz buckets. Injecting only 6 bunches, the final bunch train contains 72 bunches and 12 consecutive empty buckets, providing a gap of ~ 320 ns (13 × 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 [4].

The new scheme, though indispensable for longitudinal beam dynamics, has one drawback: 72 LHC bunches are produced from 6 PSB bunches (instead of initially 84 from 8). Therefore the intensity per PSB bunch and consequently, due to the fixed emittance, the beam brightness have to be 14% higher than with the debunching-rebunching scheme. The consequence is that the ultimate beam, which was already at the limit of the achievable brightness, can no longer be provided by the PSB due to the increase in intensity (2.04×10^{12}, 2.5 μm). Initially it was thought that by using up parts of the PS emittance budget and with some more experience one could still achieve the required beam characteristics – this possibility has now been ruled out following the observation of beam losses (Sec. 2.3). Alternative ways to produce the ultimate beam are sketched in Sec. 10.5. A comparison of debunching-rebunching and multiple splitting schemes is given in Tab. 2.3 (the intensities quoted assume 100% transmission from PSB to LHC).

Table 2.3: 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
h at PS injection	8	7
Bunch splitting at 1.4 GeV	1=>2	1=>3
h 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)
h 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}

2.3 EVOLUTION OF LHC BEAM INTENSITY REQUIREMENTS

Since the definition of nominal and ultimate LHC beam intensities in 1993 [5], several changes were made, due to LHC design parameter modifications and also the change of the bunch train production scheme in the PS. In addition, the initial intensity requirements assumed zero beam losses or 100% efficiency from capture in the PSB throughout the complete injector chain (and also the LHC), which turned out to be too optimistic. To compensate for these losses and design changes, the injectors have to provide more intensity to keep the LHC luminosity at the required level.

Any increase of beam intensity also increases the brightness of the beam that has to be produced by the PSB because of the fixed transverse emittance budget. It is therefore mandatory to review the required intensities since the brightness that can be provided by the PSB is limited by space charge effects at injection. Of course the space charge effects at PS injection flat bottom are increased by the same factor due to the bunch to bucket transfer between PSB and PS.

The different ingredients leading to an intensity increase on the LHC side were:

- LHC crossing angle change from 200 to 285 μrad (1995): requiring an intensity increase by a factor 1.10.
- LHC β^* change from 0.5 to 0.55 m (2003): requiring an intensity increase by 1.05.

On the PS side:

- The change from debunching-rebunching to multiple splitting scheme (2000): requiring an intensity increase by 1.14.

It is important to note that compensation of crossing angle and β^* changes is only required for the nominal beam and not for the ultimate, where the intensity is fixed by the LHC beam-beam limit. The factor 1.14 to compensate for the scheme change in the PS is required for both beams.

Extensive beam tests with nominal and ultimate intensities allowed a beam loss inventory to be established. With the present performance an overall efficiency of 0.85 is realistic for the nominal beam whereas the figure for the ultimate beam is only around 0.8. The major part of the beam losses (~10% for nominal and ~15% for ultimate beams) appears at start of acceleration in the SPS; studies to understand the mechanism leading to these losses and hopefully to reduce them are being made at the time of writing.

Tab. 2.4 compares PSB bunch intensities estimated in 1993 and 2003 to obtain the nominal and ultimate beams in the LHC, taking into account the observed losses and all modifications to the LHC and the injectors.

Table. 2.4: PSB beam intensities required for nominal and ultimate beams in 1993 and 2003.

	1993	2003	Correction factor
LHC nominal bunch	1.00×10^{11}	1.15×10^{11}	1.10·1.05
PSB nominal bunch	10.50×10^{11}	16.25×10^{11}	1.10·1.05·1.14/0.85
LHC ultimate bunch	1.70×10^{11}	1.70×10^{11}	1.00
PSB ultimate bunch	17.85×10^{11}	25.50×10^{11}	1.14/0.80

In conclusion it can be stated that the nominal beam is well within reach but the intensity and brightness required from the PSB are moving closer to what was defined as ultimate beam in 1993. There is no longer a comfortable margin left over from the emittance budget, which will make operation more critical. In fact, the ultimate beam is currently not feasible in the PSB. Potential solutions are sketched in Chap. 10.

2.4 OVERVIEW OF HARDWARE CHANGES

The project to convert the PS complex to an LHC pre-injector was launched in 1995, based on a project proposal which included budget and manpower estimates [5]. 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 ~1/4 of the resources needed for the PS upgrading project. Major systems and their hardware components are listed in Tab. 2.5, together with Canadian contributions and installation dates. The project was essentially finished by 2001.

Table 2.5: 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 RF h=1	RF cavities "C02" (4), tune range 0.6-1.7 MHz	1998	ferrites, HV power supplies	one cavity per ring
PSB RF h=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 RF h=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 RF h=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

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