CHAPTER 12

BEAM PARAMETERS AND REQUIREMENTS

12.1 CYCLE AND OPERATIONAL REQUIREMENTS

12.1.1 Standard LHC Filling Cycle

In the standard LHC filling cycle [1] between two and four PS batches are transferred from PS to the SPS at 26 GeV/c with an interval of 3.6 seconds between injections. After the injection of the last batch a ramp to 450 GeV/c is started. A ramp rate similar to that used for the p-pbar Collider is used (an average ramp rate of 78 GeV/sec), with the principal limitation from the RF power requirements at low energies. Once at 450 GeV/c the following actions take place during the flat-top, which is approximately 1 second long:

- The ramping of the extraction elements (magnetic septa and closed orbit bumpers) ready for extraction,
- The fine re-phasing of the SPS with respect to the LHC in order to inject into the LHC at the required azimuthal position,
- The compression of the bunch length by an RF voltage increase,
- Cleaning of the tails of the beam distribution down to 3-3.5σ by means of fast scrapers.
- The status and settings of various elements of the LHC, the transfer lines, the SPS and the extraction channel must be surveyed and checked before extraction is permitted.

Towards the end of the flat top the beam is extracted to one of the LHC rings, either via the west extraction zone to TI 2, or via the east extraction to TI 8. Once the beam has been extracted the machine is ramped back to the injection level for the next cycle. Fig. 12.1 shows the SPS supercycle required for a single injection into the LHC. Cycles having two, three or four PS batches will be required [2,3]. Injections occur at 0, 3.6, 7.2 and 10.8 s from the start of the supercycle, as 3.6 s is the cycle length for the LHC beam in the PS. A total of 24 such supercycles will be required to fill both rings of the LHC with beam. The length of any supercycle must be a multiple of the PS elementary cycle (1.2 s), which in this case is 21.6 s. The rms power consumption (for the machine dipoles and quadrupoles) is 19 MW. Using the above specifications, and neglecting the time required for changing from LHC Beam 1 to Beam 2, the LHC filling time will be about 9 minutes.

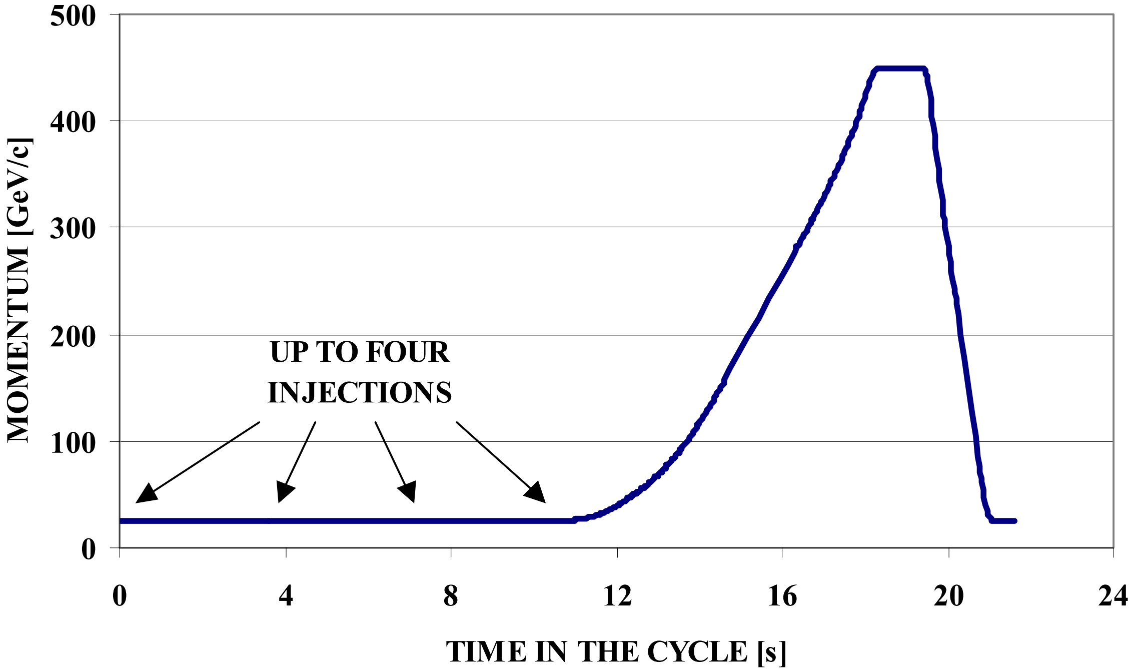

Figure 12.1: SPS supercycle for LHC filling.

Before starting the LHC filling process for each physics coast, one or more pilot bunches will be required [2,3,4]. The pilot bunch must be measurable by the beam observation systems of the LHC and its intensity must allow the complete loss of the beam at injection without quenching the LHC magnets, for this reason the pilot bunch is also called the safety beam. The safety beam will therefore consist of a single bunch, with an intensity of around 5×10^9 protons. The pilot bunch can be produced in the injector chain with the required intensity and emittance as well as with good parameter reproducibility [5]. This beam has been delivered for the TT40 extraction tests [6]. Its injection and acceleration in the SPS nevertheless requires specific settings for the machine. An alternative scheme would consist in injecting a more intense bunch in the SPS (e.g. a nominal LHC bunch) and reducing the intensity before extraction by scraping at 450 GeV/c. This would minimise the amount of tuning needed in the SPS in order to switch from pilot to nominal operation [7].

With the pilot intensity, the LHC beam instrumentation does not provide accurate enough measurements to guarantee a safe injection of the nominal beam into the LHC. For this reason, once the injection process and the LHC machine parameters have been roughly checked and adjusted with the safety beam, an intermediate beam consisting of 12 bunches (4 in the case of a 75 ns spacing beam) having nominal bunch parameters will be injected. These can be produced in the PS Complex by using a single Booster bunch instead of the usual 6 for the nominal beam. The intermediate beam can be used to fine tune the settings of the LHC machine. Once the LHC is ready, the nominal LHC beam will be injected, but only after having re-injected the pilot beam [2].

Recently it has been observed that dipole and quadrupole magnetic fields in the SPS injection plateau for the LHC filling cycle are not stable and trims in the functions driving the main dipoles and quadrupoles are required to compensate for their decay. The observations are consistent with a decay time constant of about 1 s for the main dipoles and around 0.5 s for the quadrupoles. This effect is very likely due to the decay of the eddy currents induced in the vacuum chambers during the ramp-down of the magnets [5]. Although a compensation for the field decay is applied, this is only approximate and the effect of the residual errors is not known. For this reason a longer supercycle might be required. This would allow for a longer pre-injection plateau in order to provide enough time for the eddy currents to decay. Investigations with beam are being performed during 2004 to try and disentangle the effects of the eddy currents and to provide operational solutions while minimising the total length of the SPS supercycle for the LHC.

Studies are also ongoing to reduce the PS Booster cycle length to 0.9 s or even to 0.6 s. This would allow a reduction of the PS LHC cycle and therefore of the injection plateau in the SPS with beneficial effects not only for the LHC filling time but, in particular, for the preservation of the emittance in the SPS.

12.1.2 Scrubbing

Operation of the SPS with the LHC beam during machine studies has shown that electron multipacting occurs in the SPS vacuum chamber as a result of the high bunch intensity, the short bunch spacing and the high Secondary Emission Yield (SEY) of the stainless steel vacuum chamber surface (see Sec. 15.6). Electron multipacting induces desorption of molecules from the vacuum chamber and dramatic pressure increases have been observed.

Experiments performed in the SPS in 2002 have shown that the SEY can be reduced by the electron bombardment induced by the beam. This conditioning, or scrubbing, effect reduced the SEY of a test surface from 2.1-2.3 (the as received surface) to about 1.5 during a 10-day period. During dedicated runs the machine is operated close to the vacuum interlock level, by acting on the number of PS batches injected and on the amount of time spent by the beam in each supercycle (adjustable by varying the timing of the beam dump in the supercycle). The initial SEY value is recovered as soon as a conditioned vacuum chamber is vented to air, although the re-conditioning is faster if the length of time that the chamber is at atmospheric pressure is kept short. As interventions on the vacuum system are inevitable during the annual accelerator shutdowns, 'scrubbing' runs lasting a few days will have to be scheduled in the SPS at the beginning of each year's operation, before operation with LHC beams starts.

During the scrubbing run, the SPS is normally operated with a flat 26 GeV/c supercycle, having the possibility of injecting more batches. The length of the 'scrubbing' cycle is dictated mainly by the lifetime of the beam (which is poor at the beginning or the run) and the need to minimise the number ofPS complex cycles devoted to this purpose and therefore the impact on other Physics programmes. An SPS supercycle length of 43.2 s has proved to be a reasonable compromise. The modification of the SEY is localised, particularly in the main dipole magnets where the electron cloud is concentrated in stripes symmetrically placed with respect to the beam and parallel to the magnetic field lines. The separation of the stripes is proportional to the bunch intensity and inversely proportional to the bunch length. The location of the 'scrubbed' area also moves with the beam position and the bunch length. As a result it also varies during the acceleration. For this reason a 'scrubbing' period with acceleration to 450 GeV/c, on the cycle shown in Fig. 12.1, must follow the scrubbing run at 26 GeV/c.

The duration of a scrubbing run and/or the intensity of the beam injected in the SPS are presently limited by the beam-induced heating of the ferrites of the kickers installed in the machine. In particular the horizontal tune kicker (MKQH) and the extraction kickers (MKE) are affected, because of their relatively small vertical aperture [4]. Once the Curie temperature is reached in the ferrite, there is a reversible loss of the magnetic properties of the kicker. Even higher temperatures could result in mechanical damage to the ferrite blocks. The present understanding of the phenomenon indicates that the SPS can be operated at injection energy with two nominal intensity PS batches for a few days without interruption (assuming a beam duty factor close to 1). However, operation with the nominal LHC beam (4 PS batches) and with acceleration to 450 GeV/c is limited to less than 24 hours. These durations proved to be sufficient in order to reduce the SEY to acceptable values in the SPS and hence allow operation with the LHC beam. However, SPS kicker heating might be a limitation for the scrubbing of the LHC itself, if frequent injections are required [8]. Studies and experiments have been started to upgrade the kickers in order to eliminate, or at least reduce their heating.

12.1.3 Constraints on Cycle Composition and Controls Requirements

Although a significant reduction of the SEY is attained during the scrubbing runs, no complete suppression of the multipacting can be obtained in the arcs for the nominal LHC beam. When the SPS is operated with the LHC beam in parallel to fixed target physics, abnormal sparking of the electrostatic septa used for the slow-extraction and transverse instabilities affecting the fixed target beam have been observed, even after scrubbing. These effects come about as a result of the long time constant for the decay of the electron cloud. Operation with the nominal LHC beam in parallel with fixed target physics is therefore not planned at present.

Currently, during dedicated machine studies with the high intensity LHC beam, the high voltage on the cathodes of the electrostatic septa (ZS) is reduced to zero and the ZS ion traps are powered to help prevent electron multipacting. In addition, as a cautionary measure, the extraction girders are retracted. The fast vacuum valves in the extraction area are also blocked out in order to prevent intermittent closure that could damage the valves themselves. These fast valves are designed to protect the electrostatic septa from water inrush in the case of a mechanical failure of the coils of the magnetic septa. For this reason the cooling circuits of the magnetic septa are closed during operation with LHC beam.

All these actions, acceptable during machine study sessions prevent rapid supercycle changes between the LHC filling mode and conventional operation for fixed-target physics. The movement of the girders takes some minutes to complete, however, moving the girders can probably be avoided once the LHC beam is routinely in operation. On the other hand, applications to perform all the other actions in a rapid and deterministic sequence will have to be implemented.

The beams required by the LHC (pilot, intermediate and nominal) during a standard filling sequence will be accelerated using the same cycle but some retuning of the machine parameters (e.g. the betatron tunes) and of the settings of the beam observation and RF systems will be needed.

The LHC injectors will have to be able to switch between the different beams required for the LHC filling phase and between extractions to either one of the two LHC rings on a cycle-by-cycle basis [9]. In routine operation LHC filling will occur during SPS operation for fixed target physics, or during machine studies. Fixed-target physics periods are likely to include CNGS operation as well as slow extracted beams to the north experimental area. Rapid switching between LHC filling and other modes of operation is needed to maximise the efficiency for physics whilst guaranteeing equipment safety. The SPS control system must provide the tools for multicycling in terms of settings generation and maintenance, cycle timing, cycle management, interlock handling, hardware status and beam measurements.

12.2 BEAM PARAMETERS

The different beams required by the LHC cover a wide range of bunch and total beam intensities. In all cases the SPS will have to deliver beams to the LHC with the nominal longitudinal characteristics and the specified transverse emittances. In the case of the pilot beam the tolerance on the transverse emittance is looser, but the intermediate beam should be a good approximation to the nominal beam. The main parameters of the nominal and pilot LHC beams are listed in Tabs. 12.1 and 12.2, respectively. Realistic values of the SPS transmission efficiency have been taken into account based on the experience with the present machine set-up [5,8].

Table 12.1: Nominal LHC beam parameters

	Injection	**Extraction**
Proton momentum [GeV/c]	26	450
Number of bunches/PS batch	72	72
Number of PS batches/SPS batch	2-4	2-4
Number of particles per bunch [10^{11}]	1.3	1.15
Circulating beam current [A]	0.13-0.26	0.12-0.23
Bunch spacing [ns]	24.97	24.95
Bunch train spacing	224.7	224.6
Transverse normalised emittance (H/V) [μm.rad]	3.0/3.0	3.5/3.5
Longitudinal emittance [eV.s]	0.35	<0.8
Rms. bunch length [cm]	30	<15
Rms. energy spread [10^{-4}]	10.7	<2.8

Table 12.2: Pilot beam parameters

	Injection	**Extraction**
Proton momentum [GeV/c]	26	450
Number of bunches/PS batch	1	1
Number of PS batches/SPS batch	1	1
Number of particles per bunch [10^{11}]	0.055	0.05
Circulating beam current [A]	3.9×10^{-5}	3.5×10^{-5}
Bunch spacing [ns]	-	-
Bunch train spacing	-	-
Transverse normalised emittance (H/V) [μm rad]	0.9-3.0/0.9-3.0	1.0-3.5/1.0-3.5
Longitudinal emittance [eV s]	0.35	<0.8
Rms. bunch length [cm]	30	<15
Rms. energy spread [10^{-4}]	10.7	<2.8

Operation with the 25 ns beam will certainly start with bunch populations lower than the nominal one and the requested intensity will increase with the understanding of the machine and experiments. As the bunch population increases the brightness of the beam should be a constant to a rough approximation. However, experience shows that this is unrealistic at low intensities where additive sources of blow-up like injection errors and dispersion mismatch become the dominant source of emittance growth (see Chap. 15).

Beams with 75 ns spacing will be required during the early phases of LHC operation in order to minimise the problems associated with electron multipacting and keep the beam power in the LHC down. The basic parameters for this beam are listed in Tab. 12.3. In this table the baseline filling scheme is given [2,8]. This assumes the same PS batch spacing as for the 25 ns beam and provides some margin for the LHC injection and beam dump kicker without any additional margin for the SPS injection kicker. An alternative filling scheme with increased PS batch spacing (from 224.7 to 274.6 ns) in the SPS could provide some margin for the rise-time of the SPS injection kicker, while only partially reducing the corresponding margin for the LHC kickers.

Table 12.3: Nominal parameters for the 75 ns LHC beam.

	Injection	**Extraction**
Proton momentum [GeV/c]	26	450
Number of bunches/PS batch	24	24
Number of PS batches/SPS batch	2-4	2-4
Number of particles per bunch [10^{11}]	1.3	1.15
Circulating beam current [A]	0.043-0.087	0.038-0.077
Bunch spacing [ns]	74.90	74.85
PS batch spacing	224.7	224.6
Transverse normalised emittance (H/V) [μm rad]	3.0/3.0	3.5/3.5
Longitudinal emittance [eV.s]	0.35	<0.8
Rms. bunch length [cm]	30	<15
Rms. energy spread [10^{-4}]	10.7	<2.8

One of the phases of the LHC commissioning will be the production of collisions with no crossing angle at the interaction points. This implies a large bunch spacing to avoid parasitic beam-beam encounters. The baseline filling scheme fulfilling these requirements consists of injecting 43 bunches into each ring of the LHC [2,3]. The corresponding filling scheme in the SPS, together with the requested beam parameters are listed in Tab. 12.4. This scheme will require the acceleration of a single bunch per PS cycle. The displacement of some bunches by 75ns with respect to their nominal position in the LHC might be needed to allow collisions in the LHCb experiment (values in parenthesis in Tab. 12.4).

Table 12.4: The '43-bunch' beam in the SPS.

	Injection	**Extraction**
Proton momentum [GeV/c]	26	450
Number of bunches/PS batch	1	1
Number of PS batches/SPS batch	2-4	2-4
Number of particles per bunch [10^{11}]	1.2	1.15
Circulating beam current [A]	1.66-3.32 × 10^{-3}	1.6-3.2 × 10^{-3}
Bunch spacing [ns]	2022.57 (2097.48)	2020.95 (2095.8)
PS batch spacing	2022.57 (2097.48)	2020.95 (2095.8)
Transverse normalised emittance (H/V) [μm rad]	3.0/3.0	3.5/3.5
Longitudinal emittance [eV.s]	0.35	<0.8
Rms. bunch length [cm]	30	<15
Rms. energy spread [10^{-4}]	10.7	<2.8

An additional filling scheme with 156 bunches with 525 ns spacing has been conceived for the TOTEM experiment. This scheme will also be useful for commissioning and early operation [2,3]. The bunch spacing is still sufficiently large to allow operation of the LHC with zero crossing angles. This will require the acceleration of 4 equidistant bunches per PS cycle. The main parameters for this beam in the SPS are listed in Tab. 12.5. Some of the PS batches might be rotated by 75 ns in order to allow for collisions in the LHCb experiment (values in parenthesis in the Tab. 12.5).

Table 12.5: The 156-bunch beam for TOTEM Operation

	Injection	**Extraction**
Proton momentum [GeV/c]	26	450
Number of bunches/PS batch	4	4
Number of PS batches/SPS batch	2-4	2-4
Number of particles per bunch [10^{11}]	0.33	0.3
Circulating beam current [A]	1.83-3.67 × 10^{-3}	1.67-3.33 × 10^{-3}
Bunch spacing [ns]	524.37	523.95
PS batch spacing	524.37 (599.28)	523.95 (598.8)
Transverse normalised emittance (H/V) [µm rad]	0.8/0.8	0.9/0.9
Longitudinal emittance [eV s]	0.35	<0.8
Rms. bunch length [cm]	30	<15
Rms. energy spread [10^{-4}]	10.7	<2.8

Table 12.6 summarises the parameters of the ultimate LHC beam in the SPS. The ultimate beam has a 25ns structure, just like the nominal beam. However, the bunch intensity is increased while keeping the emittance constant until the point at which the assumed beam-beam limit is reached.

Table 12.6: Ultimate LHC beam parameters

	Injection	**Extraction**
Proton momentum [GeV/c]	26	450
Number of bunches/PS batch	72	72
Number of PS batches/SPS batch	2-4	2-4
Number of particles per bunch [10^{11}]	1.9	1.7
Circulating beam current [A]	0.19-0.39	0.17-0.34
Bunch spacing [ns]	24.97	24.95
PS batch spacing	224.7	224.6
Transverse normalised emittance (H/V) [µm.rad]	3.0/3.0	3.5/3.5
Longitudinal emittance [eV.s]	0.35	<0.8
Rms. bunch length [cm]	30	<15
Rms. energy spread [10^{-4}]	10.7	<2.8

REFERENCES

[1] P. Collier, ed., '*The SPS as LHC Injector for LHC – Conceptual Design*', CERN-SL-97-07-DI.

[2] P. Collier, '*Baseline Proton Filling Schemes*', Proceedings of the LHC Project Workshop – CHAMONIX XIII – Chamonix, January 19-23, 2004, J. Poole ed., CERN-AB-2004-014 ADM, p. 30-33.

[3] R. Bailey, P. Collier, '*Standard Filling Schemes for Various LHC Operation Modes*', LHC-Project Note 323, LHC-OP-ES-0003, EDMS No. 489439, 2004.

[4] M. Benedikt, *'LHC Operational Beam Definitions'*, LHC-OP-ES-0002, EDMS No. 487892, 2004.

[5] G. Arduini, '*LHC Beam in the SPS: Where do We Stand?*', Proceedings of the LHC Project Workshop – CHAMONIX XIII – Chamonix, January 19-23, 2004, J. Poole ed., CERN-AB-2004-014-ADM, p. 34-43.

[6] J. Uythoven, '*TT40 Experience and TI8 Beam Tests*', Proceedings of the LHC Project Workshop – CHAMONIX XIII – Chamonix, January 19-23, 2004, J. Poole ed., CERN-AB-2004-014-ADM, p. 77-80.

[7] G. Arduini, A. Verdier*, 'Poor Mans Pilot and TOTEM bunches'*, AB-Note-2003-017 MD.

[8] G. Arduini, J.-P. Delahaye, '*Outstanding Issues in the Injector Complex – Summary'*, Proceedings of the LHC Project Workshop – CHAMONIX XIII – Chamonix, January 19-23, 2004, J. Poole ed., CERN-AB-2004-014-ADM, p. 1-8.

[9] S. Baird, '*Routine Operation of the LHC'*, Proceedings of the Workshop on LHC Performance – CHAMONIX XII – Chamonix, March 3-8, 2003, J. Poole, S. Dubourg, M. Truchet, eds., CERN-AB-2003-008 ADM, p. 282-284.