CHAPTER 2

BEAM PARAMETERS AND DEFINITIONS

2.1 LHC BEAM PARAMETERS RELEVANT FOR THE PEAK LUMINOSITY

This Chapter provides a summary of the main parameters for the nominal proton beam operation, a glossary and a list of definitions that are used throughout the chapters of the LHC design report. The equipment names and the circuit counts are summarized in dedicated tables at the end of this Chapter. A derivation and detailed explanation of the parameters can be found in Chapters 3 to 6 of Volume I of the design report. A discussion of the variation of the beam parameters from these nominal values in different operation scenarios is given in Chapter 20.

Table 2.1: LHC beam parameters relevant for the peak luminosity

		Injection	**Collision**
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5[a]
Transverse normalized emittance	[μm rad]	3.5[b]	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[cm^{-2}sec^{-1}]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[cm^{-2}sec^{-1}]	-	3.56×10^{30}

[a] The base line machine operation assumes that the longitudinal emittance is deliberately blown up at the middle of the ramp in order to reduce the intra beam scattering growth rates.

[b] The emittance at injection energy refers to the emittance delivered to the LHC by the SPS without any increase due to injection errors and optics mis-match. The RMS beam sizes at injection assume the nominal emittance value quoted for top energy (including emittance blowup due to injection oscillations and mismatch).

[c] Dimensions are given for Gaussian distributions. The real beam will not follow a Gaussian distribution but more realistic distributions do not allow analytic estimates for the IBS growth rates.

[d] The RMS beam sizes in IP1 and IP5 assume a β-function of 0.55 m.

[e] The RMS beam sizes in IP2 and IP8 assume a β-function of 10 m.

[f] The geometric luminosity reduction factor depends on the total crossing angle at the IP (see Sec. 3.1.1). The quoted number in Table 2.1 assumes a total crossing angle of 285 μrad as it is used in IR1 and IR5.

2.2 LHC BEAM PARAMETERS RELEVANT FOR THE LUMINOSITY LIFETIME

Table 2.2: LHC beam parameters relevant for the luminosity lifetime

		Injection	**Collision**
Interaction data			
Inelastic cross section	[mb]	60.0	
Total cross section	[mb]	100.0	
Events per bunch crossing		-	19.02
Beam current lifetime (due to beam-beam)	[h]	-	44.86
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	$[10^{-4}]$	3.06	1.129
RMS bunch length	[cm]	11.24	7.55
Longitudinal emittance growth time	[hours]	30[a]	61
Horizontal emittance growth time	[hours]	38[a]	80
Total beam and luminosity lifetimes[b]			
Luminosity lifetime (due to beam-beam)	[hours]	-	29.1
Beam lifetime (due to rest-gas scattering)[c]	[hours]	100	100
Beam current lifetime (beam-beam, rest-gas)	[hours]	-	18.4
Luminosity lifetime (beam-beam, rest-gas, IBS)	[hours]	-	14.9
Synchrotron Radiation			
Instantaneous power loss per proton	[W]	3.15×10^{-16}	1.84×10^{-11}
Power loss per m in main bends	$[\mathrm{Wm}^{-1}]$	0.0	0.206
Synchrotron radiation power per ring	[W]	6.15×10^{-2}	3.6×10^{3}
Energy loss per turn	[eV]	1.15×10^{-1}	6.71×10^{3}
Critical photon energy	[eV]	0.01	44.14
Longitudinal emittance damping time	[hours]	48489.1	13
Transverse emittance damping time	[hours]	48489.1	26

[a] IBS growth times are given without the 200 MHz RF system.

[b] lifetime estimates including the effect of proton losses due to luminosity production, IBS and vacuum rest gas scattering. It is assumed that the effect of the non-linear beam-beam interaction and RF noise are compensated by the synchrotron radiation damping.

[c] The desorption lifetime should be slightly better at injection energy because the cross sections for rest gas scattering decrease with energy. For more information see Vol II, Chap. 28 and [1].

2.3 LHC MACHINE PARAMETERS RELEVANT FOR THE PEAK LUMINOSITY

Table 2.3: LHC machine parameter relevant for the peak luminosity

		Injection	**Collision**
Interaction Data			
Number of collision points		4	
Half crossing angle for ATLAS and CMS (IP1/IP5)	[μrad]	± 160	± 142.5
Half parallel separation at IP for ATLAS and CMS (IP1/IP5)	[mm]	± 2.5	0.0
Half crossing angle at IP [a] for ALICE (IP2)	[μrad]	± 240	± 150
Half parallel separation at IP for ALICE	[mm]	± 2.0	± 0.178 (5 σ total separation)
Half crossing angle at IP [a] for LHCb (IP8)	[μrad]	± 300	± 200
Half parallel separation at IP for LHCb (IP8)	[mm]	± 2.0	0.0
Plane of crossing in IP1		vertical	
Plane of crossing in IP2		vertical	
Plane of crossing in IP5		horizontal	
Plane of crossing in IP8		horizontal	
β at IP1 and IP5	[m]	18	0.55
β at IP2	[m]	10	0.5 for Pb / 10 for p
β at IP8	[m]	10	1.0 $\leftrightarrow$ 50

[a] The crossing angle in IP2 and IP8 is the sum of an external crossing angle bump and an 'internal' spectrometer compensation bump and depend on the spectrometer polarity. The values quoted above represent the maximum values from the different possible configurations. The external bump extends over the triplet and D1 and D2 magnets. The internal spectrometer compensation bump extends only over the long drift space between the two triplet assemblies left and right from the IP.

2.4 LHC STORAGE RING PARAMETERS

Table 2.4: LHC storage ring parameters

		Injection	Collision
Geometry			
Ring circumference	[m]	26658.883	
Ring separation in arcs	[mm]	194	
Bare inner vacuum screen height in arcs	[mm]	46.5	
Effective vacuum screen height (incl. tol.)	[mm]	44.04	
Bare inner vacuum screen width in arcs	[mm]	36.9	
Effective vacuum screen width (incl. tol.)	[mm]	34.28	
Main Magnet			
Number of main bends		1232	
Length of main bends	[m]	14.3	
Field of main bends	[T]	0.535	8.33
Bending radius	[m]	2803.95	
Lattice			
Maximum dispersion in arc	[m]	2.018 (h) / 0.0 (v)	
Minimum horizontal dispersion in arc	[m]	0.951	
Maximum β in arc	[m]	177 (h)/ 180 (v)	
Minimum β in arc	[m]	30 (h) / 30 (v)	
Horizontal tune		64.28	64.31
Vertical tune		59.31	59.32
Momentum compaction	10^{-4}	3.225	
Slip factor η	10^{-4}	3.182	3.225
Gamma transition γ_{tr}		55.68	
RF System			
Revolution frequency	[kHz]	11.245	
RF frequency [a]	[MHz]	400.8	
Harmonic number		35640	
Total RF voltage	[MV]	8	16
Synchrotron frequency	[Hz]	61.8	21.4
Bucket area	[eVs]	1.46	8.7
Bucket half height ($\Delta E/E$)	[10^{-3}]	1	0.36

[a] A second optional low harmonic 200 MHz RF system can be installed after the initial running period.

2.5 GLOSSARY AND DEFINITIONS

2.5.1 Glossary

β^*: Optical β-function at the IP.

η: Machine slip factor.

η_D: Normalized dispersion: $\eta_D = D/\sqrt{\beta}$, where D is the machine dispersion.

γ: Optic gamma function: $\gamma(s) = (1 + \alpha^2(s))/\beta(s)$ where $\beta(s)$ is the optical betatron function along the machine and $\alpha(s) = -\frac{1}{2}\frac{d\beta}{ds}$.

γ_r: The relativistic gamma factor.

abort gap: Area without any bunches in the bunch train that fits the time required for building up the nominal field of the LHC dump kicker.

arc: The part of the ring occupied by regular half-cells. Each arc contains 46 half cells. The arc does not contain the dispersion suppressor.

arc cell: It consists of two arc half-cells and presents the basic period of the optic functions.

arc half-cell: Periodic part of the LHC arc lattice. Each half-cell consists of a string of three twin aperture main dipole magnets and one short straight section. The cryo magnets of all arc half-cells follow the same orientation with the dipole lead end pointing upstream of Beam 1 (downstream of Beam 2).

batch:

PS batch: Train of 72 bunches injected into the SPS in one PS to SPS transfer.

SPS batch: Train of 4×72 or 3×72 bunches injected into the LHC in one SPS to LHC transfer.

Beam 1 and Beam 2: Beam 1 and Beam 2 refer to the two LHC beams. Beam 1 circulates clockwise in Ring 1 and Beam 2 circulates counter clockwise in Ring 2. If colours are used for beams, Beam 1 is marked blue and Beam 2 red.

beam cleaning: Removal of the large amplitude (larger than 6 sigma) particles from the beam halo. The LHC has two beam cleaning insertions: one dedicated to the removal of particles with large transverse oscillation amplitudes (IR7) and one dedicated to the removal of particles with large longitudinal oscillation amplitudes (IR3). These insertions are also referred to as the betatron and momentum cleaning or collimation insertions.

beam crossing angle: Dedicated orbit bumps separate the two LHC beams at the parasitic beam crossing points of the common beam pipe of Ring 1 and Ring 2. The crossing angle bumps do not separate the beams at the IP but only at the parasitic crossing points. These orbit bumps generate an angle between the orbit of Beam 1 and Beam 2 at the IP. The full angle between the orbit of Beam 1 and Beam 2 is called the crossing angle. In IR2 and IR8 the crossing angle orbit bumps consist of two separate contributions. One external bump generated for the beam separation at the parasitic beam crossing points and one internal bump generated by the experimental spectrometer and its compensator magnets. The LHC baseline has vertical crossing angles in IR1 and IR2 and horizontal crossing angles in IR5 and IR8.

beam screen: Perforated tube inserted into the cold bore of the superconducting magnets in order to protect the cold bore from synchrotron radiation and ion bombardment.

beam types:

- **pilot beam:** Consists of a single bunch with 0.5×10^{10} protons. It corresponds to the maximum beam current that can be lost without inducing a magnet quench.
- **commissioning beam:** Beam tailored for a maximum luminosity with reduced total beam power (i.e. increased operational margins related to beam losses and magnet quenches) and possibly smaller beam sizes (i.e. increased mechanical acceptance in terms or the transverse beam size and larger tolerances for orbit and β-beat).
- **intermediate beam:** Beam tailored for a high accuracy of the beam measurements with reduced total beam power (i.e. increased operational margins related to beam losses and magnet quenches).
- **nominal beam:** Beam required to reach the design luminosity of $L = 10^{34}$ cm^{-2}s^{-1} with $\beta^* = 0.55$ m ($\rightarrow$ normalized emittance $\epsilon_n = 3.75$ μm; $N_{\rm b} = 1.15 \times 10^{11}; n_{\rm b} = 2808$).
- **ultimate beam:** Beam consisting of the nominal number of bunches with nominal emittances (normalized emittance of 3.75μm) and ultimate bunch intensities ($I = 0.86$A $\rightarrow N_{\rm b} = 1.7 \times 10^{11}$). Assuming the nominal value of $\beta^* = 0.55$ m and 2808 bunches, the ultimate beam can generate a peak luminosity of $L = 2.3 \times\ 10^{34}$ cm^{-2}s^{-1} in the two high luminosity experiments.

BPM: Beam Position Monitor.

bunch: Collection of particles captured within one RF bucket.

bus bar: Main cable that carries the current for powering the magnets outside the magnet coil.

channel: The two apertures of the double bore magnets form two channels of the LHC. Each arc has one outer and one inner channel.

cold mass: The cold mass refers to the part of a magnet that needs to be cooled by the cryogenic system, i.e. the assembly of magnet coils, collars, iron yoke and helium vessel.

crossings: The two machine channels cross at the experimental insertions, i.e. at IP1, IP2, IP5 and IP8.

cryo magnet: Complete magnet system integrated into one cryostat, i.e. main magnet coils, collars and cryostat, correction magnets and powering circuits.

DA: See dynamic aperture.

damper: Transverse or longitudinal feedback system used to damp injection oscillations and / or multi-bunch instabilities of a beam.

decay and snap back: Persistent current decay is a change in the persistent current contribution to the total magnetic field in superconducting magnets powered at constant current (e.g. at injection). This effect varies among magnets and is a function of the powering history (i.e. previous current cycles). When the magnet current is changed (e.g. during the acceleration ramp) the magnetic field comes back to the original value before the decay. This effect is called snap back and occurs for the LHC main dipole magnets within the first 50 A change of the LHC ramp.

dispersion suppressor: The dispersion suppressor refers to the transition between the LHC arcs and insertions. The dispersion suppressor aims at a reduction of the machine dispersion inside the insertions. Each LHC arc has one dispersion suppressor on each end. The length of the dispersion suppressors is determined by the tunnel geometry. Each LHC dispersion suppressor consists of four individually powered quadrupole magnets which are separated by two dipole magnets. In the following this arrangement of four quadrupole and eight dipole magnets is referred to as two missing dipole cells. For the machine lattice these two missing dipole cells are referred to as one dispersion suppressor. However, reducing the dispersion at the IPs to zero requires a special powering of two more quadrupole magnets on each side of the arc. In terms of the machine optics the dispersion suppressor refers therefore to the two missing dipole cells plus one additional arc cell.

dog leg magnets: Special dipole magnet used for increasing the separation of the two machine channels from standard arc separation. The dogleg magnets are installed in the cleaning insertions IR3 and IR7 and the RF insertion IR4.

dynamic aperture: Maximum initial oscillation amplitude that guarantees stable particle motion over a given number of turns. The dynamic aperture is normally expressed in multiples of the RMS beam size (σ) and together with the associated number of turns.

eddy currents: Eddy currents are screening currents that tend to shield the interior of a conductor or a superconducting cable from external magnetic field changes. In the case of a strand the eddy currents flow along the superconducting filaments in the strand (without loss) and close across the resistive matrix of the strand (copper for the LHC). In the case of a cable the eddy currents flow along the strands (without loss) and close resistively at the contact points among strands in the cable. Eddy currents are also referred to as coupling currents.

experimental insertion region: Insertion region that hosts one of the four LHC experiments.

filament: Superconducting filaments are fine wires of bulk superconducting material with typical dimension in the range of few microns. The superconducting filaments are embedded in the resistive matrix in a strand.

insertion region (IR): Machine region between the dispersion suppressors of two neighbouring arcs. The insertion region consists of two matching sections and, in the case of the experimental insertions, of two triplet assemblies and the separation / recombination dipoles.

interaction point (IP): Middle of the insertion region (except for IP8). In the insertions where the two LHC beams cross over the IP indicates the point where the two LHC beams can intersect. In IR8 the experimental detector is shifted by 3/2 RF wavelengths and the IP refers to the point where the two LHC beams can intersect and it does not coincide with the geometric centre of the insertion.

ions: The LHC will have collisions between heavy ions, $^{208}\mathrm{Pb}^{82+}$ (fully stripped) during the first years (208 is the number of nucleons, 82 the number of protons of this particular nucleus).

Ions, early scheme: Approximately 60 bunches per beam, with 7×10^{7} Pb ions each, are colliding to yield initial luminosity of $L = 5.0 \times 10^{25}$ cm^{-2}sec^{-1} with ($\beta^{*} = 0.5$ m).

ions, nominal scheme: Approximately 600 bunches per beam, with 7×10^{7} Pb ions each, are colliding at 2.76 TeV/u to yield initial luminosity of $L = 1.0 \times 10^{27}$ cm^{-2}sec^{-1} with ($\beta^{*} = 0.5$ m).

lattice correction magnets: Correction magnets that are installed inside the Short Straight Section assembly.

lattice version: The lattice version refers to a certain hardware installation in the tunnel. It is clearly separated from the optics version and one lattice version can have more than one optics version.

left and right: See the definition under 'right and left'.

long range interactions: Interaction between the two LHC beams in the common part of the Ring 1 and Ring 2 where the two beams are separated by the crossing angle orbit bumps.

Long Straight Section (LSS): the quasi-straight sections between the upstream and downstream dispersion suppressor of an insertion, including the separation / recombination dipole magnets.

machine cycle: The machine cycle refers to one complete operation cycle of a machine, i.e. injection, ramp up, possible collision flat top, ejection and ramp down. The minimum cycle time refers to the minimum time required for a complete machine cycle.

magnet quench: Loss of the superconducting state in the coils of a superconducting magnet.

main lattice magnets: Main magnets of the LHC arcs, i.e. the arc dipole and quadrupole magnets.

matching section: Arrangement of quadrupole magnets located between the dispersion suppressor and the triplet magnets (or the IP for those insertions without triplet magnets). Each insertion has two matching sections: one upstream and one downstream from the IP.

n_1**:** The effective mechanical aperture n_1 defines the maximum primary collimator opening in terms of the rms beam size that still guarantees a protection of the machine aperture against losses from the secondary beam halo. It depends on the magnet aperture and geometry and the local optics perturbations.

N_b**:** Number of particles per bunch.

n_b**:** Number of bunches per beam.

nominal bunch: Bunch parameters required to reach the design luminosity of $L = 10^{34}\mathrm{cm}^{-2}s^{-1}$ with $\beta^* = 0.55$ m. The nominal bunch intensity is $N_\mathrm{b} = 1.15 \times 10^{11}$ protons.

nominal powering: Hardware powering required to reach the design beam energy of 7 TeV.

octant: An octant starts in the centre of an arc and goes to the centre of the next downstream arc. An octant consists of an upstream and a downstream half-octant. A half-octant and a half-sector cover the same part of the machine even though they may not have the same number.

optical configuration: An optical configuration refers to a certain powering of the LHC magnets. Each optics version has several optical configurations corresponding to the different operation modes of the LHC. For example, each optics version has different optical configurations for injection and luminosity operation and for the luminosity operation the optics features different optical configurations corresponding to different β^* values in the four experimental insertions of the LHC.

optics version: The optics version refers to a consistent set of optical configurations. There can be several different optics versions for one lattice version.

pacman bunches: Bunches that do not experience the same number of long-range beam-beam interactions left and right from the IP.

parallel separation: Dedicated orbit bumps separate the two LHC beams at the IP during injection, ramp and the optics squeeze. The total beam separation at the IP is called the parallel separation. The LHC baseline has horizontal parallel separations in IR1 and IR2 and vertical separations in IR5 and IR8.

parasitic crossing points: Positions in the common part of Ring 1 and Ring 2 where the two beams can experience long range interactions.

persistent currents: Persistent currents are eddy currents with (ideally) infinitely long time constants that flow in the bulk of the superconducting filaments of a strand and tend to shield the interior of the filament from the external magnetic field changes. These screening currents close inside the superconducting filament, with zero resistance (in steady state). Hence, for practical purposes, they do not decay in time and for this reason they are referred to as ’persistent’.

physics run: Machine operation at top energy with luminosity optics configuration and beam collisions.

pilot bunch: Bunch intensity that assures no magnet quench at injection energy for an abrupt loss of a single bunch but is still large enough provide BPM readings. The pilot bunch intensity of the LHC corresponds to 0.5×10^{10} protons in one bunch.

ramp: Change of the magnet current during the beam acceleration when the magnets are ’ramped up’ and after the end of a physics store the magnets are ’ramped down’.

resistive matrix: One of the two main constituents of the strand. The resistive matrix embeds the filaments in the strand and provides a low resistance current shunt in case of quench (transition of the superconducting material to the normal state).

RF bucket: The RF system provides longitudinal focusing which constrains the particle motion in the longitudinal phase space to a confined region called the RF bucket.

right and left: Describes the position in the tunnel relative to an observer inside the ring looking out (same definition as for LEP).

Ring 1 and Ring 2: There are two rings in the LHC, one ring per beam. Ring 1 corresponds to Beam 1 which circulates clockwise and Ring 2 corresponds to Beam 2 which circulates counter-clockwise in the LHC.

satellite bunch: Collection of particles inside RF buckets that do not correspond to nominal bunch positions. The nominal bunch spacing for the LHC is 25 ns while the separation of RF buckets is 2.5 ns. In other words, there are 9 RF buckets between two nominal LHC bunch positions that should be empty.

sector: The part of a ring between two successive insertion points (IP) is called a sector. Sector 1-2 is situated between IP1 and IP2.

separation / recombination magnets: Special dipole magnets left and right from the triplet magnets that generate the beam crossings in the experimental insertions.

Short Straight Section (SSS): Assembly of the arc quadrupole and the lattice corrector magnets. Each SSS consists of one quadrupole magnet, one Beam Position Monitor (BPM), one orbit corrector dipole (horizontal deflection for focusing and vertical deflection for defocusing quadrupoles), one lattice correction element (i.e. trim or skew quadrupole elements or octupole magnets) and one lattice sextupole or skew sextupole magnet.

SPecial Straight Section (SPSS): Quadrupole assemblies of the insertion regions. The SPSS features no lattice corrector and sextupole magnets and has only orbit correction dipole magnets and BPMs.

spool piece correction magnets: Correction magnets directly attached to the main dipole magnets. The spool piece correction magnets are included in the dipole cryostat assembly.

strand: A superconducting strand is a composite wire containing several thousands of superconducting filaments dispersed in a matrix with suitably small electrical resistivity properties. The LHC strands have NbTi as superconducting material and copper as resistive matrix.

superconducting cable: Superconducting cables are formed from several superconducting strands in parallel, geometrically arranged in the cabling process to achieve well controlled cable geometry and dimensions, while limiting the strand deformation in the process. Cabling several strands in parallel results in an increase of the current carrying capability and a decrease of the inductance of the magnet, easing protection. The LHC cables are flat, keystoned cables of the so-called Rutherford type.

super pacman bunches: Bunches that do not collide head-on with a bunch from the other beam in one of experimental IPs.

TAN: Target Absorber Neutral: absorber for the neutral particles leaving the IP. It is located just in front of the D1 separation / recombination dipole magnet on the side facing the IP.

TAS: Target Absorber Secondaries: absorber for particles leaving the IP at large angles. It is located just in front of the Q1 triplet quadrupole magnet on the side facing the IP.

tune: Number of particle trajectory oscillations during one revolution in the storage ring (transverse and longitudinal).

triplet: Assembly of three quadrupole magnets used for a reduction of the optical β-functions at the IPs. The LHC triplet assembly consists in fact of four quadrupole magnets but the central two quadrupole magnets form one functional entity. The LHC has triplet assemblies in IR1, IR2, IR5 and IR8.

ultimate bunch intensity: Bunch intensity corresponding to the expected maximum acceptable beam-beam tune shift with two operating experimental insertions. Assuming the nominal emittance (normalized emittance of 3.75μm) the ultimate bunch intensity corresponds to 1.7×10^{11} protons per bunch.

ultimate powering: Hardware powering required to reach the ultimate beam energy of 7.54 TeV, corresponding to a dipole field of 9 T.

upstream and downstream: Always related to the direction of one of the two beams. If no beam is specified Beam 1 is taken as the default. This implies that stating a position as being 'upstream' without indicating any beam is equivalent to stating that the position is to the left.

2.5.2 Definitions

beam half-life: Time during beam collision after which half the beam intensity is lost.

luminosity half-life: Time during beam collision after which the luminosity is halved. The luminosity half-life is generally smaller than the beam half-life.

bunch duration: The bunch duration is defined as

$$\sigma_t = \frac{\sigma_s}{v}, \tag{2.1}$$

where σ_s is the bunch length and v is the speed of the particles in the storage rings.

bunch length: The bunch length is defined as the 'RMS' value of the longitudinal particle distribution in one RF bucket. The bunch length is denoted as

$$\sigma_s. \tag{2.2}$$

damping times: Time after which an oscillation amplitude has been reduced by a factor $1/e$. If no explicit explanation of the types of damping times is given the damping times refer to the amplitude damping times.

- **longitudinal emittance damping time:** Half of the longitudinal amplitude damping time for a Gaussian approximation of the bunch distribution.
- **transverse emittance damping time:** Half of the transverse amplitude damping time for a Gaussian approximation of the transverse bunch distribution.

synchrotron radiation damping times: If no explicit explanation of the types of damping times is given, the damping times refer to the amplitude damping times.

- **longitudinal amplitude damping time:** The ratio of the average rate of energy loss (energy lost over one turn divided by the revolution time) and the nominal particle energy.
- **transverse amplitude damping time:** Time after which the transverse oscillation amplitude has been reduced by a factor $1/e$ due to the emission of synchrotron radiation. For a proton beam it is just twice the longitudinal amplitude damping time due to the emission of synchrotron radiation.

energy spread: The energy spread is defined as the 'RMS' value of the relative energy deviations from the nominal beam energy in a particle distribution. The energy spread is denoted as

$$\sigma_{\delta E/E0}. \tag{2.3}$$

longitudinal emittance: The longitudinal emittance is defined as:

$$\epsilon_s = 4\pi\sigma_t\sigma_{\delta E/E0}E_0, \quad (2.4)$$

where σ_t is the bunch duration in seconds, $\sigma_{\delta E/E0}$ the relative energy spread.

transverse beam size: The transverse beam size is defined as the 'RMS' value of the transverse particle distribution.

transverse emittance: The transverse emittance is defined through the invariance of the area enclosed by the single particle phase space ellipse. The single particle invariant under the transformation through the storage ring is given by

$$A = \gamma x^2 + 2\alpha x x^{'} + \beta x^{'2}, \quad (2.5)$$

where α, β and γ are the optical functions. The area enclosed by the single particle phase space ellipse is given by

$$\text{area of ellipse} = \pi A \quad (2.6)$$

For an ensemble of particles the emittance is defined as the average of all single particle invariants (areas enclosed by the single particle phase space ellipsoids divided by π).

The transverse betatron beam size in the storage ring can be written in terms of the beam emittance as

$$\sigma_{x,y}(s) = \sqrt{\beta_{x,y}(s)\epsilon_{x,y}}, \quad (2.7)$$

where $\beta_{x,y}(s)$ is the optical β-function along the storage ring.

The transverse emittance is given by the following expression:

$$\epsilon_z = \sqrt{\langle z^2\rangle\langle z'^2\rangle - \langle zz'\rangle^2}; z = x, y, \quad (2.8)$$

where it is assumed that the particle coordinates are taken at a place with vanishing dispersion and where $\langle\ \rangle$ defines the average value of the coordinates over the distribution. z and $z^{'}$ are the canonical transverse coordinates ($z = x, y$).

normalized transverse emittance: The beam emittance decreases with increasing beam energy during acceleration and a convenient quantity for the operation of a hadron storage rings (and linear accelerators) is the 'normalized emittance' defined as

$$\epsilon_n = \epsilon\gamma_r\beta_r, \quad (2.9)$$

where γ_r and β_r are the relativistic gamma and beta factors:

$$\beta_r = \frac{v}{c} \quad (2.10)$$

$$\gamma_r = \frac{1}{\sqrt{1-\beta_r^2}} \quad (2.11)$$

(v is the particle velocity and c the speed of light in vacuum).

The nominal normalized transverse emittance for the LHC is

$$\epsilon_n = 3.75\ \mu\text{m}. \quad (2.12)$$

2.6 LHC SYSTEM PREFIXES

Table 2.5: LHC system prefixes

LHC Systems Prefix Definitions [a]	
Letter	System description
A	Acceleration, RF and dampers
B	Beam instrumentation
C	Communication and controls
D	Electrical distribution
E	Electricity
F	Fluids (Demineralized water excluded)
G	Geodesy and geometry
H	Mechanics, supports and handling
I	Injection and transfer lines
J	Infrastructure
K	Civil engineering
L	Layouts
M	Magnetic elements
N	Particle sources
O	
P	Personnel safety
Q	Cryogenics
R	Power converters
S	General safety
T	Targets, dump and collimators
U	Ventilation and air conditioning
V	Vacuum
W	Demineralized water
X	Experiments
Y	Access systems
Z	Electrostatic systems

[a] No change has been introduced in system type identification. The first letter identifies a system as defined in the document 'Naming conventions for the LHC components', edited by P. Faugeras, AC.DI/FA Note 92–04.

2.7 LHC MAGNET SYSTEM EQUIPMENT NAMES AND CIRCUIT COUNT

Table 2.6: LHC magnet equipment names and circuit count

Magnet Type	Order	Description	Number of Magnets
MB	1	Main Dipole Coldmass	1232
MBAW	1	Alice Spectrometer (Muon Dipole)	1
MBLW	1	LHC-b Spectrometer	1
MBRB	1	Twin Aperture Separation Dipole (194 mm) D4	2
MBRC	1	Twin Aperture Separation Dipole (188 mm) D2	8
MBRS	1	Single Aperture Separation Dipole D3	4
MBW	1	Twin Aperture Warm Dipole Module D3 and D4 in IR3 and IR7	20
MBWMD	1	Single Aperture Warm Dipole Module Compensating Alice Spectrometer	1
MBX	1	Single Aperture Separation Dipole D1	4
MBXW	1	Single Aperture Warm Dipole Module D1 in IR1 and IR5	24
MBXWH	1	Single Aperture Warm Horizontal Dipole Module Compensating LHC-b Spectrometer	1
MBXWS	1	Single Aperture Warm Horizontal Dipole Short Module	2
MBXWT	1	Single aperture warm compensator for ALICE	2
MCBCH	1	Orbit Corrector in MCBCA(B,C,D)	78
MCBCV	1	Orbit Corrector in MCBCA(B,C,D)	78
MCBH	1	Arc Orbit Corrector in MSCBA(B,C,D), Horizontal	376
MCBV	1	Arc Orbit Corrector in MSCBA(B,C,D), Vertical	376
MCBWH	1	Single Aperture Warm Orbit Horizontal Corrector	8
MCBWV	1	Single Aperture Warm Orbit Verticall Corrector	8
MCBXH	1	Horizontal Orbit Corrector in MCBX(A)	24
MCBXV	1	Vertical Orbit Corrector in MCBX(A)	24
MCBYH	1	Orbit Corrector in MCBYA(B)	44
MCBYV	1	Orbit Corrector in MCBYA(B)	44
MCD	5	Decapole Corrector in MCDO, (Spool Piece Corrector)	1232
MCO	4	Octupole Corrector in MCDO, (Spool Piece Corrector)	1232
MCOSX	3	Skew Octupole Spool-Piece Associated to MQSX in MQSXA	8
MCOX	4	Octupole Spool-Piece Associated to MQSXA	8
MCS	3	Sextupole Corrector, (Spool Piece Corrector)	2464
MCSSX	3	Skew Sextupole Spool-Piece Associated to MQSX in MQSXA	8
MCSX	3	Sextupole Spool-Piece Associated to MCBXA	8
MCTX	6	Dodecapole Spool-Piece Associated to MCBXA	8
MKA	1	Tune kicker	2
MKD	1	Ejection dump kicker	30
MKI	1	Injection kicker	8
MKQ	1	Kicker For Q And Aperture Measurement	2

Table 2.7: LHC magnet equipment names and circuit count continued

Magnet Type	Order	Description	Number of Magnets
MO	4	Octupole Lattice Corrector in Arc Short Straight Section	336
MQ	2	Lattice Quadrupole in the Arc	392
MQM	2	Insertion Region Quadrupole 3.4 m	38
MQMC	2	Insertion Region Quadrupole 2.4m	12
MQML	2	Insertion Region Quadrupole 4.8 m	36
MQS	2	Skew Quadrupole Lattice Corrector in Arc Short Straight Section	64
MQSX	2	Skew Quadrupole Q3	8
MQT	2	Tuning Quadrupole Corrector in Arc Short Straight Section	320
MQTLH	2	(MQTL Half Shell Type)	48
MQTLI	2	(MQTL Inertia Tube Type)	72
MQWA	2	Twin Aperture Warm Quadrupole Module in IR3 and IR7. Asymmetrical FD or DF	40
MQWB	2	Twin Aperture Warm Quadrupole Module in IR3 and IR7. Symmetrical FF or DD	8
MQXA	2	Single Aperture Triplet Quadrupole (Q1, Q3)	16
MQXB	2	Single Aperture Triplet Quadrupole (Q2)	16
MQY	2	Insertion Region Wide Aperture Quadrupole 3.4 m.	24
MS	3	Arc Sextupole Lattice Corrector Associated to MCBH or MCBV in MSCBA, MSCBB, MSCBC and MSCBD	688
MSDA	1	Ejection dump septum, Module A	10
MSDB	1	Ejection dump septum, Module B	10
MSDC	1	Ejection dump septum, Module C	10
MSIA	1	Injection septum, Module A	4
MSIB	1	Injection septum, Module B	6
MSS	2	Arc skew Sextupole Corrector Associated to MCBH in MSCBC and MSCBD	64

Table 2.8: LHC power converter circuit names and count

Type	Number of Circuits
RB	8
RBAWV	1
RBLWH	1
RBWMDV	1
RBXWH	1
RBXWSH	2
RBXWTV	2
RCBCH10	16
RCBCH5	4
RCBCH6	12
RCBCH7	14
RCBCH8	16
RCBCH9	16
RCBCV10	16
RCBCV5	4
RCBCV6	12
RCBCV7	14
RCBCV8	16
RCBCV9	16
RCBH11	16
RCBH12	16
RCBH13	16
RCBH14	16
RCBH15	16
RCBH16	16
RCBH17	16
RCBH18	16
RCBH19	16
RCBH20	16
RCBH21	16
RCBH22	16
RCBH23	16
RCBH24	16
RCBH25	16
RCBH26	16
RCBH27	16
RCBH28	16
RCBH29	16

Table 2.9: LHC power converter circuit names and count (continued)

Type	Number of Circuits
RCBH30	16
RCBH31	16
RCBH32	16
RCBH33	16
RCBH34	8
RCBV11	16
RCBV12	16
RCBV13	16
RCBV14	16
RCBV15	16
RCBV16	16
RCBV17	16
RCBV18	16
RCBV19	16
RCBV20	16
RCBV21	16
RCBV22	16
RCBV23	16
RCBV24	16
RCBV25	16
RCBV26	16
RCBV27	16
RCBV28	16
RCBV29	16
RCBV30	16
RCBV31	16
RCBV32	16
RCBV33	16
RCBV34	8
RCBWH4	4
RCBWH5	4
RCBWV4	4
RCBWV5	4
RCBXH1	8
RCBXH2	8
RCBXH3	8
RCBXV1	8
RCBXV2	8
RCBXV3	8
RCBYH4	10
RCBYH5	8

Table 2.10: LHC power converter circuit names and count (continued)

Type	Number of Circuits
RCBYH6	2
RCBYHS4	16
RCBYHS5	8
RCBYV4	10
RCBYV5	8
RCBYV6	2
RCBYVS4	16
RCBYVS5	8
RCD	16
RCO	16
RCOSX3	8
RCOX3	8
RCS	16
RCSSX3	8
RCSX3	8
RCTX3	8
RD1	6
RD2	8
RD3	2
RD34	2
RD4	2
RMSD	2
ROD	16
ROF	16
RQ10	12
RQ4	12
RQ5	14
RQ6	18
RQ7	10
RQ8	12
RQ9	12
RQD	8
RQF	8
RQS	24
RQSX3	8
RQT12	32
RQT13	32

Table 2.11: LHC power converter circuit names and count (continued)

Type	Number of Circuits
RQT4	4
RQT5	4
RQTD	16
RQTF	16
RQTL10	8
RQTL11	32
RQTL7	8
RQTL8	8
RQTL9	8
RQX	8
RSD1	16
RSD2	16
RSF1	16
RSF2	16
RSS	16

REFERENCES

[1] O. Gröbner, ’Overview of the LHC vacuum system’, VACUUM **60**, pg. 25-34, 2001