Glossary and Definitions

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 $\alpha(s) = -\dfrac{d\beta}{2\,ds}$.

γr:

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 that is injected into the SPS in one PS to SPS transfer.

 SPS batch:

  Train of 4×72 or 3×72 bunches that is 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 colors 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 foresees 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 $\varepsilon_n = 3.75$ μm; $N_b = 1.15 \times 10^{11}$; $n_b = 2808$).
>**ultimate beam:**
>Beam consisting of the nominal number of bunches with nominal emittances (normalized emittance of 3.75μm) and ultimate bunch intensities ($I = 0.86A \rightarrow N_b = 1.7 \times 10^{11}$). 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 4 quadrupole and 8 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.

hourglass effect 'H':
Luminosity loss due to longitudinal modulation of beta function over the length of the bunch for small β*.

insertion region (IR):
Machine region between the dispersion suppressors of two neighboring 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 wave length and

the IP refers to the point where the two LHC beams can intersect and does not coincide with the geometric center of the insertion.

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

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).

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).

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.

luminous region: The 3-dimensional distribution of the collision event vertices.

Luminosity reduction:
> **Geometric luminosity reduction factor due to beam offset 'R':** Reduced beam overlap due to transversal offset of collisions, frequently used for reduction of luminosity (levelling) and VdM scans.
> **Luminosity reduction factor due to crossing angle 'S':** Reduced beam overlap due to tilted bunch shape due to crossing angle.

Total luminosity reduction factor 'F' = R*H*S[1]

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.

machine statistics:

run time: annual time allocated to running with beam [days].
scheduled physics time: annual time allocated to physics (excluding initial beam commissioning, scrubbing, TS, recovery from TS, MDs, special physics) [days].
physics efficieny: time with both beams present and stable beams, versus scheduled physics time [%].
machine availability: time when machine is in a state allowing operations to take beam and run through nominal physics cycle, versus run time [%].
turnaround time: Time between the end of one and the start of the next physics run / data taking by the experiments (delimited by the loss of beam presence/beam dump back to declaration of STABLE_BEAMS) [hours].
recovery time: Time between the end of one and the readiness for injection of new particles of the next (delimited by the loss of beam presence/beam dump and resuming of the normal operational cycle) [hours].

magnet quench:

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

main lattice magnets:

Main magnets of the LHC arcs, i.q. 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.

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[1] Strictly speaking no direct multiplication, but providing a reasonable indication of the different contributions (while dominated by crossing angle contribution).

nominal bunch:

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

nominal powering:

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

octant:

An octant starts in the center of an arc and goes to the center 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 configuration 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 foresees horizontal parallel separations in IR1 and IR2 and vertical separations in IR5 and IR8.

parasitic crossing points:

Positions in the common part of the 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.

pile-up:
>**Event pile-up μ:** Number of visible inelastic proton-proton interactions in a given bunch crossing.
>**Average pile-up:** Mean value of the pile-up over a fill (averaged over all bunch crossings).
>**Peak pile-up:** Maximum pile-up in any bunch crossing at any time (usually at the start of the fill).
>**Peak average pile-up:** Mean pile-up at the beginning of the fill. It corresponds to the peak luminosity of the fill. In practice, it is determined as the maximum of the pile-up values obtained by averaging over all bunch crossings within time intervals of typically one minute.
>**Average pile-up density:** Number of inelastic proton-proton interactions in a given bunch-crossing divided by the size of the luminous region in Z.

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.

Piwinski parameter:
>Parameterisation of reduced beam overlap due to finite crossing-angle.

ramp:
>Change of the magnet current during. During the beam acceleration 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 provide a longitudinal focusing which constrains the particle motion in the longitudinal phase space to a confined region called the RF bucket.

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.

right and left:

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

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 of 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 4 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.

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

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

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

$$\sigma_s.$$

damping times:
Time after which an oscillation amplitude has been reduced by a factor $1/e$.
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.

If no explicit mentioning of the types of damping times is given the damping times refer to the amplitude damping times.

synchrotron radiation 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.

If no explicit mentioning of the types of damping times is given the damping times refer to the amplitude damping times.

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

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

longitudinal emittance:

The longitudinal emittance is defined as:

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

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

$$A = \gamma x^2 + 2\alpha x x' + \beta x'^2,$$

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

$$\text{area of ellipse} = \pi A$$

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

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

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

The transverse emittance is given by the following expression:

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

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

$$\epsilon_n = \epsilon \gamma_r \beta_r,$$

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

$$\beta_r = \frac{v}{c}$$
$$\gamma_r = \frac{1}{\sqrt{1 - \beta_r^2}}$$

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

The nominal normalized transverse emittance for the LHC is

$$\epsilon_n = 3.75 \; \mu\text{m}.$$