# THE LATTICE OF THE CERN LARGE HADRON COLLIDER

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The lattice of the CERN Large Hadron Collider is designed with 23 regular cells per arc, each containing 6 tightly packed 14.2 m long dipoles. This allows to reach 7 TeV per beam with a dipole field of 8.4 Tesla. There are four experimental insertions, two of which are devoted to high luminosity experiments with ±Ê23Êm of free space for the detector. The other two experimental insertions are combined with injection. The value of §* at the interaction points is tunable from 6 m at injection to 0.5 m in collision. The energy deposition in the inner triplets is carefully reduced to sustain the nominal luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. Two insertions are devoted to collect the halo particles with large emittance and momentum spread surrounding the beam core: escaping rates of the protons are estimated to be less than $4á10^{6}$ sec$^{-1}$m$^{-1}$. Finally, one insertion is used to extract the particles in the vertical direction with a minimized deflecting strength.

## I. OVERALL LATTICE

The LHC geometry is dictated by the existing LEP tunnel, and the peak LHC beam energy is broadly given by the maximum magnetic field sustainable by the superconducting dipoles. The present optimization of the optical layout, called *version 4*, aims to increase the bending length of the standard cell, and to use the same cell design in all arcs. The energy of 7 TeV per beam can now be reached with a 8.4 Tesla dipole field. The lattice is designed to lie in a beam plane parallel to that of LEP and the two machines are almost collinear in plane view (the arcs tend to be at the exterior of the LEP theoretical position by up to 4 cm, while the dispersion suppressors -DS- are up to 10 cm on the interior, a price to be paid for standard length dipoles and longer straight sections in the DS).

The two beams of the LHC pass through the same twin bore magnets separated horizontally by 180 mm. They are exchanged from inner to outer circle four times around the circumference in order to avoid any difference in total path length. There are four interaction points (IPs), with the assignment of Fig. 1. The high luminosity insertions are located in points 1 and 5. The combined experimental and injection insertions are in points 2 and 8. There are two cleaning insertions in points 3 and 7, a dump insertion in point 6, and an insertion devoted to the RF in point 4. The betatron phase advance has different values in the insertions: 2.43 in points 1 and 5, 2.57 in points 2 and 8, and 1.80 in the other points. The machine is thus mirror symmetric about the axis IP1-IP5 and its superperiodicity is 1.

The two-in-one design of the magnets means that the optical polarities of adjacent quadrupoles in the two LHC rings are opposite. This is also true for the first triplet on either side of the IPs, made of single bore quadrupoles. The most natural design of each ring is thus antisymmetric, so that on either side of an IP corresponding quadrupoles have equal and opposite strength. At the IPs, the horizontal and the vertical § functions have equal values and both beams are round.
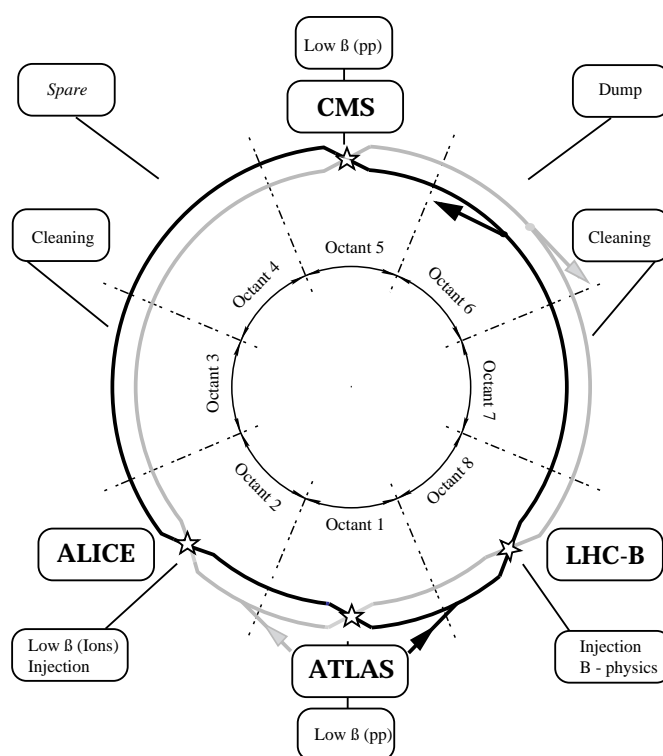


Fig. 1 Layout of the LHC

Equal horizontal and vertical tunes is a feature of the antisymmetric design. The arcs are then adapted to separate slightly the tunes, $Q_x = 63.28$, $Q_y = 63.31$. With a superperiodicity of 1, the choice of the integral part of the tunes is based on the estimated strength of resonances close to the working point. With respect to the betatron coupling, the working point is equivalent to that of the version 1 of the LHC lattice [1]. The necessary changes to make it more robust against dynamic variations of the coupling are the subject of ongoing studies.

## II. LATTICE MODULES

*The regular cell:* the regular cell is 106.92 m long and contains six 14.2 m dipoles and two 3 m quadrupoles. The quadrupoles are centered w.r.t. the bending center of the dipoles in order to have identical cells in every arc, irrespective of its polarity. The cryostat assembly of the quadrupole is symmetrical w.r.t. the quadrupole center. On its left is an octupole corrector and a beam position monitor, and on the right a nested dipole and sextupole corrector. Next to each dipole, in the shadow of the magnet ends, a sextupole and a decapole windings are located on either side. These correctors compensate locally the main systematic imperfections due to persistent currents, which affect the beam stability at the injection plateau and at the beginning of the ramp. The precise magnetic strength of the various correctors will depend on the final optics and should include requirements from the dynamic behaviour of the machine, yet to be estimated.

The nominal betatron phase advance is 90Υ. It is in practice slightly adjustable with separate power supplies for the F and the D quadrupoles of each ring, needed to control the horizontal and vertical betatron tunes. With the maximum quadrupolar gradient of 250 T/m, it is possible to shift and/or split the tune by $\pm$ 2 integers in each ring. The peak values of § and of the horizontal dispersion D are 182.7 m and 2.15 m respectively. The regular arc is made of 23 cells, for a total length of 2456.16 m.

*The dispersion suppressors:* The lay-out of the 16 DS is identical, except for a small difference in length of the short straight section next to the odd and even arcs (the LEP tunnel has a slightly irregular octagonal shape). The four quadrupoles of the DS (Q7-Q10) are interleaved with four blocs of two dipoles each. The dipoles have the same length as in the cell (14.2 m). The separation between the dipole blocs is not regular in order to obtain exact superposition of the LHC and LEP interaction points, and to get sufficient free space for the quadrupoles and the associated correctors. The quadrupoles are split in two sections. The main sections, 3.25 m long, are powered in series with the cell quadrupoles of the same polarity. The 1.5 m tuning sections, with a maximum gradient of 120 T/m, have all independent power supplies. As the number of parameters in the straight sections of the insertions is smaller than the number of matching constraints, the quadrupoles of the DS contribute to the global matching of the insertions. Therefore, the exact optics of the DS in the various insertions are all somewhat different even if their layouts are the same. The orbit functions are sufficiently smooth and of moderate value to allow the use of magnets with the same aperture as in the regular cell.

*The high luminosity experimental insertions:* The high luminosity insertions in points 1 and 5 comprise the inner triplet of quadrupoles (Q1, Q2, Q3) close to the interaction point for focusing the beam size in both planes, and the outer

triplet (Q4, Q5, Q6), placed close to the DS for tuning the betatron functions. Between the inner and outer triplets, a doublet of separation-recombination dipoles (D1, D2) brings the two counter-rotating beams to almost collinear trajectories. The position of the lenses is adjusted to minimize the §-functions at all stages of the §-squeeze, especially in the region of the outer triplets, so that magnets with regular aperture can be used. D1 and D2 are 10.2 m long medium-field superconducting dipoles (4.5 T) spaced by 35.7 m. The inner triplet is designed to minimize the irradiation effects due to particle losses in collision. The single-bore quadrupoles Q1, Q2, Q3 are built of identical 5.5 m, 70 mm aperture units. They are powered in series for an operational gradient of 225 T/m. Two additional independently powered quadrupoles, Q01 and Q03, are used for fine tuning of the triplet. Appropriate absorbers are located in front of Q1 and Q2 to reduce the energy deposit to below 25 W per quadrupole. The free space for the detectors, absorbers and associated infrastructure is $\pm$ 23 m. The insertions are tunable for a range of §* from 0.3 m up to 10 m; the nominal §* at injection is 6 m, and 0.5 m in collision. The change of the gradients during the §-squeeze is smooth. The orbit functions in collision are shown in Fig.2.
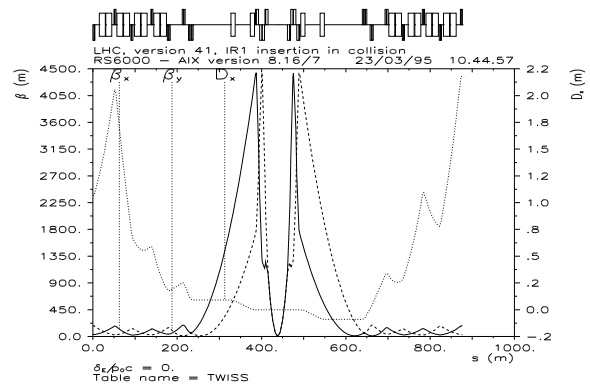


Fig. 2. Orbit functions of the high luminosity insertion in collision

*The combined experimental and injection insertions:* The layout of the insertions in points 2 and 8 is conceptually identical to that of the high-luminosity insertions. The free space around the interaction point is $\pm$ 21 m, while a free space of 100 m between Q4 and D2 is provided for the injection system (kickers and septa). A low waist of the horizontal §-function is needed close to the inner triplet, where protection stoppers intercept badly injected beams. It has been chosen to inject the beams into the outer ring. The insertion are tunable over the same range of §* as the high-luminosity insertion with a smooth variation of the quadrupole gradients. However, the value of the §-function in the outer triplet is somewhat larger.

*The cleaning insertion:* Two insertions are used for collimation, one in point 3 for betatron cleaning, and the other

in point 7 for momentum cleaning. Their layout is almost identical: a 500 m straight section with a FODO-like structure of warm two-in-one quadrupoles is matched to the DS on each side by a superconducting quadrupole Q6. Immediately downstream of Q6, two dogleg dipoles increase the horizontal beam separation from 180 mm to 220 mm, sweeping away the neutral secondaries from inelastic interactions. This also makes the design the cross section of the warm two-in-one quadrupoles easier. The FODO-like structure contains three pseudo-cells with a total phase advance of 216$\Upsilon$ for a maximum § around 350. The normal-conducting quadrupoles are built of 3.55 m, 30 T/m modules, resulting in total quadrupole lengths of 10.5, 14 and 17.5 m. Corresponding quadrupoles on either side of the center of the insertion are powered in series with opposite polarities to provide the required optical antisymmetry.

The entire 500 m straight section is free of superconducting magnets and thus available for cleaning. Collimation of the particles circulating in the halo of the stored beams causes scattering in both transverse planes. The primary collimators must be placed at large § values to maximize the impact parameters and thus reduce the out-scattering probability. They have to be backed by secondary collimators placed at suitable phase advances in order to intercept the out-scattered particles.

*The dump insertion:* The dump insertion is located in point 6. Its purpose is to dispose of the circulating beam at the end of the runs and to protect the machine in case of hardware failure or beam instability. The design benefits from the fact that the two beams do not cross in this point.

Horizontal kickers are used to deflect the circulating beams into a Lambertson type septum which bends vertically the extracted protons to the external absorbers. The antisymmetry of the optics allows to optimize simultaneously the extraction of both beams with a common septum magnet placed at the center of the insertion. On each side of the septum there are four superconducting quadrupoles Q3, Q4, Q5, Q6 to match the optical constraints. The fast kicker is located between Q4 and Q3. In the upstream side, the quadrupole Q3 is horizontally defocusing to enhance the deflection of the kicker and thus the displacement in the septum. On the other hand, the septum must be strong enough to deviate the extracted beam away from Q3 in the downstream side. The position of Q3 thus results from a compromise between the kick enhancement and the required strength of the septum, taking into account realistic assumptions about the aperture of Q3 and the outer radius of its cryostat. In the preferred solution there is a very long drift of about 340 m between the upstream and downstream positions of Q3. Because of this the value of § rises above 600 m, by far the largest around the LHC at injection.

The quadrupoles Q3 and Q4 will need an increased aperture of 70 mm, whilst their length is still standardized to modules of 3.25 m. Enlarged quadrupoles could be used also in the outer triplets of the combined experimental/injection insertions. Like in other insertions, the field quality of the quadrupoles needs to be assessed to ensure that the insertions do not limit the dynamic aperture at injection. Alternatively, it should be possible to reduce the § function at injection to about 450 m by introducing a small warm quadrupole at either end of the septum.

*The insertion for the RF:* The insertion in point 4 will probably be used to house the two 15 m long superconducting RF modules (one per beam). The optics could be similar to the layout of the dump insertion.

## III. APERTURE

The mechanical aperture in the LHC is limited by the collimators in order to localize the beam loss in the cleaning section. The inner coil diameter of the regular magnets is 56 mm. However, the free space for the circulating particles is reduced by the beam screen for synchrotron radiation. Realistic tolerances for the sagitta and alignment of the beam pipe, and for the closed orbit deviations have to be taken into account as well. The available aperture in units of the rms beam size is 10$\sigma$. It allows to accommodate 3$\sigma$ for the beam distribution, 2$\sigma$ for the transverse and longitudinal injection errors, and 1$\sigma$ for drifts in time of the orbit. The remaining 4$\sigma$ is the clearance needed between the primary collimators and the beam screen.

At the nominal LHC luminosity, the proton losses per beam are expected to be 4á10$^9$ proton sec$^{-1}$, while it is estimated that at 7 TeV a longitudinal flux of 4á10$^6$ protons sec$^{-1}$m$^{-1}$ falling onto the vacuum chamber induces a quench. The cleaning system must therefore trap the protons at an amplitude smaller than the aperture of the ring, with an efficiency much better than 10$^3$. This will be achieved by installing circular collimators in point 3, approximated by eight jaws forming an octagon. A set of primary collimators made of beryllium or aluminum is followed by three secondary collimators made of copper located at optimized phase advance. Detailed simulations, including nuclear and electromagnetic scattering in the jaws and tracking around the ring indicate that the needed performance can be reached with a good margin.

At injection, momentum losses will be trapped by a system located in point 7. Simulations indicate that the expected efficiency is sufficient even in the case of a large fraction of RF-uncaptured protons.

## VI. REFERENCES

[1] Design Study of the Large Hadron Collider (LHC), CERN 91-03, (1991).