Linear Optical Layouts of the L.H.C. for P-P and P-Pbar options

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Introduction

The LHC is a hadron collider to be located on top of LEP inside the same tunnel.

Options for PP or PPbar collisions have been considered.

In a P-P machine 2 pipes are required for the 2 counter-rotating beams. Both of them are assumed to lie in the horizontal plane 70 cm above LEP, with a separation of 18 cm. The magnets must have a layout in which the 2 pipes are included in a unique magnetic circuit (2-in-1) producing the appropriate field in each channel. The 2 pipes must coincide around the interaction points (IP's). Obviously for the P-Pbar machine one pipe and one magnetic channel are sufficient to contain the two beams.

Both LEP and LHC are made up of regular arcs and interaction regions. As for LEP a cell of 79 meter long and 60 degrees phase advance is a convenient choice for LHC. The dispersion has to vanish at the interaction point (IP) to avoid synchro-betatron coupling. The beams are focussed at the IP to increase the luminosity as much as possible.

The differences between LEP and LHC are:

a) In the LHC the problem of synchrotron radiation is marginal and the RF system is very modest. Consequently, the weak BW dipoles used in LEP to reduce the synchrotron radiation and the special RF sections along the interaction regions are no longer necessary in LHC.
b) In the proton beams the vertical and radial emittances are equal, so horizontal and vertical beta values can be equal at the IP. Consequently, a triplet of quadrupoles is more convenient that a doublet to limit the maximum beta values near the crossing point.
c) Many bunches are required in the proton beams to increase the luminosity. Crossings at small angle are thus required to avoid unwanted interactions outside the IP. Furthermore, the 2 beams must be completely separated as quickly as possible by a doublet of dipoles with opposite field.
d) The dumping of the proton beams at the maximum energy is a very serious problem and 2 straight insertions must be dedicated to this.
e) The (2-in-1) design of the magnets strongly couples the optics of the 2 proton rings.

The last 2 points put severe limitations on the possible periodicities, symmetries and identity of the 2 proton machines. Possible designs of insertions are shown, and layouts of the overall machine are proposed here which satisfy the constraints on the LHC defined in the Green Book [1].

The geometry of the dipoles in the dispersion suppression region

In LEP the quadrupole gradients of the dispersion suppressor (DS) are noticeably stronger than those of the regular arc (RA). Consequently, the reproduction of the DS scheme of LEP in the LHC would imply a relatively greater shortening of the available space for dipoles than in the RA. That would limit the maximum achievable energy.

A way to overcome this limitation is to suppress the BW dipole from the DS of LHC and to use only 4 identical dipoles of 30.6 m each to bend the beam by the same total angle as in the DS of LEP, namely, 42.2E-03 rad. Then the bending radius is practically the same in the DS and in the RA and equal to 2715 m.

Because of the different layout of LHC w.r.t. LEP, the axis of the 2 machines along the DS will no longer coincide. But the transverse discrepancy can be made small by a convenient choice of the spacing between the dipoles of the DS of LHC. An achievable solution to this problem, found numerically by a dedicated computer program, gives the maximum displacements of the LHC axis w.r.t. that of LEP of 30.6 mm towards the exterior, 8.0 mm towards the centre.

The Low-beta and DS Region

Among the possible arrangements of the IR near the IP we have adopted the one described in [1], shown schematically in fig.1. A free space of ± 10 m is available around the crossing point, to locate the experimental devices, followed by the strong-focussing triplet of quadrupoles Q1, Q2, Q3 to squeeze the spot size of the proton beams at the IP. As soon as possible after the triplet a doublet of dipoles with opposite fields, B1 and B2, is installed to separate and displace the 2 proton beams parallel to the average axis. The total separation is 18 cm, consequently, the doublet of dipoles creates 2 opposite dispersion functions of + 9 and - 9 cm in the 2 rings.

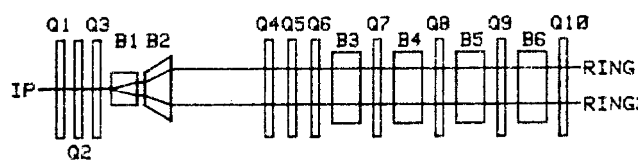

Fig.1 Schematic layout of half an IR.

At the other extreme of the IR near the RA, 4 quadrupoles Q7 to Q10, alternating with the 3 dipoles B4 to B6, are necessary to ensure the approximate vanishing of the 2 dispersion functions and their derivatives before B3 in the 2 rings.

In fact the 2 dispersion functions must vanish exactly only at the IP, therefore the doublet B1, B2 and the quadrupoles Q4, Q5, Q6 play a role in the DS scheme.

The coupling of the optical functions in the 2 rings will be clarified later.

IR's with 9 or 11 quadrupoles per arm may also be considered.

Optical constraints in the IR

A distinctive feature of the LHC is that the (2-in-1) quadrupoles produce opposite gradients in the 2 pipes. So if the gradient is fixed at its maximum possible value the magnetic length represents the only degree of freedom available in each quadrupole. The same happens for the triplet of quadrupoles near the I.P. having only one hole for both beams. Consequently, the 2 rings are not independent machines

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but form, roughly speaking, a double machine with about twice the number of optical constraints.

This situation has 2 peculiar consequences:
a) We have to design 2 coupled DS's for the 2 rings.

b) The radial and vertical beta values at the IP must be equal otherwise a radially flat beam would cross a vertically flat beam with a consequent decrease of the luminosity. Fortunately, the equality of beta values was already the desired case.

To clarify the optical problem let's assume that the IR of the 2 rings starts just before the last quadrupole of a regular octant. Then the initial conditions on the optical functions are:

$\beta_x = 133.82$ m $\alpha_x = -1.732$ $\beta_z = 46.671$ m $\alpha_z = .629$

$D = 2.21$ m $D' = .029$

for the ring with the IR starting from an F quadrupole and:

$\beta_x = 46.671$ m $\alpha_x = .629$ $\beta_z = 133.82$ m $\alpha_z = -1.732$

$D = 1.36$ m $D' = -.018$

for the other ring with the IR starting from a D quadrupole.

The matching conditions at the IP for both rings are

$$\beta_x = \beta_z = 1\text{m} \qquad \alpha_x = \alpha_z = 0 \qquad D = 0 \text{ m} \qquad D' = 0$$

The total constraints would be 12 and would required 12 quadrupoles at least per half insertion. Fortunately, the 4 betatron conditions of the second ring follow almost exactly from those of the first one. It is worthwhile to clarify how good this approximation is. The situation is:

a) Every dipole and every quadrupole has the same length in the 2 rings
b) All the rectangular dipoles produce the same deflection in the radial plane and the same focussing in the vertical plane in each ring.
c) All the quadrupoles produce opposite focusing in the 2 rings.

If the focussing of the dipoles could be neglected the beta functions would be identical but horizontally and vertically exchanged in the 2 rings.

If we do not neglect the focussing of the dipoles and we match the first ring, then the second ring will be slightly mismatched because of b).

Quantitatively the vertical integrated gradient due to the dipoles is given by:

$$k = \sum\Phi/\rho = 2 \cdot 10^{-5} \text{ m-1}$$

a value which is 3 orders of magnitude smaller than the integrated gradient of the weakest quadrupole of the IR. From a practical point of view and as a consequence of the previous considerations, only 8 conditions have to be simultaneously satisfied by every half IR.

Numerical solutions which satisfy the above optical conditions have been found by a dedicated program using the Newton-Raphson algorithm. [2].

A look at the complete machine

In the P-P option, the 2 rings of LHC must have:

a) Identical lengths
b) Possibly identical optical properties

The first requirement is very strict and imposes that the 2 rings must cross each other in some IP's from outside to inside and vice-versa in an equal number of other IP's. The best solution is to have 8 octants in each ring which stay alternately inside and outside.

The second requirement will simplify theoretical computations and eventually speed up the running-in and the setting up of the 2 rings.

There are different ways of satisfying the above two features, linked to the choice of the following possibilities. In each ring,

a) Through every IP we can change or maintain the sign of the focussing.
b) For every IR we can choose equal or opposite focussing of extreme quadrupoles depending on the number of quadrupoles on every half IR.
c) For every octant of RA we can make the focussing of extreme quadrupoles equal or opposite, by choosing the number of half cells to be even or odd.

An example of a possible insertion with 19 and 20 quadrupoles is shown in figs. 2 and 3. To get a complete layout we have to insert 8 IR's of this kind among 8 octants of RA, alternately F-F and D-D.

The unavoidable requirement of a dumping system breaks the periodicity of the ring. The most straightforward possibility is to install the dumping system of each beam in 2 diametrically opposed uncrossed IR's, leaving 6 IP's for physics.

The PPbar option

The layout of LHC for PPbar option, proposed in [1] contains one unique magnetic channel in which the 2 beams are simultaneously confined. The doublets of dipoles are no longer required and the dispersion function must vanish after the last dipole of the DS. The optical constraints are reduced to 6 namely:

$$\beta_x = \beta_z = 1 \text{ m}, \quad \alpha_x = \alpha_z = 0. \quad D = 0\text{m} \quad D' = 0.$$

Solutions for them can be easily found with the same layout of PP insertions, without the dipoles doublets, as in fig. 4.

Conclusions

Possible insertions for the LHC options have been presented.

A precise choice of a possible overall layout will be made once the problems of dynamical aperture [3] chromaticity correction and dumping systems have been clarified.

The conclusion of this work is that from an optical point of view no serious problems have to be faced for the linear lattice.

References

1] CERN-84-10 Large Hadron Collider in LEP tunnel.
2] M. Bassetti et al, NIM 45 (1966) 93-101.
3] M. Bassetti, W. Scandale, CERN, LEP-TH/84-15.

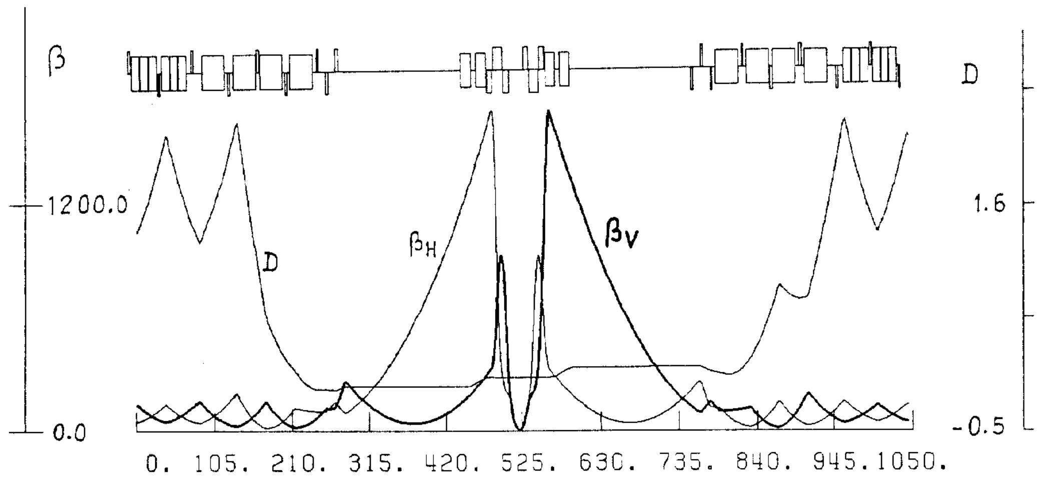

Fig. 2 Full insertion for LHC P-P option, 10 quadrupoles per arm, Ring 1

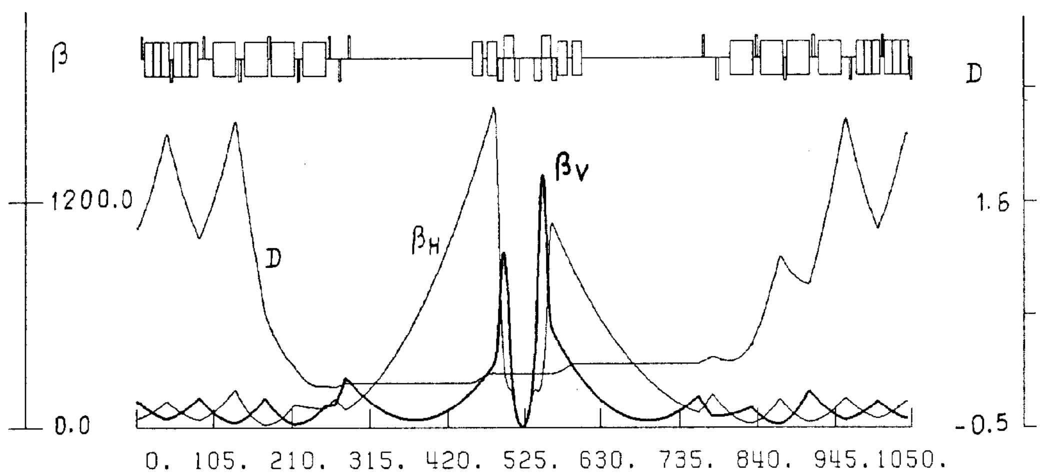

Fig. 3 Full insertion for LHC P-P option, 10 + 9 quadrupoles. Ring 1

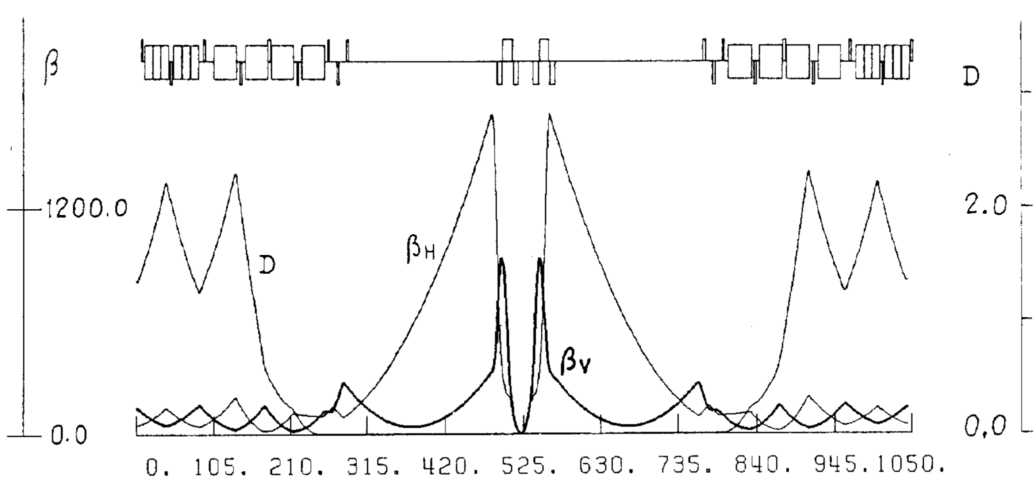

Fig. 4 Full insertion for LHC P-$\bar{P}$ option, 10 quadrupoles per arm.