

# MODULAR OPTICAL DESIGN OF THE LHC EXPERIMENTAL INSERTIONS

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## Abstract

To optimize the use of space, the LHC insertions combine dispersion matching (arc and ring separation/recombination), beam focalization at the interaction point and betatron phase advance control within a unique optical module. In this paper, we show that the significant dispersion produced by the separation/recombination dipoles can be treated separately, allowing a separation of the optical functions in the insertion. This methodology yields the flexibility and robustness needed to adapt the insertion to a lattice with a variable tune split.

## 1 THE LHC HIGH-LUMINOSITY INSERTION

The high-luminosity insertion (fig. 1) is made of two dispersion suppressors and a low- $\beta$  section. Its lay-out is strongly influenced by the geometrical constraints of the LEP tunnel and other non-optical constraints such as the shielding of the super-conducting elements against particle losses [1]. As a

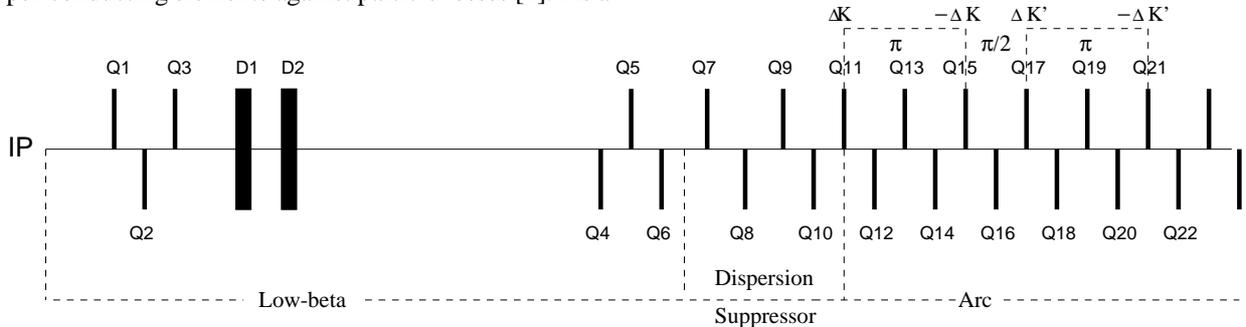


Figure 1: Lay-out of a half-insertion; the other half is antisymmetric w.r.t the IP.

result, the beams of the two rings are separated or recombined by the dipoles D1/D2 between the focusing triplet, common to the two rings, and the matching sections, made of three quadrupoles in each ring. A two-cell dispersion suppressor separates the low- $\beta$  section from the arc. Given the dispersion produced by the separation/recombination dipoles (D1/D2) in the middle of the low- $\beta$  section, the optical functions are not separated; each quadrupole contributes both to the dispersion suppression and the focusing.

The requirements on the high-luminosity experimental insertions are primarily to reduce  $\beta^*$  to 0.5 m for high luminosity. At injection the machine acceptance should be max-

imized by detuning  $\beta^*$  by a factor of the order of 15. The ability to reduce  $\beta^*$  to 0.25 m is considered an interesting option that requires an ultimate total tunability by a factor 30. The dispersion and its derivative should vanish at the interaction point to avoid synchro-betatron coupling.

## 2 OPTICAL DESIGN PRINCIPLES

To demonstrate the feasibility of the LHC experimental insertions in the available space of the LEP straight-sections, their optical design was simplified by adopting two exact antisymmetry rules (about the interaction point in the same ring and from ring to ring at the same azimuth). These rules extend the natural antisymmetry of the common focusing triplet to the whole machines. They reduce the insertion design to a minimization problem involving only ten parameters (quadrupoles); the minimization can then be made in a single step involving the matching of the focusing and of the dispersion functions. This approach demonstrated that satisfactory solutions can be found for all

LHC versions. However the combination of the functions prevents the highly successful modular approach adopted for LEP and give rise to some identified rigidities.

New requirements arise from the LHC implementation studies, where flexibility and robustness are highly ranked. Amongst other things, the adaptability of the insertions to a variable tune split is mandatory [2] and largely incompatible with an exact antisymmetry. The rigidities, such as the correlation between separator and focusing polarities should be removed. The betatron phase shift over the insertion should preferably be a free parameter. Satisfying all these constraints requires an increase of the number of parameters (more quadrupole circuits are actually available) on the one

hand and a separation of the functions on the other hand to obtain both flexibility and robustness.

The study of a symmetric LHC low- $\beta$  insertion [3] (versus antisymmetric in the nominal case) revealed that the matching of the dispersion due to the D1/D2 dipoles was unexpectedly difficult. In this study it is treated separately from the global matching of the insertion with the perspective of separating the functions of the low- $\beta$  section proper and of the dispersion suppressor.

### 3 MATCHING THE SEPARATION/RECOMBINATION MAGNETS

Although the deflection by the D1/D2 dipoles is almost an order of magnitude lower than the bending angle in one lattice half-cell, it occurs close to the inner low- $\beta$  triplet, where the  $\beta$ -function can reach very high values. The resulting perturbation can be put in evidence by first matching the insertion without exciting D1/D2 and exciting them subsequently (figure 2). The modulation of the dispersion function in the arc is indeed very large. Rather than matching

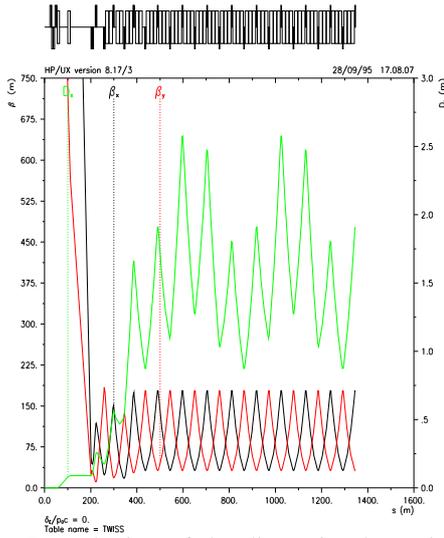


Figure 2: Perturbation of the dispersion by switching on D1/D2

this effect globally together with the arc dispersion and the low- $\beta$  focalization, the dispersion due to D1/D2 is treated here as a perturbation of a reference optics where the D1/D2 dipoles would be switched off. In this optics, the dispersion suppressor would simply cancel the dispersion coming from the arc and the low- $\beta$  section would only provide the focusing at the interaction point. The propagation of the dispersion wave due to D1/D2 to the rest of the lattice can be prevented by closing the dispersion bump with two dispersion correctors as close as possible from D1/D2. Main dipoles cannot be used as dispersion correctors given the tight geometrical constraints. We thus need to correct the dispersion with quadrupoles. For that purpose, we need individually

powered quadrupoles placed at a position where both the  $\beta_x$  and  $D_x$  are largest [4]. The traditional two-cell dispersion suppressor does not offer this functionality in case of antisymmetric design. Indeed, on one side of the interaction point, the dispersion almost vanishes in one of the two focusing quadrupoles, as shown in table 1. The minimum re-

Table 1: Efficiency of the dispersion suppressor quadrupoles Q7 to Q10 with respect to D1/D2.L1 in the upper table and D1/D2.R1 in the lower table

Position	NAME	$ \sqrt{\beta_x} D_x \cos \Delta\mu_x $
Arc 81	QF11.L1	21.20
Left Side	QF9.L1	15.10
	QF7.L1	1.35
Right Side	QF8.R1	11.81
	QF10.R1	16.98
Arc 12	QF12.R1	16.98

quirement for the dispersion suppressor in an antisymmetric design is therefore 2 1/2 cells to guaranty the availability of two focusing quadrupoles where the dispersion is large.

The dispersion correctors act as well on the  $\beta$ -function and the phase advance. The minimum scheme discussed above, based on the use of two focusing quadrupoles spaced by about  $90^\circ$ , may give rise to a large focusing perturbation if the gradient increments in the two quadrupoles happen to be of opposite signs. The sign pattern depends on the phase advance to the D1/D2 dipoles. All side-effects can be cancelled to first-order by using a pair of correcting quadrupoles installed at positions where the  $\beta$ -functions are identical, spaced by  $\pi$  in betatron phase and excited antisymmetrically. In the LHC, where the cell phase advance is  $90^\circ$ , this is most easily achieved by selecting two correcting quadrupoles 2 cells apart. One may verify that:

- the tune shift vanishes,
- the  $\beta$ -beating vanishes except between the pair of correctors,
- the dispersions created by the two quadrupoles add.

The dispersion produced by D1/D2 can be closed by two such ‘correctors’  $\pi/2$  apart, each corrector being made up of two quadrupoles spaced by  $n\pi$ . This scheme is not only fully general, but optimized: it allows the control of 8 constraints ( $D_x, D'_x, \beta_x, \alpha_x, \beta_y, \alpha_y, \mu_x, \mu_y$ ) to first order with four quadrupoles powered in two circuits, taking advantage of the LHC cell phase advance of  $90^\circ$ . The integrated strengths of the correcting quadrupoles are given by the well known three magnet bump formula. It is at most 2% of that of the arc quadrupoles. It should be noted that the excitation pattern is not antisymmetric with respect to the interaction point, as the nominal dispersion on which the method is based is itself not antisymmetric by construction (the main dipoles bend only in the horizontal plane). The perturbation to the  $\beta$ -function (confined to the dispersion bump) is insignificant.

The possibility of treating the dispersion due to D1/D2 separately opens the possibility of dividing the insertion into

genuine dispersion suppressors and low- $\beta$  section modules that may be designed separately.

## 4 THE DISPERSION SUPPRESSOR

With the capability of separating the functions and the help of the extension of the dispersion suppressor by 1/2 cell, the dispersion suppressor can be specialized to guiding the beam in the LEP tunnel and cancelling the dispersion from the arc:

- the dipoles are used for the sole purpose of guiding the beam on the reference trajectory. In this way, it is possible to decrease by a factor of 2.5 the transverse displacement of the LHC machine with respect to the LEP tunnel. Figure 3 shows the relative transverse displacement in one arc; the former arrangement is on the left and the new one on the right.
- the quadrupoles are used for the sole purpose of imposing a vanishing dispersion at the exit of the dispersion suppressor. This arrangement has proven to exhibit the required flexibility to be matched to the arc within the range of cell phase advances specified.

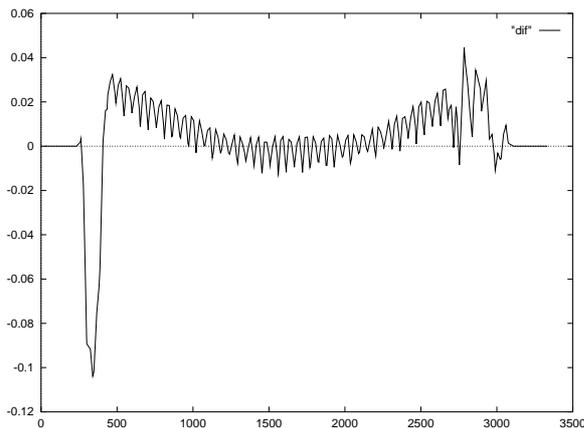


Figure 3: Relative transverse displacement of LHC in meter, between IP1 and IP8

## 5 THE LOW- $\beta$ SECTION

We presently still favor antisymmetry for this section which naturally allows both beams to be identical. The strength of the quadrupoles of the inner triplet is defined by the length of the free space required by the experiments. The matching section controls  $\beta^*$ ,  $\alpha^*$  at the IP. It also maintains a constant phase advance in the straight section during the tuning of  $\beta^*$  from injection to collision values. Our aim is to perform all these functions without modifying the dispersion suppressor settings. We already developed optical solutions which allow to vary  $\beta^*$  from 50 cm to 6 m for tune splits of 1, 2 and 3 units. We presently attempt to enlarge the tuning range and to standardize the quadrupoles needed in the different LHC insertions.

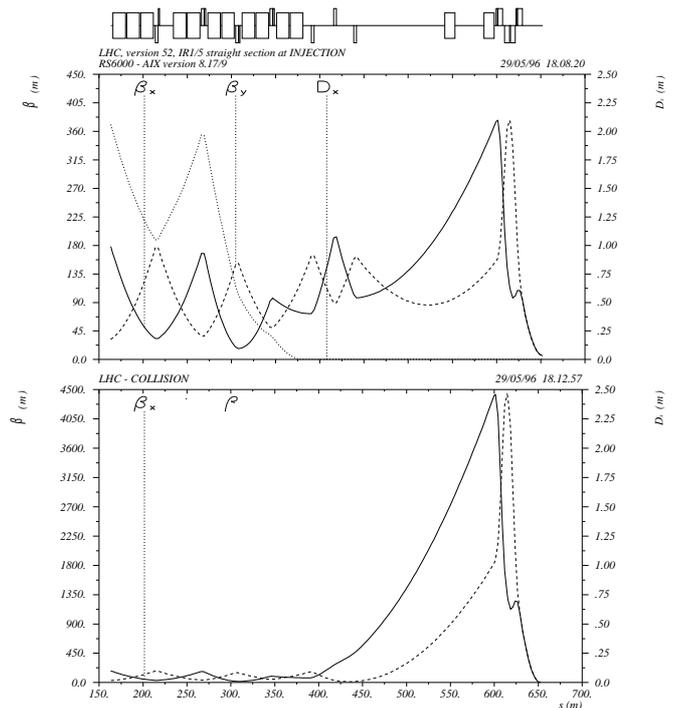


Figure 4: Insertion optics at injection and in collision

## 6 CONCLUSION

We have shown that it is possible to disentangle the functionalities of the LHC insertion, despite its compactness. By treating separately the dispersion excited by the separation/recombination scheme, the functions corresponding to the dispersion suppression and the focusing split naturally into largely independent modules. The analysis of the dispersion suppression module puts into light an exotic consequence of antisymmetry: the classical 2-cell dispersion suppressor is not applicable and must be increased to 2 1/2 cells. In this way, the insertion gains the required flexibility and can be matched to the various cell phase advances foreseen in the arc. A more general correction scheme based on two pairs of weak trim quadrupoles per half-insertion is shown to provide an orthogonal control of the D1/D2 dispersion in all optical conditions.

## 7 REFERENCES

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