A MORE ROBUST AND FLEXIBLE LATTICE FOR LHC

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Abstract

To correct more efficiently the arc dispersion , the exact antisymmetry of the LHC optics is now broken, except in the low-β triplets common to the two rings. A new quadrupole is added between the experimental insertions and the dispersion suppressors and several arc quadrupoles are complemented by a small trim quadrupole. The larger number of parameters gives flexibility to the lattice and allows a partial separation of the optical functions, with a decrease of the total number of quadrupole units. It is possible to change rather freely the phase advances of the arc cells. The nominal tunes are split by 4 units to reduce coupling. The β^* tuning range in the experimental low-β is significantly increased, allowing e.g. a larger beam separation at injection. The super-periodicity of LHC remains 1. We plan to study whether it can be increased within the LHC hardware constraints.

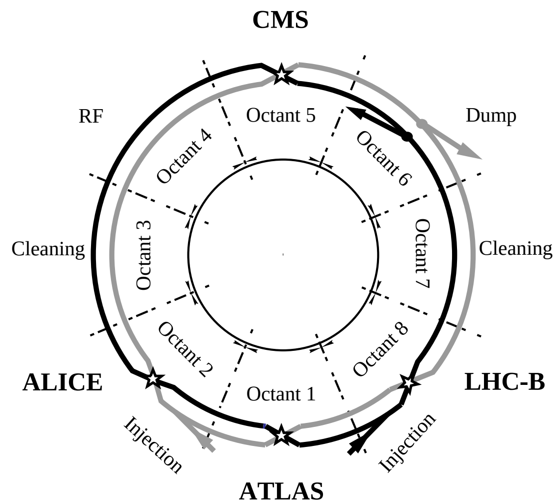

Figure 1: layout of LHC

1 INTRODUCTION

The common low-β triplet in the LHC insertions is naturally antisymmetric for the two counter-rotating beams. An antisymmetric excitation of the two triplets on either side of the interaction point (IP) allows the same sequence of magnetic fields to be experienced by the two beams along their respective paths. This elegant principle had been extended to the whole rings, leading to a simplified design [1] of LHC by reducing drastically the number of parameters.

However in order to cope with a possibly large systematic skew quadrupolar imperfection, the betatron tunes must be split by several units [3]. This requires to break the exact antisymmetry. A second motivation arises from the requirements of robustness and flexibility: the dispersion function cannot be antisymmetric in a plane ring; its suppression by an antisymmetric scheme caused optical distortions and a lack of robustness [2]. In the new version 5 of the LHC optics, the antisymmetry, although underlying, is not imposed, opening a larger parameter space and requiring new methods.

2 THE LHC ARCS

The LHC is composed of 8 arcs separated by 8 insertions. Each arc is made of 23 standard FODO cells. The horizontal and vertical cell betatron phase advances are close to $90^\circ \pm 2^\circ$ yielding a tune split of 2 units in the arcs. Enough gradient is available to split the tunes by up to 8 units, which is optimal for the compensation of systematic resonances in each arc. However the nominal phase advance is purposely chosen close to 90° to avoid a significant dephasing between the sextupoles of the same family (45° at most) in the 4 family scheme required in collision.

3 DISPERSION SUPPRESSION

The aim of the dispersion suppressors (D.S.) is four-fold:

- guide the LHC beam in the LEP tunnel,
- cancel the dispersion arising in the arc,
- cancel the dispersion arising in the separation/recombination dipoles D1/D2,
- cancel the dispersion caused by the horizontal crossing angle at the IP.

The LHC straight-sections have a limited adaptability: their phases are constrained (collimation sections);the space is restricted (long decay of the large β-function) and the number of parameters is small. The D.S. therefore has to act as an optical buffer, allowing an independent tuning of the arc cells and of the insertions. However economy favours the use of standard arc dipoles and quadrupoles in series with the arc which increases further the difficulty.

The LEP dispersion suppressor, which defines the geometry of the tunnel, is made of 3.5 cells with a 90° phase advance, optimized to suppress the dispersion. With the 2.5-longer LHC dipoles and quadrupoles, only two LHC cells can be fitted in the D.S. tunnel. It is still possible to follow accurately the LEP tunnel (Figure 2) but the dispersion is only reduced by a factor of 2. Quadrupoles have to be used to cancel it. Due to the approximate antisymmetry, on one side of the IP, only one of the 5 D.S. quadrupoles is both focusing and efficient (at a place where the dispersion is large). It is thus necessary to complement the D.S. sec-

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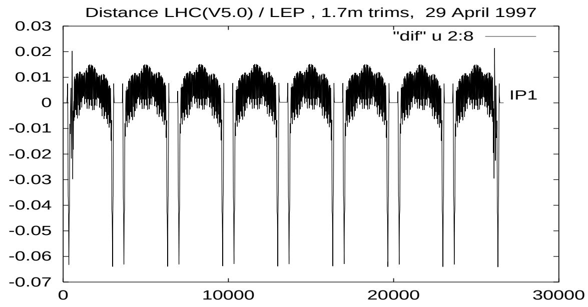

Figure 2: Transverse distance between LHC and LEP in m.

tion proper by the first quadrupole of the arc, thereby using 2.5 cells for the D.S.. In this way, the dispersion can be suppressed but the horizontal optics can hardly be changed due to a lack of parameters. Some additional trim quadrupoles are foreseen in the arc to recover a flexibility however limited by the physical aperture of the arc elements. On the other side of the IP, the D.S, with two efficient focusing quadrupoles, is tuned differently and is more flexible. In spite of the mentioned limitations, the new D.S. is robust. It allows a large adaptability of the arc and, combined to the straight-section, a reasonable flexibility of the insertions.

4 EXPERIMENTAL INSERTIONS

The counter-rotating beams cross at four non-equidistant locations around the LHC circumference (Figure 1). Two of the experimental insertions are designed to provide the highest luminosities while the two others are combined with the beam injection systems. All these insertions are built along the same principle (Figure 3):

- the low-β triplets, optimal for round beams, are common to the two rings. The quadrupole lengths and positions are optimized to power each triplet in series, with a gradient independent of β^*, allowing to tune each ring independently.
- the combination/separation dipoles D1 and D2 bring the two beams into collision and back into their respective rings.
- the matching section, increased to 4 two-in-one quadrupoles allows an extended tuning range of β^* from more than 12 to 0.5 m and beyond.

4.1 High Luminosity Insertions

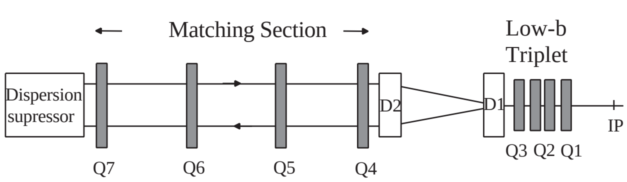

Figure 3: Lay-out of the experimental insertions

The large forward flux of particles produced at the IP's requires to use warm dipoles for D1. This fixes the distance between D1 and D2 and constrains the space available for the matching quadrupoles. In the injection optics, a β^* of 12 m (or even 20 m if required), maximizes the acceptance of the low-β triplet, allowing a large beam separation. The collision β^* of 0.5m is obtained with an adjustment of the normalized gradients of the four matching quadrupoles only. The total phase advances of the insertions can be varied at constant β^*, a criterion of robustness. The number of parameters is however not sufficient to fix the phase advances from the IP to the arc. It is small enough not to decrease the efficiency of the 4-family sextupole scheme.

4.2 Combined Injection/Experimental Insertions

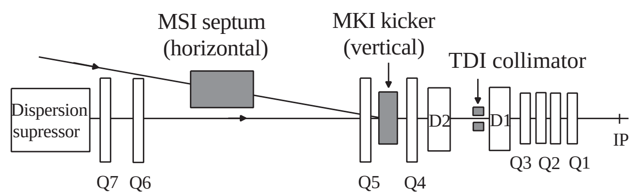

Figure 4: lay-out of the injection

In LHC version 5, the incoming beam is bent horizontally by the septum magnet (MSI) and kicked vertically (MKI) onto its orbit (Figure 4). The absorber (TDI) has to protect the machine and experiments in case of misfiring. This requires the vertical phase advance from MKI to TDI to exceed 70° [5]. This condition can be satisfied if the Q4 quadrupole is defocusing; Q5 then enhances the efficiency of the kicker magnet. The polarity of the machine is thus defined. To maximize the drift space for injection elements, D1 and D2 are super-conducting which is allowed by the lower luminosity of these insertions. In Point 8, which hosts a single arm spectrometer, the collision point is displaced longitudinally by 11.25 m to best explot the existing LEP cavern. The matching section allows continuous tuning of β^* from 250 m to 12 m and from 20 m to 0.5 m as requested by the experiments. The robustness is equivalent to that of the experimental insertion except at injection where no flexibility is left.

5 SERVICE INSERTIONS

Cleaning Insertions: The size of the secondary halo after passing the betatron collimators at 6σ and 7σ is decreased to 8.5 σ by increasing the modulation of $\mu_y - \mu_x$ in the insertion. A separate study [4] shows that this result is optimum.

RF and Instrumentation: Point 4 is dedicated to RF and instrumentation. The dispersion vanishes in the RF cavities. In the absence of other constraints, it is the most flexible of the LHC insertions: the phase can be varied by $\pm 0.2 * 2\pi$ and β^* from 19m to 1000m.

Dump: The dump insertion is essentially identical to the former design [1] with a septum common to the two rings and quadrupoles of enlarged aperture.

6 GLOBAL PARAMETERS

The D.S.'s provide naturally a tune split of 2 units. The betatron tunes are adjusted with the arcs to 63.28/59.31 at injection, and 63.31/59.32 in collision. With 2 sextupole families, the non-linear chromatic aberration in collision (Figure 5) would be too large [6] for chromaticity measurement or a further reduction of β^*. The LHC will have 4 families of sextupole.

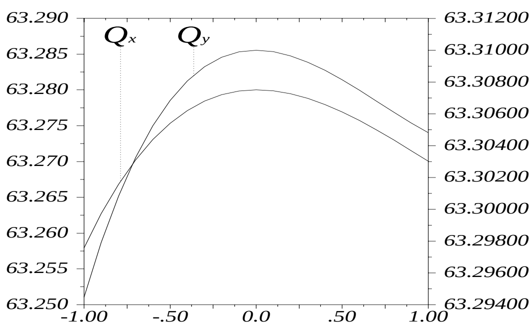

Figure 5: Tune versus relative momentum over ± 0.001

7 CORRECTION SYSTEMS

Closed Orbit: An x/y beam position monitor and a dipole corrector are foreseen at each quadrupole.

Tune-shifts: the two LHC rings share the focusing and defocusing quadrupole circuits. To adjust each ring separately 8 small quadrupoles connected in 2 families are placed at both extremities of each arc. The maximum tune shift is limited by optical aberrations to ± 0.5. This is sufficient to compensate for different focusing errors in the two rings and to explore the tune space between the integer and half-integer resonances. Larger tune shifts are of course possible in the two rings simultaneously.

Chromaticity: the chromaticity arising from the quadrupoles is corrected by sextupoles placed close to the arc quadrupoles. As the optics flexibility is insufficient to control the phase advance between IP's, four families of sextupoles are needed.

Dipole Field Harmonics b_3 and b_5: The persistent currents in the dipoles cause a chromaticity of some 500 units expected to vary by 30% during injection and snap-back. This effect is corrected by sextupolar spool-pieces in the dipole ends.The decapole, detrimental to the dynamic aperture, is corrected in the same way.

Betatron Coupling: 16 skew quadrupole pairs (at $\pi/2$) correct the coupling arising in the arc from the a_2 in the dipoles. A few skew quadrupoles placed at 90° in $(\mu_x - \mu_y)$ in the insertions form a second family.

Landau Damping: 144 short octupoles in the arc, powered in F and D circuits, damp the dipole and higher-order coherent transverse modes at 7 TeV [7]. At injection energy, instabilities are suppressed by feedback and the direct space-charge tune spread.

8 FLEXIBILITY

The optics flexibility necessary to produce tune shifts or tune splits by at least 4 units is now part of the nominal design. Experience with other colliders (ISR, LEP) shows that optics changes over the machine lifetime go much beyond what is required by tune shifts/splits. Care must be taken that the lenses located in the arcs and the D.S.'s but used to correct or adapt the insertions can face possibly changing requirements in the insertions.

We use the adaptability of the betatron phase as an index of flexibility. The present achievement is about ± 0.2 (in tune units) in the experimental and RF insertions. This is sufficient to cope with small displacements of quadrupoles and with the equalization of the betatron phase advance between the two high luminosity collision points. Reaching a higher symmetry in phase advance or controlling the phase advance between the IP and the arcs seems presently both out of reach and not justified. The additional quadrupole added in the matching sections of the experimental insertions provides the flexibility mentioned above. The RF insertion is less constrained and was designed with this goal in mind. The other insertions however still show very little flexibility and work is continuing to improve them. The arc cell itself is already constrained by the 4 family sextupole scheme and the optimization of the dynamic aperture at injection. The sextupole scheme in the arc is able to cope with a reduction of β^* by a factor of 2.

9 CONCLUSION

The optics of LHC, while retaining the main options of its former versions, has been profoundly reworked to allow robustness and minimal provisions for flexibility. While the main goal, a large split between the betatron tunes, was satisfied, more stringent requirements have emerged: the protection of the low-β quadrupoles against mis-injected beams and the effect of the long-range beam-beam interaction on the dynamic aperture at injection. In both cases, the implemented flexibility allowed to face the requirements. Further studies are necessary to attempt providing some more flexibility in the strongly constrained insertions such as the collimation and dump insertions by reconsidering the flexibility of the focusing in the dispersion suppressors.

10 REFERENCES

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