ANALYSIS OF OPTICAL LAYOUTS FOR THE PHASE 1 UPGRADE OF THE CERN LARGE HADRON COLLIDER INSERTION REGIONS*

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Abstract

In the framework of the studies for the upgrade of the insertions of the CERN Large Hadron Collider, four optical layouts were proposed with the aim of reducing the beta-function at the collision point down to 25 cm. The different candidate layouts are presented. Results from the studies performed on mechanical and dynamic aperture are summarized, together with the evaluation of beam-beam effects. Particular emphasis is given to the comparison of the optics performance, which led to retain the most promising layouts for further development.

INTRODUCTION

A recent result in the studies for the LHC performance upgrade is the definition of a staged approach (see Refs. [1-4] and references therein). It is now customary to distinguish between a Phase 1 and a Phase 2 upgrade:

- The Phase 1 upgrade aims at a consolidation of the LHC performance with ultimate beam parameters, corresponding to a bunch intensity of 1.7×10^{11} p and luminosity significantly larger than $L = 10^{34}$ cm^{-2} s^{-1}. The path to this is via a reduction of β^* to 0.25 m, requiring the design of new large-aperture triplet quadrupoles based on Nb-Ti superconducting cables and very limited modifications in the long straight sections (LSS). The cable is the spare cable used for the production of the LHC main dipole magnets.
- The Phase 2 upgrade aims at an ambitious increase of the LHC luminosity by about a factor of ten, thus imposing a deep revision of the insertions, including new triplet quadrupoles possibly based on Nb_3Sn superconducting cables, special protections, and absorber elements. Also, the detectors will have to be upgraded to exploit fully the new potential reach of the LHC machine.

In this paper four layouts are studied in details to assess their performance and narrow down the number of potential solutions for the Phase 1 upgrade. It is worth stressing that each layout represents a specific implementation of a given triplet strength and corresponding maximum possible aperture.

LAYOUT DESCRIPTION

- Compact: It is based on a triplet layout and the lowest possible gradient compatible with tolerable aberrations [3]. The overall length is minimized by optimising the gradient of Q1 and the lengths of Q1, Q2, and Q3. The gap between the quadrupoles is 1 m for the interconnection. Suitable collision optics requires an additional Q6 module.
- Modular: It uses a quadruplet design with intermediate gradient [3]. All the modules share the same length, but the first two feature a larger gradient, thus implying either a reduced aperture for the first two modules or reduced aperture margins in the others. The gap between the quadrupoles is 1 m. The large set of gaps can be used for masks, absorbers or corrector magnets. Suitable collision optics *requires* an additional Q6 module.
- Low β_{max}: It is based on a triplet layout and the highest gradient compatible with additional aperture margin in the triplet [3] (see Fig. 1). The first element features a reduced aperture and the modules are of three different lengths. Such a layout limits the beta function in the triplet. No additional quadrupole modules are installed in the LSS.
- Symmetric: It uses a triplet layout and the highest gradient compatible with additional aperture margin in the triplet [2]. The two modules differ only by the length and are arranged almost symmetrically with respect to the centre of the triplet assembly. The gaps are the same as the nominal layout.

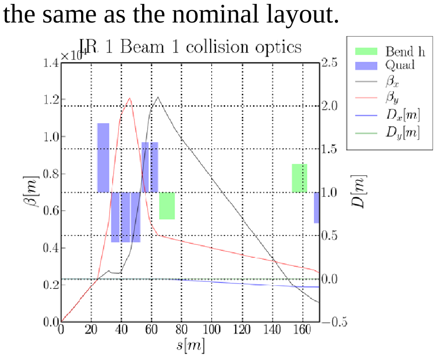

Figure 1: Low β_{max} layout and optical parameters.

The proposed magnet cross-sections are shown in Fig. 2, while the main parameters are reported in Table 1.

PERFORMANCE EVALUATION

Mechanical aperture

The mechanical aperture available for the beam has been evaluated using the techniques and the tools developed for the nominal LHC (see Ref. [5]). The aperture description for the triplet modules is listed in Table 2 (based on the sketch in Fig. 3), together with the mandatory modifications for the D1 separation dipole [6].

*Work supported by the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395)

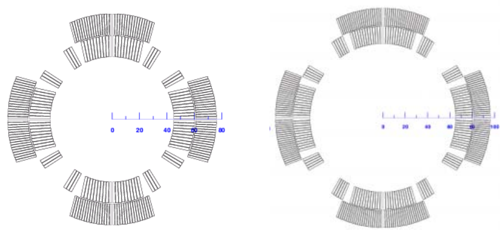

Figure 2: Inner and outer layers of the Q1 (left) and Q2/Q3 (right) for the low β_{max} layout.

Table 1: Summary of the main layout parameters.

Parameter	Compact	Modular	Low β_{max}	Symmetric
L* (m)	23	23	24	23
Gradient (T/m)	91/68	115/88/82/84	168/122	122
Module L (m)	12.2/14.6/11	4.8	7.4/5.7/4.9	9.2/7.8
Total L (m)	55	68	40	41
Aperture (mm)	160/210	115/160	80/115	115

For the remaining elements, the aperture model is the same as for the nominal LHC machine, with the exception of D2, Q4, and Q5. Indeed, the nominal orientation of the beam screens was based on the injection optics for Q5, while an optimisation was not deemed necessary for Q4 due to its large aperture. To mitigate the observed LSS aperture limitations for the upgrade layouts, it is assumed that the beam screen orientation will be re-optimised so maximise the aperture margin [6].

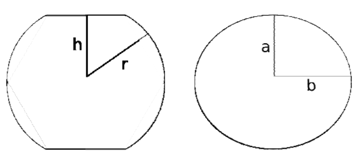

Figure 3: Sketch of the beam screen (left) and D1 vacuum chamber cross-section (right).

Table 2: Assumed beam screen dimensions (h, r) (triplets) and vacuum chamber size (a, b) (D1).

Magnet	Compact	Modular	Low β_{max}	Symmetric
Triplets (mm)	(74, 79)/ (99, 104)	(54, 59)/ (99, 104)	(34, 39)/ (54, 59)	(54, 59)
D1 (mm)	(50, 64)	(50, 64)	(50, 64)	(50, 64)

The details of the parameters used for the aperture computations can be found in Ref. [5]. The summary is reported in Table 3.

Dynamic aperture

The Dynamic Aperture (DA) for the LHC studies has been traditionally defined as the minimum initial transverse amplitude becoming unstable over a given number of turns, typically larger or equal to 10^5 turns, and over a collection of 60 different machine realizations. The transverse phase space is sampled by tracking a large amount of initial conditions restricted to five angles in the first quadrant of the *x-y* plane and one value of the momentum offset corresponding to 3/4 of the bucket height or 2.7×10^{-4}. The associated error is usually of the order of 0.5 σ (see Ref. [8] for more details).

Table 3: Summary of available aperture in terms of n1 [7] (no liner included in Q1).

Magnet	Compact	Modular	Low β_{max}	Symmetric
Q1/Q2,3	20.0/16.9	14.1/12.6	7.8/8.8	15.5/8.4
D1	5.3	6.3	7.6	7.3
D2	5.3	4.2	7.9	6.5
Q4	7.3	6.4	8.6	7.1
Q5	4.7	3.8	10.4	7.0

The minimum DA for the upgrade options is shown in Table 4 with and without non-linear correction (NLC) and with and without triplet field errors for comparison. For reference, some special configurations are also included in the Table, in order to highlight the source of the DA (field quality of the arcs and matching sections or triplet).

Table 4: Summary of DA.

	Compact	Modular	Low β_{max}	Symmetric
DA w/o NLC (σ)	16.5	11.0	14.4	12.0
DA w/o triplets	16.0	11.0	20.0	16.0
DA only triplets	22.0	17.0	14.0	12.0
DA with NLC (σ)	NA	14.5	16.0	14.5

The magnetic errors are those of the machine "as-built", while for the upgraded triplets the magnetic errors are based on the scaling laws in [9]. As the actual implementation of the D1 and D2 separation dipoles is not known to-date, their field quality is not included in the simulations. The correction is achieved by inserting non-linear elements in the insertion region as described in Ref. [10]. The Compact option is the best one in terms of DA (even without non-linear correctors). Despite the similarity between the Low β_{max} and the Symmetric, the first one has a better DA, both before and after correction. It is worth noting that the inclusion of beam-beam effects would induce a strong reduction of the DA (as for the nominal LHC), but still in favour of the Low β_{max} and Symmetric layouts.

Crossing scheme and beam-beam effects

Due to the large number of bunches the two beams have to collide with a finite crossing angle to avoid multiple head-on collisions. Such a crossing angle should be the largest possible to ensure the transverse separation at the long range beam-beam (LRBB) encounters, while not reducing too much the luminosity.

The detrimental effects of long range interactions depend on the normalized separation between parasitic encounters and the total number of long range interactions. These might lead to resonance excitation [11, 12], resulting in a loss of dynamic aperture and reduced beam lifetime. For the nominal LHC parameters the normalized separation is between 7 and 10 σ in the region where the beams share a common vacuum chamber. This assumes a crossing angle $\alpha = \pm 142.5$ μrad, $\sigma^* = 16.6$ μm, $\beta^* = 0.55$ m. A minimum crossing angle of 220 μrad is required when $\beta^* = 0.25$ m.

To ensure the independent control of the two beams, the crossing angle bumps are generated outside the D2 separation dipoles by dedicated orbit correctors. To reduce the required strength and maximise the aperture in Q4 and Q5, the insertion orbit correctors near Q1 are also used as in the nominal crossing scheme [13]. The obtained crossing schemes are shown in Fig. 4.

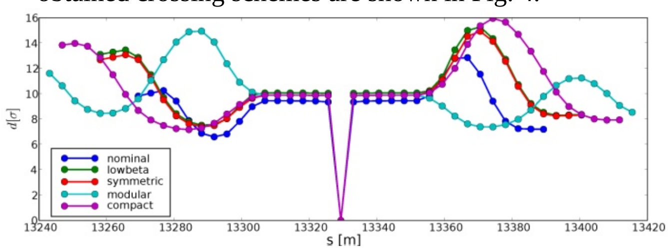

Figure 4: Normalised beam separation and position of the beam-beam encounters for upgrade and nominal layout.

The strength of the existing orbit correctors is still sufficient, except for the Modular layout, where an extra strength (factor of two with respect to nominal) is required to increase the beam-beam separation at the level of the D1 dipole. The situation is summarised in Table 5.

Table 5: Summary of crossing scheme and performance.

	Compact	Modular	Low β_{max}	Symmetric
α (μrad)	220	220	220	225
Min. Sep (σ)	7.1	7.2	7.2	7.2
LRBB	24	27	20	20
L gain	46%	46%	46%	44%

CONCLUSIONS AND OUTLOOK

A systematic study of the performance of the four layouts proposed for the LHC Phase 1 insertion upgrade was carried out and presented in this paper.

Mechanical aperture is the crucial issue not only at the level of the triplet itself, but also in the LSS, which should match the new requirements imposed by the new triplet layout. Certainly, both the Compact and the Modular layouts feature serious aperture bottlenecks. The Symmetric solution also has some limitations at the level of the D2, but it is promising, while the Low β_{max} layout does not offer the possibility of inserting an absorber (liner) in Q1. The need of an absorber in Q1 was recently assessed. Such an absorber should provide the necessary protection of Q1, Q2 w.r.t. the debris produced at the interaction point. In the light of these new findings, the aperture in the Q1 for the Low β_{max} layout will become extremely tight, while for the Symmetric one it could be still above 9 σ with a liner 13 mm thick.

The DA of the various configurations, assuming the proposed scaling law for the field quality of the triplet as a function of the magnet aperture, is sufficient, either because the aperture is large enough to ensure an excellent field quality (Compact) or because of the non-linear correctors used to minimise the impact of triplet magnetic field imperfections.

Finally, the evaluation of the beam-beam effects confirm that, apart from the Modular layout, a separation scheme can be successfully designed and, for the most promising layout, i.e., the Symmetric one, the number of long range beam-beam encounters is comparable with the one of the nominal LHC (20 per side per interaction point for about 15 in the nominal layout).

From the analysis presented, it is clear that the Symmetric layout could be a good starting point for the design of a realistic layout. A key issue to be addressed for such a layout is the correction of the off-momentum beta-beating and, in general, of the chromatic effects. These might be a serious obstacle in the design of the upgrade optics, also because of the impact on other crucial systems, such as the collimation system.

In view of the shortcomings of all four optics presented, recently a triplet of symmetric type was presented [14], which complies with the aperture requirements. Combined with a deep revision of the LHC optics (insertions and arcs) aimed at correcting the chromatic aberrations, such as non-linear chromaticity, off-momentum beta-beating, spurious dispersion, it is the best candidate for the layout for the LHC Phase 1 upgrade.

REFERENCES

[1] O. Brüning, “The CERN View on Accelerator Physics R&D”, presentation at the US LARP meeting, April 2007.
[2] J.-P. Koutchouk, L. Rossi, E. Todesco, CERN LHC Project Report 1000, 2007.
[3] O. Brüning, R. De Maria, R. Ostojic, CERN LHC Project Report 1008, 2007.
[4] R. De Maria, CERN LHC Project Report 1051, 2007.
[5] J.-B. Jeanneret, R. Ostojic, CERN LHC Project Note 111, 1997.
[6] S. Fartoukh, CERN LHC Project Report 1050, 2007.
[7] R. De Maria, “Phase 1 Optics: Merits and Challenges”, proceedings IR07 workshop, in press.
[8] M. Böge, H. Grote, Q. Qin, F. Schmidt, EPAC’96, Sitges, June 1996, p. 920 (1996).
[9] E. Todesco, B. Bellesia, J.-P. Koutchouk, Phys. Rev. ST Accel. Beams 10, 062401, 2007.
[10] R. Tomás, R. De Maria, M. Giovannozzi, these proceedings.
[11] W. Herr, Part. Acc. **50**, p. 69, 1995.
[12] W. Herr, CERN LHC Project Report 628 (2003).
[13] O. Brüning *et al.*,“LHC design report, Vol. I”, CERN-2004-003, 2004.
[14] S. Fartoukh, “Optics challenges and solutions for Phase-I upgrade”, presentation at the CERN LHC Insertion Upgrade Working Group, May 2008.