PERFORMANCE LIMITATIONS OF LHC LOW BETA INSERTIONS

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1. Abstract

One desired feature of the CERN Large Hadron Collider is the possibility for some experiments to work at luminosities about an order of magnitude higher than the design value of 10^{33} cm^{-2} s^{-1}. Special low beta insertions have to be designed for this purpose, which will provide a value of the beta-functions at the interaction point, smaller than the nominal value of 1 m. Limitations arise from geometrical and optical constraints, from chromatic aberations and multipole error tolerances in the superconducting dipoles and quadrupoles and from the dynamic aperture requirements. Realistic designs are proposed and limiting factors are analysed by computer simulation.

2. Introduction

The most significant restriction of the dynamic aperture of a large proton collider is caused by the random component of the multipole moments of its magnetic elements. Their principal effect is seen already by tracking particles for a few hundred turns, while many other effects, such as synchro-betatron coupling, need long term tracking, requiring enormeous amounts of cpu-time and making a systematic study prohibitive. Systematic magnetic imperfections are another source of aperture limitation, which is accessible by short term tracking. Their effect, however, is tightly coupled to the applied corrector schemes, which have not yet been studied in detail for the LHC and therefore are not explored in this study.

3. Lattice

A lattice has been designed for the LHC with regular FODO cells of 100 m length, 90° phase advance and with dispersion suppressors of the type that allows one to minimize the transverse separation from the LEP-ring and to have trajectories of identical length for the protons in LHC and for the leptons in LEP [1]. The lattice has four identical high beta insertions in the straight sections with even numbers, occupied by the LEP experimental areas. Interleaved with them, in the odd numbered points there are the injection insertion (IR1), which can accomodate a compact experimental apparatus and has $\beta^* = 0.5$ m, $L^* = \pm 10$ m, the dump insertion (IR3), where the two proton beams are extracted, and two main experimental insertions (IR5, IR7) with $\beta^* = 0.5$ m, $L^* = \pm 20$ m. A detuning path from collision to injection optics is available from $\beta^* = 0.5$ m to 4 m. All the insertions have the same phase advance and contain quadrupoles with gradients not exceeding 250 T/m .The curvature of the LHC is made by eight arcs with 49 half-cells each. Four dipoles 10 m long are located in each half-cell. The magnets are of the two - in - one design with a horizontal separation of 180 mm. The length of the two proton rings are made equal by changing from outside to inside arc and vice-versa eight times around the circumference. The separation is achieved by doublets of dipoles with low fields . Conventional dipoles of 1.8 T and super-conducting dipoles of 3.75 T are used. Because of the modularity of the odd insertions a test lattice is used in which the experimental insertion IR5 (identical to IR7) replaces the injection and the dump insertions. By that a four-fold symmetry is obtained, which facilitates the lattice description for tracking. The tunes values in the horizontal and vertical planes are 69.28 and 69.31, respectively.

4. Magnet Errors

Throughout this study we consider only the random part of the magnetic imperfections. The errors used to model the arc and dispersion suppressor dipole magnets are based on the values given in ref. [2]. Due to the lack of knowledge about the field quality of the LHC quadrupoles these were modelled by using the SSC values scaled from 4 cm to 5 cm inner coil diameter d_c according to :

$$a_k^{LHC} = a_k^{SSC} \times \left(\frac{d_c^{SSC} + 2}{d_c^{LHC} + 2} \right)^{k + \frac{1}{2}}$$

For all but the final focusing IR triplet quadrupoles the used SSC values are those given in ref. [3], while the IR triplet values are based on ref. [4], where the moments of order 2 - 5 have been assumed to be corrected to 0.1 units. Table 1 summarizes the r.m.s. values used for the random errors.The imperfections of the separating dipole doublets are assumed to be negligible.

Table 1: Random Errors in Units of 10^{-4} at $r_0 = 10^{-2}$ m

order	dipole		quadrupole		IR-triplet	
k	$\sigma_{b,k}$	$\sigma_{a,k}$	$\sigma_{b,k}$	$\sigma_{a,k}$	$\sigma_{b,k}$	$\sigma_{a,k}$
0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0
2	1.5	0.5	2.28	2.10	0.1	0.1
3	0.15	0.2	0.34	0.72	0.1	0.1
4	0.2	0.07	0.16	0.17	0.1	0.1
5	0.0	0.0	0.12	0.06	0.1	0.1
6	0.02	0.04	0.02	0.02	0.022	0.022
7	0.0	0.0	0.0	0.0	0.016	0.016
8	0.05	0.002	0.007	0.006	0.013	0.013
9	0.0	0.0	0.005	0.004	0.009	0.009

[Number of poles = 2 * (multipole order+1)]

5. Tracking

The particle simulations were carried out excluding synchrotron oscillations using the code FASTRAC [5]. The dynamic aperture was determined by persuing an ensemble of 10 particles equally spaced between 0 and a_{max} along the x = y - axis. As particles got lost, a_{max} was gradually reduced until all 10 particles remained stable over 400 turns. The final a_{max} is considered the dynamic aperture a_{dyn} of the lattice and its linear aperture, based on a given maximum variation of the Courant-Snyder invariant ("smear") and / or a maximum tune shift, is determined also. The usefulness of the linear aperture criteria, as they have been applied for the SSC, becomes marginal for realistic lattices [6] and collision optics, thus their results are not reported here. No physical aperture limit was used in the simulation.

The maximum LHC emittance ($\varepsilon_n = 4\,\sigma^2\,\gamma\,/\,\beta$) is 20 π µm. For β = 1m this corresponds to an r.m.s. beam radius σ of 102 µm at injection and of 24.2 µm at collision energy. At injection an aperture of at least 4σ is required for an acceptable performance. At collision, based on experience at the SppS [7], an aperture of at least 6σ is needed. Allowing additional 2σ for effects not taken into account by the simulation (e.g.closed orbit distortions), one arrives for β = 1m at needed apertures of : 0.61 mm at injection (450 GeV) and 0.19 mm at collision (8 TeV). The apertures provided by tracking refer always to β = 1m and have to be compared with the above numbers.

The dynamic aperture is limited by various lattice components. A useful baseline is established by determining the aperture of the cell-lattice, i.e. a lattice made up entirely of the regular arc cells of the realistic lattice, which are slightly detuned to produce the same working point. Its dynamic aperture is primarily determined by the strength of the multipole moments of the arc dipoles and the chromaticity corrector strengths. The inclusion of the IRs causes an increase of the chromaticity and thus stronger sextupole correctors, and a loss in dynamic aperture results. The imperfections of the IR-elements contribute to further aperture losses to an extent that depends on the actual IR-optics. Since the final focusing quadrupoles are shared by the two beams and due to a crossing angle of 96 µrad the beams pass through these elements off-axis. Because of the large β-function values at this location, this is a non-negligible effect, which has been taken properly into account in the simulation.

6. Tracking Results

a) Cell - lattice : The bare, chromaticity corrected cell-lattice (ξ_{nat} = - 62) has an on- momentum dynamic aperture of

$$a_{dyn,bare} = 8.535 \pm 0.107 \text{ mm},$$

far larger than the physical aperture, whose radius is 20 mm ,which translates for β_{arc} = 169 m to 1.53 mm at β = 1 m . Including the random part of the arc dipole errors the average on-momentum dynamic aperture of the chromaticity corected cell-lattice based on 5 different random seeds was obtained as

$$< a_{dyn} > = 1.174 \pm 0.162 \text{ mm}.$$

This value is obviously well within the physical aperture. The off-momentum behaviour was investigated also and the chromatic aperture observed for one given random seed tis given in table 2.

Table 2 : Chromatic aperture of cell-lattice

$\delta\,[10^{-3}]$	-5	-2	0	2	5
a_{dyn} [mm]	0.710 ±.010	1.257 ±.024	1.381 ±.022	1.165 ±.018	0.779 ±.011

b) 4 - fold symmetry lattice : The dynamic aperture was determined for 4 IR optics leading from the injection to the collision conditions. The obtained values are summarized in table 3 and represent the average of 5 different random seeds. Columns 1 and 2 give the minimum and maximum β-function values; column 3 shows the natural chromaticity, while in columns 4 - 7 the dynamic apertures are given for the following error configurations : a_0 is the on-momentum dynamic aperture for the bare, chromaticity corrected lattice; a_1 is the aperture when the arc and dispersion suppressor dipole errors are taken into account; a_2 is the aperture including additionally the arc and dispersion suppressor quadrupole errors, while a_3 represents the aperture, if the remaining IR quadrupole errors are also included.

Table 3 : Summary of 4-fold symmetry lattice data

β^*_{IR5} [m]	β_{max} [m]	$-\xi_{nat}$	a_0 [mm]	a_1 [mm]	a_2 [mm]	a_3 [mm]
3.5	572	111	2.004 ±.019	1.023 ±.158	0.976 ±.153	0.747 ±.042
2.0	1033	124	1.828 ±.023	0.990 ±.152	0.937 ±.144	0.523 ±.017
1.0	2055	151	1.486 ±.010	0.963 ±.143	0.937 ±.095	0.341 ±.013
0.5	4084	204	1.105 ±.016	0.931 ±.160	0.941 ±.157	0.218 ±.014

Conclusions : The obtained dynamic aperture at injection taking into account all random errors is acceptable, though marginal should injection errors be allowed for. The dynamic aperture of the bare lattices is inversely proportinal to the natural chromaticity and going from the injection to collision optics it gets reduced by a factor of 2.

This effect, however, gets covered up once the random dipole errors are included. Further inclusion of the arc and dispersion suppressor quadrupole errors affects the aperture only slightly, while the IR quadrupole errors, in particular those of the final focusing triplet, dominate the dynamic behavior increasingly as β^* decreases. The importance of the IR triplet errors is demonstrated by the case where all but the IR triplet errors are included. For this configuration in collision mode ($\beta^* = 0.5$ m) an average aperture of 0.796 ± 0.081 mm was found. Therefore, an important issue here is the aperture dependence on the amount of correction of the IR triplet multipole moments. This was studied for the collision optics assuming that the moments of order 2 - 5 are corrected in such a way as to leave values for σ of 0.05, 0.1, 0.2 and 0.5 units and the results are listed in table 4.

Table 4 : Aperture dependence on degree of correction of IR-triplet

$\sigma_{a,k}$, $\sigma_{b,k}$ (k = 2 - 5)	0.05	0.1	0.2	0.5
$< a_{dyn} >$ [mm]	0.223 ±.011	0.218 ±.014	0.199 ±.008	0.156 ±.018

Conclusions : While an increase in σ from 0.1 to 0.2 units results in an insignificant loss of aperture, an increase to 0.5 units produces a 25% loss, which is still acceptable. Once the multipoles of order 2 - 5 are corrected to 0.1 units the dynamic behavior is dominated by the uncorrected higher order multipoles, and thus a correction of σ_k for k = 2 - 5 to better than 0.1 units does not result in an larger aperture.

c) 1 & 2 - fold symmetry lattices : The basic difference here is, that of the 4 odd-numbered insertions 2 are kept at injection conditions and the other 2 are tuned to collision optics. The tunable insertions for the lattice with super symmetry 1 were #5 and #7, while for the 2-fold symmetry case these were #1 and #5. The data of these lattices are listed in table 5.

Conclusions : The higher order symmetries are essentially removed by the inclusion of the random errors. The increase in bare lattice aperture is entirely due to the lower natural chromaticities for the two lattices considered here. Once the random errors are taken into account, however, there is no difference in dynamic aperture between the lattices with two IRs tuned for collision and the previous one, where all four IRs had the same optics. This result underlines how strongly the aperture of a realistic LHC lattice is dominated by the field quality of the final focusing IR elements.

Chromatic aperture : The off-momentum behaviour was studied for the 2-fold symmetry lattice with $\beta^* = 0.5$ m. The average values based on 5 random number seeds listed in table 6 indicate that the aperture within the RF-bucket ($\pm 3 \times 10^{-4}$) is sufficiently constant .

Table 5 : Summary of 1- & 2-fold symmetry lattice data

β^*_{IR5} [m]	β_{max} [m]	$-\xi_{nat}$	a_0 [mm]	a_1 [mm]	a_3 [mm]
4.0 Sym. 1	521	109	2.063 ±.038	0.991 ±.155	0.792 ±.068
3.0 Sym. 1	692	112	1.994 ±.031	1.021 ±.157	0.709 ±.029
2.0 Sym. 1	1033	117	1.889 ±.022	0.994 ±.137	0.558 ±.027
1.0 Sym. 1	2055	130	1.708 ±.028	0.975 ±.162	0.359 ±.021
0.5 Sym. 1	4084	157	1.419 ±.025	0.963 ±.148	0.225 ±.014
0.5 Sym. 2	4084	157	1.472 ±.028	0.980 ±.152	0.230 ±.015

Table 6 : Chromatic aperture of 2-fold symmetry lattice

$\delta\,[10^{-3}]$	-1.4	-0.7	0	0.7	1.4
$< a_{dyn} >$ [mm]	0.248 ±.009	0.248 ±.023	0.230 ±.015	0.225 ±.020	0.217 ±.006

7. Conclusions

Under the made assumptions, that the systematic errors are taken care of by a corrector scheme and neither closed orbit distortions nor the synchro-betatron coupling cause substantial aperture losses, the dynamic apertures obtained by tracking the realistic LHC lattices with the described random errors are satisfactory. The results indicate that the field quality of the final focusing IR triplet are the most performance limiting elements. This is in full agreement with the result of a similar study made for the SSC [6].

8. References

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