DYNAMIC APERTURE LIMITATIONS OF THE LHC IN PHYSICS CONDITIONS DUE TO LOW-β INSERTIONS

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Abstract

The dynamic aperture of LHC in collision is determined by the multipole field errors of the low-beta triplet quadrupoles. Their effect, combined with that of the systematic and random magnetic imperfections expected in all machine magnets is analysed here. The effect of crossing angle is taken into account.

1 INTRODUCTION

The effects of the multipole components in the low-β quadrupoles was investigated some time ago [1] on a preliminary version of LHC, with a short term tracking. It was noticed that the errors in the triplet dominate the non-linear dynamics. As the field errors are now better known, it is important to remake the analysis with long term tracking including synchrotron oscillations. This is the subject of this paper, it is shown that the triplet errors still dominate with the latest LHC design.

2 THE LHC LATTICE

The LHC lattice we consider is that described in the conceptual design report [2]. It is labelled version 4.2 and has four physics insertions where β^* has a value of 0.5m in physics conditions in both planes, in order to achieve a luminosity of about $10^{34}\ cm^{-2}s^{-1}$. This low β^* value is obtained by means of highly focusing quadrupoles triplets [2][3]. As the free space between the interaction point and the first low-β quadrupole is about 20m, the peak β-value in the triplets is of the order of 4000m. This gives an enormous importance to the multipole components at this location as shown below.

3 FIELD ERRORS IN THE LHC MAGNETS

The field errors are divided into :

- average or design errors, associated with a given magnet type. They obey symmetry rule, e.g. in the dipoles, all b_n with n even change sign when going from an inner aperture to an outer one.
- uncertainty on average errors. This is indicated by a $\pm$ sign in the tables [2]. They are randomly assigned to each LHC arc.
- random errors from magnet to magnet, distributed according to a Gaussian law cut at 3σ, except for the low-β quadrupoles where the cut is at 2σ.

An input for the MAD program [4], used for the optics calculations and trajectory tracking, has been made to specify all errors at a time, so that the distribution of a given error remains the same whatever the others. This procedure is a little heavy but it makes it possible to obtain the effect of any multipole component in any context.

3.1 Arc cell magnets

The multipole errors in the dipoles and the arc quadrupoles are those given in the “yellow book” [2]. It can be shown with equation 1 below that the quadrupole errors are only a few percents of the dipole errors and hence negligible, except b_6 which will be studied separately.

3.2 Other LHC magnets

Quadrupoles similar to the arc cell quadrupoles are used to match the insertions and dispersion suppressors. They behave similarly to the arc cell quadrupoles.

The two LHC beams are brought in collision by means of dipole magnets sitting between the dispersion suppressors and the insertions. Under physics conditions the value of the β functions in these dipoles is large. Their effect on the dynamic aperture is then important. As they have not yet been designed, no error table is available and they are not considered here.

In the cleaning, dump and RF insertions there are conventional quadrupoles. Their field errors are determined by the design and are known within one percent. Their effect is examined below.

3.3 Low-β quadrupoles

The multipole errors in the low-β quadrupoles are given in table 1 [3]. In order to compare them with the field errors in the dipoles, an equivalent dipole error $b_{n,q,d}$ can be defined :

$$b_{n,q,d} = b_{n,q}\frac{Krl_q}{\theta} \quad (1)$$

where K is the normalised quadrupole gradient (0.00972m^{-2}), l_q the quadrupole length (5.5m), θ the angle of the dipole (5mrad) and $b_{n,q}$ the field error in the dipoles [2]. It can be noticed that the mean b_6 and b_{10}, which are the only important components, are smaller

Table 1: Multipole errors in the low-beta quadrupoles in physics. The errors are field errors at 10mm from the quadrupole axis, in units of 10^{-4}. b11, b12 and b13 are zero.

	Mean		Random	
n	b_n	a_n	b_n	a_n
3	0	0	0.68	0.68
4	0	0	0.23	0.23
5	0	0	0.08	0.08
6	-0.008	0	0.028	0.028
7	0	0	0.004	0.004
8	0	0	0.0009	0.0009
9	0	0	0.0002	0.0002
10	-0.005	0	0.00005	0.00005

than those in the main dipoles by one order of magnitude. However, in order to compare their effects, the non-linear aberrations, which scale with $Krl_q\beta^{\frac{n}{2}}$ for b_n have to be compared.

For the low-β quadrupoles, β_x is 4000m in half of them and 1000 in the others with opposite sign. The value of $b_6Krl_q{\beta_x}^3$ merely summed over all triplet quadrupoles is $4.3{\times}10^6m^3$. For the dipoles the similar quantity $b_6\theta{\beta_x}^3$ is only $4.1{\times}10^4m^3$. Such a calculation is extremely crude but it shows that the effect of the quadrupoles on the non-linear betatron oscillations is expected to be larger than that of the dipoles by about two orders of magnitude.

The accurate estimation of the effect of these errors is done below by long term tracking of particle trajectories.

4 DYNAMIC APERTURE

The dynamic aperture is defined as the maximum action in both planes simultaneously for which transverse betatron oscillations remain stable over 10^5 turns. Tracking the particle trajectories is done with the MAD program [4]. The trajectories start at the interaction point IP1 where both β^* are 0.5m. Both starting coordinates are equal, the initial relative momentum deviation is 3.6×10^{-4} and all canonical momenta are zero. Under these conditions, the initial amplitude (the same value in x and y) has to be multiplied by $\sqrt{2}$ in order to give the maximum radius in the $\{$x,y$\}$ plane.

The tunes are Qx=63.28, Qy=63.31, Qs=0.001 (16MV RF voltage for an energy of 7TeV).

Neither alignment errors nor quadrupole errors are included (a2=b2=0). The b3 and b5 compensators, the so called “spool pieces” in the dipole ends, are turned on. Both tune derivatives are set to 1.0 after the errors are introduced in order to take into account the tune modulation associated with the synchrotron oscillations. A physical aperture limitation has only been introduced only for the case of individual multipoles (section 7).

5 DYNAMIC APERTURE DUE TO THE ARC CELL ERRORS

The dynamic apertures as well as their average and standard deviation obtained for 10 random distributions of the errors in the arc cell magnets are listed in table 2. Under physics

Table 2: Dynamic aperture associated with the dipole and arc quadrupole errors, both systematic and random.

seed	10^4 turns		10^5 turns	
eopt	x at QF/mm	n_σ	x at QF/mm	n_σ
1	11.9	39.2	9.6	31.7
2	12.7	42.0	11.6	38.3
3	11.9	39.2	11.3	37.3
4	13.0	42.9	11.9	39.2
5	10.7	35.5	9.1	29.9
6	12.7	42.0	11.6	38.3
7	11.9	39.2	11.0	36.4
8	15.6	51.3	14.7	48.5
9	13.9	45.7	11.3	37.3
10	11.0	36.4	10.7	35.5
x_{av}	12.5	41.4	11.3	37.3
σ_x	1.3	4.4	1.4	4.7

conditions the primary collimators limit the aperture to 6σ at most and the betatron motion must be regular enough for the particles scattered by the primary collimators and reaching 10σ [6]. This is largely fulfilled with a dynamic aperture of 10σ at 10^4 turns.

The results in table 2 show that we are well above these limits. If the systematic multipoles in the warm quadrupoles are added, the reduction of the dynamic aperture is of the order of 5%, i.e. negligible.

6 DYNAMIC APERTURE DUE TO THE LOW-β QUADRUPOLES

6.1 *No crossing angle*

Table 3: Average dynamic aperture associated with the dipole, arc quadrupole and low-β quadrupole errors, both systematic and random.

	10^4 turns		10^5 turns	
	x at QF/mm	n_σ	x at QF/mm	n_σ
x_{av}	4.0	13.3	3.8	12.5
σ_x	0.2	0.6	0.2	0.7

The summary of the results of the computation of the dynamic apertures obtained for the same 10 random distributions of the errors as in the previous section is shown in table 3. Its variability with the distribution of the random errors is considerably reduced compared with that in table 2 : It is clear that the multipoles in the low-β quadrupoles dominate the dynamic aperture.

6.2 *Crossing angle*

The LHC beams cross at a full angle of 200μrad. This is achieved with a local closed orbit distortion made independently in both rings. The angle of 100μrad in each ring makes a closed orbit excursion of about 5mm in the low-β quadrupoles. Because of the multipole components in the quadrupoles, lower order multipoles are created (this is often referred to as “multipole feed-down”). The summary of

Table 4: Dynamic aperture associated with the dipole, arc quadrupole and low-β quadrupole errors, both systematic and random. Crossing angle scheme on. If the warm quads are added, x_{av} increases by 3%.

	10^4 turns		10^5 turns	
	x at QF/mm	n_σ	x at QF/mm	n_σ
x_{av}	3.2	10.6	3.0	9.9
σ_x	0.2	0.6	0.2	0.6

the results of the computation of the dynamic aperture obtained by turning the crossing angle scheme on, with the errors described in the preceding section, is shown in table 4. A reduction by a factor 0.8 is observed.

In fact, turning the crossing angle scheme on produces little effects on the linear optics. The tunes-shifts are 1.1×10^{-4} in the horizontal and -3.3×10^{-3} in the vertical plane, they are compensated by means of auxiliary quadrupoles [7] which produce a negligible optics perturbation. The chromaticities do not change. A negligible linear coupling is due to the feed-down effect of the skew multipole components (the resulting width of the coupling resonance is 3.4×10^{-3}, it is not compensated). The observed effect must be then due to the "feed-down" of low-order multipoles. Indeed the anharmonicity increases by about 20% on average when the crossing angle is turned on.

7 EFFECT OF INDIVIDUAL COMPONENTS IN THE LOW-β QUADRUPOLES

The dynamic aperture was computed for each multipole component in the low-β quadrupoles in presence of the chromaticity sextupoles only. The results are shown in table 5. If the aperture limitation due to the vacuum chamber is introduced both in the arc quadrupoles and in the triplet, the results are identical, with the present amplitude steps.

The dominating multipole is b10. This can be easily understood by computing the field errors at the maximum amplitude in the low-β quadrupoles. For the case where the maximum horizontal amplitude is 3.4mm in the arc where β_x is 181m, it is 16mm in the low-β quadrupoles where β_x is 4000m. The vertical field error at 16mm is then -0.084×10^{-4} for b6 and -0.34×10^{-4} for b10. It is clear that the reference radius of 10mm does not give a right idea of the relevant errors in the low-β quadrupoles.

8 SOLUTIONS TO THE MULTIPOLE PROBLEM

In order to obtain a dynamic aperture of 10σ, it is probably not possible to re-optimise the field error in the triplet, as a reduction of b10 by a factor of about 5, which may not be possible, gives a just acceptable dynamic aperture (table 5). A safe solution is to use compensators for the most dangerous component and this is presently under study. With the present field errors, three b10 compensators placed close to each quadrupole are probably necessary.

Table 5: Dynamic aperture associated with low-β quadrupole systematic errors and chromaticity sextupoles only (upper), random b6 and b10 are added in the lower part (the r.m.s. deviation in indicated with $\pm$. Crossing angle scheme on. $\hat{x}$ is the maximum amplitude at QF. The dynamic aperture according to the Liapounov exponent is given in Liap.

	10^4 turns		10^5 turns		
mult.	$\hat{x}$/mm	n_σ	$\hat{x}$/mm	n_σ	Liap.
b6	7.1	23.3	7.1	23.3	23.3
b10	3.4	11.2	3.4	11.2	11.2
b6+b10	3.7	12.1	3.4	11.2	11.2
b6+.2b10	4.8	15.9	4.5	14.9	
b6+r	4.8±0.4	15.9	4.3±0.3	14.3	
b10+r	3.4±0.0	11.2	3.3±0.1	11.0	
b6+b10+r	3.4±0.1	11.2	3.3±0.1	10.7	

Eventually increasing β^* reduces the maximum β's in the low-β quadrupoles. The dynamic aperture computed with a β^* of 1m in presence of b6, b10 and chromaticity sextupoles increases to 28σ, which shows the its sensitivity to β^*.

9 CONCLUSION

The multipole errors in the low-β quadrupoles limit the dynamic aperture under physics conditions because of the large values of the β-functions in these quadrupoles. They are one of the main contributors to the lower limit on β^*. A compensation system, necessary to reach very small β^* is now under study.

10 REFERENCES

[1] B.T. Leemann and W. Scandale, Performance limitations of LHC low beta insertions. EPAC Rome, June 1988.

[2] The LHC study group, The LARGE HADRON COLLIDER Conceptual design. CERN/AC/95-05(LHC), 20 October 1995.

[3] R. Ostojic, T.M. Taylor, private communication.

[4] H. Grote and F.C. Iselin, The MAD program (Methodical Accelerator Design) version 8.16, User's reference manual, CERN/SL/90-13(AP), (rev. 4) (March 27, 1995).

[5] M. Giesch, Twin aperture quadrupoles for the LHC cleaning insertions. Magnet Technology Conference (MT14), June 1995, Tampere, Finland. Also CERN AT/95-15(MA) and LHC Note 323.

[6] J. B. Jeanneret, private communication.

[7] A. Verdier, Operational Q-shifts and $b2$ compensation in LHC. LHC Project Note 26 (January 8, 1996).