DYNAMIC APERTURE REDUCTION FROM THE DODECAPOLE COMPONENT IN THE LHC MAINQUADRUPOLES AND ITS MECHANISM

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Abstract

The systematic dodecapole component in the Main Quadrupoles of the LHC lattice has a strong influence on the machine dynamic aperture at injection. In this paper we quantify this effect with the help of tracking studies, explain the mechanism for the loss in dynamic aperture and look into potential correction schemes. Finally, we provide an estimate for the maximum allowed systematic dodecapole component in the MQ.

INTRODUCTION

The LHC is composed of 8 arcs, each containing 23 FODO cells. Each basic cell, 107 m long, contains 6 main bending (MB) and 2 main Quadrupoles (MQ). Each MB is equipped with a sextupole corrector and every other one has in addition a nested octupole and decapole corrector. Each MQ is equipped with orbit correctors and sextupoles; MQs are alternatively equipped with an octupole or trim quadrupole. The phase advance over one cell is about 90 degrees in both planes. The nominal injection working point for the LHC is at a tune of 64.28 in the horizontal plane and 59.31 in the vertical. This working point is just below the 7^{th} order resonance. To date some 400 MBs and some 60 MQs have been produced and their field measured. The results of the field measurements are the harmonic content up to the 14^{th} harmonic. The MQ field can be expressed as a sum of all the harmonics components as

$$B_y + iB_x = B_{ref} \sum_{n=2}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

where B_{ref} represents the field measured at the reference radius R_{ref}, which is 17 mm for the LHC magnets and b_n and a_n represent the normalised straight and skew harmonics. They are specified in units of 10^{-4}.

The MBs are the biggest elements of the LHC cells and due to their importance and their complexity they drive the dynamic aperture of the machine. The dynamic aperture, quantified in units of r.m.s. beam size (sigma), is defined as the maximum initial amplitude stable after 10^5 turns, calculated by sampling over 5 angles in real space (15,30,45,60 and 75 deg), at injection energy and nominal emittance (450 GeV; emit=3.75 µm norm.). To achieve an accuracy of 0.5 sigma on the dynamic aperture estimate, 60 error configurations are randomly generated and the minimum and average values of the dynamic aperture are recorded. The minimum dynamic aperture in presence of the MB field errors is 11.5 sigma and this is the target value of the LHC machine design.

Dynamic aperture studies done in the past [1] have assumed a total systematic component of the dodecapole in the MQ of b6= -1 units. To that level the effect on the dynamic aperture is in the shadow of the MBs. The systematic component at injection is the sum of the contribution from the persistent current and of the geometrical component. The LHC MQ geometry has been designed such as to create a strong positive dodecapole with the aim of cancelling out the strong negative dodecapole coming from the persistent current at the beginning of injection. After some 50 quadrupoles were measured at warm in industry, it became clear that an overall positive b6 component of at least 3 units was to be expected for the MQs.

DYNAMIC APERTURE STUDIES

The scope of the studies reported in the following is to evaluate whether the strongly positive component measured on the first 50 quadrupoles has a negative effect on the machine dynamic aperture at injection and if so if it can be mitigated by simple means.

Dynamic Aperture vs. b6 for Nominal Working Point

Fig. 1 shows the minimum and average dynamic aperture for the LHC machine for the nominal working point in presence of the MB and MQ field errors, varying the systematic dodecapole component in the MQs. No attempt is done to correct the effects.

Three observations emerge from this figure:

- that the dodecapole strongly influences the dynamics aperture ;
- that the dynamic aperture as a function of b6 is not symmetric around zero. This effect, which is present only in the horizontal plane, must be due to a compensation of other imperfections driving resonances and/or detuning. It will be investigated and explained in the next paragraphs; and
- that generally a positive value of the MQ dodecapole is not acceptable. It causes the minimum dynamic aperture to drop below the target value requiring a machine operation or hardware change.

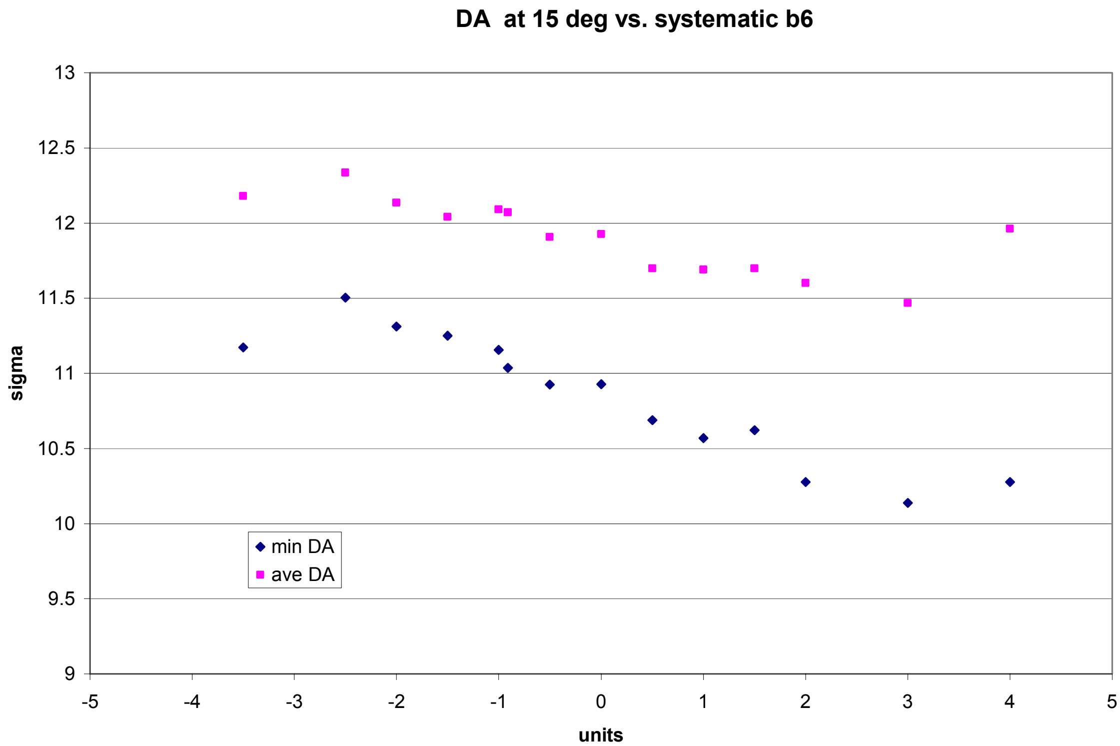

Figure 1: Dynamic aperture vs. the systematic component of the dodecapole in the LHC Main Quadrupoles.

Dynamic Aperture vs. b6 for Different Working Points

In order to understand the mechanism of the dynamic aperture asymmetry with respect to the dodecapole component the strength of the MQ has been changed to slightly move the machine working point. Two working points above the nominal and one below nominal have been simulated, the horizontal tune changing from 64.275 to 64.285, the vertical tune fixed at the nominal value of 59.31. Fig. 2 shows that by changing the tune the slope of the curve changes signs which implies that the effect of b6 on the behaviour of the DA is tune-dependent.

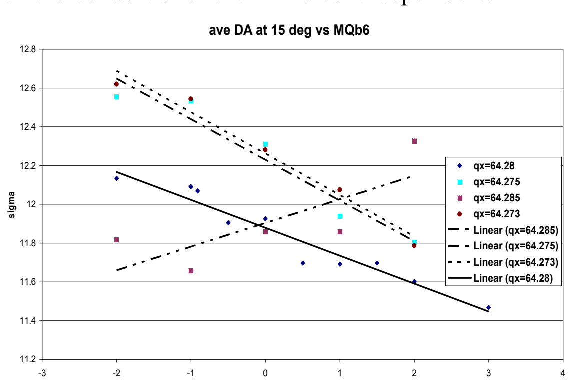

Figure 2: Dynamic aperture vs. b6 for varying horizontal machine tune. The bold line corresponds to the nominal tune.

Compensation of Errors in the Main Bending by the b6 in the Main Quadrupoles

An hypothesis on the asymmetric behaviour of the dynamic aperture is that the b6 in the MQ compensates some error in the MBs. In order to verify this hypothesis a series of runs with selected MB harmonics switched off have been done. The most significant are shown in Fig. 3, 4 and 5.

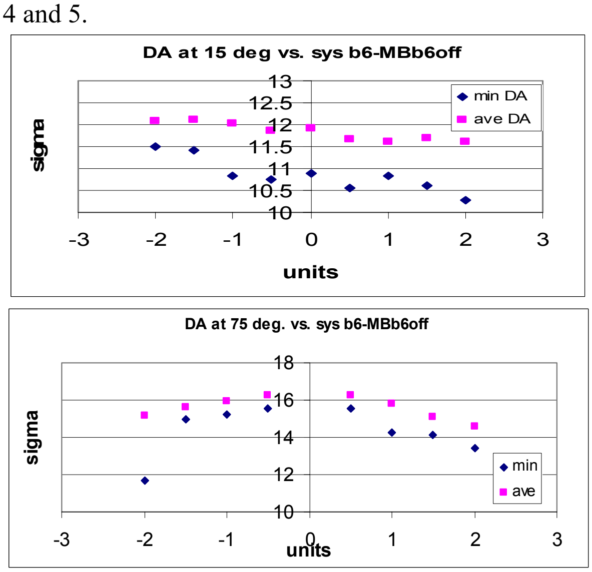

Figure 3: Dynamic aperture (horiz,top; vertical, bottom) vs. b6 in MQs with b6 in the MBs switched off.

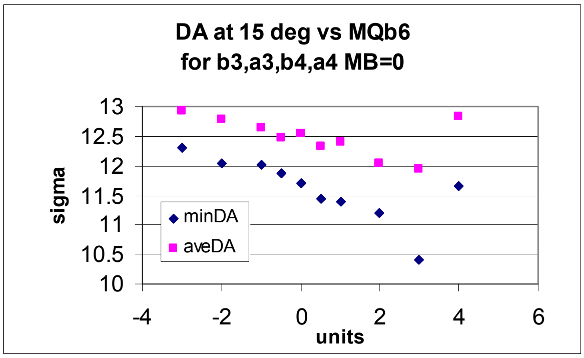

Figure 4: Dynamic aperture vs. b6 in the MQs with skew and straight sextupole and octupole in the MBs switched off.

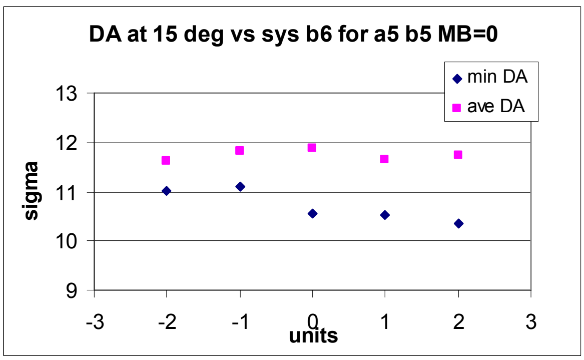

Figure 5: Dynamic aperture vs. b6 in MQs with skew and straight decapole in the MBs switched off.

From Fig. 3, 4 and 5 we can deduce that the negative value of b6 in the MQ compensates the second-order effect of a decapole in the MBs exciting the 7th order resonance. In fact Fig. 5 is the only case where the average dynamic aperture is symmetric with respect to zero. Hints to this interpretation can be found in [2].

POSSIBLE CURES

In parallel to the investigation of the problem, some cures have been tried out. These include:

A resonance free lattice. A new lattice, with intrinsic resonance compensation after each arc [3], was designed to see if in this configuration the effect of the dodecapole in the MQ could be mitigated. The phase advances in such a lattice are adjusted to cancel all first order resonance driving terms up to 6th order for each arc. The dynamic aperture obtained with this lattice was comparable to that obtained with the nominal. This shows that the problem with the dynamic aperture did not come from the single resonance driving terms associated with the systematic dodecapole component in first order.

The compensation with the dodecapole spool piece. An attempt was made to compensate the detuning induced by the MQ dodecapole by using the dodecapole spool piece located in the triplet of the interaction region 1,5,2 and 8. Unfortunately the strength needed turned out to be out of range by a factor 3 to 4.

The compensation with the lattice octupoles. An attempt was made to compensate with the lattice octupoles the detuning of the dodecapole in the MQ. Tracking revealed that this approach was beneficial in the vertical plane but not very effective in the horizontal one. Besides, the lattice octupoles would be used at 1 per mil of their nominal current, requiring accurate cycling procedures to avoid hysteresis effects.

The change of MQ cross section. Having demonstrated that the dynamic aperture cannot be recovered by adjustment of the LHC correctors, a change of cross section has been implemented on the MQs, change that brought the b6 component within the wanted boundaries at all time during injection. Nevertheless, enough quadrupoles were already produced to fill almost two octants. Beam tracking studies show that the situation is tolerable although it reduces the minimum dynamic aperture by a fraction of sigma.

CONCLUSIONS

The dodecapole component in the LHC main quadrupoles has a considerable effect on the machine dynamic aperture and it must be carefully controlled at all time during injection. The optimal value of the dodecapole is found to be -1 units and this asymmetry is explained by a compensation of the decapole component of the main bendings. Alternative solutions have been tried to avoid modifying the cross section of the magnets but none of them gave the wanted results.

REFERENCES

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