NUMERICAL STUDIES OF THE IMPACT OF THE SEPARATION DIPOLES AND INSERTION QUADRUPOLES FIELD QUALITY ON THE DYNAMIC APERTURE OF THE CERN LHC

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Abstract

A wide range of magnets, both warm and superconducting, will be used in the LHC. In addition to main dipoles, quadrupoles are used to focus the beam in regular arcs. Special dipoles separate or merge the two beams in insertion regions. A few very strong superconducting quadrupoles squeeze the beam to achieve the required luminosity, while warm quadrupoles are used in the collimation insertions. At injection the main dipoles largely dominate beam dynamics, but contributions from smaller classes of magnets should not be neglected. Peculiar optical configurations may dramatically enhance beam dynamics effects of a few magnetic elements. This paper will focus on the effect of insertion quadrupoles, e.g. wide-aperture, and warm quadrupoles, as well as separation dipoles on the dynamic aperture of the LHC machine.

INTRODUCTION

Although the performance of the CERN LHC will be dominated by main dipoles (MBs) and by triplet quadrupoles field quality at injection and collision energy, respectively, separation dipoles (cold and warm D1s, cold D2s and cold and warm D2s, D3s, and D4s) as well as insertion quadrupoles (cold MQMs, and MQYs, and warm MQWs) are potentially critical due to optical conditions that could enhance the harmful effects of magnetic field errors.

The results presented here (see Ref. [1] for a detailed overview) concern the impact of the magnets' field quality on the dynamic aperture (DA), the maximum stable amplitude in phase space. DA will be considered the main quality factor, required to be larger than 11σ. The DA computation relies on numerical simulations performed with the SixTrack [2] code according to a well defined protocol [3]. Particle motion is studied up to 10^5 turns. Initial coordinates lying along 5 angles are chosen, with 30 initial conditions uniformly distributed over an amplitude range of 2σ. The momentum offset is 7.5×10^{-4}, i.e. $3/4$ of the bucket half height at injection energy, while at collision energy the momentum offset is 2.7×10^{-4}. This approach is believed to guarantee accuracy in the DA computation of about 0.5σ [4]. The influence of random magnetic errors is taken into account by repeating the DA computation for 60 realisations of the LHC with magnetic field errors so to evaluate minimum, maximum, and average values of the DA over the ensemble of realisations.

The lattice model considered is the version 6.4 [5] with the Q3 insertion quadrupole moved 0.30 m towards the IP.

IMPACT OF COLD MAGNETS ON DA

Insertion Quadrupoles

The MQM insertion quadrupoles are installed in the dispersion suppressors (DS) and matching sections (MS) at positions between Q6 and Q10, in experimental insertions IR1, IR2, IR5, IR8, and in rf-insertion IR4 and dump-insertion IR6. MQY insertion quadrupoles are installed in the MS at positions between Q4 and Q6 in all insertions but IR3 and IR7.

Both MQMs and MQYs are located in sections where the beta-functions are well beyond the average value in the arcs, thus amplifying not only field errors, but also alignment errors [6]. As an example, at injection the beta-functions at the location of MQMs or MQYs can be as high as 650 m (to be compared to 180 m peak value in the regular arc), while in collision values in excess of 1500 m are achieved.

A tracking campaign was launched to quantify the impact on the DA of the field quality of the MQMs and MQYs [7] and to identify critical multipoles. MQ-like field errors were assigned to MQMs and MQYs. The results are reported in Fig. 1, where the DA is plotted for a reference case with errors in MBs, MQs and cold D1s and D2s, a case comprising also errors in MQMs quadrupoles, one case where errors in both MQMs and MQYs are included, and another case where MQMs and MQYs are also included. The latter has the b_6 component (random and systematic) set to zero. The strong impact on DA of MQMs and MQYs is clearly visible: MQMs reduce the minimum DA by about 0.6σ, and MQYs generate an additional loss of more than 1.5σ. Contrary to MQs, for which b_6 is responsible for DA

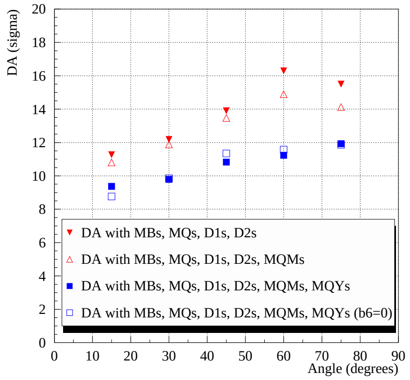

Figure 1: Minimum DA vs. angle for configurations with errors in MBs, MQs, cold D1s and D2s, including MQMs, MQYs, and a special configuration where b_6(MQY)$= 0$ (both systematic and random).

loss [8], it does not have a strong impact on the DA.

The analysis then focused on MQYs to identify the critical multipoles. Several configurations where studied, with multipoles selectively set to zero, e.g. all $a_n = 0$, all $b_n = 0$, $a_n = 0$ and $b_n = 0, n > 7$, $a_n = 0$ and $b_n = 0, n < 7$ (b_1 stands for the dipole component). One case where MQYs have the same errors as triplet quadrupoles MQXB has been considered. The results are reported in Fig. 2, for comparison the case b_6(MQY)$= 0$ is also shown. The main sources of DA reduction are skew multipoles, which govern DA at small angles, while at large angles, low order normal multipoles dominate. The best configuration is found with $a_n = 0$ and $b_n = 0, n < 7$, since the DA recovers its value without any MQYs (see Fig. 1). A similar performance is obtained with MQXB-like errors in MQYs, as both $a_n(\mathrm{MQXB})$ and low order normal multipoles are rather small at injection.

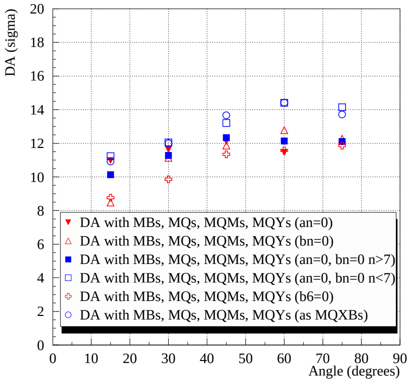

Figure 2: Minimum DA vs. angle at injection for various configurations with errors in MBs, MQs, cold D1s and D2s, MQMs, and selected error components of MQYs set to zero.

Beginning at 2004 the MQ cross-section has been modified to steer b_6 towards the limits imposed by DA preservation [1, 8], thus changing the distribution of b_6 in MQs among sectors. Furthermore, magnetic measurements on first MQMs and MQYs showed strong hysteresis effects for b_6, b_{10} [9]. As MQMs and MQYs are used in matching sections, large magnet-to-magnet variations in b_6 and b_{10} are to be expected. All these findings will be considered in the next tracking campaign.

Computation of DA in collision (proton configuration) was also performed assuming that the MQMs behave as MQs, as far as the field quality is concerned, while MQYs have the same errors as the MQXB low-beta quadrupoles. The addition of new elements (MQMs and MQYs) following the above assumptions leaves the DA unchanged as seen in Fig. 3. These results should be confirmed by additional tracking studies for the ions optics.

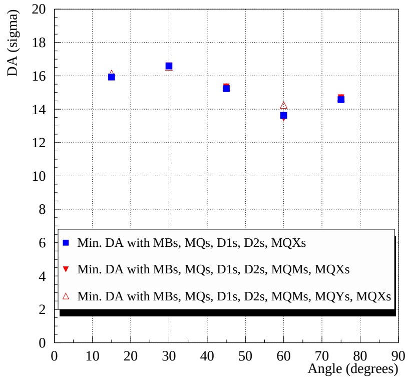

Figure 3: Minimum DA vs. angle for three error configurations for collision energy (proton configuration) and with parallel separation.

Separation Dipoles

The detailed study of the impact of the cold separation dipoles can be found in Ref. [10], only the main results are summarised here.

The cold D1 separation dipoles are located in the experimental insertions IR2 and IR8, while the D2 separation dipoles are in all four experimental insertions and bring the two beams back to the nominal arc separation, i.e. 194 mm. Additional cold separation dipoles, D3 and D4, are installed in IR4 to increase the beam separation to 420 mm, thus allowing the installation of independent rf-systems for each beam.

For all types of separation dipoles, expected error tables are available [11, 12] and they have been used to study the impact on DA. The results are shown in Fig. 4, where both the minimum value as well as the average DA is plotted. The influence of the D3s, and D4s on the average DA is negligible, but it shows up in the minimum DA. Even though such a reduction is at the limit of the numerical accuracy of the DA computation, this calls for a careful follow-up of the results of the magnetic measurements on the D3s and D4s to confirm that the expected errors tables reflect the measured magnetic errors.

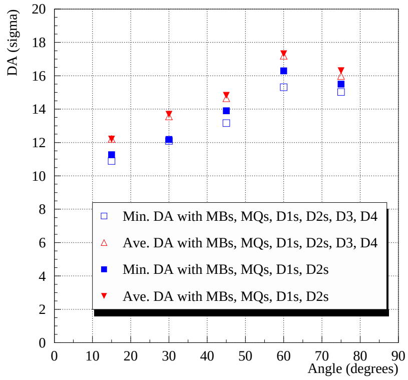

Figure 4: Minimum DA vs. angle for the configuration with errors in MBs, MQs, cold D1s and D2s, as well as cold D3s, and D4s for injection energy.

IMPACT OF WARM MAGNETS ON DA

Insertion Quadrupoles

Special two-bores warm quadrupoles are installed in IR3 and IR7 to stand in the high-losses environment related with the presence of the collimation system. Each Q4 or Q5 quadrupoles in IR3 and IR7 consists of six MQWs.

Critical aspects of the MQWs field quality, i.e. non-zero dipole component, its energy dependence, and nonlinear field quality, have been considered in detail [13]. The influence of MQWs on DA at injection was already studied for a previous version of the LHC lattice [15], giving target errors based on the conservation of DA. For the LHC V6.4 optics error tables derived from magnetic measurements [16] were used for the tracking studies. The results are shown in Fig. 5, where the DA vs. angle is plotted for two configurations, namely including errors in MBs, MQs, cold D1s and D2s, and a second configuration with MQWs included. At injection, the impact of MQWs on DA is clearly in the shadow of the other magnet classes. It is worth mentioning that magnetic measurements of additional MQWs (twenty-two in total) were successfully completed. Based on these results, updated error tables for MQWs were compiled [17] and tracking studies confirmed that the impact on the DA is marginal [13].

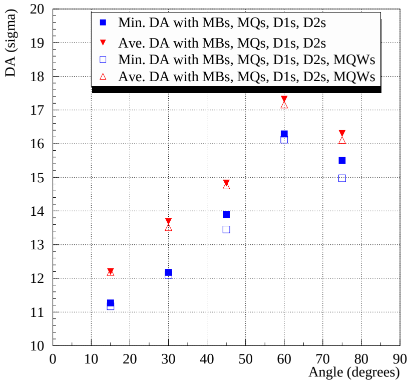

Figure 5: DA computation at injection for the configuration including errors in the MBs, MQs, cold D1s and D2s, and also the warm quadrupoles MQWs.

Separation Dipoles

Warm separation dipoles are installed in IR1 and IR5, where the high-luminosity prevents installating cold magnets. Due to their location in high-beta regions, the warm D1s are rather critical in collision, and it is essential that they have a very good field quality. Indeed, magnetic measurements performed with rotating coils on the first magnet that has been produced, show that the field quality is much better when compared with that of cold D1s [18]. However, tracking studies will be needed to verify that the impact on DA is indeed small.

Warm separation magnets, called D3 and D4, installed in IR3 and IR7 to increase the beam separation to 224 mm. Although these magnets are expected to have a negligible impact on DA since the beta-functions are not too large, further studies will be required for the new layout of IR3, IR7, implemented in the newly released LHC optics V6.5.

CONCLUSIONS AND OUTLOOK

A review of the main issues for the LHC magnets other than the MBs and MQs has been presented. The cold MQMs and MQYs, proved to be critical for the machine performance due to the large values of the beta-functions. Numerical simulations allowed to identify harmful multipole components. Further investigations will provide a detailed set of target multipolar errors taking into account recent results on field quality of MQs.

While cold D1s and D2s proved to be in the shadow of MBs and MQs, D3 and D4 have an impact on the minimum DA at the limit of the numerical accuracy, thus requiring a careful follow-up of the actual magnet field quality.

Warm quadrupoles revealed potential problems such as non-negligible dipole component, variation of magnetic centre vs. field strength, and field quality proper. Detailed analysis showed that all three issues are indeed not critical for machine performance.

Finally, warm separation dipoles proved to be non critical, either because their field quality is extremely good (D1s) or because the beta-functions are not enhancing the impact of magnetic errors on beam dynamics (D3s and D4s).

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REFERENCES

[1] O. Brüning, S. Fartoukh, M. Giovannozzi, A. Lombardi, T. Risselada, F. Schmidt, *CERN-AB-2004-014-ADM* (2004).

[2] F. Schmidt, *CERN-SL-* **94-56** (1994).

[3] M. Hayes, F. Schmidt, *LHC-PROJECT-NOTE-* **300** (2002).

[4] M. Hayes, E. McIntosh, F. Schmidt, *LHC-PROJECT-NOTE-* **309** (2003).

[5] The LHC Design Report, Vol. I The LHC Main Ring, Chapter 3, CERN-2004-003.

[6] M. Giovannozzi, A. Verdier, in preparation.

[7] M. Giovannozzi, talk at the FQWG meeting, 09/12/03, http://fqwg.web.cern.ch/fqwg/031209/mg031209.pdf.

[8] A. M. Lombardi, O. Brüning, S. Fartoukh, T. Risselada, F. Schmidt, A. Verdier, these proceedings.

[9] R. Ostojic, talk at the FQWG meeting, 09/12/03, http://fqwg.web.cern.ch/fqwg/031209/ro031209.ppt.

[10] O. S. Brüning, S. Fartoukh, M. Giovannozzi, T. Risselada, *LHC- PROJECT-NOTE-* **349** (2004).

[11] E. Willen, *LHC-MBR-ES-0001* **rev. 2.0** (2000).

[12] A. Jain, P. Wanderer, E. Willen, *BNL, Magnet Division Note 598-32* **(AM-MD-299)** (2000).

[13] M. Giovannozzi, T. Risselada, F. Schmidt, in preparation.

[14] M. Giovannozzi, talk at the LTC Meeting, 19/03/03, http://lhcp.web.cern.ch/lhcp/ab-ltc/ltc_2003-03.html.

[15] F. Schmidt, *LHC-PROJECT-NOTE-* **229** (2000).

[16] E. Boter, G. de Rijk, *LHC-PROJECT-NOTE-* **289** (2002).

[17] S. Ramberger, private communication, 2004.

[18] M. Giovannozzi, talk at the LTC meeting, 05/05/04, http://lhcp.web.cern.ch/lhcp/ab-ltc/ltc_2004-6b.pdf.