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DYNAMICAL APERTURE STUDIES FOR THE CERN LHC: COMPARISON BETWEEN STATISTICAL ASSIGNMENT OF MAGNETIC FIELD ERRORS AND ACTUAL MEASURED FIELD ERRORS

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Abstract

It is customary to evaluate the performance of a circular particle accelerator by computing the dynamical aperture, i.e. the domain in phase space where bounded single-particle motion occurs. In the case of the LHC the dynamical aperture computation is performed by assuming a statistical distribution of the magnetic field errors of various magnets classes: the numerical computations are repeated for a given set of realisations of the LHC ring. With the progress in the magnet production and allocation of the available positions in the ring, the statistical approach has to be replaced by the computation of one single configuration, namely the actual realisation of the machine. Comparisons between the two approaches are presented and discussed in details.

INTRODUCTION

The dynamic aperture (DA), i.e. the amplitude of the region in phase space where stable motion occurs, is a key quantity in the evaluation of the performance of the future LHC. Therefore, an accurate numerical estimate is mandatory as well as a good knowledge of the error associated with the protocol used to compute the DA (see Ref. [1] for a detailed account on the subject). The computation of such a quantity relies on numerical simulations, performed with the MAD-X [2] and/or the Sixtrack [3] codes. For the case of the LHC studies, the number of turns N is equal to 10^5. A polar grid is defined in the physical space (x, y). Five angles, corresponding to different transverse emittances ratio $\varepsilon_x / \varepsilon_y$, are considered. Along each of these radial directions, 30 initial conditions uniformly distributed over an amplitude range of 2 σ (each initial condition is in fact split into two nearby conditions to allow chaos detection by means of the computation of the maximal Lyapunov exponent [4, 5]) are considered. The momentum off-set of the initial conditions is set to 0.75×10^{-3}, corresponding to 3/4 of the bucket half-height. The use of such an approach should guarantee an accuracy in the computation of the DA of about 0.5 σ [6]. Indeed, the need of taking into account the influence of random magnetic errors requires that the DA computation is repeated for a number of different sequences of generated errors so as to evaluate minimum, maximum, and average values of the DA over the ensemble of realisations of random errors. An analysis of the statistical error was carried out in Ref. [7]. To have a 95 % confidence that only 5 % of the total number of all possible LHC realisations have a DA lower than the lowest one found by particle tracking, one needs an unbiased sample of 60 realisations of the LHC with magnetic field errors. It is worth mentioning that it is customary to express the DA in units of transverse beam size, i.e. sigmas.

The DA is used to qualify the performance of the machine and its target value is set to 12 sigma (see Ref. [1] for a detailed discussion about the target DA value and the break down of the sources on uncertainty).

While in Ref. [8] the issue of determining the accuracy of the protocol used to compute the DA is dealt with, in this paper the main focus is the evolution of the value of the DA for various versions of the LHC optics, as a function of the number of magnet classes included in the computation and, more relevant, the use of statistical errors or deterministic ones based on the situation of the machine as installed. The latter case is addressed for the first time, as, with the progress of the magnetic measurement programme and of the magnets allocation to machine slots, it is now possible to replace gradually the pure statistical approach in the magnetic error assignment.

It is customary to define typical distributions for the multipoles and to draw randomly from these distributions the values of the magnetic imperfections assigned to each machine location. However, for a given slot it is possible to use the values of the measured magnetic imperfections corresponding to the ones of the allocated magnet. As the magnet allocation is still in progress, whenever a given slot is still unassigned, the magnetic errors are drawn randomly from the measured distributions.

This approach allows studying the most representative model of the machine and, what is even more important, it allows to take into account the optimisation carried out with the sorting procedures applied to the various magnet classes (see, e.g., Refs. [9, 10] for the sorting strategies for the main dipoles and main quadrupoles, respectively).

EVALUATION OF DA FOR V6.4 OPTICS WITH STATISTICAL ERRORS

As far as the LHC model is concerned, the optics version V6.4 used for the computations presented in this paper is indeed very similar to the latest layout version V6.5 [11]. In fact, it contains already the displacement of the nonlinear corrector packages in the low-beta triplet quadrupole Q3, which is one of the main features of the optics change from plain V6.4 to V6.5. However, the optimisation of the orientation of the warm quadrupoles in Interaction Region (IR) 3 and IR7 to reduce the doses delivered to the electrical connections is not included. This has an impact on the sign of multipoles.

In terms of the optics, the main difference between V6.4 and V6.5 refers to the configuration of the cleaning insertions IR3 and IR7, the rest being the same.

This model of the LHC was used to intensive analysis of the impact of the field quality of various classes of magnet. While the approach of random error generation is still based on statistics, the set of multipoles are derived also from magnetic measurement results. Furthermore, some detailed effects were included in the simulations, such as impact of hysteresis on the field quality of the insertion quadrupoles (type MQM and MQY) affecting b_6 and $b_{10,}$ i.e. the allowed components for a quadrupole (see Ref. [11] for more details on the way magnetic multipoles are represented), and the impact of feed down effects for long trim quadrupoles (type MQTL). The first effect is relevant because of the wide range of the powering level at injection for the magnets of this class, while the second one is due to a strong b_{10} component revealed by the magnetic measurements, which could generate a sizeable a_9 via feed down. Such a multipole component proved to have a strong impact on DA.

The results concerning the DA computation are shown in Fig. 1 for both the minimum and the average DA as a function of the angle. Three configuration are considered, namely: i) the baseline with magnetic errors assigned only to main dipoles, main quadrupoles and cold separation dipoles; ii) the situation with magnetic errors assigned to all magnets (warm and cold) including also the feed down effect from MQTL; iii) the same configuration as ii) including also hysteresis effects.

The DA reduction due to the increase in detail of the model used in the numerical simulations is clearly seen. In particular a strong reduction for large values of the angles is observed. Interestingly enough, the reduction occurs not only for the minimum, but also for the average DA, showing that the impact cannot be neglected or considered a statistical effect. On the other hand, the hysteresis effects have a significant impact on the average DA, which is decreased nearly to the minimum value.

EVALUATION OF DA FOR V6.500 OPTICS WITH STATISTICAL ERRORS

Similar computation were also carried out for the present layout of the LHC ring, namely V6.500. Such a layout features small differences with respect to the V6.5 version.

Numerical simulations were repeated using the statistical approach to evaluate the DA for this version of the LHC machine. The results are summarised in Fig. 2, where similar data for V6.4 are also shown for the sake of comparison.

The triangles and squares identify the results for V6.4 and V6.500 layout, respectively. Open markers stand for simulation results obtained by using only the systematic part of the magnetic errors, while the full markers refer to the case where random errors are also included. In the latter case, the DA is computed as the minimum value over the 60 realisations of the LHC layout. For both layouts the magnetic errors are assigned to all classes of magnets.

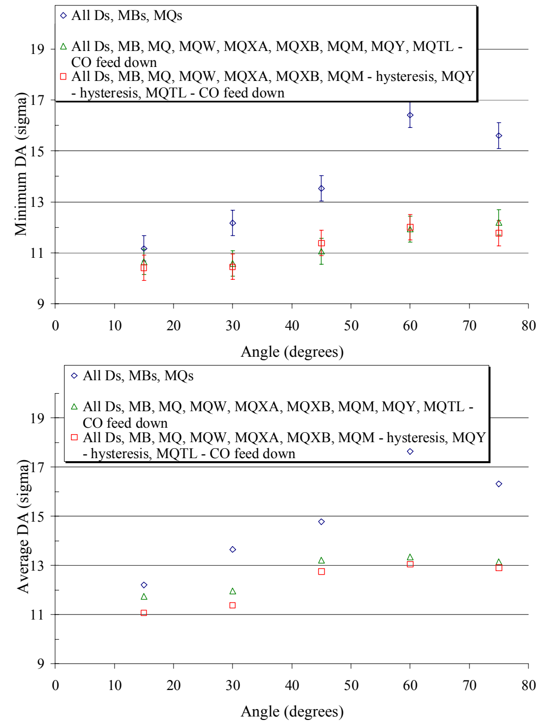

Figure 1: Minimum (top) and average (bottom) DA for three configurations of the V6.4 layout as a function of the angle. Both minimum and average are taken of the 60 realisation of the LHC. The error bars correspond to the assumed error on the DA estimate.

When only systematic errors are taken into account the results for the two configurations are remarkably similar, but at 60° for which the version V6.500 features a reduction of DA of about 2 sigma. Whenever the random errors are included in the numerical simulations the difference between the two layouts is negligible and the performance can be assumed to be the same.

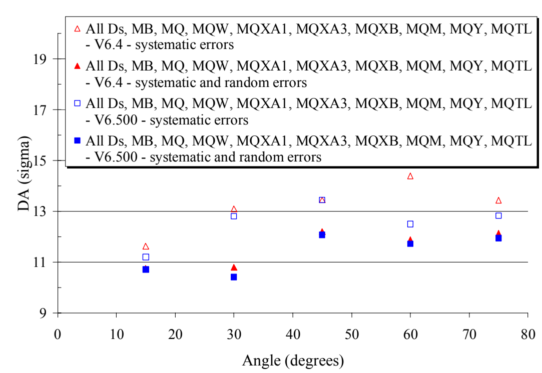

Figure 2: DA for two configurations of the V6.500 layout as a function of angle. Similar cases for V6.4 are reported for comparison. Whenever random errors are used the minimum DA over the 60 realisations is plotted.

EVALUATION OF DA FOR V6.500 OPTICS WITH MACHINE MODEL AS INSTALLED

Even though the latest model of the LHC lattice used for DA computation is the most complete statistical model available, it does not take full advantage of the huge amount of magnetic data and, what is even more important, of the fine optimisation performed when allocating magnets to the available slots in the machine. In fact, in the case of the main dipoles, a sorting strategy is applied [9] so that not only mechanical aperture and linear magnetic imperfections are optimised, but also the driving terms of the 3rd order resonance, which, in principle, could have an impact on the nonlinear beam dynamics and, hence, on the DA.

Recently, a new tool called Windows Interface to Simulation of Errors (WISE) [12] was developed, which allows extracting the field quality of each magnet produced and assign it to the corresponding slot in the LHC sequence selected for this magnet. Using warm-to-cold correlation factors, it is possible to evaluate the field quality under cold conditions for those magnets measured only at warm. In this respect, the statistical approach is replaced by a model representing the machine as installed. Whenever a slot is not yet assigned, the field quality is drawn from the distribution of measured data: this statistical part will reduce to zero once the installation of the machine will be completed. The results presented in this paper are obtained with a single realisation of the LHC machine is used. They are shown in Fig. 3, where the minimum (over the realisations) DA for V6.4 (statistical errors), V6.500 (statistical errors) and V6.500 with measured errors is reported as a function of the angle. In this case neither hysteresis effects for MQM and MQY quadrupoles, nor feed down effects from MQTL are considered. The use of measured errors produces an increase of the value of the DA of about 0.5 sigma at small angles, while it is even more pronounced at larger angles.

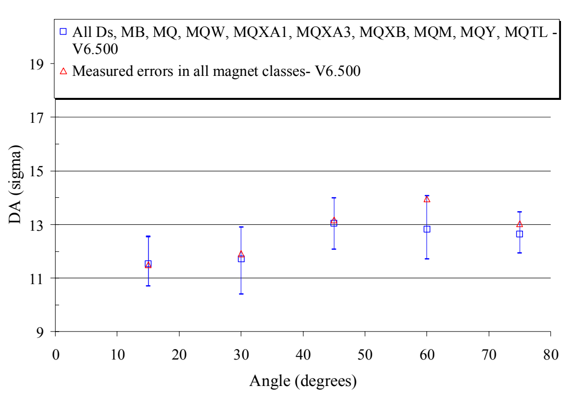

Figure 3: DA as a function of angle for V6.500 (statistical error) and V6.500 (measured errors as installed). In the case of statistical errors the markers represents the average, while the errors bars the minimum and maximum over the 60 realisations.

The evolution of the DA over the two layouts and the two approaches for magnetic errors, namely statistical and measured, is reported in Fig. 4. In this case the DA value represents minimum over the angles in addition to the minimum over the realisations (whenever applicable).

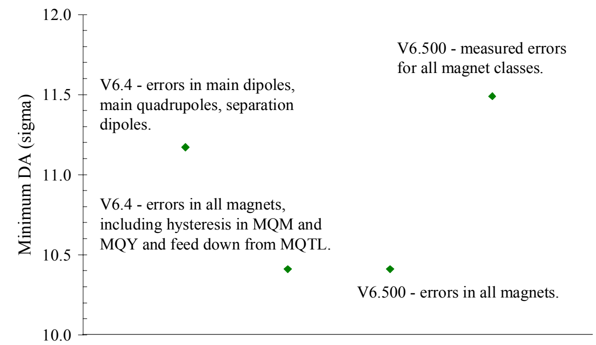

Figure 4: Evolution of the value of the DA for the various versions of the LHC optics and for different configurations of magnetic errors used in the simulations. In this case the minimum over the angles is shown.

The increase in DA is clearly seen. Starting from this new result, the novel approach allowing to study the machine as installed, will have to be exploited in order to assess the dependence of the DA estimate on the measurement errors or power converter errors. In a second stage this approach will be combined with the analysis of the impact of linear errors, dipole and quadrupole (normal and skew) to study the machine performance/behaviour under realistic operational conditions.

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