DYNAMIC APERTURE COMPUTATION FOR THE AS-BUILT CERN LARGE HADRON COLLIDER

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Abstract

During the design phase of the CERN Large Hadron Collider the dynamic aperture, i.e., the domain in phase space where stable motion occurs, was used as figure-of-merit to specify the field quality of the various classes of superconducting magnets. The programme of magnetic measurements performed within the framework of the magnets' acceptance process has produced a large amount of information available, which can be used to estimate the value of the dynamic aperture for the actual machine. In this paper the results of massive numerical simulations based on the measured field quality, both for injection and top energy configurations, are presented and discussed in detail.

INTRODUCTION

The dynamic aperture (DA), i.e. the amplitude of the region in phase space where stable motion occurs, has been a key quantity for the specification of the performance of the CERN LHC in its design stage. This is common to all other modern colliders and storage rings. 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 3/4 of the bucket half-height. The use of such an approach should guarantee the computation of the DA with an accuracy of about 0.5 σ [6]. In the design stage, a target value for the DA was set (see Ref. [1] for a detailed account of the rationale behind this choice as well as the breakdown of the various factors determining the target value). This was used for defining bounds on the field quality of the various classes of magnets, both super- and normal-conducting ones. The specification of the so-called error tables originally based on extrapolation from the field quality of existing machines, such as Tevatron or HERA, required CPU-intense tracking campaigns in past years, which resulted in a number of key publications, such as Refs. [7-11] and also summarised in Ref. [12]. In this context, a number of realisations of the LHC machine had to be taken into account in order have a reliable estimate of the DA. The considerations made in Ref. [7] fixed to 60 the number of realisations, or "seeds", used in the standard protocol of DA computation.

The beginning of the magnet production opened a new phase: the issue of allocating the magnets in a optimised slot, or the so-called magnets sorting (see, e.g., Ref. [13] for an overview of the strategy put in place for the installation of the LHC magnets), was raised. This activity was co-ordinated by the Magnet Evaluation Board [14]. At the end of the installation stage, the large amount of information gathered during the allocation stage and based on the heavy programme of magnetic measurements, was available. This made it possible a new approach to the numerical simulation of the LHC performance. To this aim the tool WISE [15, 16] was developed. It is capable of performing data mining in the numerous CERN databases to extract relevant information for beam dynamics simulations. The capabilities range from extraction of alignment data to magnetic field quality data, including the possibility of generating random errors based on different physical models. The latter is particularly relevant for the study described in this paper. In fact, it is now possible to simulate not a particular realisation of a statistical distribution of field errors, but exactly the machine as-built. The measured errors can be assigned to the magnets in their actual location. In principle this could remove completely the need of performing numerical simulations with different seeds. Still, due to the fact that only a limited number of magnets was measured in cold conditions, while the whole set of magnets was measured at warm, warm-to-cold correlations are required. These quantities are affected by unavoidable measurements errors: the 60 seeds used in the simulations described here represent realisations of warm-to-cold correlations in the range of the experimental error.

It is worth stressing that this new approach was already presented in Ref. [10], however, here many more configurations are analysed. Furthermore, it is now possible to simulate not the clockwise beam (Beam 1), but also the counter clockwise (Beam 2). Even if this might seem a rather straightforward point, a number of technical details had to be tackled and solved to obtain this new result.

NUMERICAL RESULTS

Tune Scan

It is customary to check the sensitivity of the DA on the fractional part of the tunes. In the design phase this study highlighted a number of dips in the value of the DA corresponding to resonances excited by the non-linear field errors (see Ref. [12] and references therein). In the case of the as-built machine the injection optics (featuring beta* of 11m/10m/11m/10m for IR1, IR2, IR5, IR8, respectively) was used. The fractional part of the tunes is changed in steps of 2×10^{-3} moving along the main diagonal. The results are shown in Fig. 1. There, the DA (averaged over the 60 seeds and taking the minimum over the five angles) is reported as a function of the fractional part of the tune for both beams.

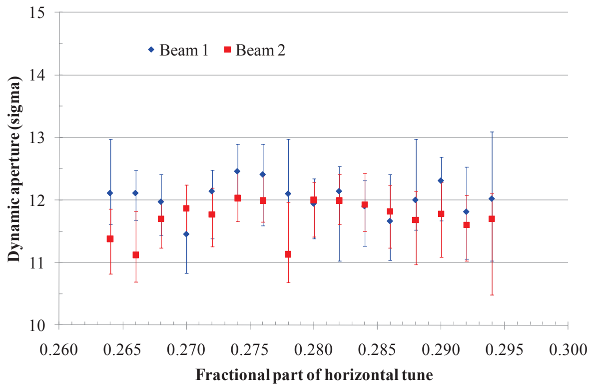

Figure 1: Dynamic aperture vs. fractional part of the horizontal tune at injection. The standard computation of long-term DA has been performed.

The error bars represent minimum and the maximum DA over the seeds (always taking the minimum over the five angles). No systematic difference is found between the two beams, even if Beam 2 features a slightly lower DA for tune around 0.265. Apart from this, a rather constant DA over tunes is observed, which is a nice feature for the operation of the LHC. It is also worth stressing the DA is essentially within the specified target value of 12 σ for a wide range of tunes.

DA at Injection Energy for the as-built LHC

The situation of the DA is particularly critical at injection. In fact, the beam is rather large and the magnetic errors particular relevant. All this makes it possible to reduce considerably the domain in phase space where stable motions occur. It is also clear that the main source of DA reduction are the main dipoles and the insertion quadrupoles, as, in some of the insertions, beta-functions can be as large as several hundred metres.

In Fig. 2 the average DA is shown as a function of the phase space angle. Unlike the standard protocol, 25 angles have been used to increase the coverage. The error bars are as for Fig. 1. Both beams are plotted. Once more, the performance in terms of DA is rather similar for the two beams. The target value is achieved for almost all the angles and the error bars are above 11 σ apart from a single case. This situation is relieving as during the campaign for the specification of the target field quality for the various magnet classes, much lower DA values were observed (see also next sections).

DA at Nominal Top Energy for the as-built LHC

At top energy, i.e. 7 TeV/beam, the situation is somewhat different. Clearly the DA is no more dominated by the field quality of the main dipoles, but rather by the insertion quadrupoles and low-beta triplets.

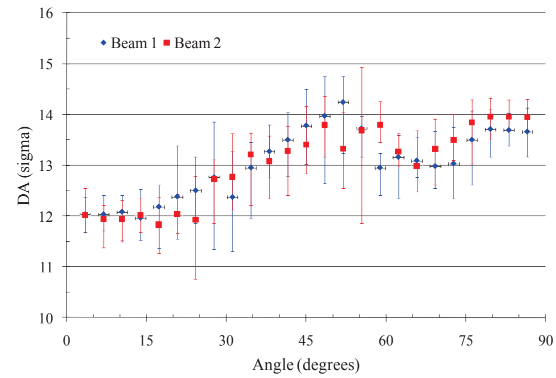

Figure 2: Dynamic aperture vs. angle for the standard injection optics. The standard computation of long-term DA, but with 25 angles has been performed.

Furthermore, the beam-beam effect is an essential source of non-linear behaviour and strongly dominates the DA. In this study, only single-particle effects are taken into account, and the beam-beam is completely neglected. Nevertheless, the computations reflect the quality of the magnets in the machine and, in general, indicate that the situation is within tolerances.

In Fig. 3 the minimum DA (over angles and seeds) for several configurations at top energy is plotted. In the case of unsqueezed optics (equal to the injection one) the DA is huge, indicating that the field quality of the main dipoles is really excellent and the beam size that shrunk due to acceleration, explores regions in the phase space where the dynamics is quasi-linear.

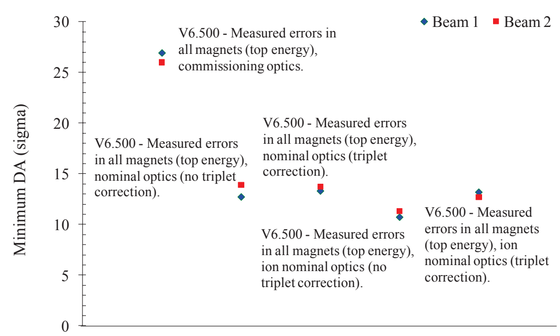

Figure 3: Global situation in terms of DA for various configurations at top energy. The standard computation of long-term DA, but with 11 angles has been performed.

The other four configurations considered refer to squeeze optics: for protons, i.e., only IR1 and IR5 with beta*=0.55 m, or for ions, with also IR2 squeezed to beta*=0.5 m. The impact of the triplet field quality is clearly visible.

DA for the as-built LHC after Re-installation

The tools available allowed re-analysing the performance of the LHC after the re-installation of a sizeable number of magnets as a consequence of the incident occurred in September 2008. In Fig. 4 the situation before and after the re-installation is compared. Both injection and 7 TeV are shown (top) as well as injection and 3.5 TeV (bottom).

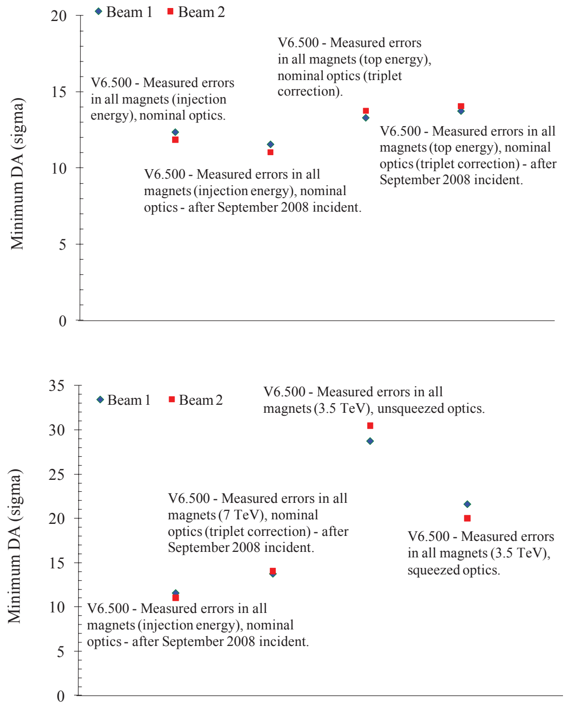

Figure 4: Global situation in terms of DA for injection and 7 TeV (top). The impact of the magnets; change due to the September 2008 incident is shown. Global situation in terms of DA for injection and 3.5 TeV (bottom). In both cases the standard computation of long-term DA, but with 11 angles has been performed.

A slight reduction of DA at injection is clearly visible, while the situation at top energy is essentially unchanged. This is a direct consequence of the fact that the re-installation had an impact on some arc magnets, leaving untouched the insertions.

DA for as-built and Statistical Errors at Injection

Finally, it is interesting to compare the DA for the as-built machine with the one for the statistical error tables for injection energy, where the concept of DA is the most relevant. In Fig. 5 three configurations are shown, namely: as-built, as-built after re-installation, statistical. It is clearly seen that the statistical errors provide the most pessimistic estimate of the DA, while the as-built configurations provide values fundamentally within specifications, with a minor impact of the magnets exchanged after the incident in September 2008.

CONCLUSIONS

The patient and accurate work done during the design and specification stage of the LHC seems to have well paid off given the very encouraging results for the DA of the as-built machine, which is fundamentally within the design tolerances.

ACKNOWLEDGEMENTS

Many colleagues have contributed in different ways to the results presented in this paper. In particular S. Fartoukh, P. Hagen, E. McIntosh, and F. Schmidt are warmly acknowledged for support, discussions and help.

The volunteers of LHC@home are warmly thanked as without their contribution of CPU-time the intense tracking campaign reported in this paper would not have been possible.

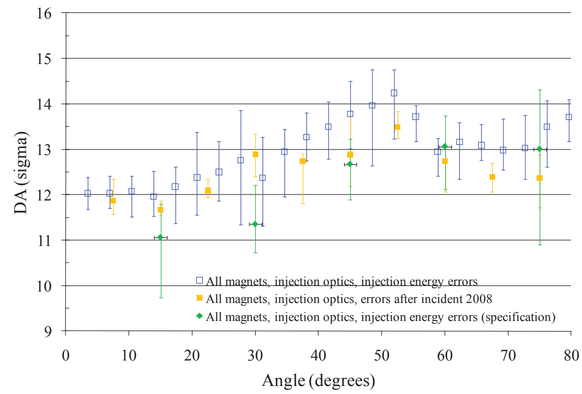

Figure 5: Comparison of DA for as-built configurations (injection energy and optics before and after the September 2008 incident) and a similar configuration, but with specified errors based on statistical error tables. Only Beam 1 results are shown.

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