TRACKING STUDIES FOR THE LHC OPTICS VERSION 4 AT INJECTION ENERGY

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Abstract

Extensive Tracking Studies have been performed for a realistic model of the LHC at the injection energy of 450 GeV. The underlying model contains all static multipole magnet errors and linear imperfections. The imperfect machines are corrected using control room techniques. The paper gives estimates for the dynamic aperture (Dyn.Aper.) for 60 different realizations of errors for the versions 4. To get a better picture of the dynamics the emittance ratios are varied to sample a large fraction of the phase space. Phase space averaged apertures are compared with averages over different imperfect machines for selected emittance ratios. Lastly it is checked if the reduced systematic a_4 and b_4 multipolar components of the main bending magnets remain an important aperture limitation.

1 INTRODUCTION

During the long injection period of about 15 minutes that is needed to fill the LHC with 2835 bunches per beam the particles have to survive in guiding and focusing fields with large high order multipolar errors. These errors result from the magnets which are superconducting and without field shaping material in order to reach the highest possible fields. Besides the geometric part there are large persistent current contributions. The latter are important at injection energy in particular because the ratio between top and injection energy is large (≈ 15.5). The same reason makes it difficult to built a power supply system that achieves, at injection level, a current ripple of a few ppm only. Moreover, the fact that the magnets are produced by different suppliers introduce additional uncertainties in the error components around the machine.

All these effects have to be considered to arrive at a meaningful estimate for the Dyn.Aper. . For this purpose a multiple processor system with shared memory architecture [1] has been acquired recently which has the fastest floating point performance below the supercomputer level. The tracking programs [2, 3] have been optimized with considerable effort. Nevertheless, the system is still far from being able to track a large hadron collider like the LHC in real time. In fact only 1% of the total injection time can be covered by systematic numerical studies assuming an acceptable response time. This paper therefore attempts to give an estimate of the Dyn.Aper. for the full injection period using an extrapolation technique based on a recently discovered relation between the phase space averaged Dyn.Aper. and the number of turns [8].

2 TRACKING PREREQUISITES

Each node of the mentioned multiple processor system allows to track one particle once around the LHC lattice including all errors in about 1.4 ms. The total throughput of the 10 processors is therefore roughly 7,000 per second and $600 \cdot 10^6$ turns day. Even though these numbers seem to be large at first sight, they are not large when compared to the actual computational needs:

- To cover the injection time some 10^7 turns have to be tracked.
- The Dyn.Aper. has to be found in the full six–dimensional phase space.
- 60 representations of the random errors (seeds) have to be tracked for each case to find a lower bound of the Dyn.Aper. . This lower bound does exclude an even lower Dyn.Aper. with a 95% probability [5].

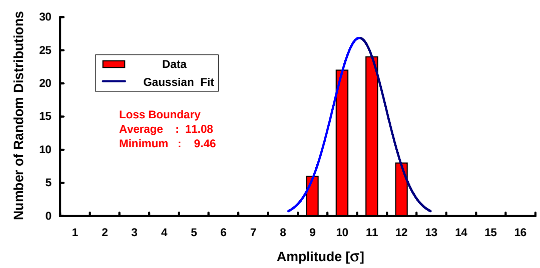

Figure 1: *Histogram of Dyn.Aper. (60 seeds) for the nominal LHC lattice including a Gaussian fit*

- Many cases have to be studied to obtain a good understanding of what causes the reduction of the Dyn.Aper. and to test if there are cures to improve it.

3 EXPLORATION OF PARAMETER SPACE

Owing to the above reasoning it is necessary to find ways to sample only a fraction of the large parameter space while still obtaining the essential information about the Dyn.Aper. . This is done in the following fashion:

- The angular phase in a single tracking run is not varied. Instead as many tracking data as possible are kept to reconstruct the sampling of the phase space in subsequent post–processing runs.
- Both transverse amplitudes are varied while keeping the ratio between the emittances constant. In most cases a ratio equal to one has been used called the "$45°$ case". K=$atan\sqrt{e_{II}/e_I}$ can be varied between $0°$ to

$90°$, with e_I and e_{II} the emittances of mode I and II respectively. Figure 2 shows how the Dyn.Aper. depends on this emittance ratio.

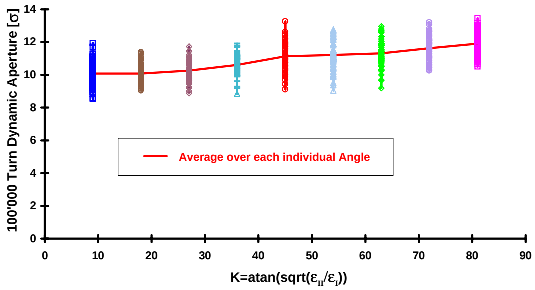

Figure 2: *Dyn.Aper. versus emittance ratio*

- In the longitudinal plane the relative momentum is fixed to a deviation of 0.00075 which is 75% of the bucket half size. This is sufficiently close to the bunch edge and at the same time avoids the vicinity of the separatrix with its very special properties. Moreover in Ref. [6] it has been found for LHC version 4.1 that the Dyn.Aper. tends to decrease weakly towards larger relative momentum deviations.

- The Dyn.Aper. is determined in in the following way: in a first step a rough estimate of the Dyn.Aper. is found. In a second step the amplitude is varied from well below up to this rough border in very fine amplitude steps. This allows to pick up small nests in the amplitude range where particles have short survival times. To this end 30 pairs of particles per beam sigma are used and in most cases a total of 300 particles are tracked. In fact it is observed that this fine amplitude scan guarantees an error of about –0.5%. Spreading the 30 pairs over 3σ can easily result in an overestimation of the Dyn.Aper. by 2σ.

Therefore the simulation time needed for one single case with 60 seeds, 300 particles, 5 emittance ratios and tracked for just 10^5 turns requires two full weeks of the cpu–time and 100% availability of the computer system. Of course not all cases can be studied in such depth. One possible shortcut is to gain a factor of 5 by tracking the $45°$ case only and applying a correction factor for the emittance ratio variation which has been derived from a thorough systematic study.

4 REDUCTION FACTORS

This correction is part of a sequence of reduction factors that are applied to arrive at an estimate for the 10^7 turn Dyn.Aper. . In detail, the following steps are considered:

- Traditionally the Dyn.Aper. has been stated as a function of initial amplitude. Of course it is much better to use the average amplitude, obtained via postprocessing, to avoid local deviations due to phase space distortions. In the LHC case it leads to a variation of the Dyn.Aper. between +4% and -5%. To be safe a correction factor of 0.95 is applied.

- a 5% reduction to cover the error introduced by the finite step size of the amplitude has to be taken into account.

- The above mentioned correction factor for the variation of emittance ratios is about 0.97.

- To cover the effect of the linear imperfections a reduction factor of 0.93 is used (see below).

- The inverse logarithmic conjecture [8] has been thoroughly checked for the LHC. This study is documented in a separate contribution to this conference [9]. Here the conjecture is used to derive the Dyn.Aper. at 10^7 turns from the tracking data obtained at up to 10^5 turns. The reduction factor turns out to be about 0.93. It goes without saying that the conjecture has been checked for several cases at 10^6 turns. 3 runs have even been extended to 10^7 turns.

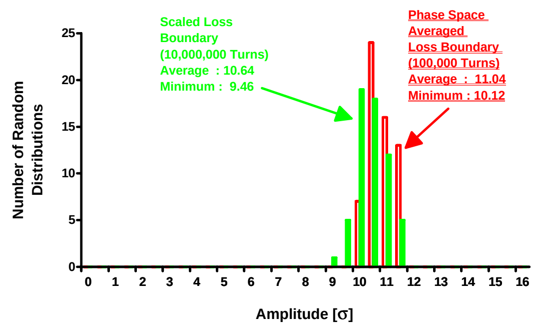

Figure 3: *Scaling of the loss bound histogram from* 10^5 *to* 10^7 *turns*

- Besides the magnetic errors it is equally important to consider the power supply ripple which tends to make particle motion weakly chaotic in large fractions of the phase space. The performed preliminary studies together with the experimental experience [4] suggest a reduction factor of about 0.93.

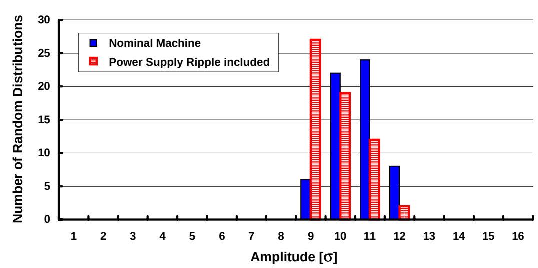

Figure 4: *Effect of ripple on Dyn.Aper.*

- Lastly a reduction factor of 0.8 is applied for all unknown effects. This seems to be adequately pessimistic when comparing tracking results with experiments at various existing machines [4].

A linear addition of these effects, which is of course a pessimistic assumption, reduces the Dyn.Aper. at 10^7 turns to about 56% of the 10^5 turns Dyn.Aper. .

It should be noted that this may not even be sufficient as not all all known effects are included up to now like tolerances of the magnetic errors and all the dynamic effects which are most important at the beginning of the ramp. These will be evaluated in the near future and added to the above list.

5 TRACKING RESULTS

The histogram in Figure 1 visualises the loss boundaries (10^5 turns, 45° case) of 60 different seeds for the nominal LHC lattice and its Gaussian fit which is consistent with the distribution. The minimum and the average value is determined to be 9.5σ and 11σ respectively.

For the same number of machine realizations a scan has been performed in order to find the dependence of the Dyn.Aper. on the emittance ratio (see Figure 2). The average value for the individual ratios increases monotonically with the emittance ratio. This feature remains to be explained. It should be noted that the 45° case coincides with the arithmetic average value of the angular distribution as well as with the phase space average within 2%. Although this agreement cannot be generalised it can be used as a justification for the strategy to track the 45° case and to check the dependence on the angle for selected cases only.

This scan shows that in order to get a realistic lower bound of the Dyn.Aper. a further reduced of 3% has to be applied.

The scaling of the Dyn.Aper. to 10^7 turns using phase space averaged data from 100 to 10^5 turns lowers the average of the distribution by 4% and the minimum by 7% (see Figure 3).

It is well known that power supply ripple in conjunction with nonlinearities lead to a reduction of the Dyn.Aper. [4]. Lacking a proper electrical model of the LHC transmission line the SPS tune modulation spectrum has been used and scaled to the LHC case. With tune modulation switched on the loss boundary distribution becomes asymmetric with its peak shifted towards lower amplitude values (Figure 4). The average and minimum value is reduced by 7% and 1% respectively.

In the presence of linear imperfections the average Dyn.Aper. is reduced by 4% and the minimum by 7%. In

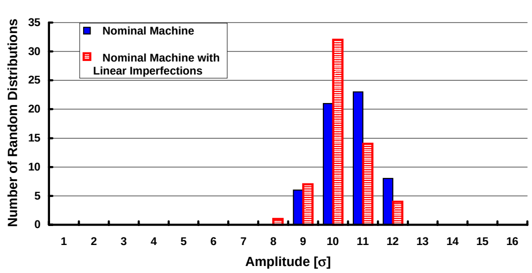

Figure 5: *Effect of linear imperfections on the Dyn.Aper.*

Ref. [7] it has been demonstrated that a correction of the large octupolar components leads to significant increase of the Dyn.Aper . In response to this study the estimates for the b_4 and a_4 have been revised and it was found possible to lower them by a factor of 3 and 2 respectively. As expected these reduced errors lead to a loss boundary distribution halfway between the two extreme cases as seen in Figure 6. It remains to be investigated if a correction of the residual octupoles is still needed.

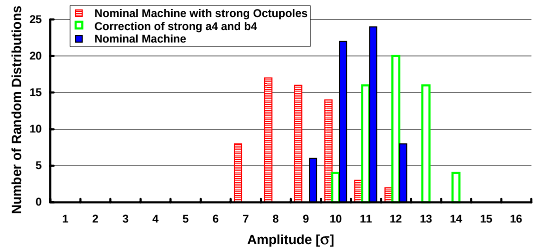

Figure 6: *Histograms of Dyn.Aper. for cases with large octupolar components, large but corrected and reduced values respectively*

6 CONCLUSIONS

An extensive study of the Dyn.Aper. of the LHC version 4 at injection energy has been performed. The Dyn.Aper. is found to be roughly 9.5σ for the nominal LHC lattice including realistic errors. Various potential influences on the Dyn.Aper. have been addressed in detail: transverse emittance ratio, uncorrected multipolar components b_4, a_4, linear imperfections and power supply ripple. The dedicated multiprocessor system allows to do systematic studies of about 1% of the LHC injection period. In addition, the available pre– and postprocessing tools can handle the simultaneous variation of several tracking parameters.

To estimate the Dyn.Aper. at 10^7 turns a sequence of reduction factors have been applied to the data obtained at 10^5 turns. Taking into account all known effects and using an estimate for the unknowns the actual Dyn.Aper. is expected to be about a factor of two smaller with respect to the tracking results.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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