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DYNAMIC APERTURE STUDIES FOR THE LHC VERSION 4

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Abstract

The limitations of the dynamic aperture due to field errors of the super-conducting magnets is a notorious problem for the LHC. Given the large amount of independent studies performed by a sizeable research team it becomes necessary to define a common tracking strategy. The emphasis is placed on an elaborate on - and off - line processing of the tracking data making use of all tools presently available. To manage the very time-comsuming investigations our approach is two-fold: firstly we are maximising the computing power running optimised code on state of the art equipment which is continuously upgraded and secondly we speed up the studies by using reliable and automated early indicators for long-term losses. The procedure is exemplified with a series of tracking runs for the LHC version 4 at injection.

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DYNAMIC APERTURE STUDIES FOR THE LHC VERSION 4

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Abstract

The limitations of the dynamic aperture due to field errors of the super–conducting magnets is a notorious problem for the LHC. Given the large amount of independent studies performed by a sizeable research team it becomes necessary to define a common tracking strategy. The emphasis is placed on an elaborate on– and off–line processing of the tracking data making use of all tools presently available. To manage the very time–consuming investigations our approach is two–fold: firstly we are maximising the computing power running optimised code on state of the art equipment which is continuously upgraded and secondly we speed up the studies by using reliable and automated early indicators for long–term losses. The procedure is exemplified with a series of tracking runs for the LHC version 4 at injection.

1 PREPARATION

1.1 Tools

For the tracking studies of the LHC the programs MAD [1] and SIXTRACK [2] are used. MAD8 is the LHC workhorse while SIXTRACK allows an independent check and is used for special purposes. Most results of this report were obtained with the latter program.

It was recognised that for a comparison between the two programs a more automated transfer procedure was needed. This MAD2SIX [3] transfer procedure allows to create the necessary input files needed for SIXTRACK including a full list of all systematic and random magnetic imperfections starting from the MAD data base. Survival plots obtained with the two programs for LHC version 4.1 are shown in Fig. 1. The agreement is good up to the maximum tracked turn number of 100,000. In fact, a better agreement cannot be expected due to the chaotic behaviour of the tracked particles.

To allow the usage of SIXTRACK for non–experts a menu–driven tool was written [4]. This tool, using the MAD2SIX transfer program, allows to produce error–free input files for a series of different tracking runs, to start and control those runs and to post–process the produced tracking data including interactive graphical display.

During the latest tracking campaign it became apparent that for a successful study of a large sample of different machine set–ups a high level of automation was needed for both tracking and post–processing. For the time being, this has been realized with simple Shell scripts. However, for the new tracking computer facility [5], to be installed at CERN in the near future, more modern tools will be used. It is planned to have a graphically structured control of the complete tracking study using the facilities of the Open Inventor program package. In this way the involved tracking procedure (see below) can be provided using any of the two tracking programs. But at the same time, this graphical structure will allow modifications and extensions with utmost ease.

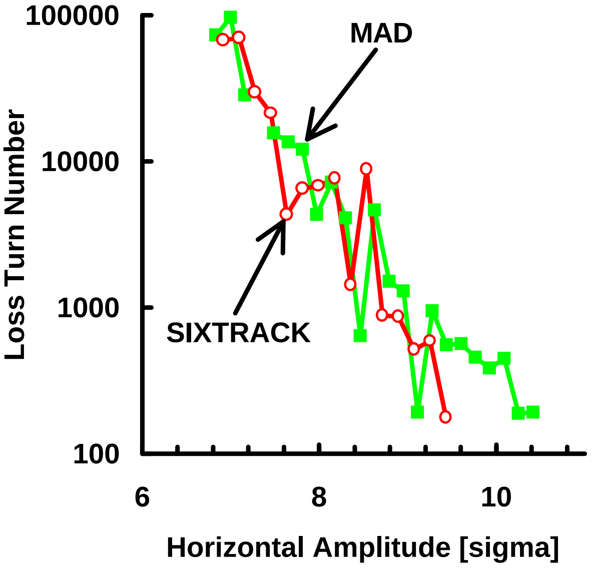

Figure 1: Comparison of MAD and SIXTRACK

1.2 Tracking Procedure

Dynamic aperture studies for hadron machines are naturally very time consuming as the particles have to be followed over many turns. Usually many machine configurations have to be tested and the dynamic aperture itself depends on many parameters. To arrive at consistent results there is the need for an elaborate tracking procedure, in particular when the work is done in a team. The objectives and tools [1] are:

- Detection of pathological cases before long tracking runs are launched.

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[1] The program MAD is now providing similar tools [6].

- Extensive post–processing of tracking data to understand the nonlinear behaviour of the motion and to limit the number of parameters to be studied.
- Carry the tracking to the largest possible turn number for a minimum set of parameters and record the result in survival plots.
- Use early indicators for long–term particle stability.

To this end the tracking studies were done in several steps: firstly short–term tracking were done for each case to find the detuning as a function of momentum deviation and transverse amplitude. A rough estimate of the dynamic aperture and the onset of chaos was determined as well. This allowed to detect unreasonably bad cases and served as a base for the longer term tracking. Secondly medium–term tracking was carried out over 100,000 turns over the amplitude interval between short–term losses and chaotic border. Various parameters were tested:

- Instead of varying the initial phases 1σ of the amplitude variations (smear) and the maximum and minimum amplitude were calculated from the tracking data.
- The dependence of the dynamic aperture on the ratio of the horizontal and vertical amplitudes was evaluated.
- The effect of the longitudinal oscillation on the dynamic aperture was evaluated by varying the initial momentum deviation.

Finally some cases were prolonged to 1,000,000 turns which is still only 10% of the expected LHC injection period.

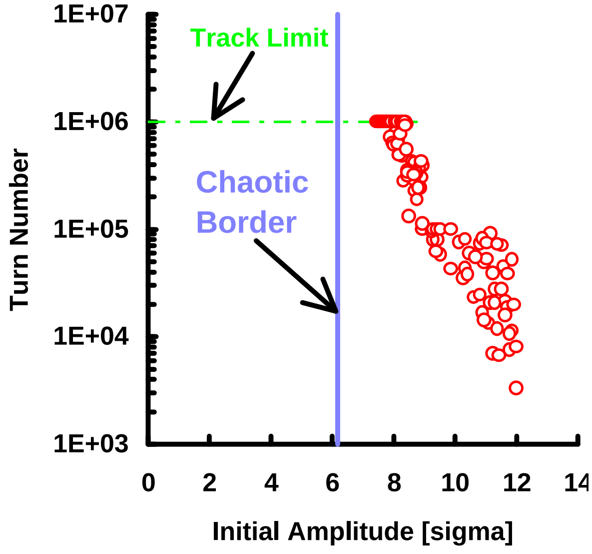

Figure 2: Survival Plot for LHC V4.2

Fig. 2 shows a typical example of a survival plot obtained for LHC version 4.2. It shows that the loss border is reduced by one third when the tracking is prolonged from 1000 to 1,000,000 turns. It also shows that the chaotic border found using only 100,000 turns stays some 20% below the 1,000,000 turn loss border. It has to be mentioned that a very fine amplitude scan is needed to obtain meaningful survival plots. Otherwise large errors may be introduced due to the fact that at any given amplitude the loss turn number may vary by a factor of ten or even more.

2 RESULTS FROM TRACKING

Two tracking campaigns were carried out for the recent subversions of the LHC lattice 4. Optically these subversions are not significantly different, but version 4.2 includes newly defined multipolar errors. The new error tables have large systematic parts which vary from octant to octant due to different production lines of the magnet vendors.

2.1 Version 4.1

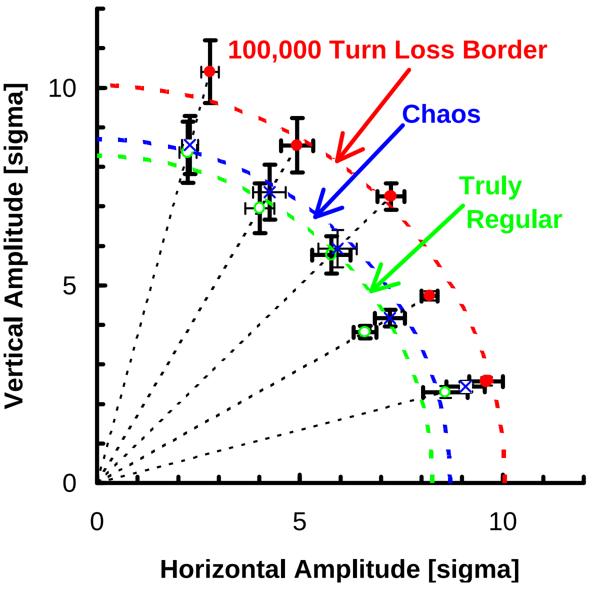

Figure 3: Dynamic Aperture for LHC V4.1

The main result for the subversion 4.1 [7] can be found in Fig. 3: the tracking was done for 9 random distributions (called “seeds” in the following) and 5 amplitude ratios. For each case the 100,000 loss border, the border of strong chaotic motion and the border of truly regular motion was determined. In the figure the data points are averaged over the 9 seeds and shown with their 1σ error bars. The circles indicate the average over the 5 data points. We concluded that the dynamic aperture of LHC version 4.1 was just sufficient: the averaged loss border of 10 sigma for 100,000 turns, where sigma is the transverse r.m.s. beam size, gives the safety margin needed to obtain the required long–term dynamic aperture of 6 sigma once all other effects, which are disregarded in this study, are included.

This 6d tracking was done with the initial momentum deviation at 75% of the bucket size. A reduction of the initial momentum deviation to very small values led to an increase of the dynamic aperture of 25%. Finally, it can be reported that the detuning with amplitude showed a dramatic increase, in the off–momentum cases, once the b_5 spool piece correction in the magnet ends was turned off. This demonstrates how the automatic recording of the detuning can become useful to avoid “blind” long–term studies.

2.2 Version 4.2

For version 4.2 it was decided that the dynamic aperture should be determined such that a lower bound can be stated. A dynamic aperture below this bound should be excluded by a 95% probability. To this end a minimum of 60 different seeds had to be studied.

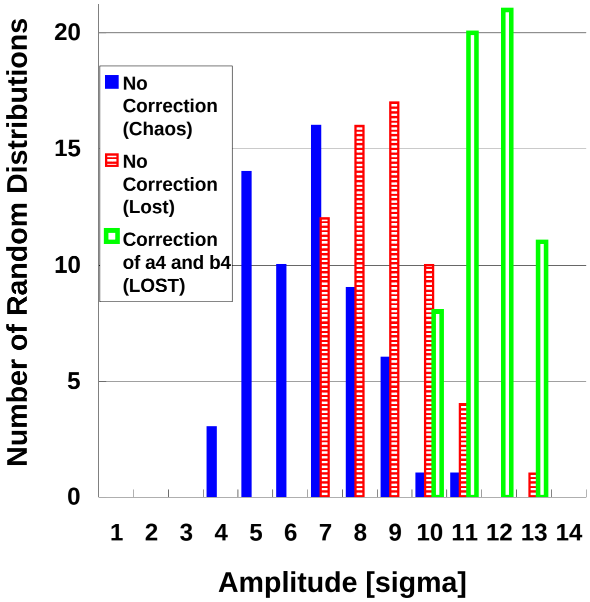

Figure 4: Influence of Octupoles on Loss Distribution

The short–term studies showed that the detuning due to nonlinear chromaticity stayed within ± 0.005 at 75% of the bucket in all cases. There was however a considerable transverse detuning of up to 0.007 for some seeds at an amplitude as small as 5 sigma. The smear at 6 sigma was 12% on average, but reached a maximum value of 34% for one seed. Nevertheless, it was found that the initial starting amplitude agreed to about 3% with the amplitude averaged over 1000 turns.

The results from long–term tracking are summarised in Fig. 4: The averaged loss border is 9.2 sigma ranging from 7.2 to 13.8 sigma, while the chaotic border is located on average at 7.4 sigma in a range between 4.6 and 12.5 sigma. The assumption of a Gaussian distribution is consistent with a χ^2 test in both cases, the standard deviations being 1.4 and 1.5 sigma respectively.

The conclusion is that the safety margin is no longer sufficient for version 4.2 with the large “systematic per arc” errors assumed in this study. As shown elsewhere [8] the culprits are b_4 and a_4. A simple correlation plot of the dynamic aperture versus the integral values around the machines of the octupolar components (see Fig. 5) reveals a moderate correlation ($r = 0.78$). The integral value of octupoles can be corrected with additional (b_4, a_4) spool pieces placed next to the existing b_3 and b_5 spool pieces in the magnet ends. This correction leads to a dramatic increase of the dynamic aperture to an average of 12.1 sigma with a lower bound of 10.2 sigma. For one case the correction was also attempted using normal and skew octupoles close to the cell quadrupoles. With this technique the improvement was half that obtained with the spool pieces.

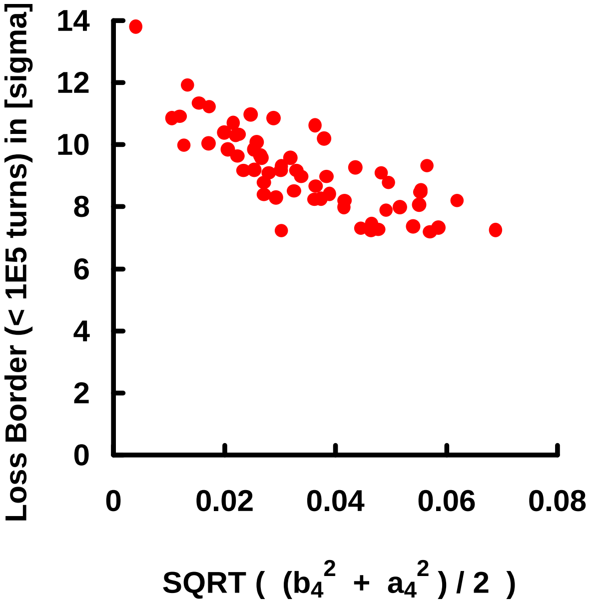

Figure 5: Dynamic Aperture versus Octupole Strength

3 CONCLUSIONS

The general conclusions are that brute force tracking has to be complemented with extensive post–processing of the tracking data. It is also mandatory to define, in detail, a tracking procedure which has to be fully automated making use of modern tools which combine flexibility with utmost user–friendliness.

For the LHC lattice version 4 it can be concluded that the dynamic aperture is sufficiently large. However with systematic errors as large as assumed in this study octupole corrections are needed in the magnet ends.

4 REFERENCES

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