Simulating Dynamic Effects in Superconducting Magnets at the LHC

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Abstract

Changes in multipole errors (during injection or ramping) of the superconducting magnets in the LHC affect important beam parameters such as the closed orbit, tune and chromaticity. In the following it is described how the currently used simulation tool (SixTrack) has been modified to simulate this time dependence in order to reproduce these effects. Preliminary results are shown.

1 INTRODUCTION

During injection at the LHC most simulations done to date assign static field errors to the superconducting dipoles. These errors are assumed to be made of three parts: a systematic for all magnets, a random for all magnets and a systematic which is different for each of the arcs. The latter two are assumed to have truncated Gaussian distributions and all three are combined as follows for any field error component

$$\mathrm{b_n} = \mathrm{b_n^{sys}} + \mathrm{b_n^{unc}} \times \frac{\xi^{\mathrm{unc}}}{1.5} + \mathrm{b_n^{ran}} \times \xi^{\mathrm{ran}} \tag{1}$$

where ξ^{unc} and ξ^{ran} are random numbers from a Gaussian distribution truncated at 1.5 and 3.0 σ respectively and $\mathrm{b_n^{sys}}$, $\mathrm{b_n^{unc}}$ and $\mathrm{b_n^{ran}}$ are the systematic, systematic per production line and random error per magnet respectively. Each of these individual parts consists of up to three contributions: a geometric error, a persistent current error and a ramp induced error. Depending which stage of the LHC cycle is considered only certain of these contributions need be considered. Trivially in the case of collision energy only the geometric unit need be considered. During injection both the geometric and persistent current contributions are needed. All three contributions are needed for ramping. The values normally used in simulations are shown in table 1 for the three lowest normal field errors. The random part of the error values are deduced from magnets at HERA and RHIC and the other values come from simulation.

The numbers are obtained from a combination of magnet simulations and measurements on similar existing magnets.

In this paper only the effects at injection are considered, but the code developed is also applicable to any dynamic effect involving field errors. At the start of injection the geometric and persistent current errors are added in quadrature. Most simulations then treat this error to be a constant. In reality the persistent current component immediately starts to decay exponentially with a time constant of roughly 900s to two thirds of its initial value. It then stays constant at the “flat top” of the exponential until ramping starts. At this point it regains its original value in a short amount of time (typically of the order of one minute), this is referred to as the snap-back[1]. At this point the ramp induced errors also have to be considered. The code developed and results shown in this paper focus on simulating the initial exponential decay of the persistent current and stop at the “flat top”.

Table 1: The systematic per magnet, systematic per production line and random contribution to the first three normal error components in the superconducting dipoles. The units are 10^{-4} of the main dipole field.

	Geometric	Persistent Current	Ramp Induced
Systematic			
$\mathrm{b_1}$	0.0000	-8.6300	5.0000
$\mathrm{b_2}$	-1.4021	-0.0030	0.0000
$\mathrm{b_3}$	1.3295	-11.0300	0.7970
Systematic per production line			
$\mathrm{b_1}$	10.0000	0.8600	1.6000
$\mathrm{b_2}$	0.8500	0.0000	0.6630
$\mathrm{b_3}$	0.8670	1.0690	0.2460
Random			
$\mathrm{b_1}$	5.0000	0.4900	1.1000
$\mathrm{b_2}$	0.6800	0.3060	1.5346
$\mathrm{b_3}$	1.4450	0.2890	0.5490

2 SIMULATING DYNAMIC EFFECTS

SixTrack v3.0[2] is normally used in long term particle tracking studies of the LHC, mostly because of its speed. It is therefore appropriate to be used for dynamic effects, as to simulate the full exponential decay at injection would require at least 10^8 turns. SixTrack typically reads in a file with the multipole field errors for each magnet. Modifications were made so this file represented the initial errors (at the beginning of the injection) and a new file input was added which allows the user to feed in the target errors (at the flat top of the exponential). The code then smoothly changes the field errors turn by turn so they follow the exponential decay (currently hard-wired into the code).

In this paper the initial errors are taken in the standard form for static errors as described in section 1. The final errors are calculated as

$$\mathrm{b_n(on\ flat\ top)} \quad = \quad \mathrm{b_n(g+p)} - \frac{1}{3}\mathrm{b_n(p)}$$

where $\mathrm{b_n(g+p)}$ are the full initial errors (geometric and persitent) and $\mathrm{b_n(p)}$ are only the persistent errors. These are explicitly defined as

$$
\begin{aligned}
b(g+p) &= (b_p^{\rm sys}+b_g^{\rm sys}) \\
&\quad +\sqrt{(b_p^{\rm unc})^2+(b_g^{\rm unc})^2}*\frac{G_1}{1.5} \\
&\quad +\sqrt{(b_p^{\rm ran})^2+(b_g^{\rm ran})^2}*G_2 \\
b(p) &= (b_p^{\rm sys})+|b_p^{\rm unc}|*G_3+|b_p^{\rm ran}|*G_4
\end{aligned}
$$

where the i subscript has been dropped for clarity and the G_i are appropriately truncated gaussianly distributed random numbers (as detailed in equation 1). Care has been taken that the gaussian random numbers labelled G_1 and G_2 have the same values as those used in the initial errors, so that the generated values for the flat top correspond to the same magnets.

The equation for exponential decay is given as

$$
\begin{aligned}
\mathrm{b_n} &= (\mathrm{b_n(start)}-\mathrm{b_n(on\ flat\ top)})\times\frac{\exp(-t/900)}{3} \\
&\quad +\mathrm{b_n(on\ flat\ top)}
\end{aligned}
$$

where t is the time elapsed since the beginning of injection and hence the start of the persistent current decay and 900 is the exponential time constant of 900s ($\approx 10^7$ turns). *The plots in this paper are all produced using a reduced time constant of* 10^5 *turns (or roughly 9s).* This was done for test purposes and to facilitate plot production.

Unless otherwise stated the results shown here are using realistic errors from table 1, however no correction circuits have been used. The LHC model used[3] is linear and uncoupled, except for sextupoles which are used to correct the chromaticity to two units. The tunes are corrected before tracking starts to 64.28 and 59.31.

3 RESULTS

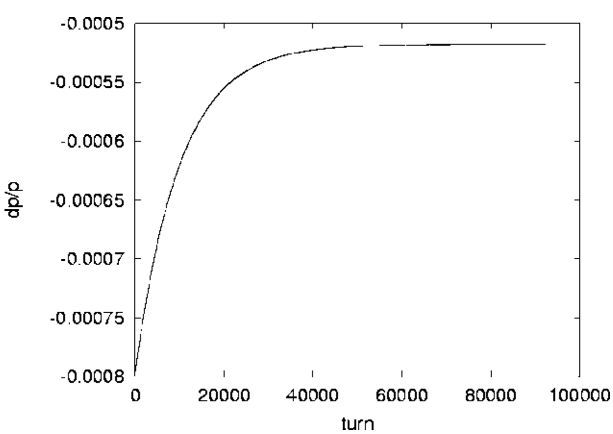

Figure 1: dp/p of a particle as the $\mathrm{b_1}$ field error is changed exponentially.

Firstly the standard $\mathrm{b_1}$ dipole errors were allowed to decay. All other errors were set to zero. A particle initially in the center of the RF bucket was tracked over 1,000,000 turns allowing the decay to reach the flat top of the exponential. The relative momentum offset ($\delta p/p$) is shown in figure 1 versus turn number. The figure shows an increasing $\delta p/p$ corresponding to the exponential persistent current decay of $\mathrm{b_1}$.

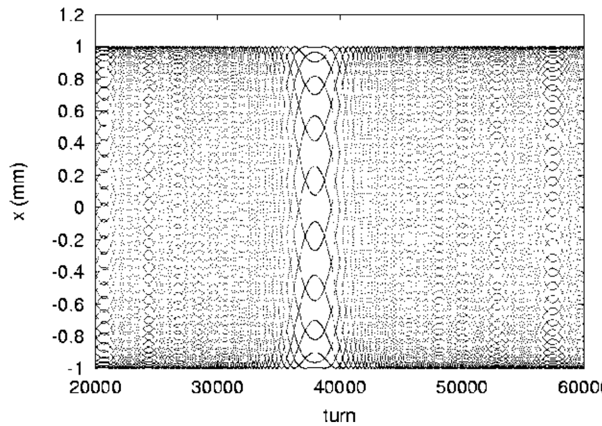

Figure 2: Horizontal coordinate of a particle as the $\mathrm{b_2}$ field error is changed exponentially.

The standard $\mathrm{b_2}$ dipole errors were then allowed to decay. All other errors were set to zero. A particle with a 1mm offset in both horizontal and vertical planes was tracked over 100,000 turns. The horizontal position is shown in figure 2 against a range of turns from 20000 to 60000. The $\mathrm{b_2}$ persistent current error decay causes the tune to decrease. As this happens the particle passes briefly over different order resonances which appear as fixed points in the figure. For example between 35000 and 40000 turns the particle crosses what appears to be an 18th order resonance.

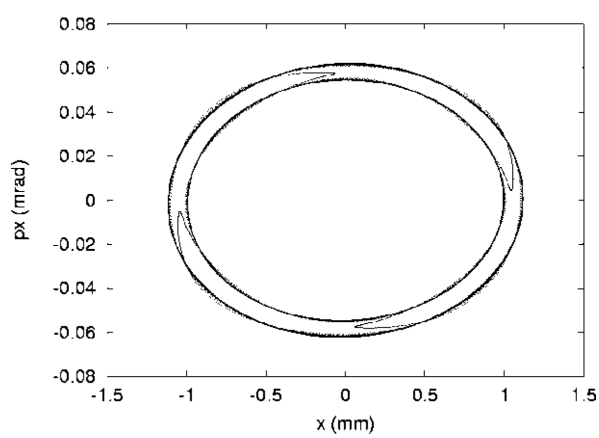

Figure 3: Horizontal phase space of a particle as the $\mathrm{b_2}$ field error is changed exponentially.

A special case of the $\mathrm{b_2}$ decay was studied, where the decay was increased artificially so that the particle crossed over a quarter integer resonance. The horizontal phase space is shown in figure 3. The particle jumps from one stable ellipse to another one. This is also seen in figure 4

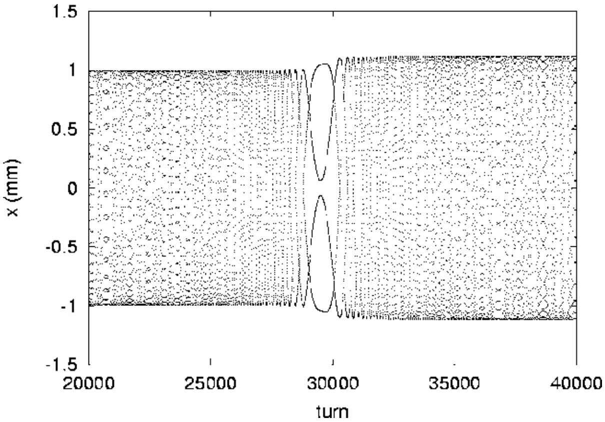

Figure 4: Horizontal coordinate of a particle as the b_2 field error is changed exponentially causing the tune to go through a fourth order resonance.

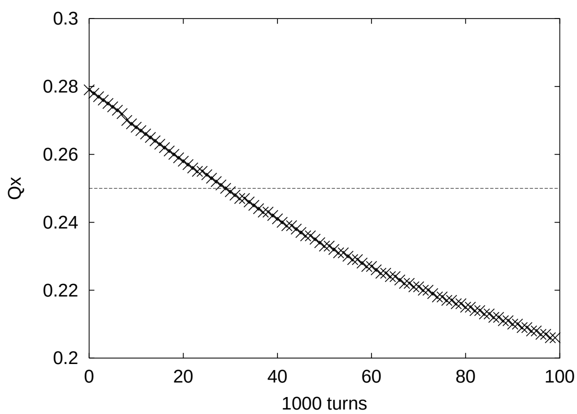

Figure 5: The fractional horizontal tune of a particle as the b_2 field error is changed exponentially. The quarter integer tune is indicated by the horizontal line.

where the horizontal position of the particle is shown versus turn number. In this special case just before 30000 turns the particle goes through a fourth order resonance which causes it to increase its oscillation amplitude. The result of a sliding window FFT on this horizontal position data is shown in figure 5. Every 1000 turns is fourier transformed to give the fractional tune at that point. The horizontal fractional tune starts at 0.28 and decreases steadily until it goes through 0.25 just before 30000 turns.

Finally the standard b_3 dipole errors were allowed to decay. All other errors were set to zero. A particle with a 1mm offset in both horizontal and vertical planes was tracked over 100,000 turns. The horizontal phase space is shown in figure 6. In this case the particle's motion in phase space starts off circular. It slowly degenerates into what appears to be the start of three islands. It then briefly regains a regular motion with a somewhat larger amplitude before finally being lost on what appears to be a third order resonance.

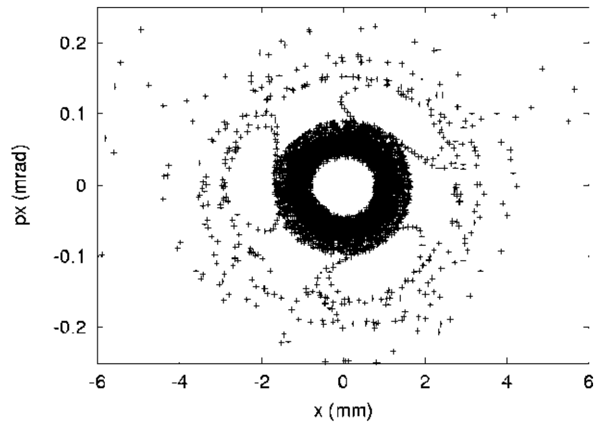

Figure 6: Horizontal phase space of a particle as the b_3 field error is changed exponentially. The particle is lost on a third order resonance.

4 CONCLUSIONS

A modification to the SixTrack code was presented in this paper. It allows the field errors assigned to magnets to decay exponentially with time. The effects of pure b_1, b_2 and b_3 decays were presented in this paper using realistic errors, however without considering correction systems. A decay of the tune across a quarter integer resonance was shown as an example.

5 ACKNOWLEDGEMENTS

Many thanks to F. Schmidt for help in modifying SixTrack.

6 REFERENCES

[1] This is an older simplified model as mentioned in:
L. Bottura, "Superconducting versus warm magnets", 10th Workshop on LEP-SPS Performance, Chamonix, France, 17-21 Jan 2000.
More recent fits and models may be found in:
S. Amet et al., "The Multipoles Factory: An Element of the LHC Control",LHC Project Report 554 (2002).

[2] F. Schmidt, "SixTrack, User's Reference Manual", CERN SL/94-56 (AP).

[3] Database versions may be found in `/afs/cern.ch/eng/lhc/optics` in particular:

- `V6.2/V6.2thin.seq_30_08_01` was used for the lattice.
- `V6.1/errors/9901m` was used for the errors. For the purposes of this study it is equivalent to the table 9901.