TIME DEPENDENT SUPERCONDUCTING MAGNETICS ERRORS AND THEIR EFFECT ON THE BEAM DYNAMICS AT THE LHC

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Abstract

During injection and ramping at the LHC the time dependence of the errors in the main dipoles will have an effect on the beam dynamics. These time dependencies are simulated using the latest tracking codes. The effects on beam dynamics and beam stability are examined. Collimation and control feedback issues are also studied.

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 up to three units: 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 sub units need be considered. Trivially in the case of collision energy only the geometric unit (including saturation effects) need be considered. During injection both the geometric and persistent current units are needed. All three units are needed for ramping. The values of the field errors are obtained from a combination of magnet simulations and measurements on similar existing magnets.

At the start of injection the geometric and persistent current errors are added in quadrature. The persistent current component immediately starts to decay exponentially 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 short amount of time (typically of the order of one minute), this is referred to as the snap-back[1]. In this paper we consider the effect of snap-back on the optics, the feedback systems and the collimation inefficiency.

2 SET UP OF THE SIMULATION

It was assumed that the machine can be left on the "flat-top" before snap-back long enough to set all the available correction systems properly. Hence the basic set up for the simulation before snap-back was:

- LHC lattice v6.2 and error table 9901m were used[2].
- The main dipoles were misaligned by 0.5 mm r.m.s. and then relative to these the spool piece correction circuits by 0.75 mm r.m.s. and 0.3 mm systematically.
- The main quadrupoles were misaligned by 0.37 mm r.m.s. and a 0.5 mrad tilt and then relative to these the beam position monitors (0.5 mm r.m.s.), lattice sextupoles (0.3 mm r.m.s.) and skew sextupoles (0.3 mm r.m.s.).
- All linear and non-linear dipole field errors were activated to pre-snap-back values (or "flat-top"), i.e. $\mathrm{b_n(g+p)} - \frac{1}{3}\mathrm{b_n(p)}$, where g means geometric and p persistent current field errors.
- $\mathrm{b_3}$,$\mathrm{b_4}$ and $\mathrm{b_5}$ spool piece correctors were set to the values given by the magnet measurement procedure (for full details see [3]). The systematic $\mathrm{b_4}$ component due to feed down was not corrected.
- The correction of $\mathrm{a_2}$,$\mathrm{a_3}$ coupling terms was done in two stages(for details see [3]). Firstly an arc by arc correction of the difference coupling coefficient is performed based on magnet measurements ($\mathrm{a_2}$,$\mathrm{a_3}$). Secondly a global fine tuning of $\mathrm{a_2}$ was performed using the closest tune approach.
- The closed orbit was corrected to 1mm r.m.s. The chromaticity was corrected to 2 units, using the lattice sextupoles and the tunes were corrected to 64.28 and 59.31, using the main arc quadrupoles.

In order to simulate snap-back, all that was changed were the field errors in the dipoles to their maximum snap-back values (i.e. their initial injection values). The correction systems were left at pre-snap-back settings.

3 FEEDBACK LOOPS

Feedback loops will be required to maintain orbit, tune and chromaticity within the ranges that are acceptable for beam dynamics and collimation.

Time constants, delays and sampling rates are important for such feedback loops since they determine performance and robustness of the system. For the LHC control loops, the dynamics is dominated by the power converters and associated magnets and the overall time delays.

The majority of the LHC orbit correctors are superconducting magnets with an inductance of $7H$ and a warm cable resistance of 30 mΩ. The natural time constant of the electrical circuit is 230 s, much larger that the time scale relevant for the snap-back. The magnets are driven by power converters equipped with a digital control loop that is using the available power to accelerate the response of the system [4]. For small current increments, this results in significantly shortening the effective time constants that are relevant for the design of the feedback loops.

At 450 GeV small current steps of $\pm$ 0.1 A, that correspond to 2 μrad deflections, are largely sufficient to correct the orbit deviations induced by the snap-back (shown in figure 1). To maintain the orbit drift during the snap-back within $\sim$ 20 μm r.m.s., maximum integrated corrector kicks of 4 μrad are sufficient. For such small steps, the effective time constant is reduced to 100 ms.

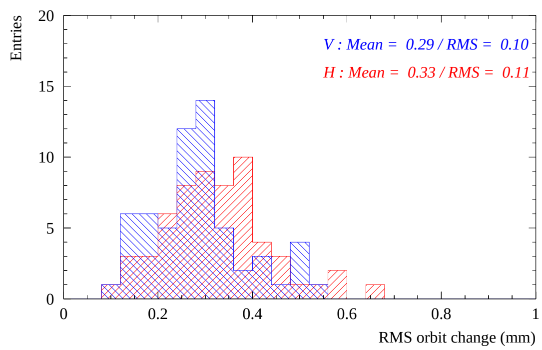

Figure 1: The horizontal and vertical r.m.s orbit changes during snap-back for 60 different cases of field errors and alignment errors.

For a centralized global orbit feedback loop, the overall time delay to transfer the orbit data across the LHC site, to evaluate a correction and to send a correction to the power converters is estimated to be in a range of 50 to 120 ms.

The LHC orbit measurement system has been designed for a sampling rate of 10 Hz. Since for a robust control loop, the ratio between the sampling frequency and the highest perturbing frequency should be at least 20, it is clear that the 10 Hz sampling rate limits the performance of a global orbit feedback to frequencies of 1 Hz or less. For the snap-back with its time scale of $\sim$ 10 s, we are mainly concerned with frequencies of $\sim$ 0.1 Hz. In this range a relatively simple and robust control loop can provided a gain (error reduction) by more than a factor 10 [5]. Such a gain is perfectly adequate.

From the expected beta-beating shown in figure 2, the change of the orbit response matrix is less than 5% during the snap-back, which leads to an equivalent (and negligible) reduction of the feedback gain.

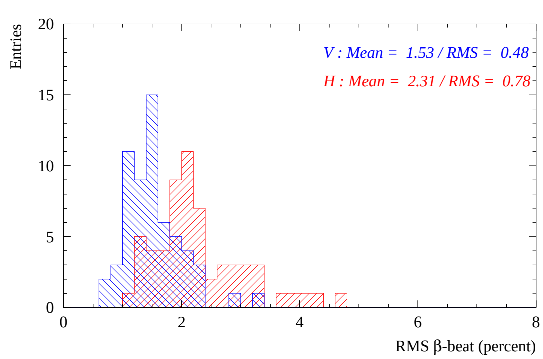

Figure 2: The horizontal and vertical r.m.s beta-beating shift during snap-back for 60 different cases of field errors and alignment errors.

The situation for tune control is similar to the orbit case in so far as fast tune corrections can only be obtained for small signal increments. The expected tune changes as shown in figure 3 are however sufficiently small not to pose any problem for a tune feedback loop. The sampling frequency of the tune measurement, although not finalized, is expected to be approximately 10 Hz. The time constants of the systems are similar to the situation for orbit control and a large gain is expected for the loop.

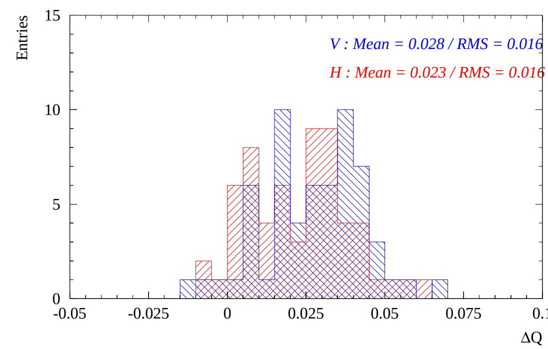

Figure 3: The horizontal and vertical tune shift during snap-back for 60 different cases of field errors and alignment errors.

The chromaticity variations due to the decay of the b_3 field errors is the most severe effect expected during the snap-back (3 units $b_3 \approx \pm$ 150 units), particularly during the early commissioning phase. The chromaticity must be adequately corrected, but contrary to the case of orbit and tune, no design of a feedback loop exists yet due to the absence of a non-destructive measurement procedure for chromaticity. Although measurements based on RF phase modulations have been tested at the SPS.

In the absence of a fast and non-destructive measurement of the chromaticity, the correction of the b_3 field error can be inferred from a set of reference magnets equiped with search coils. Within the reference magnet system, the b_3 field error can be sampled at a few Hz and applied to the machine as a correction.

4 COLLIMATION INEFFICIENCY

Collimation efficiency is required to be high during all phases of LHC operation [6]. Tolerances are most tight at 7 TeV where a global inefficiency of below 10^{-3} is required for nominal intensity, assuming that losses are distributed over 50 m. Here, inefficiency is defined as the number of protons at a normalized amplitude of 10 σ (available aperture) divided by the numbers absorbed in the cleaning insertions. Requirements are more relaxed at injection energy because the quench limit is higher. A global cleaning inefficiency of 4×10^{-2} should be sufficient. The perturbations during snap-back for orbit and beta beat should be compared to the tolerances for a 50% increase (each) of cleaning inefficiency, namely 0.6 σ ($\sim$ 0.6 mm) for orbit and 8% for beta beat [7]. Those tolerances were obtained with a simplified linear tracking program. They should be taken as preliminary estimates but indicate that no strong change of cleaning inefficiency is expected.

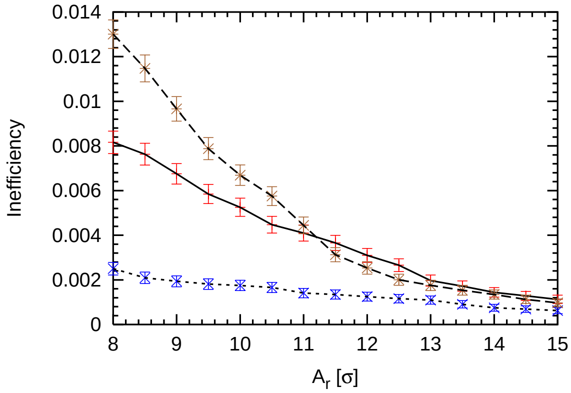

Figure 4: Inefficiency versus normalized radial amplitude A_r for three different cases (1,10,11) of LHC errors.

The program routines for scattering 0.45-7.0 TeV protons in collimator jaws were implemented into SixTrack v3.0[8]. The full error model of the LHC, as described above, can now be used for collimation studies. The SixTrack tracking with collimators is fully chromatic, includes all linear and non-linear magnetic fields and field errors (e.g. coupling), takes into account orbit and optics perturbations, correctly treats jaw misalignments (offset and collinearity errors). The full potential of this complete model is still to be exploited. Here first preliminary results are presented. Tracking was performed for a limited number of cases, each with 32000 particles in the impacting primary halo. It is noted that the collimation depths in the non-linear, coupled simulation could not be adjusted to the same accuracy as in the linear model.

The calculated cleaning inefficiency is shown in figure 4 for three different error cases. For each case the collimators are adjusted around the particular closed orbit and beta functions. The error bars estimate the statistical error due to the number of scattered protons. Pronounced differences are observed with the inefficiency at 10 σ varying between $2 \cdot 10^{-3}$ and $7 \cdot 10^{-3}$. The differences are clearly larger than the statistical uncertainty in the data. The causes for these variations remain to be analyzed in detail. It is noted that the inefficiency for all three cases meet the requirement at injection.

The effect of the snap-back was studied for one particular case. The inefficiency was calculated before (start of the ramp) and after snap-back, for the same errors and assuming tune correction and orbit feedback to the 1 mm r.m.s. The result is shown in figure 5 indicating that modest changes are observed, however not noticeably changing the inefficiency at 10 σ. The result is in agreement with the expectation from the tolerances obtained with linear tracking.

For comparison the inefficiency was also calculated at the bottom at the snap-back and with readjustment of collimator jaws to the changed orbit and beta functions. Within the statistical errors the situation before snap-back is nicely reproduced.

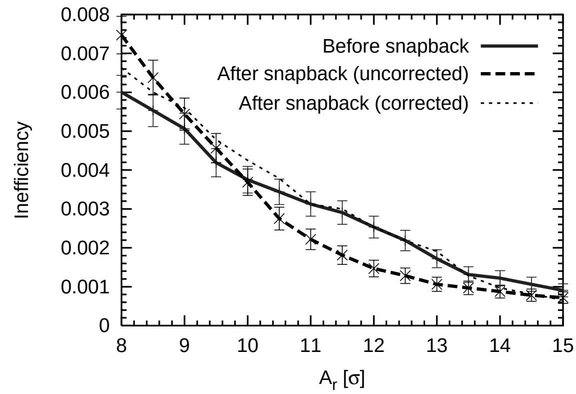

Figure 5: Inefficiency versus normalized radial amplitude A_r before snap-back, at the bottom of snap-back without readjustment of collimator settings (uncorrected) and after readjustment (corrected). The errors were omitted on the latter curve.

5 CONCLUSIONS

In this paper was presented the most complete model of the LHC at injection to date, inclusive of all field errors in dipoles, alignment errors in most components and an implementation of all available correction circuits. Using this model the machine was taken through a simulated snap-back to see the effect on the beam. The orbit and tune shifts during snap-back are extremely small and can be corrected with the currently proposed feedback system, which should be able to correct the orbit by 20μmm at 1Hz. On the other hand the chromaticity shift is large ($\approx$ 150 units) and no fast and feedback friendly correction system exists.

A new version of the SixTrack tracking code with collimation was also presented. It allows full non-linear tracking with collimation. The inefficiency of the collimation system was found to be 4×10^{-3} above 10 σ before snap-back considerations. Snap-back itself was found to have only a marginal effect provided the dipole field quality are within specifications.

REFERENCES

[1] L. Bottura, “Superconducting versus warm magnets”, Proc. of the Xth Chamonix Workshop, France (2000).

[2] /afs/cern.ch/eng/lhc/optics

[3] S. Fartoukh, “LHC installation scenarios and dynamic aperture”, LHC Project Report 449.

[4] F. Bordry, Proc. of the XIth Chamonix Workshop, CERN-SL-2001-003-DI (2001) 250.

[5] J. Wenninger et al., “Prototyping LHC orbit control”, these proceedings.

[6] R. Aßmann et al, ”Requirements and Design Criteria for the LHC Collimation System”, these proceedings.

[7] R. Aßmann, J.B. Jeanneret, D. Kaltchev, ”Efficiency for the Imperfect LHC Collimation System”, these proceedings.

[8] F. Schmidt, “SixTrack, User’s Reference Manual”, CERN SL/94-56 (AP).