European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 522

The Effect of Spool Piece Mispowering on the Dynamic Aperture of the LHC During Injection

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Abstract

During injection at the LHC the dominant factor of the dynamic aperture comes from the non-linear errors in the arc dipoles. This report shows the effect of partial and total failures of the spool piece correction systems on the dynamic aperture for version 6.2 of the LHC lattice. Also presented is a model independent way of finding the b_3 spool piece optimal settings on an arc-by-arc basis.

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1 Introduction

During injection at the LHC, the dynamic aperture is constrained most by the arcs, in particular the non-linear errors in the superconducting dipoles. Spool piece correction elements are provided on each dipole for the b_3 error and every other dipole for b_4 and b_5. These are powered by arc to compensate the average field error per arc.

The first part of this report discusses the effect on dynamic aperture by individual failures of some of these circuits. This was initially studied in [1]. The results presented here include linear imperfections (a closed orbit and beta beating) as well as the latest version of the LHC lattice correction circuits (with half as many b_4 and b_5 spool pieces). Some different scenarios of misbalanced arcs are also presented.

The second part of the report examines a procedure for determinating the ideal setting of the b_3 spool piece.

2 Machine Set Up

The simulation was set up with the following parameters:

- LHC lattice v6.2 [2].
- All non-linear dipole errors were activated. The error table 9901m [2] was used. These results will change with changes of the error table.
- b_3,b_4 and b_5 spool piece correctors were turned on to the values given by the magnet measurement procedure (see section 3).
- Chromaticity was corrected to 2 units, using the lattice sextupoles.
- Tunes corrected to 64.28 and 59.31, using the arc quadrupoles (QF,QD).

The following linear imperfections were introduced:

- Beta-beating around the ring of 25% to 35%. This was generated by random b2 arc quadrupole errors.
- Closed orbit errors generated by quadrupole misalignment errors (generated using a truncated gaussian at 2.5σ with a mean of 0.1 mm). The closed orbit was then corrected to 1 mm r.m.s.

To calculate the dynamic aperture the latest SixTrack v3.0[3] was used and its associated run environment [4]. To calculate a dynamic aperture 300 different realisations of the random errors in the main dipoles are tracked (in the following each realisation is referred to as a seed). These seeds are launched split into five angles (15°, 30°, 45°, 60° and 75°), for a series of amplitudes until a particle is lost. The dynamic aperture for a seed is defined as the smallest amplitude at which the particle is lost within 100,000 turns. The minimum dynamic aperture of the machine is defined as the minimum of all the dynamic apertures of all the seeds. The minimum dynamic aperture is the most conservative measure for particle stability and is used throughout this article.

3 Spool piece failure scenarios

The standard way of setting the spool piece strengths in simulations is as follows:

1. Measure the total component of b_3, b_4 and b_5 from each dipole in one arc. From this calculate the mean error per magnet.
2. Set the correction in each spool piece circuit to correct the average total error in one arc.
3. Repeat this procedure for each of the eight arcs.

This is explained in detail in [5]. The quality of the correction may be changed by multiplying the correction value for the spool piece by a real number between 0 and 1. The

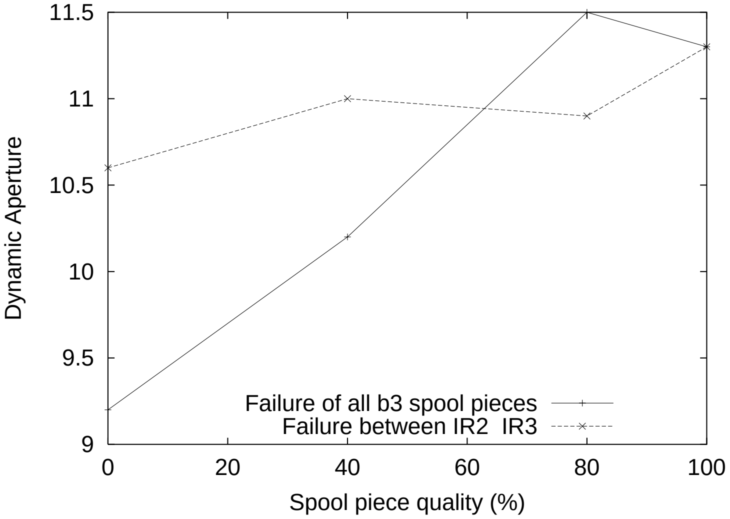

Figure 1: The minimum dynamic aperture (in units of the r.m.s. beam size σ) as a function of b_3 spool piece quality at injection at the LHC. 100% represents full correction and 0% none. The solid line represents the failure of all arcs simultaneously. The dashed line represents the failure of a single arc. Q' is always corrected to 2 units using the lattice sextupoles.

spool piece quality (in percentage) can be defined by this number multiplied by one hundred. 100% then represents a fully working and properly set spool piece and 0% represents a turned off spool piece.

Three independent scenarios were considered for each spool piece set (b_3,b_4 and b_5).

Scenario A This is a global mispowering of all the spool pieces in one set by 100%, 80%, 40% and 0%.

Scenario B This is where one arc is mispowered by 100%,80%,40% and 0%. The other arcs are left properly powered at 100%.

Scenario C This is where one arc is underpowered by 50% or 20% and is compensated by overpowering another arc also by 50% or 20% respectively. All other arcs are correctly powered. This situation could arise by use of a global correction method.

In each scenario only one spool piece set is investigated and the other two sets are left fully powered.

3.1 b_3 spool pieces

The results for b_3 mispowerings of scenarios A and B are shown in figure 1. The chromaticity was corrected with the lattice sextupoles after the spool pieces were mispowered. The dynamic aperture for a working set of spool pieces or 100% quality is around 11.3±0.5. A reduction to 0% of one arc reduces the dynamic aperture to around 10.6±0.5, whereas for a reduction to 0% in all arcs it is reduced to 9.2±0.5. This shows that any correction has to be accurate to within roughly 50%, since dynamic aperture losses of one unit are unacceptable.

The dynamic aperture for scenario C is 11.0±0.5 and 10.1±0.5 for balanced mispowerings of 20% and 50% respectively. This shows that in any correction method for b_3 should be accurate to 50% on an arc to arc basis to avoid the dynamic aperture loss in this case. These results are based on the assumption that the integrated b_3 can be corrected using the lattice sextupoles. If this is not the case (possibly by limited powering at

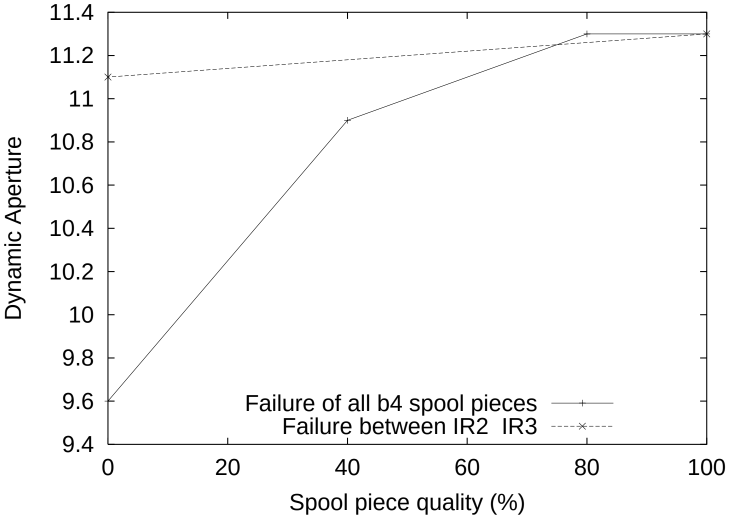

Figure 2: The minimum dynamic aperture (in units of the r.m.s. beam size σ) as a function of b_4 spool piece quality at injection at the LHC. 100% represents full correction and 0% none. The solid line represents the failure of all arcs simultaneously. The dashed line represents the failure of a single arc.

Scenario		Dynamic Aperture
no linear imperfections,	b_4 correction	11.7±0.5
	no b_4 correction	11.2±0.5
linear imperfections,	b_4 correction	11.3±0.5
	no b_4 correction	9.6±0.5

Table 1: The dynamic aperture of the LHC at injection with and without linear imperfections, with and without b_4 spool pieces being used for correction.

collision energy) the remaining global b_3 has to be corrected to better than a 1% accuracy.

3.2 b_4 spool pieces

The results of b_4 mispowerings of scenarios A and B are shown in figure 2. The dynamic aperture for a working set of spool pieces or 100% quality is around 11.3±0.5. A reduction to 0% of one arc reduces the dynamic aperture only marginally and within errors, whereas a reduction to 0% in all arcs reduces it to 9.6±0.5. The figure shows that any correction has to be accurate to within roughly 70%, since dynamic aperture losses of one unit are unacceptable. It should be noted that Q'' terms are not investigated in this study and would also have to be kept under control in any correction system.

The dynamic aperture for scenario C is 11.7±0.5 and 11.5±0.5 for balanced mispowerings of 20% and 50% respectively, which is within errors on the baseline. This implies that the correction method can be global and need not be on an arc to arc basis.

The table 1 shows the effect with and without b_4 correction for the cases with and without linear imperfections for the current set up of the machine. As can be seen the larger loss in dynamic aperture appears to be coming from the linear imperfections. The skew b_2 feed-down coming from the closed orbit through the lattice sextupoles is not corrected in this study and could be a contributing factor.

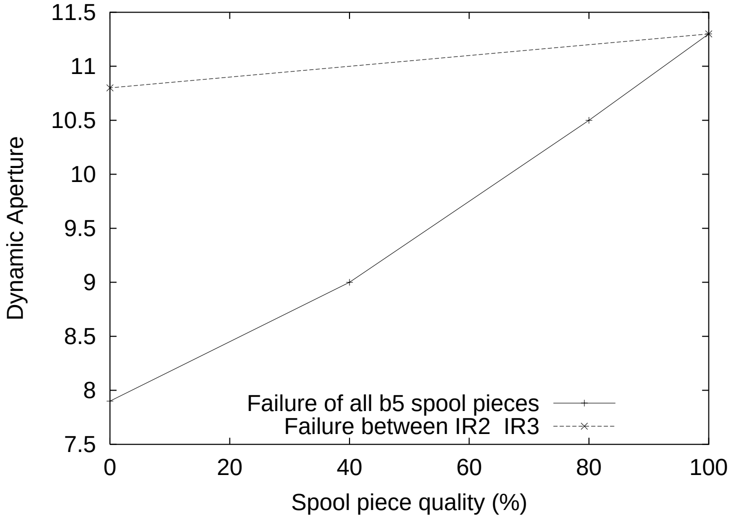

Figure 3: The minimum dynamic aperture (in units of the r.m.s. beam size σ) as a function of b_5 spool piece quality at injection at the LHC. 100% represents full correction and 0% none. The solid line represents the failure of all arcs simulaneously. The dashed line represents the failure of a single arc.

3.3 b_5 spool pieces

The results of b_5 mispowerings of scenarios A and B are shown in figure 3. The dynamic aperture for a working set of spool pieces or 100% quality is around 11.3±0.5. A reduction to 0% of one arc reduces the dynamic aperture only marginally and within errors, whereas a reduction to 0% in all arcs reduces it to 7.9±0.5. From this graph it is concluded that any correction method would have to be accurate to within 30% to limit the loss in dynamic aperture to one unit.

The dynamic aperture for scenario C is 11.0±0.5 and 10.6±0.5 for balanced mispowerings of 20% and 50% respectively. This implies that a correction method on an arc to arc basis is preferred and should be better than 50%.

4 A method for setting the b_3 spool pieces correctly

It is possible in a running machine to create a closed orbit bump in a non-destructive$^{1)}$ manner over one arc. This bump will cause field feed down from b_3 to b_2, causing any uncorrected b_3 error to appear as a tune shift. The essence of this method is to correct the tune shift with the b_3 spool piece correctors and hence correct the b_3 error from the dipoles. In order to amplify the effect of this feed down over the arc in question, seven π-bumps are created horizontally across the arc as shown in figure 4 for a 3 mm high bump. Each of the seven bumps is created independently by three consecutive orbit correctors.

The height of the bump may be altered and the resulting fractional tune shifts are shown in figure 5. The difference in fractional tune shifts $(Q_x - Q_y)$ is also shown. The upper figure of 5 shows the result for no correction of the b_3 errors (i.e. a b_3 spool piece quality of 0%). The lower figure shows the shifts for a perfectly corrected machine (i.e. a b_3 spool piece quality of 100%). These show that the slope of the fractional tune difference is linear and goes to zero as the correction improves.

Since 3 mm is the largest practicable bump in the arc at the LHC, the following

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1) Non-destructive in the sense that it may be implemented during normal machine running

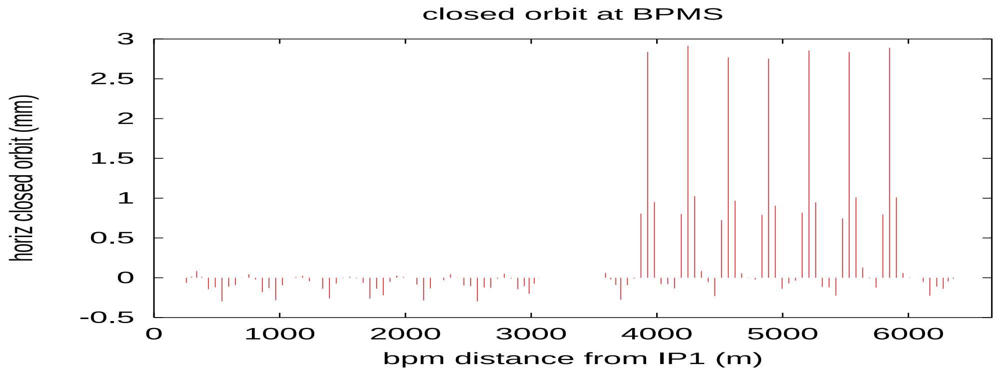

Figure 4: The seven π-bumps installed between IP2 and IP3. The plot shows the horizontal bpm readings of the closed orbit along the first two arcs of the machine.

observable may be constructed

$$(Q_x - Q_y)_{+3\mathrm{mm\ bump}} - (Q_x - Q_y)_{-3\mathrm{mm\ bump}}. \tag{1}$$

This quantity is shown versus spool piece quality in figure 6. As can be seen by minimising the value of this observable the optimal setting for the b_3 spool pieces may be obtained to within 10%.

These results were in the ideal situation of the lattice sextupoles turned off. The same bump measurements were simulated with the lattice sextupoles turned on and correcting to a small positive chromaticity. No large effect was seen compared to figure 6, and the method was still accurate to within 10%. This is due to the fact that a positive orbit bump through one arc of lattice sextupoles is partially cancelled by the small negative bump in the other seven arcs. This small negative bump is shown between IP1 and IP2 (0 and 3500 metres) in figure 4 and is caused by the fixed orbit length defined by the RF.

The advantage of this method is that it is accurate and model independent. If the operation software is written to provide a quick implementation of these required seven π-bumps the method is also quick to perform. The resolution of tune measurement required is not difficult to attain (10^{-2}) but if a higher resolution is available, for instance by a PLL based measurement, then a smaller bump size may be used. In this case the adjustment of the spool pieces may even be performed continuously.

5 Conclusions

It is clear from section 3 that methods of correcting all three lowest order upright non-linear errors (b_3, b_4 and b_5) generated by the dipoles are needed. The results of this study are based on the error table 9901 [2] and should be considered an update to [1] using the latest error tables and tune splits. Also they should not be directly compared to [6] which uses a different error table.

This study shows that the b_3 spool pieces have to be set to within 50% of their ideal correction to avoid a loss of one unit of dynamic aperture. The method presented in section 4 for setting the b_3 spool pieces adjusts them to at least 90% of the required correction so adequately satisfying this condition.

The b_4 spool pieces are necessary for a global correction of b_4 and need to be set to at least 30% of their required strength. This is without a study of the Q'' terms.

In the case of b_5 the spool pieces have to be set to at least 70% of the required correction. This is without a study of Q''' terms. Only the b_5 spool pieces are available

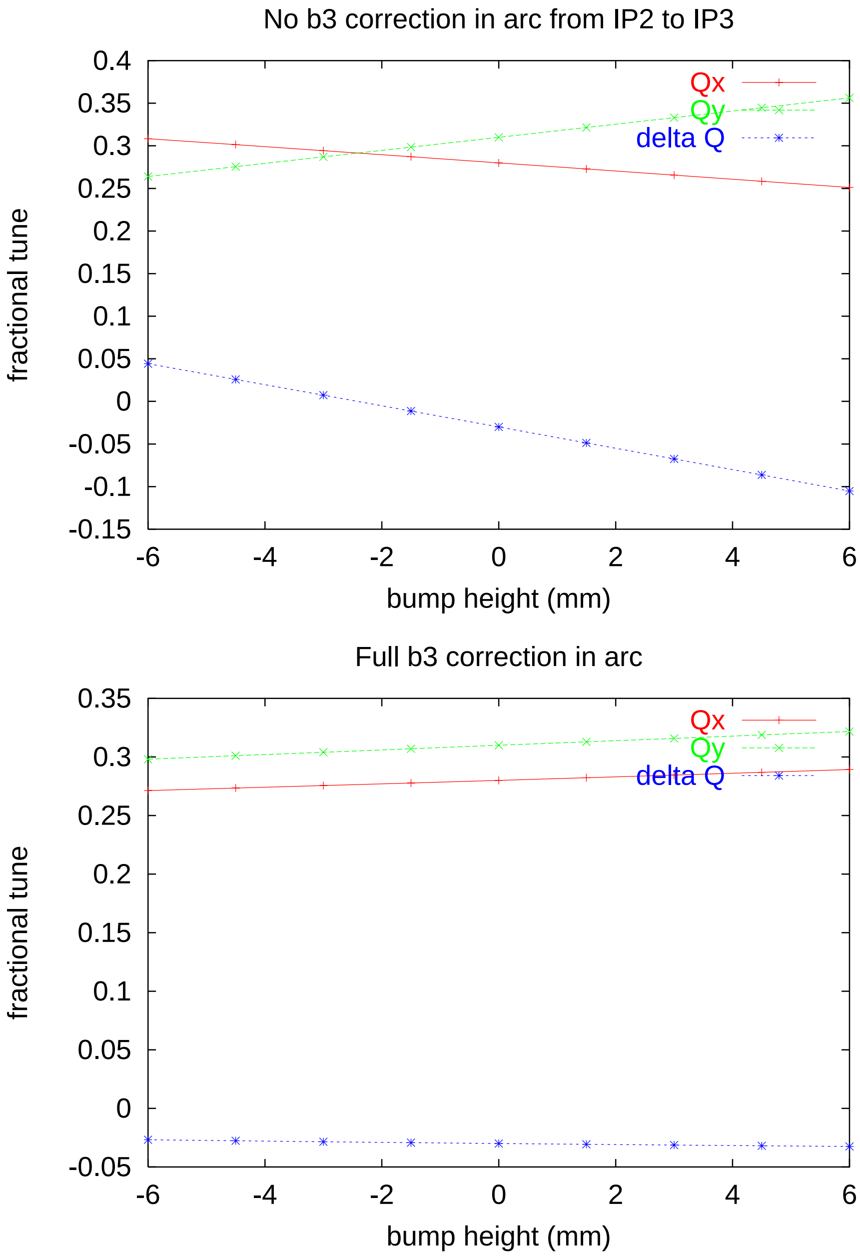

Figure 5: Two plots showing the fractional tune in the transverse planes with respect to the height of a bump in the horizontal plane. Also shown is the difference in fractional tunes or $Q_x - Q_y$. The upper plot is for no b$_3$ correction, and the lower for 100% spool piece quality.

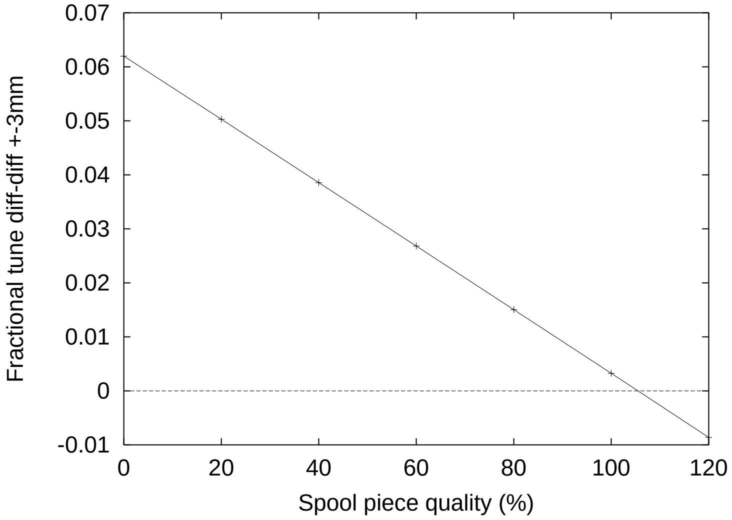

Figure 6: The fractional tune difference $(Q_x - Q_y)$ for two bumps at ± 3 mm as a function of spool piece quality. The line at $y = 0$ is drawn in to guide the eye.

for this correction. They are therefore indispensable to the operation of the machine at injection energies. It is important to find a method of setting the b_5 spool pieces to within this margin and preferably on an arc-by-arc basis to better than 50%.

6 Acknowledgements

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References

[1] F. Schmidt and G. Xu, "Effects of Partial Failure of Correction Systems on the Dynamic Aperture of LHC Version 4", LHC Project Note 96.

[2] 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 is equivalent to the table 9901.

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

[4] F. Schmidt, "Run Environment for SixTrack", Beam Physics Note 53.

[5] S. Fartoukh, "LHC installation scenarios and dynamic aperture", LHC Project Report 449.

[6] S. Fartoukh and O. Brüning, "Field quality specifications for the LHC main dipole magnets", LHC Project Report 501.