TOLERANCES OF THE SPOOL PIECE CORRECTION SYSTEM FOR THE LHC

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Abstract

The LHC main superconducting dipoles are provided with a spool piece correction system which is to be used to correct locally the non-linear multipole errors b3, b4 and b5. The tolerances of this correction system to failures are discussed. Also discussed are simple methods of ensuring they are set correctly during commissioning.

1 SET UP OF THE SIMULATION

The simulation was set up with the following parameters:

- LHC lattice v6.2 [1].
- All non-linear dipole errors were activated. The error table 9901m [1] was used. These results will slightly 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 subsection 1.1).
- Chromaticity was corrected to 2 units, using the lattice sextupoles.
- Tunes corrected to 64.28 and 59.31, using the arc quadrupoles.

The following linear imperfections were introduced:

- Beta-beating around the ring of 25% to 35%. This was generated by random b_2 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[2] was used and its associated run environment [3]. 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 betatron 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 long term particle stability and is used throughout this article.

1.1 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 [4]. 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 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 multipole set is investigated and the other two sets are left fully powered.

2 RESULTS

The dynamic apertures for scenarios A and B for each of the b_3, b_4 and b_5 spool pieces are shown in figures 1 and 2. The dynamic aperture results for scenario C are shown in table 1. The fully corrected system has a dynamic aperture of 11.3 ± 0.5.

A failure of the b_3 spool pieces in one arc reduces the dynamic aperture to 10.6 ± 0.5 and a failure in all arcs reduces it to 9.2 ± 0.5. If it is assumed that a loss of dynamic aperture of one unit is inacceptable, figure 1 shows that the correction has to be accurate to within roughly 50%. The results of table 1 show that a 50% balanced failure in one arc results in a reduction of dynamic aperture to 10.1 ± 0.5. Hence a local arc-by-arc correction method is needed. 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 collision energy) the remaining global b_3 has to be corrected to better than a 1% accuracy.

A failure of the b_4 spool pieces in one arc reduces the dynamic aperture only marginally and a global failure reduces it to 9.6 ± 0.5. The results for scenario C show also only a marginal reduction in dynamic aperture. Hence a global correction to within 70% is needed. 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.

A failure of the b_5 spool pieces in one arc reduces the dynamic aperture only marginally but a global failure reduces it to 7.9 ± 0.5. From figure 1 it may be concluded that any correction method would have to be correct to within 30% to prevent a loss of one unit of dynamic aperture. A balanced mispowering of 50% results in a reduction of dynamic aperture to 10.6 ± 0.5. This implies that any correction method should be on an arc-by-arc basis and be accurate to within 50%.

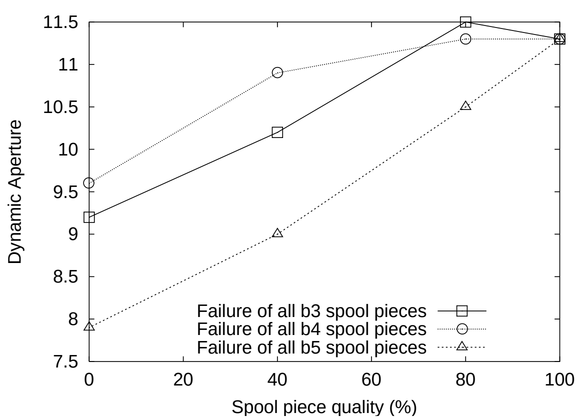

Figure 1: The minimum dynamic aperture (in units of the r.m.s. beam size σ) as a function of b_3,b_4 and b_5 spool piece quality at injection at the LHC. 100% represents full correction and 0% none. For b_3, Q' is always corrected to 2 units using the lattice sextupoles.

3 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 manner over one arc (i.e. that it may be implemented during normal machine running). 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 3 for a 3 mm

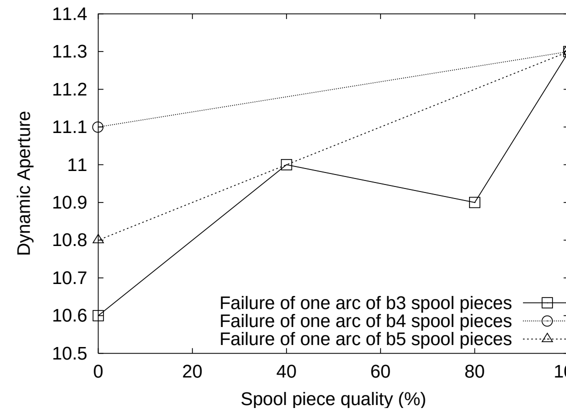

Figure 2: The minimum dynamic aperture (in units of the r.m.s. beam size σ) as a function of b_3,b_4 and b_5 spool piece quality of the arc between IR2 and IR3 at injection at the LHC. 100% represents full correction and 0% none. For b_3, Q' is always corrected to 2 units using the lattice sextupoles.

Table 1: Dynamic apertures of two cases for each spool piece system where a) one arc is underpowered by 20% and is compensated by overpowering another arc also by 20% and b) similarly for 50%. All other arcs are correctly powered. This situation could arise by use of a global correction method. For b_3, Q' is always corrected to 2 units using the lattice sextupoles.

Spool piece	DA after mispowering	
	a) 20%	b) 50%
b_3	11.0 ± 0.5	10.1 ± 0.5
b_4	11.7 ± 0.5	11.5 ± 0.5
b_5	11.0 ± 0.5	10.6 ± 0.5

high orbit bump. Each of the seven bumps is created independently by three consecutive orbit correctors.

Since 3 mm is the largest practicable bump in the arc at the LHC, the following observable may be constructed

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

This quantity is shown versus spool piece quality in figure 4. 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%. The magnitude of the tune shift and hence the sensistivity of the correction can be shown to be proportional to the bump height.

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 4, 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

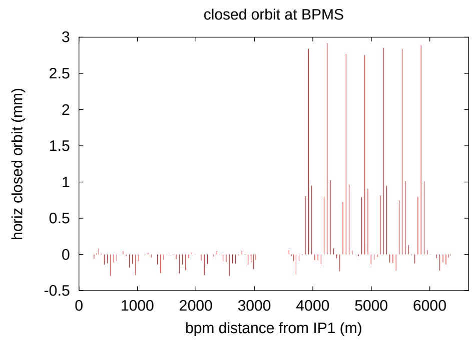

Figure 3: The seven π-bumps installed between IP2 and IP3. The plot shows the horizontal bpm readings of the closed orbit along the first two arcs of the machine.

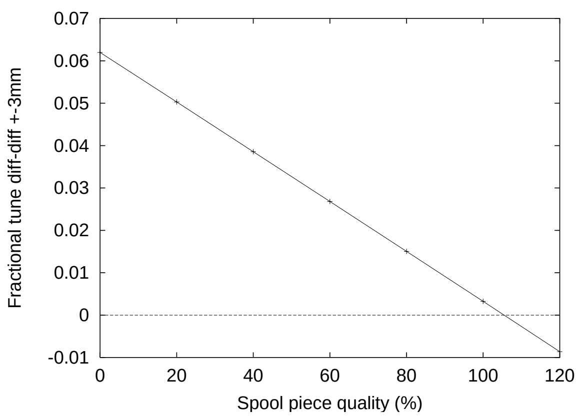

Figure 4: The fractional tune difference ($Q_x - Q_y$) for two bumps at $\pm$ 3 mm as a function of spool piece quality. The line at $y = 0$ is drawn in to guide the eye.

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 3 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.

4 CONCLUSIONS

The results shown in this paper indicate the need for correction systems for all three of the lowest order upright non-linear errors (b_3, b_4 and b_5) generated by the dipoles.

Specifically the b_3 spool pieces have to be set to within 50% of their ideal correction preferably locally. The method described in this paper allows the arc-by-arc b_3 correction to be found correctly to within 10%. The b_4 spool pieces have only to be set to within 70% of their correct value globally. However this is not taking into account Q'' terms which would also have to be corrected. The b_5 spool pieces need to be set to within 50% of their ideal value on an arc-by-arc basis and to within 30% on a global basis. This is also not taking Q''' terms into account.

5 REFERENCES

[1] 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.

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

[3] F. Schmidt, "Run Environment for SixTrack", Beam Physics Note 53 (unpublished).

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