Measurements of Chromatic Coupling in the LHC


Keywords: LHC, chromatic coupling, chromatic functions, beam optics, beam based correction, skew sextupole

Summary

Chromatic coupling was regularly measured in the LHC throughout 2012. A first beam-based correction of chromatic coupling was applied during a dedicated MD. In this note we summarise the measurements and results showing a significant reduction in the chromatic coupling for both beams.

1 Introduction

Due to a relatively strong known $a_3$ (skew sextupole) component in the main arc dipoles in the LHC, a significant care has been taken to correct for the chromatic coupling during the design [1, 2, 3]. In 2012, as part of both the optics commissioning [4] and during optics measurements in MDs [5, 6, 7], the chromatic coupling was measured and corrected.

There is one family of four skew sextupoles installed per arc. These are installed with 1, 2, and 1 FODO cell(-s) in between. Since each FODO cell is about 90 degrees, that means that the phase advance between the four skew sextupoles in an arc is 90°, 180°, 90°. For correcting the difference coupling this works well, but the two latter magnets will cancel (approximately) the correction of sum coupling done by the first two magnets.

In 2012 a polarity check of the skew sextupoles was performed. They were found to have the opposite convention to the MAD-X convention [8]. This was expected, as the same had been found earlier for the skew quadrupoles.

For the LHC it is expected that the difference coupling is much larger than the sum coupling. The resonance condition for sum/difference coupling is that the sum/difference of the tune in the two planes is close to an integer. The LHC operates with a factional tune about 0.3 in both planes, so the sum of the tunes is still far from any integer.
The resonance driving terms $f_{1001}$ and $f_{1010}$ can be written as [9]

$$f(s)_{1001}^{1010} = - \sum_{v} k_v \sqrt{\beta^v_x \beta^v_y} e^{i(\Delta \phi^v_x \pm \Delta \phi^v_y)} \frac{\beta_x}{4(1 - e^{2\pi i(Q_x \mp Q_y)})}$$

where $k_v$ is the $v$th integrated skew quadrupole strength, $\beta^{v}_{x,y}$ are the twiss functions at the location of the $v$th skew quadrupole, $\Delta \phi^{v}_{x,y}$ are the phase advances between the observation point, noted $s$, and the $v$th skew quadrupole, and $Q_{x,y}$ are the horizontal and vertical tunes, respectively.

In this MD-note we define the chromatic coupling as the change in coupling per relative momentum change.

$$|C_{ch}^-| \equiv \left| \frac{\partial C^-}{\partial \delta} \right| \approx 4\Delta Q \left| \frac{\Delta f_{1001}}{\Delta \delta} \right|$$

The results and comparison to model and other correction algorithms are also presented in [10]. A presentation of the chromatic coupling correction was given at the OMC Review in 2013 [11].

### 1.1 Procedure

We measure chromatic properties of the beam optics by exciting beam oscillations at different momentum. Changing the beam momentum is done by RF manipulations, and the change is in the order of $5 - 10 \times 10^{-4}$ relative to the reference momentum. We measure both on momentum, and $\pm$ the change, giving three measurement points. The excitation is usually done using the AC dipole [12], in particular when the beam energy is different from the injection energy. One can also excite the beam using a fast kicker magnet, but this measurement is disruptive as the beam emittance quickly increases.

The correction algorithm is using a response matrix to calculate the correction, in similar fashion as for the linear coupling correction. It is described in more detail in [10]. Another algorithm combining both a local and global correction exist [13, Ch. 2.3].

### 2 Measurements and Corrections

Commissioning of the LHC optics for 2012 was mainly performed in March. Relevant to chromatic coupling measurements were the injection tests on the 15th, and the measurements at 4 TeV and 60 cm $\beta^*$ on the 30th.

#### 2.1 15. of March

See the logbook for more details [14].

Measurements at injection were performed. Differing from the later measurements, we here mostly used the kicker for our measurements, instead of the AC dipole. The kicker is a significantly more disruptive measurement, which is OK at injection but impractical at higher beam energies, since the LHC magnet cycle is slow.
In figure 1 the measured chromatic coupling at injection is shown for both beams. The error bars for Beam 2 (not shown) are larger. We observed a very good agreement between the model and measurement for Beam 1.

2.2 30. of March

See the logbook for more details [15].

There were some earlier measurements at 4 TeV done in March, but we redid these with a new local correction on the 30th. In figure 4 and 5 the comparisons between the measurements done this day and during a dedicated MD in October are shown. In particular for Beam 1, the measurements done in March were much better for technical reasons, which resulted in these data being used for our beam based corrections during the dedicated MD in October, see section 2.4.1.

Measurements of the impact of the octupoles on the coupling was also discussed in [16].

2.3 10. of October

See the logbook for more details [17].

The 10th of October 2012 a test of squeezing the $\beta^*$ to lower than nominal $\beta^*$ was performed. The $\beta^*$ was first reduced 50 cm and then to 40 cm. The two optics were measured both on and off-momentum in order to check the optics parameters. In figure 2 and figure 3 the chromatic coupling for Beam 1 and Beam 2 are shown. The error bars have
Figure 2: The measured Beam 1 chromatic coupling for different $\beta^*$ at 4 TeV.

been removed from the plot to easier compare the $\beta^*$. There is a tendency towards increased chromatic coupling as the beam is squeezed. This is in particular visible for Beam 1.

2.4 12. of October

See the logbook for more details [18].

During this day a measurement of the chromatic coupling was performed for a $\beta^*$ of 60 cm. A comparison between the measurement performed this day together with the measurement from March is presented in figures 4 and 5. Unfortunately, the error bars are very large for the measurement of Beam 1. The problem was that as we increased the oscillation amplitude, induced by the AC-dipole, we observed losses. As a consequence the noise to signal ratio was high for this measurement which resulted in the large uncertainty of the measurement. A qualitative agreement between the two measurements is, however, observed.

For Beam 2 it was possible to create higher oscillations resulting in a decrease of the uncertainty of the measurement. The agreement between the two measurements is very good. This shows that the chromatic coupling stayed stable over a long time period.

2.4.1 Correction

Since the measurement performed in March had smaller uncertainty while showing the same behaviour it was decided to base the corrections on that measurement for beam 1. The correction was trimmed in and the chromatic coupling was remeasured. In this case we could increase the amplitude of the AC-dipole also for Beam 1 resulting in a better measurement. A comparison between the amplitude of the chromatic coupling before and after correction
Figure 3: The measured Beam 2 chromatic coupling for different $\beta^*$ at 4 TeV.

Figure 4: Comparison between the chromatic coupling in March and October for Beam 1.
is given in figure 6. A reduction of the chromatic coupling is clearly visible for both beams, showing that the correction was successful. In order to reduce the chromatic coupling further it would be possible to calculate a new correction based on the measurement after the correction and apply it. The strengths of the skew sextupoles used for the corrections are shown in table 2.4.1. Note that the for Beam 1 the skew sextupoles were not available in arc 81. Comparisons to other algorithms are discussed in [10].

3 Discussion and Outlook

The chromatic coupling has been measured for the first time in the LHC. Injection optics as well as squeezed optics at 4 TeV beam energy have been looked at. The measurements done in March 2012 and October 2012 are very similar indicating that the chromatic coupling stays constant over long time scales. This is an encouraging observation since any correction used in normal operation would rely on being valid for as long as possible in order to be effective.

A correction of the chromatic coupling has also been successfully demonstrated for both beams. In order to reduce the chromatic coupling further the measurement could be repeated and new corrections could be calculated on top of the old. Another limiting factor for the correction is the accuracy of the BPM measurements. This could be improved by taking more measurements.
Figure 6: The absolute value of the chromatic coupling before (red) and after (blue) correction.

Table 1: The calculated correction strength for the two beams. Note that arc 81 was not possible to use for the correction of Beam 1

<table>
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<tr>
<th>Arc</th>
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References


