NON-LINEAR CHROMATICITY STUDIES OF THE LHC AT INJECTION

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Abstract

The non-linear chromaticity of the LHC has been studied. Measurements of variation in tune with dp/p on both beams at injection optics are being compared with Q'' and Q''' as calculated with the LHC effective model. This model uses the best currently available measurements of magnetic field harmonics. An attempt is being made to optimize the b_4 and b_5 spool-pieces corrections in view of the corresponding chromaticity terms.

INTRODUCTION

During the initial phase of LHC operation substantial progress has been achieved with regard to the measurement, correction and modelling of the linear optics[1][2][3]. However, to avoid limitations on the LHC performance knowledge of higher order effects are crucial.

Variation of tune with momentum offset is given by:

$$Q\left(\frac{dp}{p}\right) = Q_0+Q'\left(\frac{dp}{p}\right)+\frac{1}{2!}Q''\left(\frac{dp}{p}\right)^2+\frac{1}{3!}Q'''\left(\frac{dp}{p}\right)^3 ... \quad (1)$$

Q' is the linear chromaticity, while Q'' and Q''' are the second and third order chromaticity terms, typically produced by octupoles and decapoles respectively.

Measurements of the LHC Non-Linear (NL) chromaticity at injection energy were performed in April 2010, June 2011, and July 2011. The standard technique of measuring tune whilst varying RF frequency was used. Results of these measurements are presented. During July an attempt was made to correct for the second and third order chromaticity terms. The results of this correction are presented. Comparisons to the LHC model are made.

NL-CHROMATICITY MEASUREMENTS

April 2010

A first measurement of the LHC non-linear chromaticity was performed in April 2010. RF frequency was trimmed by the standard Q/Q' diagnostics tool to vary dp/p according to a preprogrammed sequence to optimise the total time required for the measurement[4]. Third order polynomials were fit to the data. Results of these initial measurements are shown in Table 1.

Table 1: Results of the April 2010 non-linear chromaticity measurements.

	$Q''_x[10^3]$	$Q''_y[10^3]$	$Q'''_x[10^6]$	$Q'''_y[10^6]$
Beam 1	-3.1	-0.79	0.74	-1.8
Beam 2	-2.7	-0.22	0.23	-1.2

10 June 2011

In 2011 an application within the operations tune viewer was used to automatically vary RF frequency whilst recording the tune, potentially allowing rapid re-measurement and correction if necessary. Each data point corresponded to $\sim$ 10s of beam oscillation data, equivalent to ~ 25 independent tune measurements.

Measurements were performed with Landau octupoles (MOs) at nominal and zero field. The RF was varied over two ranges $\frac{dp}{p} = \pm 1 \times 10^{-3}$ and $\frac{dp}{p} = \pm 2 \times 10^{-3}$.

Measurements were performed with both beams for the MOs in operational conditions. The MOs were then turned off without being degaussed and the scans repeated. The unperturbed horizontal tune of beam 2 drifted during the measurements and this data has been discounted. Results are presented in Table 2. The effect of the lattice octupoles is clearly apparent on Q''.

Table 2: Results of the 10 June 2011 non-linear chromaticity measurements. (Values) represent the errors on fitted Q'' and Q'''.

$\mathbf{MO}_{off}$	$Q''_x[10^3]$	$Q''_y[10^3]$	$Q'''_x[10^6]$	$Q'''_y[10^6]$
	$\frac{dp}{p} = \pm 1 \times 10^{-3}$			
beam1	-1.7 (0.06)	0.98 (0.05)	-3.4 (0.3)	0.46 (0.3)
beam2	-	0.93 (0.05)	-	0.90 (0.3)
	$\frac{dp}{p} = \pm 2 \times 10^{-3}$			
Beam1	-1.8 (0.02)	0.88 (0.02)	-2.3(0.06)	0.81 (0.06)
Beam2	-	0.82 (0.02)	-	0.94 (0.05)
$\mathbf{MO}_{nom}$	$Q''_x[10^3]$	$Q''_y[10^3]$	$Q'''_x[10^6]$	$Q'''_y[10^6]$
	$\frac{dp}{p} = \pm 1 \times 10^{-3}$			
Beam1	-6.0 (0.09)	2.8 (0.09)	-4.8 (0.5)	1.3 (0.5)
Beam2	-5.7 (0.2)	2.4 (0.1)	-5.2 (1.4)	1.4 (0.6)
	$\frac{dp}{p} = \pm 2 \times 10^{-3}$			
beam1	-5.9 (0.08)	2.6 (0.04)	-0.70 (0.2)	1.1 (0.1)
beam2	-5.0 (0.2)	2.6 (0.03)	-2.5 (0.7)	1.1 (0.1)

The fitted value for the third order chromaticity in the horizontal plane changed substantially when the MOs were turned off. The large $\sim 30\%$ error on the fitted Q'''_x does bring the quality of the data into question regarding the third order term; however the change in Q'''_x lies substantially outside of this error and may be worth further consideration.

Clearly there has been a substantial change between 2010 and 2011. During part of April 2010 the spool piece magnets were powered wrongly by a factor $\sim$ 2. This is currently being investigated to determine if it can account for the change in behaviour.

The observed Q'' values are significantly higher than expected from the best model of the LHC we have available, this will be discussed further.

2 July 2011

During the July 2011 machine development period the non-linear chromaticity of Beam 2 was re-measured, and a first attempt at correction of second and third order terms performed.

Care was taken to ensure that all octupoles and decapoles were properly pre-cycled. The MOs were powered off and the octupolar spool pieces *MCO* (used for local correction of b_4 errors in the main dipoles) were cycled from their nominal currents to ± 3A to give a zero field. MCOs were then used for the correction of the second order term. The third order term was corrected using the decapolar spool pieces *MCD* (used for local correction of b_5 errors in the main dipoles). These were initially at their nominal values.

Following initial measurement of the uncorrected NL-chromaticity, corrections were calculated and applied. Results of the NL-chromaticity measurements before and after correction are shown in Figure 1 and Table 3. Details of the correction applied to the MCO and MCD are shown in Table 4. It should be noted that the MCOs in arcs 78 and 81 remained unpowered due to hardware issues.

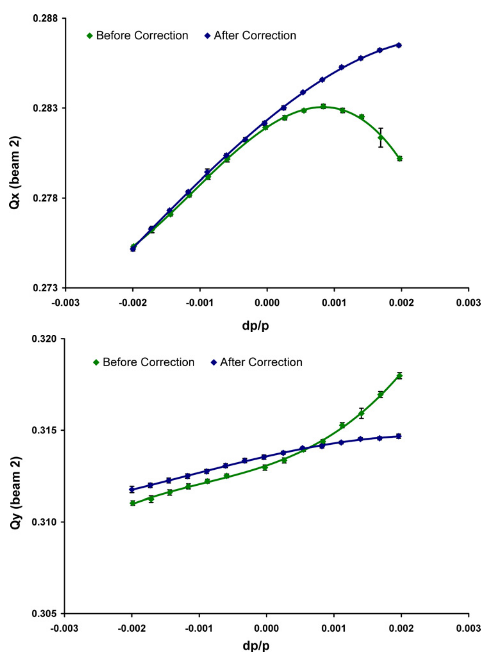

Figure 1: Nonlinear chromaticity of Beam 2 before and after the Q'' and Q''' corrections were applied to the MCO and MCD spool pieces.

Table 3: Measured non-linear chromaticities of Beam 2 before and after correction of the NL-chromaticity.

	$\mathbf{Q''_x}[10^3]$	$\mathbf{Q''_y}[10^3]$	$\mathbf{Q'''_x}[10^6]$	$\mathbf{Q'''_y}[10^6]$
Before	-2.1 (0.02)	0.74(0.03)	-1.9 (0.06)	0.8 (0.09)
After	-0.72(0.02)	-0.19(0.02)	-0.37(0.05)	-0.15(0.04)

The uncorrected second order term in the vertical plane agrees well with the measurements performed on the 10th of June. We can therefore exclude the fact that during the

Table 4: Octupole (MCO) and decapole (MCD) spool piece settings in Beam 2 before and after the Q'' and Q''' correction.

Arc	MCO I_{before} (A)	MCO I_{after} (A)	MCD I_{before} (A)	MCD I_{after} (A)
a12	3.00	9.41	-120.10	-85.41
a23	-3.00	3.41	-120.10	-85.41
a34	-3.00	3.41	-128.83	-94.14
a45	-3.00	3.41	-122.75	-88.05
a56	3.00	9.41	-110.29	-75.6
a67	3.00	9.41	-134.91	-100.22
a78	0	0	-184.54	-149.85
a81	0	0	-145.57	-110.88

June measurements the MOs were not degaussed as the source of the higher than expected Q''.

The correction applied to the MCOs and MCDs substantially reduced the higher order chromaticities. The effect was further observed as a significant reduction in the magnitude of the amplitude detuning [5], which depends to first order on the octupolar fields. Figure 2 shows as an example the effect on the observed detuning of Q_x for kicks in the x plane. An improvement of a factor of ~ 4 is seen. Note that the action J_x is related to the emittance: $2J_x = \epsilon_x$.

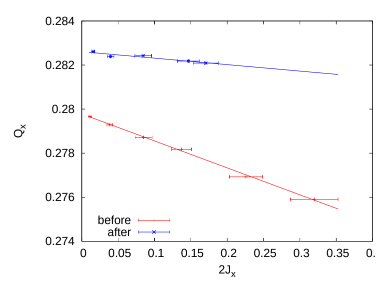

Figure 2: Amplitude detuning of Q_x for horizontal kicks before (red) and after (blue) correction of the NL-chromaticity.

A substantial improvement was also observed in the decoherence of the beam on application of transverse kicks during the amplitude detuning measurements.

NL-CHROMATICITY MODELLING

Based on the best available knowledge of misalignment and magnetic errors in the LHC an effective model has been constructed using the Polymorphic Tracking Code (*PTC*) with a MAD-X front end[3]. This model has proved effective in reproducing the observed beta-beating.

Comparing predictions of the higher order chromatic terms to measurements detailed above, however, demonstrates a very poor agreement: Table 5 compares model predictions for second and third order chromaticities of Beam 1 on 10 June (considering the $\frac{dp}{p} = \pm 2 \times 10^{-3}$ scan of the RF frequency) and Beam 2 on 2 July with measurements performed on those days.

However, in relative terms the model still performs well. Table 6 compares the expected change in Q'' and Q''' due to the corrections applied to the MCO and MCDs during the 2 July machine study. An excellent agreement is observed.

Table 5: Modelled and measured NL-chromaticities for Beam 1 (**B1**) on 10 June 2011 and Beam 2 (**B2**) on 2 July 2011.

	$\mathbf{Q_x''}[10^3]$	$\mathbf{Q_y''}[10^3]$	$\mathbf{Q_x'''}[10^6]$	$\mathbf{Q_y'''}[10^6]$
B1	-1.8 (0.02)	0.88 (0.02)	-2.3 (0.06)	0.81 (0.06)
B1 model	0.060	0.28	-1.0	0.12
B2	-2.1 (0.02)	0.74 (0.01)	-1.9 (0.06)	0.82 (0.09)
B2 model	-0.20	0.21	-0.86	0.12

Table 6: Modelled and measured changes in higher order chromaticity terms of Beam 2 due to corrections applied to MCO and MCD magnets on 2 July 2011

Horizontal	$\mathbf{\Delta Q''}[10^3]$	$\mathbf{\Delta Q'''}[10^6]$
Measured	1.4 (0.03)	1.5 (0.08)
Modelled	1.3	1.6
Vertical	$\mathbf{\Delta Q''}[10^3]$	$\mathbf{\Delta Q'''}[10^6]$
Measured	-0.93 (0.04)	-0.97 (0.1)
Modelled	-0.90	-0.91

Table 7: Beam 2 non-linear chromaticity: effect of hysteresis of nominal MCO field in the case of a pre-cycle and effect of systematic 0.5mm horizontal misalignment of MCDs w.r.t main dipoles. Shown are the difference between measured and no-hysteresis-no-misalignment-model NL-chromaticities ($meas$-mod), the difference between models with and without the MCO hysteresis contribution ($hyst$-mod), and the difference between models with and without the MCD misalignment ($align$-mod).

	$\Delta Q_x''[10^3]$	$\Delta Q_y''[10^3]$	$\Delta Q_x'''[10^6]$	$\Delta Q_y'''[10^6]$
$meas$-mod	-1.9(0.02)	0.53(0.01)	-1.0(0.06)	0.70(0.09)
$hyst$-mod	-0.49	0.34	$+0.006$	-0.003
$align$-mod	-1.8	1.4	$+0.03$	-0.01

The model of Table 5 however does not account for the hysteresis of the magnets. Given their low powering at injection the field of the MCOs may be very dependent on the magnetic history. Incorporating an estimate [7] of the effect of hysteresis on the nominal MCO field given a pre-cycle, alters the second and third order chromaticity estimate as shown in Table 7.

Evidently the hysteresis of the MCO field may be a major source of the observed non-linear chromaticity, though on the basis of this field estimate, it fails to fully explain the second order terms. The hysteresis estimate however is known to become imprecise at the low fields of the MCOs[7].

Another potential source of second order chromaticity is a systematic misalignment, not accounted for in the magnetic measurements, of the MCD spool pieces with respect to the main dipoles[8]. Incorporating an additional 0.5mm misalignment of the MCDs in the horizontal plane (the maximum feasible), alters the NL-chromaticity as shown in Table 7.

Clearly a systematic misalignment of the MCD may therefore explain a substantial fraction of the observed Q'', dependent on the magnitude of the misalignment.

Finally Table 8 compares the measured effect of the landau octupoles (10 June 2011) with predictions from the model. Second order agrees well, if outside of the error on the fit. The model offers no explanation for the change seen in the Q''' and this may merit further investigation.

Table 8: Effect of the landau octupoles (MO) on the Beam 1 (**B1**) and Beam 2 (**B2**) NL-chromaticity for 10 June 2011. $\Delta Q''^{\cdots} = Q''^{\cdots}_{MO\ operational} - Q''^{\cdots}_{MO\ off}$.

	$\Delta Q_x''[10^3]$	$\Delta dQ_y''[10^3]$	$\Delta dQ_x'''[10^6]$	$\Delta dQ_y'''[10^6]$
B1 mea	-4.1(0.08)	1.72(0.04)	1.6(0.2)	0.29(0.1)
B1 mod	-4.7	2.0	0.96	0.045
B2 meas	-	1.8(0.04)	-	0.16(0.1)
B2 mod	-4.7	2.0	0.055	-0.023

CONCLUSION & OUTLOOK

Results of LHC non-linear chromaticity measurements have been presented. Large change is observed between April 2010 and Summer 2011, this is under investigation. June and July 2011 data are relatively consistent.

Corrections designed for second and third order chromaticities were tested in July. Their effectiveness is verified directly and from measurements of amplitude detuning.

We appear to understand well the relative effects on the NL-chromaticity of the octupolar and decapolar magnets (though the impact of the MO on Q''' bears further examination). However, our best available model of the LHC appears to be missing a b_4 effect. It has been shown that hysteresis of the MCO magnets and additional misalignment of the MCDs w.r.t. the main dipoles may be major sources of this error: further studies will be of interest.

ACKNOWLEDGEMENTS

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