UNDERSTANDING THE TUNE, COUPLING, AND CHROMATICITY DEPENDENCE OF THE LHC ON LANDAU OCTUPOLE POWERING

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Abstract

During the 2012 LHC run observations were made of shifts to tune, coupling and chromaticity (Q, Q' and $|C^-|$) which were correlated with changes in the powering of Landau octupoles. We summarize the observations and describe our understanding to-date of the relationship between Q, Q', $|C^-|$ and Landau octupole powering.

INTRODUCTION

Understanding the source of Q, Q' and $|C^-|$ dependencies on Landau octupole (MO) powering is important, both with a view to anticipating shifts, to correction, and identifying artifacts in the measurements. This is particularly true of Q', which may have a significant influence on the instabilities the MO are intended to damp.

SUMMARY OF OBSERVATIONS

Observations were made at $4\,\mathrm{TeV}$ during four machine development (MD) studies performed on the LHC in 2012. A summary of all observations is given in Table 1.

Dedicated measurements of Q' were performed during the *Octupole instability Threshold MD* of the 20th June [1, 2]. They showed a substantial dependence. Small tune shifts were observed on all occasions; notably Q_x and Q_y are driven in the same direction suggesting higher order effects are relevant. Measurements of $|C^-|$ were performed using the LHC Base Band Tune (BBQ) system [3], and were consistently seen to decrease on the trimming of the MO towards zero. This occurred irrespective of the MO polarity. Two measurements of linear coupling resonance driving terms (RDTs) f_{1001} and f_{1010} were also performed via spectral analysis of turn-by-turn BPM data with kicked beams. They showed no appreciable change on depowering the MO, in contradiction with BBQ based measurements.

UNDERSTANDING THE DEPENDENCE ON MO POWERING

One likely cause of a variation in the fundamental beam parameters with octupole powering is feed-down from misalignments and closed orbit. Another is the field quality of the MO. These effects have been modelled in MAD-X.

Known Misalignments of the Landau Octupoles

Estimates of geometric errors in the LHC lattice are generated by the Windows Interface to Simulation Errors (WISE) [4] from measurements and known uncertainties. Mean misalignments of focusing (MOF) and defocusing (MOD) Landau octupoles are of order 10^{-2} to $6 \times 10^{-2}\,\mathrm{mm}$. Q' shifts on depowering the MO to zero in a MAD-X model including these misalignments are presented in Table 2.

Table 2: Q' shifts on depowering the MO in MAD-X, with measured misalignments applied to the MO.

	Beam 1		Beam 2	
	model	measured	model	measured
$\Delta Q'_x$	0.96	6.3±0.8	1.36	4.7±0.7
$\Delta Q'_y$	−0.53	−2.3±0.4	−1.12	−2.2±0.6

We conclude that alignment errors of the MO represent a significant contribution to the Q' dependence. Tune shifts were not reproduced, with Q_x and Q_y being shifted in opposite directions. The modelled coupling did not change appreciably, this is consistent with RDT observations and inconsistent with BBQ data.

Closed Orbit at the Landau Octupoles

Another potential source of feed-down is the closed orbit. During the *Octupole instability threshold MD* the orbit in the LHC BPMs was recorded. All MO in the LHC are located next to a BPM ($|s_{MO} - s_{BPM}| = 0.751\,\mathrm{m}$), we therefore approximate the closed orbit in the MO to that of the neighbouring BPM.

Figure 1 shows an example of the logged horizontal orbit. BPMs logged as having $Status = OK$ are plotted in green. All other BPMs are plotted in red. The lower plot in Fig. 1 shows the orbit logged for all BPMs around the ring, and we see that the orbit is not substantially dispersive ($\frac{\delta p}{p} = 0.057 \times 10^{-3}$). Considering the upper plot however, which only displays the orbit at BPMs neighbouring a Beam 1 MOF, there is a substantial systematic orbit at these BPMs.

We have averaged the systematic orbit obtained from functioning BPMs next to an MOF or MOD over the duration of the Q' measurements. Corrections were applied to incorporate the available knowledge of BPM misalignments. Table 3 summarizes the mean systematic orbit in the MOF and MOD. This is observed to be substantial.

To assess the role of feed-down from this closed orbit, corresponding systematic misalignments were applied to the MOF and MOD in MAD-X (in addition to MO alignment errors). The resulting shifts to Q' on depowering the MO are presented in Table 4.

Table 1: Summary of Q, Q' and C^- shifts. A $\Delta|C^-|$ equivalent to the change in f_{1001} at the closest available BPM to the BBQ has been calculated, and is quoted in the table in order to characterise the f_{1001} measurements.

	$\Delta = off - on$	30/3/12 250→0[A] (60 cm)	22/4/12 450↔50[A] (60 cm)	20/6/12 450→0[A] (60 cm)	20/6/12 450→ 0[A] (Flattop)	27/11/12 -500→ 0[A] (Flattop)
Beam 1	ΔQ_x ($\times 10^{-4}$)	2±1	5±2	7±4	5±4	−10±1
	ΔQ_y ($\times 10^{-4}$)	3±1	5±2	4±1	8±1	−10±3
	$\Delta Q'_x$	-	-	6.6±0.3	6.3±0.8	-
	$\Delta Q'_y$	-	-	−2.1±0.6	−2.3±0.4	-
	$\Delta\|C^-\|_{from\ BBQ}$ ($\times 10^{-3}$)	−0.6±0.1	−3.2±0.2	−0.9±0.1	−2.5±0.5	−4.5±0.3
	$\Delta\|C^-\|_{from\ f_{1001}}$ ($\times 10^{-3}$)	−0.02	-	-	-	−0.2
Beam 2	ΔQ_x ($\times 10^{-4}$)	4±1	6±3	-	20±6	-
	ΔQ_y ($\times 10^{-4}$)	7±1	13±6	-	8±2	−19±4
	$\Delta Q'_x$	-	-	-	4.7±0.7	-
	$\Delta Q'_y$	-	-	-	−2.2±0.6	-
	$\Delta\|C^-\|_{from\ BBQ}$ ($\times 10^{-3}$)	−0.4±0.3	−3.5±0.8	-	−3.5±0.2	−4.7±0.4
	$\Delta\|C^-\|_{from\ f_{1001}}$ ($\times 10^{-3}$)	−0.1	-	-	-	+0.2

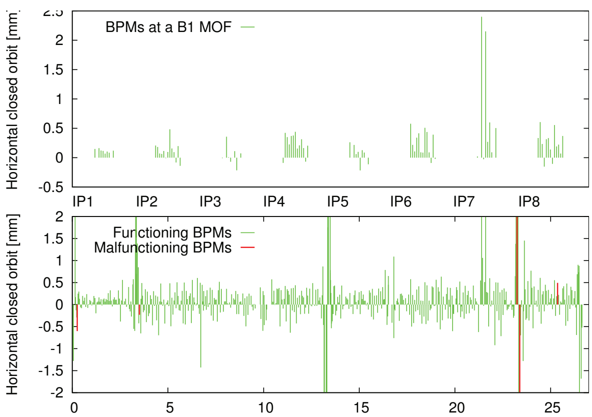

Figure 1: Beam 1 horizontal orbit logged at 02:19:54 during the *Octupole instability threshold MD*. Functioning BPMs are shown in green, others in red. The lower plot shows measured orbit at all BPMs. The upper plot shows the orbit measured at BPMs immediately preceding Beam 1 MOF.

The majority of the observed Q' dependence is explained by MO alignment errors and feed-down from closed orbit. The coherent shift in Q has not been reproduced and the $\Delta|C^-|$ is again consistent with RDT observations.

We observe substantial contributions to the systematic closed orbit from a minority of MO with substantial deviations. Notable are BPM.29R7.B1 and BPM.33R7.B1, seen in Fig. 1 to have a closed orbit in excess of 2 mm. This alone accounts for $\sim 30\%$ of Beam 1 $\Delta Q'_x$. Consultation with the CERN operations group revealed this results from a broken orbit corrector right of IR7.

Consideration of the local feed-down is of relevance to the tune. The same sign of ΔQ in both planes implies a higher order effect, for which the distribution of sources

Table 3: Summary of mean systematic closed orbits at MOF and MOD for the relevant period of the *Octupole instability threshold MD*.

			logged orbit	logged orbit & BPM align'
Beam 1	MOF	$\bar{\delta}_x$[mm]	0.27±0.04	0.25±0.04
		$\bar{\delta}_y$[mm]	-0.029±0.001	0.239±0.001
	MOD	$\bar{\delta}_x$[mm]	0.01±0.02	0.01±0.02
		$\bar{\delta}_y$[mm]	0.016±0.001	0.189±0.001
Beam 2	MOF	$\bar{\delta}_x$[mm]	0.17±0.03	0.17±0.03
		$\bar{\delta}_y$[mm]	-0.032±0.001	0.214±0.001
	MOD	$\bar{\delta}_x$[mm]	0.04±0.02	0.00±0.02
		$\bar{\delta}_y$[mm]	0.024±0.002	0.308±0.002

Table 4: Q' shifts on depowering the MO in MAD-X, with measured MO alignments applied and systematic misalignments of MOF and MOD incorporated to model feed-down from the measured systematic closed orbit.

		Model	Measurement
B1	$\Delta Q'_x$	5.3	6.3±0.8
	$\Delta Q'_y$	-1.5	-2.3±0.4
B2	$\Delta Q'_x$	4.1	4.7±0.7
	$\Delta Q'_y$	-1.6	-2.2±0.6

around the ring is relevant. We have considered the orbit logged at a specific instant during the *Octupole instability threshold MD* and applied misalignments to model feed-down due to closed orbit locally as opposed to systematically. Results for Beam 1 are given in Table 5.

Modelling the closed orbit feed-down locally, rather than

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Table 5: Q shifts on depowering MO in MAD-X, with measured alignments applied, and additional misalignments of individual MO applied locally or systematically to simulate feed-down due to the measured closed orbit.

BEAM 1	systematic orbit	local orbit
$\Delta Q_x(\times 10^{-4})$	-10	1
$\Delta Q_y(\times 10^{-4})$	12	3

systematically, gives a coherent tune shift in both planes of the expected magnitude. Modelling the closed orbit locally did not significantly alter the tune shift of Beam 2, however second order effects are difficult to simulate with precision and only a simple model has been considered, which includes a non-negligible degree of uncertainty in the measured orbit. In regard of the Beam 1 simulation we do not claim to have truly explained the tune shift. This result should be considered a demonstration that second order effects carry the potential to explain the tune observations.

Magnetic Errors

Another potential source of the dependence of the Q, Q' and $|C^-|$ on the MO powering are magnetic errors in the MO. Estimates of the magnetic errors based on measurements and known uncertainties are generated by WISE. These errors have been incorporated in the MAD-X simulation. They do not have a substantial influence on the Q'.

Coupling

When MO are trimmed to lower settings we consistently see a reduction in the $|C^-|$ measured by the LHC BBQ. Considering all data collected however, we see no clear trend in the $\Delta|C^-|$ dependent on the size of the MO trim. Indeed the $\Delta|C^-|$ recorded by the BBQ is independent of the MO polarity, which excludes the common sources of a linear coupling dependence on octupolar elements, namely feed-down and field quality.

Measurements of linear coupling RDTs were performed on two occasions when coupling drifts were seen by the BBQ. No corresponding shifts in the RDTs were observed. The RDT approach has been well verified during LHC commissioning. In regard of these measurements we conclude that linear coupling is not changing appreciably due to MO powering. The reason for the differing observations is unknown.

Figure 2 shows an example of shifts to the BBQ and RDT coupling measurements on depowering the MO. The shift in f_{1001} is approximately an order of magnitude smaller than the shift in the BBQ $|C^-|$.

Throughout 2012 the BBQ and RDT measurements have been found to be consistent when the MO are depowered. This is seen in Fig. 2. We conclude that we should not trust the BBQ $|C^-|$ measurement when MO are powered.

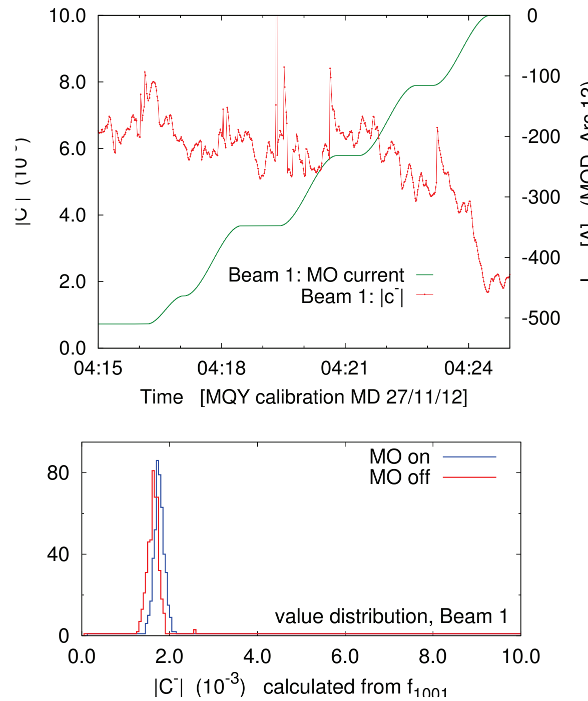

Figure 2: BBQ (upper plot) and RDT (lower plot) shifts on depowering the MO during November 2012.

CONCLUSIONS

The Q' dependence of the LHC on MO powering is well understood. The dominant source is feed-down due to a systematic closed orbit in the MO, and feed-down due to misalignments. The role of the magnetic errors is limited. There are substantial contributions from a minority of octupoles with particularly significant orbit excursions.

The Q dependence may be explained by higher order effects, as illustrated by a modelling of the local closed orbit, however we do not claim this is fully understood.

$|C^-|$ shifts correlated with changes in MO powering were observed by the LHC BBQ, in contradiction with measurements of coupling RDTs. The RDT measurement has been well verified throughout 2012, therefore we conclude that there is no significant change to linear coupling dependent on MO powering, and we should not trust the BBQ $|C^-|$ measurement when the MO are powered.

A complete analysis of the study summarized here may be found in [5]. Details of the dedicated chromaticity measurement are reported in [2].

REFERENCES

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