COMMISSIONING OF NON-LINEAR OPTICS IN THE LHC AT INJECTION ENERGY

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Abstract

Commissioning of nonlinear optics at injection in the LHC was carried out for the first time in 2015 via beam-based methods. Building upon studies performed during Run I, corrections to nonlinear chromaticity and detuning with amplitude were obtained. These corrections reduced beam-loss during measurement of linear optics.

INTRODUCTION

Measurements of nonlinear chromaticity with depowered Landau octupoles in 2011 [1, 2] revealed substantial second and third order chromaticities in the LHC at injection. Comparison to simulations, including the best knowledge of the magnetic and geometric errors in the LHC, indicated the Q'' and Q''' were significantly larger than expected [3]. Similar features were observed in measurements of amplitude detuning. It was shown in 2011 that a global trim of octupole and decapole spool-pieces (corrector magnets mounted directly to the LHC main dipoles) could significantly reduce the second and third order chromaticity [3]. This correction also reduced amplitude detuning and the decoherence of kicked beams [2–5].

While it is necessary to introduce nonlinearity into the accelerator for stabilization of instabilities (Landau damping of e-cloud instabilities is particularly significant for operation at injection) [6–8], the strategy envisaged in the LHC is that this should be generated in a well controlled and understood manner via dedicated Landau octupoles. Magnetic errors should be corrected locally by the spool-piece magnets. Furthermore, the large nonlinear chromaticity and amplitude detuning observed in Run I generate substantial asymmetries in the response of the accelerator to different polarities of the Landau octupoles [1, 9] complicating operation. Correction of the nonlinear errors is also expected to be a significant advantage for operation with depowered Landau octupoles: for example during linear optics measurements.

During commissioning for LHC Run II nonlinear chromaticity was measured at injection and showed similar behaviour to 2011. Beam-based corrections for Q'' and Q''' were applied, significantly reducing nonlinear chromaticity. As in 2011 the corrections reduced the decoherence of kicked beams, indicating an improvement in detuning with amplitude and hence a local correction. These beam-based corrections were implemented operationally at injection, representing the first inclusion of nonlinear single-particle dynamics in LHC commissioning.

2015 & 2011 MEASUREMENTS

Measurements of nonlinear chromaticity for Run II commissioning were performed in April 2015 by scanning the RF-frequency over a momentum range $\frac{\delta p}{p} = \pm 2.5 \times 10^{-3}$ and monitoring the change in tune. Measurements were performed with nominal corrections for b_4 and b_5, calculated from the magnetic model, applied and with Landau octupoles off. Figure 1 compares the tune variation with momentum observed for LHC Beam 1 in 2015 to a fit of comparable measurements performed in June 2011. Similar results were obtained for LHC Beam 2. Values for second and third order chromaticity were remarkably consistent between 2011 and 2015.

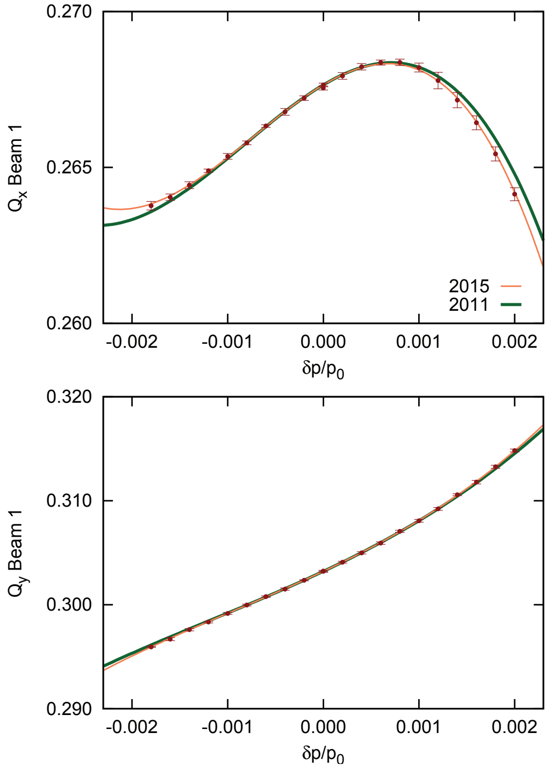

Figure 1: Nonlinear chromaticity of LHC Beam 1 at injection during 2015, compared to 2011.

BEAM-BASED CORRECTION

Octupole (MCO) and decapole (MCD) spool-piece magnets are powered arc-by-arc, and to first-order affect Q'' and Q''' respectively. For correction the MCO and MCD could be trimmed uniformly over all 8 arcs, or be divided into two families per beam (4 arcs per family) located at different average ratios of β_x/β_y. A two family correction allows for

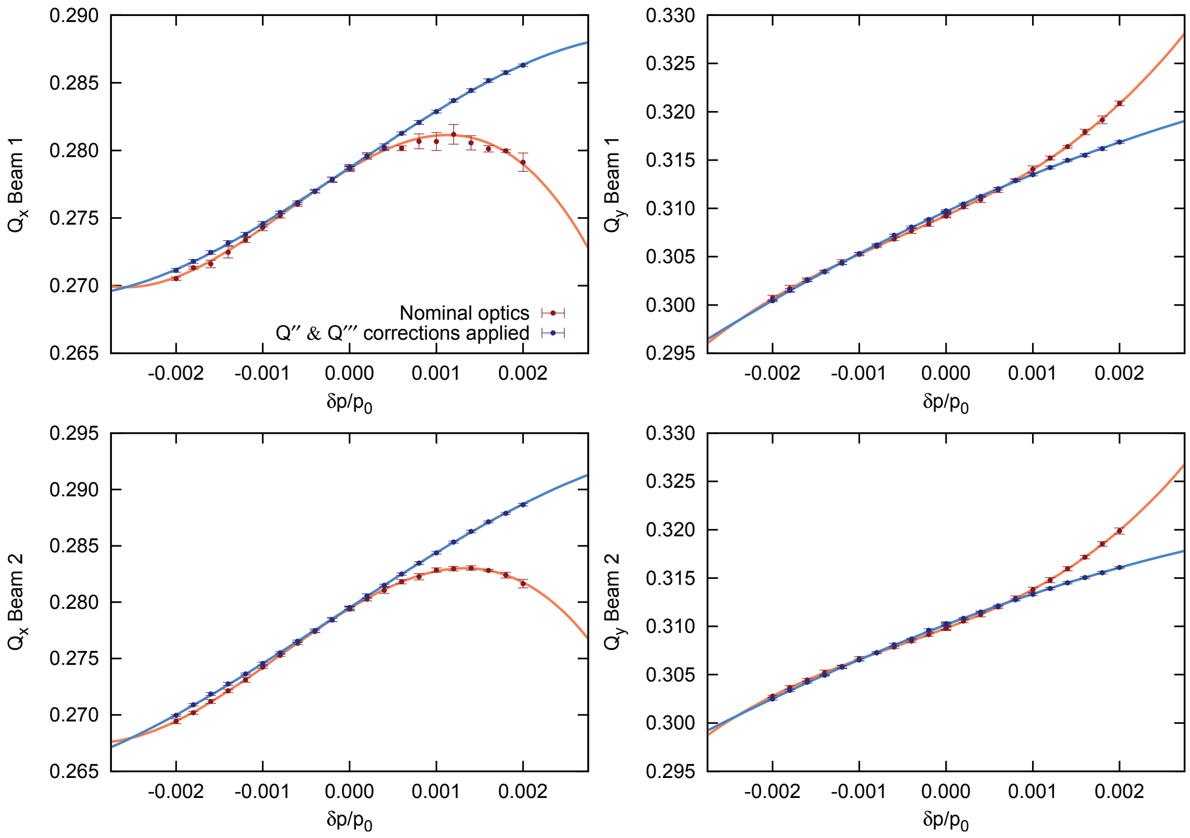

Figure 2: Tune variation with momentum, with and without beam-based correction of nonlinear chromaticity.

Table 1: 2nd Order Chromaticity Before & After Correction

	$\mathbf{Q''_x}[10^3]$	$\mathbf{Q''_y}[10^3]$
B1 before	-2.03 ± 0.02	0.97 ± 0.02
B1 after	0.02 ± 0.01	-0.51 ± 0.02
B2 before	-2.06 ± 0.02	0.89 ± 0.01
B2 after	-0.08 ± 0.02	-0.44 ± 0.02

exact compensation of the nonlinear chromaticities in each plane, but required larger trims leading to concern over feed-down. Additionally, during Run I a significant proportion of the missing Q'' was identified with hysteresis errors in the MCO [1,3]. These were approximately uniform over the arcs, indicating a global correction to be appropriate. Correction in 2011 using a uniform trim over all arcs had also been demonstrated to achieve local correction of b_4. Given the close similarity of Run II and Run I measurements shown above it was decided to correct the nonlinear chromaticity using uniform trims of the MCO and MCD. Figure 2 shows tune variation with momentum before and after application of the corrections, Tables 1 & 2 show the second and third order chromaticity determined from fits to the tune variation.

Turn-by-turn BPM data of kicked beams showed improved decoherence in all planes after correction, verifying local correction of b_4. An example is shown in Fig. 3.

Table 2: 3rd Order Chromaticity Before & After Correction

	$\mathbf{Q'''_x}[10^6]$	$\mathbf{Q'''_y}[10^6]$
B1 before	-2.31 ± 0.08	1.06 ± 0.04
B1 after	-0.74 ± 0.04	0.01 ± 0.05
B2 before	-2.12 ± 0.05	1.02 ± 0.02
B2 after	-0.47 ± 0.04	-0.02 ± 0.04

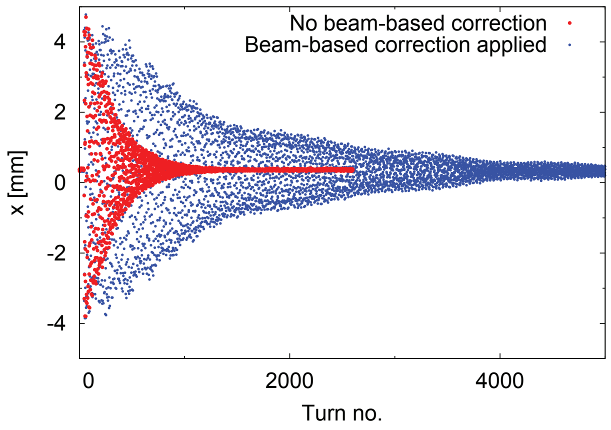

Figure 3: Beam 2 horizontal decoherence with and without correction of nonlinear chromaticity.

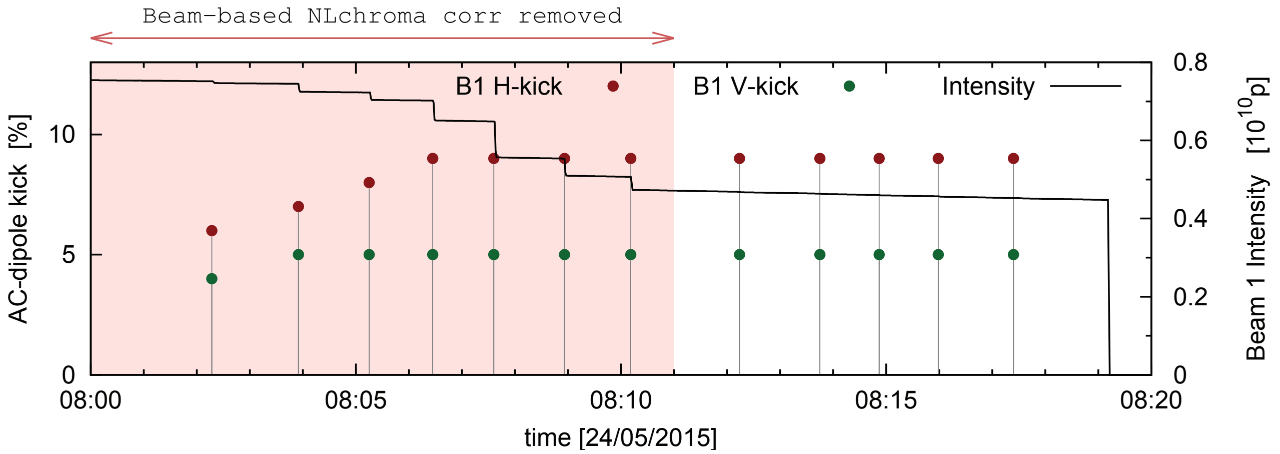

Figure 4: Beam loss upon AC-dipole excitation, with (white region) and without (pink region) nonlinear chromaticity corrections applied.

The reduction in nonlinear chromaticity and improvement in decoherence indicate the effectiveness of the beam-based corrections (in particular for b_4), however their impact was also observed in beam-losses when exciting with the AC-dipole. Figure 4 shows beam intensity during linear optics measurements with the AC-dipole. Kicks were performed with nonlinear chromaticity corrections removed (region in pink), and with them re-applied. Losses upon kicking were substantially reduced by applying the nonlinear chromaticity corrections. This may indicate some improvement in the short-term dynamic aperture, which can be probed through AC-dipole excitation [10, 11].

The beam-based corrections of nonlinear chromaticity represent large shifts to the nominal powering of the MCO and MCD. Changes of ~ 100% were applied to MCO strength, half being required to compensate hysteresis errors in the MCO [1, 3]. MCD powering was reduced by a ~ 40 %, which remains to be understood. The nonlinear corrections were implemented operationally for the 2015 LHC run.

DECAPOLE EFFECT ON Q''

While the corrections did significantly reduce the second and third order chromaticity, Tab. 1 indicates there was an over correction of the Q''. This was inconsistent with the expected behaviour of the applied correction. By trimming out the second and third order corrections independently the source was identified primarily as an unexpected dependence of Q'' upon decapole spool-piece powering.

Decapoles can affect second-order chromaticity via feed-down. To reproduce the observation a systematic ~ 0.2 mm horizontal offset of the beam in the MCD is required. This is significantly larger than that generated by the measured closed orbit and measured misalignments. The source remains under investigation. The decapole effect on Q'' can be compensated via a second iteration of the correction, however this was not implemented operationally in 2015. Extrapolating the Q'' dependence on MCD trims to their nominal powering can explain the remainder of the MCO correction required to minimize Q''.

CONCLUSIONS

Before application of beam-based corrections, the nonlinear chromaticity of the LHC in 2015 was large and significantly in excess of intended design parameters. The 2nd and 3rd order chromaticities are similar to those present in the machine during Run I. Beam-based corrections for 2nd and 3rd order chromaticities were applied to the LHC during the initial commissioning phase of Run II. These corrections were based upon global trims of octupole and decapole spool-pieces respectively, and reduced the relevant chromatic terms. Decoherence of kicked beams was seen to improve upon application of the correction, indicating that local correction of b_4 was achieved. The nonlinear chromaticity corrections were observed to reduce beam-loss upon excitation with the AC-dipole. Beam-based corrections of nonlinear chromaticity were deployed operationally in the LHC for the first time in 2015.

It was observed that decapole spool-pieces had a significant impact upon Q''. This was not accounted for in the original correction and led to an over-correction of Q''. Further iterations of the correction can compensate this effect, but were not used operationally in 2015. Known alignment errors and closed orbit data were inconsistent with the systematic decapole offset required to generate the necessary feed-down. The source is still under investigation.

More detail on these studies can be found in [12].

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