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OBSERVATIONS OF AN ANOMALOUS OCTUPOLAR RESONANCE IN THE LHC

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Abstract

While linear LHC dynamics are mostly understood and under control, non-linear beam dynamics will play an increasingly important role in the challenging regimes of future LHC operation. In 2012, turn-by-turn measurements of large betatron excitations of LHC Beam 2 at injection energy were carried out. These measurements revealed an unexpectedly large spectral line in the horizontal motion with frequency $-Q_x - 2Q_y$. Detailed analyses and simulations are presented to unveil the nature of this spectral line.

INTRODUCTION

Linear beam dynamics in the LHC is currently well understood [1–4]. Nonlinear dynamics will play an increasingly important role in the challenging regimes of future LHC operation. Nonlinearities in circular accelerators can significantly affect the dynamic aperture [5, 6] and can lead to poor beam lifetime. Understanding these nonlinearities and their underlying sources is therefore important to improve the performance of the machine. Great progress has been made in recent years in this field in the LHC [7–12].

Spectral analysis of turn-by-turn data obtained from beam position monitors after large betatron excitations provide accurate measurements of the main tunes and secondary spectral lines related to specific resonant driving terms. Such measurements of resonant driving terms can provide insight on the presence machine nonlinearities. The theory of resonant driving terms is extensively discussed in [13–16].

In 2012, turn-by-turn measurements of large betatron excitations of LHC Beam 2 at injection energy were carried out [11]. These measurements revealed an unexpectedly large spectral line in the horizontal motion with frequency $-Q_x - 2Q_y \approx 0.1$, whose amplitude is well above model expectations. Details of these measurements can be found in [11]. This spectral line, later referred to as the (-1,-2) spectral line only appears for large diagonal excitations with nominal kick amplitudes higher than $5\sigma_{x,\mathrm{nom}}$ and $4\sigma_{y,\mathrm{nom}}$. This paper presents observations of the (-1,-2) spectral line and possible sources.

OBSERVATIONS

Figure 1 shows the complex spectra of turn-by-turn data for a measurement and multiparticle tracking simulation with 5000 particles for 1000 turns in the horizontal plane with measured kick amplitudes of $8.2\sigma_{x,\mathrm{nom}}$ and $6.5\sigma_{y,\mathrm{nom}}$. The large (-1,-2) line is observed in the measurement spectrum at $freq \approx 0.1$ corresponding to the generating term f_{2020} related to the $2Q_x + 2Q_y = p$ resonance, while its conjugate (1,2) line, corresponding to f_{1102}, is not visible. Furthermore, the amplitude of the (-1,-2) line reaches 8% of the main horizontal tune amplitude, while in tracking simulation it is not visible. Though other spectral lines are correctly reproduced from the model (0,1), (1,1), the discrepancy between model and measurement indicate a clear lack of understanding of the machine at such large betatronic excitations.

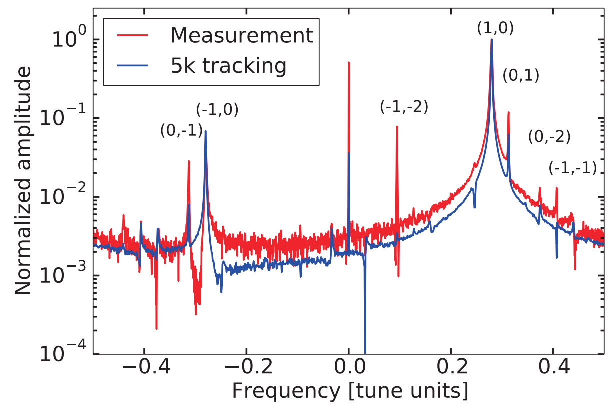

Figure 1: Complex spectra amplitude of $h_x^- = x - ip_x$ reconstructed from two BPM signals at BPM.12L1.B2 from the LHC with $8.2\sigma_{x,\mathrm{nom}}$ and $6.5\sigma_{y,\mathrm{nom}}$ measured kick amplitudes. A large amplitude is observed at $freq \approx 0.1$, but not at -0.1.

Further observations of the (-1,-2) line show its frequency is linear with the calculated frequency from the main tunes as it is shown in Fig. 2. This result confirms that the (-1,-2) line is not an artifact unrelated to the beam.

The decoherence of the (-1,-2) line over the number of turns is shown in Fig. 3. The measured (-1,-2) line cleary decoheres much slower than the main horizontal tune. This result motivates the study of possible surviving lines [15] as part of the cause of the large measured amplitude.

Anharmonicities for first and second order amplitude detuning have been calculated in 2012 [12]. These can be used to calculate the amplitude detuning for specific frequencies. Figure 4 shows the amplitude detuning for the (-1,-2) line for different anharmonicities than in [12], but still within the error margins of the measurements. The obtained amplitude detuning for the (-1,-2) line shows a saddle point on the diagonal of the $(2J_x, 2J_y)$-plane where the gradient is zero. A beam kicked near this critical point would have zero amplitude detuning for the (-1,-2) line and therefore a decreased

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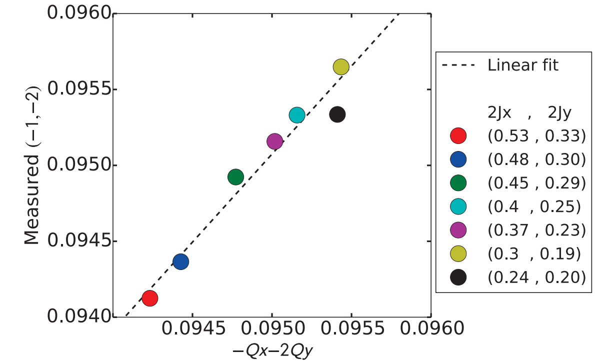

Figure 2: Measured frequency of (-1,-2) line over expected frequency calculated with the main tunes. The (-1,-2) line is clearly tune dependent.

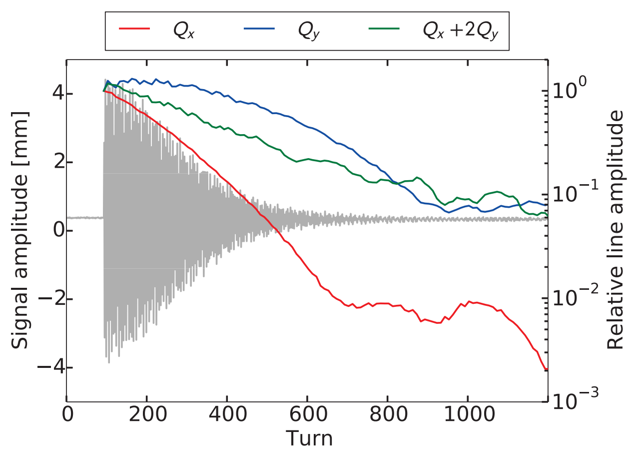

Figure 3: Single BPM spectrum characteristics (BPM.30L1.B2), analyzed by a running window FFT of 256 turns width. The line amplitudes were scaled to 1 at kick for better comparison of the slopes.

decoherence. Further multiparticle simulations are needed to study this effect on the $-Q_x - 2Q_y$ frequency. Though this can contribute to the surviving aspect of the measured line, this does not by itself provide a possible source for the (-1,-2) line excitation.

BPM ABERRATIONS

For a perfect linear measurement the BPM signal would be $u_{\mathrm{bpm}} = Cu_{\mathrm{raw}}$ with $u \in \{x, y\}$. However, BPM measurements are subject to geometrical nonlinearities. Additional second order dependencies can therefore introduce additional frequencies in the BPM turn-by-turn spectra. Two appropriate BPM correction procedures can be found in [17] and were implemented.

$$
\begin{aligned}
P_5(u_{\mathrm{raw}}) &= Au^5_{\mathrm{raw}} + Bu^3_{\mathrm{raw}} + Cu_{\mathrm{raw}} && (1)\\
P_{5,\mathrm{new}}(u_{\mathrm{raw}}) &= Au^5_{\mathrm{raw}} + Bu^3_{\mathrm{raw}} + Cu_{\mathrm{raw}} + Du^3_{\mathrm{raw}}v^2_{\mathrm{raw}} \\
&+ Eu_{\mathrm{raw}}v^4_{\mathrm{raw}} + Fu_{\mathrm{raw}}v^2_{\mathrm{raw}} && (2)
\end{aligned}
$$

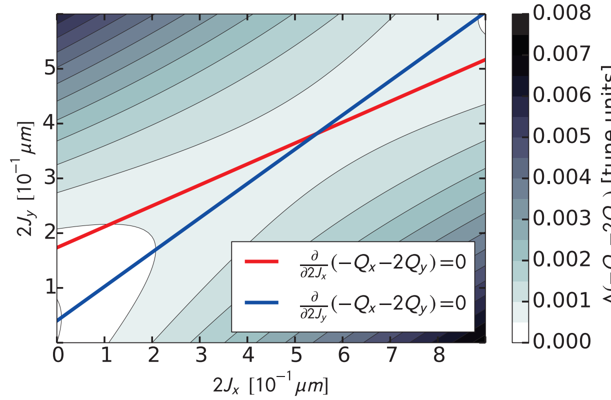

Figure 4: The resulting detuning $\Delta(-Q_x - 2Q_y)$ as calculated using anharmonicities within the measured error margins. A saddle point is observed where the derivative of the detuning is zero. Kicking the beam in such a domain would lead to decreased decoherence for the (-1,-2) spectral line.

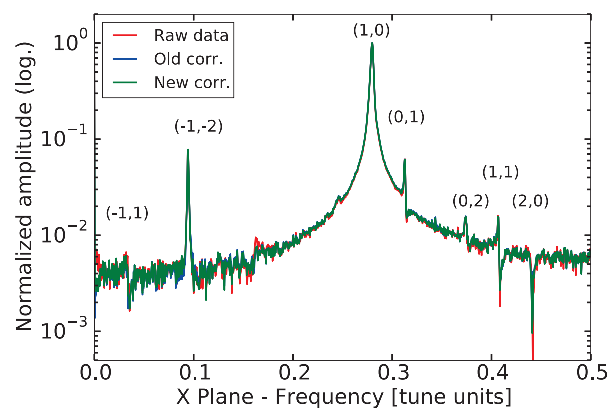

Figure 5: Spectrum comparison between raw measurement data, old and new correction for one example BPM (BPM.12L6.B2) with $8.2\sigma_{x,\mathrm{nom}}$ and $6.5\sigma_{y,\mathrm{nom}}$ measured kick amplitudes. Note that the raw measurement data and the old correction are overlapping for most of the spectrum and therefore are not distinguishable.

with $u, v \in \{x, y\}$. The P_5 corrections were applied in 2012 data. The $P_{5,\mathrm{new}}$ corrections will be applied in future LHC runs and introduce cross terms $u^i_{\mathrm{raw}}v^j_{\mathrm{raw}}$ which are needed in order to correct x-y-correlation effects.

Both corrections were applied to the raw data and the resulting spectra are shown in Fig. 5. The corrected spectra show no major change, and the large (-1,-2) line amplitude remains unchanged. Further studies were done, by varying the $Fu_{\mathrm{raw}}v^2_{\mathrm{raw}}$ term in the $P_{5,new}$ corrections that could contribute to the (-1,-2) line. Figure 6 shows the resulting spectrum. The (-1,-2) line amplitude could only be decreased by half, while distorting the spectrum and introducing additional spectral lines (2,1) and (1,-2). BPM aberrations are

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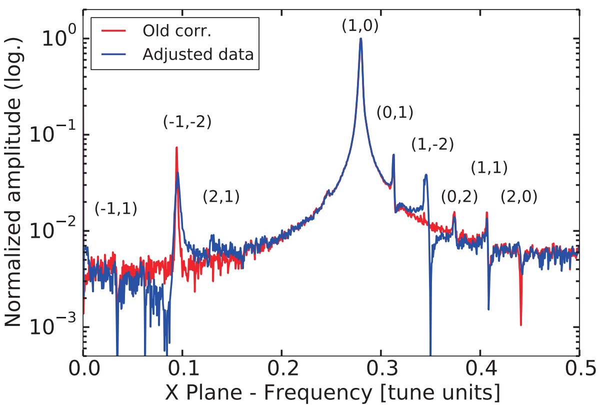

Figure 6: Comparison of spectra for measurement data corrected with the old P_5 corrections (blue) and using the adjusted $P_{5,new}$ corrections (red) minimizing the (-1,-2) line.

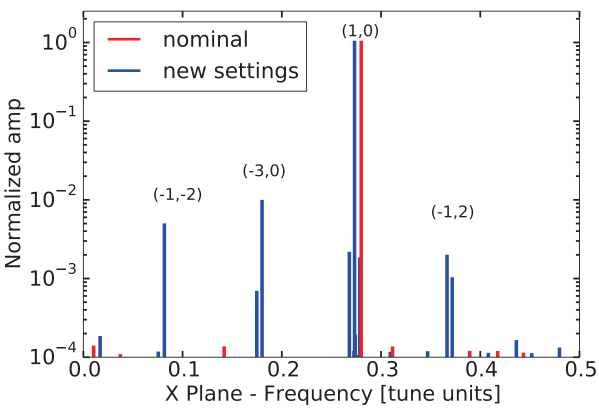

Figure 7: The resulting spectra of the tracking simulations with the new MCO settings obtained to maximize the real part of f_{2020} are shown for the horizontal plane.

therefore not likely to be the source for the large measured (-1,-2) amplitude.

DIPOLE OCTUPOLAR ERRORS

Octupolar corrector magnets (MCO) are used for corrections of octupolar errors in the main dipoles. The resonant driving terms as generated in the models can be accurately calculated using the phase and β-function of the model. A response matrix can be constructed relating the specific MCO family strengths to the RDTs. Singular value decomposition can be used to find new MCO settings (α) given a specific set of target RDTs f_{jklm}. However, as this solution relies on the least square solution, the success of this method is not guaranteed.

New MCO settings were computed to maximize f_{2020}. The new coefficients can be scaled to generate the desired (-1,-2) line. Figure 7 shows the turn-by-turn spectra of single particle tracking simulations with new MCO settings for a nominal model with sextupoles and Landau octupoles turned off. Octupolar lines are clearly generated with the new settings. However, this does not solely happen for the (-1,-2) frequency as all octupolar lines also appear. The (-3,0) and (-1,2) line could be supressed or changed in multiparticle systems. Still, the (-1,-2) amplitude reaches a few tenths of a percent (0.5‰) of the main tune amplitude. Compared to the measured relative amplitude of 4 to 8‰, this is still a factor of 8 to 16 short of the measured resonance amplitude.

CONCLUSION

Spectral analysis of the LHC nonlinear MD measurements of the 24th of June 2012 with large diagonal betatron excitations show a (-1,-2) line with frequency $-Q_x - 2Q_y \approx 0.1$ with an abnormally large amplitude. This octupolar line only appears in measurements with large diagonal kicks above $5\sigma_x$ and $4\sigma_y$. The measured line could be compared to the best nonlinear model available through single and multiparticle tracking simulations, and results indicate that the amplitude of the measured (-1,-2) line is well above model expectations. The associated resonant driving term is f_{2020}, which drives the $2Q_x + 2Q_y = p$ resonance.

Geometrical nonlinear corrections for the BPMs were studied and possible BPM aberrations could be discarded as a source for the large measured (-1,-2) line.

Observations of decoherence show a surviving characteristic of the (-1,-2) line. This may be caused by decreased amplitude detuning of $-Q_x - 2Q_y$ in the diagonal of the $(2J_x, 2J_y)$-plane. Studies show that zero detuning of the (-1,-2) line could be obtained for these kicks and motivates further studies of the (-1,-2) line as a surviving line.

Using MCOs to mimic octupolar errors in the dipoles, the (-1,-2) could not be excited independently in single particle tracking simulations. The large measured (-1,-2) amplitude was also not reached. This indicates that octupolar errors in the main dipoles are not likely to be the main source of the octupolar excitation, but can still contribute to the (-1,-2) spectral line.

Other possible sources, such as errors in the quadrupoles, and combinations of contributing factors should also be studied to explain the possible origins of this large measured (-1,-2) spectral line.

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