OBSERVATIONS OF RESONANCE DRIVING TERMS IN THE LHC DURING RUNS I AND II

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Abstract

Future operations of the LHC will require a good understanding of the nonlinear beam dynamics. In 2012, turn-by-turn measurements of large diagonal betatron excitations in LHC Beam 2 were taken at injection energy. Spectral analysis of these measurements shows an anomalous octupolar spectral line at frequency $-Q_x - 2Q_y$ in the horizontal motion. The presence of this spectral line, as well as other lines, was confirmed by measurements taken for LHC Beam 1 and Beam 2 during the commissioning in 2015. We take a close look at the various spectral lines appearing in the LHC transverse motion in order to improve the LHC nonlinear model.

INTRODUCTION

Nonlinear beam dynamics in circular colliders are playing an increasingly important role as more challenging regimes of operation are reached. Undesired machine nonlinearities can generate resonances, affect the dynamic aperture [1, 2] and significantly decrease the beam lifetime. As such, a good understanding of such descrepancies with the nonlinear magnetic model is important for the performance of the LHC at future regimes of operation and for future machines such as the High-Luminosity LHC. In recent years, progress has been made to understand these nonlinearities and their underlying sources in the LHC [3–10].

Nonlinearities can be studied, among other methods, by exciting the beam to large transverse amplitudes. Spectral analysis of the obtained turn-by-turn data provides accurate measurements of the main tunes and secondary lines generated by various resonance driving terms (RDTs). The amplitudes of secondary lines in the spectra are a direct measure of the magnitude of the underlying resonance driving terms, and can therefore be used to identify different nonlinear sources. The spectral line amplitudes are given by

$$H(1-j+k, m-l) = 2j \cdot D|f_{jklm}|(2I_x)^{\frac{j+k-1}{2}}(2I_y)^{\frac{l+m}{2}},$$
$$V(k-j, 1-l+m) = 2l \cdot D|f_{jklm}|(2I_x)^{\frac{j+k}{2}}(2I_y)^{\frac{l+m-1}{2}},$$

where the decoherence factor D for a given spectral line (m, n) is given as a function of the detuning coefficients ν'_{yx} and ν'_{xx} by

$$D = \left| m + n\frac{\nu'_{yx}}{\nu'_{xx}} \right| \qquad (1)$$

and where f_{jklm} are the resonance driving terms and $2I_x$ and $2I_y$ are the motion invariants obtained from the main tune lines as in [11]. More detailed treatments of resonance driving terms can be found in [11–14].

In the LHC the beam is either excited with a single kick, using the aperture kicker (MKA) or the tune kicker, or by adiabattically ramping up an ac dipole. Exciting the beam using an ac-dipole is non-destructive, in contrast to the single kick method where the beam decoheres, and therefore provides the only viable method to excite the beam at top energy.

This paper compares measurements taken at large diagonal betatron excitations for Run I and Run II. Furthermore, observations of third and fourth order spectral lines at top energy are presented for Run II.

OCTUPOLAR SPECTRAL LINES

In 2012, turn-by-turn measurements were taken at large diagonal betatron excitations [7] revealing the presence of anomalous octupolar resonance lines (1,2) and (-1,-2) related to the f_{1102} and f_{2020} resonance driving terms respectively with amplitudes much larger than model expectations [15]. Improved analysis using an interpolated FFT [16] reveals a more detailed structure of secondary sextupolar and octupolar lines as shown in Fig. 1.

Fig. 2 shows the measured $|f_{1102}|$ and $|f_{2020}|$ from the complex spectra along the circumference of the LHC. As both lines have identical decoherence factors a relative comparison between $D|f_{1102}|$ and $D|f_{2020}|$ is justified. Both terms show large variations around the IPs. This is due to unfavorable phase advances between BPMs or less reliable BPM signals in the IPs. Improvements in this area will be crucial to better understand the nonlinearities in the insertion regions. Observations of the RDTs show no strong local sources in the accelerator. Furthermore, f_{2020} is identified as the dominant octupolar term.

Measurements with large diagonal betatron excitations were taken in 2015 during the commissioning of Run II. The excitation amplitudes were limitted to 50% of MKA strength due to considerable losses in IR6 and IR7. The measurements, for both Beam 1 and Beam 2, were taken on a virgin machine before any optics corrections and with crossing angles turned off. Furthermore, the most recent nonlinear BPM corrections were applied for these measurements [15] [17].

Fig. 3 shows the complex spectra for the horizontal plane obtained for Beam 1 and Beam 2. The octupolar spectral line (-1,-2) as well as its conjugate (1,2) are observed in the

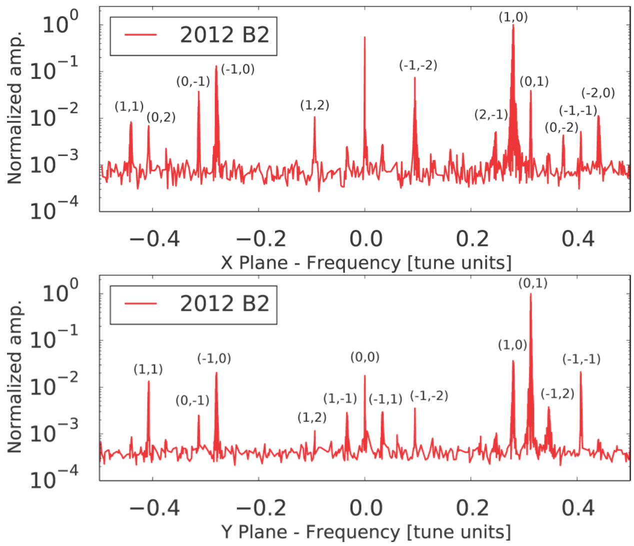

Figure 1: Complex spectra of 2012 data for Beam 2 at injection energy with diagonal excitation using the aperture kicker. Large octupolar spectral lines are observed in the horizontal motion at frequencies $Q_x + 2Q_y \approx -0.1$ and $-Q_x - 2Q_y \approx 0.1$, while not in the vertical plane.

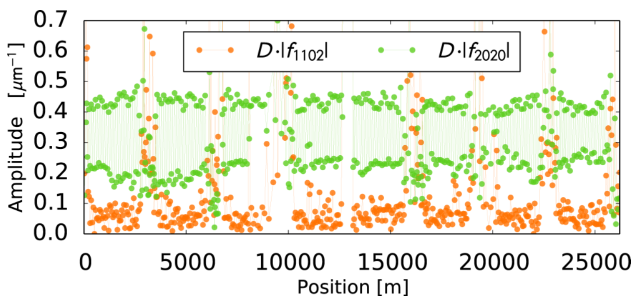

Figure 2: The calculated $|f_{1102}|$ and $|f_{2020}|$ terms generating the large octupolar lines around the accelerator in 2012 data for Beam 2 at injection energy.

horizontal plane of the motion for Beam 2, while Beam 1 only shows the (-1,-2) line. As in 2012, the dominant term is f_{2020} for both beams. The presence of the octupolar lines in the 2015 data shows that the most recent BPM geometrical nonlinear corrections currently do not account for the observed spectral line. However, aberrations in the BPM corrections cannot be fully discarted [15].

The measured $|f_{2020}|$ terms for Beam 1 and Beam 2 of the 2015 data and of Beam 2 of the 2012 data are compared in Table 1. The measured $\langle|f_{2020}|\rangle$ of the different measurements are within their respective errors and in agreement. It is important to note that no linear corrections were applied during the 2015 measurements. Furthermore, nominal nonlinear corrections were applied, which were later proven to be in disagreement with computed beam-based nonlinear corrections [10].

In 2016, measurements with diagonal excitations were taken using the ac dipole at top energy and $\beta^* = 0.40$ m. Figure. 4 shows the obtained spectrum for the 2016 data

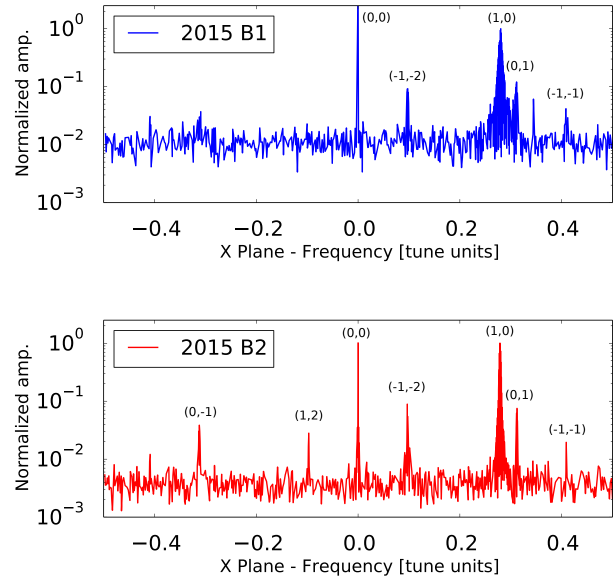

Figure 3: Horizontal complex spectra of 2015 data for Beam 1 and Beam 2 at injection energy with diagonal excitation using the aperture kicker. The octupolar lines are still observed in the horizontal motion for Beam 2, and the (-1,-2) line is observed for the first time in Beam 1.

Table 1: Average Magnitude of f_{2020} Around the Accelerator Actions for the 2012 and 2015 Measurents

Data	$2J_x$ [μm]	$2J_y$ [μm]	$\langle D\|f_{2020}\|\rangle$ [μm^{-1}]
2012 B 2	0.55 ± 0.04	0.35 ± 0.036	0.14 ± 0.09
2015 B 2	0.43 ± 0.10	0.45 ± 0.093	0.16 ± 0.13
2015 B 1	0.37 ± 0.10	0.61 ± 0.097	0.20 ± 0.14

with $2J_x = 3.9 \pm 0.9 \cdot 10^{-3}\,\mu$m and $2J_y = 5.0 \pm 0.9 \cdot 10^{-3}\,\mu$m The kick amplitudes are limited by the aperture due to the squeezed optics. The octupolar spectral lines are not observed for the 2016 data at top energy.

These measurements illustrate that the (-1,-2) spectral line is clearly still present after Long Shutdown 1 (LS1) at injection energy. More thorough measurements at large diagonal excitations at injection and top energy should be

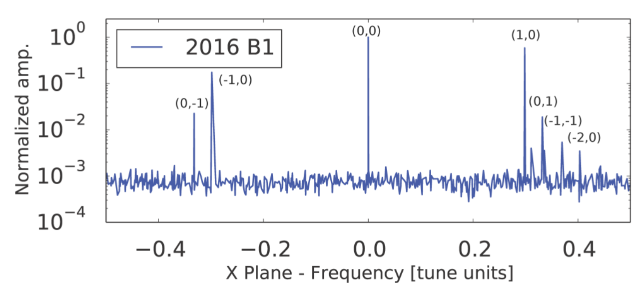

Figure 4: Horizontal complex spectra of 2016 data for Beam 1 at top energy with diagonal excitation using the ac dipole. The (± 1, ± 2) octupolar lines are not observed in the horizontal spectra.

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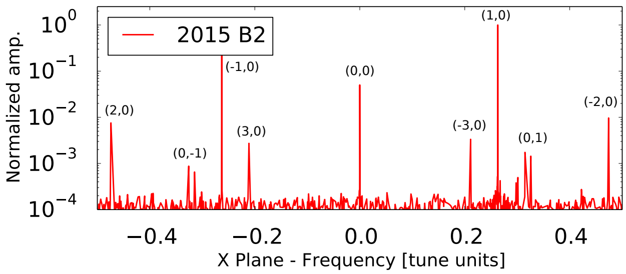

Figure 5: Complex pectra of 2015 data for Beam 2 at large horizontal excitations at top energy using the ac dipole driven at $Q_x^{\mathrm{AC}} = 0.298$ and $Q_y^{\mathrm{AC}} = 0.332$. The 1D sextupolar and octupolar resonances are clearly observed.

taken after optics corrections in Run II for more detailed studies.

MEASUREMENTS OF $|f_{3000}|$ AND $|f_{4000}|$ AT TOP ENERGY

In 2015, amplitude detuning measurements were taken with large horizontal betatronic excitations using the ac dipole at top energy and $\beta^* = 0.40$m for IP1 and IP5. The beam was excited at $2J_x = 0.26$ μm and $2J_y = 0.0013$ μm. Figure. 5 shows the complex spectra of turn-by-turn data. Several sextupolar and octupolar secondary lines of the ac dipole tune are observed in the spectrum. The normal sextupolar lines (±2,0) and normal octupolar lines (±3,0) are clearly measurable. The results obtained from the turn-by-turn data clearly reveal the presence of 1D higher order resonances $3Q_x^{\mathrm{AC}} = p$ and $4Q_x^{\mathrm{AC}} = p$, where Q_x^{AC} is the ac dipole tune. The observed resonances are driven by the resonance terms, f_{3000} and f_{4000} respectively. Note that the (-1,-2) line previously discussed is not observed as the applied kick is purely horizontal.

The calculated $|f_{3000}|$ and $|f_{4000}|$ are shown in Fig. 6, and both RDTs are constant throughout the accelerator. Results obtained at top energy and end of squeeze are significantly less perturbed around the IPs as compared to injection measurements in Fig. 2. These results obtained at top energy show that higher order resonance driving terms can provide an accurately measurable signal to determine the nonlinearities in the LHC and improve the nonlinear magnetic model.

CONCLUSIONS

Spectral analysis of Run I measurements at injection energy with large diagonal betatron exitations revealed an abnormally large octupolar resonance line in the horizontal motion of both beams. This octupolar line only appears in measurements with large diagonal kicks above $5\sigma_{x,\mathrm{nom}}$ and $4\sigma_{y,\mathrm{nom}}$. Improved spectral analysis reveals a much more detailed structure of secondary lines in the 2012 measurements. The terms $|f_{1102}|$ and $|f_{2020}|$ associated with the (1,2) and (-1,-2) lines, respectively, have been calculated. Observations of the underlying RDTs confirm that f_{2020} is

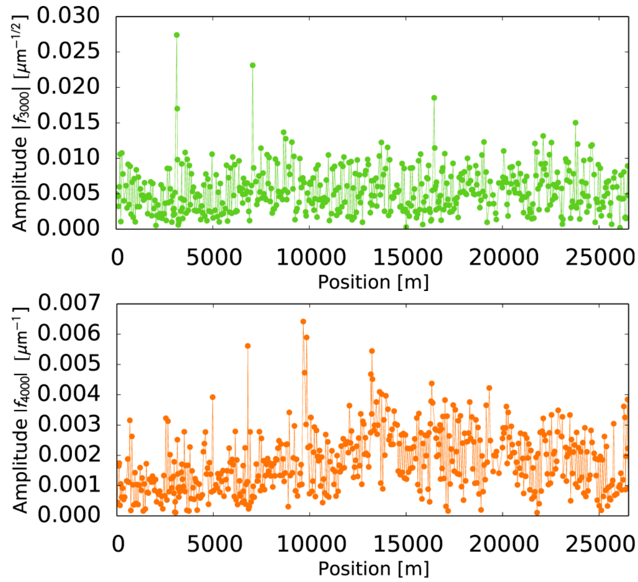

Figure 6: Amplitude of $|f_{3000}|$ (upper) and $|f_{4000}|$ (lower) along the LHC circumference for 2015 data for Beam 2 with large horizontal excitations using the ac dipole driven at $Q_x^{\mathrm{AC}} = 0.298$ and $Q_y^{\mathrm{AC}} = 0.332$. The results show that there are no strong local sources.

the dominant one. No source for the octupolar spectral line could be identified.

Measurements at large diagonal excitations taken during the 2015 commissioning period confirm that the (-1,-2) spectral line is still present after Long Shutdown 1 and after implementation of the most recent BPM corrections. Furthermore, the (-1,-2) spectral line related to f_{2020} is now observed for the first time in Beam 1.

Obtained data in 2016 for diagonal excitations with the ac dipole at top energy did not show the octupolar lines. Measurements with larger excitation amplitudes should be performed to obtain a better understanding of the possible sources at top energy.

In 2015, measurements with large horizontal excitations were taken during amplitude detuning studies using the ac dipole. Spectral analysis of the turn-by-turn data shows large sextupolar and octupolar lines in the horizontal motion corresponding to the $3Q_x = p$ and $4Q_x = p$ resonances. Measurements of the underlying resonance driving terms were made and will be used as accurate measurables for machine nonlinearities in the LHC.

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