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# IMPACT OF POWER SUPPLY RIPPLE ON THE BEAM PERFORMANCE OF THE LARGE HADRON COLLIDER AND THE HIGH-LUMINOSITY LHC *

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*Abstract*

Harmonics of the mains frequency (50 Hz) have been systematically observed in the form of dipolar excitations in the transverse beam spectrum of the Large Hadron Collider (LHC) since the beginning of its operation. The power supply ripple, consisting of both fundamental and higher frequency components, is proven not to be the result of an artifact of the instrumentation systems with which they are observed. Potential sources of the perturbation have been identified through systematic analysis and experimental studies. Single-particle tracking simulations have been performed including a realistic power supply ripple spectrum, as acquired from experimental observations, to demonstrate the impact of such noise effects on beam performance.

## INTRODUCTION

Since the start of the Large Hadron Collider (LHC) operation, harmonics of the mains power frequency (50 Hz) in the form of dipolar excitations have been perturbing the transverse beam spectrum. Similar observations of power supply ripple, including high-order harmonics, have also been reported in the past by several other accelerators such as the Relativistic Heavy Ion Collider (RHIC) and the Tevatron [1–4]. The presence of such perturbation may degrade the accelerator's performance by acting as an additional diffusion mechanism through the excitation of specific resonances. Together with the other resonances excited by the lattice non-linear fields and the beam-beam interactions, this effect can prove detrimental to the beam lifetime.

To this end, identifying the origin of the perturbation and applying mitigation measures is of paramount importance, especially for the High-Luminosity LHC (HL-LHC) era where a good understanding and control of all the beam degradation mechanisms is necessary, as unprecedented values of integrated luminosity are envisaged [5]. The present paper summarizes the main findings, which provide evidence that the 50 Hz harmonics correspond to real beam excitations rather than being an artifact of the instrumentation systems. It furthermore presents the dedicated experiments and measurements performed to identify their origin and illustrates the simulation analysis used to evaluate their impact on the beam lifetime. A thorough analysis of the 50 Hz harmonics in the LHC can be found in [6, 7].

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## OBSERVATIONS FROM THE LHC

The presence of a series of 50 Hz harmonics in the beam signal has been confirmed with measurements with several independent instruments. One of these instruments is the transverse Observation Box (ADTObsBox) which provides bunch-by-bunch and turn-by-turn calibrated position measurements [8–10]. The high-sampling rate allows the spectrum to be computed in a broad high-frequency range. Thanks to the calibrated metric of the turn-by-turn data used to compute the spectrum, the amplitude of each harmonic can be extracted.

Figure 1 shows the beam spectrum for the horizontal plane of Beam 2 as computed with the data obtained from the ADTObsBox for a frequency range up to 10 kHz. Two regimes of interest are identified: a cluster of 50 Hz harmonics extending up to 3.6 kHz (blue), referred to as the *low-frequency cluster*, and another regime with spectral components around 7-8 kHz (yellow), namely the *high-frequency cluster*. Based on the fact that the LHC revolution frequency, hence the sampling frequency, is not an exact multiple of 50 Hz (11.245 kHz), it can be seen that both clusters consist of 50 Hz harmonics and not aliases that could arise from the sampling of the data. Higher amplitudes of the harmonics in the high-frequency cluster are observed. Similar observations have been collected for both beams and planes.

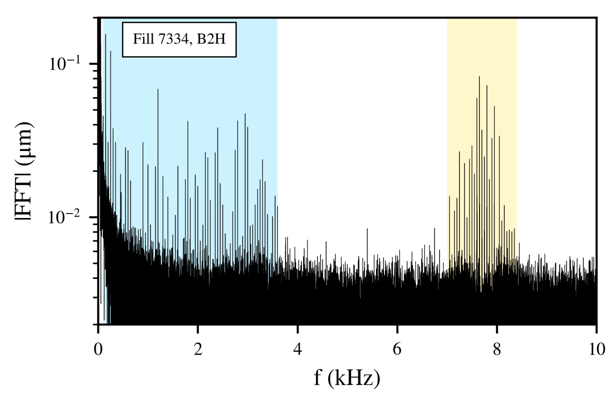


Figure 1: The horizontal spectrum of Beam 2 extending up to 10 kHz using the bunch-by-bunch and turn-by-turn data of the ADTObsBox. The low and high-frequency clusters, both consisting of 50 Hz harmonics, are illustrated with blue and yellow shaded areas, respectively.

Several observations confirm that the observed beam excitation is not an artifact of the instrumentation system. First, the harmonics are visible in several unrelated instruments and a comparison between the spectra before and after the

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dump of the beam shows that they are visible only in the presence of the beam, which is a first indication that they do not emerge from instrumentation noise.

Secondly, modifications in the beam or machine configuration, such as changes in the betatron phase advance, tune and beam energy have a direct impact on the amplitude evolution of the harmonics on the beam. Specifically, Fig. 2 depicts the response of the $h$=12 harmonic (≈600 Hz) when the horizontal betatronic phase advance between Interaction Point (IP) 1 and 5 is modified within a range of ± 20 degrees while maintaining a constant tune. The current of the quadrupole trimming the phase scan is shown (red) together with the amplitude evolution of the 600 Hz line (black). The clear correlation between the betatron phase and the amplitude of the harmonics confirms that this harmonic is not caused by an instrumental effect.

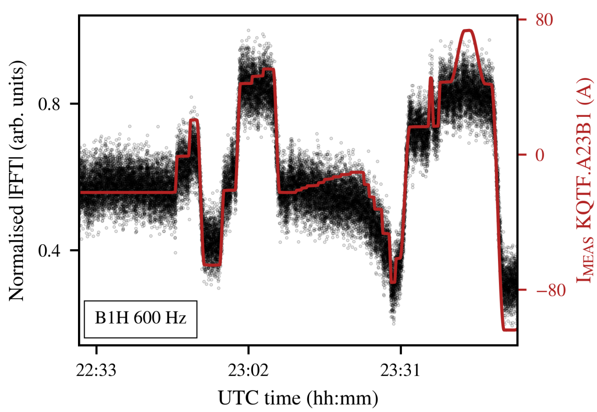


Figure 2: The amplitude evolution of the $h$=12 harmonic observed on the beam spectrum (black) when changing the phase advance between IP1 and IP5, as indicated by the change of quadrupole current (red), while the tune is kept constant.

As a complement to the amplitude-based observations, the phases of the 50 Hz reveal additional information concerning their nature. Figure 3 presents the dephasing of a high-order harmonic ($h$=156) as a function of the train number in the accelerator for two pickups, Q7 (blue) and Q9 (green). The two pickups are located at a relatively close distance with respect to each other so that no other noise perturbation is likely to be present in between them (e.g. no main dipole magnets). The phase difference between the signal of the two pickups ($\Delta\phi$=113.78 degrees) is in agreement with the betatronic phase advance for the collision optics ($\Delta\mu$=110 degrees). Similar observations were collected for the majority of the 50 Hz harmonics. All the previous observations confirm that the 50 Hz harmonics are a feature seen by the beam and not an artifact of the instrumentation system.

The 50 Hz harmonics are visible in both beams, all beam modes and all fills. Changes in the betatron tune do not impact their frequency, which reveals the dipolar nature of the source, as the presence of quadrupolar field errors would lead to the appearance of sidebands around the tune. Further-

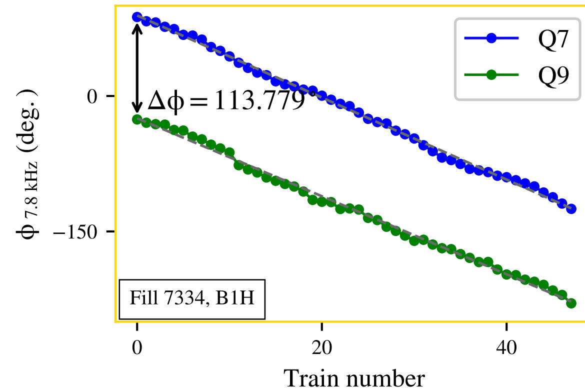


Figure 3: The dephasing of the $h$=156 harmonic as a function of the train number, hence the bunch position in the beam, for two closely separated pickups Q7 (blue) and Q9 (green). The phase difference of the ripple between the two pickups ($\Delta\phi$=110 degrees) matches the betatronic phase advance.

more, Fig. 4 illustrates a comparison between the horizontal (magenta) and vertical (cyan) spectra of Beam 1 (left) and Beam 2 (right). A comparison of the amplitudes, normalized to the beam size, shows that the harmonics mainly impact the horizontal plane, an effect that is compatible with a dipole field error, while the attenuated perturbation in the vertical plane appears to be the result of transverse coupling. The maximum amplitude of the perturbation in the horizontal plane corresponds to $10^{-3}$ $\sigma$. An asymmetry in the amplitudes of the 50 Hz between Beam 1 and 2 is systematically observed, with Beam 1 being more impacted by a factor of two.

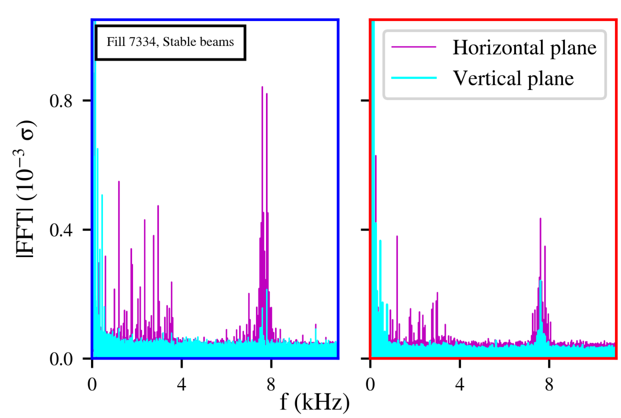


Figure 4: The spectrum in the horizontal (magenta) and vertical (cyan) plane at collisions for Beam 1 (left) and 2 (right), normalized to the beam size.

## DEDICATED EXPERIMENTS AND MEASUREMENTS

All the parasitic observations collected during the operation of the accelerator revealed the dipolar nature of the

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source. To determine the exact origin of the perturbation, simple modifications to the configuration of the eight Silicon Controlled Rectifier (SCR) power supplies of the main LHC dipoles were applied. In particular, the active filters of the main dipole power supplies, responsible for the attenuation of the 50 Hz harmonics ripple, were enabled and disabled sector-by-sector during dedicated experiments [11–13]. At the same time, measurements of the beam's spectrum were collected and analyzed.

Figure 5 presents the amplitude evolution of the $h$=12 harmonic (top) in Beam 1 (blue) and 2 (red) when the active filters are switched on and off. The status of the active filters is also depicted (bottom) color-coded with the sector number. The abrupt changes in the amplitude of the 600 Hz line when the filter status is changed provides evidence that the eight power supplies of the main dipoles contribute to the perturbation and the ripple is, thus, propagating across the whole accelerator. This correlation is established for all the harmonics in the low-frequency range (<3.6 kHz). However, no clear impact was observed in the harmonics of the high-frequency cluster during these tests. It must be noted that the active filters cover a lower range of harmonics and they do not act on the high-frequency part of the spectrum. In addition, although common power supplies are used for Beam 1 and 2, a different behavior is observed between the two beams when the status of the active filters is modified due to their different betatronic phase advance along the arcs with respect to the observation point.

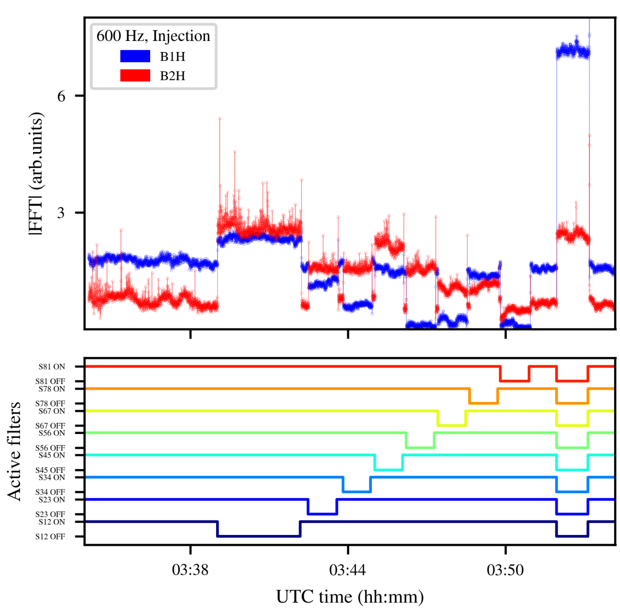


Figure 5: Amplitude evolution of 600 Hz line (top) in Beam 1 (blue) and 2 (red) during the experiments with the active filters of the main dipole power supplies. The status of the eight active filters, color-coded with the sector number, is also illustrated (bottom).

Concerning the high-frequency cluster, the exact origin has yet to be identified, although many similarities are observed with the low-frequency cluster. The importance of identifying its origin lies in the fact that the high-frequency cluster components are expected to have a more important impact on the beam performance as indicated by the simulations reported in the next section. Possible ripple sources such as the Uninterruptible Power Supply (UPS) system are currently being investigated.

Preliminary measurements in a spare LHC UPS system were performed to identify whether the UPS output voltage spectrum is a possible source of the high-frequency cluster. Figure 6 presents the UPS output voltage spectrum in the normal mode of operation (blue), i.e. a configuration similar to the one used during operation with beam. The environmental and instrumentation noise was also measured (black). A zoomed view of the spectrum (light blue box) shows that the UPS voltage spectrum consists of several 50 Hz harmonics around the switching frequency of the inverter and its first harmonic (4 and 8 kHz, respectively). Therefore, the UPS spectrum contains 50 Hz harmonics in a regime that corresponds to the high-frequency cluster observed on the beam spectrum and further studies reveal that they depict a similar signature to the one observed on the beam. However, additional studies are necessary in the next LHC Run (from 2022) to determine whether there is a correlation between the UPS and the high-frequency cluster and to identify the exact coupling mechanism of the noise to the beam.

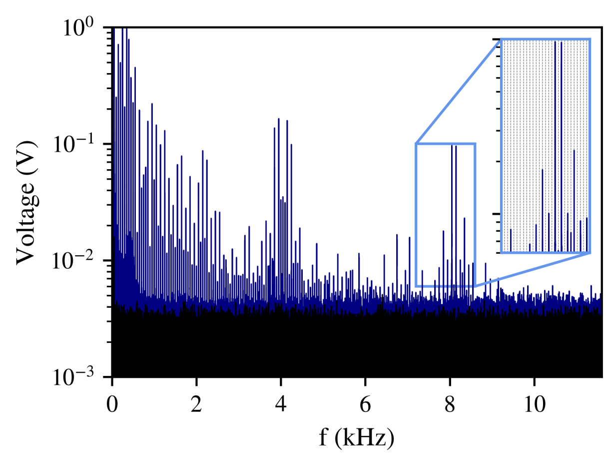


Figure 6: The UPS output voltage spectrum in normal operation (blue) and due to environmental noise (black). A zoomed window (light blue box) depicts the harmonics present in the UPS spectrum coinciding with multiples of 50 Hz (gray lines).

## IMPACT ON THE BEAM PERFORMANCE

Tracking simulations are performed to evaluate the impact of the 50 Hz harmonics in terms of tune diffusion and beam lifetime. Using the single-particle element-by-element tracking code SixTrack [14, 15], a distribution of particles is tracked in the LHC lattice including strong non-linearities, such as head-on and long-range beam-beam interactions. The simulated conditions correspond to the start of colli-

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Table 1: The LHC parameters at Top Energy Used in the Tracking Simulation That Correspond to the Start of Collisions

| **Parameters (unit)** | **LHC (values)** |
|---|---|
| Beam energy (TeV) | 6.5 |
| Bunch spacing (ns) | 25 |
| RMS bunch length (cm) | 7.5 |
| Bunch population (protons) | $1.25 \times 10^{11}$ |
| Normalized emittance ($\mu$m rad) | 2.0 |
| Chromaticity | 15 |
| Octupole current (A) | 550 |
| IP1/5 Half crossing angle ($\mu$rad) | 160 |
| IP1/5 $\beta^*$ (cm) | 30 |
| Relative momentum deviation $\delta p/p$ | $27\times10^{-5}$ |

sions. Table 1 presents a summary of the most important parameters.

A modulated dipole is used to simulate the power supply ripple spectrum including the 40 largest 50 Hz harmonics from both the low and high-frequency clusters. The applied kick at each frequency is selected such that the offsets observed experimentally in the transverse beam spectrum are reproduced in the simulations. Based on the observations of the previous section, the power supply ripple is distributed across the whole LHC ring. An accurate representation of the power supply ripple propagation across all the LHC dipoles requires a model of the transfer function for all the frequencies present in the spectrum. However, an accurate model of the LHC dipoles as a transmission line for such high frequencies is not available at the moment. Therefore, a simplified model is used where all the noise sources are lumped in a single location and the power supply ripple spectrum observed experimentally is reproduced.

Frequency Map Analysis (FMA) [16–19] is used to depict the increase of tune diffusion due to the power supply ripple. A distribution of particles is tracked for a specific number of turns ($10^4$) and the turn-by-turn data are divided into two-time intervals. The tune of each particle is computed at each time interval and the variation of the tune between these two-time intervals defines the tune diffusion.

Figure 7 illustrates the frequency maps (left panel) and the initial configuration space (right panel) in the absence (top) and in the presence of the 50 Hz harmonics (bottom), color-coded with the logarithm of the tune diffusion. The resonances excited due to the non-linear fields such as beam-beam interactions and magnet non-linearities are depicted in gray. Including the dipolar perturbations, the strength of some of the resonances is enhanced, while additional resonances are excited in a location equal to the excitation frequency (green) or its alias (purple) in the horizontal plane. The increase of tune diffusion in the configuration space illustrates that both the core and the tails of the distribution are affected.

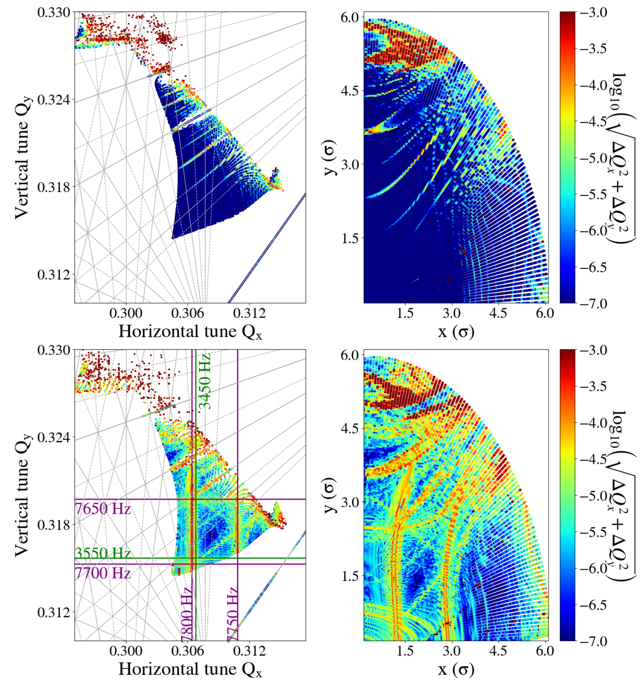


Figure 7: Frequency map (left panel) and initial configuration space (right panel) in the absence of power supply ripple (top) and including a realistic 50 Hz spectrum (bottom). The color-code illustrates the tune diffusion, the nominal resonances and the additional resonances excited due to power supply ripple are also presented (gray and purple/green, respectively).

To compute the degradation of the beam lifetime due to the power supply ripple, simulations with realistic beam distributions are performed. Experimental observations indicate that the tails of the LHC bunch profiles have overpopulated and underpopulated tails in the transverse and longitudinal plane, respectively, compared to a normal Gaussian distribution. For an accurate description of the simulated bunch profiles, a weight is assigned in the post-processing depending on the amplitude of each particle as derived by the Probability Density Function (PDF) of a q-Gaussian distribution with $q$=0.88 and 1.15 for the longitudinal and transverse plane, respectively [20, 21].

Figure 8 presents the intensity evolution for a duration of $10^6$ turns, corresponding to 90 seconds of LHC operation, in the absence of power supply ripple (black) compared to the cases when including the spectrum of Beam 1 (blue) and 2 (red). As the amplitudes of the 50 Hz harmonics observed in Beam 2 are lower by approximately a factor of two compared to Beam 1, an asymmetry between the lifetime of the two beams is observed. To quantify this effect, a fit of the intensity evolution in each case is applied. Starting from a beam lifetime of 28.4 h, the lifetime is reduced to 22.3 and 27.4 for Beam 1 and 2, respectively. Additional studies show that the main contributor to the reduction of the beam intensity is the high-frequency cluster. An asymmetry between the lifetime of the two beams has been observed

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during the whole duration of Run2 and the simulations indicate that, amongst other mechanisms, the 50 Hz harmonics can contribute to this effect.

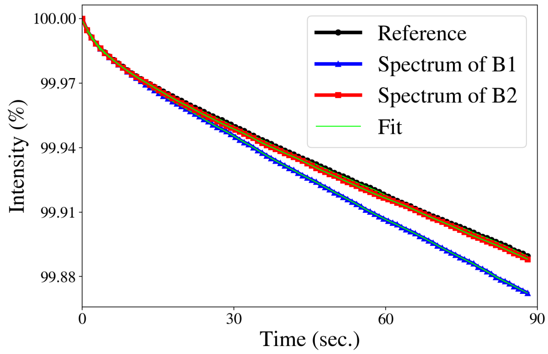


Figure 8: Intensity evolution in the absence of noise (black), including the power supply ripple spectrum observed in Beam 1 (blue) and 2 (red) and the fit used to compute the beam lifetime (green).

## SUMMARY

The present paper summarized the main findings concerning the 50 Hz harmonics that have been observed across several unrelated instruments in the transverse LHC beam spectrum since its commissioning. Two regimes of interest have been identified in frequency domain, namely the low-frequency cluster extending up to 3.6 kHz and the high-frequency cluster located around 7-8 kHz. Both regimes correspond to actual beam oscillations and the possibility of an instrumentation artifact has been excluded based on several beam observations. Both regimes consist of 50 Hz harmonics and not alias frequencies.

By changing the status of their active filters and observing the impact on the beam, it was shown that the eight SCR power supplies of the main dipoles are the origin of the low-frequency cluster. It is the first time that such a correlation has been demonstrated in the LHC. Concerning the high-frequency cluster, the exact underlying mechanism has not been clearly identified and other systems are currently being investigated such as the UPS and the transverse damper.

Single-particle tracking simulations including realistic power supply ripple spectra as acquired by experimental observations indicate that the presence of the harmonics results in increased tune diffusion and eventually to the degradation of the beam lifetime. It was found that the high-frequency cluster is the main contributor and that the asymmetry in the power supply ripple spectrum of Beam 1 and 2 can contribute to the lifetime asymmetry observed in operation. It must be noted that a simplified model was used where all the noise sources were lumped in a single location and further studies are needed for an accurate model of the ripple transfer function across the LHC ring.

Based on the observations collected in Run2, the 50 Hz harmonics are also expected to be present in the future operation of the accelerator. Additional studies and measurements during the next operation of the accelerator will provide more insight into the present research and the possibility of identifying and applying mitigation measures for their suppression.

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