Origin of the 50 Hz harmonics in the transverse beam spectrum of the Large Hadron Collider

S. Kostoglou
CERN, Geneva 1211, Switzerland
and
National Technical University of Athens, Athens 15780, Greece

G. Arduini, Y. Papaphilippou, and G. Sterbini
CERN, Geneva 1211, Switzerland

L. Intelisano
CERN, Geneva 1211, Switzerland
and
INFN, Sapienza Università di Roma, Rome 00185, Italy
(Dated: June 20, 2021)

Since the beginning of the Large Hadron Collider (LHC) commissioning, spectral components at harmonics of the mains frequency (50 Hz) have been observed in the transverse beam spectrum. This paper presents an overview of the most important observations, collected during the latest physics operation of the LHC in 2018, which clearly indicates that the harmonics are the result of a real beam excitation rather than an instrumental feature. Based on these findings, potential sources of the perturbation are discussed and a correlation with power supply ripple originating from the magnets’ power supplies is presented.

I. INTRODUCTION

In particle accelerators, studies of the beam spectrum can reveal important information concerning the existence of external noise sources that perturb the motion of the particles. Noise effects such as power supply ripple, ground motion and the noise induced by the transverse feedback system are an important issue for the single-particle beam dynamics in past, present and future accelerators. In the presence of non-linearities such as non-linear magnets and beam-beam effects, depending on the spectral components and the nature of the source, power supply ripple can act as a diffusion mechanism for the particles in the beam distribution, through the excitation of resonances in addition to the ones driven by the lattice non-linearities, an effect that can prove detrimental to the beam lifetime [1–4]. This paper focuses on the investigation of such a mechanism that has been observed in the transverse beam spectrum of the Large Hadron Collider (LHC) [5], which is contaminated by harmonics of 50 Hz [6–9].

Observations of harmonics of the mains power frequency in the beam spectrum have been reported in the past from several accelerators including the Super Proton Synchrotron (SPS) [10,14], the Hadron-Electron Ring Accelerator (HERA) [3,15,16], the Relativistic Heavy Ion Collider (RHIC) [17,18] and the Tevatron [19,20]. The studies in the SPS excluded the factor of instrumentation noise as the origin of the perturbation and it was shown that the beam was excited by high-order harmonics, in the form of dipolar excitations, mainly affecting the horizontal plane [10]. The source of the perturbation was identified as the main dipoles by injecting an external sinusoidal ripple on their power supply.

The study conducted at RHIC demonstrated that high-order harmonics (h > 100) were visible in several unrelated instruments as a result of a real beam excitation rather than an artifact of the instrumentation system [17]. By modifying machine parameters such as the betatron tune and the coupling the source was identified as a dipolar field error. Through a set of experiments, a correlation with power supply ripple was established and specifically, with the 12-pulse line-commutated thyristor power supplies of the main dipoles [18].

A similar observation of 50 Hz high-order harmonics perturbing the beam spectrum in the form of dipolar excitations is also systematically made in the LHC. In this paper, we present the analysis of the experimental data acquired during the 2018 LHC operation aiming to identify the origin of the perturbation. The key observations that lead to the understanding that the harmonics are the result of a real beam excitation are presented in Section II. A correlation with power supply ripple arising from the power supplies of the main dipoles is confirmed with dedicated experiments for the first time in the LHC operation. The analytical formalism of dipolar power supply ripple and the tracking simulations aiming to de-
termine whether the observed power supply ripple leads to a degradation of the beam performance are treated in a second paper [? ].

II. EXPERIMENTAL OBSERVATIONS IN THE LHC

Throughout this paper, the main observable is the representation of the beam signal in frequency domain as computed with the Fast Fourier Transform (FFT). Based on the Fourier analysis, information concerning the origin of the 50 Hz can be extracted. This can be achieved by following the evolution of the lines in frequency domain, both in terms of amplitude and phase, during normal operation, i.e., without any modification in the beam or machine parameters (Sections II.B). Then, the findings are further extended by observing the response of the harmonics during modifications in the beam or machine configuration (Sections II.C). These modifications refer to changes, first, in the betatron motion with parameters such as the tune, the phase advance and the beam energy, second, in the power supplies and last, in the settings of the transverse damper.

A. Overview of the LHC beam modes

The fact that different beam energies and phases of the LHC nominal cycle have been explored in this study justifies the need to include a brief description of the beam modes that are relevant to the next sections of this paper. Figure 1 illustrates the operational cycle for a physics fill (Fill 7333). The different beam modes (gray) are presented along with the intensity evolution of Beam 1 (blue) and 2 (red) in the right axis and the beam energy (black) in the left axis.

In brief, the nominal LHC cycle is organized as follows. After injecting low-intensity single bunches for machine protection reasons, high-intensity batches (two or three trains of 48 or 72 bunches and a bunch spacing of 25 ns) are injected from the SPS to the LHC rings until the requested filling scheme is reached. The Injection is performed in the Interaction Region (IR) 2 and 8 for Beam 1 and 2, respectively, with an energy per beam equal to 450 GeV.

Then, during Ramp, the current of the main dipoles and quadrupoles increases while the beams are accelerated. An intermediate squeeze of the $\beta$-functions at the IPs, $\beta^*$, is performed [21].

At Flat Top, each beam has reached the maximum total energy of 6.5 TeV (as compared to the nominal design total energy of 7 TeV). After a few minutes, the betatron tunes are trimmed from the injection ($Q_x, Q_y$) = (0.28, 0.31) to the collision ($Q_x, Q_y$) = (0.31, 0.32) values (magenta). With the Achromatic Telescopic Squeezing (ATS) optics [22], the beams are squeezed to $\beta^* = 30$ cm at the IPs of the two high luminosity experiments (ATLAS and CMS).

During Adjust, the separation bumps in the IRs collapse and the beams are brought to collision. At the end of this beam mode, the settings of the transverse damper are modified (cyan).

The declaration of Stable Beams signals the start of the data acquisition from the experiments. In this beam mode, luminosity optimization techniques are employed such as the crossing angle anti-leveling and the $\beta^*$-leveling [23, 24]. Finally, the beams are extracted from the ring to the dump.

B. Beam measurements in normal operation

The concept of the 50 Hz lines on the beam spectrum is illustrated using the turn-by-turn data from the High Sensitivity Base Band measurement system (HS BBQ) [25, 26]. Figure 2 depicts the spectrogram of the horizontal plane of Beam 1 (Fill 7056) for the first few minutes of the fill, extending up to the first few minutes of the beam dump (red dashed line). The Fourier analysis for each time interval in the horizontal axis is performed with a window length of $2^{13}$ consecutive turns and an overlap of $2^{11}$ turns between windows. The frequency range is zoomed below the Beam 1 horizontal tune ($\approx 3.49$ kHz) to observe the 50 Hz harmonics in its proximity. A color code is assigned to the Power Spectral Density (PSD) to distinguish the main spectral components (yellow and red) from the noise baseline (blue).

The spectrum clearly shows that a series of 50 Hz harmonics are present in the beam signal. The fact that the lines appear as multiples of 50 Hz and not as sidebands around the betatron tune is one of the first indications
FIG. 2. Horizontal HS BBQ spectrogram of Beam 1 at the end of a physics fill (Fill 7056), centered around 3 kHz and color-coded with the PSD. The red dashed line indicates the end of the fill and the start of the dump of the beam.

among others (see Section II C) that the nature of the power supply ripple is dipolar.

Furthermore, the harmonics are visible only in the presence of the beam. All signals acquired after the end of the fill (red dashed line) are dominated by the noise of the instrument. A comparison between the signals prior and after the dump of the beam provides a first indication that the lines do not emerge as a by-product of instrumentation noise.

To further exclude the factor of instrumental or environmental noise, the presence of these harmonics has been validated from several unrelated beam instruments. Position measurements from multiple pickups, located at different positions in the LHC ring, are collected. The main observables are the HS BBQ, the transverse damper Observation Box (ADTObsBox) [27, 28], the Diode Orbit and Oscillation System (DOROS) [30, 31] and the Multi-Band Instability Monitor (MIM) [32, 33]. Measurements from all the aforementioned instruments are available for the Machine Development (MD) Fill 7343, dedicated to studies concerning the 50 Hz harmonics [34].

Figure 3 shows the spectra for one of these instruments, the HS BBQ, for the horizontal plane of Beam 1, while the vertical gray lines represent the multiples of 50 Hz. To illustrate that the lines in the beam spectrum correspond to 50 Hz harmonics, a zoomed region of the spectrum is depicted (light blue). From the analysis of the various spectra, it is confirmed that a series of 50 Hz harmonics is visible across all unrelated instruments.

The turn-by-turn acquisitions, such as the ones from the HS BBQ and DOROS, allow accessing a frequency regime up to approximately 5.6 kHz, which is the Nyquist frequency assuming a single observation point along the accelerator (the sampling frequency is \( f_s = f_{rev} \) with \( f_{rev} = 11.245 \) kHz) [35]. If present in the signal, frequency components beyond this limit will be aliased in the spectrum.

On the contrary, the ADTObsBox and the MIM provide high sampling rate measurements. Specifically, the ADTObsBox instability buffer contains calibrated bunch-by-bunch position measurements for \( 2^{16} \) turns. Firstly, the fact that a calibrated metric is provided allows computing the offsets induced on the beam motion from the 50 Hz harmonics. Secondly, the bunch-by-bunch information is needed to study the evolution of the 50 Hz in the cycle and to compute a high bandwidth spectrum, in the presence of a regular filling scheme.

As shown in Appendix A, the noise floor of the single-bunch ADTObsBox spectrum exceeds the amplitude of the 50 Hz harmonics and therefore, a decrease of the noise baseline is necessary to study their evolution during the cycle. To overcome this problem, a method to combine the information from several bunches has been developed, taking into account the dephasing of the spectrum, due to the time delay, across the different bunches (Appendix A). Assuming a regular filling scheme (equal spacing between bunches), this signal averaging algorithm not only provides a reduction of the noise floor but also extends the measurable frequency range of the beam spectrum, while suppressing the aliases and preserving the signal metric.

The horizontal spectrum of Beam 2 is computed for the physics Fill 7334 during collisions, using the bunch-by-bunch and turn-by-turn acquisitions from the Q7 pickup of the ADTObsBox. Although only the spectrum of Beam 2 is depicted, similar observations exist for both beams and planes.

Figure 4 illustrates the Fourier analysis, first, for a frequency range up to 10 kHz (Fig. 4 top). From the review of the spectrum, two areas of particular interest are identified. The first regime (blue span) consists of 50 Hz harmonics extending up to 3.6 kHz. The second area (orange span) is a cluster of 50 Hz at 7-8 kHz. In particular,
FIG. 4. The horizontal spectrum of Beam 2 at Flat Top for a frequency range up to 10 kHz (top), with the low and high-frequency cluster indicated by the blue and orange span, respectively, and centered around the high-frequency cluster (bottom). The red and gray dashed lines represent the expected position of aliased \( f_{\text{rev}} - f_{50} \) and physical 50 Hz harmonics \( f_{50} \), respectively.

The cluster is centered at the frequency \( f_{\text{rev}} - f_x \), where \( f_x \) is the horizontal betatron frequency, which is \( \approx 3.15 \) kHz at injection and \( \approx 3.49 \) kHz at collision energy (see also Section [II]). In the frequency interval between the two clusters, either no harmonics are present in the signal or their amplitude is below the noise threshold of the instrument.

Throughout this paper, the two regimes of interest are referred to as the low-frequency cluster and the high-frequency cluster, respectively. It must be noted that the lowest order harmonics are excluded from the analysis as their amplitude is affected by the noise of the instrument. Then, the calibrated spectrum indicates that the harmonics of the high-frequency cluster are more important in terms of amplitude.

As the high-frequency cluster is situated at \( f_{\text{rev}} - f_x \), the question that naturally arises is whether these frequency components emerge from aliasing. In fact, even in the case of a physics fill, the sampling rate is only approximately uniform as not all trains are equally spaced. This error can give rise to the aliasing of the low-frequency cluster around the revolution frequency. It must be noted however, that the beam revolution frequency \( (f_{\text{rev}} = 11.245 \) kHz) is not a multiple of 50 Hz and therefore, the aliases can be distinguished from the excitations at 50 Hz.

Figure 4 (bottom) presents the spectrum centered around the high-frequency cluster. The red dashed lines represent the expected position of aliased 50 Hz harmonics \( f_{\text{rev}} - f_{50} \), while the gray dashed lines illustrate the multiples of 50 Hz \( f_{50} = h \cdot 50 \) Hz, where \( h \) is a positive integer. As the spectral components of the high-frequency cluster coincide with the 50 Hz multiples (gray), it is concluded that they are not aliased frequencies.

The time variation of the beam spectrum can reveal important information concerning the source of the perturbation. Due to the variation of the power grid load, the frequency of the mains power supply is not strictly 50 Hz. The study focuses on the impact of the aforementioned drift on the frequency evolution of the 50 Hz harmonics in order to illustrate their distinct signature in the frequency domain.

The spectrogram of the horizontal position of Beam 1 is computed from the MIM data for a time interval at Stable Beams. In Fig. 5 the horizontal axis represents the timestamp of each spectrum with a window length of 214 turns, the vertical axis is centered around a value in the low (left) and high (right) frequency cluster and a color code is assigned to the PSD.

An important finding is that, although the lines are harmonics of 50 Hz, a time variation of their frequency is observed. Specifically, all harmonics are affected by a similar frequency modulation, the amplitude of which is proportional to the order of the harmonic \( h \). For this reason, the aforementioned effect is more pronounced in the harmonics of the high-frequency cluster, an observation which provides yet another indication that these components are not aliases.

To illustrate quantitatively that the harmonics experi-
experience a similar frequency modulation, the amplitude of which scales with the order of the harmonic $h$, an algorithm that can precisely follow their evolution has been implemented. The steps of the algorithm are the following: for each measured time interval the amplitude of the Fourier spectrum is computed. The algorithm focuses on a regime in the vicinity of a single harmonic and, by employing a maximization routine, an accurate determination of its frequency is achieved by detecting the local maximum. The algorithm returns the frequency and the amplitude of the harmonic at each time step. This procedure is repeated for all the time intervals in the spectrogram.

Iterating over all the harmonics in the spectrum with the aforementioned algorithm validates the existence of a similar frequency modulation with an amplitude proportional to the order of the harmonic $h$. Figure 6 shows the frequency evolution of all the harmonics (black) after normalizing with the order of each harmonic $h$.

Figure 6 presents the modulation of the lines in the power supply due to these harmonics. The switching frequencies are well defined, they can be easily identified and no 50 Hz harmonics are present in the signal.

On the contrary, in the SPS case, the power supply is a Silicon Controlled Rectifier (SCR). Hence, the 50 Hz harmonics are visible on the signal and the stability of the mains has an impact on the output current of the power supplies. In the following studies, when the expected position of the 50 Hz harmonics is illustrated, the drift of the harmonics due to this modulation is taken into account.

Therefore, if environmental noise is excluded as the origin of the perturbation, the signature of the 50 Hz harmonics in the beam spectrum suggests that the possible sources are limited to magnets with SCR power supplies. The magnets powered by SCR in the LHC are presented in Table I [40, 41].
FIG. 7. The spectrum of the B-Train in PS (top) and SPS (bottom). The strong component at 5 kHz in the PS spectrum is one of the switching frequencies of the switch-mode power supply. The SPS spectrum illustrates the signature of a SCR power supply, which is characterized by a series of 50 Hz harmonics with a frequency modulation induced by the mains.

TABLE I. The SCR power supplies in the LHC [40, 41].

| Power supply type | Use                                   |
|-------------------|---------------------------------------|
| RPTE              | Main dipoles                           |
| RPTF              | Warm quadrupoles (Q4, Q5)              |
| RPTG              | Dogleg dipoles (D1-D4, spare)          |
| RPTL              | Alice compensator                      |
| RPTM              | Dump septa                             |
| RPTI              | Alice and LHCb dipoles                 |
| RPTN              | LHCb compensator                       |
| RPTJ              | CMS Solenoid                           |
| RPTH              | Alice Solenoid                         |
| RPTK              | RF Klystron                            |

The phase evolution of the 50 Hz harmonics between two locations in the ring can clarify whether the power supply ripple lines are the result of a real beam excitation. To this end, their phase advance is measured between two closely separated pickups and compared to the betatron phase advance between the same pickups.

For the validity of the comparison, the two observation points must be situated in a relatively close distance, so that the beam does not encounter a noise perturbation while crossing this path.

If the harmonics are a by-product of noise in the beam instrumentation then their phase advance is not expected to correspond to the betatronic one. Furthermore, an arbitrary dephasing between the low and high-frequency cluster should be observed. On the contrary, in the case of a real excitation, the power supply ripple phase advance must correspond to the betatron one for all the harmonics present in the spectrum.

Two pickups of the transverse damper, referred to as Q7 and Q9, are selected for the analysis. At collision energy, the betatron phase advance between the two observation points is defined by the optics and it is approximately equal to 110 degrees. The first step is to compute the complex Fourier spectra for a single pickup and for each bunch in a physics fill to observe the dephasing of the lines across the full machine. As previously reported, with the present noise floor, the evolution of the lines cannot be determined with a single bunch. For this reason, the average signal is computed from five consecutive LHC trains, each one of which consists of 48 bunches. Then, the phase evolution of each harmonic is computed across the accelerator.

Figure 8 depicts the dephasing of a harmonic in the high-frequency cluster ($h=156$) as a function of the train number for Q7 (blue) and Q9 (green). The gray dashed lines illustrate the expected dephasing, which is proportional to the frequency and the time delay of the trailing trains from the first train in the machine (Appendix A). It must be noted that by averaging over a few consecutive trains the signal is sub-sampled to $f_{\text{rev}}$, similarly to the single bunch case. The negative slope of the 7.8 kHz line shows that the phase evolution of the harmonic was computed through aliasing, i.e., by following the phase evolution of the reflected frequency component around the revolution frequency ($f_{\text{rev}}−7.8$ kHz). The phase advance of each harmonic is the difference in the phase determination of the two pickups. A correspondence to the betatron phase advance is found, an observation that clearly proves, for the first time, that the two harmonics correspond to a real beam excitation. Similar results are obtained for all the harmonics present in the beam spectrum.

The filling scheme of the physics Fill 7334 is divided in three groups of consecutive trains. Each group corresponds to approximately one-third of the total beam. The average value and the standard deviation of the dephasing between Q7 and Q9 are computed from the three groups for all the harmonics above noise level.

Figure 9 demonstrates the average phase advance for the harmonics in the low (blue) and high (orange) frequency cluster. The error bars represent one standard deviation since following the frequency drift of lower-amplitude harmonics can introduce uncertainties. The gray dashed line indicates the betatron phase advance.
The phase evolution of the $h=156$ harmonic as a function of the train number for Q7 (blue) and Q9 (green). The gray lines illustrate the expected phase evolution of the harmonics in the accelerator (Appendix A).

FIG. 8. The average phase advance from Q7 to Q9 for the harmonics in the low (blue) and high (orange) frequency cluster. The error bars represent one standard deviation and the gray dashed line illustrates the betatron phase advance (110 degrees).

The average value demonstrates that, within an uncertainty represented by the standard deviation, the phase advance for all the harmonics is the one of the beam, thus proving that the observations are not instrumental.

C. Observations during changes in the beam and machine configuration

The response of the harmonics during a simple modification of the betatron motion such as the change of the tune at Flat Top is investigated. Figure 10 presents the HS BBQ spectrogram for the horizontal plane of Beam 1 in the physics Fill 7056. The spectrogram is centered around the betatron tune for the whole duration of Flat Top and a color code is assigned to the PSD. The black dashed line represents an approximation of the horizontal tune evolution.

First, one must observe that the frequencies of the lines are not affected by the tune change. This fact proves that the harmonics are the result of a dipolar field error rather than a tune modulation [42]. Second, a comparison prior and after the trim leads to the conclusion that the amplitude of the lines in the vicinity of the betatron tune is strongly enhanced. This resonant behavior is in agreement with a dipolar perturbation, with an excitation frequency that approaches the betatron tune [?].

To investigate the impact of the tune change on the high-frequency cluster, the high bandwidth spectrum is computed from the ADTObsBox prior and after the tune trim. Figure 11 shows the horizontal spectrum of Beam 2 up to 10 kHz (top) at Flat Top with the injection (blue) and collision (black) tune. Similar observations exist for both beams and planes.

The closest harmonics to the tune of the low-frequency cluster are enhanced in terms of amplitude. A shift is also observed at the position of the high-frequency cluster. To further illustrate this effect, the spectrum is centered around the high-frequency cluster in Fig. 11 (bottom). Although the effect is dipolar in both cases (the harmonics coincide with the 50 Hz multiples indicated with the gray lines), this observation shows that the location of the cluster is at $f_{rev} - f_x$ and thus, depends on the betatron tune. The fact that the changes in the beam configuration affect the amplitude of the power supply ripple lines provides further proof that the harmonics are the result of a real beam excitation.

The response of the harmonics is studied when another modification is applied to the betatron motion and specifically, to its phase advance, while the tune is constant. During the MD Fill 6984, the betatron phase advance between the Interaction Point (IP) 1 and 5 were modified [43]. This was achieved through the incorporation of a set
FIG. 11. The horizontal spectrum of Beam 2 prior (blue) and after (black) the tune change at Flat Top in a frequency range up to 10 kHz (top) and centered around the high-frequency cluster (bottom). The gray dashed lines represent the multiples of 50 Hz. The dashed blue and black vertical lines illustrate the location of $f_{\text{rev}} - f_x$.

of optics knobs, which allow scanning the phase between the two IPs, based on the ATS scheme [22]. The knobs lead to a trim in the current of the quadrupole families responsible for the control of the tune. Throughout these modifications, the betatron tune is constant.

Figure 12 illustrates the supply current for a single quadrupole (red). The evolution of the current corresponds to a change of the phase advance within a range of ±20 degrees for the horizontal plane of Beam 1. During this time interval, the amplitude evolution of the harmonics is computed.

Figure 12 also denotes the response of the $h=12$ harmonic (black curve). The amplitude evolution of the lines in the low-frequency cluster is clearly impacted by the variation of the betatron phase advance, an effect that provides definitive indications that they correspond to actual beam motion. As far as the high-frequency cluster is concerned, no impact is observed in their amplitude evolution throughout these tests, which is possibly due to the mitigation of these lines from the transverse damper as shown later in this paper.

Following the change of the betatron tune and phase advance, we explore the evolution of the spectrum across different beams modes and thereby, different energies and optics. Some of the magnets in Table I can be excluded as potential sources by observing the evolution of the spectrum across the cycle.

First, due to the fact that the 50 Hz harmonics are systematically present in all beam modes and fills, the power supplies of the spare magnets and the septa are excluded. Specifically, the separation/recombination dipoles D1-D4 are currently powered by switch-mode power supplies, while the SCR power supplies of these dipoles are only used in case of failure. An analysis of the fills where the spare SCR power supplies were employed did not reveal any modification on the beam spectrum and thus, can be excluded. In addition, the magnetic field of the dump septa only affects the beam during extraction and not in operation.

Second, the amplitude of the power supply ripple lines does not significantly attenuate with increasing beam energy. Considering a non-ramping power supply as the source, a reduction of the angular deflection and thus, of the amplitude of the power supply ripple, should be observed with increasing beam rigidity. The absence of such an attenuation leads to the conclusion that the power supply ripple originates from a ramping power supply. Consequently, all non-ramping power supplies can also be excluded.

Through this process of elimination, the remaining candidates of Table I are the main dipoles and the warm quadrupoles. Combining this finding with previous indications of the dipolar nature of the source, the investigation focuses on the power supplies of the Main Bends. The main dipoles have undoubtedly the highest filling coefficient in the ring and, as previously mentioned, the studies conducted in other synchrotrons have proved that the arc circuit was systematically the dominant contrib-
FIG. 13. The horizontal spectrogram of Beam 1 during the tests of the active filters at injection centered around 600 Hz. The blue lines represent the amplitude evolution of the spectral components in this regime.

Based on the previous findings, the pursued investigations focus on the main dipoles circuit. To establish a correlation between the harmonics of the beam and the ones in the output of their power supplies, a modification in the configuration of the latter is needed. An important observation was made when the status of the active filters of the Main Bends, which are installed for the attenuation of the 50 Hz ripple [44–46], was changed. During dedicated MD fills, the eight active filters were disabled sector-by-sector.

Figure 13 depicts the 3D spectrogram for the horizontal plane of Beam 1, as acquired from the MIM, for the time interval of the tests conducted at injection (Fill 7343). For a first demonstration, the frequency range is limited around 600 Hz. The projection of the spectrogram, which represents the amplitude evolution of the \( h=12 \) harmonic, is shown with the blue curve. Disabling the eight filters leads to abrupt changes in its amplitude evolution.

The amplitude evolution of the \( h=12 \) harmonic is extracted from the 3D spectrogram. Figure 14 (top) presents the response of the 600 Hz line in Beam 1 (blue) and 2 (red) at injection energy. The status of the eight active filters is color-coded with the sector number (bottom). The distinct changes in the amplitude coincide with the disabling of the filter of each sector. As a last step, the filters were disabled simultaneously, which led to an important increase in the amplitude of the line. Similar observations are collected by conducting the same tests at top energy.

The correlation with the power supplies is not only valid for the 600 Hz line, but for most of the 50 Hz harmonics included in the low-frequency cluster. Figure 15 shows the amplitude evolution of various harmonics at injection, represented with a different color code. The abrupt changes in the amplitude when disabling the active filter of each sector are reproduced for harmonics up to 3.6 kHz. In addition to the observations at 600 Hz, the contribution of each sector also varies across the harmonics.

Applying a simple modification in the configuration of the dipole power supplies, such as modifying the status of the active filters, has a direct impact on the low-frequency cluster harmonics of the beam. These results provide evidence that the power supplies of the main dipoles are the source of the harmonics up to 3.6 kHz observed in the beam spectrum. It is the first time that such a corre-
loration has been demonstrated in the LHC. As no modifications are envisaged for the power supplies of the main dipoles, this perturbation is expected to be present also in the future upgrade of the LHC, the High Luminosity-LHC (HL-LHC) [47]. It must also be underlined that no change in the amplitude evolution of the harmonics in the high-frequency cluster is reported during these tests.

Figure 16 demonstrates the voltage spectrum of the power supply of the main dipoles in one of the LHC arcs (Sector 1-2) with the active filter enabled (top) and disabled (bottom). The vertical gray lines represent the multiples of 600 Hz. The comparison of the spectrum prior and after the modification shows that the active filter is suppressing some of the harmonics up to approximately 3 kHz, while it enhances the high-order harmonics [46]. However, the amplitude of the high-frequency cluster in the beam spectrum did not increase when disabling the active filter possibly due to the interplay of this cluster with the transverse damper as explained later in the present paper.

The spectra of both beams and planes in a physics fill are measured and compared. As the pickups for the two beams and planes are located at different positions in the ring, the ADTObsBox calibrated spectra are normalized with the corresponding $\beta$-functions. The $\beta$-functions at the location of the ADTObsBox Q7 pickup for both beams and planes, at injection and top energy are listed in Table II.

Figure 17 shows the spectra for the horizontal (magenta) and vertical (cyan) plane for Beam 1 (left) and 2 (right). Comparing the amplitudes of the spectral lines yields that the perturbation is mainly affecting the horizontal plane, an effect compatible with a field error of the main dipoles. Due to the transverse coupling of the machine, an attenuated perturbation is also present in the vertical plane. To demonstrate that this effect results from the coupling, controlled excitations have been applied using the transverse damper during dedicated experiments. Although only the horizontal plane was excited, the oscillation was visible also in the vertical plane.

The maximum offset observed in the horizontal spec-
FIG. 17. The spectrum of the horizontal (magenta) and vertical (cyan) plane of Beam 1 (left) and 2 (right) in Stable Beams, normalized with the corresponding \(\beta\)-functions.

The spectrum of Beam 1 is approximately 0.1 \(\mu m\), which corresponds to \(10^{-3}\) \(\sigma\). As shown in [?], assuming a single dipolar perturbation, this value corresponds to a deflection of 0.09 mrad at a location with \(\beta = 105\) m for an excitation frequency in the vicinity of the tune \((|Q - Q_p| = 5 \times 10^{-3}, \text{ where } Q \text{ is the betatron tune and } Q_p \text{ is the ripple tune})\). Comparing the equivalent kick with the bending angle of a single dipole in the LHC (\(\approx 5\) mrad) and neglecting additional effects (e.g. transverse damper, magnet’s beam screen) yields a field stability of \(1.8 \times 10^{-8}\), a value which is well within the power supply specifications.

Comparing the spectra of the two beams yields an asymmetry in the amplitude of the ripple between Beam 1 and 2 and that a more significant effect is visible in Beam 1. To verify the reproducibility of this observation, the spectra of both beams and planes are computed for all the proton physics fills of 2018. For each fill, the maximum offset induced by the 50 Hz harmonics is computed, which corresponds, in Stable Beams, to a frequency of 7.7 kHz.

Figure 18 depicts the maximum amplitude observed in the spectrum as a function of the fill number for the horizontal (magenta) and vertical (cyan) plane in Beam 1 (blue) and 2 (red). The dashed lines represent the average offset over all the fills for each plane. These results confirm that the power supply ripple is systematically more pronounced in Beam 1 than Beam 2 by approximately a factor of two in the horizontal plane. Although the dipole power supplies are common for both beams, this discrepancy is possibly attributed to the different phase advances of the two beams in the accelerator.

The fill-by-fill analysis of the spectra in Fig. 18 reveals an increase of the ripple amplitude in the physics Fill 7035. An additional parameter that has not been included in the analysis so far is the activity of the transverse damper and the interplay with the 50 Hz harmonics.

In the nominal LHC cycle, the ADT settings are modified and in particular, the extended ADT bandwidth is changed to standard bandwidth at the end of Adjust [18, 19]. An increase in the gain of the transverse damper is reported for the standard bandwidth compared to the extended one. In the Fill 7035, this modification was not applied and the extended bandwidth was used at Stable Beams.

Figure 19 illustrates the horizontal spectrum of Beam 2 at Stable Beams centered around the low (left) and high (right) frequency cluster and for the Fills 7033 (top) and 7035 (bottom) with the standard ADT bandwidth and extended bandwidth, respectively. Comparing the two spectra yields an increase in the amplitude of the 50 Hz harmonics in the regime above 3 kHz, which is particularly important for the high-frequency cluster.

This observation indicates that the amplitudes of the high-order harmonics are reduced by the damper in normal operation. This also explains why an amplitude increase of the high-frequency cluster was not observed when the corresponding harmonics in the power supply’s voltage spectrum increased during the active filters tests. The impact of the ADT settings is also systematically observed in other beam modes of the machine cycle during which the bandwidth was modified such as the Adjust.

The importance of this finding resides on the fact that a strong asymmetry is present between the frequencies of the low and high cluster in terms of amplitude. In particular, these observations indicate that, lowering the transverse damper gain or in the absence of the damper, the amplitude of the harmonics in the high-frequency cluster is expected to be further enhanced compared to the values that have been observed experimentally.

In contrast, Fig. 16 shows that the ripple in the power supply voltage spectrum attenuates with increasing frequency. Although the active filters enhance the high-order harmonics in the power supply voltage spectrum, their amplitude is still lower than the ones of the low-order harmonics. Furthermore, high-frequency perturba-
FIG. 19. The horizontal spectrum of Beam 2 at Stable Beams centered around the low (left) and high (right) frequencies such as the high-frequency cluster strongly exceed the cutoff frequency of the LHC main dipoles due to the shielding effect of the beam screen [50]. To this end, if the high-frequency cluster is driven by a direct excitation due to power supply ripple, a significant attenuation of its amplitude should be observed compared to the low-frequency cluster, while experimentally we observed the opposite.

Additionally, it should be mentioned that the increase of the power supply ripple by a factor of two in Fill 7035 did not lead to an increase of losses or emittance growth compared to the rest of the fills. However, as the duration of the fill was limited to 40 minutes, the impact of the power supply ripple lines on the beam lifetime cannot be excluded.

To conclude, Table III presents a summary of the most important experimental observations for each cluster. Combining this information suggests that, rather than a direct excitation, the high-frequency cluster is the result of the interplay between ripple in the dipole power supplies and a mechanism originating from the beam. The transfer function from the power supply voltage to the magnetic field seen by the beam does not consider

| TABLE III. The summary of the observations for the low and high-frequency cluster. |
|---------------------------------------------------------------|
| **low-frequency cluster** | **high-frequency cluster** |
| Presence of 50 Hz harmonics | Presence of 50 Hz harmonics |
| Frequency modulation from the mains | Frequency modulation from the mains |
| Phase advance Q7-Q9 compatible with betatronic dipole | Phase advance Q7-Q9 compatible with betatronic dipole |
| Dipolar nature | Dipolar nature |
| Mainly in the horizontal plane | Mainly in the horizontal plane |
| Largely amplitudes in Beam 1 | Largely amplitudes in Beam 1 |
| Impact from IP1/5 phase scan | Impact from change of tune |
| Impact from active filters Mitigation from transverse damper | Impact from active filters Mitigation from transverse damper |

* Extending up to 3.6 kHz.

* Located at 7–8 kHz, depending on the tune.

the beam’s response. Therefore, the asymmetry between the two clusters can be explained if there is a higher sensitivity of the beam’s response in the regime \( f_{\text{rev}} - f_x \) compared to \( f_x \), leading to important offsets from small power supply ripple perturbations at these frequencies. A potential candidate is the interplay of the beam with the machine transverse impedance, as the first unstable mode is at \( f_{\text{rev}} - f_x \) [51]. Other ripple source such as the Uninterruptible Power Supply (UPS) must be investigated [52]. Further observations and experiments are necessary to identify the exact mechanism that is responsible for the high-frequency cluster.

III. SUMMARY AND CONCLUSIONS

The purpose of the current study was to investigate the origin of the 50 Hz harmonics, an effect that has been observed in the beam signal since the start of the LHC operation. For this reason, a detailed review of the beam spectrum during several beam and machine configurations has been performed that revealed the existence of harmonics in two regimes in the frequency domain: the low-frequency cluster that extends up to 3.6 kHz and the high-frequency cluster at the location \( f_{\text{rev}} - f_x \). The methodology presented in this paper allowed us to identify, for the first time in the LHC operation, the existence of the high-frequency cluster on the beam signal. Although many similarities have been identified between the low and high-frequency cluster, the need to distinguish the two regimes is justified by their different response when modifications in the machine configuration are applied.

It is concluded that the two regimes are the result of a real beam excitation. A common signature between the two clusters has been identified; both regimes consist of a set of 50 Hz harmonics, that experience a frequency modulation induced by the mains. These findings indicate that the low and high-frequency clusters emerge from a common source. The signature of the harmonics in both regimes is compatible with a ramping SCR power

supply. Based on the fact that the harmonics are multiples of 50 Hz rather than sidebands around the tune, and that the horizontal plane is mainly affected, it is concluded that the nature of the source is dipolar.

In terms of amplitude, an asymmetry between the two clusters has been identified. In particular, more significant amplitudes of the beam oscillations are reported for the high-frequency cluster. During the proton run of 2018, the measured effect of the power supply ripple in the horizontal plane of Beam 1 was larger than the one of Beam 2 by a factor of two.

As far as the low-frequency cluster is concerned, a correlation with the eight thyristor, line-commutated power supplies of the Main Bends is established, through experiments with the active filters. It is concluded that the eight power supplies of the main dipoles are the source of the low-frequency cluster in the transverse beam spectrum. It is the first time that such a correlation has been demonstrated in the LHC operation.

The amplitude of the beam oscillations in the high-frequency cluster is larger if compared to the low-frequency cluster, hence the importance to identify its origin. If both clusters emerge from a common source, the question that arises is what is the mechanism that allows these high-frequency components to excite the beam. Oscillations at such high frequencies are expected to be significantly attenuated by the shielding effect of the beam screen in the dipole magnets. A review of the power supply’s voltage spectrum reveals that there is a reduction of the ripple with increasing frequency.

On the contrary, experimental observations indicate the presence of important spectral components in the high frequency cluster. More interestingly, the amplitude increase of the lines when the ADT settings are modified indicates that, in normal operation, a mitigation of the high-frequency cluster occurs due to the transverse damper. This fact underlines that, in the absence of the damper, the amplitude of the high-frequency cluster is expected to be further enhanced. The exact mechanism responsible for the appearance of the high-frequency cluster on the beam spectrum must be identified in the future operation of the accelerator.

Based on the source and the fact that no modifications are foreseen for the power supplies of the main dipoles, the 50 Hz harmonic are also expected to be present in the HL-LHC era. It has been demonstrated that the transverse damper can effectively reduce the amplitude of these harmonics and its capabilities can be employed in the future to mitigate this power supply ripple perturbation.

The analysis presented in this paper improves our understanding of the ripple effects that were present during the LHC operation. In the context of these studies, a general framework for the analysis of the experimental data has been developed, which can also be used to address other types of noise effects.

ACKNOWLEDGMENTS

The authors gratefully acknowledge H. Bartosik, A. Bland, O. S. Brüning, X. Buffat, J.-P. Burnet, L. R. Carver, R. De Maria, D. Gamba, R. T. Garcia, M. Martino, V. Montabonnet, N. Mounet, D. Nisbet, H. Thiesen, Y. Thurel and J. Wenninger for valuable suggestions and discussions on this work. We would like to thank D. Valuch and M. Soderen for all ADT related measurements and experiments, T. Levens for the MIM measurements and discussions, M. C. Bastos and C. Bacigalupi for the power supply acquisitions and discussions and J. Olexa for the DOROS measurements.

Appendix A: Beam spectrum from bunch-by-bunch acquisitions

In the presence of a regular filling scheme, the bunch-by-bunch and turn-by-turn ADTObsBox data can be combined to increase the effective bandwidth of the instrument. Signal averaging is not only needed to access the high-frequency components of the signal without aliasing, but also to reduce the noise floor of the spectrum compared to the single bunch case. Averaging the signals of $N_b$ bunches yields a $\sqrt{N_b}$ increase in the signal to noise ratio, in the presence of random noise with zero mean that is uncorrelated with the signal [53].

The spectrum of individual bunches and after averaging over all the bunches in the machine is shown in Fig. 20 for the horizontal plane of Beam 1, for a physics fill and a window length of $4 \times 10^4$ turns. The colored lines show the envelope of the spectra of several individual bunches, which is computed by setting a parametric peak threshold of $2 \times 10^{-3} \sigma$. The single bunch noise floor is approximately one order of magnitude higher than the 50 Hz harmonics and thus, signal averaging is necessary.

FIG. 20. The spectral envelope of several individual bunches (colored lines) and the spectrum after averaging over all the bunches in the machine (black).

The time delay $\Delta t_i$ of a trailing bunch $i$ with respect
to the first bunch in the machine, considered as the reference, results in a phase angle:

\[ \Delta \phi_i = 2\pi f \Delta t_i, \]

where \( f \) is the frequency under consideration. Consequently, the dephasing of the signals across the ring is proportional to the frequency and the longitudinal spacing of the bunches in the machine.

To illustrate this effect, three trains of 48 bunches are considered in simulations with a dipolar excitation at 3 kHz. The bunch spacing is 25 ns and the trains are equally spaced in the LHC ring. The complex spectrum is computed for each bunch and the phase evolution of the 3 kHz line is extracted.

Figure 21 depicts the phase evolution of the excitation for the three trains as a function of the bunch position in the ring. The color code represents the bunch number and the gray line is the expected phase evolution of Eq. (A1), with respect to the first bunch that is considered as the reference. The linear phase evolution of an excitation across the trains in the machine has been experimentally verified by injecting power supply ripple with the transverse damper kicker.

For frequencies much lower than the sampling frequency (\( f \ll f_{\text{rev}} \)), the dephasing is negligible and the bunch-by-bunch data can be directly averaged in time domain. For frequencies comparable to the revolution frequency, such as the high-frequency cluster, the dephasing between the bunches cannot be neglected. In this case, simply averaging the bunch-by-bunch information will lead to an error in the resulting metric. To illustrate this effect, the first bunches of the three trains are selected.

Figure 22 illustrates the spectra for the first bunches (Fig. 22a) of the first (black), second (blue) and third (green) train, respectively, in the presence of a dipolar excitation at 3 kHz. The excitation results in an offset of 13.9 \( \mu m \) (red dashed line), while the second peak corresponds to the betatron tune.

Then, the complex Fourier coefficients at 3 kHz are computed. Figure 22b presents the vector of the excitation in the spectrum, whose angle corresponds to the phase of the excitation, for each bunch (left). For a filling scheme consisting of three trains located in azimuthally symmetric locations in the ring, the dephasing at 3 kHz is important. Averaging over the three vectors without correcting for the dephasing will lead to an error in the offset of the final spectrum.

To this end, an algorithm that applies a phase correction has been implemented. The steps of the method are the following: first, the complex spectra \( F_i(\omega) \) are computed for each bunch, where \( \omega = 2\pi f \). Then, a rotation is applied to correct for the dephasing of Eq. (A1). The impact of the rotation is depicted in the second plot of Fig. 22b. Finally, the average over all bunches is computed. The procedure is described by the following ex-
FIG. 23. The impact of a frequency modulation on a harmonic dipolar excitation described in Eq. (B1) for \( f_0 = 100 \) Hz.

expression:

\[
F(\omega) = \frac{1}{N_b} \sum_{i=1}^{N_b} F_i(\omega)e^{-j\omega \Delta t_i}.
\]  

(A2)

Appendix B: Impact of a frequency modulation of the fundamental frequency on its harmonics

This section presents the impact of a frequency modulation on a harmonic dipolar excitation, similar to the one observed in the 50 Hz harmonics. To simulate this effect, a single particle is tracked in the LHC lattice using the single-particle tracking code SixTrack in the presence of a dipole field error [54, 55].

The dipole strength is modulated with the absolute value of a sinusoidal function:

\[
\Delta k(t) = |A_r \cos (2\pi f_m t)|,
\]  

(B1)

where \( t \) is the time, \( A_r \) the amplitude and \( f_m \) the frequency, which experiences a frequency modulation. The expression of \( f_m \) as a function of the fundamental frequency \( f_0 \) is:

\[
f_m = f_0 + A_{FM} \sin (2\pi f_{FM} t),
\]  

(B2)

where \( A_{FM} = A_{FM}'/(2\pi f_{FM}) \) is the amplitude and \( f_{FM} \) the frequency of the frequency modulation. This perturbation mimics a non-linear transfer function exciting all the even harmonics of the fundamental frequency \( f_0 \) that also experiences a low-frequency modulation at \( f_{FM} \).

Figure 23 illustrates the spectrogram for a frequency range up to 1.8 kHz, color-coded with the PSD with \( f_0 = 100 \) Hz. All harmonics experience a similar frequency modulation with a peak-to-peak variation proportional to the order of the harmonic.

[1] T. J. Satogata, *Nonlinear resonance islands and modulational effects in a proton synchrotron*, Ph.D. thesis, Northwestern U. (1993).
[2] F. Zimmermann, *Emittance growth and proton beam lifetime in HERA*, Ph.D. thesis, Hamburg U. (1993).
[3] O. S. Brüning and F. Willeke, *Diffusion-like processes in proton storage rings due to the combined effect of nonlinear fields and modulational effects with more than one frequency*, in *European Particle Accelerator Conference (EPAC 1994)* (1994).
[4] O. S. Brüning, M. Seidel, K. Mess, and F. Willeke, *Measuring the effect of an external tune modulation on the particle diffusion in the proton storage ring of HERA*, Tech. Rep. (P00021147, 1994).
[5] O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock, *LHC Design Report* CERN Yellow Reports: Monographs (CERN, Geneva, 2004).
[6] M. Kuhn, G. Arduini, J. Emery, A. Guerrero, W. Hofle, V. Kain, F. Roncarolo, M. Sapinski, M. Schaumann, and R. Steinhaagen, LHC Emittance preservation during the 2012 run., in *Proceedings, 4th Evian Workshop on LHC beam operation: Evian Les Bains, France, December 17-20, 2012* (2012) pp. 161–170. 10 p.
[7] S. Cettour Cave, R. De Maria, M. Giovannozzi, M. Ludwig, A. MacPherson, S. Redaelli, F. Roncarolo, M. Solfaroli Camillocci, and W. Venturini Delsolaro, *Non-linear beam dynamics tests in the LHC: Measurement of intensity decay for probing dynamic aperture at injection* (2013).
[8] G. Arduini, *50 Hz lines studies: First observations*, https://indico.cern.ch/event/436679/contributions/1085928 (2015), accessed: 2019-12-13.
[9] R. De Maria, *Observation of 50 Hz lines in the LHC BBQ system*, https://lhc-beam-operation-committee.web.cern.ch/lhc-beam-operation-committee (2012), accessed: 2019-12-14.
[10] T. Linnecker and W. Scandale, *Phenomenology and causes of the 50 Hz spaced lines contaminating the Schottky signal*, Tech. Rep. CERN-SPS-DI-MST-TL-WS-EEK CERN-SPS-Improvement-Report-203 (CERN, Geneva, 1986).
[11] X. Altuna, C. Arimatea, R. Bailey, T. Bohl, D. Brandt, K. Cornelis, C. Depas, F. Galluccio, J. Gareyte, R. Giachino, M. Giovannozzi, Z. Guo, W. Herr, A. Hilaire, T. Lundberg, J. Miles, L. Normann, T. Risselada, W. Scandale, F. Schmidt, A. Spinks, M. Venturini, M. Giovannozzi, and F. Schmidt, *The 1991 dynamic aperture experiment at the CERN SPS*, AIP Conference Proceedings 255, 355 (1992), https://aip.scitation.org/doi/pdf/10.1063/1.42289
[12] O. S. Brüning, Diffusion in a FODO cell due to modulation effects in the presence of nonlinear fields, Part. Accel. 41, 133 (1992).
[13] W. Fischer and M. Giovannozzi, Dynamic aperture experiment at a synchrotron, Physical Review E 55, 3507 (1997).
[14] M. Gasior and R. Jones, The principle and first results of betatron tune measurement by direct diode detection Tech. Rep. LHC-Project-Report-853. CERN-LHC-Project-Report-853 (CERN, Geneva, 2005) revised version submitted on 2005-09-16 09:23:15.
[15] O. S. Brüning, M. Seidel, K. Mess, and F. Willeke, Measuring the effect of an external tune modulation on the particle diffusion in the proton storage ring of HERA, Tech. Rep. (P00021147, 1994).
[16] O. S. Brüning and F. Willeke, Reduction of particle losses in HERA by generating an additional harmonic tune modulation, in Proceedings Particle Accelerator Conference Vol. 1 (1995) pp. 420–422 vol.1.
[17] P. Cameron, M. Gasior, R. Jones, and C. Tan, The effects and possible origins of mains ripple in the vicinity of the betatron spectrum., Tech. Rep. (Brookhaven National Lab,(BNL), Upton, NY (United States), 2005).
[18] P. Cameron, M. Gasior, R. Jones, and C. Tang, Observations of direct excitation of the betatron spectrum by mains harmonics in RHIC, Tech. Rep. (Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider, 2006).
[19] C.-Y. Tan, Novel tune diagnostics for the Tevatron, in Proceedings of the 2005 Particle Accelerator Conference (IEEE, 2005) pp. 140–144.
[20] V. Slütkov, G. Stancari, and A. Valishev, Ambient betatron motion and its excitation by “ghost lines” in Tevatron, Journal of Instrumentation 6 (08), P08002.
[21] M. Solfaroli Camillocci, S. Redaelli, R. Tomás, and J. Wenninger, Combined Ramp and Squeeze to 6.5 TeV in the LHC, in Proceedings, 7th International Particle Accelerator Conference (IPAC 2016): Busan, Korea, May 8-13, 2016 (2016) p. TUPMW031.
[22] S. Fartoukh, Achromatic telescopic squeezed scheme and application to the LHC and its luminosity upgrade, Phys. Rev. ST Accel. Beams 16, 111002 (2013).
[23] B. Muratori and T. Pieoni, Luminosity levelling techniques for the LHC (2014) pp. 177–181. 5 p, comments: 5 pages, contribution to the ICFIA Mini-Workshop on Beam-Beam Effects in Hadron Colliders, CERN, Geneva, Switzerland, 18-22 Mar 2013.
[24] N. Karastathis, K. Fuchsberger, M. Hostettler, Y. Papaphilippou, and D. Pellegrini, Crossing angle anti-leveling at the LHC in 2017, in Journal of Physics: Conference Series, Vol. 1067 (IOP Publishing, 2018) p. 022004.
[25] M. Gasior, Faraday cup award: High sensitivity tune measurement using direct diode detection, Conf. Proc. C1204151, MOAP02. 7 p (2012).
[26] O. Jones, LHC beam instrumentation, in 2007 IEEE Particle Accelerator Conference (PAC) (IEEE, 2007) pp. 2630–2634.
[27] L. Carver, X. Buffat, A. Butterworth, W. Höße, G. Iadarola, G. Kotzian, K. Li, E. Métral, M. Ojeda Sandonís, M. Söderén, and D. Valuch, Usage of the transverse damper observation box for high sampling rate transverse position data in the LHC, in 8th Int. Particle Accelerator Conf. (IPAC’17), Copenhagen, Denmark, May 2017. CERN-ACC-2017-117 (2017) pp. 389–392.
[28] M. Ojeda Sandonís, P. Baudrenghien, A. Butterworth, J. Galindo, W. Höße, T. Levens, J. Molenjif, F. Vaga, and D. Valuch, Processing high-bandwidth bunch-by-bunch observation data from the RF and transverse damper systems of the LHC, in Proceedings, 15th International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS 2015): Melbourne, Australia, October 17-23, 2015 (2015) p. WEPGF062.
[29] M. Söderén, G. Kotzian, M. Ojeda Sandonís, and D. Valuch, Online bunch by bunch transverse instability detection in LHC, in Proceedings, 8th International Particle Accelerator Conference (IPAC 2017): Copenhagen, Denmark, May 14-19, 2017 (2017) p. MOPAB117.
[30] T. Persson, J. M. Coello de Portugal, A. Garcia-Tabares, M. Gasior, A. Langner, T. Lefèvre, E. Maclean, L. Malina, J. Oleza, P. Skowronski, and R. Tomás, Experience with DOROS BPMs for coupling measurement and correction, in 7th Int. Particle Accelerator Conf.(IPAC’16), Busan, Korea, May 8-13, 2016 (JACOW, Geneva, Switzerland, 2016) pp. 303–305.
[31] J. Oleza, O. Ondracek, Z. Brezovic, and M. Gasior, Prototype system for phase advance measurements of LHC small beam oscillations Tech. Rep. CERN-ATS-2013-038 (CERN, Geneva, 2013).
[32] R. Steinhagen, T. Lucas, and M. Boland, A Multiband-Instability-Monitor for high-frequency intra-bunch beam diagnostics (2013).
[33] T. Levens, T. Lefèvre, and D. Valuch, Initial results from the LHC Multi-Band Instability Monitor, in Int. Beam Instrumentation Conf.(IBIC’18), Shanghai, China, 09-13 September 2018 (JACOW Publishing, Geneva, Switzerland, 2019) pp. 314–318.
[34] S. Kostoglou, G. Aruini, C. Baccigalupi, H. Bartosik, X. Buffat, J.-P. Burnet, L. R. Carver, M. Cerqueira Bastos, R. De Maria, S. Fartoukh, R. Tomás Garcia, G. Iadarola, I. Icel, T. Levens, D. M. Louro Alves, O. Michels, V. Montabonnet, D. Nisbet, J. Oleza, Y. Papaphilippou, M. Pojer, A. Poyet, M. Soderen, M. Solfaroli Camillocci, G. Sterbini, H. Thiessen, G. Trad, N. Triantafyllou, D. Valuch, and J. Wenninger, MD1147: 50 Hz harmonics perturbation, Tech. Rep. (CERN, 2019).
[35] H. Nyquist, Certain topics in Telegraph transmission theory, Transactions of the American Institute of Electrical Engineers 47, 617 (1928).
[36] Network frequency, https://clients.rte-france.com (2020), accessed: 2020-06-03.
[37] M. Buzio, P. Galbraith, S. Gilardoni, D. Giloteaux, G. Golluccio, C. Petrone, L. Walckiers, and A. Beaujont, Development of upgraded magnetic instrumentation for CERN’s real-time reference field measurement systems, Proceedings, 1st International Particle Accelerator Conference (IPAC’10): Kyoto, Japan, May 23-28, 2010, Conf. Proc. C100523, MOPEB016 (2010).
[38] T. Bohl, Functional specification for upgrade of SPS B-train, CERN, Geneva, Switzerland, Rep. EDMS 1689759 (2016).
[39] A. Huschauer, A. Blas, J. Borburgh, S. Damjanovic, S. Gilardoni, M. Giovannozzi, M. Hourican, K. Kahle, G. Le Godec, O. Michels, G. Sterbini, and C. Hernalsteens, Transverse beam splitting made operational: Key features of the multiturn extraction at the CERN Proton Synchrotron, Phys. Rev. Accel. Beams 20, 061001 (2017).
[40] H. Thiesen and D. Nisbet, Review of the initial phases of the LHC power converter commissioning, *Particle accelerator. Proceedings, 11th European Conference, EPAC 2008, Genoa, Italy, June 23-27, 2008*, Conf. Proc. C0806233, THPP132 (2008).

[41] O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock, *LHC Design Report*, CERN Yellow Reports: Monographs (CERN, Geneva, 2004) Chap. Power converter system.

[42] S. Kostoglou, H. Bartosik, Y. Papaphilippou, G. Sterbini, and N. Triantafyllou, Tune modulation effects in the high luminosity large hadron collider (2020), arXiv:2003.00960 [physics.acc-ph].

[43] N. Karastathis, S. Fartoukh, S. Kostoglou, Y. Papaphilippou, M. Pojer, A. Poyet, M. Solfaroli Camillocci, and G. Sterbini, *MD 3584: Long-Range Beam-Beam 2018*, Tech. Rep. (CERN, 2020).

[44] A. Verweij, V. Baggiolini, A. Ballarino, B. Bellesia, F. Bordry, A. Cantone, M. Casas Lino, A. Serra, C. Trello, N. Catalan Lasheras, Z. Charfoulline, G. Coelingh, K. Dahlerup-Petersen, G. D’Angelo, R. Denz, S. Feher, R. Flora, M. Gruwe, V. Kain, and M. Zerlauth, Performance of the main dipole magnet circuits of the LHC during commissioning, EPAC 2008 - Contributions to the Proceedings (2008).

[45] O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock, Power converter system, in *LHC Design Report*, CERN Yellow Reports: Monographs (CERN, Geneva, 2004) Chap. 10, pp. 275–307.

[46] J.-P. Burnet, Test results of RPTE LHC thyristor rectifier with active filter (2019), unpublished.

[47] G. Apollinari, I. Béjar Alonso, O. Brüning, P. Fessia, M. Lamon, L. Rossi, and L. Tavian, High-Luminosity Large Hadron Collider (HL-LHC), CERN Yellow Rep. Monogr. 4, 1 (2017).

[48] F. Dubouchet, W. Holle, G. Kottzian, and D. Valuch, "What you get" - Transverse damper, in *Proceedings, 4th Evian Workshop on LHC beam operation: Evian Les Bains, France, December 17-20, 2012*, CERN (CERN, Geneva, 2012) pp. 73–78.

[49] J. P. O. Komppula, G. Kottzian, S. Rains, M. Söderén, and D. Valuch, ADT and ObsBox in LHC Run 2, plans for LS2, in *Proceedings, 9th Evian Workshop on LHC beam operation: Evian Les Bains, France, January, 2019* (2019).

[50] M. Morrone, M. Martino, R. De Maria, M. Fitterer, and C. Garion, Magnetic frequency response of High-Luminosity Large Hadron Collider beam screens, Phys. Rev. Accel. Beams 22, 013501 (2019).

[51] F. Ruggiero, Single beam collective effects in the LHC, *Collective effects in large hadron colliders. Proceedings, International Workshop, Montreux, Switzerland, October 17-22, 1994*, Part. Accel. 50, 83 (1995).

[52] V. Chareyre, *Assessment of the high frequency noise produced by the UPS systems in the LHC Machine*, Tech. Rep. (CERN, 2015).

[53] U. Hassan and S. Anwar, Reducing noise by repetition: Introduction to signal averaging, *European Journal of Physics* 31, 453 (2010).

[54] SixTrack, [http://sixtrack.web.cern.ch/SixTrack/](http://sixtrack.web.cern.ch/SixTrack/) (2019), accessed: 2019-11-26.

[55] R. D. Maria, J. Andersson, V. B. Olsen, L. Field, M. Giovannozzi, P. Hermes, N. Høimyr, S. Kostoglou, G. Iadarola, E. McIntosh, A. Mereghetti, J. W. Molson, D. Pellegrini, T. Persson, M. Schwinzerl, E. H. Maclean, K. Sjobak, I. Zacharov, and S. Singh, SixTrack project: Status, runtime environment, and new developments, in *Proceedings, 13th International Computational Accelerator Physics Conference, ICAP2018: Key West, FL, USA, 20-24 October 2018* (2019) p. TUPAF02.