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HARMONICS OF 50 HZ ON THE BEAM SPECTRUM OF THE LARGE HADRON COLLIDER

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Abstract

Studies of the beam spectrum of the Large Hadron Collider (LHC) have revealed the existence of harmonics of the mains frequency (50 Hz), ranging from 50 Hz to 8 kHz, in the form of dipolar excitations. The restart of the LHC operation in Run 3 was accompanied by substantial improvements in the beam instrumentation. In particular, the upgrade of the transverse damper's observation system (ADTObsBox), currently providing bunch-by-bunch and continuous position measurements, allows for the first time a systematic follow-up of the evolution of harmonics during the run. In this paper, we present parasitic observations collected during the LHC physics operation, as well as results from dedicated experiments with the aim of providing further insights into the source of the perturbations, especially concerning the 50 Hz harmonics around 8 kHz. These tests include modifications in the operation mode of systems such as some of the Uninterruptible Power Supplies, while looking out for potential changes in the spectrum of the beam position data.

INTRODUCTION

The presence of 50 Hz harmonics has been consistently observed in the transverse beam spectrum of the LHC during both Run 2 and Run 3 [1, 2]. These harmonics appear across all fills and beam modes, in both beams and planes. Two clusters of harmonics have been identified. The first cluster includes 50 Hz harmonics extending up to approximately 3.6 kHz and has been extensively studied. The origin of these harmonics is understood, with the main source being the eight power converters of the arc dipoles. The second cluster is a high-frequency cluster consisting of 50 Hz harmonics around 8 kHz. Single particle tracking simulations suggest that these harmonics increase the tune diffusion of particles due to their larger amplitude, reduce the Dynamic Aperture and eventually lead to degradation of the beam lifetime [3]. To this end, identifying their origin is currently the focus of ongoing studies with the aim of providing mitigation measures.

OBSERVATIONS IN THE 2023 RUN

The systematic monitoring of the LHC beam spectrum relies on the continuous bunch-by-bunch transverse position measurements from the high-sensitivity pickups of the transverse damper, also known as the ADTObsBox [4]. The analysis of these data involves the complex task of combining the spectra of all the bunches, while taking into account the dephasing of the spectrum on a bunch-by-bunch basis as described in Ref. [1]. This technique increases the effective sampling rate beyond the beam revolution frequency,

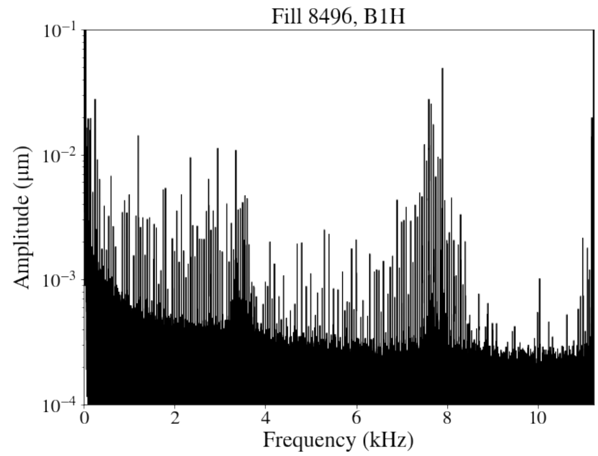

Figure 1: Transverse spectrum from ADTObsBox position data for the horizontal plane of Beam 1 during collisions.

and allows for the first time a systematic study of the beam spectrum in a high-frequency range and for all fills. Figure 1 presents the transverse spectrum for the horizontal plane of Beam 1 during collisions. The maximum ripple amplitude is approximately 0.1 μm.

In Fig. 2, the spectrogram for the horizontal plane of Beam 1 is shown, with a focus on the 8 kHz cluster. The black horizontal lines in the figure illustrate the different beam modes. It is interesting to note that the spectrogram reveals a strong enhancement of the amplitude of the 8 kHz cluster at the end of the energy ramp (Ramp). This observation has never been made before, and may provide valuable insights into its origin.

MEASUREMENTS OF A SPARE LHC UPS

In the LHC, a number of Uninterruptible Power Supplies (UPSs) are utilized to guarantee continuous availability of critical systems. In order to identify potential sources of high-frequency clusters, measurements of the output voltage spectrum were performed on a spare UPS of the same model as those employed in the LHC [5].

It is important to note that the UPS can operate in a variety of modes, each with its own set of characteristics. For example, during nominal operation, the UPS is connected to the AC power mains and a rectifier converts the AC power to DC, which is used to charge the UPS battery and power an inverter. The inverter converts the DC power back into AC power, which is then used to power the load. In the event of a power outage or other interruption to the AC power supply, the UPS can switch to battery mode and use the battery to provide backup power to the load. Bypass modes

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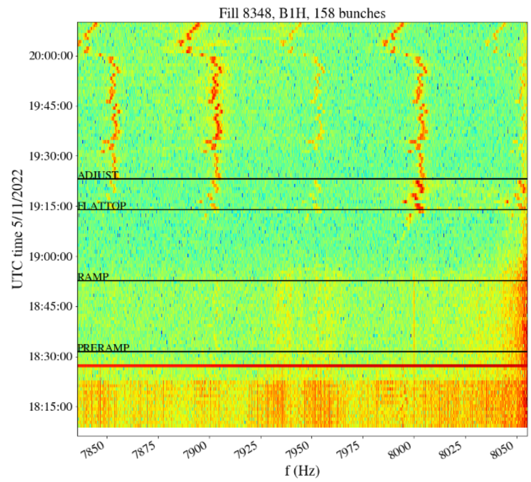

Figure 2: Spectrogram of the horizontal plane of Beam 1 for a nominal physics fill of Run 3. The vertical black lines illustrate the different beam modes.

are also available to allow the load to be powered directly from the incoming AC power supply, in the event that the UPS experiences a fault or requires maintenance.

Figure 3 (top) shows the UPS output voltage spectrogram during nominal operation, centered around the low (left) and high (right) frequency clusters. The spectrum displays 50 Hz harmonics around the inverter switching frequency, SF (4 kHz), as well as its harmonics, which indicates that 50 Hz harmonics are expected in the UPS output at around 8 kHz, similar to what is observed in the LHC beams. Additionally, a modulation of the mains harmonics is clearly visible, which is also observed in the LHC beams. This modulation is induced by the stability of the main network frequency [6].

Figure 3 (bottom) depicts the UPS output voltage spectrogram during battery mode operation. In this mode, the control of the battery is carried out using an internal clock, rather than the AC power supply. As a result, a loss of synchronization with the mains is observed in the battery mode spectrum, and there is no modulation of the harmonics. This observation is of significance because it can be used to determine whether a loss of synchronization in the harmonics of the LHC beam spectra occurs when switching a UPS to battery mode. Such an observation could demonstrate that the UPS is the source of the 8 kHz cluster.

DEDICATED EXPERIMENTS IN THE LHC

Two separate experiments were carried out in the LHC to determine if certain UPS systems were responsible for the 8 kHz perturbation by measuring the beam spectrum for different UPS configurations [7, 8]. The focus of the studies was on two UPS systems located in Point 4 of the LHC, which are connected to RF systems such as the transverse damper. The hypothesis was that these UPS systems could potentially excite the beam at 8 kHz through the connected transverse damper hardware. The aim was to modify the UPS configurations and observe changes in the beam spectrum,

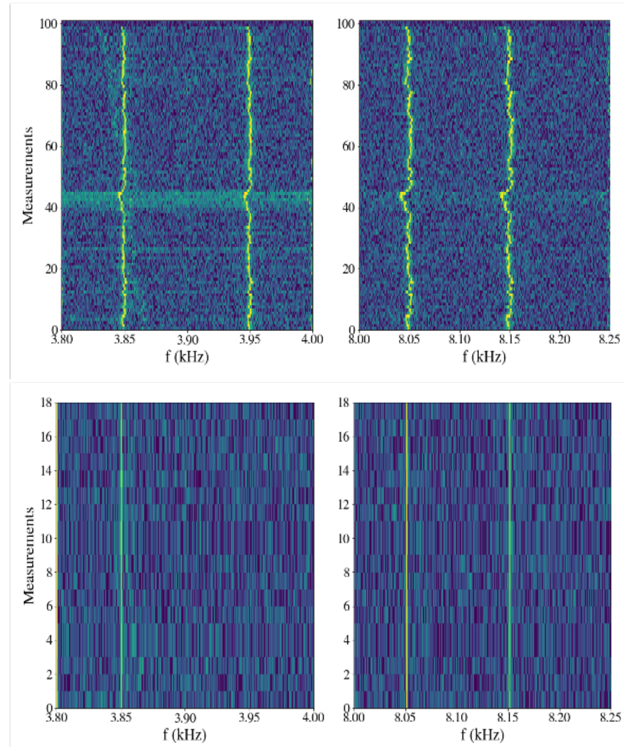

Figure 3: UPS output voltage spectrogram for nominal operation (top) and battery mode (bottom) zoomed around 3.8 kHz and 8.1 kHz.

such as changes in the amplitude of the harmonics or loss of synchronization to the mains when switching the UPS to battery mode.

The first experiment was conducted at injection energy, but unfortunately, due to the limited number of bunches and the low amplitude of the 8 kHz cluster at injection energy, it was not possible to observe or study the 8 kHz cluster under these conditions and, thereby, to determine whether there was any impact on the 8 kHz cluster during the test.

However, a clear impact from a UPS was observed on a few low-order 50 Hz harmonics when switching from the nominal configuration to battery mode (e.g., 550, 750, 1150, 1950, 2950, 3150 Hz). Figure 4 shows the spectrograms for some of these frequencies (550 Hz, top, and 2050 Hz, bottom). The expected modulation of the two harmonics is also depicted (blue line), which is computed from the data on the main frequency evolution provided in Ref. [6]. The expected modulation scales with the order of the harmonic, which explains the larger fluctuation of the blue line in the case of 2950 Hz compared to 550 Hz. The horizontal lines indicate the various tests. A comparison between the two spectrograms and the expected modulation from the mains reveals a loss of synchronization of the specific harmonics when the UPS is operated in battery mode (from around 19:30 to 19:38). Although these harmonics are part of the low-frequency cluster and have low amplitudes, meaning that they are not of significant concern for beam quality, this observation could be an indication of the impact of the UPS

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on the beam. Therefore, further tests with this specific UPS were deemed necessary.

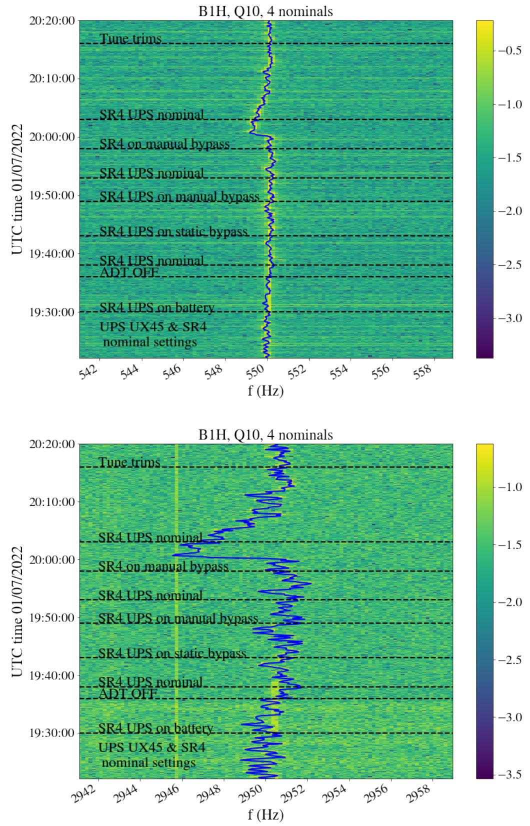

Figure 4: Spectrogram of Beam 1 centered around 550 Hz (top) and 2950 Hz (bottom) along with the expected modulation due to the stability of the network frequency (blue). The horizontal dashed lines represent changes in the UPS and transverse damper configuration.

A second experiment was conducted at top energy when the 8 kHz cluster is clearly visible and can be easily detected and studied. In particular, the aim was to observe the loss of synchronization of the 8 kHz cluster with the mains when the UPS is switched to battery mode, similar to the observations made with the LHC spare UPS. Such an observation would serve as direct evidence that the UPS is the source of the perturbation.

Figure 5 shows the spectrogram centered around a harmonic of the high-frequency cluster. The dashed black horizontal lines illustrate the two time ranges during which the UPS was operated in battery mode. Comparing with the expected time evolution (blue), no loss of synchronization was observed in any of the harmonics of the 8 kHz cluster during these tests. This indicates that this specific UPS can be excluded as the source of the perturbation.

CONCLUSIONS

Harmonics of 50 Hz have been systematically observed in the transverse beam spectrum of the LHC. Although the origin of the low frequency cluster has been understood, the

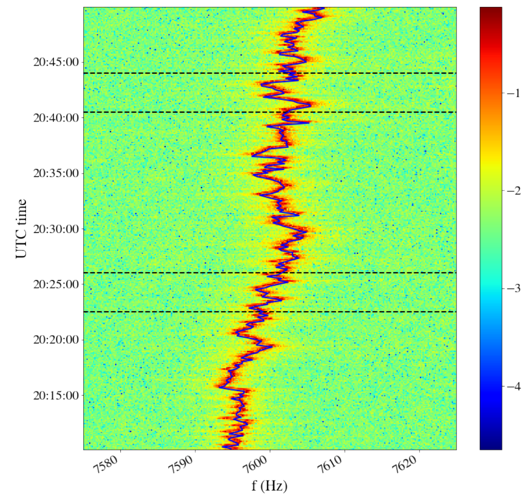

Figure 5: Beam 1 spectrogram centered around one of the frequencies in the 8 kHz cluster. The horizontal dashed black lines illustrate the time ranges during which the UPS is switched to battery mode while the expected time evolution is marked in blue.

origin of the 8 kHz cluster is still not identified. This paper presents an investigation into a possible source: two UPS systems connected to the hardware of the transverse damper. The transverse damper is one of the few LHC components capable of exciting the beam at 8 kHz. The hypothesis for this investigation stemmed from the fact that measurements of a spare UPS of a similar type revealed a strong similarity in its output voltage spectrum with the 8 kHz cluster observed in the LHC beams. The approach in both experiments was to modify the configuration of some UPS systems and observe if noticeable changes occur in the beam spectrum. Despite these modifications, no loss of synchronization with the mains modulation was observed in the 8 kHz cluster, suggesting that these UPS systems can be excluded as the source of the perturbation. It is important to note, however, that only two such UPS systems have so far been tested.

Although the investigation was unable to identify the source of the 8 kHz cluster, it provided valuable insights for future investigations into noise effects in the LHC. The new capabilities of the beam instrumentation, such as the ADTObsBox, enabled the observation that the 8 kHz cluster is strongly enhanced at the end of the energy ramp. This finding highlights the importance of closely monitoring the 8 kHz cluster during the next LHC operation period, with the aim of collecting further observations that will allow identification of its origin.

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