OBSERVATIONS OF 50 Hz HARMONICS IN THE LHC TRANSVERSE BEAM SPECTRA

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Abstract

In the Large Hadron Collider (LHC), several beam diagnostic systems provide turn-by-turn and bunch-by-bunch position, enabling a precise characterization of the transverse beam spectra up to high frequency. Using these instruments, the presence of external excitations at 50 Hz harmonics have been observed to affect the beam motion. In this work, we combine these measurements to study the evolution of the noise content in the LHC, with particular focus on the 50 Hz harmonics clustered around 8 kHz, which corresponds to an important range of the transverse beam spectrum. While the exact source of the excitation remains unknown, this study provides new insights into the mechanisms behind this excitation and the evolution of the harmonic lines along the LHC cycle based on statistics collected from operational physics fills in 2025.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with a variety of transverse beam diagnostics that provide turn-by-turn and bunch-by-bunch position measurements [1]. These systems enable detailed spectral analyses of transverse beam dynamics up to high frequency throughout the different phases of the LHC cycle, from injection to collision energy.

Among the spectral features observed in the transverse beam planes, a cluster of 50 Hz mains harmonics has been systematically observed in previous LHC runs, in particular around 8 kHz in close proximity to the lower betatron sideband of the revolution frequency. The spectral signature of this noise points to a dipolar excitation, rather than a tune modulation. In the current study, the focus is on the horizontal plane, since the amplitude of its harmonics is systematically larger than the harmonics in the vertical plane [2–4].

The 8 kHz cluster is of particular interest as it may be linked to the unexplained emittance growth observed in the LHC at injection and top energy. In fact, the measured emittance growth is not consistent with the expected emittance evolution considering Synchrotron Radiation (SR) and Intrabeam Scattering (IBS) effects. Furthermore, recent tracking simulations using a realistic 8 kHz harmonic excitation confirm a possible emittance growth contribution [5]. This motivates a deeper investigation into the nature and origin of the 8 kHz excitation and its role in emittance growth.

While these harmonics have been systematically observed at injection and top energy, their evolution during the energy ramp was not studied in the past. In addition, no mechanism responsible for changes in their amplitude had been found up to now that could help identify their underlying origin.

In the first part of this work, we study the evolution of the 8 kHz cluster throughout the energy ramp. A Fast Fourier Transform (FFT) is computed, showing the frequency content of the centroid motion of the bunches in the vicinity of the 8 kHz cluster as a function of time. An algorithm combining bunch-by-bunch and turn-by-turn position measurements, including a phase-advance correction between bunches, is used to extend the spectrum beyond the LHC turn-by-turn Nyquist frequency (≈5.5 kHz given the beam revolution frequency of ≈11 kHz) [2]. In the second part, we demonstrate a clear link between the Main Dipole Active Filters (AFs) and the enhancement of the 50 Hz harmonic amplitudes.

BEAM ENERGY DEPENDENCE

To highlight the dependence of the harmonic amplitudes on the beam energy, two representative fills are compared: a fill where the top energy was limited to 2.68 TeV and a physics fill at the nominal flat top energy of 6.8 TeV. Figure 1 shows the horizontal spectra in the range between 7400 Hz and 8700 Hz, from the start of the ramp to top energy, for the two cases. The different phases of the cycle are also indicated. Focusing on the nominal case (left), the amplitudes of the harmonics closest to the lower betatron sideband (blue) are strongly enhanced, which is consistent with the fact that the beam is more sensitive to external dipolar excitations close to the betatron tune. When the machine tune is changed from the injection working point to the collision one before the beams are brought into collision (ADJUST phase), the amplitudes of the harmonics above 8 kHz are attenuated while those below 8 kHz are enhanced, following the tune frequency evolution. This explains the change of the cluster location that is systematically observed at every fill.

However, an additional observation is that at 2.68 TeV, the 8 kHz cluster is either absent or just barely above the noise floor level (Fig. 1, right). Examining the evolution of the harmonic lines during the energy ramp in a nominal physics fill, a pronounced enhancement is observed at beam energies above approximately 5.5 TeV. Below this threshold the spectral content remains mostly unchanged, while the harmonic amplitudes increase rapidly above it during the

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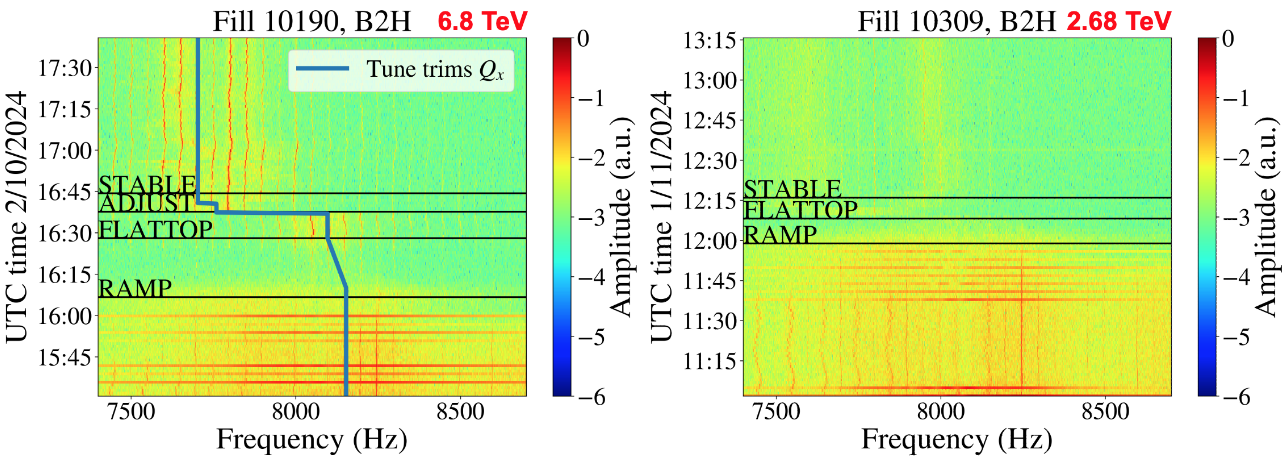

Figure 1: Spectrograms from turn-by-turn bunch-by-bunch horizontal position data zoomed around the 8 kHz cluster for a fill with a top energy of 6.8 TeV (left) and for a fill with a top energy of 2.68 TeV (right). The x-axis shows the frequency, y-axis shows the time evolution and the color code is the amplitude in log scale. Q_x represents the lower betatron sideband.

energy ramp. This is consistent with the absence of these lines in the low energy fill.

The observed behavior suggests a source linked to machine systems whose operating conditions change significantly during the energy ramp. In particular, the main dipole circuits seem to be an obvious candidate, as they represent some of the most relevant circuits of the machine [6] with substantial increase in current as the beam energy rises. In addition, the dipole signature of the harmonic lines observed in the beam spectrum would also be consistent with the dipole circuits, rendering them indeed a plausible contributor to the observed 50 Hz harmonics. These observations motivated further dedicated measurements targeting the main dipole circuits, as discussed in the following section. Previous investigations have additionally considered the role of the Uninterruptible Power Supplies (UPS) and other infrastructure-related sources, which could introduce electrical noise [2].

IMPACT OF ACTIVE FILTERS

The main dipole power converters are of Silicon Controlled Rectifier (SCR) type, which are known to generate harmonic noise due to their switching characteristics [7, 8]. To suppress the resulting low-frequency perturbations, such as those at 300 Hz and 600 Hz, Active Filters (AFs) have been installed at the output of all main dipole power converters. These AFs are usually enabled in routine LHC operation.

To investigate the impact of the AFs on the transverse beam spectrum, dedicated measurements were performed. Figure 2 shows the results of an experiment at 6.8 TeV, in which the AFs were switched on and off twice. A clear and reproducible impact on the 8 kHz harmonics amplitude is observed each time the AF state is changed. While the primary purpose of the AFs is to reduce low-frequency noise, they appear to enhance higher-frequency noise, including the 8 kHz cluster [2]. This represents the first observation of a controlled and reproducible change of the 8 kHz harmonic amplitudes, establishing a clear link between the main dipole AFs and the enhancement of the 8 kHz harmonic amplitudes.

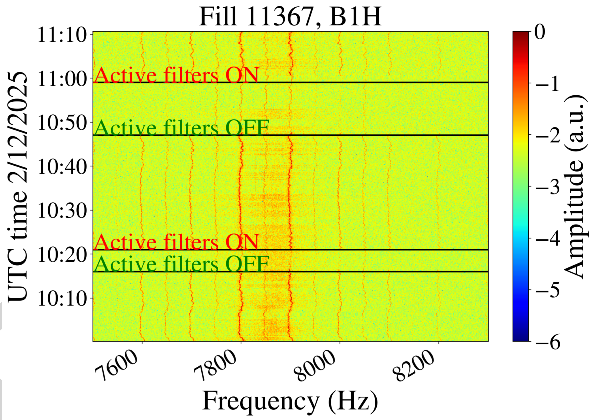

Figure 2: Harmonic amplitude measurements at flat-top energy - 6.8 TeV, highlighting the enhancement observed when the AFs are enabled.

Figure 3 compares measurements taken during the energy ramp with the AFs enabled (left) and disabled (right). The impact of the AFs on the harmonic amplitudes is clearly visible: while the 50 Hz harmonics around 8 kHz are present in both cases, their amplitudes are approximately one order of magnitude lower when the AFs are disabled (even harmonics particularly). Thus switching off the AFs significantly reduces the harmonic amplitudes but does not fully suppress them, indicating that the AFs are not the single source of the excitation but rather a significant contributor.

Figure 4 shows a time slice from Fig. 2, with the AF-on case on the left and the AF-off case on the right. The spectra are shown in linear scale with amplitudes calibrated in micrometers, allowing a quantitative comparison of the two cases. The amplitude reduction upon disabling the AFs is approximately one order of magnitude. In the case of AFs off an enhanced spectral component at 600 Hz is observed, consistent with the switching frequency of the SCR power supplies [2]. This confirms that the AFs successfully sup-

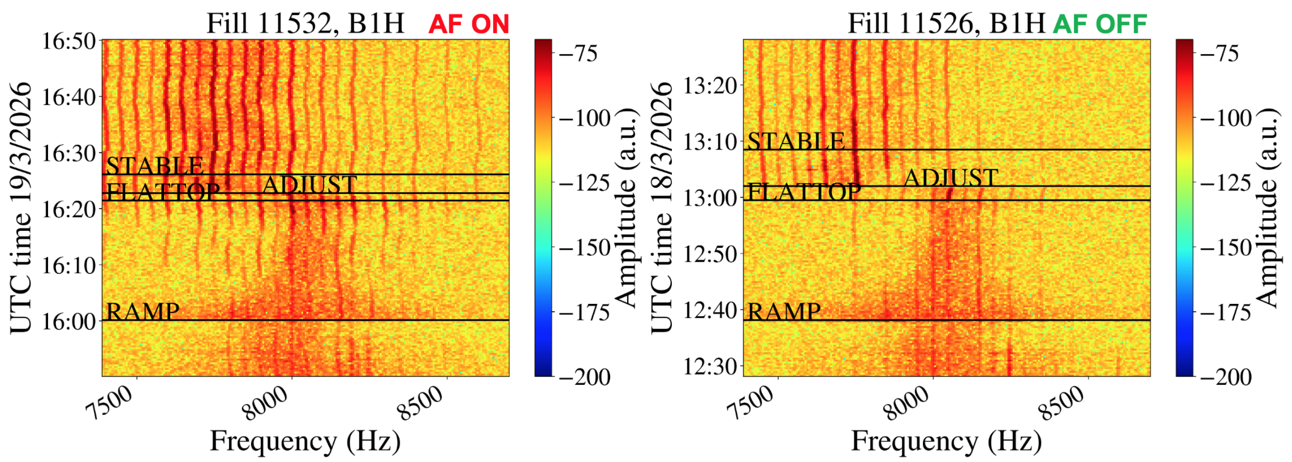

Figure 3: Spectrogram obtained from the Multi-band instability monitor (MIM) [9] showing a comparison between an energy ramp with AFs enabled (left) and energy ramp with AFs disabled (right).

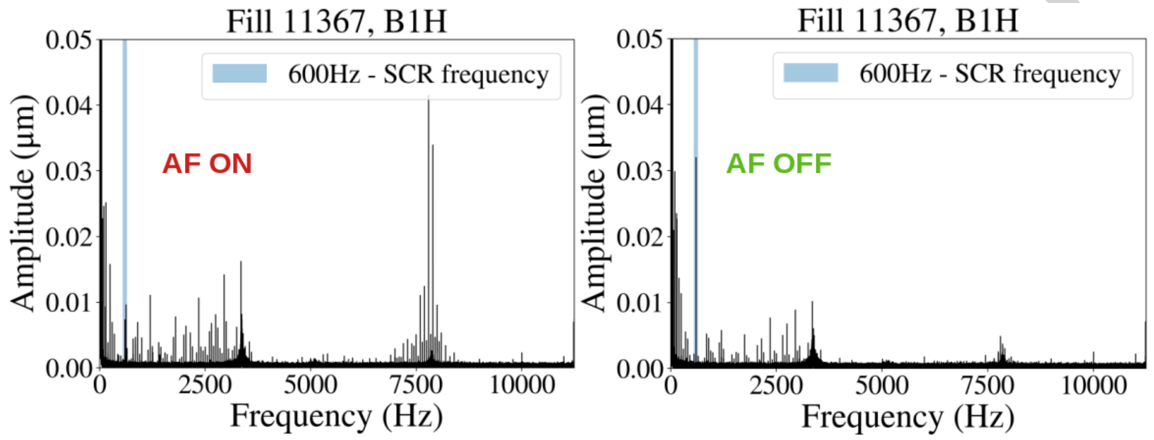

Figure 4: A time slice from 2. The x-axis represents the frequency in Hz and the y-axis in the amplitude of the oscillation. The frequency range is from 0 Hz to the revolution frequency. Left: AFs on, right: AFs off.

press the low-frequency SCR noise they are designed to mitigate, but enhance the 8 kHz harmonic cluster.

CONCLUSION AND OUTLOOK

In this paper, transverse beam measurements have been used to investigate the evolution of the 8 kHz cluster of 50 Hz harmonics throughout the LHC cycle. A clear dependence of the harmonic amplitudes on beam energy has been observed. The enhancement of the 8 kHz cluster consistently appears at beam energies above approximately 5.5 TeV and persists at the 6.8 TeV flattop energy, while no comparable enhancement is observed if the ramp stops at lower energies. The exact underlying mechanism of this energy-dependent excitation is under investigation.

A key result of this study is the first experimental observation of a strong enhancement of the 8 kHz harmonics associated with enabling the main dipole AFs. Dedicated measurements show that enabling the AFs leads to an increase in harmonic amplitudes by approximately one order of magnitude. The effect is reproducible across fills.

While the precise physical mechanism responsible for the observed enhancement of the harmonic amplitudes remains under investigation, the results presented here significantly narrow down the range of possible sources and establish a clear link between machine configuration, beam energy, and harmonic excitation.

Future work will focus on systematic studies of machine parameters during the energy ramp, including power converter settings and filtering schemes, with the goal of fully identifying the origin of the 8 kHz cluster and assessing its impact on the beam quality and emittance preservation.

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