

# EMITTANCE GROWTH DUE TO POWER CONVERTER RIPPLE AND NOISE AT 50 Hz HARMONICS DURING LHC COLLISIONS

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## Abstract

Transverse emittance growth can adversely affect the luminosity production performance of colliders such as the Large Hadron Collider (LHC) at CERN. While Intra-Beam Scattering (IBS) and Synchrotron Radiation (SR) effects represent important ingredients for the emittance evolution, measurements in the LHC do not match predictions from these two effects, suggesting the presence of additional emittance growth mechanisms. External excitations, such as power supply ripple and noise at 50 Hz harmonics, are additional sources of emittance growth especially in the presence of non-linearities as induced by beam-beam effects. In the LHC, the most prominent excitations during collisions are harmonics of 50 Hz clustered around 8 kHz. In this work, we quantify the expected contribution of these excitations to the emittance evolution and proton losses using single particle tracking simulations including a realistic excitation spectrum as observed in operation.

## INTRODUCTION

In high-energy hadron colliders, such as the Large Hadron Collider (LHC), preserving low transverse emittances is essential to maximize the integrated luminosity. At the LHC top energy, Intra-Beam Scattering (IBS) and Synchrotron Radiation (SR) effects are expected to be the main contributors to the emittance evolution. However, measurements in the LHC indicate the presence of additional sources of emittance growth that are not captured by the present models.

One potential source of this extra emittance growth is power converter ripple, systematically observed on the transverse beam spectrum. It appears as dipolar excitations at harmonics of 50 Hz clustered around 8 kHz, close to the lower betatron sideband ( $1 - Q_x$ ). The origin of this high-frequency cluster is still under investigation and is beyond the scope of this paper [1]. Here we focus on the impact of the 8 kHz cluster on the horizontal plane of the beam, since the measured amplitude of the harmonics in the horizontal plane is higher than the one in the vertical plane.

Analytical estimates suggest that power supply ripple can drive emittance growth, depending strongly on its proximity to the betatron tune [2]. In addition, beam-beam interactions generate a significant tune spread which, in the presence of external excitations, can enhance diffusion and ultimately lead to emittance growth.

In this paper, we use tracking simulations, including the measured excitation spectra [3], to quantify the contribution of the 8 kHz cluster to horizontal emittance growth

during collisions. The analysis covers both nominal LHC operation and special runs, such as the Van der Meer (VdM) configuration, where beam and machine parameters deviate significantly from those of standard physics operation. In nominal operation, we observe a discrepancy between measured emittance growth and predictions based on IBS and SR alone. In contrast, in VdM configurations, simulations and measurements show good agreement, suggesting a reduced sensitivity to external excitations in this regime.

## SIMULATION SETUP

This section describes the methodology used to evaluate horizontal emittance growth at top energy with  $\beta^* = 120$  cm in Interaction Points 1 and 5 (IP1 and IP5). This is the first step of the luminosity levelling process in the LHC, where the optical  $\beta$ -functions at the IPs is dynamically changed during the fill to ensure constant luminosity. At this stage, the beams are colliding head-on with the maximum bunch intensity, which then decreases due to burn-off. All simulations are performed in this configuration as it corresponds to the case with the largest head-on tune spread, and thus it is expected to be most sensitive to the impact of power supply ripple.

The analysis workflow consists of three main steps:

- Extraction of calibrated spectrum of horizontal turn-by-turn beam oscillations from measurements.
- Including modulated dipolar kicks in the simulations to reproduce the measured spectrum.
- Element-by-element tracking simulations including beam-beam effects and noise.

## Experimental Data

The data used to reproduce the noise in simulations were obtained from a calibrated beam position monitor, namely the ADTObBox [3]. It consists of four high-sensitivity pickups measuring turn-by-turn, bunch-by-bunch transverse centroid beam motion.

The LHC revolution frequency is 11245.5 Hz. In order to resolve frequency components beyond the Nyquist limit of a single observation point, multiple observation points are required. This is achieved using a method previously introduced in [4], where individual bunches are treated as independent observation points. After correcting for the betatron phase advance between bunches, the signals can be combined, effectively extending the observable frequency range from  $\approx 5.5$  kHz up to  $\approx 11.2$  kHz (revolution frequency).

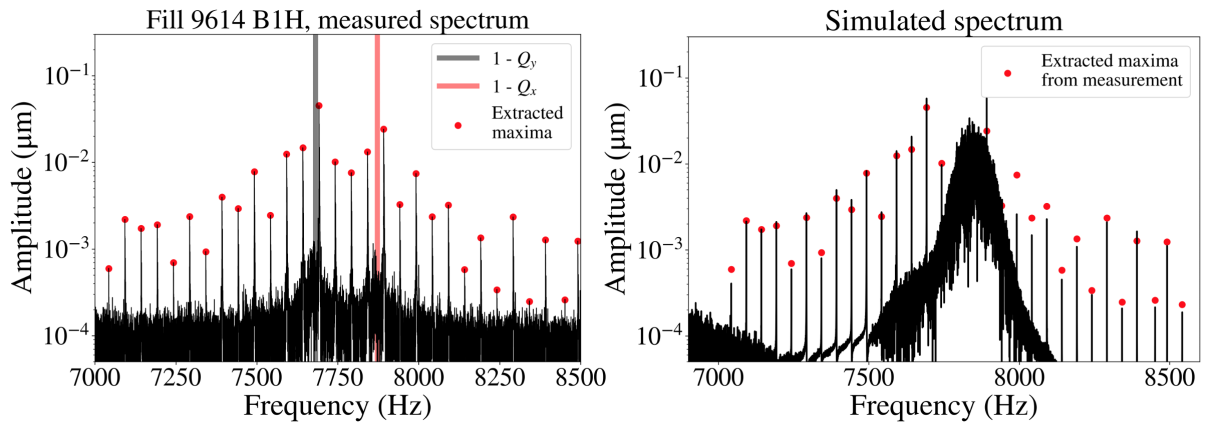


Figure 1: Left: Calibrated horizontal spectrum from ADTObSBox during collisions. The red points are the extracted amplitudes. Right: Result from tracking simulation with the inclusion of realistic noise excitations.

Using this method, a calibrated transverse excitation spectrum is obtained, as shown in Fig. 1 (left). The dominant features correspond to harmonics clustered around 8 kHz. The red markers indicate the extracted physical amplitudes of the individual harmonics, which we try to reproduce in simulations.

### Conversion to a Dipole Kick

The measured transverse oscillation amplitudes are converted into equivalent dipolar kicks that can be applied in tracking simulations. For this purpose, we use the analytical expression for a dipolar excitation [4]

$$|x_{max,N}| = \left| \frac{\beta \theta_p \sin(2\pi Q)}{2[\cos(2\pi Q_p) - \cos(2\pi Q)]} \right|, \quad (1)$$

where  $\beta$  is the optical  $\beta$ -function at the excitation location and observation point (they are chosen equivalent in this representation),  $\theta_p$  is the dipolar kick amplitude,  $Q$  is the betatron tune, and  $Q_p$  is the excitation frequency expressed in tune units.

It should be noted that this expression does not account for tune spread effects. In the presence of beam–beam interactions, the tune spread significantly modifies the excitation response. Consequently, an additional optimization of the effective kick amplitudes is performed to ensure that the simulated spectral response matches the measured one as best as possible.

### Tracking Simulations

Six-dimensional tracking simulations are performed using Xsuite [5] with the full LHC lattice. The simulations include beam–beam interactions.

As a first step, the excitation model is benchmarked by tracking one million particles for 100k turns. For each particle, a Fast Fourier Transform (FFT) of the transverse motion is computed, and the complex spectra are averaged over all particles to suppress statistical noise. The resulting averaged spectrum is shown in Fig. 1 right. The red markers represent the measured excitations and the black curve shows

the absolute value of the averaged complex FFT, where the broader peak is the result of the average beam–beam tune spread in the distribution. A sufficiently good agreement is observed between the measured spectrum (Fig. 1 left) and the simulated one (Fig. 1 right), validating the excitation model. The tracking simulations are then performed with 100k particles over one million turns to study the impact of the noise on the horizontal emittance growth.

Two operational scenarios are considered: VdM–type fill and a nominal physics fill. The two configurations differ in optics, intensity, and emittance, which results in different beam–beam induced tune spreads. In the VdM case, the measured emittance evolution is well described by the combined effects of IBS and SR. In contrast, the nominal physics fill exhibits a clear excess emittance growth. To quantify the origin of this discrepancy, frequency map analysis (FMA) is employed to characterize the tune spread and diffusion properties of the two configurations in the presence of noise.

## RESULTS

We compare the tune footprint and tune diffusion properties for two operational scenarios: a VdM fill and a nominal 2024 physics fill. The corresponding FMAs are shown in Fig. 2 (left and right, respectively). The nominal physics fill exhibits a significantly larger tune spread than the VdM configuration, due to stronger head-on beam–beam interactions. This enhanced tune spread increases the overlap of nonlinear resonances with the resonances excited by the power supply ripple, leading to stronger incoherent diffusion, as visible in the colormap. The vertical solid black lines represent the horizontal 50 Hz excitations. The observed difference in the two footprints points to a substantially different diffusion regime between the two configurations.

Additional tracking simulations are performed to evaluate the contribution of the 8 kHz noise cluster to the emittance growth shown in Fig. 3. Due to computational constraints associated with element-by-element tracking, the simulations are limited to  $10^6$  turns, corresponding to approximately 90 seconds of operation.

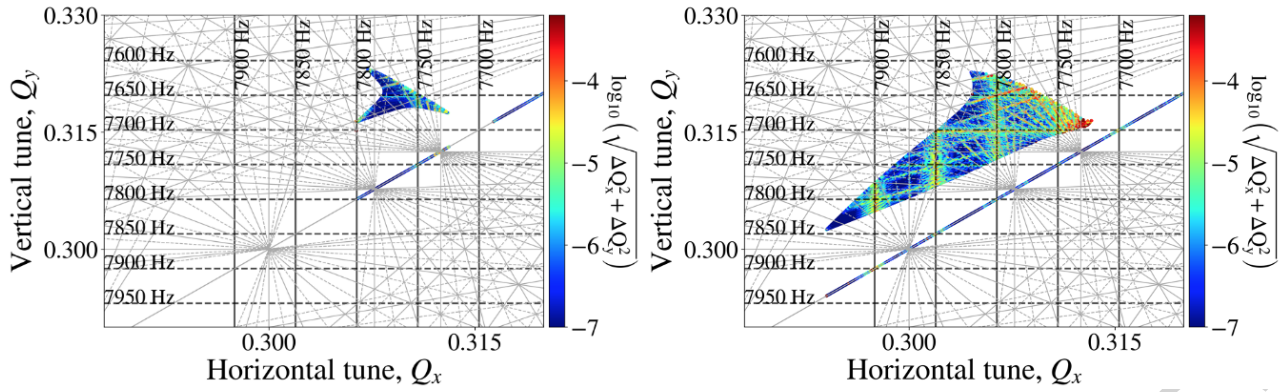


Figure 2: Left: FMA for a VdM fill. Right: FMA for a nominal 2024 physics fill. The x- and y-axis represent the horizontal and the vertical tunes, respectively. The horizontal and vertical lines represent the external excitation included in the simulation. The color code shows the tune diffusion rate on the corresponding particles.

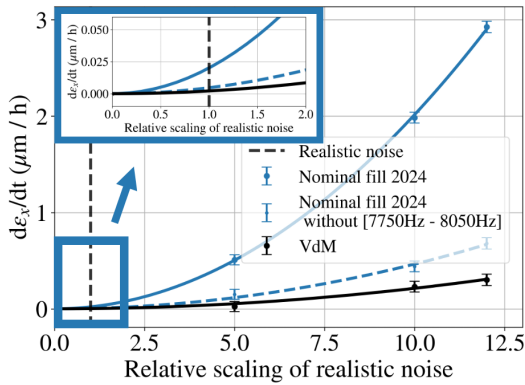


Figure 3: Simulated emittance growth induced by the 8 kHz excitation cluster during collisions. The x-axis shows the noise level scaled relative to the measured spectrum (Fig. 1), while the y-axis shows the emittance growth rate.

Dipolar noise is expected to induce emittance growth with a quadratic dependence on its amplitude [2]. The simulations therefore use scaled versions of the measured noise spectrum, with amplitudes scaled by a factor of up to 10, and a quadratic fit is then applied to the simulated emittance growth as a function of the scaled noise as shown in Fig. 3.

For the nominal physics fill, the extrapolated emittance growth (solid blue) reaches approximately  $\sim 0.02 \mu\text{m}/\text{h}$  (extracted from the intersection with the vertical black dashed line, representing the realistic noise), comparable in order of magnitude to the unexplained growth observed during 2024 operation.

A simulation without the noise harmonics in the 7750–8050 Hz range, corresponding to the harmonics in the vicinity of the  $1 - Q_x$  and overlapping most strongly with the tune spread, yields the emittance growth shown by the dashed blue curve, exhibiting a clear reduction in emittance growth. This confirms the central role of the 8 kHz noise cluster for emittance growth.

For the VdM configuration, represented by the solid black line, the predicted emittance growth is negligible, consistent

with the absence of discrepancies between measurements and the predictions from IBS and SR models.

## CONCLUSIONS AND OUTLOOK

The noise spectrum measured in turn-by-turn beam oscillations has been reproduced in tracking simulations. The simulations allow for a quantitative estimate of the contribution of power converter ripple and noise clustered around 8 kHz to the horizontal emittance growth in the LHC. During collisions, strong non-linearities, dominated by beam–beam interactions, significantly increase the tune spread. In this regime, the simulations indicate that external excitations can drive incoherent diffusion, leading to measurable emittance growth in the order of magnitude similar to what is observed in operation.

A significant reduction in the simulated emittance growth is observed when spectral lines in the vicinity of the tune are removed, which indicates that harmonics located close to  $1 - Q_x$  are primarily responsible for this emittance growth. In contrast, for VdM-type fills, where the tune spread is significantly smaller, the predicted emittance growth is negligible, consistent with observations and with expectations from IBS and SR models.

These results provide a consistent explanation for part of the excess emittance growth observed during LHC collisions beyond the expectations from IBS and SR alone. They highlight the critical interplay between external noise and non-linear beam dynamics in high-luminosity collider operation.

Future studies will focus on experimentally isolating the contribution of the 8 kHz cluster and identifying its underlying sources. A deeper understanding of these excitations and their mitigation could lead to improved control of emittance growth and enhanced luminosity performance in future LHC operation. Ongoing studies on the effect of the power converter active filters [1, 6], which are observed to enhance the amplitudes of the 8 kHz harmonics, are expected to provide further insight into their measurable contribution to the emittance growth during collisions.

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