EMITTANCE GROWTH STUDIES DUE TO CRAB CAVITY INDUCED AMPLITUDE NOISE IN THE SPS*

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Abstract

In the context of the HL-LHC upgrade, RF Crab Cavities (CCs) are one of the key components to achieve the target integrated luminosity. Due to the increased bunch intensity, the collider will operate with a large crossing angle scheme to alleviate the long-range beam-beam effect. The CCs will counteract the geometrical luminosity reduction factor coming from the large crossing angle. Amplitude and phase noise injected from the CC low-level RF control are known to induce transverse bunch emittance growth. This contribution presents measurements of emittance growth induced by amplitude noise, performed in the CERN Super Proton Synchotron (SPS). The measured emittance growth was found to be dependent on the amplitude detuning induced by the SPS octupoles, although no dependence was predicted by the available theories and models. In this paper, the measurement results will be presented and compared with tracking simulations.

INTRODUCTION

After more than 10 years of operation [1], the LHC will be upgraded to the High Luminosity LHC (HL-LHC) [2], which is expected to start beam operation in 2029. The aim is to increase the integrated luminosity by one order of magnitude with respect to the current LHC operational scenario, totalling ~ 3000 1/fb over its lifetime (about 12 years). To achieve this result a doubling of the bunch intensity (from 1.15 to 2.2×10^{11} protons) and a reduction of β^* to 15 cm is needed. This particular configuration would cause critical long-range beam-beam (LRBB) effects [3]. Their detrimental effect can be alleviated by deploying a large crossing angle scheme ($\frac{\theta_c}{2} = 250\,\mu\text{rad}$). The installation of 4 CCs [4] per beam and per IP will restore the geometrical luminosity loss in the two main experiments, ATLAS and CMS. In addition, the CCs will lengthen the longitudinal luminous region during the whole luminosity levelling process, and effectively reduce the longitudinal pile-up density of the collisions [5].

Each CC imparts a longitudinal dependent dipolar kick in the plane of the beams crossing (horizontal in ATLAS and vertical in CMS), coupling the longitudinal plane to the transverse plane. Due to amplitude and phase noise coming from the CCs low-level RF (LLRF) [6], this coupling can lead to a transverse emittance blow-up, $\frac{d\epsilon}{dt} = \dot{\epsilon} > 0$ [7].

The theoretical relationship between $\dot{\epsilon}$ and phase and amplitude noise in the CCs has been developed in [8]. If $S_{\Delta A}$ [Hz^{-1}] is the Power Spectral Density (PSD) of the amplitude noise across all the synchro-betatron lines, we can obtain the following estimates:

$$\dot{\epsilon} = \beta_{\text{CC}} \left(\frac{eV_{\text{CC}} f_{\text{rev}}}{2E_b} \right)^2 C_{\Delta A} \sum_{k=-\infty}^{+\infty} S_{\Delta A}\left((k \pm \bar{\nu}_b \pm \bar{\nu}_s) f_{\text{rev}} \right), \tag{1}$$

where β_{CC} is the β function at the location of the CC, e is the proton's charge, V_{CC} the CC voltage, f_{rev} the revolution frequency of the bunch, E_b the bunch energy and $\bar{\nu}_b$ and $\bar{\nu}_s$ the mean of the betatron and synchrotron tune distribution. The factor $C_{\Delta A}$ is introduced in order to take into account the bunch length and is defined as:

$$C_{\Delta A}\left(\sigma_\phi\right) = e^{-\sigma_\phi^2} \sum_{l=0}^{+\infty} I_{2l+1}\left(\sigma_\phi^2\right) , \tag{2}$$

with σ_ϕ the r.m.s. bunch length (in radians) w.r.t. the CC frequency f_{CC} and $I_n(x)$ the modified Bessel function of the first kind.

An intuitive interpretation of the model is the following: a linear growth of ϵ is expected as a function of the PSD. The series does not diverge because of two concurrent reasons: first, a CC is a resonator tuned at the kHz level, therefore the power decreases rapidly away from $f_{\text{CC}} \sim 400$ MHz, and secondly the bunch samples the noise only at the synchro-betatron lines so that the whole series can be reduced to 4 finite terms, i.e. $S_{\Delta A}(0 + \bar{\nu}_b + \bar{\nu}_s)$, $S_{\Delta A}(0 + \bar{\nu}_b - \bar{\nu}_s)$, $S_{\Delta A}(0 - \bar{\nu}_b + \bar{\nu}_s)$, $S_{\Delta A}(0 - \bar{\nu}_b - \bar{\nu}_s)$. The $C_{\Delta A}\left(\sigma_\phi\right)$ is a monotonic function equal to 0 for a bunch length $\sigma_\phi = 0$, that increases with σ_ϕ to a maximum of ~ 0.25, leading to head-tail motion in the bunch. In this study, a value of $C_{\Delta A} = 0.12$ is assumed.

Effect of the Beam Coupling Impedance on $\dot{\epsilon}$

The analytical model in [8] does not include the effect of the beam coupling impedance to obtain the expected $\dot{\epsilon}$. The experimental campaign on phase noise showed a dependence of the measured $\dot{\epsilon}$ on octupole strength and thus on the incoherent tune spread, which could be reproduced in simulations afterwards [9]. In Ref. [10], it was shown that the $\dot{\epsilon}$ induced by the CC phase noise can be suppressed by the beam coupling impedance, when the coherent motion of mode 0 (dipole oscillations) is separated from the incoherent spectrum, a condition that is valid for the SPS CC experiments. This mechanism was clearly visible in simulations, by incorporating the SPS transverse impedance model in PyHEADTAIL [11, 12].

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The $\dot{\epsilon}$ as described in [8] is restored for appropriate values of incoherent tune spread (e.g. amplitude detuning induced by the octupole circuit). With amplitude noise, where a mode 1 (head-tail) motion is induced, this behaviour was not expected and indeed in [9] the simulations do not predict a dependence on the tune spread.

This work aims to complement, with the experimental study of CC amplitude noise in the SPS, these previous studies that mainly focused on phase noise. The aim is to test the model of Eq. (1), and in particular if there is a dependence of the emittance growth on the tune spread in the case of amplitude noise.

EXPERIMENTAL MEASUREMENTS

General Setup

The experimental setup is the one used previously for the phase noise studies [9]: a low intensity bunch with 3×10^{10} protons stored at a constant energy of 270 GeV/c. The ”Q26” optics [13] with $(Q_x, Q_y) = (26.13, 26.18)$ is used. A single vertical CC is active during the measurement campaign.

During the experiment, two main nonlinearities are present: the sextupoles to provide a positive chromaticity value of $Q' \approx 1$ in order to stabilise the beam, and the Landau octupoles for amplitude detuning (LOD) [14]. The LOD strength was varied to probe the validity limit of Eq. (1).

The PSD was measured by a signal noise analyzer, which provides the single sideband measurement with respect to the carrier (the CC resonant frequncy) in dBc/Hz to be converted to Hz^{-1} following the definitions in [15]. In the experimental condition, the PSD was -104 dBc/Hz, that is 4×10^{-11} Hz^{-1}. During the measurement, the phase noise level was kept at least 10 dB lower than the level of the amplitude noise (amplitude noise dominated regime). Finally, the noise extends in the frequency domain to well above 10 kHz, so that the first betatron sideband at ~ 8 kHz is excited.

Measurements

In this section, the experimental protocol will be described. A given amplitude noise level is injected in the CC for about 10 minutes, while the low-intensity bunch is circulating in the SPS with constant energy. During this time, the emittance is measured every ~ 30 seconds. The bunch is then dumped and a new measurement begins.

During the previous studies wire scanners (WS) [16] were used to obtain the transverse distribution information, but at the time of this study they were not available. The Beam Synchrotron Radiation Telescopes (BSRTs) [17] was used as diagnostic device to characterize the vertical bunch profile. A dedicated configuration of the BSRTs was used to minimize the uncertainty on the measured ϵ_y: a set of several hundreds of consecutive transverse measurements of the bunch are provided, which can then be fitted with a Gaussian distribution and averaged to obtain the ϵ_y at a particular time. These consecutive measurements are taken within several microseconds, a window reasonably small to assume that the emittance remains constant during the time of the measurement, as shown in Fig. 1. Several of these measurements are then used to perform a linear fit and extract the $\dot{\epsilon}$, as shown in Fig. 2 to be compared with Eq. (1). Thanks to its precision, the large set of measurements, and the negligible vertical dispersion at its location, the BSRT was able to measure the evolution of the beam transverse distribution quite accurately.

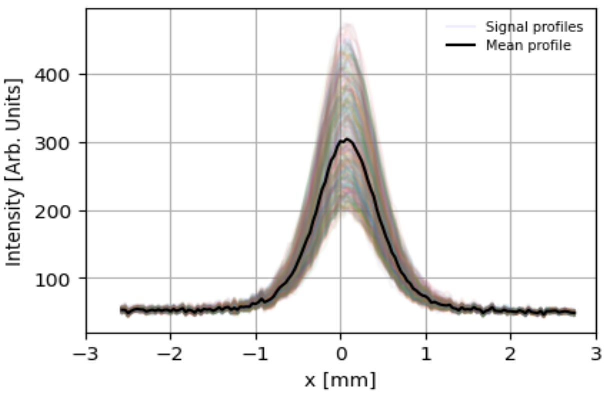

Figure 1: BSRT profiles measured during a single acquisition. A Gaussian fit is performed to each profile and the average variance is extracted. Note that the large variation in the amplitude of the profiles is due to a periodic variation of the shutter in front of the CCD camera recording the synchrotron light image.

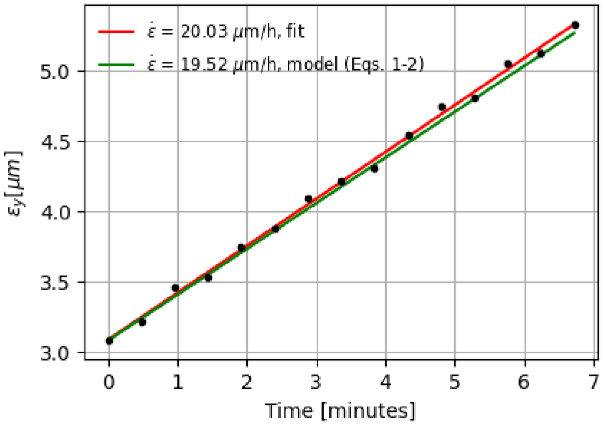

Figure 2: Emittance evolution during a single fill with amplitude noise injected in the CC at $S_{\Delta A} = 4 \times 10^{-11}$ Hz^{-1}.

RESULTS

The measurements carried out in the SPS in 2023 are summarized in Fig. 3. A clear dependence of the $\dot{\epsilon}$ induced by amplitude noise in the CC is observed as a function of the octupole strength (and thus of the incoherent tune spread). This dependence was not expected from the simulation model previously developed in [9].

In order to investigate this phenomenon, a new simulation model based on a thin lens lattice has been developed. It

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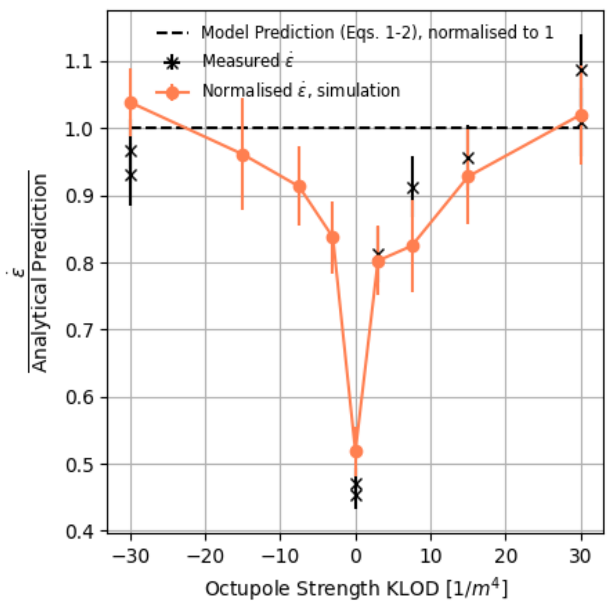

Figure 3: $\dot{\epsilon}$ normalised to the analytical prediction as a function of the octupolar strength in the LOD circuit. Data points (black) reveal a dependence that can be explained by the full lattice with wakefields (orange).

has been implemented using the tracking tool Xsuite [18, 19]. Collective effects coming from the beam coupling impedance were included in the simulations by leveraging on the PyHEADTAIL interface available in the tracking tool, which allows the definition of wakefields and the calculation of their turn by turn effect on the bunch. By varying the octupole strength [13] in the simulations, we reproduced the scan performed during the measurement. A CC element is added to the lattice at the location of the real installation, where $(\beta_{\mathrm{CC},x}, \beta_{\mathrm{CC},y}) \sim (30\ \mathrm{m}, 78\ \mathrm{m})$. The noise in the CC is modeled as a uniform frequency spectrum produced from a Gaussian distribution with $\mu = 0$ and $\mathrm{Var} = S_{\Delta_A}$, for the phase and amplitude noise, respectively. This assumption is justified by the measurements from the spectrum analyzer that show a flat noise distribution until well above the first betatronic line. The new simulation was benchmarked against the PyHEADTAIL simulation of the previous measurements concerning phase noise, showing perfect agreement between the two. Three main transverse impedance [20] sources are taken into account: the wall impedance, the SPS kickers and the steps of the vacuum chamber transition. Both dipolar and quadrupolar components are taken into account. Studies including the impedance of the main fundamental mode of the CC were also performed, showing that no significant effect was present for the purpose of this analysis. Each of the sources is included as an element in the line that acts on the bunch by a kick that is both decaying with time over several turns and that is weighted with the β-function at the location of the line where the source is positioned. The bunch under study has a Gaussian distribution in all transverse coordinates and is matched longitudinally to the non-linear RF bucket. The $\dot{\epsilon}$ obtained in a single simulation is subject to fluctuations due to the limited amount of particles that can be tracked within a reasonable amount of time. To solve this problems multiple parallel simulations are performed on GPU on the same lattice with different sets of particles and the average between different simulations is taken as a measure of the $\dot{\epsilon}$. In this study, 100k particles per simulation are tracked for 50k turns, and each simulation is repeated 20 times to take the average. The results of the Xsuite simulations are also reported in Fig. 3 (orange). The results obtained with this new simulation model are in very good agreement with the measurement data and show the observed dependence of the emittance growth induced by CC amplitude noise on the tune spread. At this moment it is not clear why this dependence is not observed in the simulation model previously developed in PyHEADTAIL. A possible answer to this discrepancy between the two simulation models is to be found in the linearization of the longitudinal motion used in the studies in [9] w.r.t. the non-linear RF bucket included in the new simulations. To test this hypothesis the voltage of the main RF can be doubled and its frequency halved in the Xsuite simulation to linearise the map at constant $\tilde{\nu}_s$, Eq. (1). This and other tests are currently being performed to understand the source of discrepancy.

CONCLUSIONS AND FUTURE DEVELOPEMENTS

In 2023, a new campaign of measurements of emittance growth induced by amplitude noise was performed. The BSRT monitor allowed to reach an unprecedented precision on this kind of measurement thanks to the high statistics used to calculate each point. A scan in the octupoles strength of the SPS lattice has been performed, revealing a dependence of the emittance growth on the octupoles setting. This was not expected by the intially available models. A new simulation was developed with a thin lens model in Xsuite. This allowed to reproduce the newest experimental results on the amplitude noise while also reproducing the phase noise simulations and experimental results in the SPS. Several tests are now being performed to point out the main contribution to the discrepancy between the previous simulation models and the experimental data.

The study presented here can serve as a foundation for at least two directions of research: (I) the collected set of BSRT's measurement allow to not only study the emittance of the bunch but also how its distribution evolves in time. By using q-Gaussian fits [21] one can monitor the evolution not only of the emittance but also of the q-parameter. These results can be used to benchmark the tracking of q-Gaussian transverse profiles [22]; (II) in 2025 a horizontal CC will be installed in SPS and a new campaign of measurements will begin. These newly developed simulation tools can guide the analysis and studies that will follow.

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