SUPPRESSION OF CRAB CAVITY NOISE INDUCED EMITTANCE GROWTH BY TRANSVERSE BEAM COUPLING IMPEDANCE*

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Abstract

Crab cavities are a key component of the High Luminosity LHC (HL-LHC) upgrade, as they aim to mitigate the luminosity reduction induced by the crossing angle. Two superconducting crab cavities (CCs) were installed in the Super Proton Synchrotron (SPS) at CERN in 2018 to demonstrate their operation in a proton machine for the first time. An important point to consider is the transverse emittance growth induced by noise in the CC RF system. During a first experimental campaign in 2018, the measured emittance growth was found to be a factor of 4 lower than predicted by analytical models. In this paper, the effects of transverse beam coupling impedance on emittance growth driven by CC RF noise are presented and the results of the second experimental campaign, which took place in the SPS in 2022, are discussed.

INTRODUCTION

Crab cavities (CC's) are key components for achieving the luminosity goals in HL-LHC, in particular to optimize the luminous region in the detectors [1]. Transverse emittance growth due to noise in the CC RF system [1]is a concern, as it degrades luminosity [3]. In order to define the specifications for acceptable noise levels for the design of the HL-LHC CC RF system, an analytical formula predicting the transverse emittance growth caused by such noise has been derived and validated through HEADTAIL simulations [4]. However, to gain confidence in the validity of the theoretical model benchmark against experimental data was deemed necessary.

During a dedicated experiment that took place in the SPS in 2018 with the prototype CCs, the measured emittance growth was found to be a factor four (on average) lower than expected from the theory [5]. The reason for this discrepancy remained unresolved for some time, as detailed studies excluded the possibility that the discrepancy is a result of some error in the analysis of the experimental data or the actual level of noise in the CCs.

It was recently found that the transverse beam coupling impedance, which is not included in the above mentioned theory, may impact the noise-induced emittance growth and may therefore explain the experimental observations. In particular, PyHEADTAIL [6] simulations including the accurate SPS impedance model [7] demonstrated that the noise-induced emittance growth is suppressed by about a factor four for the experimental machine conditions [5]. In this paper, the damping mechanism from the transverse impedance is discussed and the measurements that took place in 2022 in the SPS aiming to validate the impedance as the source of the discrepancy are presented.

EMITTANCE GROWTH FROM CRAB CAVITY NOISE AND SUPPRESSION FROM BEAM COUPLING IMPEDANCE

Amplitude and phase noise in the CCs result in emittance growth through decoherence. The noise generates momentum kicks which drive betatron oscillations of the particles. If the noise spectrum overlaps with the betatron tune distribution, the betatron oscillations can reach large amplitudes which translate the oscillations to emittance growth [4, 8].

The impact of CC amplitude and phase noise to bunch motion can be different. In particular, the momentum kicks from amplitude noise are out of phase by 90° from the phase noise kicks [4]. Given that in its usual operational mode the CC RF wave has its zero crossing at the longitudinal bunch center, amplitude noise kicks the head and the tail of the bunch in opposite transverse directions, resulting in intra-bunch (head-tail) oscillations. On the other hand, the phase noise induces mostly a centroid shift of the bunch, corresponding to a dipole mode, in which the transverse oscillations at each point along the bunch are in phase.

Emittance growth suppression mechanism

PyHEADTAIL simulations including the SPS impedance model [7] revealed that decoherence of the dipole oscillations and thus the phase-noise-induced emittance growth is suppressed once the coherent betatron tune is shifted outside of the incoherent tune spectrum. A similar effect of decoherence suppression was studied in the past [9–12] in the context of beam-beam modes. It was shown that when the coherent tune is outside the incoherent spectrum only part of the energy from the noise kick drives incoherent motion, resulting in irreversible emittance growth, while the rest of the energy from the noise kick is absorbed by the coherent mode, which can be damped. By separating the coherent and incoherent tunes, transverse impedance leads to an effective suppression of phase-noise-induced emittance

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* Work supported by the HL-LHC project and partially by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC-0019287

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[1] Past studies with CC RF noise performed in KEKB with leptons can be found in Ref. [2].

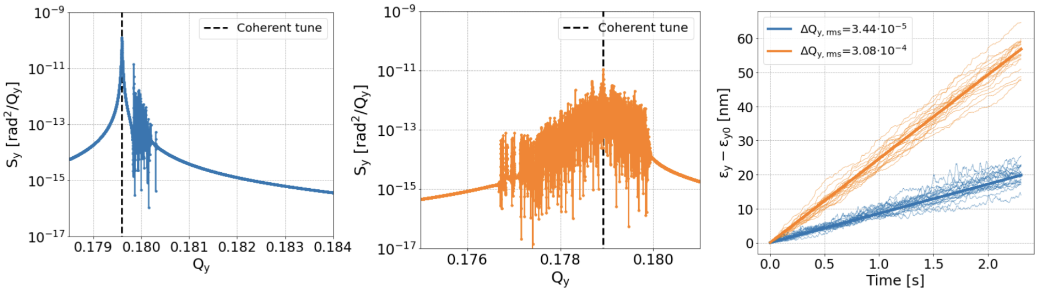

Figure 1: Frequency spectrum of the vertical bunch centroid motion for the SPS tests, calculated over 10^6 turns with $5 \cdot 10^4$ macroparticles for $Q_{y,rms} = 3.44 \cdot 10^{-5}$ (left) and $Q_{y,rms} = 3.08 \cdot 10^{-4}$ (center). Emittance growth due to CC phase noise (right) for the two different values of $Q_{y,rms}$. The emittance increase for $Q_{y,rms} = 3.44 \cdot 10^{-5}$ is significantly smaller.

growth. Recently, this approach was adapted for configurations featuring linear detuning and a complex tune shift from a collective force, supporting the simulation results [13].

The emittance growth suppression from transverse impedance was studied with PyHEADTAIL simulations for the parameters used during experiments in the SPS, as shown in Table 1. It is important to note that during the 2018 experiments the Landau octupoles in the SPS were switched off. However, intrinsic non-linearities in the machine lead to a residual rms tune spread estimated to be $\sim 3 \cdot 10^{-5}$ [5]. Therefore, for the emittance growth experiments in the SPS at 270 GeV with $3 \cdot 10^{10}$ protons per bunch, the small tune shift of $\sim 3 \cdot 10^{-4}$ from the transverse impedance is sufficient to move the coherent mode out of the incoherent spectrum. This is illustrated in Fig. 1 (left), which shows the vertical spectrum of the centroid (coherent) oscillation of a bunch as simulated with PyHEADTAIL. The initial bunch was generated with Gaussian distributions in transverse and longitudinal planes and an initial vertical offset of 0.2 times the vertical beam size. The bunch population of $3 \cdot 10^{10}$ particles was represented by $5 \cdot 10^4$ macroparticles and tracked for 10^6 turns. The frequency spectrum of the centroid was obtained from Fourier analysis of the turn-by-turn centroid motion. It is evident that the coherent mode is outside of the incoherent spectrum. The simulation was repeated for a larger value of rms tune spread, $3 \cdot 10^{-4}$ which is achieved by introducing additional amplitude detuning. For this case (Fig. 1, center), the coherent tune lies within the incoherent spectrum.

Table 1: Parameters in the SPS CC emittance growth studies.

Parameters	**Values**
Beam energy, E	270 GeV
Vertical tune, Q_y	26.18
Chromaticity, Q'_x, Q'_y	~0.5, ~0.5
Vertical beta function at CC, $\beta_{y,CC}$	76.07 m
CC voltage and frequency, V_{CC} / f_{CC}	1 MV / 400.8 MHz
R.m.s. bunch length, σ_{rms}	1.83 ns

The emittance growth due to phase noise is simulated for the same set of parameters and the results are shown in Fig. 1 (right). In this simulation $5 \cdot 10^5$ macro-particles were used and the tracking was performed for 10^5 turns. Twenty simulation runs were conducted, to reduce the uncertainty of the results, for a white phase noise with power spectral density of $1.68 \cdot 10^{-10}$rad^2/Hz. The noise power is much higher than in reality to get significant emittance growth during the course of the simulation. The emittance growth over the course of the simulation is comparable to that during a coast though. The emittance evolution in each run is shown in Fig. 1 with thin lines. The emittance growth rate was found from a linear fit. The mean growth rate is computed over all runs and is shown for two different cases of incoherent tune spread by the thick lines in Fig. 1. The emittance growth rates for the rms tune spreads of $3 \cdot 10^{-5}$ and $3 \cdot 10^{-4}$ were found to be 10 nm/s and 25 nm/s respectively. These results indicate a clear suppression of the emittance growth for the case where the coherent mode lies outside of the incoherent spectrum.

Sensitivity to amplitude-dependent tune shift

The preceding analysis suggests that the suppression of the emittance growth as a result of the transverse impedance depends on the tune spread resulting from amplitude detuning. This dependence was studied with PyHEADTAIL, following the procedure described above for the emittance growth simulations. The simulation was repeated for a large range of amplitude detuning coefficients used to represent the detuning that would result from use of the SPS Landau octupoles. The focus is on the vertical plane, since the SPS CC's provide vertical deflections.The results are shown in Fig. 2, where the lower horizontal axis shows the equivalent octupole strength of one family of Landau octupoles (that affects mainly the vertical detuning), and the upper horizontal axis shows the corresponding rms tune spread for the initial transverse emittance of the beam. Without wakefields, the emittance growth rates agree (within the errorbars) with the values predicted from the theoretical model, independent of the tune spread. With wakefields included, a suppression of the emittance growth is observed and indeed depends on the overlap of the incoherent tune spread with the coherent tune.

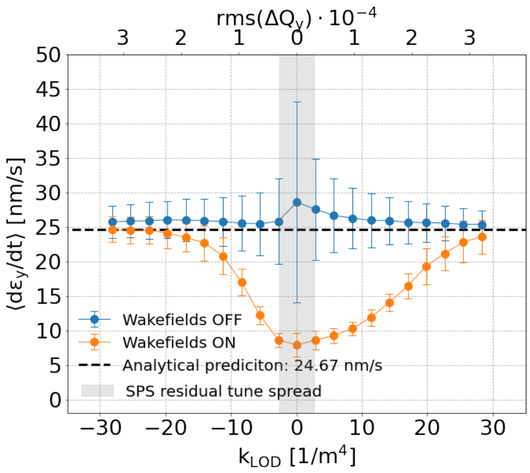

Figure 2: Simulated emittance growth due to CC phase noise with and without impedance effects for different values of vertical tune spread introduced by the Landau octupoles.

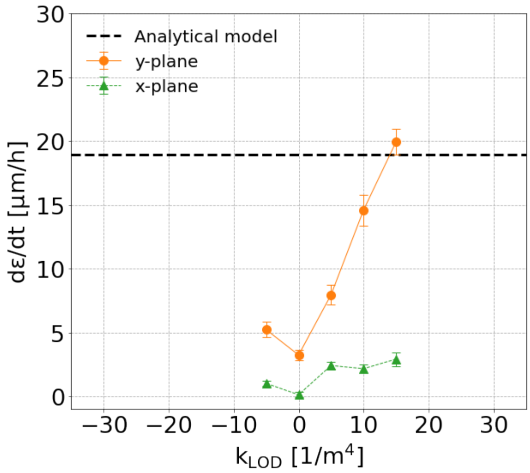

Figure 3: Measured emittance growth for different octupole settings. The growth predicted from the analytical model without taking into account the impedance induced emittance growth suppression is ~ 19 m/h.

EXPERIMENTAL STUDIES 2022

Another experimental campaign took place in SPS in 2022 to investigate effects of impedance and amplitude detuning on emittance growth from CC phase noise. Achieving a good understanding of the 2018 results is essential for developing confidence in the theoretical model and its predictions for the HL-LHC. The emittance growth measurements in 2022 were performed following the same procedure as in 2018 [5] and for very similar machine and beam conditions, as listed in Table 1.

The CC noise was a mixture of phase and amplitude noise, however the contribution of amplitude noise to the total emittance growth was insignificant (about 6%). The phase noise was applied on the first betatron line only, with a power spectral density of $3.4 \cdot 10^{-11}\mathrm{rad}^2/\mathrm{Hz}$. Different octupole settings were tested with the aim of reproducing the behavior shown in Fig. 2. In the limited time available for the measurements, only five different octupole strengths could be used, $\mathrm{k_{LOD}} = \pm 5\ \mathrm{m}^{-4}$, $10\ \mathrm{m}^{-4}$ and $15\ \mathrm{m}^{-4}$; the last value of octupole strength is expected to restore the growth rate to almost the values predicted from the theoretical model [4]. For each setting the bunch evolution was recorded for about 30 minutes by acquiring repeated wire scanner measurements and then performing a linear fit. For the measurements of each setting a fresh bunch was used. The results are summarised in Fig. 3.

The background emittance growth observed in the SPS without any noise injected in the CC ($d\epsilon_x/dt = 0.81$ m/h and $d\epsilon_y/dt = 0.84$ m/h) is subtracted from the measured values. Even though past studies [5] considered the total measured emittance growth given by $d\epsilon_y/dt + d\epsilon_x/dt$ to account for coupling effects, in 2022 measurements the growth in the horizontal plane seems independent from the growth in the vertical.

Figure 3 shows a clear dependence of the measured vertical emittance growth rate on the octupole strengths which is qualitatively close to what is expected from the simulations. However, there is some uncertainty about the level of quantitative agreement. In particular, the measured emittance growth for the large octupole strength appears already in agreement with the analytical prediction within the errorbars. Further measurements are needed for more octupole settings to check the full dependence on amplitude detuning.

The experimental results of 2022 demonstrate that impedance effects indeed suppress the emittance growth induced by CC phase noise and seem to explain the experimental observations of 2018. However further studies are needed towards better quantitative agreement between measurements and simulations.

CONCLUSIONS AND FUTURE PLANS

During the SPS CC tests in 2018, it was found that theoretical calculations of the transverse emittance growth from CC RF noise overestimated the measurements by a factor 4. Simulations with PyHEADTAIL indicated that the discrepancy might be explained by impedance effects, in particular when the coherent tune is shifted outside of the incoherent spectrum. The simulations also indicated a strong dependence on amplitude detuning: this was tested experimentally in the SPS in 2022. The results show good qualitative agreement with the expected impact of impedance and amplitude detuning: they represent a proof of concept for the mechanism of emittance growth suppression from transverse impedance.

Further dedicated experiments in the SPS are planned, and aim at refining the experimental observations by varying the octupole strengths over a larger range, investigating the impact of linear chromaticity and the sensitivity to transverse instabilities. Finally, the understanding developed from these studies will be applied to the HL-LHC, in order to characterize the long-term emittance evolution and to define limits on the acceptable noise levels for the CC's.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEOZSP2

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