EMITTANCE GROWTH WITH CRAB CAVITY AND DAMPER NOISE IN LHC*

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Abstract

Strong-strong beam-beam simulations are employed to investigate the noise sensitivity of the emittance in the future High Luminosity (HL)-LHC. Noise in the accelerator causes fluctuations of the bunch centroids at the interaction points (IPs) which cause emittance growth for large beam-beam parameters. Two noise sources are examined: crab cavities and the transverse damper. The damper noise is adjusted to bring simulations in agreement with an emittance measurement in a past LHC run. Results from simulations with HL-LHC beam parameters using different CC noise levels, damper gains and working points are discussed.

INTRODUCTION

Crab cavities (CCs) are an essential part of LHC's High Luminosity Upgrade. However, crab cavities may have a detrimental impact on the beam quality due to imperfections. While the development of the cavities is ongoing, computer simulations are carried out to assess side effects on the beam quality. Phase noise in the CCs leads to a fluctuation of the bunch position at the interaction point, which causes emittance growth. Simulations have been done to assess the implications for the LHC[1, 2], but changing HL parameters demand new simulations.

The emittance's sensitivity to noise depends on the damping of excitation. Non-linearities, in particular due to the beam-beam force, damp coherent excitations by virtue of Landau damping. This damping mechanism results in emittance growth, though. An active transverse damper can ideally damp a coherent motion without interfering with the emittance. But in reality the finite accuracy of beam position measurements adds its own noise to the beam, which promotes emittance growth [3]. Therefore the final emittance growth depends on the CC noise, the pick-up noise, damper gain and beam parameters.

In this paper we present simulations accomplished using BeamBeam3D [4], with CCs, white CC noise and a noisy transverse damper. In the next section, we briefly describe the damper and CC noise model. The following section is dedicated to simulation settings and results.

DAMPER AND CC NOISE MODEL

The original feedback algorithm of LHC's transverse damper was implemented in BeamBeam3D [5]. The measured offsets are processed by a Hilbert notch filter. Based on 7 earlier position measurements, the correction kick is calculated by

$$\Delta \bar{x}'_n = \frac{a_0 g}{\sqrt{\beta_p \beta_k}} \sum_{m=1}^{7} H_m(\varphi_H) \times (\bar{x}_{n-d+1-m} - \bar{x}_{n-d-m}), \tag{1}$$

where we introduced the gain g, the beta function at the pick-up β_p and at the kicker β_k, the Hilbert coefficients H_m, the phase of the Hilbert filter φ_H, and the delay d. Since the damper comprises two pick-ups and one kicker, the final correction kick is given by the superposition of both contributions. Figure 1 illustrates the damper layout.

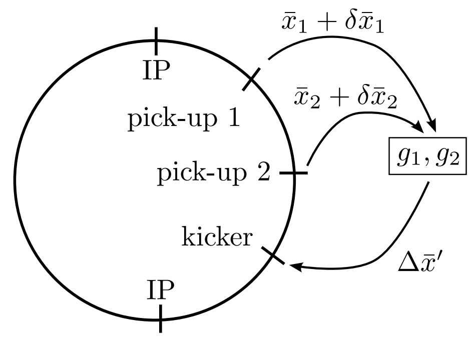

Figure 1: Scheme of the transverse damper.

The beam position measurement is considered the dominating noise source in the damper. In our model it is accounted for by substituting $\bar{x}_n \to \bar{x}_n + \delta\bar{x}_n$, with a random number $\delta\bar{x}_n$ of a Gaussian distribution, in Eq. 1.

The noise of the CCs was modeled as white noise on the phase which gives rise to an offset at the collision point. For a crossing angle θ_c, CC frequency ω_{cc} and a phase deviation $\delta\varphi$, the offset is given by

$$\delta\bar{x} = \frac{c\theta_c}{2\omega_{cc}}\delta\varphi, \tag{2}$$

where c is the speed if light.

SIMULATIONS

The emittance growth in dependence of the damper and CC noise was simulated for beams with HL parameters [6]. Here we show results for the 25 ns bunch spacing scenario. Results for the 50 ns bunch spacing scenario are discussed in Ref. [7]. For the purpose of luminosity leveling, the beta function at the IPs was increased to $\beta^* = 0.49$ m. CCs were fully compensating the crossing angle in all HL simulations.

As the measuring uncertainty of the damper's pick-ups is not precisely known, we simulated a LHC run from 2012

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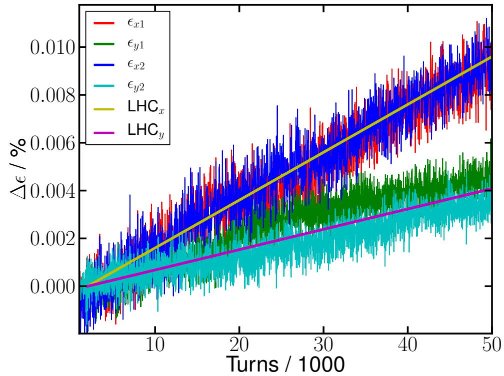

Figure 2: Simulated emittance growth in LHC in 2012. The straight lines visualize the measured emittance growth in the reference run in 2012.

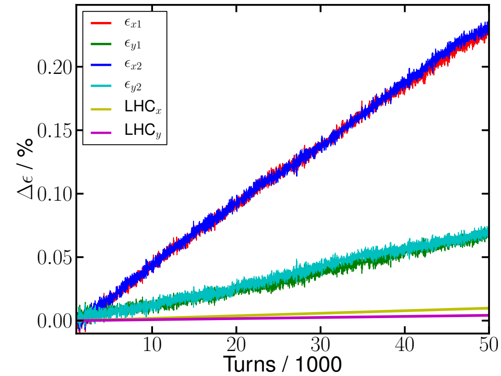

Figure 4: Emittance growth in the HL-LHC with CC noise only. The straight lines visualize the measured emittance growth in the reference run in 2012.

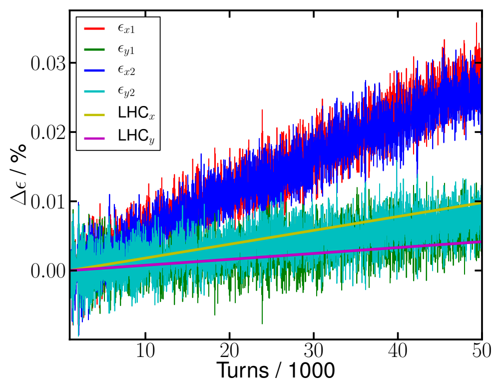

Figure 3: Emittance growth in the HL-LHC with pick-up noise only. The straight lines visualize the measured emittance growth in the reference run in 2012.

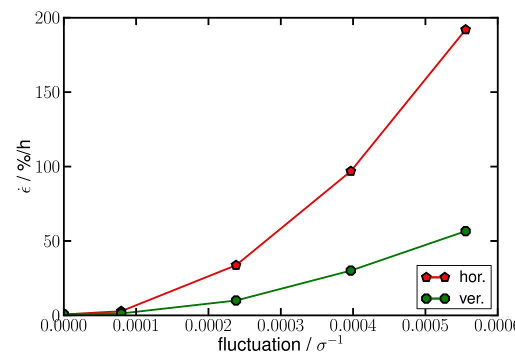

Figure 5: Emittance growth versus noise level on CC phase, average of both beams, expressed as offset at the IP relative to the local beam size.

as a reference and adjusted the noise level in the position measurement to reproduce the measured emittance growth. The good agreement of the simulation with the measurement can be seen in Fig. 2. For details about this procedure we refer to Ref. [7]. The resulting centroid fluctuation at the interaction point is about 0.11 μm horizontally and 0.09 μm vertically. The same pick-up noise was used in the HL simulations, unless specified differently.

The impact of the larger beam-beam parameter for the HL beams, $\xi = 0.021$ for two collisions, compared to $\xi = 0.016$ in our reference run from 2012, was examined in a simulation with the same pick-up noise as in previous simulations. For this purpose, CC noise was set to 0. The result is shown in Fig. 3. The horizontal and vertical growth rate are 22.7 %/h and 5.7 %/h, respectively, which clearly exceeds the numbers for the 2012 run (8.7 %/h and 3.5 %/h).

Starting to study CC noise, we first switched off the pick-up noise. The emittance versus time is shown in Fig. 4 for a noise level of $\delta\varphi = 0.2$ mrad, which is the estimated rms equivalent white noise level to the measured noise spectrum of LHC's acceleration cavities [8]. This noise level does *not* represent the expected noise level in the CCs. Lacking knowledge of the noise in the future CCs, we merely decided to use this number as an upper boundary for our study.

The emittance growth rate as a function of the the actual rms offset fluctuation at the IP is shown in Fig. 5. Note that this offset is not the excitation amplitude (calculated by Eq. 2) but the rms fluctuation of the bunch, which depends, in addition to the excitation by external noise, on the strength of the beam-beam kick, the damper gain and the tune. The rightmost data points in Fig. 5 correspond to the data shown in Fig. 4.

In all cases considered so far, the horizontal growth clearly exceeds the associated vertical growth. In simulations with the 50 ns bunch spacing parameters, a horizontal excitation of the beams by 7^{th} or 9^{th} order resonances was avoided by increasing the horizontal tune [7]. With the 25 ns parameters, however, the tune spread does not reach these resonances, as Fig. 6 reveals. The beam is clearly located in the domain of 10^{th} order resonances, though.

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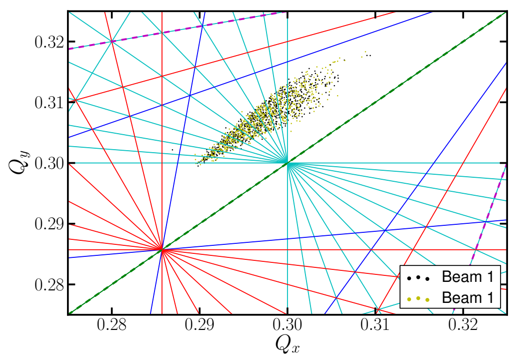

Figure 6: Tune footprint of HL beams. The cyan colored lines represent 10^{th} order resonances, red 7^{th} order, blue 9^{th} order and green 2^{nd} order.

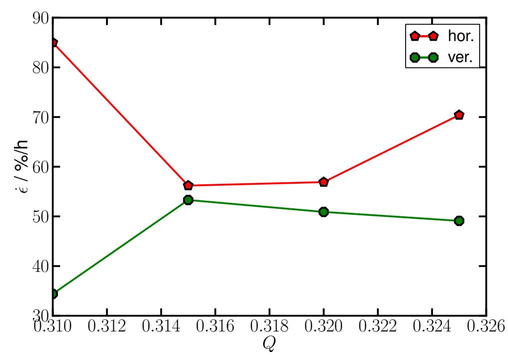

Figure 7: Horizontal and vertical emittance growth versus working point, average of both beams.

Increasing the horizontal tune towards the vertical tune should eliminate the x–y asymmetry by virtue of coupling. Simulations were done to see if the total growth of the transverse emittance would change. Figure 7 demonstrates that the horizontal and vertical emittance indeed approach each other when the horizontal tune comes closer to the vertical tune of 0.32, but the total growth is only mildly reduced. Increasing the working points in both planes in order to avoid the 10^{th} order resonance completely might yield better results. A similar experience was already made in LHC [9].

Another issue we addressed is the optimization of the gain. The results from a number of runs with CC noise only, and with CC noise and pick-up noise together, are presented in Fig. 8. Again, the CC noise level was 0.2 mrad. Obviously a larger gain suppresses emittance growth more effectively with an ideal damper, up to the largest gain we considered. With noise in the damper, the damping efficiency naturally suffers increasingly with increasing gain. Horizontally, the largest gain is still the best. Vertically, however, there is hardly a difference between $g = 0.1$ and $g = 0.3$ with a weak minimum in the middle. With a noisy damper and the chosen CC noise, the emittance growth cannot be pushed below 50 %/h.

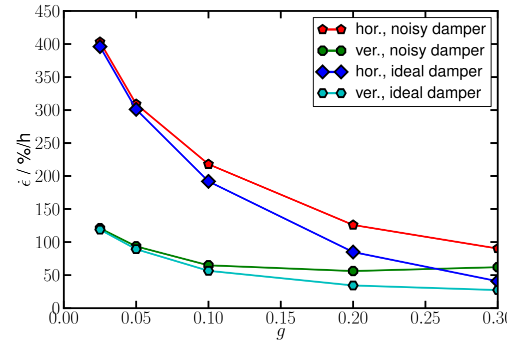

Figure 8: Horizontal and vertical emittance growth versus damper gain, with and without pick-up noise, average of both beams.

CONCLUSION AND OUTLOOK

Simulations with crab cavities and the damper have been carried out to investigate the emittance growth in the HL-LHC with the 25 ns bunch spacing due to noise. A very high sensitivity to white phase noise in the CCs was found. The damper was proven to mitigate the impact of noise, but its performance is limited, also by its own noise. If an acceptable growth rate can be achieved needs to be examined with a realistic CC noise model. The working point has a moderate importance in the range considered. Searching a better working point may be useful. Simulations will be continued and updated as the projected HL parameters change.

REFERENCES

[1] R. Calaga et al., TUPAS089, PAC07 Proceedings, Albuquerque, USA, 2012

[2] K. Ohmi at al., TUPAN048, PAC07 Proceedings, Albuquerque, USA, 2012

[3] Y. I. Alexahin,"On the emittance growth due to noise in hadron colliders and methods of its suppression", NIM A, 391, 1996

[4] J. Qiang et al., Journ. of Comp. Phys., 198, 2004

[5] S. Paret and J. Qiang, TUPPC091, IPAC2012 Proceedings, New Orleans, USA 2012

[6] O. Brüning and F. Zimmermann, MOPPC005, IPAC2012 Proceedings, New Orleans, USA, 2012

[7] S. Paret and J. Qiang, "Simulation of beam-beam induced emittance growth in the HL-LHC with crab cavities", Proceedings of ICFA Mini-workshop on beam-beam effects in hadron colliders (BB2013), Geneva, Switzerland, 2013

[8] P. Baudrenghien, "LLRF for crab cavities", 2nd Joint HiLumi LHC-LARP Annual meeting, 2012, Frascati, Italy

[9] S. Paret and J. Qiang, TUPME060, IPAC2013 Proceedings, Shanghai, China, 2013