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STRONG-STRONG BEAM-BEAM SIMULATION FOR LHC UPGRADE*

J. Qiang#, S. Paret, LBNL, Berkeley, CA94720, U.S.A.
G. Arduini, T. Pieloni, CERN, Geneva, Switzerland
J. Barranco, EPFL, Lausanne, CH-1015, Switzerland

Abstract

The LHC upgrade will significantly improve the performance of the current LHC operation with higher collision energy and luminosity. In the paper, we report on progress in the strong-strong beam-beam simulation of the HL-LHC upgrade with crab cavity compensation. We will present the study of the effects of crab cavity phase errors, accelerator working points, and potential dipole noise, on colliding beam emittance growth rate.

INTRODUCTION

The High Luminosity (HL) LHC upgrade [1], aims at a tenfold increase (3000 fb^{-1}) of the integrated luminosity by 2035 as compared to its initial goal (300 fb^{-1}). This will be achieved by an increase of the instantaneous luminosity by almost an order of magnitude and therefore we expect the electromagnetic interaction (i.e. beam-beam effects) to become stronger. It is important to evaluate the potential impact of these effects on the beam quality (e.g. emittance) in the high luminosity upgrade. In the HL-LHC upgrade, crab cavities (CCs) are proposed to compensate geometric luminosity loss during the crossing angle collision and to improve the overlapping of the beams at the collision points. On the other hand, crab cavities may also have a detrimental impact on the beam quality due to imperfections. Phase noise error in the CCs leads to a fluctuation of the bunch position at the interaction point, which causes emittance growth. Simulations were carried out to assess the implication for the LHC parameters [2, 3, 4]. New development in the HL LHC design parameters and the improvement of the simulation tool to include transverse damper model [5] demand new simulations. In this paper we present simulation study using BeamBeam3D [6], with crab cavity phase error modulation and a noisy transverse damper. We also evaluated the potential effects from the 600 Hz dipole noise and the effects of working points.

COMPUTATIONAL SETUP

All simulations presented in this study were done using a strong-strong collision model implemented in the code BeamBeam3D. In order to reduce numerically induced emittance growth, and to gain computation speed, the fields were computed assuming a Gaussian particle distribution, instead of a self-consistent approach. This assumption is justified by the fact that the initial Gaussian particle distribution does not change significantly in a short period of time under stable conditions. In order to keep the residual noise level low, 8 million macroparticles were used. The particle distribution along longitudinal direction was divided into 8 slices. Two collisions per turn, corresponding to the interaction points (IPs) 1 and 5 in LHC, were simulated. The crossing plane was horizontal in one IP and vertical in the other IP. Linear transfer maps, calculated using the working point tunes, were employed to transfer the beams between collisions. The crab cavities are located 90 degree phase advance from the collision point. The damper model uses a Hilbert-notch filter and two pick-ups per beam and plane, as the actual system in LHC does. The correction kick at turn n due to one pick-up is given by [7]

$$\Delta X' \propto g \sum_m H_m(\varphi_H) \times (X_{n-d+1-m} - X_{n-d-m}) \quad (1)$$

where H_m are the coefficients of the Hilbert filter and φ_H is the phase that needs to be determined as a function of the tune and damper gain g, and d is the delay of the damper. The actual kick is the superposition of two terms associated with different pick-ups. In the simulation, the damper's gain was set to 0.05 at each pickup. Noise is inserted by adding random numbers, to match the measurement [5]. The detailed physical parameters used in the simulations are given in Table 1 [8].

Table 1: Physical parameters used in the simulations

Parameter	Value
N_p	2.2×10^{11}
ε_n / μm	2.5
β^* / m	0.49
σ / μm	12.8
Q_x	64.31
Q_y	59.32
θ / mrad	0.59
g_1, g_2	0.05
Damper noise	on
Crab cavities	on
Collisions / turn	1 hor., 1 ver.
ξ	0.022

EFFECTS OF CRAB CAVITY PPHASE ERROR

Under ideal conditions, the crab cavity will compensate the crossing angle collision completely and there is no centroid offset between two beams at the collision point. In practice, the noise in the RF control system results in phase and amplitude fluctuation of the crab cavity voltage. In this study, we focused on the phase fluctuation error. Under the short bunch approximation, the phase fluctuation leads to the centroid offset of two beams at the collision point given by the following equation:

$$\delta X = -\frac{c}{\omega_{cc}} \tan\left(\frac{\theta}{2}\right) \delta\varphi \quad (2)$$

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jqiang@lbl.gov

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where ω_{cc} is the crab cavity angular frequency, θ is the crossing angle, c is the speed of light in vacuum, and $\delta\varphi$ is the crab cavity phase error. The phase error has a spectral distribution in the frequency domain. In this study, instead of using the detailed information of the phase noise spectrum (which is still under development), we sampled the spectrum at a number of frequencies near the betatron frequency that might have most impact to the beam. In this case, the cavity phase error induced offset can be approximated as

$$\delta X = A_p \cos(\omega_p t + \varphi_p) \qquad (3)$$

where A_p is amplitude of the modulation, ω_p is the sampled modulation frequency, and φ_p is the phase of the modulation. Here, we assumed that the φ_p is 0 for beam one and π for beam two. The sampled frequency varied from 3238.56 Hz to 3598.4 Hz, which corresponds to a fractional tune ranging from 0.288 to 0.32. The modulation amplitude was chosen as 20 nm in the frequency scan. This is inferred from the -65 dB amplitude error observed at the KEK crab cavity study [1]. Figure 1 shows the emittance growth rate in horizontal (x) and vertical plane (y) as a function of the modulation frequency. It seen that the emittance growth shows strong frequency dependence. A peak emittance growth in horizontal plane occurs around a fractional tune of 0.3 (3382.5 Hz modulation) and in vertical plane around 0.31 (3490.45 Hz modulation). To understand this resonance, we overlap these two driven frequency on the top of the tune footprint diagram in Fig. 2. It is seen that the 0.3 fractional tune phase modulation will drive the major 10th order resonance in the horizontal plane, while the 0.31 fractional tune phase modulation drives mostly 13th order resonance in the vertical plane.

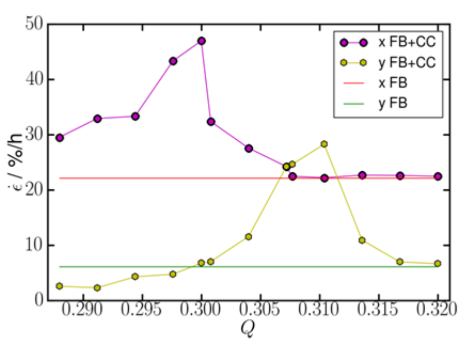

Figure 1: Emittance growth rate as a function of the modulation frequency.

To see the effects of modulation amplitude on beam emittance growth, we chose three modulation frequencies corresponding to fractional tune of 0.291, 0.3 and 0.31, and scanned the amplitude from 5 nm to 45 nm (i.e. 0.00039 to 0.0035 sigma). The emittance growth rate for this scan is given in Fig. 3. It is seen that for the fractional tune phase modulation 0.291, outside the resonance, the emittance growth changes slowly with the increase of the modulation amplitude. The sligthly decrease of vertical emittance growth at large modulation amplitude might be due to some coupling between the horizontal and the veritcal plane. For the modulation fractional tune inside the resonance (0.3 and 0.31), the emittance growth rate shows strong depedence on the modulation amplitude in the correponding horizontal and vertical plane. This suggests that within these modulation frequency, the modulation amplitude needs to be kept as small as posssible in order to avoid significant emittance blow up.

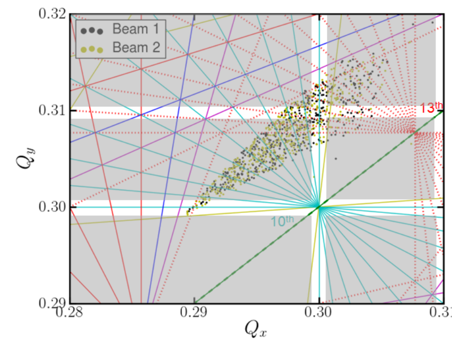

Figure 2: Particle tune footprint in resonance diagram.

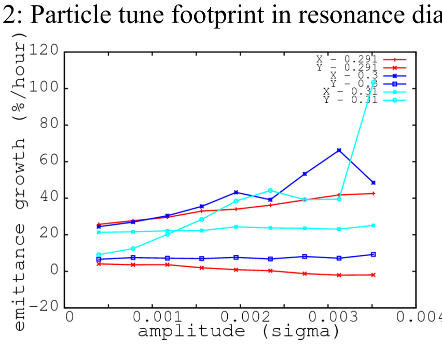

Figure 3: Emitance growth rate as a function of modulation amplitude at different modulation frequencies.

EFFECTS OF DIPOLE NOISE

During the LHC operation at 3.5 TeV, a horizontal spectrum of beam was taken as shown in Fig. 4.

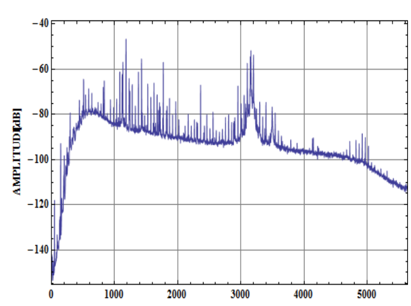

Figure 4: Horizontal spectrum during an LHC operation.

It is noted that in this figure there are large spikes around the line 1200, 1800 and 2400 Hz. These frequency lines are multiples of 600 Hz and indicate that the problem might be related to the ripple of power supplies of dipoles. In order to evaluate the potential effects of the dipole noise on beam quality in the HL LHC upgrade, we carried out beam-beam simulations including the 600 Hz offset modulation at the collision points. Figure 5 shows the emittance growth rate as a function of modulation amplitude in horizontal and vertical plane including the

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feedback model. It is seen that at this modulation frequency, the emittance growth is not sensitive to the modulation amplitude. The measured noise amplitude at LHC operation is about 40 nm (~0.003 σ) at the collision point. Such a modulation amplitude will not cause significant extra emittance growth in the HL LHC.

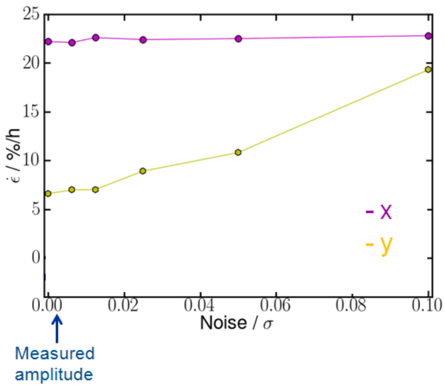

Figure 5: Emitance growth rate as a function of modulation amplitude with/without feedback.

EFFECTS OF WORKING POINT

The choice of tune working point affects the beam emittance growth. Figure 6 shows the relative emittance evolution for the nominal HL LHC parameters with a working point (64.31, 59.32) in tune space. The averaged emittance growth rate is about 14%/hr.

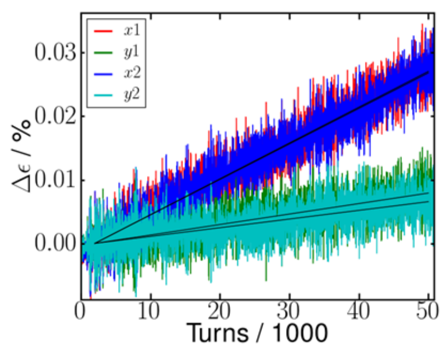

Figure 6: Emittance evolution with nominal working point (59.31, 64.32).

Figure 7 shows the tune footprint diagram of this working point. The particles fall primarily in the 10th and 13th order resonance region. It is expected by moving away from the lower 10th order resonance, one might get less emittance growth. Figure 8 shows the particle tune footprint with a working point (59.47,64.475). With this working, most particles fall into the 11th and 13th resonance region. Moving to a higher order resonance helps to reduce the emittance growth. The averaged emittance growth rate with this working point is about 3.4%/hr. The nominal working point used in this study have a different integer part from the updated HL LHC working point. To check this effect, we carried out beam-beam simulation for the HL LHC parameters uing the new working point (62.31, 60.32). Figure 9 shows the emittance evolution with this working point. It has very similar emittance growth to the working point (59.31, 64.32). The averaged emittance growth rate is also about 14%/hr.

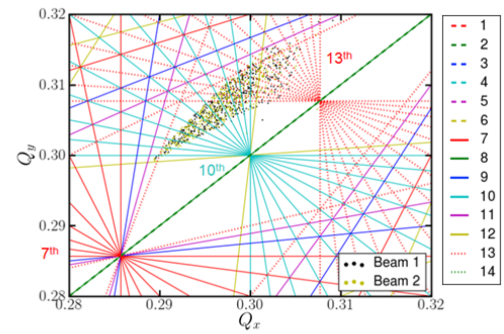

Figure 7: Particle tune footprint with nominal working point (59.31, 64.32).

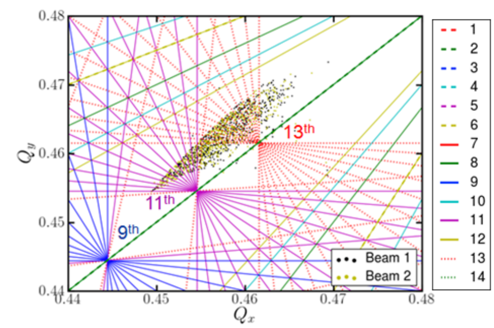

Figure 8: Particle tune footprint with nominal working point (59.47, 64.475).

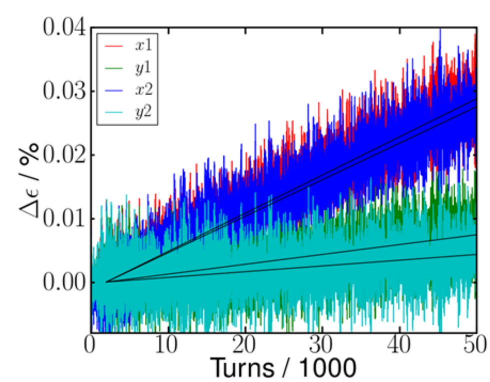

Figure 9: Emittance evolution with new integer working point (62.31, 60.32).

CONCLUSIONS

Using a strong-strong beam-beam simulation model, in this paper, we studied the effects of crab cavity phase error with sampled frequencies on beam emittance growth in the HL-LHC and observed strong noise frequency dependence. We also investigated the potential effects from the 600 Hz dipole noise on the beam emittance growth and found no significant effect with the current measured noise level. We also studied the effects of working point on beam emittance growth and found no sigificant effects from changing of integer tune, and reduction of emittance growth with fractional tune near the half integer. In the future study, we will employ the detailed phase noise spectrum in the simulation to determine the tolerance level of the noise.

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