WEAK-STRONG BEAM-BEAM SIMULATION WITH CRAB CAVITY NOISES FOR THE HADRON STORAGE RING OF THE ELECTRON-ION COLLIDER*

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Abstract

The Electron Ion Collider (EIC), to be constructed at Brookhaven National Laboratory, will collide polarized high-energy electron beams with hadron beams, achieving luminosities of up to $1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ in the center-mass energy range of 20-140 GeV. Crab cavities are employed to compensate for the geometric luminosity loss caused by a large crossing angle of 25 mrad in the interaction region. The phase noise in crab cavities will induce a significant emittance growth for the hadron beams in the Hadron Storage Ring (HSR). Various models have been utilized to study the effects of crab cavity phase noise. In this article, we present our numerical simulation results using a weak-strong beam-beam model. In addition to horizontal emittance growth, we also observed vertical emittance growth resulting from both crab cavity noises and beam-beam interaction. The tolerance for crab cavity phase noise was determined and compared with analytical predictions.

INTRODUCTION

Crab cavities are employed in the EIC to compensate for the geometric luminosity loss caused by a large crossing angle of 25 mrad in the interaction region [1,2]. It had been predicted from analytical estimation and later confirmed with beams in the CERN SPS that phase noises in crab cavities will generate significant emittance growth for hadron beams [3,4]. For the Hadron Storage Ring (HSR) of the Electron-Ion Collider (EIC), to maintain a physics store for around 10 hours, we need to keep the proton emittance growth less than a few percent per hour. Based on analytical estimation, to achieve about 20 percent per hour horizontal emittance growth rate, the crab cavity phase noise level should be less than 1.75×10^{-6} rad [5], which is more than one to two orders of magnitude smaller than current technology can deliver. Countermeasures are under study, such as low-level RF phase feedback and fast beam damper.

The analytical estimation [3] does not take into account the interplay between the crab cavity noises and the beam-beam interaction, which is very important for the flat beam collision with a large crossing angle in the EIC. To include the effects of beam-beam interaction, we carried out strong-strong, weak-strong, and element-by-element simulations with both crab cavity phase noises and beam-beam interaction [6]. Since the weak-strong model is able to detect a few percent per hour emittance growth in a million-turn tracking, it becomes our main tool for the crab cavity noise studies.

Table 1: Beam-Beam Related Machine and Beam Parameters Used for the Crab Cavity Phase Noise Simulation Study

quantity	unit	proton	electron
Beam energy	GeV	275	10
Bunch intensity	10^{11}	0.668	1.72
(β_x^*, β_y^*) at IP	cm	(80, 7.2)	(55, 5.6)
Beam sizes at IP	μm	(95, 8.5)	
Bunch length	cm	6	0.7
Energy spread	10^{-4}	6.8	5.8
Transverse tunes		$(0.228, 0.210)$	$(0.08, 0.06)$
Longitudinal tune		0.01	0.069

In the following, we first present our weak-strong beam-beam simulation model and the generation of crab cavity phase noises in our simulation code. Then we numerically determine the tolerances of the crab cavity phase noises with beam-beam interaction. Two kinds of noises are used in our simulations: pink and white noises. The actual spectrum of noises may fall between them. We also calculated the proton beam size growth rate with a banded spectrum centered at the revolution frequency to better understand the physics underlying the emittance growth.

SIMULATION SETUP

Simulation Model

In the following study, we will adopt the beam and optics parameters for the collision mode between 275 GeV protons and 10 GeV electrons. For this mode, both proton and electron beams reach their highest beam-beam parameters in the EIC, and the peak luminosity reaches 1.0×10^{34} cm^{-2} s^{-1}. Table 1 lists the beam-beam related design parameters for this collision mode.

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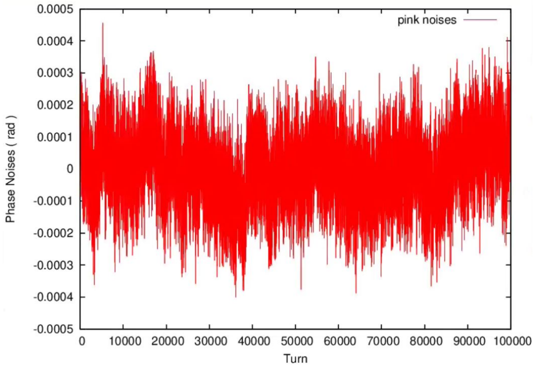

Figure 1: One example of raw data of pink phase noises with RMS value normalized to 10^{-4} rad.

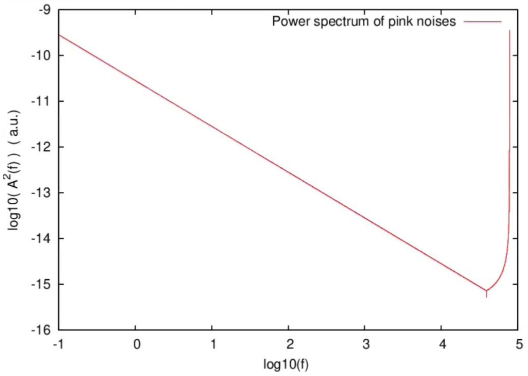

Figure 2: One example of power spectrum for pink noises.

For our weak-strong simulation model, the electron bunch is modeled as a rigid 3-D Gaussian charge distribution, while the proton bunch is represented by 10,000 macro-particles. At the IP, the protons are transferred into a head-on collision frame, where they interact with each slice of the electron bunch in a timed order. There is one interaction point in this study. The one-turn map is assumed to be a 6-D uncoupled linear matrix. On each side of the IP in the HSR ring, there are 4 197 MHz crab cavities and 2 394 kHz crab cavities. We assume that the phase advances between the IP and crab cavities are exactly 90 degrees in this study

Generation of Phase Noises

We will use two kinds of phase noises for these studies: pink and white noises. The actual noise spectrum will fall between them. To generate the noises with a 1-million data set, we first prepare a random spectrum in the frequency domain according to the characteristics of pink or white noises. Then we use inverse real FFT to obtain the phase noises in the time domain. The RMS values of each set of noises are normalized to 10^{-4} rad. During the simulation, we will scale the raw data to the required RMS values. As an example, Figure 1 shows one sample of raw data of pink phase noises. Figure 2 shows its spectrum with double log scales

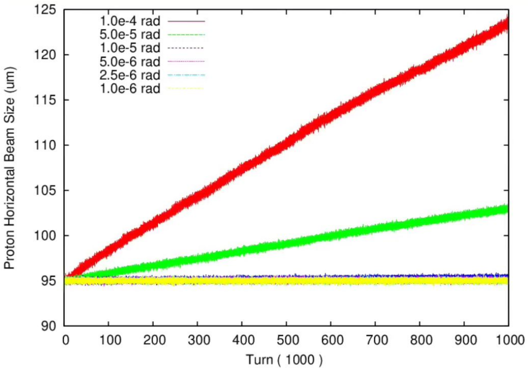

Figure 3: Vertical emittance growth rates as function of the RMS values of phase noises.

SIMULATION RESULTS

Tolerance Studies

First, we carry out weak-strong beam-beam simulations to determine the tolerances of crab cavity phase noises with beam-beam interaction. As stated earlier, the maximum allowed vertical beam size growth rate in HSR is 10% per hour, which is determined by the strong hadron cooling design. As an example, Figure 3 shows the proton bunch's horizontal beam size evolution with different RMS values of pink noises from 10^{-4} to 10^{-6} rad. To calculate the beam size growth rate, we fit the turn-by-turn beam sizes with a linear function. Then we convert the beam size absolute increase per turn into a growth rate in units of %/hour. Table 2 lists the calculated beam size growth rates for both pink and white noises.

From Table 2, the simulated beam size growth rates are similar for both pink and white noises with the same RMS value of noise. To ensure that both horizontal and vertical proton beam size growth rates are less than 10% per hour, the RMS values of crab cavity phase noises should not exceed 1 μrad. We further calculated the integrated spectrum power in the betatron tune spread [0.21:0.243] or in the frequency domain between [16432:19014] Hz. With the same RMS value of noise, the integrated spectrum power of the pink noise is double that of the white noise.

Also from Table 2, the horizontal beam size growth rates are much larger than the vertical beam size growth rates with a larger RMS value of noise greater than 10^{-5} rad. Both the horizontal and vertical beam size growth rates can be fitted well with a quadratic function ax^b. The fitting parameters are basically determined by the growth rates with large RMS values of noise. For the horizontal beam size growth rates, the fitting parameter b is approximately 1.7, while for the vertical beam size, b is approximately 2.0. As an example, Figure 4 shows the calculated proton beam size growth rates and their fitting curves.

With a Banded Spectrum

Next, we will simulate with a banded spectrum of phase noises centered at the revolution frequency. The purpose of

Table 2: Calcualted Proton Beam Size Growth Rates with Crab Cavity Phase Noises and Beam-Beam Interaction

RMS (10^{-4} rad)	Horizontal Growth Rate	Vertical Beam Growth Rate
Pink Noises:		
1	31900	7460
0.5	12100	1790
0.1	567	152
0.05	145	52
0.025	39	23
0.01	5.7	4.6
White Noises:		
1	32700	7900
0.5	12400	1850
0.1	580	150
0.05	149	51
0.025	40	23
0.01	1.9	9

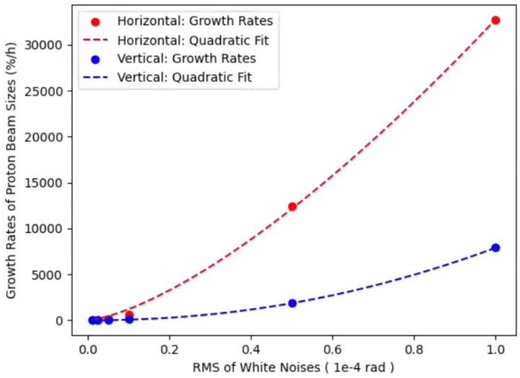

Figure 4: Proton beam size growth rates with crab cavity phase noises and beam-beam interaction.

this study is to see if these noise spectra can excite $2Q_x - 2Q_y + pQ_z$ synchro-betatron resonances and lead to beam size growth. We scanned the bandwidth of the rectangular noise spectrum from 0.01 f_{rev} to 0.5 f_{rev}. Figure 5 shows the spectrum of the raw phase noises. For each banded spectrum, we scanned its RMS values from 1×10^{-4} rad down to 1×10^{-6} rad. In our simulation, we did not observe clear proton beam size increase due to the crab cavity phase noise until the noise spectrum covers the proton betatron tune spread. For the spectrum with a bandwidth of 0.25 f_{rev}, we have to increase its RMS value to 0.01 rad to observe a sizable proton beam size growth. Of course, the actual RMS value of crab cavity phase noises will be much smaller than 0.01 rad.

With The Same Phase Noises

We also simulated the case with the same phase noises for all the crab cavities. We hoped to see some cancellation between the phase noises from crab cavities on the forward and rear sides of the IP. However, for both the pink and white noises, we did not observe cancellation or a reduction in beam size growth rates compared to uncorrelated noises for each crab cavity. The possible cause may be that the actual transfer between the crab cavities on both sides is not exactly $-\mathbf{I}$ matrix due to the beam-beam interaction.

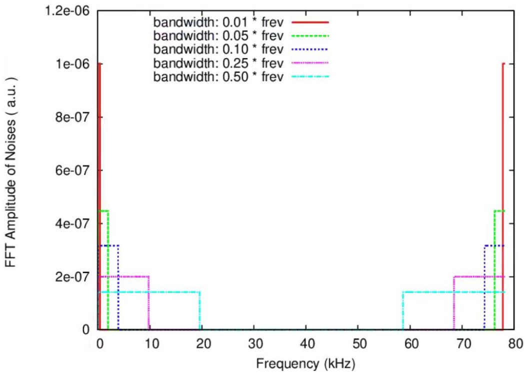

Figure 5: Banded spectrum centered at the revolutionary frequency.

Voltage Noises

We also performed weak-strong simulation with crab cavity voltage noises. The voltage noises are measured by the relative change to the design voltages of the crab cavities. We scanned the relative RMS voltage noises from 10^{-4} to 10^{-6} for both white and pink noises. To ensure that both horizontal and vertical proton beam size growth rates are less than 10% per hour, the tolerance for the pink noise is 1×10^{-5}, while for the white noise, it is 2.5×10^{-6}. The analytical estimate is about 1×10^{-5}. The reason for this difference is currently under investigation.

SUMMARY

In this article, we presented our numerical simulation results using a weak-strong beam-beam model for the crab cavity phase noises in the HSR of the EIC. The tolerance of RMS value for the phase noises is 1 μrad for both white and pink noises. We did not observe proton emittance growth with a banded spectrum centered at the revolutionary frequency until its RMS value reaches 0.01 rad. The tolerance for the relative crab cavity voltage noises is 1×10^{-5} for the pink noises and 2.5×10^{-6} for white noises. The reasons for the difference is currently under investigation.

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