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# TOLERANCES OF RF PHASE AND VOLTAGE NOISES WITH BEAM-BEAM INTERACTION IN 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 polarized proton and ion beams, achieving peak luminosities of up to $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$ in the center-of-mass energy range of 20-140 GeV. In this article, we present recent simulation studies focused on the effects of phase and voltage noise originating from the storage RF cavities in both the Electron Storage Ring (ESR) and the Hadron Storage Ring (HSR). The goal of this study is to determine acceptable tolerances for RF phase and voltage noise in the EIC storage rings and to provide critical input for the RF engineering design of the collider.

## INTRODUCTION

The Electron-Ion Collider (EIC), to be constructed at Brookhaven National Laboratory, will collide polarized high-energy electron beams with polarized proton and ion beams, achieving peak luminosities of up to $1 \times 10^{34}$cm$^{-2}$s$^{-1}$ in the center-of-mass energy range of 20-140 GeV [1, 2]. To achieve such high luminosities, the EIC employs high bunch intensities for both beams, small and flat transverse beam sizes at the interaction point (IP), and a large 25 mrad crossing angle in the interaction region (IR) to accommodate more than one thousand bunches in each storage ring.

In previous studies, we examined the impact of position and beam size fluctuations at the IP due to magnet power supply current ripples in the Electron Storage Ring (ESR) [3], as well as the phase and voltage noise introduced by the crab cavities in the Hadron Storage Ring (HSR) [4]. These studies showed that proton emittance growth is primarily driven by synchro-betatron resonances, which are enhanced by the flat-beam collision configuration of the EIC.

In this article, we extend our study to include the effects of phase and voltage noise from the storage RF cavities in both the ESR and HSR. A weak-strong beam-beam simulation is used to detect subtle beam size growth over one million tracking turns. The objective is to determine tolerances for RF phase and voltage noise, which will serve as critical input for the RF cavity engineering design of the EIC.

## SIMULATION SETUP

In the current EIC design, the typical physics store duration with electron–proton collisions is expected to be about 4-5 hours without strong hadron cooling at collision energies. To preserve beam quality, the goal is to limit proton emittance growth from non-intrabeam scattering (non-IBS) sources to less than 20% per hour, or equivalently, a proton beam size growth rate of less than 10% per hour. Non-IBS sources of proton emittance growth include beam–beam interactions, power supply current ripples, noise from crab and storage cavities, ground vibrations, beam instabilities, and other machine-induced perturbations.

To detect small proton beam size growth rates on the order of a few percent per hour, we employ a weak–strong beam–beam simulation model. Unlike the electron beam, the proton beam does not benefit from synchrotron radiation damping, making it more susceptible to emittance growth, particularly in the vertical plane. In our model, the proton beam is represented by macro-particles, while the electron bunch is modeled as a rigid six-dimensional Gaussian charge distribution. The proton ring is modeled using a 6D linear uncoupled matrix. Simulations typically track the protons for up to one million turns.

For the RF phase and voltage noise spectra, we assume white noise, with a uniform power spectral density over the chosen frequency range. The revolution frequency of the EIC storage rings is approximately 78 kHz. Noise signals are generated in the frequency domain and then transformed to the time domain using inverse FFT to produce turn-by-turn noise profiles. The RMS value of the time-domain signal is used to characterize the phase noise strength, while for voltage noise, we use the RMS value of the relative voltage variation.

Table 1 summarizes the beam parameters used in this study. We adopt the parameters corresponding to the highest peak luminosity collision mode: 10 GeV electrons colliding with 275 GeV protons. In this configuration, both beams reach their maximum beam-beam parameters in the EIC. As shown in the table, the vertical beam size at the IP is approximately 11 times smaller than the horizontal one, making it particularly vulnerable to beam–beam perturbations and machine noise.

## SIMULATION WITH ESR RF NOISES

As mentioned earlier, in our weak–strong simulation model, the electron bunch is assumed to be rigid, and the simulation code does not support explicit modeling of RF cavities. Instead, we simulate the effects of RF noise by applying random perturbations to the electron bunch's arrival time and bunch length at the interaction point (IP). Phase noise in the RF cavities leads to arrival time jitter of the electron bunch at the IP, while voltage noise affects the bunch length. We are currently developing an analytical framework to map the electron bunch arrival time jitter and bunch

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Table 1: Main Beam Parameters for the Collision Mode between 10 GeV Electrons and 275 GeV Protons

| Quantity | Unit | Proton | Electron |
|---|---|---|---|
| Beam energy | GeV | 275 | 10 |
| Bunch intensity | $10^{11}$ | 0.668 | 1.72 |
| $(\beta_x^*, \beta_y^*)$ 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, 0.14) |
| Longitudinal tune | | 0.01 | 0.069 |

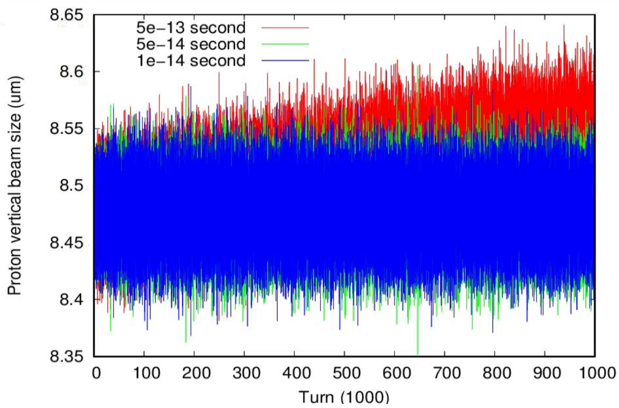


Figure 1: Proton RMS vertical beam size evolution with electron bunch arrival time noises at the IP.

length variations back to the corresponding ESR RF phase and voltage noise levels.

To determine the tolerance for electron bunch arrival time jitter at the IP, we perform a parameter scan using pre-generated noise signals with varying RMS values. Our target is to limit the proton transverse beam size growth rate to less than 10% per hour. As an example, Figure 1 shows the evolution of the proton RMS vertical beam size under three different levels of RMS arrival time jitter for the electron bunch. In all cases presented in this article, the beam–beam interaction is included in the simulation.

Table 2 presents the simulated proton beam size growth rates for different levels of electron bunch arrival time jitter. The RMS values of the arrival time noise are scanned from $5 \times 10^{-13}$ s to $1 \times 10^{-14}$ s in six steps. From the results, it is observed that the proton horizontal beam size growth is negligible across this range, while the vertical beam size growth is significant. The tolerable RMS electron bunch arrival time jitter is approximately $1 \times 10^{-13}$ s for head-on collisions, and about $5 \times 10^{-14}$ s for collisions with crab crossing. Given the RF frequency of the ESR is 591 MHz, an arrival time jitter of $5 \times 10^{-14}$ s corresponds to a phase error of roughly 0.02 degrees.

Next, we apply white noise to the electron bunch length at the IP to simulate the effect of RF voltage fluctuations. Table 3 shows the simulated proton beam size growth rates under varying levels of electron bunch length fluctuations.

Table 2: Proton RMS Beam Size Growth Rates with Electron Bunch Arrival Time Noises

| RMS Noise ($10^{-12}$ Second) | Head-on Collision (%/hour, %/hour) | Crab Collision (%/hour, %/hour) |
|---|---|---|
| 0.5 | (-1.9, 181) | (1.4, 227) |
| 0.2 | (0-.48, 30) | (-0.45, 34.6) |
| 0.1 | (-0.49,9.6) | (-0.35, 19.5) |
| 0.05 | (0.36, -0.87) | (-0.21, 4.5) |
| 0.02 | (-0.24,2.9) | (-0.50, 3.4) |
| 0.01 | (-0.21,0.95) | (-0.13, 1.4) |

Table 3: Proton RMS Beam Size Growth Rates with Relative Electron Bunch Length Variation Noises

| Relative Electron Bunch Length Noise (100%) | Proton Horizontal Growth Rate (%/hour) | Proton Vertical Growth Rate (%/hour) |
|---|---|---|
| 0.1 | -0.12 | 1.8 |
| 0.01 | -0.04 | 1.5 |
| $1 \times 10^{-3}$ | -0.15 | 3.9 |
| $1 \times 10^{-4}$ | -0.11 | 3.1 |
| $1 \times 10^{-5}$ | -0.08 | 5.1 |
| $1 \times 10^{-6}$ | -0.51 | 3.9 |

In this study, the relative variation of the electron bunch length is scanned from 0.1 to $1.0 \times 10^{-6}$ of its design RMS value. As shown in the table, the resulting proton beam size growth rates are negligible across the full range of simulated bunch length variations. All simulated growth rates remain well below the acceptable threshold of 10% per hour.

## SIMULATION WITH HSR RF NOISES

To determine the tolerances for RF phase and voltage noise in the HSR, we include RF cavities directly in the simulation model. The HSR contains two types of RF cavities: 591 MHz and 197 MHz, with total voltages of 20 MV and 6 MV, respectively. In the simulation, we model a single 591 MHz cavity and a single 197 MHz cavity, each carrying their full total voltage to simplify implementation.

We observed that protons with longitudinal coordinates beyond $3\sigma_l$ or momentum deviation exceeding $3\sigma_{\delta p/p_0}$, as defined in the EIC CDR, fall outside the stable region of the RF bucket. Therefore, in calculating proton beam size growth rates, we include only protons within $2.8\sigma_\ell$ in the longitudinal phase space.

Table 4 presents the simulated proton beam size growth rates under various levels of HSR RF phase noise. The phase noise is quantified as arrival time jitter at the RF cavities. To convert this to RF phase, we multiply the arrival time noise by $2\pi f_{\rm RF}$, where $f_{\rm RF}$ is the RF cavity frequency. The arrival time jitter is scanned from $5 \times 10^{-13}$ s to $1 \times 10^{-14}$ s.

The HSR RF phase noise affects both horizontal and vertical proton beam sizes: typically reducing the horizontal beam size and increasing the vertical size. For the crab crossing collision configuration, the tolerable RF phase noise

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Table 4: Proton RMS Beam Size Growth Rates with HSR RF Phase Noises

| Noise RMS (Second) | Head-on Collision (%/hour, %/hour) | Crab Collision (%/hour, %/hour) |
|---|---|---|
| $5 \times 10^{-13}$ | (-12, 173) | (-10.2, 162) |
| $2 \times 10^{-13}$ | (0.6, 20.6) | (-2.8, 41.4) |
| $1 \times 10^{-13}$ | (-3.6, 21.7) | (-1.7,12.7) |
| $5 \times 10^{-14}$ | (-1.2, 5.5) | (-2.3, 11.3) |
| $2 \times 10^{-14}$ | (-1.1, 3.9) | (-0.71, 4.25) |
| $1 \times 10^{-14}$ | (-0.46. 4.4) | (-0.59, 2.45) |

Table 5: Proton RMS Beam Size Growth Rates with Relative HSR RF Voltage Noises

| RMS Noise (Second) | Head-on Collision (%/Hour, %/Hour) | Crab Collision (%/hour, %/hour) |
|---|---|---|
| $1 \times 10^{-2}$ | (-61.5, 4220) | (-240, 3950) |
| $1 \times 10^{-3}$ | (-4.2, 52) | (-3.6, 53.3) |
| $1 \times 10^{-4}$ | (-0.44, 6.4) | (-0.91, 10.1) |
| $1 \times 10^{-5}$ | (-0.23, 7.4) | (-0.52, 3.7) |
| $1 \times 10^{-6}$ | (-0.46, 3.7) | (-0.17, 1.1) |
| $1 \times 10^{-7}$ | (-0.17, 18) | (-0.65, 3.2) |

level corresponds to an arrival time jitter of approximately $2 \times 10^{-14}$ s.

Table 5 presents the simulated proton beam size growth rates under different levels of relative RF voltage noise in the HSR. In this study, the relative RF voltage noise is scanned from $1 \times 10^{-2}$ to $1 \times 10^{-7}$ of the nominal design voltage. From the simulation results, we find that the tolerance for relative RF voltage noise is approximately $1 \times 10^{-4}$ for both head-on and crab crossing collision scenarios.

## SIMULATION WITH BANDED RF NOISES

Since RF noise components near the synchrotron motion frequencies are expected to have the strongest impact on beam dynamics, we simulate banded RF noise centered at one or two times the synchrotron frequency $Q_s$. The synchrotron tunes for the ESR and HSR are 0.069 and 0.01, respectively. We assume the width of the banded spectrum to be equal to the synchrotron frequency in each case. The banded noise is generated in the frequency domain and then transformed into the time domain using an inverse FFT to produce turn-by-turn RF phase or voltage noise signals. As an example, Figure 2 shows a banded noise spectrum centered at 5.4 kHz, corresponding to the synchrotron tune frequency of the electron beam in the ESR. As shown, the spectral amplitude is mirrored below and above half the revolution frequency, a characteristic of the FFT for real-valued signals.

Table 6 summarizes the RF phase and voltage noise tolerances obtained from early simulations using white noise. Table 7 presents the corresponding tolerances for simulations with banded noise spectra. The tolerances for the banded

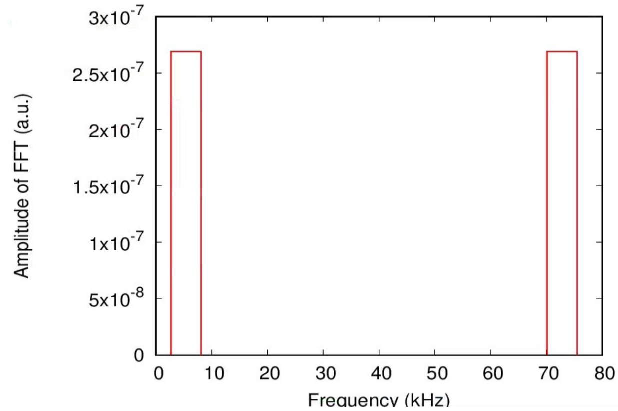


Figure 2: The amplitude of banded RF noise spectrum. Here the spectrum is centered at half of electron synchrotron frequency.

Table 6: Tolerances of RF Phase and Voltage White Noises

| RF Noise | Unit | White Noise |
|---|---|---|
| HSR RF phase | second | $2 \times 10^{-14}$ |
| HSR RF voltage | 100% | $1 \times 10^{-4}$ |
| e-bunch arrival time | second | $5 \times 10^{-14}$ |
| e-bunch length | 100% | huge |

Table 7: Tolerances of Banned RF Phase and Voltage Noises Centered at $Q_s$ or $2Q_s$

| RF Noise | Unit | $Q_s \pm Q_s/2$ | $2Q_s \pm Q_s/2$ |
|---|---|---|---|
| e-bunch arrival time | second | $1 \times 10^{-13}$ | $5 \times 10^{-14}$ |
| e-bunch length | 100% | huge | huge |
| HSR RF phase | second | $5 \times 10^{-14}$ | $5 \times 10^{-14}$ |
| HSR RF voltage | 100% | $1 \times 10^{-4}$ | $1 \times 10^{-4}$ |

noise are generally within a factor of 2 of those determined for white noise. From both tables, it is evident that the tolerances related to electron bunch length variations are relatively large.

## SUMMARY

In this article, we present simulation results studying the effects of RF phase and voltage noise on beam-beam interaction in the EIC. The simulations use the design parameters corresponding to the highest peak luminosity collision mode. A weak-strong beam-beam model is employed to detect small proton beam size growth rates. To maintain the proton transverse beam size growth rate below 10% per hour, the RMS electron bunch arrival time jitter at the IP must be less than $5 \times 10^{-14}$ seconds. The RMS of HSR RF phase noise should be below $2 \times 10^{-14}$ seconds, and the RMS of relative HSR RF voltage fluctuations must be kept under $1 \times 10^{-4}$. We also observe that proton beam size growth is largely insensitive to electron bunch length noise within the studied range.

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