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# SIMULATION OF THE SIMPLE FEEDBACK SYSTEM FOR THE MITIGATION OF THE CAVITY RF NOISE EFFECTS IN EIC HSR*

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*Abstract*

The Electron-Ion Collider (EIC) conceptual design has adopted crab crossing of colliding electron and ion beams at interaction points for delivering high luminosity and unprecedent detector acceptance. The beam crossing angle is 25 mrad. This design requires superconducting RF crab cavities for both EIC electron and hadron beams. It is well understood phase and amplitude errors of the crab cavities could cause significant emittance growth, thus affect collider luminosity performance and lifetime. Recently a feedback system has been considered for mitigating such emittance growth and luminosity degradation. Here we present a simulation study to evaluate improvement of performance with a feedback system.

## INTRODUCTION

Crab crossing of colliding beams at interaction points is an integral part of the EIC nachine design. In such design, RF crab cavities are required for both electron and ion beams to compensate for the EIC no-zero crossing angle and maximize the luminosity. Imperfections in the crab cavities, such as RF phase noise, could cause significant growth of hadron beam emittance [1] since it lacks adequote synchrotron radiation damping. Key specifications of the crabbing system include crab cavity RF phase, voltage and synchronization, and phase noise tolerance. The hadron beam emittance is highly sensitive to crab cavity RF phase noise for the Hadron Storage Ring (HSR), so adqute mitigation of the noise effect is required and a feedback system will be an effective tool [2-4]. The work reported in this paper focuses on evaluation of crab cavity RF phase noise indued growth of the EIC hadron beam transverse emittance and explore mitigating schemes. Utilizing a simple angle error feedback loop, we performed a series simulations with different mitigating scenarios. We present a comparison of these results in this paper.

## SIMPLE FEEDBACK LOOP MODEL

A simple feedback system for mitigating the EIC crab cavity phase noise is shown in Fig. 1. The hadron beam is transported from the location of the crab cavity to the beam position monitor (BPM). The centroid position offset Δx of the bunch is measured by a BPM. A transverse kick is applied by a corrector (Kicker) further downstream. The transverse coordinates and momenta of a particle at the BPM and the corrector satisfy the following mapping,

$$\begin{pmatrix} x_{\mathrm{k}} \\ x'_{\mathrm{k}} \end{pmatrix} = \begin{pmatrix} \sqrt{\beta_2/\beta_1}\cos\varphi & \sqrt{\beta_1\beta_2}\sin\varphi \\ -\sin\varphi/\sqrt{\beta_1\beta_2} & \sqrt{\beta_1/\beta_2}\cos\varphi \end{pmatrix} \begin{pmatrix} x_{\mathrm{bpm}} \\ x_{\mathrm{bpm}} \end{pmatrix}, \quad (1)$$

where $x_{\mathrm{bpm}}$, $x_{\mathrm{bpm}}$ and $x_{\mathrm{k}}$, $x'_{\mathrm{k}}$ are the transverse phase coordinates at the locations of the BPM and the kicker respectively, $\beta_1$ and $\beta_2$ are the $\beta$ function at location of the BPM and the kicker respectively, $\varphi$ is the phase advance between the BPM and the kicker. In Eq. (1), we assume $\alpha \approx 0$ at both the BPM and the kicker. Since the BPM can only measure the centroid offset of the bunch, we suggested that the betatron phase advance $\varphi$ be approximately π/2, then, we can simply apply a kick $x'_{\mathrm{k}} = -x_{\mathrm{bmp}}\sin\varphi/\sqrt{\beta_{\mathrm{k}}\beta_{\mathrm{bmp}}}$ to kick the beam centroid back towards the design trajectory with minimal error cost.

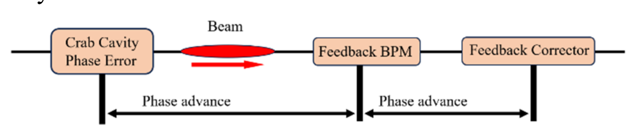


Figure 1: A simple feedback loop in a beamline.

## SIMULATION RESULTS

Simulations were performed to check the feedback effects implementing the above model in the EIC HSR. Table 1 lists some parameters of the EIC HSR used in our simulations. The proton beam is initialized with a RMS geometric emittance of 3.3 nm and 0.3 nm in the horizontal and vertical directions. Based on Bmad [5], a parallel tracking code was used in our simulations. We tracked 10,000 particles for 100,000 turns in EIC HSR with eight crab cavities in all the simulations. We chose the white Gaussian noise in the simulations, which means the power spectral density of the noise is constant in the frequency domain.

Table 1: EIC HSR Parameters in Simulations

| **Beam** | | **Proton** |
|---|---|---|
| Beam Energy | (GeV) | 275.0 |
| Beam Circulation Frequency | (MHz) | 0.782 |
| RF Cavity Frequency | (MHz) | 197 |
| $\theta_{CC}$ | (mrad) | 25 |
| $\beta$* | (m) | 0.8 |

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In the following, we will only show four representative cases in the simulation results. For all the cases, $\beta = 1300.02$ m at the end of the final downstream crab cavity. The emittance of the proton beam changes during the simulations with or without the feedback for three different noise strengths, $1 \times 10^{-5}$ rad, $5 \times 10^{-5}$ rad, and $10 \times 10^{-5}$ rad respectively, will be demonstrated in the paper.

**Case 1**: The betatron phase advance from the last crab cavity to the BPM is $\pi/2$. It is also $\pi/2$ from the BPM to the corrector. This is an ideal case since both betatron phase advances are exactly $\pi/2$. The value of the $\beta$ function at the BPM and at the kicker are 0.93 m and 38.34 m respectively. The centroid offset at the BPM are recorded every 50 turns. Two kicking patterns are exercised, namely, a micro kick is applied on each passing of the corrector; alternately, one big kick is applied only on the 50$^{th}$ turn. Figure 2 shows how the emittance of the proton beam changes during the simulations with or without the feedback for three different noise strengths. In these simulations, a kick is applied every turn to correct the beam centroid. The strength of the kick is $x'_k/50$ , hence it is called a fractional kick. Figure 3 shows another set of simulations, in which a complete kick is applied every 50 turns with the strength of $x'_k$. The two figures show different effects. Obviously, the feedback effect of Fig. 3 is much better than that of Fig. 2.

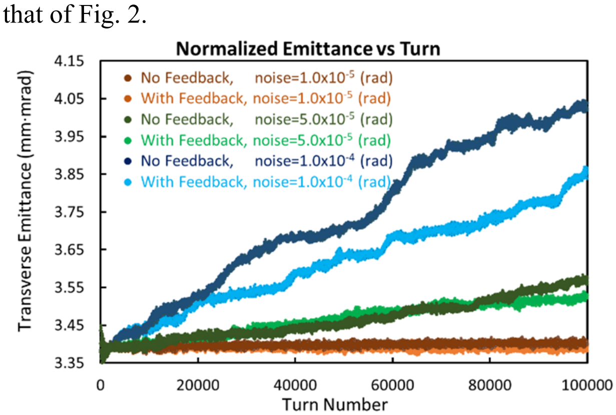


Figure 2: At BPM, $\beta = 0.93$ m and at the Kicker, $\beta = 38.34$ m. At the corrector, a fractional kick $x'_k/50$ is applied to kick the beam every turn.

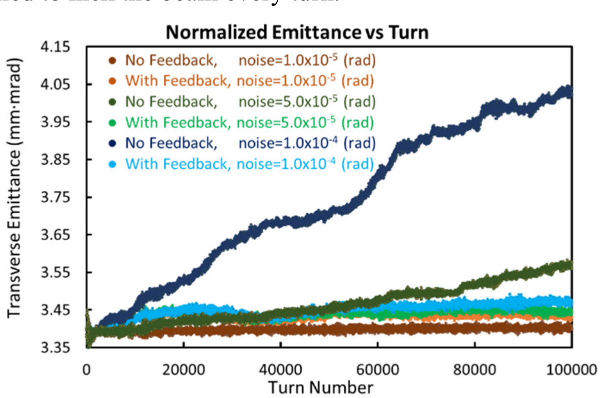


Figure 3: At BPM, $\beta = 0.93$ m and at the Kicker, $\beta = 38.34$ m. At the corrector, a single $x'_k$ is applied to kick the beam every 50 turns.

**Case 2**: In this case, the betatron phase advance is 0.446π from the final downstream crab cavity to BPM and 0.498π from BPM to the corrector. At BPM, $\beta = 22.64$ m and at the Kicker, $\beta = 13.0$ m. The centroid offset was obtained every turn (Fig. 4) or every 50$^{th}$ turns (Fig. 5).

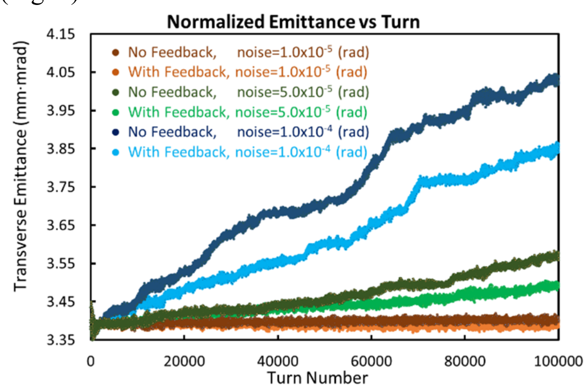


Figure 4: At BPM, $\beta = 22.64$ m and at the Kicker, $\beta = 13.0$ m. At the corrector, a fractional kick $x'_k/50$ is applied to kick the beam every turn.

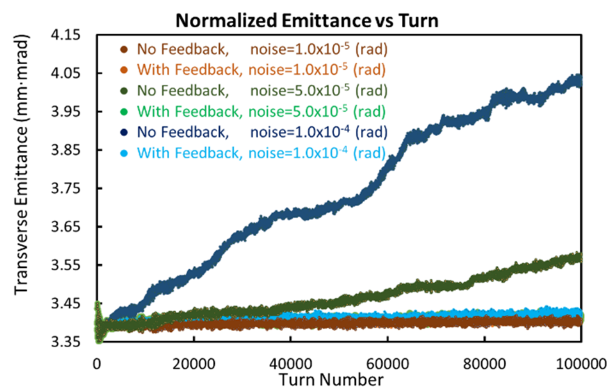


Figure 5: At BPM, $\beta = 22.64$ m and at the Kicker, $\beta = 13.0$ m. At the corrector, a single $x'_k$ is applied to kick the beam every 50 turns.

Figures 4 and 5 show different effects by implementing a fractional kick or a complete kick. Same as Case 1, the complete kick $x'_k$ for the beam correction every 50 turns, with results shown in Fig. 5, provides much better feedback effects than the fractional kick $x'_k/50$ every turn, with results shown in Fig. 4.

**Case 3**: In this case, we collected the centroid offset every 50 turns at larger values of $\beta$, 44.78 m at the feedback BPM and 35.84 m at the Kicker, with the purpose to minimize measurement errors of the centroid offset. The phase advance is 1.262π from the final downstream crab cavity to the feedback BPM and 0.514π from the feedback BPM to the corrector.

By comparing the feedback results in Figs. 3, 5 and 7, we can see that placing the BPM at a high $\beta$ location can reduce the effect of measurement error of the centroid offset for the lower noise levels. Same as Case 1 and Case 2, the complete feedback effect $x'_k$ for the beam correction applied every 50 turns, results of which shown in Fig. 7

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works much better than the fractional kick $x'_k/50$ every turn, shown in Fig. 6.

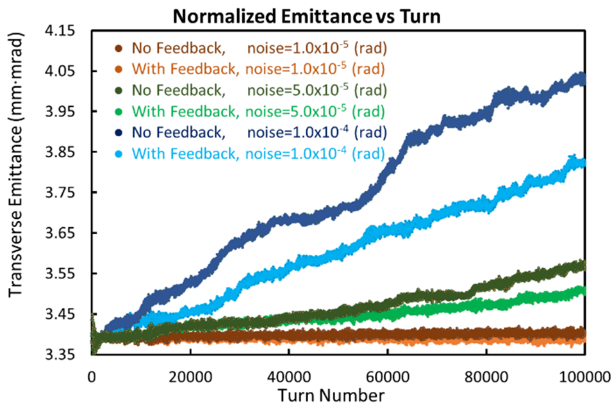


Figure 6: At BPM, $\beta = 44.78$ m and at the Kicker, $\beta = 35.84$ m. At the corrector, a fractional $x'_k/50$ is applied to kick the beam every turn.

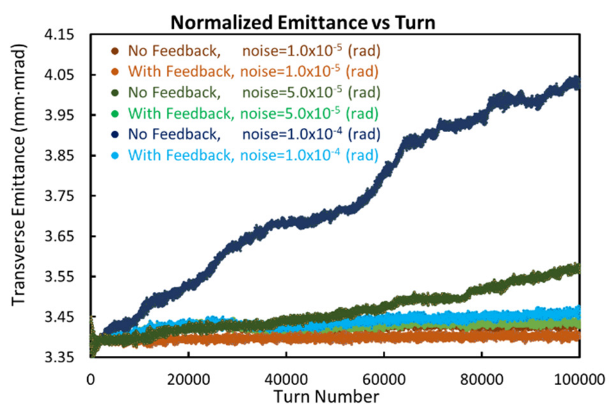


Figure 7: At BPM, $\beta = 44.78$ m and at the Kicker, $\beta = 35.84$ m. At the corrector, a single $x'_k$ is applied to kick the beam every 50 turns.

**Case 4**: This is also an ideal feedback loop with both the phase advance being exactly π/2. At the feedback BPM, $\beta = 0.93$ m and at the Kicker, $\beta = 38.34$ m.

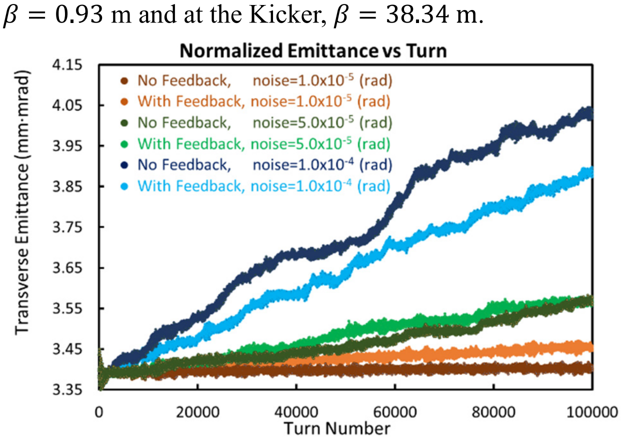


Figure 8: At BPM, $\beta = 0.93$ m and at the Kicker, $\beta = 38.34$ m. At the corrector, a single $x'_k$ is applied to kick the beam every 1000 turns.

We conducted two groups of simulations with this setup. In one group, we collect the centroid offset at the BPM and applied the complete kick $x'_k$ every 1000 turns. In the other group, we collected the centroid offset at the BPM and applied the complete kick $x'_k$ every 2000 turns. The results are shown in Fig. 8 and Fig. 9 respectively. Comparing with the previous three cases, the emittance growth was poorly mitigated in the simulations in Case 4 although we used complete operation $x'_k$ in both groups. This is because the feedback frequency was too low, resulting in very low feedback efficiency.

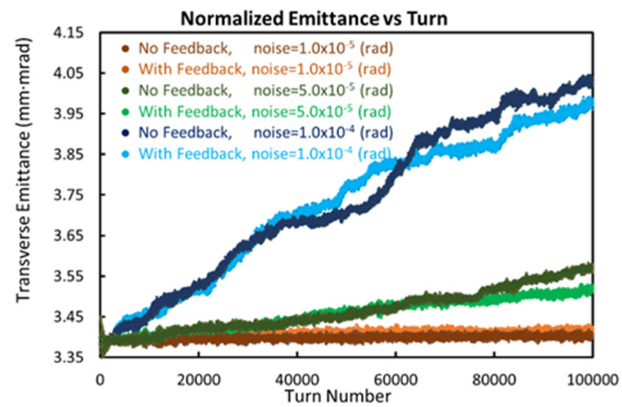


Figure 9: and at the Kicker, $\beta = 38.34$ m. At the corrector, a single $x'_k$ is applied to kick the beam every 2000 turns.

Table 2: Simulation Error of the Emittance

| Noise (μrad) | Case 1 (μm) | Case 2 (μm) | Case 3 (μm) |
|---|---|---|---|
| 10 | $4.02x10^{-3}$ | $2.67x10^{-3}$ | $3.19x10^{-3}$ |
| 100 | $4.25x10^{-3}$ | $2.84x10^{-3}$ | $3.28x10^{-3}$ |

For a single $x'_k$ is applied to kick the beam every 50 turns, Table 2 lists some error in Case 1, 2 and 3 respectively. At BPM, $\beta = 0.93$ m , $\beta = 22.64$ m and $\beta = 44.78$ m respectively. Obviously, The BPM in Case 2 and 3 is at high β location. Table 2 also shows that the error for the transverse emittance in Case 2 and 3 is less than that for Case 1.

## CONCLUSION

We performed the tracking simulations to evaluate the emittance growth due to the crab cavity RF phase noise. We evaluated the performance and the requirements in a simple angle error feedback loop for the different scenarios and compared the simulation results. Here is the conclusion:

1. Under the same phase noise level, a low sampling frequency feedback system can effectively alleviate the emittance growth due to the crab cavity RF phase noise. If the complete kick does not be applied on the beam after the measurement at the BPM, it is not very effective to correct the centroid offset due to the phase noise.
2. For the lower-level phase noise in crab cavity, placing the BPM at a high $\beta$ location can reduce the effect of measurement error of the centroid offset.
3. It is a better choice to correct the centroid offset every few hundred turns, otherwise the feedback will be less effective.

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