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Electron-Ion Collider

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# Pickup Specifications for Crab Cavity Noise Feedback Pickup

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## Abstract

The Electron-Ion Collider will employ crab cavities to compensate for the significant 25 mrad crossing angle, leading to an order of magnitude increase in luminosity. The crab cavity Radio Frequency system will inject low levels of noise to the crabbing field, generating transverse emittance growth and potentially limiting luminosity lifetime. A novel dedicated feedback system acting through the crab cavities has been proposed to mitigate emittance growth. The performance of the noise feedback will largely depend on its pickup precision. In this note we present pickup specifications to achieve the required performance.


## I. INTRODUCTION

The EIC will reuse the Relativistic Heavy Ion Collider (RHIC) infrastructure [1]. The beams will collide with a 25 mrad full crossing angle. The EIC will employ crab cavities to compensate for the significant crossing angle, leading to an order of magnitude increase in luminosity [1]. The crab cavities will be used in a local scheme; crabbing and uncrabbing cavities will be paired around the sole interaction point. The Crab Cavity Low-Level Radio Frequency system (LLRF) will regulate the crabbing and uncrabbing voltages, and try to maintain their sum to zero, so that the crabbing is localized at the interaction region. The LLRF system will also have to reduce the Crab Cavity impedance to prevent transverse instabilities. Finally, it will have to maintain extremely low Radio Frequency (RF) noise levels injected to the beam.

RF noise is a significant challenge for the EIC, especially for the Hadron Storage Ring (HSR). The 275 GeV case is the most challenging. The RF noise threshold for the HSR will be very hard to achieve technologically [2]. A dedicated feedback system to counteract RF noise effects has been proposed and studied [3]. It could mitigate these effects and thus relax the Crab Cavity RF noise threshold. The performance of the system will greatly depend on its pickup precision, location, and additional technical specifications. The pickup is a critical component for this system. This note focuses on the pickup specifications.

## II. RF NOISE FEEDBACK

Emittance growth caused by crab cavity RF noise is a two-step process. First, noise excites a bunch oscillation. Then, this oscillation results in emittance growth through decoherence due to the betatron tunespread. A feedback system can mitigate this degradation if it damps the oscillation *before* decoherence has significantly impacted the emittance. A novel dedicated feedback system is proposed that would use the *existing* crab cavities as kickers to mitigate RF noise effects. As such, no new kickers or crab cavities will have to be designed. The proposed feedback system could share pickup signals with a potential transverse damper (Figure 1). The proposed pickup will strongly couple to the bunch head-tail motion, and will extract both the dipole (mode 0) and head-tail (mode 1) motion.

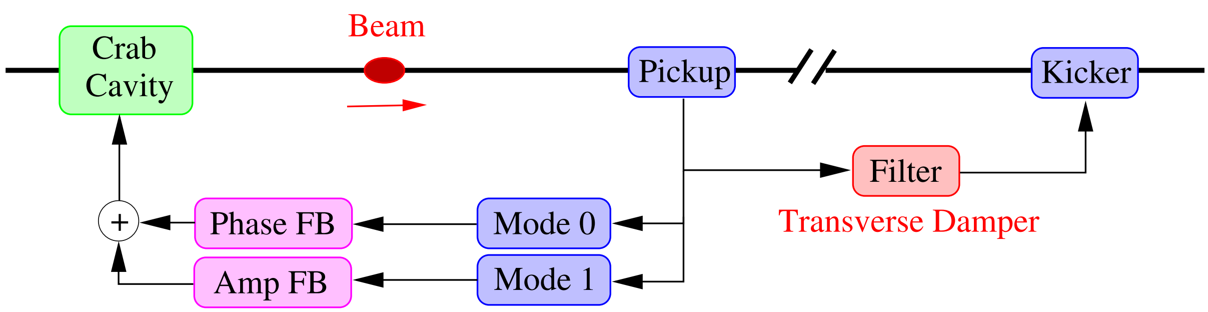


Figure 1. Block diagram including damper and proposed feedback.

The resulting error signal will be applied directly to the crab cavity voltage set point, in amplitude and phase. Therefore, the crab cavity feedback will be able to act on both phase and amplitude noise with a correction that will be a perfectly scaled version of the noise momentum kick – if it is caused by the crab cavity RF noise.

## III. EMITTANCE GROWTH RATE REDUCTION

We presented analytical expressions for the emittance growth rate reduction due to the noise feedback in [3] and used them to define the pickup specifications for the HL-LHC. The relevant equations necessary for this note are summarized in this Section and are then used to define the pickup specifications for the EIC.

The emittance growth rate reduction factor $\bar{R}_\phi$ for mode 0 through the noise feedback action is given by

$$\bar{R_\phi} = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{g\,(u)}{\left[1+\alpha_0 g(u)\right]^2 + \left[\alpha_0 f(u)\right]^2} du \tag{1}$$

with

$$\begin{aligned}
u &= \frac{\bar{\nu_b} - \nu_b}{\sigma_{\nu_b}} \\
g(u) &= \pi\sigma_{\nu_b}\rho(\bar{\nu_b} - u\sigma_{\nu_b}) \\
f(u) &= \sigma_{\nu_b} \text{ P.V.} \int_{-\infty}^{\infty} \frac{\rho\,(\nu_b)}{(\nu_b - \bar{\nu_b} + u\sigma_{\nu_b})} d\nu_b \\
\alpha_0 &= \frac{G_0 N_{cc}\sqrt{\beta_p\beta_{cc}} eV_0 e^{-\frac{\sigma_\phi^2}{2}}}{4\pi\sigma_{\nu_b} E_b}
\end{aligned} \tag{2}$$

where $\nu_b$, $\bar{\nu_b}$, $\sigma_{\nu_b}$ are the particle, mean, and rms betatron tunes, $\rho(\nu_b)$ is the probability density function of the betatron tune, $G_0$ is the proportionality factor between the pickup measurement and feedback response, $N_{cc}$ the number of crab cavities, $\beta_p/\beta_{cc}$ the beta functions at the pickup/crab cavities, $V_0$ the single crab cavity voltage, $\sigma_\phi$ the bunch length, and $E_b$ the beam energy. The functions $g(u)$, $f(u)$ are provided for various distributions in [4]. $\alpha_0$ is the feedback open loop gain:

For a given tune distribution, the feedback action on the full bunch emittance growth depends only on $\alpha_0$. If the feedback phase is optimally adjusted, the resulting damping time $\tau_0$ will be twice the revolution period divided by the overall loop gain [5].

$$\tau_0 = \frac{2T_{rev}}{G_0 N_{cc}\sqrt{\beta_p\beta_{cc}}\frac{eV_0}{E_b} e^{-\frac{\sigma_\phi^2}{2}}} = \frac{1}{\alpha_0}\frac{T_{rev}}{2\pi\sigma_{\nu_b}} \tag{3}$$

where $T_{rev}$ is the revolution period. The feedback will mitigate the noise if the damping time $\tau_0$ is smaller than the decoherence time $\tau_d = T_{rev}/(2\pi\sigma_{\nu_b})$. Actually, $\alpha_0$ is exactly equal to the ratio of these time constants.

Figure 2 from [3] shows the emittance reduction factor for various distributions. All the curves asymptotically approach $1/\alpha_0^2$ when the damping time becomes much smaller than the betatron decoherence time ($\alpha_0 >> 1$). This approximation was derived in [6], [7] for dipole kicks.

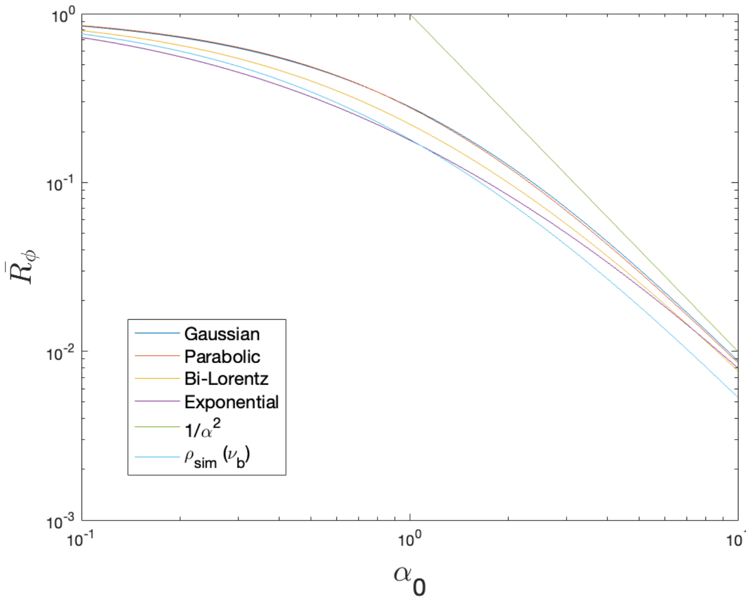


Figure 2. Emittance growth reduction factor as a function of $\alpha_0$ and tune distribution [3].

We similarly derived the expression for mode 1 in [3]

$$\bar{R_A} = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{g\left(u\right)}{\left[1+\alpha_1\frac{g(u+\frac{\bar{\nu_s}}{\sigma_{\nu_b}})+g(u-\frac{\bar{\nu_s}}{\sigma_{\nu_b}})}{2}\right]^2+\left[\alpha_1\frac{f(u+\frac{\bar{\nu_s}}{\sigma_{\nu_b}})+f(u-\frac{\bar{\nu_s}}{\sigma_{\nu_b}})}{2}\right]^2} du \tag{4}$$

$$\alpha_1 = \frac{G_1 N_{cc}\sqrt{\beta_p\beta_{cc}}eV_0 e^{-\frac{\sigma_\phi^2}{2}}}{\lambda\sigma_{\nu_b}E_b} \tag{5}$$

where $\lambda$ is the RF wavelength.

### A. Measurement noise effects

Equations 1 and 4 assume perfect knowledge of the bunch position and tilt. In reality, there will be measurement noise on these parameters. We derived analytical expressions in [3] for the emittance growth rate reduction in the presence of measurement noise.

For mode 0, the emittance growth rate reduction factor $\bar{R}_0$ is given by

$$\bar{R_0} = \bar{R_\phi}\left[1 + N_{cc}G_0^2\frac{\sigma_0^2}{\sigma_{\Delta\phi}^2}\right] \tag{6}$$

where $\sigma_0$ is the rms noise on the mode 0 measurement and $\sigma_{\Delta\phi}$ is the rms RF phase noise.

Similarly, for mode 1, the reduction factor $\bar{R}_1$ is given by

$$\bar{R_1} = \bar{R_A}\left[1 + N_{cc}G_1^2\frac{\sigma_1^2}{\sigma_{\Delta A}^2}\right] \tag{7}$$

where $\sigma_1$ is the rms noise on the mode 1 measurement and $\sigma_{\Delta A}$ is the rms RF amplitude noise.

In the above equations, the effect of the RF noise scales linearly with the number of cavities (addition in power) as their noise processes are assumed uncorrelated. But identical measurement noise samples are injected in each cavity feedback, resulting in a quadratic scaling factor.

As expected, the emittance growth rate reduction ($\bar{R}_0$, $\bar{R}_1$) is less effective with increasing measurement noise. The crab cavity noise dominates the emittance growth for low feedback gains and that makes the system beneficial, whereas the measurement noise dominates for very high feedback gains (its contribution is scaled by $G_0^2$, $G_1^2$) resulting in detrimental effects. Therefore, in the presence of measurement noise, we anticipate a limitation on the feedback performance and the existence of an optimal gain beyond which the feedback actually becomes detrimental.

### B. Maximum loop gain as a function of loop delay

The maximum loop gain as a function of loop delay was also derived in [3], and is given by

$$\alpha_{0,opt} = 0.32 \frac{\pi}{2} \frac{\tau_d}{\tau_L} \approx \frac{1}{2} \frac{\tau_d}{\tau_L} \tag{8}$$

where $\tau_d$ is the decoherence time and $\tau_L$ is the loop delay.

## IV. HSR PICKUP SPECIFICATIONS

### A. HSR parameters

In this note, we use the following parameters for the HSR at 275 GeV *in collisions.*

| $f_{rev}$ (kHz) | $\sigma_\tau$ (ns) | $\sigma_{\nu_b}$ | $\beta_{cc}$ (m) | $N_{cc}$ 197 MHz | $V_0$ 197 MHz (MV) |
|---|---|---|---|---|---|
| 78.2 | 0.2 | 1.4e-3 | 1300 | 8 | 6.1 MV |

Table I. HSR parameters at 275 GeV and in collisions.

### B. Optimal $\beta_p$ value

The crab cavities must be placed at a high $\beta$ location to achieve the required crabbing angle with the smallest possible voltage.

The ratio of the measured deviation at the pickup and the phase noise at the crab cavity is proportional to the square root of the product of the $\beta$ function values at those two points. Note that for a higher $\beta_p$, lower $G_0$ and $G_1$ are needed to maintain the same emittance growth rate reduction (Equations 2, 5). Consequently, a high $\beta_p$ also reduces the effect of measurement noise, as expected. In this work, we use $\beta_p = 30$ m at the pickup. The exact value will depend on the final optics and pickup placement. This is a conservative estimate.

### C. Optimal loop gain

With the parameters listed in Table I we compute a decoherence time $\tau_d = 1.5$ ms. From past experience with the SPS and LHC transverse dampers, we anticipate a three to five turns loop delay for the noise feedback system [8]. Using Equation 8 and the more conservative five turns ($\tau_L = 64$ $\mu$s), we obtain feedback gains $\alpha_{0,opt} = \alpha_{1,opt} = \frac{1}{2}\frac{\tau_d}{\tau_L} = 11.7$, resulting in a feedback damping time of 0.13 ms (ten turns).

### D. Single Bunch Measurement Noise Thresholds

The 197 MHz crab cavity system will contribute *significantly* more to emittance growth due to RF noise than the 394 MHz system. The RF noise thresholds in the 197 MHz system that achieve an emittance growth rate comparable to IBS are $\sigma_{\Delta\phi} = 1.75$ $\mu$rad and $\sigma_{\Delta A} = 7 \cdot 10^{-6}$ [2]. The actual noise level will strongly depend on the RF/LLRF architecture and component performance. A conservative estimate leads to $\sigma_{\Delta\phi} = 11$ $\mu$rad and $\sigma_{\Delta A} = 11 \cdot 10^{-6}$ [2]. So, the phase noise emittance growth has to be reduced by a factor of 6.3 and the amplitude noise growth by just about 1.6.

These reduction factors can be achieved with various combinations of measurement noise to RF noise ratios and feedback gains (Equations 6 and 7), as seen in Figures 3 and 4. Various combinations of noise ratios and gains satisfy the requirements, as long as we stay to the left of the $\alpha = 11.7$ line and below the emittance growth rate reduction goal.

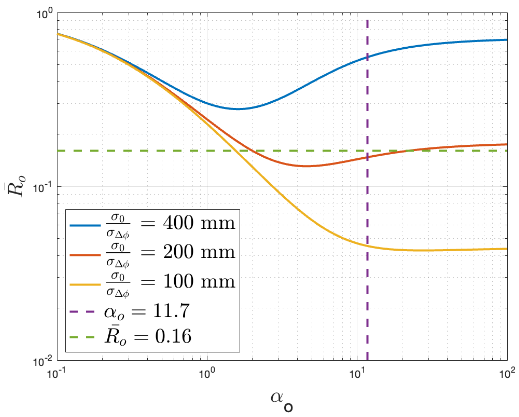


Figure 3. Emittance growth reduction factor with varying mode 0 measurement error to phase noise ratios.

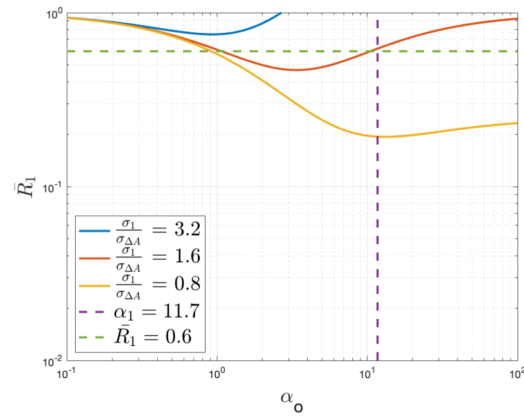


Figure 4. Emittance growth reduction factor with varying mode 1 measurement error to amplitude noise ratios.

The limiting noise ratio is given by the curve passing through the intersection of these two lines:

$$\frac{\sigma_0}{\sigma_{\Delta\phi}} < 200 \text{ mm}$$
$$\frac{\sigma_1}{\sigma_{\Delta A}} < 1.6$$

and thus $\sigma_0 < 2.2\ \mu$m and $\sigma_1 < 18\ \mu$rad.

### E. Multi-bunch Measurement Noise Threshold

The closed loop bandwidth of the crab cavity RF system will be limited to at most 650 kHz (loop delay of 320 ns). As a result, the noise bandwidth will also be limited to 136 kHz. In addition, the bunches are spaced every 41 ns and the measurement noise is uncorrelated from bunch to bunch. Therefore, there is white measurement noise extending to 12.3 MHz (half the sampling frequency). Filtering the data with a low-pass filter matching the signal spectrum will scale the measurement noise power by a factor of 650 kHz/12.3 MHz = 0.053. The noise standard deviation would be scaled by 0.23 $(= \sqrt{0.053})$, a factor of about 4.4 improvement in signal-to-noise ratio. This increases the resolution threshold to 9.6 $\mu$m rms and 78 $\mu$rad rms for the multi-bunch measurement. This is a tight, but achievable specification.

## V. CONCLUSIONS

A dedicated feedback system has been proposed to reduce RF noise effects on the transverse emittance. This system would use a dedicated pickup to measure the mode 0 and 1 motion of each bunch. After processing, it would modulate the phase and amplitude of the crab cavity voltage to correct the RF noise.

The performance of the system will greatly depend on the pickup resolution. The HSR at 275 GeV is the most critical case and has been used to determine the measurement noise thresholds for the pickup. The single bunch measurement resolution is $\sigma_0 < 2.2$ $\mu$m and $\sigma_1 < 18$ $\mu$rad. Filtering over a few bunches could be used to relax these thresholds to $\sigma_0 < 9.6$ $\mu$m and $\sigma_1 < 78$ $\mu$rad.

These thresholds are assuming a $\beta_p$ of 30 meters and using early estimates of the rms phase and amplitude noise in the crab cavities. A tune spread of $1.4 \cdot 10^{-3}$ in collisions was used. The pickup specifications should be updated if these parameters change.


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