EIC TRANSVERSE EMITTANCE GROWTH DUE TO CRAB CAVITY RF NOISE: ESTIMATES AND MITIGATION

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Introduction

- The Electron-Ion Collider (EIC) requires crab cavities to compensate for a ***25 mrad*** crossing angle.
- The crab cavity Radio Frequency (RF) system will inject low levels of noise to the crabbing field, generating tran sverse emittance growth and potentially limiting lumin osity lifetime.
- In this work, we set transverse emittance growth targets, which then allow us to quantify RF noise specifications for reasonable performance.
- Finally, we evaluate the possible mitigation of the RF n oise induced emittance growth via a dedicated feedback system.

Transverse Emittance Growth

$$\frac{d\epsilon_n}{dt} = N_{cavities}\gamma\beta_{cc}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2\left\{e^{-\sigma_\phi{}^2}\left[I_o\left[\sigma_\phi{}^2\right]+2\sum_{l=1}^{\infty}I_{2l}\left[\sigma_\phi{}^2\right]\right]\right\}\sum_{k=-\infty}^{\infty}\int_{-\infty}^{\infty}S_{\Delta\phi}\left[(k\pm\nu_b)f_{rev}\right]\rho\left(\nu_b\right)d\nu_b$$

$$= N_{cavities}\gamma\beta_{cc}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2 C_{\Delta\phi}(\sigma_\phi)\,\frac{2\sigma^2_{\Delta\phi}}{f_{rev}}$$

$$= \frac{1}{\beta*}\left[N_{cavities}\gamma\left(\frac{ec\theta_{cc}f_{rev}}{4\omega_{RF}}\right)^2\right]C_{\Delta\phi}(\sigma_\phi)\,\frac{2\sigma^2_{\Delta\phi}}{f_{rev}}$$

$$\frac{d\epsilon_n}{dt} = N_{cavities}\gamma\beta_{cc}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2\left\{e^{-\sigma_\phi{}^2}\sum_{l=0}^{\infty}I_{2l+1}\left[\sigma_\phi{}^2\right]\right\}\sum_{k=-\infty}^{\infty}\int_{-\infty}^{\infty}S_{\Delta A}\left[(k\pm\nu_b\pm\nu_s)f_{rev}\right]\rho\left(\nu_b\right)d\nu_b$$

$$= \frac{1}{\beta*}\left[N_{cavities}\gamma\left(\frac{ec\theta_{cc}f_{rev}}{4\omega_{RF}}\right)^2\right]C_{\Delta A}(\sigma_\phi)\,\frac{4\sigma^2_{\Delta A}}{f_{rev}}$$

- P. Baudrenghien and I derived a formalism to evaluate the *normalized* transverse emittance growth rate due to RF noise [1].
- Operational parameters: Little or no control. This term is effectively inversely proportional to 1/β* for a given full crabbing angle θ_{cc}.
- Bunch length dependence: Effectively constant over operational range.
- RF noise: Depends on RF and LLRF technology (to be determined).
- Setting emittance growth rate targets allows us to estimate RF noise thresholds.

Emittance growth rate targets

- HL-LHC: 1%/hr to minimize impact on luminosity.
- EIC ESR: Lower than emittance damping time (73 ms, 10 GeV).
- EIC HSR: Comparable to the IBS growth rate (for example 2 hours, 100 GeV).
- The EIC target rates are significantly relaxed compared to the HL-LHC. On the other hand, we must deal with a much higher crabbing angle (25 mrad and 0.38 mrad respectively).
- In addition, the emittance is much lower in the EIC, and thus, the emittance growth rate as a percentage is much higher.

Sampled noise threshold

- $\Delta A = \Delta V/V$

	$\sigma_{\Delta\varphi}$ (μrad)	$\sigma_{\Delta A}$ (1e-6)
HL-LHC	8.17	13.30
ESR 5 GeV	805	12700
ESR 10 GeV	860	13600
ESR 18 GeV	548	7060
HSR 41 GeV	3.09	10.1
HSR 100 GeV	2.69	9.36
HSR 275 GeV	**1.75**	**7.07**
Au 41 GeV	18.7	39.4
Au 110 GeV	5.12	17.8

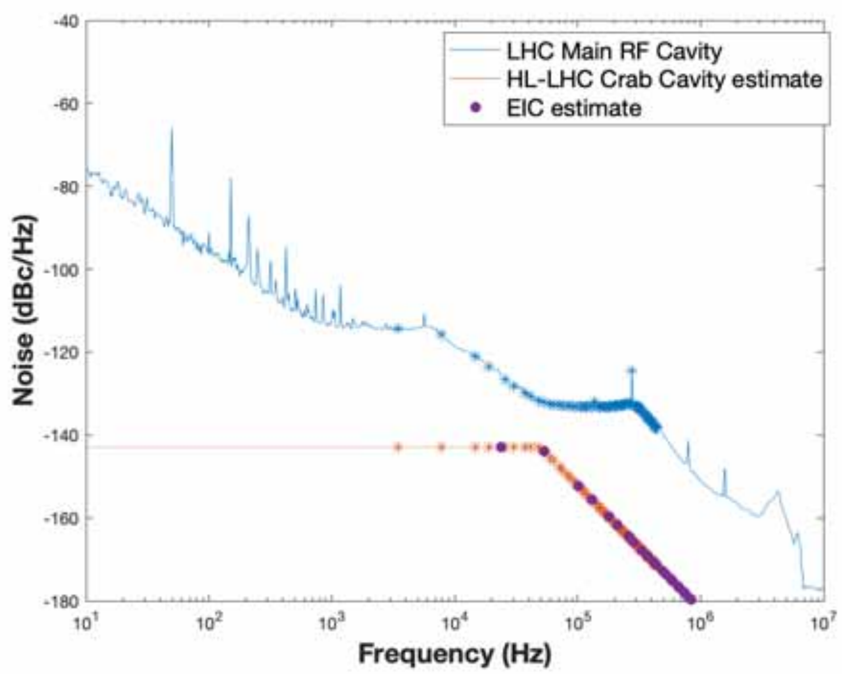
- Unsurprisingly, the ESR thresholds are manageable.
- The thresholds for the HL-LHC and the HSR are significantly lower than the state of the art. A mitigation of the Crab Cavity RF noise effects is required.

RF noise spectrum

$$\frac{2\sigma_\phi^2}{f_{rev}} = \sum_{k=-\infty}^{\infty} \int_{-\infty}^{\infty} S_{\Delta\phi}\left[(k \pm \nu_b) f_{rev}\right] \rho(\nu_b)\, d\nu_b f_{rev}$$

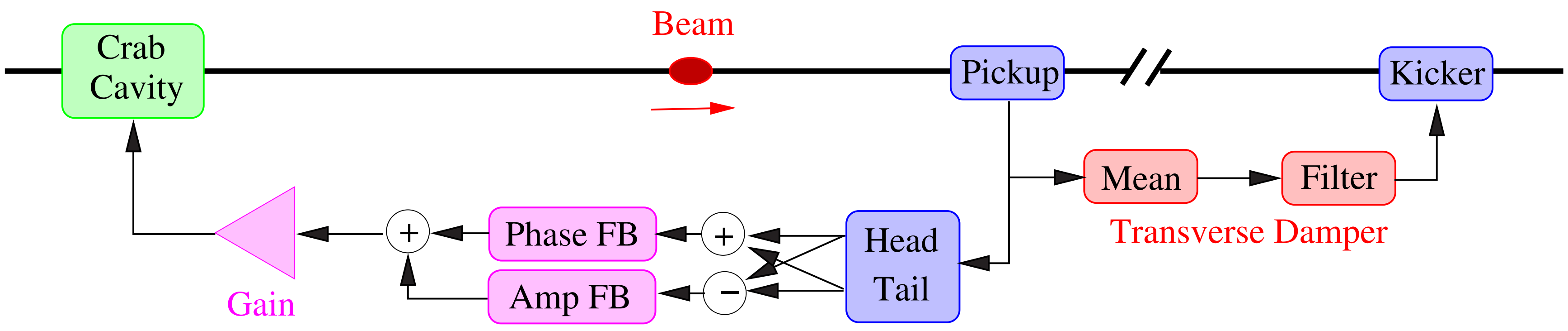
- For LLRF design purposes, the noise thresholds should be converted to a power spectral density and bandwidth.
- The higher EIC revolution frequency reduces the beam sampled power.
- Assuming **narrowband**(*) CC LLRF (~50 kHz), the figure below shows an estimated noise spectrum and the corresponding beam sampling.

- The EIC beam would sample 6.5 times lower noise power for the same spectrum.
- For a given $\sigma_{\Delta\varphi}$ and $\sigma_{\Delta A}$ level though, the PSD is largely unchanged (f_{rev} scaling).
- (*) Tradeoff with transverse instabilities to be studied.



Crab Cavity Noise Feedback

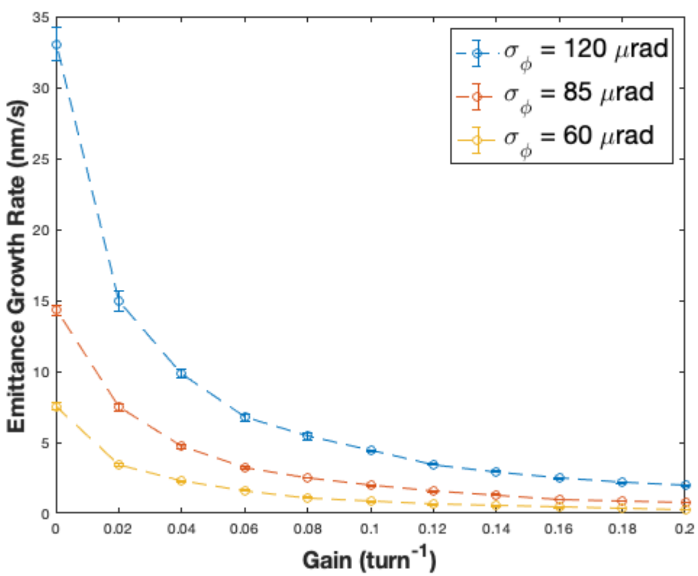
- A dedicated feedback system could mitigate these effects. A similar system is planned for the HL-LHC [2], [3].

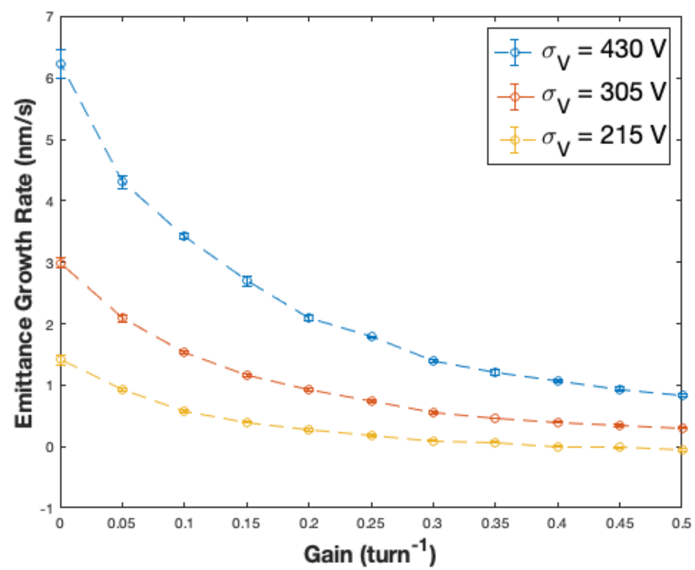


- The bunch head and tail position would be extracted from the pickup signal. The head/tail Δ and Σ estimate the bunch tilt and offset (amplitude and phase noise respectively).
- We conducted simulations of such a system for the EIC HSR to study its potential performance and limitations.

Emittance Growth with FB gain

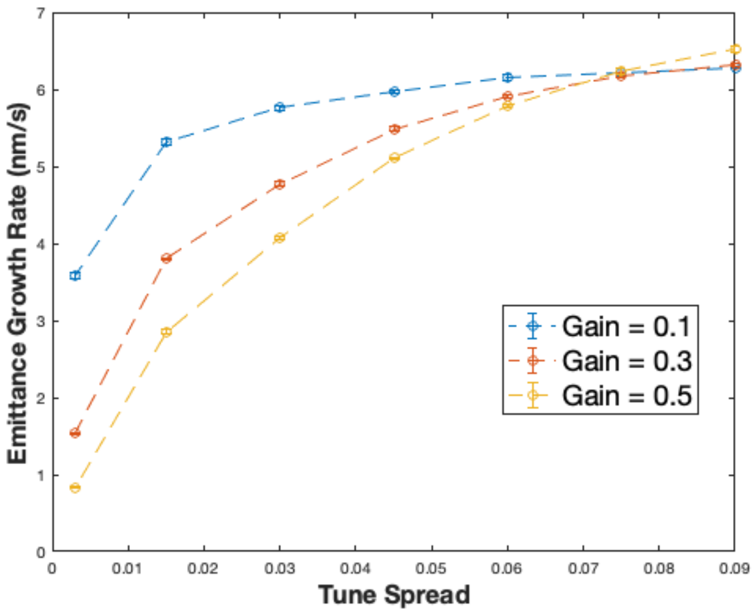
- An *ideal* Crab Cavity Noise Feedback system has the potential to significantly reduce both the phase (left) and amplitude (right) noise effects on transverse emittance growth.
- The emittance growth rate might appear unreasonably high, but the *total* emittance growth over the course of the simulation is comparable to an EIC coast.





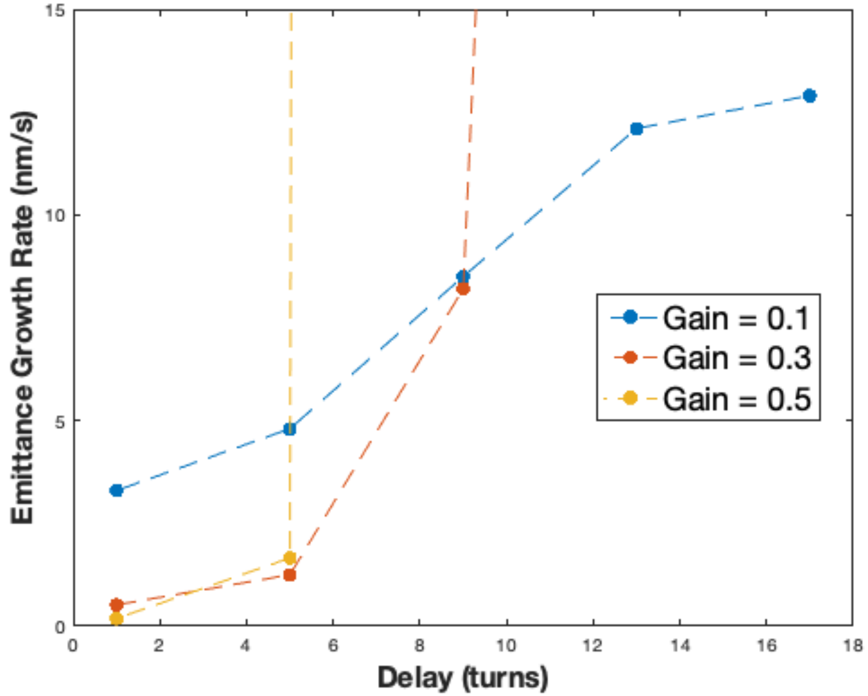
Emittance Growth with Tune Spread

- So, what would limit the system's performance?
- The feedback system can mitigate the noise if the damping time is shorter than the decoherence time.
- As the tune spread is increased, the system's effectiveness is reduced (for a fixed system delay).



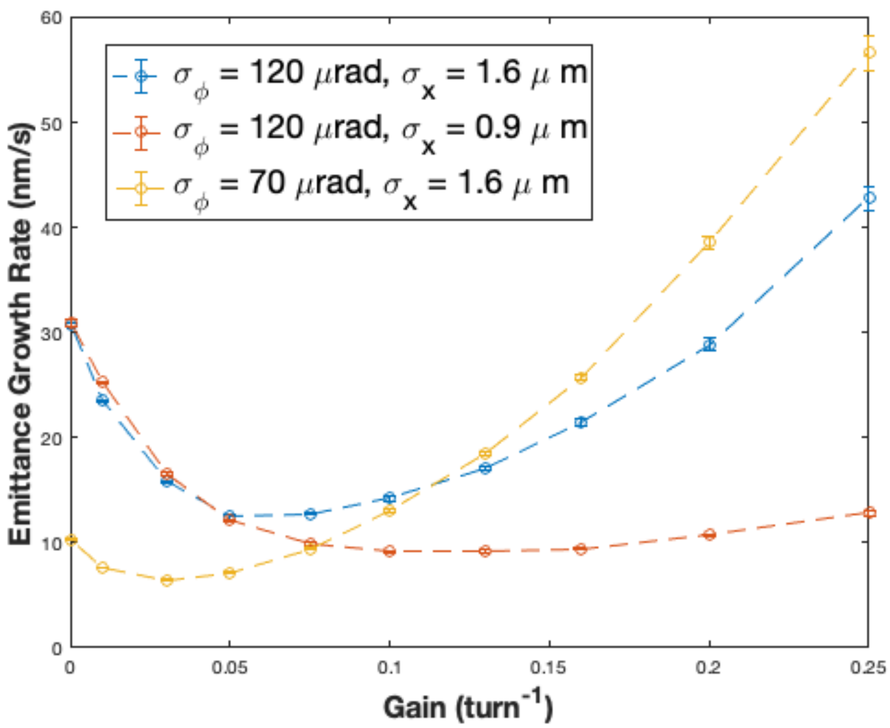
Emittance Growth with Delay

- Similarly, increasing the system's delay, reduces the performance.
- It also leads to loop instability for high gain settings.



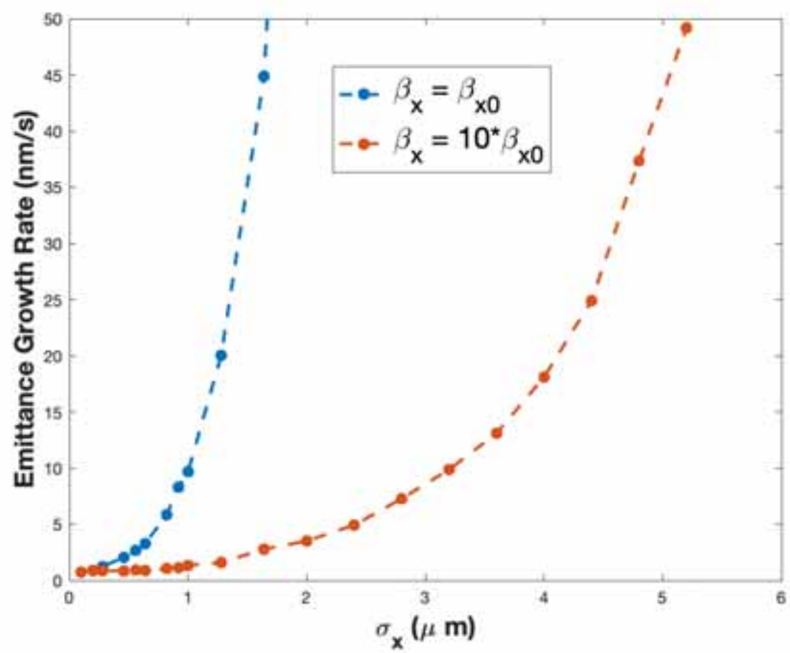
Measurement noise

- The most important limitation though is the **pickup precision**.
- Measurement noise was injected in the simulation to study this effect.
- As expected, emittance growth rate is dominated by crab cavity noise for low feedback gain and by measurement noise for high gain.



Measurement noise

- The sensitivity to measurement noise will highly depend on the crab cavity and pickup β function ratio!
- Ideally, the pickup would be placed at a high β location to minimize the effect of measurement noise.
- The pickup should also have a π/2 phase advance with respect to the crab cavity.



Conclusions

- The sensitivity to RF noise is very high in the EIC HSR.
- A dedicated feedback system could reduce the Crab Cavity RF noise effects and thus relax the RF noise threshold.
- The performance of the system will greatly depend on the pickup precision, location, and additional technical specifications (signal processing/equalization, longitudinal motion effect, etc).
- An estimate of the pickup performance is necessary to determine precision specifications, which in turn will allow us to estimate the crab cavity RF noise threshold in the presence of the dedicated noise feedback system.
- Parallel studies on the beam/LLRF interaction will also allow us to determine the viable range of RF bandwidth and proceed with the LLRF design.

References

- [1] P. Baudrenghien, T. Mastoridis, *Transverse emittance growth due to RF noise in the high-luminosity LHC crab cavities*, Phys. Rev. ST Accel. Beams 18 (2015) 101001.
- [2] P. Baudrenghien, T. Mastoridis, *Crab Cavity RF Noise Feedback and Transverse Damper Interaction*, CERN-ACC-NOTE-2019-0006, 2019-03-08.
- [3] T. Mastoridis, P. Baudrenghien, *Transverse emittance growth due to RF Noise in Crab Cavities: Theory, Measurements, Cure, and High-Luminosity LHC estimates*, prepared for publication.