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

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Abstract

The Electron-Ion Collider (EIC) requires crab cavities to compensate for a 25 mrad crossing angle and achieve maximum luminosity. The crab cavity Radio Frequency (RF) system will inject low levels of noise to the crabbing field, generating transverse emittance growth and potentially limiting luminosity lifetime. In this work, we estimate the transverse emittance growth rate as a function of the Crab Cavity RF noise and quantify RF noise specifications for reasonable performance. Finally, we evaluate the possible mitigation of the RF noise induced emittance growth via a dedicated feedback system.

INTRODUCTION AND SIMULATIONS

A theoretical formalism evaluating the transverse emittance growth rate due to RF phase ($\sigma_{\Delta\phi}$) and amplitude ($\sigma_{\Delta A}$, $\Delta A = \Delta V/V$) noise was derived in [1]. The emittance growth rate depends on:

- Operational and accelerator parameters. There is little or no control of these values. This term is effectively inversely proportional to $1/\beta^*$ for a given full crabbing angle θ_{cc}.
- The bunch length. This term is almost constant over the EIC operational range.
- The RF noise power spectral density sampled by the beam. This term depends on the RF and LLRF technology.

Simulations were performed [2] to confirm the above relationships for the EIC, using PyHEADTAIL, a macro-particle tracking code that simulates collective beam dynamics [3]. There was very good agreement between simulations and the theoretical expressions.

BUNCH LENGTH EFFECTS

The EIC Electron Storage Ring (ESR) and Hadron Storage Ring (HSR) bunch lengths vary depending on the collision energy and hadron species. The verified theoretical expressions were used to estimate the effect of the planned EIC bunch lengths on the EIC transverse emittance growth rates due to RF noise, shown in Table 1. The results were also compared to the High-Luminosity Large Hadron Collider (HL-LHC). The terms $C_{\Delta\phi}(\sigma_\phi)$ and $C_{\Delta A}(\sigma_\phi)$ show the scaling of the phase and amplitude noise effects respectively due to the bunch length. σ_ϕ is the bunch length in radians with respect to the crab cavity frequency.

Table 1: HL-LHC and EIC ESR/HSR Bunch Length and $C_{\Delta\phi}(\sigma_\phi)$, $C_{\Delta A}(\sigma_\phi)$ Terms

	σ_z (cm)	σ_ϕ (rad)	$C_{\Delta\phi}$	$C_{\Delta A}$
HL-LHC	7.5	0.630	0.726	0.137
ESR 5 GeV	0.7	0.058	0.996	0.002
ESR 10 GeV	0.7	0.058	0.996	0.002
ESR 18 GeV	0.9	0.074	0.995	0.003
HSR 41 GeV	7.5	0.309	0.913	0.043
HSR 100 GeV	7	0.289	0.922	0.038
HSR 275 GeV	6	0.248	0.942	0.029
Au 41 GeV	11.6	0.479	0.816	0.092
Au 110 GeV	7	0.289	0.922	0.038

Clearly, there is lower sensitivity to amplitude noise in the EIC than in the HL-LHC due to the shorter bunch length, especially for the ESR. This is significant if a bunch-by-bunch transverse feedback system is employed in the EIC. Such a system acts on the bunch centroid and can thus only counteract the effects of phase noise in the crabbing system. Since phase noise is dominant in the EIC, a bunch-by-bunch transverse feedback can considerably reduce transverse emittance growth due to crab cavity RF noise.

RF NOISE REQUIREMENTS

Using the verified theoretical expressions, we can then set an RF noise requirement to achieve a target transverse emittance growth rate. The target emittance growth rate for the HL-LHC is 1%/hr to minimize the impact on luminosity. For the EIC ESR, the emittance growth rate must be lower than the emittance damping time due to synchrotron radiation. For the HSR, the emittance growth rate target is set equal to the Intra-Beam Scattering (IBS) growth rate. This is possibly an optimistic threshold since the EIC Strong Hadron Cooling is designed to just counteract the IBS to maintain luminosity. There are also additional sources of growth (beam-beam effects for example). So, the HSR thresholds might have to be lowered further in the future.

The target transverse emittance growth rate for all EIC energy cases are presented in [2]. In summary, the ESR target growth rate is many orders of magnitude higher than the rate for the HSR due to the strong synchrotron radiation damping. The HSR also has much higher target rates than the HL-LHC. This is due to the very tight HL-LHC specification to achieve minimal impact on luminosity and the much lower transverse emittance. Using these targets and the theoretical

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Table 2: HL-LHC and EIC ESR/HSR Crab Cavity RF Noise Thresholds

	$\sigma_{\Delta\phi}$ (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

formalism, RF noise thresholds for phase and amplitude noise were calculated for the HL-LHC, and the EIC ESR and HSR and are shown in Table 2. The much higher EIC crabbing angle leads to a significantly higher sensitivity to noise compared to the HL-LHC. The transverse emittance growth rate scales as θ_{cc}^2, the EIC sensitivity to RF noise power is 4000 times higher than the HL-LHC. On the other hand, the emittance growth rate target for the HL-LHC is three orders of magnitude lower than for the EIC HSR, and eight orders of magnitude lower than the EIC ESR. Most other parameters are comparable, and as a result, the EIC HSR noise thresholds are in the same order of magnitude, but still lower than the already challenging levels required for the HL-LHC. The EIC ESR thresholds are much higher due to the fast transverse radiation damping time.

RF NOISE SPECTRUM

For the purposes of the Low-Level RF (LLRF) design, these noise levels should be converted to a power spectral density. The higher EIC revolution frequency reduces the beam sampled power, since there are fewer revolution harmonics within the closed loop bandwidth of the crab cavity response.

Figure 1 shows the LHC accelerating cavities noise power spectral density $S_{\Delta\phi}(f)$ for reference, and the HL-LHC and EIC crab cavity RF noise estimates, as well as the corresponding beam sampling. The EIC beam would sample 6.5 times lower noise power than the HL-LHC beam for the same spectrum.

The resulting rms sampled noise is $\sigma_\phi = 27\,\mu$rad for the HL-LHC and 11 µrad for the EIC. So, even with this extremely low RF noise PSD, the rms sampled noise is an order of magnitude higher than the target.

CRAB CAVITY RF NOISE FEEDBACK

The RF noise sensitivity is therefore very high in the EIC. The RF noise threshold for the HSR is significantly lower than the technological state of the art.

A dedicated feedback system could mitigate these effects. A similar system is planned for the HL-LHC [4, 5]. A simplified block diagram of this system is shown in Figure 2.

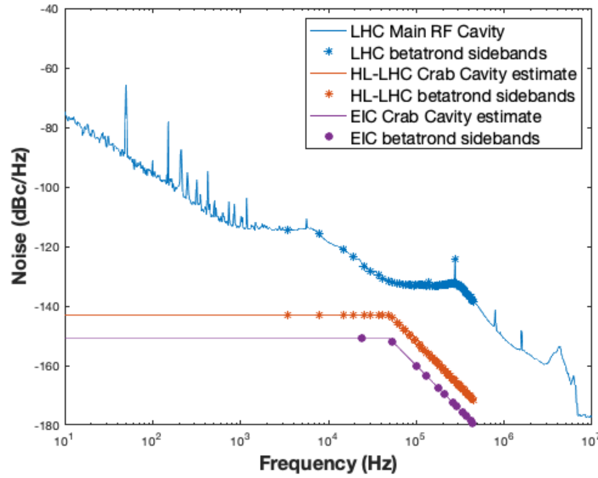

Figure 1: RF noise power spectral density $S_{\Delta\phi}(f)$ for LHC accelerating cavities and HL-LHC/EIC crab cavity estimate.

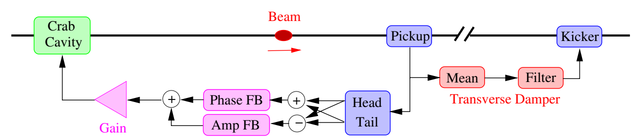

Figure 2: Block diagram for proposed crab cavity RF noise feedback system.

The bunch head and tail position would be extracted from the pickup signal. Since we are concerned with the residual noise after *all* the crabbing and uncrabbing cavities, the pickup should be outside the IR region. The head/tail difference and sum estimate the bunch tilt and offset (due to amplitude and phase noise respectively).

We conducted simulations of such a system for the EIC HSR to study its potential performance and limitations. As shown in Figure 3, an ideal Crab Cavity Noise Feedback system has the potential to significantly reduce the phase noise effects on transverse emittance growth. Simulations on amplitude noise effects show similarly promising results. It should be noted that even though the emittance growth rates might appear unreasonably high, the *total* emittance growth over the course of the simulation is comparable to an EIC coast.

The feedback system can mitigate the noise effects if the feedback 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). Simulations were performed to quantify the tune spread effect on emittance growth reduction and showed that any changes of the operational tune spread value will negatively impact the performance of the crab cavity noise feedback system.

For similar reasons, an increase of the system's delay, leads to a performance reduction. In addition, high system delay leads to feedback loop instability for high gain settings. Simulations show that the system is unstable when the delay exceeds 9 turns for a gain of 0.3 and when it exceeds 5 turns for a gain of 0.5.

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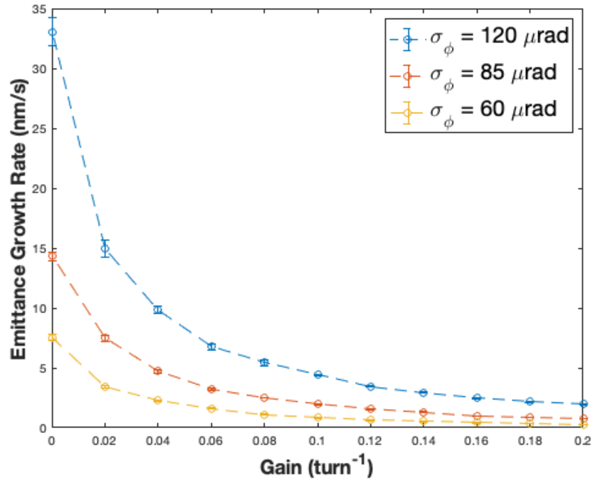

Figure 3: Emittance growth rate with feedback gain (phase noise).

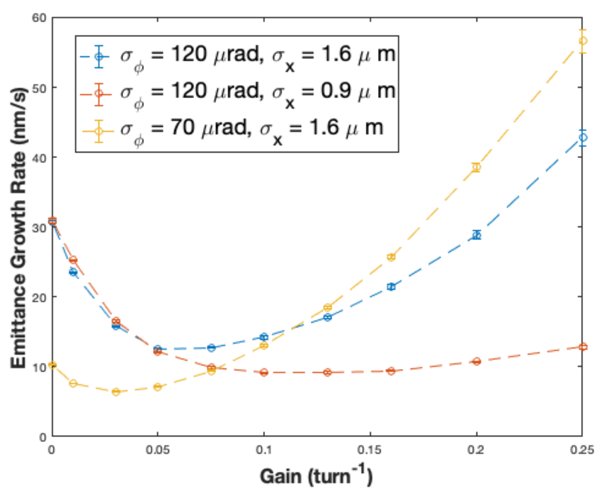

Figure 4: Emittance growth rate with feedback gain in the presence of measurement noise.

The most important limitation to the system performance though is the pickup precision. Measurement noise was injected in the simulation to study this effect. As expected, the transverse emittance growth rate is dominated by the crab cavity RF noise for low feedback gains but is dominated by the measurement noise for high gains, as seen in Figure 4. Simplistically, when the gain is high, the feedback system can suppress the crab cavity RF noise, but it also amplifies the measurement noise to the point that it leads to significant emittance growth.

It should be noted that 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 $\pi/2$ phase advance with respect to the crab cavity.

CONCLUSIONS AND FUTURE STEPS

The sensitivity to RF noise is *very* high in the EIC. The RF noise threshold for the HSR will be very hard to achieve technologically.

A dedicated feedback system could reduce the crab cavity RF noise effects and thus relax the crab cavity RF noise threshold. The performance of the system will *greatly* depend on the pickup precision, location, and additional technical specifications. The precision requirements could be relaxed by averaging over many bunches, taking advantage of the low crab cavity closed-loop bandwidth. To a lesser extent, the crab cavity noise feedback system performance will also depend on the tune spread and the system delay.

The pickup is a *critical* component for this system and the immediate future steps should be focused on its specifications.

In parallel, the crab cavity LLRF design should be studied. The LLRF should regulate individual station voltages *and* the total crabbing/uncrabbing voltage, while keeping the noise injected to the beam as low as possible. Tradeoffs probably exist between low noise and high impedance control architectures. These tradeoffs should be carefully quantified.

It should be noted that the estimates and simulations presented here do *not* include coupling with the machine transverse impedance. HL-LHC simulations have shown a potential reduction of RF noise effects due to this coupling. This reduction is up to a factor of two for *phase* noise, but there is no reduction for *amplitude* noise [6].

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