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EIC Crab Cavity LLRF Studies

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Abstract

The Electron-Ion Collider Crab Cavity Low-Level Radio Frequency system will have to reduce the Crab Cavity impedance to prevent transverse instabilities, while regulating the crabbing voltage and minimizing the Radio Frequency noise levels injected to the beam. These are challenging and partly conflicting requirements. This works summarizes the specifications to achieve these requirements and investigates the possible trade-offs in the architecture.

I. LLRF DESCRIPTION

The EIC will employ crab cavities to compensate for the significant crossing angle, leading to an order of magnitude increase in luminosity. 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 have to reduce the Crab Cavity impedance to prevent transverse instabilities. It will also have to maintain extremely low Radio Frequency (RF) noise levels injected to the beam.

Figure 1 shows a block diagram of the proposed Crab Cavity RF/LLRF. The High-Level RF is indicated in red and the LLRF in green. Elements in the dashed square are digitized. The LLRF includes an analog proportional controller and a digital narrowband integrator to regulate the mean value of the cavity voltage. In addition, a digital One-Turn Feedback system (OTFB) is included for additional impedance control. The OTFB system has high gain at the betatron sidebands of the revolution harmonics, and low gain at all other frequencies. This work studies the controller around individual stations, but, as the block diagram indicates, it might eventually be useful to add an additional controller that keeps the total crabbing and uncrabbing voltage to zero. Such a system would sample the Cavity Sum signal and act on one or all cavities. We refer to this system as the "global" controller. The LLRF is described in more detail in [1].

The LLRF objectives could lead to conflicting requirements. For example, a wider bandwidth would help transverse instability control, but would significantly increase the noise injected to the beam. It is thus important to set the specifications for each of these items and then explore the tradeoffs.

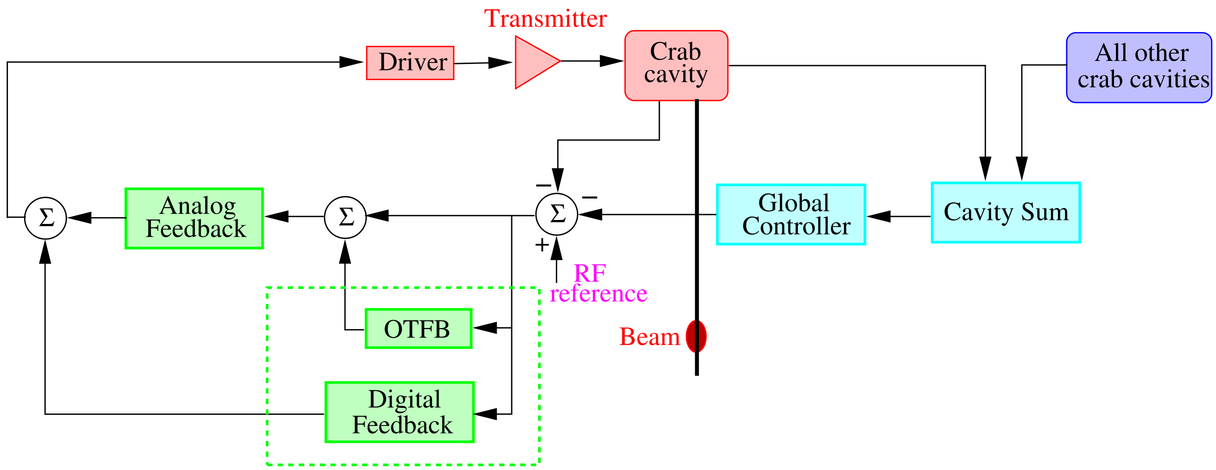

Figure 1. Crab Cavity RF/LLRF Block Diagram.

II. CRAB CAVITY RF NOISE

The Crab Cavity RF system will inject low levels of noise to the crabbing field, generate transverse emittance growth and potentially limit luminosity lifetime. We estimated the transverse emittance growth rate as a function of the Crab Cavity RF noise and quantified RF noise specifications for reasonable performance [2].

The target emittance growth rate for the EIC Electron Storage Ring (ESR) 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 there will be additional sources of emittance growth (beam-beam effects for example), and all of them collectively should not significantly exceed the IBS rate. So, the HSR thresholds might have to be further adjusted lower once an emittance growth rate target has been established.

As expected, the ESR thresholds are much higher due to the fast transverse radiation damping time. The resulting RF noise thresholds for the HSR are *very* challenging. The lowest threshold is at 275 GeV ($\approx 2\ \mu$rad phase and $\approx 7\cdot 10^{-6}\ \Delta V/V$). Therefore, a careful LLRF design *and* a mitigation of the Crab Cavity RF noise effects will be required. A dedicated feedback system is presented in [2]. 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 and the immediate future steps should be focused on its specifications.

III. TRANSIENT BEAM LOADING

A time-domain simulation was developed to study the interaction between the particle beam and the crab cavities in the EIC, including the LLRF feedback loops. A full description of the simulation, including validation, as well as a detailed study of transient beam loading effects in the crab cavities is presented in [3]. We used the following metrics: the transverse offset at the Interaction Point (Δx_{IP}), the transverse offset *after* uncrabbing ($\Delta x_{\mathrm{offset}}$, due to a *very* small asymmetry in the crabbing/uncrabbing transients), and the transmitter power transients. Beam loading is higher for the ESR at 10 GeV, so this ring and energy were used for this study.

Figure 2 shows the Δx_{IP} transients for three different LLRF gains, for a constant bunch position error of 0.6 mm. Clearly, the transient beam loading in the crab cavities leads

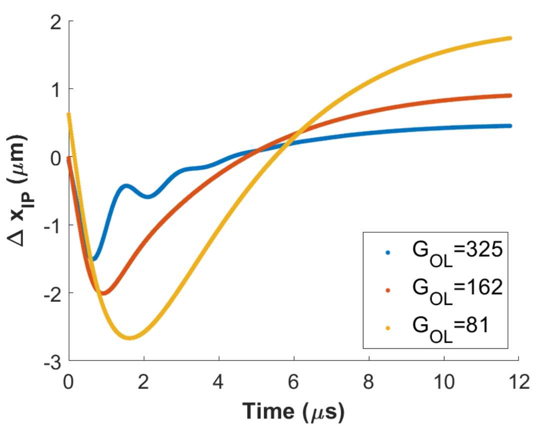

Figure 2. x-offset at the IP.

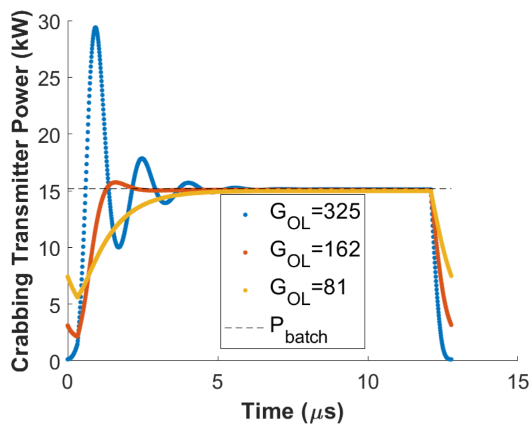

Figure 3. Crabbing transmitter power.

to *very* small effects on Δx_{IP}.

Figure 3 shows the transmitter power for the same feedback gains. Depending on the LLRF gain/bandwidth choices, the peak power can be *double* the average or analytically computed power ($\mathrm{P}_{\mathrm{batch}}$). This increase is not concerning but should be included in the transmitter specifications.

The simulation was also used to study the global controller. The main function of the global controller will be to ramp the crabbing/uncrabbing cavities down in case of a station loss, due to a quench, transmitter trip, RF/LLRF fault, etc. There is a significant trade-off between the global controller response time and the required transmitter power. The controller is tasked with reducing the voltage to zero within a couple of turns. This is effectively equivalent to *filling* the cavity to the nominal field, and thus requires significant power. The global controller response time will be a couple of turns to maintain reasonable transmitter power levels. There will be some residual bunch-by-bunch rotation as a result, comparable to the half-crabbing angle for the first few bunches and slowly reduced thereafter [3].

The unclosed crab bump in the EIC will be in the order of 1.2 mm. This is comparable to the constant bunch position error of 0.6 mm used in this study. Therefore, we do not expect significant beam loading due to the unclosed crab bump.

IV. TRANSVERSE INSTABILITIES

Estimates of the crab cavity impedance in the presence of feedback and the resulting stability margins using simplified and generalized Nyquist stability criteria were presented in [1]. Transverse instabilities are of much higher concern for the HSR rather than for the ESR, since the ESR has much faster damping times. In addition, the higher beam energy requires higher beta function at the crab cavities (β_{cc}) for a given voltage. Therefore, the HSR at 275 GeV is the most challenging case for transverse instabilities. It should be noted that this is the most challenging ring/energy for RF noise effects as well, as shown in Section II. A LLRF design/architecture that satisfies all the requirements for the HSR at 275 GeV, would work for both rings and all energies.

The open loop, closed loop, and closed loop impedance with the OTFB ($m = 0$) are shown in Figure 4 from [1]. For a delay of 320 ns, the resulting optimal gain is ≈4400 for the 197 MHz cavities and ≈2200 for the 394 MHz cavities. The impedance is reduced by these factors at the fundamental.

Figure 5 shows the resulting stability region (simplified criterion), as well as the magnitude of the complex betatron frequency shift $|\Lambda|$ for the three cases of interest. The open loop and closed loop cases are unstable by a factor of ≈18 and ≈1.3 respectively. The closed loop with the OTFB has a stability margin of about ≈8.6. The margin with the generalized Nyquist criteria in the presence of OTFB is very similar (≈8.5).

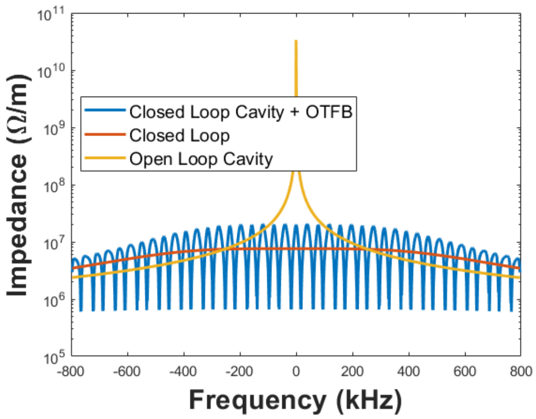

Figure 4. Crab Cavity transverse impedance magnitude ($m = 0$).

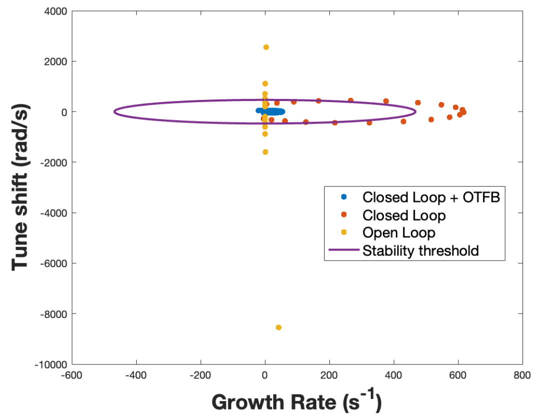

Figure 5. Coupled-bunch stability margin.

V. OPTIMAL LLRF DESIGN

It is clear from Sections II, III, and IV that transient beam loading effects don't play a significant role in the LLRF design. Also, the most critical ring/energy for RF noise effects and transverse instabilities is the HSR at 275 GeV. There are conflicting requirements: we need low gain/bandwidth to reduce RF noise effects, but high gain/bandwidth to achieve the ≈8.5 stability margin for transverse instabilities.

We present possible trade-offs below. These solutions could be used separately or concurrently.

A. Lower Feedback Gain

The effect of different LLRF settings on the stability margins was studied in detail in [1]. As expected, the maximum possible current evolves roughly linear with the RF gain, since the instability depends on the impedance at the fundamental which is decreased proportionally with the gain. We could thus reduce the feedback gain to achieve lower closed RF loop bandwidth. This would of course reduce the transverse stability margin. Figure 6 shows the RF noise power spectral density for the nominal bandwidth (197 MHz cavities), as well as for bandwidths reduced by a factor of 2 or 4. The sampled noise is reduced by almost the same factors (1.98 and 3.92 respectively). The factors are not identical to the bandwidth reduction since the beam samples the noise at the betatron sidebands, with a narrow band set by the tune spread.

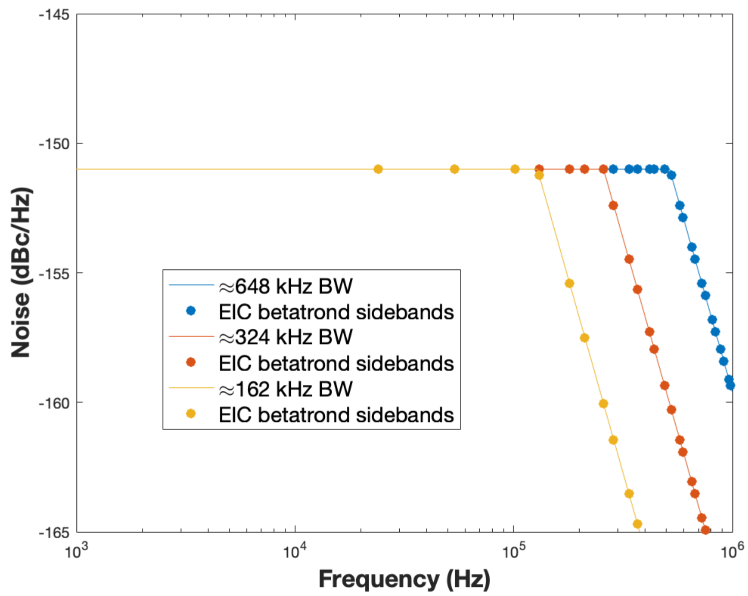

Figure 6. RF noise power spectral density for various RF loop bandwidths (single-sided).

Another approach would be to use different settings for the two crab cavity systems. The total contributions to the complex betatron frequency shift Λ from the two RF systems are comparable. On the other hand, the 197 MHz system is contributing *significantly* more to RF noise issues. As a result, a hybrid approach might be optimal: the 394 MHz system is operated with the nominal gain to reduce the impedance and contributions to transverse instabilities, whereas the 197 MHz system is operated with lower gain and bandwidth to significantly reduce RF noise effects with minimal effect on transverse instabilities.

We should note that we might have to operate with lower RF feedback gain not only to reduce the LLRF bandwidth, but also because it might not be possible to get the dynamic range required for the optimal gain values ($\approx$4400 and $\approx$2200 for the 197 and 394 MHz cavities respectively). These values also correspond to a loop delay of 320 ns, which might prove hard to achieve.

B. Adjust LLRF settings during the cycle

The RF noise and transverse instabilities are most critical at *different* parts of the cycle. We could thus explore a scenario where the LLRF settings are adjusted appropriately at different stages.

Transverse instability thresholds change during the cycle. The most critical time for transverse instabilities in the EIC cycle is right before collisions commence, since beam-beam effects are absent. Beam-beam effects *significantly* increase the tune spread σ_ν and thus the stability margin.

The RF noise effects scale with beam energy, β_{cc}, and possibly the crab cavity voltage (depending on the RF noise sources). The emittance growth is an integrated effect during the whole cycle though. Reducing the RF noise in collisions will have a significant effect on the total emittance growth.

Therefore, reducing the RF bandwidth once the beams are colliding could lead to significant reduction of the sampled RF noise. As long as the bandwidth reduction factor is not higher than the tune spread increase due to beam-beam, the stability margins will not degrade. The exact factor will be determined once there is more clarity on EIC parameters, but it could be higher than 5, a substantial improvement on RF noise effects.

VI. OTFB CHALLENGES

The OTFB notches at the betatron sidebands will have a double-sided bandwidth of ≈700 Hz. Assuming that the most unstable mode is 1 [1], the notches should be placed at the first synchro-betatron sidebands. Then, given the synchrotron frequency of ≈800 Hz, the impedance reduction for modes 0 and 2 will be lower by about 3 dB.

In addition, the tune spread at 275 GeV (before collisions), will be in the order of 1.4e-3 (≈110 Hz frequency spread). This spread, together with any imprecision in the tune measurement, will also lead to small reductions in the OTFB performance. These performance reductions should be considered when setting the minimum stability threshold.

VII. TRANSMITTER CHALLENGES

The crab cavity transmitter power requirements are reasonably low in nominal operation. Beam offsets could significantly affect the required power though. Since two cavities share a cryostat, there might a small misalignment between them. The beam would then be placed at the location that minimizes the offset amplitude from both cavities, leading to up to a 0.6 mm beam offset amplitude.

Figure 7 shows the required transmitter power as a function of the beam offset. We use the more conservative nominal voltage of 11.5 MV per 197 MHz cavity. We also use a DC currrent of 1 A. We set the Q_L to $1.75{\cdot}10^6$ and $(R/Q)_t$ to 2400 Ω/m. Clearly, the

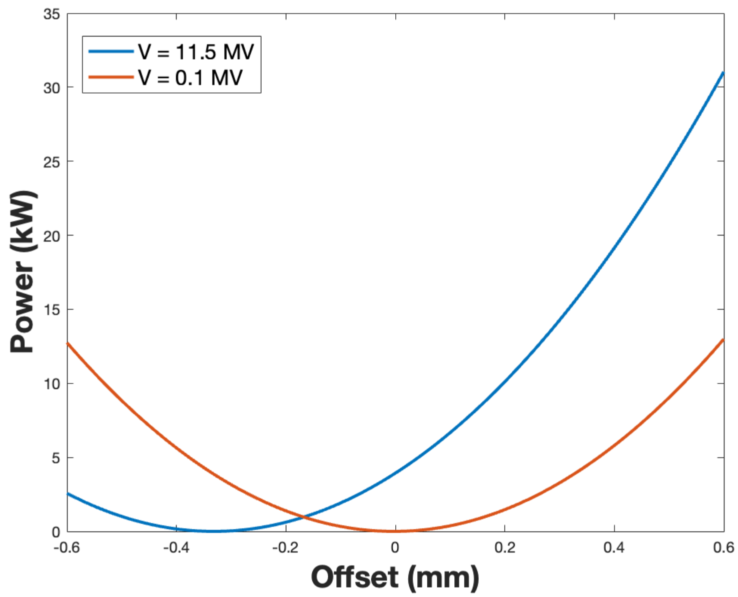

Figure 7. Crab cavity transmitter power as a function of beam offset.

required power increases with positive offset, but it does not come close to the transmitter specification of 70 kW. The concern is the very low power required for a negative offset, when power is extracted from the beam. The transmitter linearity will be very important in this operational scenario, even for very lower power levels, and should be included in the specifications.

In addition, the crab cavities will most probably be operated with very low voltage during injection, leading to a similar issue with low power requirements if there is no beam offset.

A possible mitigation would be to deliberately move the beam so it is not at the mean position between the two cavities, but rather shifted towards a positive offset. That way, both cavities will require higher power. The complication though is that the beam orbit would have to change as the voltage is increased.

VIII. FUTURE STEPS, OPEN QUESTIONS, AND CONCLUSIONS

The LLRF design is at a very early stage. As a result, there are many unknowns on the architecture and component performance:

- We assumed a loop delay of 320 ns. The impedance reduction and stability margins should be updated if the attained loop delay is higher.
- We also assumed that the *very* high RF feedback gain is feasible ($\approx$4400 for the 197 MHz cavities and $\approx$2200 for the 394 MHz cavities).
- The RF noise thresholds assume uncorrelated noise sources that do *not* scale with voltage. As the design matures, the noise sources should be identified. If they are correlated among RF stations, the noise thresholds should be updated. If they scale with voltage, a variable front-end gain could be introduced to mitigate negative effects.
- The operational plan for the crab cavity voltage during the cycle could have a significant effect on RF noise effects. RF noise thresholds should be checked once the operational plan is finalized.

There are also ongoing studies on some elements of the LLRF system:

- The RF noise feedback system will also provide damping for mode 0 and 1 transverse instabilities, and as such it would help relax the LLRF gain requirements. The achieved damping rate and effect on LLRF requirements will be estimated.
- We are investigating the effectiveness of the RF noise feedback on *both* 197 and 394 MHz cavities. The pickup would sense the total contributions to mode 0 and 1 motion from both sets of cavities, without the ability to differentiate. We want to investigate whether there will be any negative effects on the feedback performance and/or on the transverse distribution, in particular the bunch tails.
- The possibility of closing the RF loop with zero or very low voltage should be evaluated. Due to the very high Q_L, the transmitter power requirements are extremely low for low voltages. Linearity issues could significantly affect the system stability and performance at lower voltages.

Transverse instabilities and the RF noise induced transverse emittance growth will be challenging in the HSR. Previous work ([1], [2], [3]) have set specifications to address these issues. In this note, we summarize the planned LLRF architecture and present alternative designs and settings that would allow us to relax the specifications or achieve higher stability margins. We have also identified critical parameters that could significantly affect these estimates and resulting optimal settings. As the LLRF design progresses, the transverse stability margins and RF noise thresholds will be reevaluated more precisely.

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[2] K. Smith, T. Mastoridis, P. Fuller, P. Mahri, and Y. Matsumura, EIC transverse emittance growth due to crab cavity RF noise: Estimates and mitigation,, BNL-222748-2022-TECH 10.2172/1846026 (2022).

[3] T. Mastoridis, K. Smith, T. Hidalgo, T. Loe, and M. Toivola, Time-domain simulation of the crab cavity/beam interaction, Brookhaven National Laboratory Technical Notes BNL-224087-2023-TECH, 10.2172/1960268 (2023).