ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPM135

EIC CRAB CAVITY LLRF SPECIFICATIONS*

T. Mastoridis†, T. Loe, P. Mahvi, M. Toivola,
California Polytechnic State University, San Luis Obispo, USA

Abstract

The EIC Crab Cavity Low-Level Radio Frequency system will have to regulate the crabbing and uncrabbing voltages, while also keeping their sum close to zero. The system will have to reduce the Crab Cavity impedance to prevent transverse instabilities. It will also have to maintain extremely low RF noise levels injected to the beam. This work presents an estimate of the required performance for each of these conditions and a summary of the specifications to achieve them.

INTRODUCTION

The Electron-Ion Collider (EIC) will employ crab cavities to compensate for a 25 mrad crossing angle and achieve maximum luminosity. The Crab Cavity Low-Level Radio Frequency (LLRF) is under design. There are three important considerations:

- Transient beam loading effects on transverse beam position and transmitter power.
- Minimizing the RF noise sampled by the beam to reduce transverse emittance growth.
- Impedance reduction/Transverse instability control.

These LLRF goals 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.

The first two goals have been studied before and summarized here. Initial results on the transverse instability studies are presented in this work.

Figure 1 shows a block diagram of the proposed Crab Cavity RF/LLRF. The RF feedback includes a narrowband integrator to regulate the mean value of the cavity voltage, as well as a proportional controller. 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 to keep the sum to zero. We refer to this system as the "global" controller. In addition, a One-Turn Feedback system (OTFB) at the betatron sidebands of the revolution harmonics is included for additional impedance control.

* This work is supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC-0019287.
† tmastori@calpoly.edu

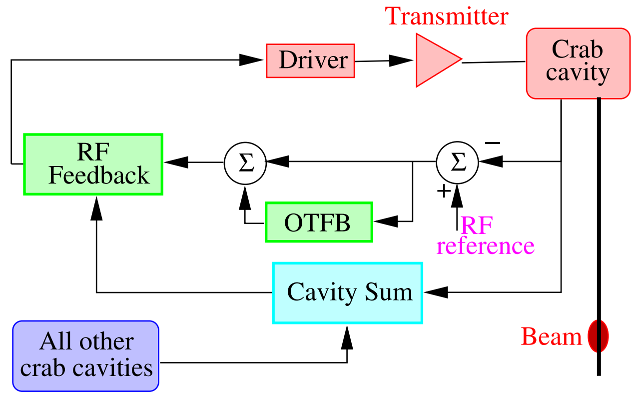

Figure 1: Crab Cavity RF/LLRF Block Diagram.

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 [1]. 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.

Figure 2 shows the Δx_{IP} transients for three different LLRF gains, for a constant bunch position error of 0.6 mm. Clearly,

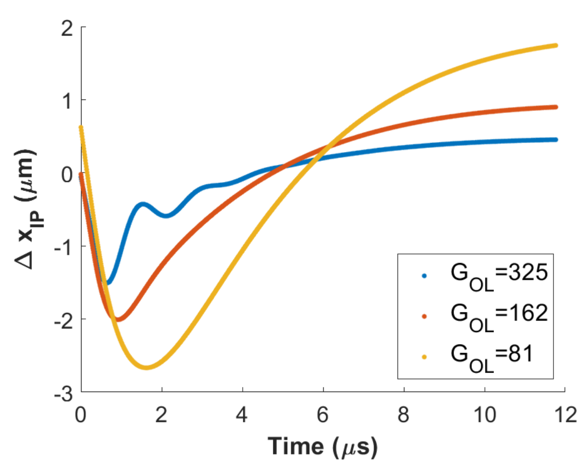

Figure 2: x-offset at the IP.

the transient beam loading in the crab cavities leads 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

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPM135

computed power (P_{batch}). This increase is not concerning but should be included in the transmitter specifications.

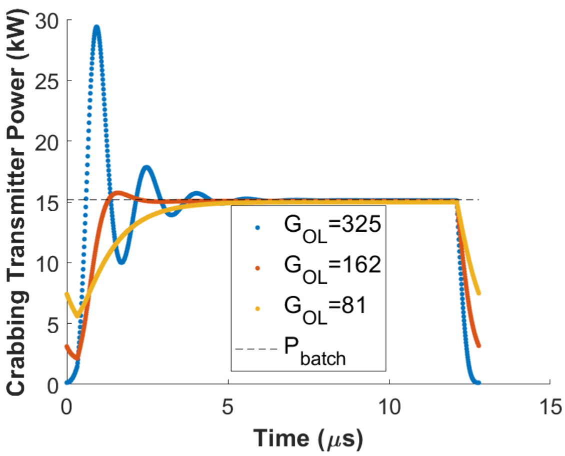

Figure 3: Crabbing transmitter power.

CRAB CAVITY RF NOISE

The Crab Cavity Radio Frequency (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 Hadron Storage Ring (HSR), the emittance growth rate target is set equal to the 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 further adjusted lower.

The resulting RF noise thresholds for the HSR are *very* challenging ($\approx 2\mu$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.

TRANSVERSE INSTABILITIES

The crab cavities introduce a very large transverse impedance for the crabbing mode, which can lead to instabilities. A model was developed by M. Blaskiewicz to estimate the stability margin for a given beam current and Crab Cavity impedance [3]. We used this model to investigate the stability margin sensitivity to LLRF parameters. Initial results are presented in this work for the HSR at 275 GeV. Eight 197 MHz Crab Cavities are included in these estimates. Four 394 MHz Crab Cavities will also be present in the HSR. Next steps include adding their impedance to this model.

Figure 4 shows the Crab Cavity transverse impedance in open loop, in closed loop (LLRF on), and in closed loop with the addition of the OTFB. The sharp resonance is significantly reduced by the LLRF (gain of 2500). An additional tenfold reduction is achieved at the betatron sidebands by the OTFB.

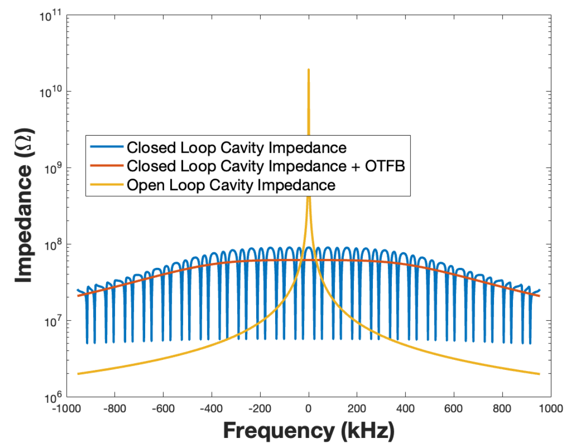

Figure 4: Crab Cavity transverse impedance.

The maximum DC beam current $I_{b,max}$ with this closed loop impedance (OTFB on) is 13.6 A, significantly higher than the HSR planned current. This corresponds to the nominal LLRF parameters (RF feedback gain of 2500, OTFB gain of 10, RF feedback and OTFB phase of zero).

Additional transverse impedance will be present of course, including the four 394 MHz cavities. So, it is useful to explore the impact of LLRF parameters on $I_{b,max}$. The gain and phase of both the main RF feedback and the OTFB can be adjusted to modify the impedance presented to the beam. Figure 5 shows for example the effect of a -10° rotation in the RF feedback (OTFB is off).

Table 1 shows the $I_{b,max}$ dependence on the RF feedback gain. As expected, the current limit is increased with gain. This of course comes at the expense of RF loop stability margin. The nominal gain corresponds to a 10 dB stability margin. Similarly, the current limit is increased with OTFB gain, as shown in Table 2. The same concerns about RF loop stability apply.

Table 1: $I_{b,max}$ with RF feedback gain.

Gain	1000	2000	2500	3000	4000
$I_{b,max}$	5.9	11.1	13.6	16.2	21.3

The RF feedback phase rotation effect is different. With a negative rotation, we reduce the impedance for unstable

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPM135

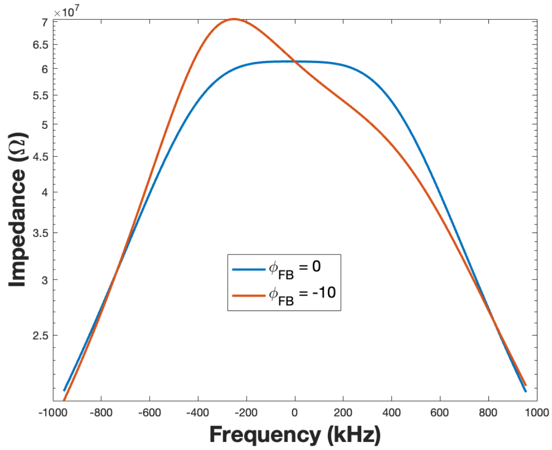

Figure 5: Crab Cavity transverse impedance with RF feedback phase rotation.

Table 2: $I_{b,max}$ with OTFB gain.

Gain	1	5	10	15	20	30
$I_{b,max}$	14.4	12.5	13.6	18.3	25.8	50

modes, while increasing it for stable modes, thus increasing $I_{b,max}$. A positive rotation makes the situation worse. The results are summarized in Table 3. Similarly to the gain increases, this phase rotation does reduce the RF loop stability margin.

Table 3: $I_{b,max}$ with RF feedback phase.

Phase(°)	-15	-10	-5	0	5	10	15
$I_{b,max}$	2.0	3.1	6.5	13.6	14.0	14.4	14.7

A similar rotation of the OTFB phase can also bring positive effects, as shown in Table 4.

Based on the preliminary results of tables 1-4, we see that all controller parameters have a drastic impact on the maximum allowed DC beam current in some part of their range. The possible improvement is very small with RF feedback and OTFB phase rotation. Very substantial increases in the maximum current can be achieved with higher RF feedback and OTFB gains though.

GLOBAL CONTROLLER

The simulation presented in the Transient Beam Loading Section 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 tradeoff 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

Table 4: $I_{b,max}$ with OTFB phase.

Phase(°)	-15	-10	-5	0	5	10	15
$I_{b,max}$	14.4	14.3	14.0	13.6	13.1	7.5	4.4

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.

CONCLUSIONS AND FUTURE STEPS

There are generally negligible transverse beam loading effects on the transverse position and thus no significant implications on the LLRF specifications. The peak transmitter power deviates somewhat from the analytical expressions, and, while not concerning, should still be taken into consideration when specifying the transmitters.

Crab Cavity RF noise is a big concern. The LLRF bandwidth should be reduced if possible to keep the integrated noise power low.

Transverse instabilities due to the Crab Cavity fundamental mode are also concerning. A very high gain RF feedback is required (high bandwidth). This is conflicting with the noise requirement. In addition, manipulations of the LLRF parameters will possibly be required to achieve the most favorable transverse impedance.

A possible solution that we will explore next, involves a high gain LLRF with appropriate filtering to only reduce the transverse impedance for modes -1, 0, and 1.

The significant tradeoffs between these requirements will also be explored. Specifications will then be set for the Crab Cavity LLRF design.

As the design matures, the tools developed for all these studies will be valuable for future Crab Cavity LLRF investigations.

ACKNOWLEDGMENTS

We want to thank M. Blaskiewicz for many useful conversations, as well as for the software tools to estimate the transverse stability margins as a function of the Crab Cavity transverse impedance.

REFERENCES

[1] T. Mastoridis, T. Hidalgo, T. Loe, M. Toivola, K. Smitth, "Time-domain simulation of the crab cavity/beam interaction", BNL-224087-2023-TECH, February 2023.

[2] K. Smith, T. Mastoridis, P. Fuller, P. Mahvi, Y. Matsumura, "EIC Transverse emittance growth due to crab cavity RF noise: Estimates and mitigation", BNL-222748-2022-TECH, February 2022.

[3] M. Blaskiewicz, "Instabilities driven by the fundamental crabbing mode", EIC-ADD-TN-023, October 2021.