Crab Cavity LLRF in Hadron Machines

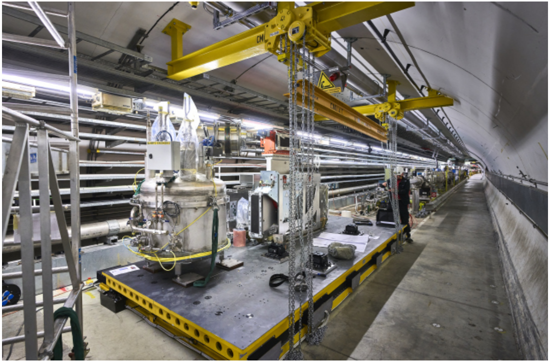
Themis Mastoridis

[1] California Polytechnic State University, San Luis Obispo, CA

October 13^{th} 2025

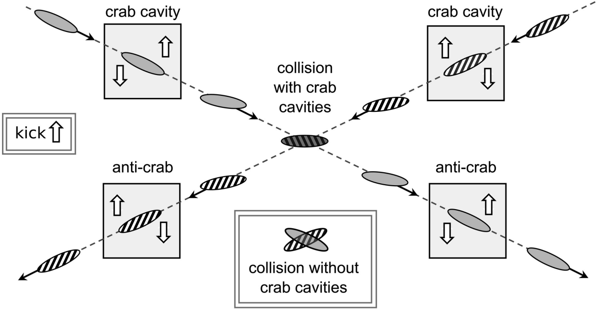
Crab Cavities

- Future accelerators will incorporate new technologies to increase the collision energy and rate.
- Crab cavities will contribute strongly to an increase in the number of recorded collisions.
- They will be used in the High Luminosity Large-Hadron Collider (HL-LHC) and in the Electron-Ion Collider (EIC).
- They have never been used in hadron colliders.



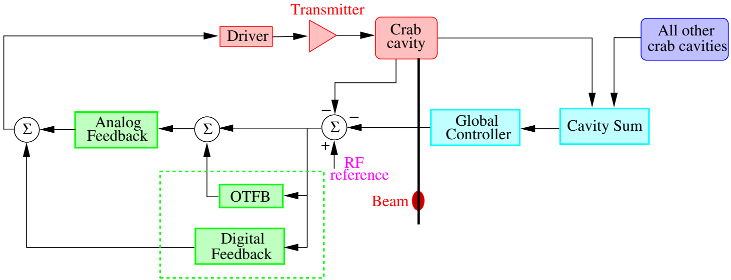
Crab Cavity Action

- Crab cavities are electromagnetic devices that cause a kick perpendicular to the direction of motion (transverse kick), as shown below [1].
- The head and tail receive kicks in opposite directions, thereby resulting in a transverse bunch rotation (crabbing) and a more head-on collision between the particle beams.
- This image is not drawn to scale: imagine bunches as few yards long pencils. The crossing angle is also *very* small (25 mrad for EIC).
- The crab cavity field has to be regulated precisely through the action of feedback systems.



LLRF objectives

- The crab cavity LLRF has to:
  - Minimize RF noise injected to the beam to reduce transverse emittance growth.
  - Regulate the cavity voltage to reduce transient beam loading effects on transverse beam position.
  - Reduce the fundamental impedance for transverse instability control.
  - Maintain local crabbing and minimize beam losses in case of a cavity trip (coupled FB).
- In this talk, I will summarize the studies that set the LLRF specs for these objectives.
  - Effectively, how do these requirements translate to specifications?
  - I will then present some new systems and LLRF implementations to achieve or mitigate these specs.
  - Finally, I will share potential challenges, areas of current research, and future steps.
  - The actual LLRF implementation for the EIC will be presented by F. Severino (EIC) on Wednesday.



RF Noise Effects

- A very high field strength is required to achieve the required beam rotation.
- Even small perturbations to this field lead to ever increasing transverse particle oscillations.
- Thus, noise injected through the RF system could cause significant transverse emittance growth and limit luminosity lifetime.

Transverse Emittance Growth due to RF noise

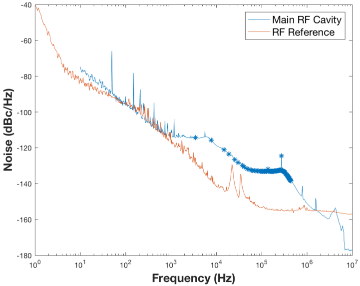
- P. Baudrenghien and I derived a formalism to evaluate the transverse emittance growth rate due to RF noise [2].
- Operational parameters (C_{AP}): Little or no control. This term is effectively inversely proportional to $1/\beta^*$ for a given full crabbing angle θ_{cc}. Strong dependence on θ_{cc}.
- Bunch length dependence ($C_{\Delta\phi}$, $C_{\Delta A}$): Effectively constant over operational range.
- RF noise ($S_{\Delta\phi,\text{eff}}(f)$, $S_{\Delta A,\text{eff}}(f)$): Depends on RF and LLRF.

$$
\begin{aligned}
\frac{d\epsilon_n}{dt} &= N_{cavities}\beta_{cc}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2\left\{e^{-\sigma_\phi{}^2}\left[I_o\left[\sigma_\phi{}^2\right]+2\sum_{l=1}^{\infty}I_{2l}\left[\sigma_\phi{}^2\right]\right]\right\}\sum_{k=-\infty}^{\infty}\int_{-\infty}^{\infty}S_{\Delta\phi}\left[(k\pm\nu_b)f_{rev}\right]\rho\left(\nu_b\right)d\nu_b \\
&= N_{cavities}\beta_{cc}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2 C_{\Delta\phi}(\sigma_\phi)\,\frac{2\sigma_{\Delta\phi}^2}{f_{rev}} \\
&= \frac{1}{N_{cavities}\beta^*}\left[\left(\frac{ec\theta_{cc}f_{rev}}{4\omega_{RF}}\right)^2\right]C_{\Delta\phi}(\sigma_\phi)\,\frac{2\sigma_{\Delta\phi}^2}{f_{rev}}
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\epsilon_n}{dt} &= N_{cavities}\beta_{cc}\left(\frac{eV_o f_{rev}}{2E_b}\right)^2\left\{e^{-\sigma_\phi{}^2}\sum_{l=0}^{\infty}I_{2l+1}\left[\sigma_\phi{}^2\right]\right\}\sum_{k=-\infty}^{\infty}\int_{-\infty}^{\infty}S_{\Delta A}\left[(k\pm\nu_b\pm\nu_s)f_{rev}\right]\rho\left(\nu_b\right)d\nu_b \\
&= \frac{1}{N_{cavities}\beta^*}\left[\left(\frac{ec\theta_{cc}f_{rev}}{4\omega_{RF}}\right)^2\right]C_{\Delta A}(\sigma_\phi)\,\frac{4\sigma_{\Delta A}^2}{f_{rev}}
\end{aligned}
$$

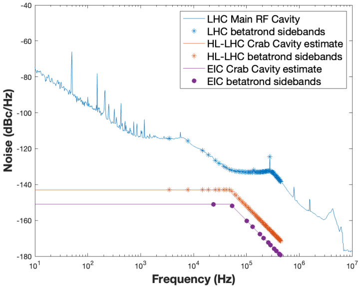
RF Noise Spectrum

- The beam samples the noise at the betatron sidebands around *all* revolution harmonics.
- The sampled noise can be reduced by a careful LLRF design and component selection OR by a reduction in the closed loop bandwidth.
- The LHC accelerating cavity noise spectrum is shown as a reference. Three main sources:
  - RF reference noise.
  - Transmitter noise reduced by the RF FB and polar loops.
  - Receiver noise: demodulation of the cavity antenna signal. The LLRF defines the closed loop bandwidth, and therefore sets the width of the plateau.
- *A* **low gain/bandwidth** *system would greatly reduce the beam sampled noise.*



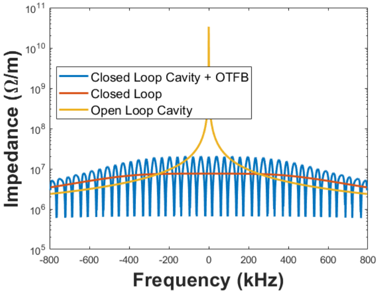
Sampled Noise Estimate

- We can then estimate the noise levels of the proposed Crab Cavity LLRF system and compare to the thresholds.
- We are assuming a LLRF noise plateau of -143 dBc/Hz for the HL-LHC and -151 dBc/Hz (LCLS-II low noise digitizer). Essentially, we can only regulate the field to the precision we measure it.
- Even this very low noise level (a couple μrad total sampled noise) will lead to emittance growth higher than the target rate for the HL-LHC and the EIC Hadron Storage Ring (HSR).
- Clearly, the sensitivity to RF noise is very high in hadron machines. This is possibly the most challenging aspect of the LLRF design.



Impedance Reduction

- The crab cavities introduce a very large transverse impedance. We want as **high** a gain/bandwidth as possible (limited by loop delay and architecture) to reduce the effective impedance $\left(G_{opt} = \frac{Q_L}{\omega_{RF}\tau_D}\right)$.
- The one-turn feedback (OTFB) further reduces the impedance at the betatron sidebands.



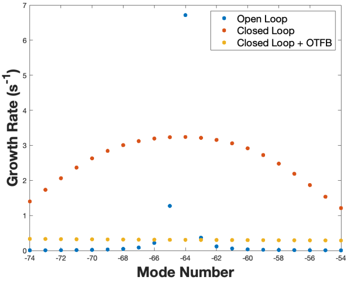
Coupled-bunch Transverse Instabilities

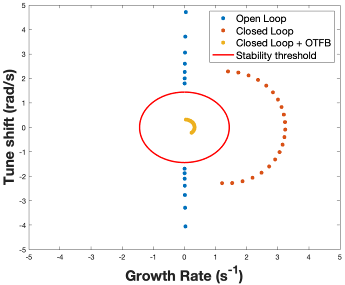
- The complex betatron frequency shift Λ for each mode is given by

$$\Lambda_{m\mu} = -i\frac{ceI_oT_o}{4\pi\omega_\beta E_T\sigma_\tau 2^{|m|}|m|!}\frac{\beta_x}{\beta_x^{\text{smooth}}}\frac{\sum_n Z_\perp(\omega_n)h_m(\omega_n-\omega_\xi)}{\sum_n h_m(\omega_n-\omega_\xi)} = \tau_{m\mu} + i\Delta\omega_{m\mu}$$

$$\omega_n = (nM+\mu)\omega_o + \omega_b + m\omega_s,\ \omega_\xi = \omega_o/\eta$$

- We use a frequency domain model of the crab cavity response and the LLRF action to estimate Λ as a function of the LLRF architecture and settings.



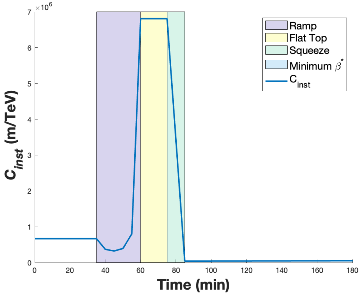


Stability Margin

- The beam stability depends on Λ and the tune spread.

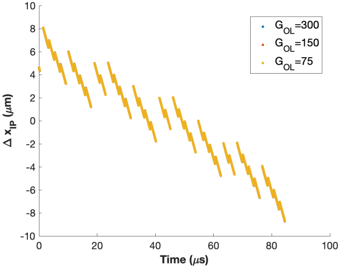
$$|\Lambda| < \frac{1}{\sqrt{3}}\Delta\omega_{1/2} = \frac{\sigma_\nu \omega_o}{2}, \text{ for an elliptical distribution (Chao 5.62).}$$

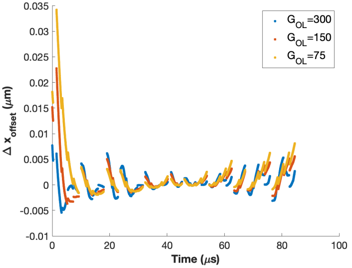
- As soon as the beams are colliding, the tune spread increases *significantly* due to beam-beam. As a result, the most critical time for both the HL-LHC and the EIC HSR is between the end of the ramp and collisions.
- With the highest possible RF FB gain and OTFB, both machines will be stable, but not with a significant margin. For the HL-LHC for example, the stability margin is around 4 at Flat Top. The beam is unstable without OTFB.
- So, a high gain feedback system with OTFB is necessary for stability.



Transient beam loading: beam effects

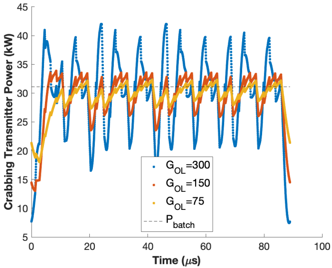
- Voltage imprecision can lead to luminosity loss. In the HL-LHC, 20 ps phase noise in the crabbing voltage will lead to a 0.5% luminosity reduction.
- In addition, if the transients are significant and not matched in the crabbing and uncrabbing cavities, the beam will have a residual offset and tilt.
- The transient beam loading depends on the beam offset in the crab cavity *and* the beam phase modulation in the accelerating cavities (gap transient in accelerating cavities, full detuning algorithm in the HL-LHC). The presented plots correspond to the very conservative situation when the beam offset is the maximum specified.
- We have developed and validated a time-domain simulation of the beam-crab cavity RF/LLRF interaction, which allows us to study beam loading effects on the crabbing kick and transmitter power, as a function of the LLRF design.
- The transient beam loading in the crab cavities leads to *insignificant effects* on the beam position at the IP and after uncrabbing.

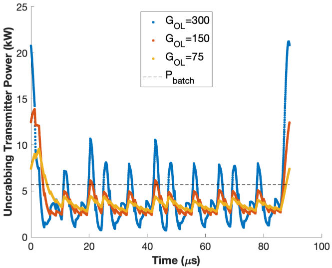




Transient beam loading: transmitter power

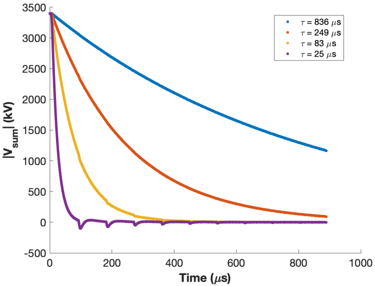
- The peak transmitter power can be *slightly* higher than the average or analytically computed power, so these transients should be taken into consideration when specifying the transmitter.
- A **low LLRF gain**/**bandwidth** significantly reduces the peak power.
- *This is the most relaxed of the specifications. We just have to be mindful of the transmitter peak power requirements.*

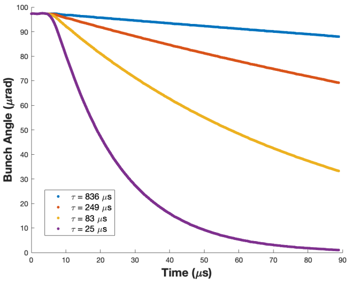




Global Crab Cavity Controller

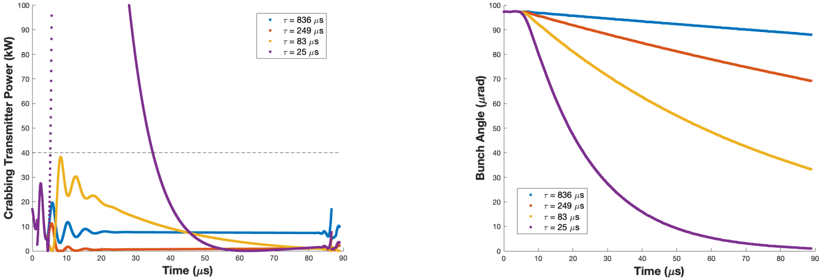
- The global controller will keep the crabbing/uncrabbing voltage sum to zero.
  - As such, it will maintain the local crabbing scheme during normal operation.
  - It will also ramp the crabbing/uncrabbing cavities down to maintain a zero voltage sum in case of a station loss due to a quench, transmitter trip, RF/LLRF fault etc.
  - The goal is to minimize the effects on the beam and thus the danger on accelerator structures for the few turns before an interlock is activated and the beam is dumped.
- The figure below shows the first ten turns after a station is lost.
  - Clearly, reducing the total voltage to zero will take multiple turns (very high Q_L).
  - Still, the residual bunch crabbing is reduced to less than half within a turn. Note that the initial value is a quarter of the full crabbing angle (*one* cavity trips).





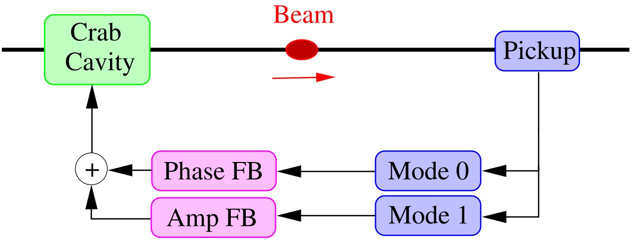
Global Crab Cavity Controller: Power Requirements

- There is a trade-off between the global controller response time and the required transmitter power (HL-LHC: 50 kW transmitter specification) → maximum gain of ≈0.2.
- Increasing the controller gain leads to a significant increase in the required power.



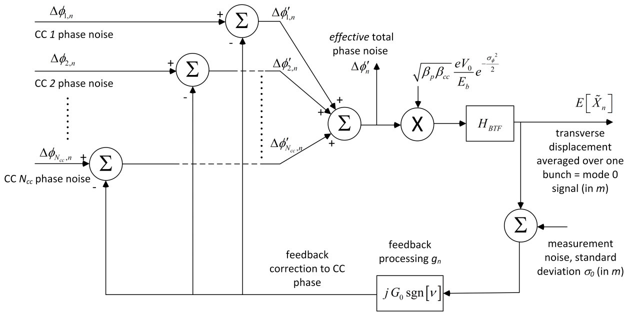
Crab Cavity Noise Feedback

- Even a state of the art RF/LLRF would inject sufficient noise in the crab cavities to cause significant transverse emittance growth.
- A dedicated feedback system could mitigate these effects [3]. D. Valuch is developing this system for the HL-LHC (talk on Wednesday).
- The pickup would extract mode 0 (bunch centroid) and mode 1 (bunch tilt) errors. The system performance would greatly depend on the pickup precision.



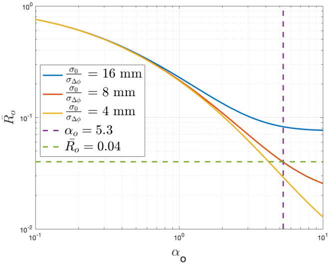
Mode 0 feedback

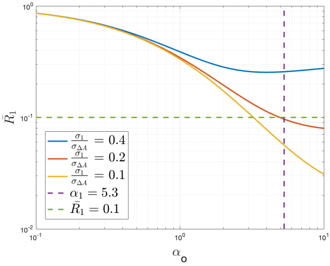
- The proposed feedback uses one pickup and N_{cc} crab cavities as kickers. The pickup would extract mode 0 (bunch centroid) and mode 1 (bunch tilt) errors.
- The feedback response is proportional to the pickup measurement (factor G_0), with a 90° phase shift (for positive frequencies around the beam response, -90° for negative frequencies).
- The filter (impulse response g_n) also includes the appropriate phase shift to achieve a total phase advance of $\pi/2$ between the pickup measurement and the kick of each crab cavity.



Pickup Precision

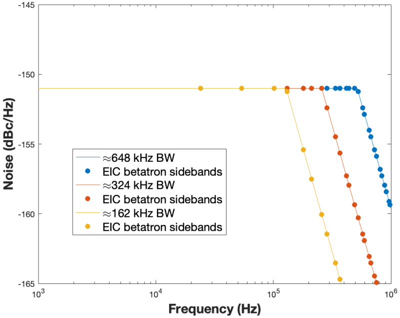
- We have derived an analytical model to estimate the performance and limitations of such a feedback system (validated via PyHEADTAIL simulations) [3]. In the same work, we present analytical expressions for the optimal noise feedback gain, achieved emittance growth rate reduction, and pickup measurement noise thresholds.
- The resulting *bunch-by-bunch* measurement noise thresholds are $\sigma_0 < 320$ nm and $\sigma_1 < 8.3$ μrad for the HL-LHC and $\sigma_0 < 2.2$ μm and $\sigma_1 < 18$ μrad for the EIC HSR.
- The noise spectrum will be limited to the LLRF closed loop bandwidth though, whereas the pickup measurement noise will extend to half the sampling frequency, **assuming uncorrelated noise from bunch to bunch**.
- We can thus filter the data and relax the measurement noise thresholds to (3.9 μm, 100 μrad) rms for the HL-LHC and (9.6 μm, 78 μrad) rms for the EIC (multi-bunch measurements).
- **Caution point:** The emittance growth rate will be higher with smaller bunch trains and depend on the beam pattern during the intensity ramp-up, thus reducing the *filtered* pickup resolution. We assume a five turn latency.





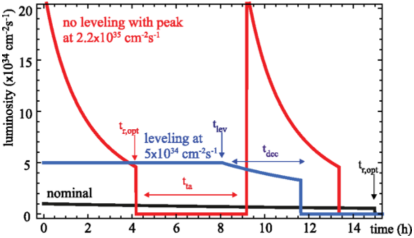
Unexplored degree of freedom

- We need a low gain/bandwidth system for emittance growth and a high gain/bandwidth system for transverse instabilities.
- These two requirements are more critical at different times in the cycle though.
- The transverse instabilities are most critical right before collisions (low tune spread).
- The noise effects are more critical in Physics (high β_{cc}, long duration).
- *We could reduce the RF BW at the start of Physics, thus maintaining high impedance reduction up to that point WHILE reducing transverse emittance growth.*



Operational choices

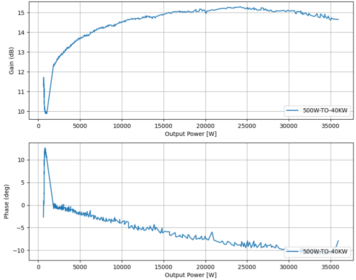
- Operational plans are still at an early stage for both machines, but they can have significant impact on the LLRF specs.
- For example, luminosity leveling in the HL-LHC can be achieved either by slowly increasing the crabbing voltage during the fill, or by using a constant voltage and adjusting β_{cc} at the crab cavity. The latter plan leads to *significantly* lower transverse emittance growth, and thus relaxes the LLRF requirements.
- On the EIC, the 197 MHz crab cavities contribute significantly more to RF noise than the 394 MHz cavities. The 394 MHz cavities contribute more to the effective impedance. We investigated operating the 197 system with lower gain/bandwidth to reduce emittance growth, while keeping the impedance at reasonable levels.



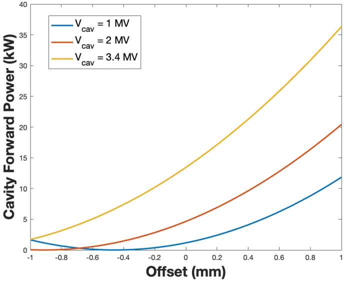
From [4]

Transmitter Nonlinearity

- The transmitter nonlinearity complicates commissioning and operation of the RF station. It is not currently possible to close the RF loop with less than 500 kV in the SPS crab cavity test bench.
- If the crab cavity offsets within the cryostat approach the high end of the specification, the operation would be even more challenging. The beam orbit through the cryostat could possibly be adjusted while the crab cavity voltage is ramped.
- The required power for one of the two cavities will be very low, in the nonlinear part of the transmitter response.

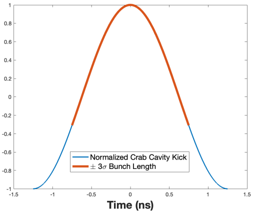


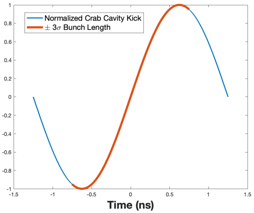
[G. Hagmann]

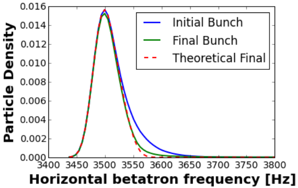


Noise Feedback Effect on Bunch Tails

- HL-LHC
  - Transverse modes 0 and 1 will be driven by *both* dipole noise (constant over the bunch) *and* crab cavity RF noise (sinusoidal).
  - They will be remedied by *both* the transverse damper (constant kick over the bunch) *and* the noise FB (sinusoidal via the crab cavities).
  - The bunch tails could potentially be kicked in the wrong direction, leading to particle loss and inadvertent tail cleaning.
- EIC
  - This is not an issue for the EIC Electron-Storage Ring: no noise FB.
  - The HSR will not have a bunch-by-bunch feedback, but it will employ crab cavities at two different frequencies: 197 and 394 MHz.
  - We could face a similar issue if the pickup cannot differentiate between motion driven by each system.

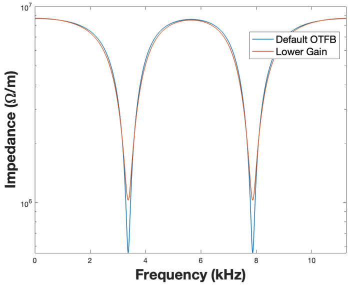


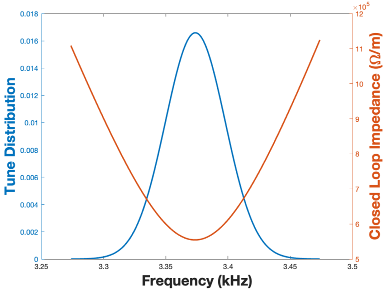




Comb Bandwidth

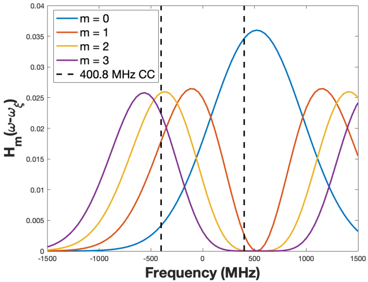
- The proposed OTFB system [5] will achieve impedance notches at all the betatron sidebands with a double-sided bandwidth of $\approx$100 Hz for the HL-LHC.
- This bandwidth has to be wider than the betatron frequency spread, any frequency shifts from bunch to bunch, and cover the synchro-betatron sidebands ($\pm\omega_s$).
- Before collisions (the most critical time for instabilities), the tune spread will be *much lower* than the bandwidth.
- The betatron frequency spread will be at most 34 Hz or so in physics, but by then the stability threshold is significant.
- Note, that reducing the OTFB gain increases the system bandwidth, but does *not* reduce the impedance further.
- Precise measurement of the tune will be required to make sure the notches are well matched with the beam response.

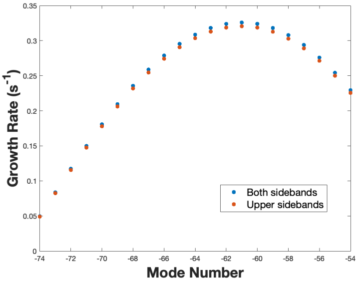




Asymmetric Comb

- Each instability mode is driven by contributions at two betatron sidebands. Due to the high chromaticity, the contributions of the two sidebands are significantly different.
- A comb filter that only reduces the impedance at the destabilizing sidebands, but keeps it the same at the stabilizing ones, would allow us to increase the bandwidth by a factor of 2 if necessary.
- We could (should?) also put the notches at the synchro-betatron sidebands since mode 1 is the most unstable. The impedance reduction for other modes will be significantly lower.





Other concerns

- The optimal gain for the EIC HSR crab cavities is really high ($G_{opt} = \frac{Q_L}{\omega_{RF}\tau_D}$).
  - The impedance reduction *has* to be reduced at that level for stability.
  - Is this feasible? Can the dynamic range be achieved?
- If the RF FB gain is reduced in physics, the transmitter noise might become an issue: the RF loop will not sufficiently reduce TX.
- Additionally, the OTFB parameters will have to be adjusted synchronously to the RF gain/bandwidth reduction.
- The RF noise thresholds assume uncorrelated noise sources that do not scale with voltage (ADCs at each RF station).
  - 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.

Future Steps

Bring the studies together to design the LLRF.

↓

Draft design, evaluate components

↓

The various specifications are so tightly interconnected, that an iterative approach will be required. As components are designed and tested (noise levels, loop delay, transmitter behavior), thresholds and requirements will have to be updated.

Evaluate performance (emittance growth rate, effects on beam distribution, motion at IP and associated luminosity production) as the design matures.

Prepare commissioning and monitoring tools.

Present studies

- Evaluate noise feedback effects on the transverse distribution (in particular the bunch tails) for both machines.
  - For the HL-LHC, evaluate loop stability with concurrent damper and noise feedback operation.
  - For the EIC, we want to investigate whether there will in addition be any negative effects on the feedback performance.
- 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.
- The possibility of closing the EIC HSR 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.
- Narrow down on the operational plan during the cycle for crabbing voltage, β_{cc}, and cavity counter-phasing.

Conclusions

- The LLRF design is at a critical juncture: major studies are complete and we are ready to finalize the architecture.
- The LLRF has to achieve conflicting specifications and depends on a multi-variable parameter space.
- Through all this work, we have created tools and developed analytical expressions that allow us to evaluate alternative LLRF architectures and operational plans.
- A noise feedback is required to achieve emittance growth rate specifications. Its performance will greatly depend on the pickup resolution. Specifications have been set for both the HL-LHC and EIC and the pickups are being designed.
- Impedance reduction is critical too. The stability margin is sufficient, but not high.

Acknowledgements

- This work is the result of collaborations with:
  - Philippe Baudrenghien
  - Mike Blaskiewicz
  - Greg Hagmann
  - Kevin Mernick
  - Freddy Severino
  - Kevin Smith
  - Daniel Valuch
- I also want to recognize my undergraduate students that have participated in this work and have co-authored papers or technical notes:
  - T. Loe, T. Hidalgo, M. Toivola, P. Fuller, P. Mahvi, Y. Matsumura, B. Miller, S. Steeper, D. Tucker, D. Wieker.

- Thank you all for your attention!

References

[1] E. Yamakawa, R. Apsimon, P. Baudrenghien, R. Calaga, A.C. Dexter, "Luminosity reduction caused by phase modulations at the HL-LHC crab cavities", Nuclear Instruments and Methods in Physics Research Section A, 908, 2018.

[2] P. Baudrenghien, T. Mastoridis, "Transverse emittance growth due to RF noise in the High-Luminosity LHC Crab Cavities", Phys. Rev. ST Accel. Beams 18, 101001, October 2015.

[3] T. Mastoridis, P. Baudrenghien, "Transverse emittance growth due to RF Noise in Crab Cavities: Theory, Measurements, Cure, and High-Luminosity LHC estimates", Phys. Rev. Accel. Beams, 27, 051001, May 2024.

[4] M. Benedikt, D. Schulte, F. Zimmermann, "Optimizing integrated luminosity of future hadron colliders", Phys. Rev. ST Accel. Beams 18, 101002, October, 2015.

[5] P. Baudrenghien, T. Mastoridis, "HL-LHC Crab Cavity Field Regulation and Resulting RF Noise Spectrum", CERN-ACC-NOTE-2023-0006.