Crab cavity RF noise mitigation and transverse tail cleaning

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Introduction

- We have been working on various studies of the RF/LLRF in the Hi-Lumi era, with an emphasis on Crab Cavity operation:

1. Longitudinal coupled-bunch instabilities due to the RF ACS cavity fundamental impedance (MD next week. Summary: no reason for concern).

2. Design a smart algorithm to reduce klystron power requirements so the present RF can work reliably with ultimate beam intensity (MD planned for October).

3. A theoretical formalism and associated simulations relating the expected crab cavity RF noise spectrum with the transverse emittance growth rate [1]
   - With this formalism a growth rate of about 4%/hour is anticipated IF we don’t manage to reduce the RF noise spectrum compared to the ACS cavity
   - Dominated by amplitude noise (ADT can only act on phase noise)

4. A mitigation of this effect by a dedicated feedback system acting directly on the crab cavity voltage was investigated next

5. We also studied the possibility of transverse tail cleaning with selective noise injection through the crab cavity
   - Both of these studies conducted with modified versions of HEADTAIL (single-bunch simulations)
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Can we use the crab cavity for tail cleaning?

- Motivation: mitigate the large particle loss following a crab cavity quench
- In the LHC, shaped RF noise in the cavities is injected to blowup the longitudinal emittance during the ramp via longitudinal kicks
- We wanted to investigate what happens when we deliberately inject additional noise in the crab cavities, resulting in transverse kicks
- The final transverse distribution is a function of the tune distribution and the spectrum of the injected noise
- We used the expected HiLumi LHC tune distribution, with a chromaticity (normal distribution) and octopole or beam-beam (exponential) contributions
Distribution evolution for a flat noise spectrum

- Let’s start with the “intuitive" case: a flat noise spectrum is injected in the crab cavity.
  - This scenario corresponds to the expected baseline RF noise, in the absence of the transverse damper.
- There was no significant change in the action and tune distribution functional form.
- These results agree with the smooth emittance increase theoretically predicted and shown through simulations in [2].

![Graph 1](image1.png)  
**Action distribution at the start and end of a wideband noise run.**

![Graph 2](image2.png)  
**Tune distribution at the start and end of the same run as Figure 5.**
Distribution evolution for narrowband noise

- The flat noise would only populate the tails. We simulated injecting narrowband noise with different center frequencies to achieve tail cleaning.

- As expected, the final action and tune distribution of the particles is highly dependent on the noise’s center frequency.

- This is because the noise only affects the particles whose betatron tune frequency overlaps with that of the noise PSD [2].

- Why are particles affected at the core of the TUNE distribution? Mostly because the noise does not roll-off sharply enough and the core is more sensitive.
Shaped noise

To minimize the effects on the core of the bunch and to increase the diffusion rate at the tail, shaped noise should be used that loosely follows the inverse of the tune distribution in the area of interest.

The noise spectrum below starts at the frequency corresponding to $\approx 2\sigma$ of the transverse distribution.
This noise shape works very well.

The final distribution is very close to the theoretical one (the distribution resulting from removing all particles outside $2\sigma$ in phase space).

The small difference is due to the noise kicks, but also due to the chromaticity induced tune spread → longitudinal motion leads to some mixing in the transverse phase space.

This scheme would NOT work as well for high chromaticity.
Phasespace evolution for shaped noise

- We can also look at the initial and final situation in phase space

Initial phase space

Final phase space
Sweeping a single tone

- We also checked the performance when a single-frequency signal is injected, with increasing frequency to progressively push particles farther out.
- Cannot replicate the performance of the shaped noise. Significant particle population remains in the tails.

**Final Action Distribution**

**Final Tune Distribution**
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Noise Feedback

Time evolution

Action distribution with shaped noise

Action distribution with sweeping single tone

Tune distribution with shaped noise

Tune distribution with sweeping single tone
**Damper**

- In all previous results, the damper was turned off to reduce complexity.
- Damper acts mostly on the core of the bunch, where it has the highest gain. Small influence on the tails.
- Previous results hold true with damper on, but require slightly higher noise for the same effect (with the same noise power we get less cleaning).

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**Final Action Distribution**

**Final Tune Distribution**
2D Cleaning

- Can we tail-clean in 2D?
- Injecting noise in x and y independently leads to high losses at the core and an asymmetric tune footprint.
- Instead, we inject correlated noise in x, y in a series of steps: clean a small rectangle at a time (sweep along an arc)
- Very promising results
- Single-bunch simulations: the small differences in tune footprints among the bunches will lead to slightly different final distributions along the ring, but the result still holds for the beam average
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The system would mitigate RF noise injected by the crab cavities. It would use the same pickup as the damper, but act on the crab cavity amplitude and phase.

Advantage vs. Damper: It would allow us to act on BOTH phase and amplitude noise; we can act on both dipole and head-tail motion.

Limitation vs. Damper: the achievable bandwidth is the closed loop crab cavity BW (≈100 kHz), BUT this is not an issue, because we are acting on noise injected by the same loop and therefore also limited to the 100 kHz BW. We only need to counteract low-order modes.

We want to evaluate the potential system performance. Also the limitations imposed by the system delay and pickup measurement noise.
Comparison with Damper

- A CC voltage phase error leads to a voltage error proportional to a cosine.
- Both systems receive the bunch position from a pickup. Due to the averaging over the bunch, there is some loss in effectiveness.
- The proposed feedback can perfectly cancel the cosine error.
- Bunch-by-bunch Damper cannot act within a bunch. It gives a rectangular kick proportional to the average value over the bunch → it actually increases the noise effect at the tails (Damper action is less efficient)
- The amplitude noise (head-tail) reduction is not affected by the presence of the damper
Emittance growth rate reduction

- An ideal system (no delay, no measurement noise) shows the potential for significant emittance noise reduction with this system.
- It also shows that the amplitude and phase feedback systems are independent: the emittance reduction is additive.
Measurement noise

- A more realistic scenario includes measurement noise in the pickup.
- The 5 $\mu$m level should be what we can achieve with the present pickup, and some smart filtering: the bunches respond to the CC noise on the betatron sidebands only, and, as the CC noise is narrow-band it will excite low-order coupled-bunch modes only. We could filter the measurements to identify these modes out of the noise.
Effects of delay

- The system will have a delay of at least 1 (2?) turns. The figure below shows the performance as a function of delay. No significant performance loss is expected due to the low system bandwidth.

- On the other hand, the phase advance between crab cavity and pickup is critical in the presence of delay. Since we can’t change the phase advance, we instead changed the tune in the simulations.

- For the actual implementation, 2 pickups at $90^\circ$ phase difference would be optimal and reduce the sensitivity on location with respect to the CC:

![Graph showing performance as a function of delay](image1)

![Graph showing performance with delay](image2)
Superposition with Damper

- In an ideal situation with a very short bunch length ($\sigma_z = 0.75 \text{ cm}$), the damper and feedback system are interchangeable and combine linearly.
- With the nominal bunch length, there is a higher loss of performance in the presence of the damper.
- When used together, as the damper gain increases, the effectiveness of both systems together is slightly reduced.

![Graph showing the relationship between feedback gain and damper gain and EGR (nm/s).](image)
Putting everything together, we can see the estimated reduction in the emittance growth rate with measurement noise, the damper, and the proposed feedback system.

We can use these studies to evaluate the optimal gain for the proposed system, once the nominal values for CC phase and pickup measurement noise are known.
Conclusions

- Tail cleaning via the crab cavities was investigated with very promising results. The final transverse distribution strongly depends on the noise PSD as expected.
- A noise feedback acting directly on the crab cavities was studied as well. It can significantly reduce the RF noise induced emittance growth rate, if the measurement noise is at reasonable levels.

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