Transverse Feedback Options For FCC-ee

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Outline

Overall Topology

Spatial Sampling

Noise, Disturbance Sources, Residual Motion

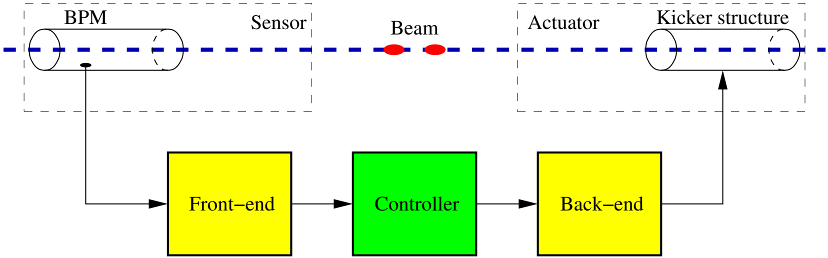
Multiple Feedback Approach

What's Next

Bunch-by-bunch Feedback

Definition

In bunch-by-bunch feedback approach the actuator signal for a given bunch depends only on the past motion of that bunch.



- Bunches are processed sequentially;
- Correction kicks are applied one turn later;
- Diagonal feedback — computationally efficient;
- De-facto standard in synchrotrons.

Topology Options

- Bunch-by-bunch feedback approach is extremely powerful;
- Applies the same feedback to all coupled-bunch eigenmodes independent of the fill pattern;
- In the last 20–30 years electron and positron machines have settled on a single pickup single kicker topology:
  - Kick for each bunch is generated by a linear combination of transverse position measurements from previous turns (FIR filter);
  - Feedback filter coefficients can be tuned to any fractional tune and pickup-to-kicker phase advance;
  - Compact and robust.
- FCC-ee, especially at Z, presents unique challenges for the feedback due to fast growth times;
- A spatial sampling approach takes advantage of high integer tune to generate appropriately phase correction signal in a single turn;
- More exotic schemes (sub-revolution delay) are possible, but not warranted at growth times of 3–4 turns.

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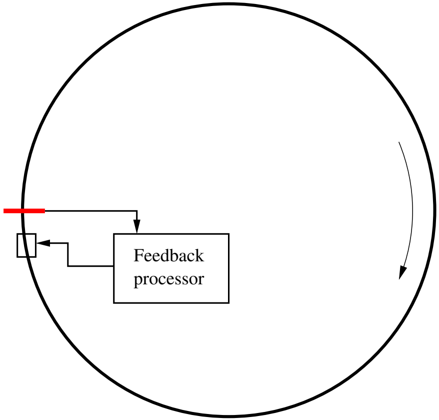

- Start with a conventional single pickup single kicker system;
- Add another pickup at 60–120° phase advance point;
- One more;
- Four is not a limit;
- Correction kick is calculated in one turn instead of using 4 turns worth of bunch motion;
- Group delay is reduced from 3 turns to 1.

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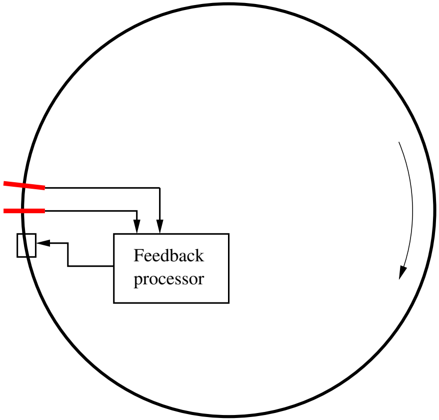

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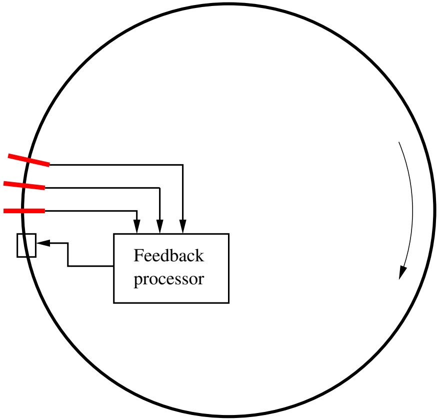

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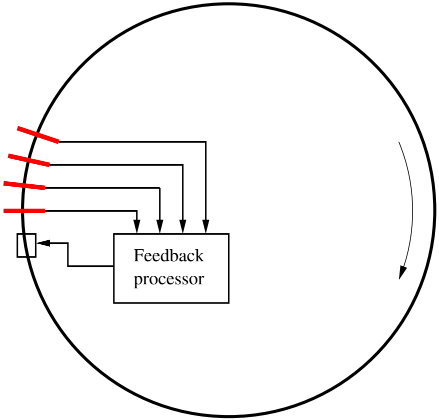

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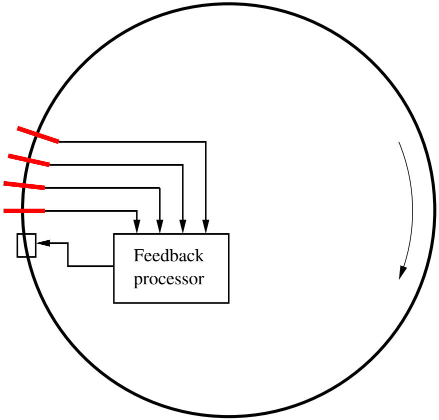

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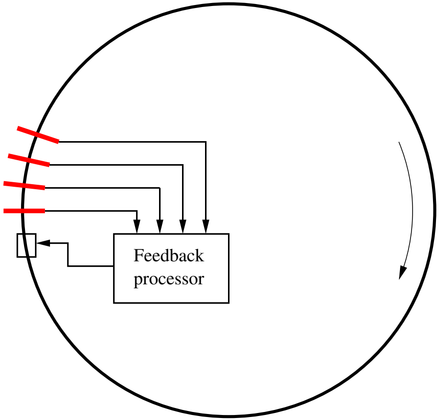

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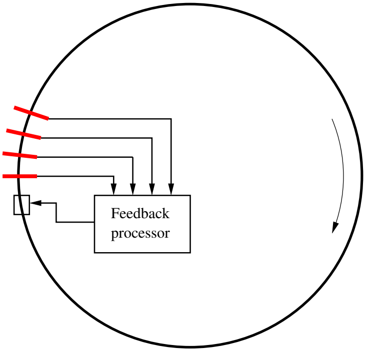

- Feedback processor must:
  - Remove bunch-by-bunch DC offset (closed orbit) from each pickup signal;
  - Calculate correction kick from a linear combination of the resulting signals;
  - At least two non-degenerate pickups are needed, 3–4 probably provide a good balance between complexity, robustness, and performance.
- Phase advance from pickup to pickup does not need to be identical;
- Avoid cases where pickups are at $n\pi$;
- Avoid large swings in beta function from pickup to pickup.

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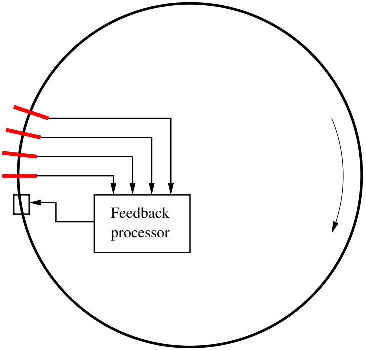

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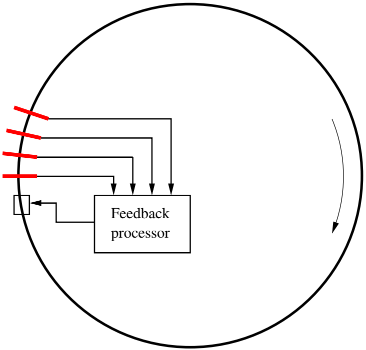

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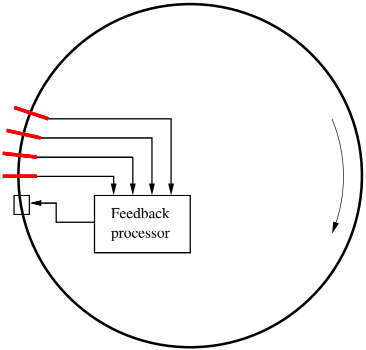

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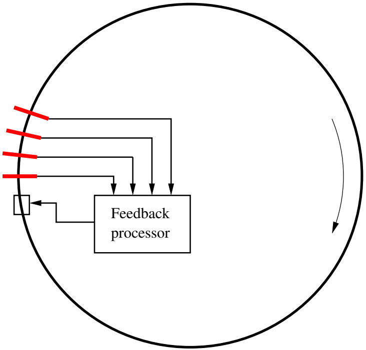

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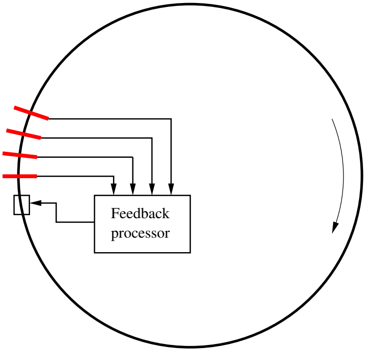

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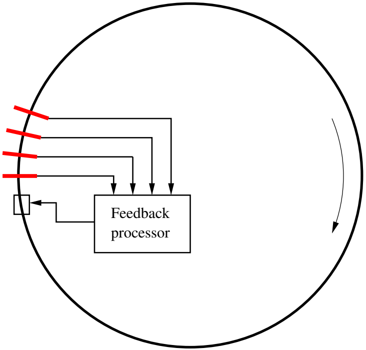
Technical Aspects



- Multiple analog receivers — need to worry about gain drifts;
  - Measure difference and sum signals simultaneously to calibrate out these drifts;
- Robustness — systems with 3+ pickups can adapt to pickup failure with a simple coefficient reconfiguration;
- Sensing noise scales as the $\sqrt{N}$;
- Hardware complexity scale as N.

Residual Motion and Disturbance Sources

- Residual dipole oscillation in collision can be converted to emittance blowup and can lead to luminosity loss;
- Without perturbation sources, residual motion under feedback control is determined by detection noise and closed-loop dynamics;
- Ions in the electron ring and electron cloud in the positron ring can excite transverse instabilities;
- Unlike HOMs and resistive wall, these will also drive steady-state dipole oscillation even under feedback stabilization;
- Suppression of these perturbations may require operation at higher loop gains than optimal from the noise-only prospective;
- With the lowest betatron lines at 520–660 Hz, mechanical disturbances can drive transverse motion;
- Special care is needed when deploying local or global orbit feedback mechanisms in FCC-ee due to the Bode sensitivity integral.

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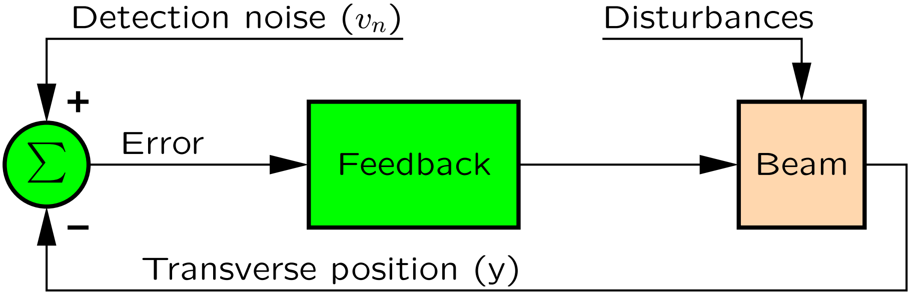
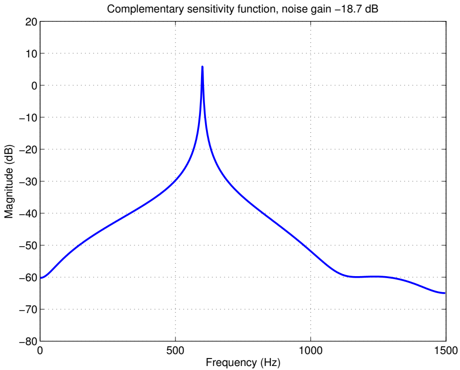
Sensitivity and Noise



- Complementary sensitivity function $T(\omega) = L(\omega)/(1 + L(\omega))$ is the transfer function between noise v_n and beam motion y;
- Assuming flat spectral density for v_n can calculate amplification or attenuation of sensing noise;
- Qualitatively, faster damping corresponds to wider bandwidth $\rightarrow$ higher noise sensitivity;
- Rule of thumb: closed loop damping rate should be of the same magnitude as open-loop growth rate.

Sensitivity Functions Compared



- Growth and damping times in turns;
- $\tau_{\mathrm{ol}} = \tau_{\mathrm{cl}} = 300$: −18.7 dB
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- $\tau_{\mathrm{ol}} = 30$, $\tau_{\mathrm{cl}} = 3.2$: −6.0 dB
- $\tau_{\mathrm{ol}} = 5.4$, $\tau_{\mathrm{cl}} = 5.4$: 3.8 dB
- $\tau_{\mathrm{ol}} = 3.3$, $\tau_{\mathrm{cl}} = 3.3$: 6.1 dB
- Fast growth rates result in higher noise sensitivity;
- Work done at CERN for the upgraded LHC and HL-LHC damping systems pushes state of the art in low-noise bunch-by-bunch sensing.

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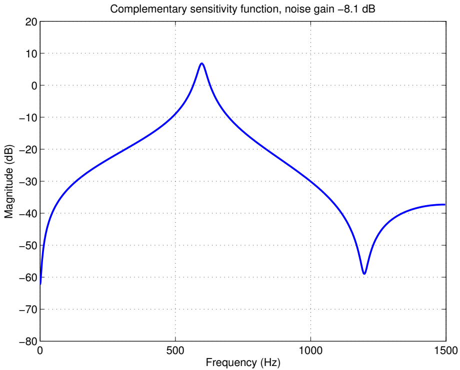

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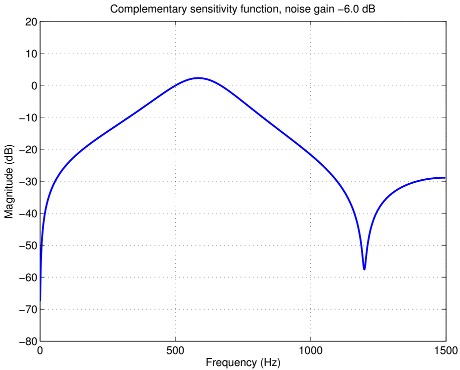

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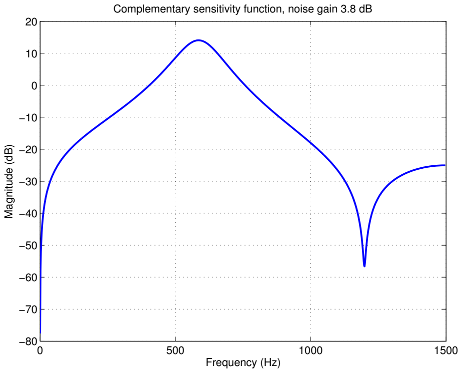

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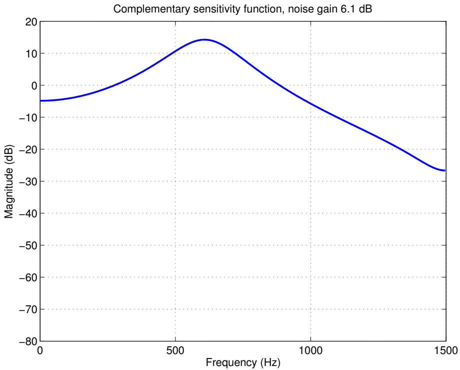

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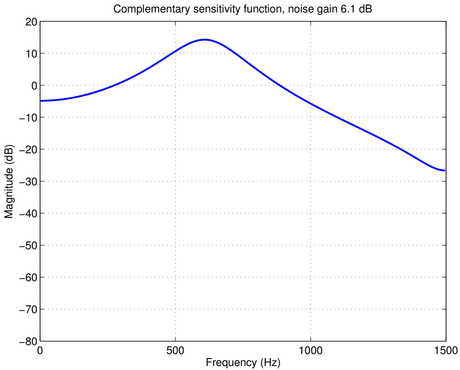

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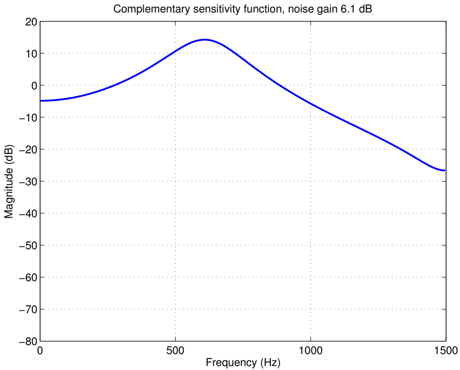

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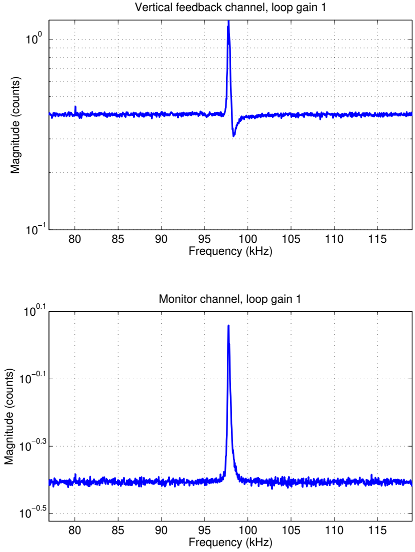
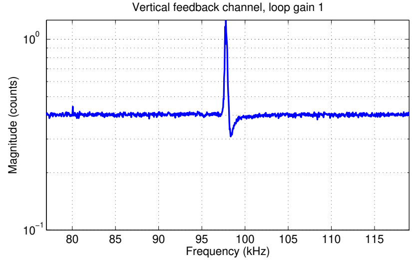
Averaged Bunch Spectra vs. Feedback Gain [1]

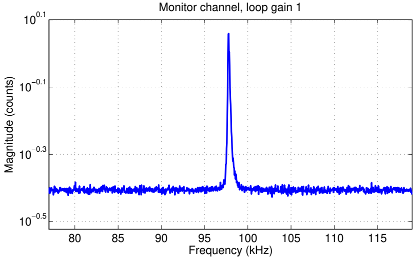


- Two independent channels monitoring vertical motion, one in the feedback loop, one out of the loop;
- Roughly similar sensitivities, 250 mA in 1000 bunches;
- At low feedback gain a visible residual motion line due to ion excitation;
- Double the feedback gain;
- Again;
- Again;
- Once more;
- A wider bandwidth comparison.

[1] Measurements courtesy of Weixing Cheng of NSLS-II.

Averaged Bunch Spectra vs. Feedback Gain [1]





- Two independent channels monitoring vertical motion, one in the feedback loop, one out of the loop;
- Roughly similar sensitivities, 250 mA in 1000 bunches;
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- Double the feedback gain;
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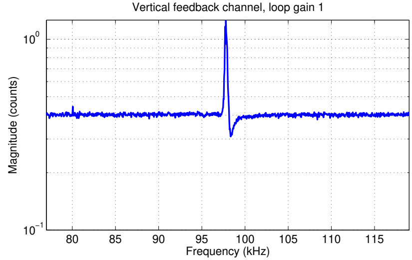

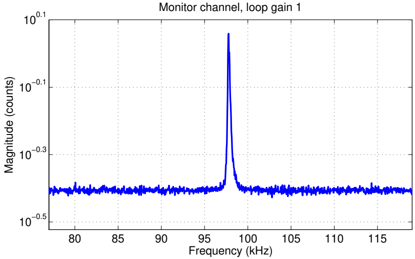

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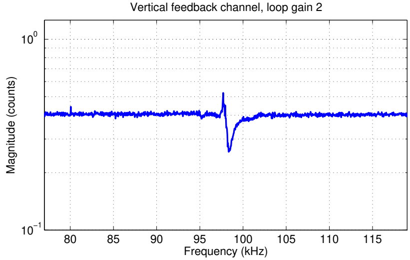

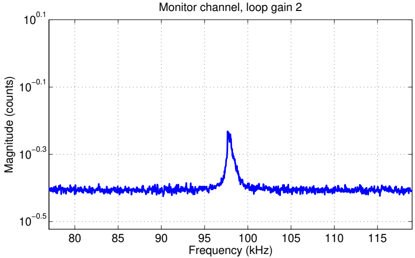

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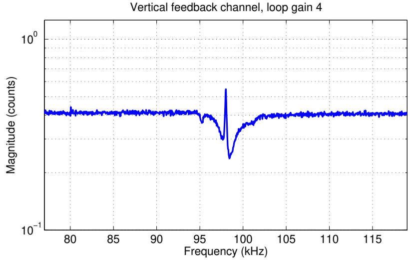

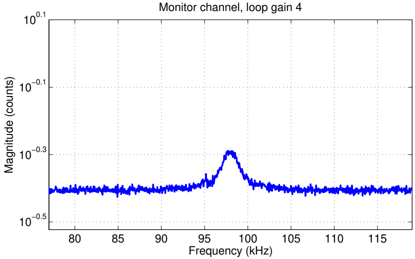

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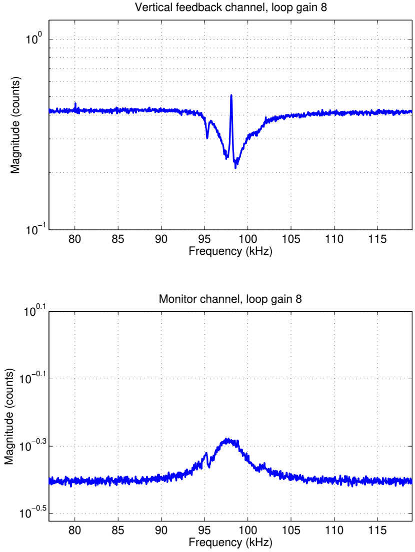

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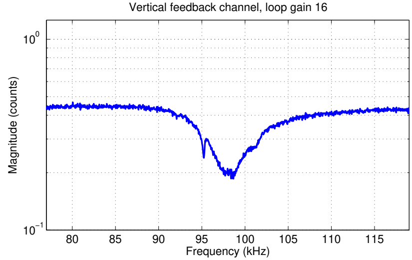

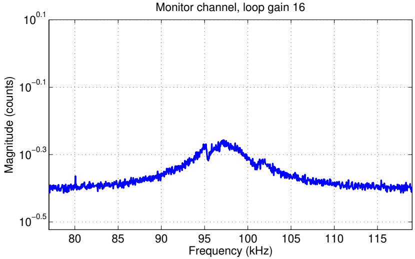

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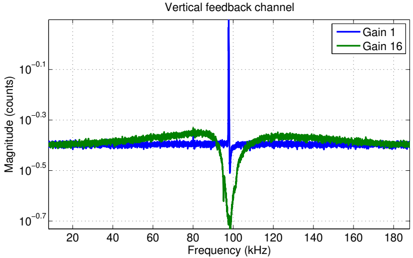

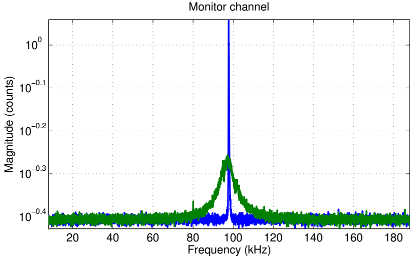

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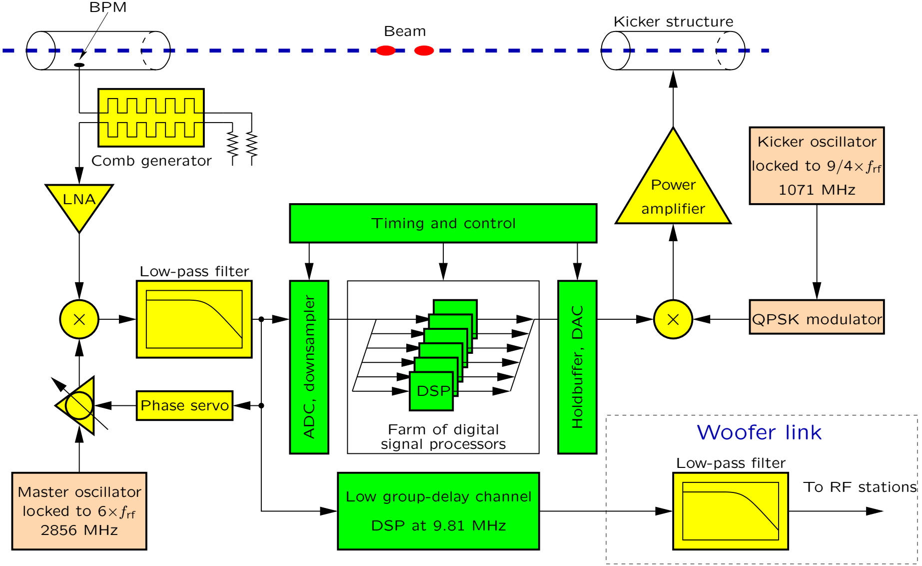

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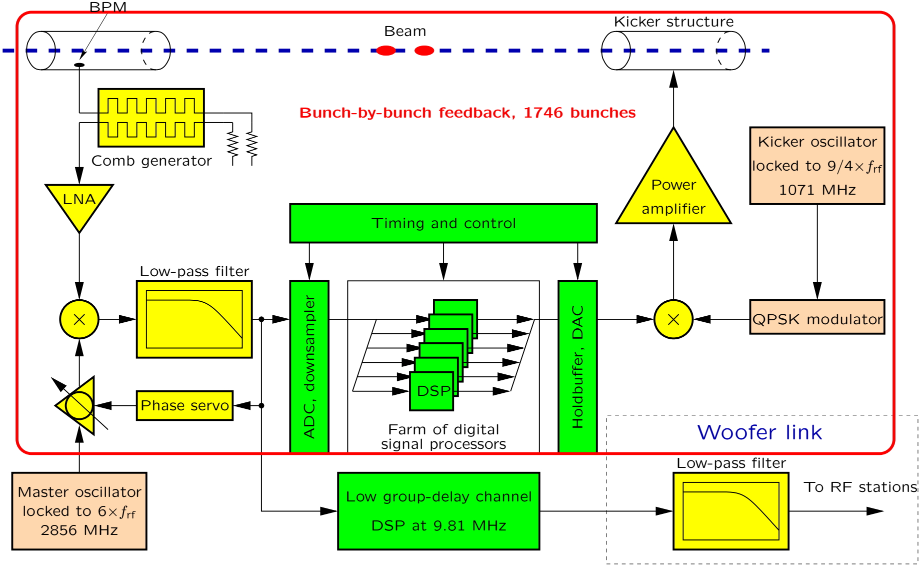

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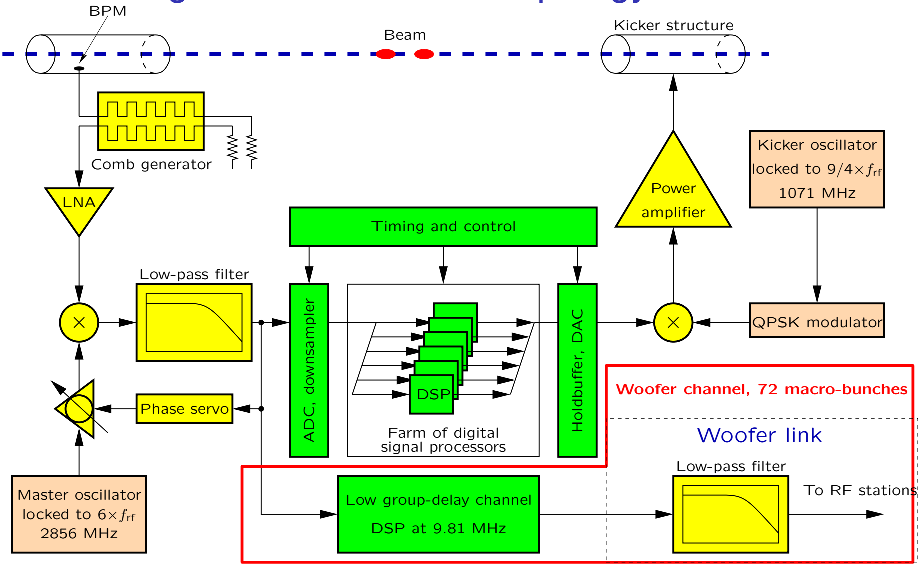

Testing the Ideas, Brainstorming

- A workshop to bring together coupled-bunch instability control, beam dynamics, and impedance experts to brainstorm and analyze ideas;
- Similar to a recent “I.FAST Workshop 2024 on Bunch-by-Bunch Feedback Systems and Related Beam Dynamics”:
  - Many experts in one room — interesting new ideas;
  - Experimental campaign at a real accelerator!
- Focus on FCC-ee specific challenges and proposals;
- Experiments: what can we test in the existing machines?
- Push conventional topology to maximum damping (models suggest 3–4 turns);
- Artificially increase the growth rates:
  - Steer the beam closer to the wall to increase the resistive wall growth rate;
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- With Dimtel iGp12 hardware one could attempt a test of the 3 pickup spatial sampling approach.

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