Feedback Scenarios

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Outline

1. Introduction
2. Fundamental Limits
   - Damping and Delay
   - Residual Motion
3. FCC-ee Considerations
   - Transverse Damping
   - Sensitivity
   - Disturbance Sources
4. Extra Slides

Coupled-bunch Instabilities in FCC-ee

- Focusing on Z — the highest beam current case;
- Transverse plane:
  - Very fast resistive wall growth times (7 turns);
  - Low vertical emittance, need excellent control of the residual dipole motion.
- Longitudinal plane:
  - Due to beam loading, cavity fundamental impedance will excite low-frequency longitudinal modes;
  - Low-level RF feedback is needed to bring the effective impedance down to the level that bunch-by-bunch feedback can handle;
  - Since longitudinal feedback is needed in any case, this may simplify the HOM damping requirements.

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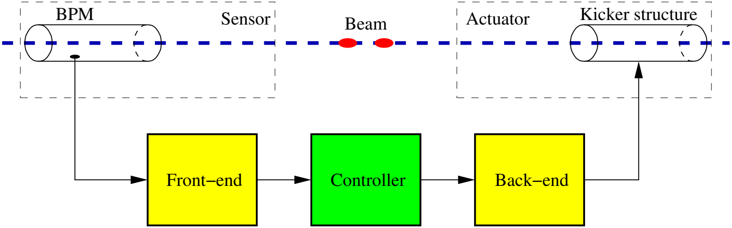
Bunch-by-bunch Feedback

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;
- Widely used in storage rings, well understood.

Conventional Topology — Applicability

- Conventional topology:
  - Single pickup;
  - Single kicker;
  - Purely bunch-by-bunch processing.
- Limits, transverse plane:
  - Good performance for moderate growth times (20+ turns);
  - Fundamental limits come into play for growth times at 3–5 turns;
  - Sensitivity and residual motion;
  - Beam-ion interactions driving residual motion.
- Limits, longitudinal plane:
  - Need to generate a 90° shift between pickup and kicker, sizable fraction of the synchrotron period;
  - Damping rates scale with synchrotron frequency;
  - Minimum controllable growth time around T_s;
  - Synchrotron tune spread reduces achievable damping.

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Conventional Topology — Applicability

- Fast growth rate corresponds to wide bandwidth around the synchrotron or betatron tune.
- Beam responds to feedback action farther and farther away from the tune.
- Delay comes from:
  - One turn between sensing and kicking;
  - Longitudinal – generating a 90° phase shift;
  - Transverse — typically takes 3–4 turns to generate the proper phase shift;
    - Thoughtful selection of pickup and kicker positions can reduce the delay to just one turn.

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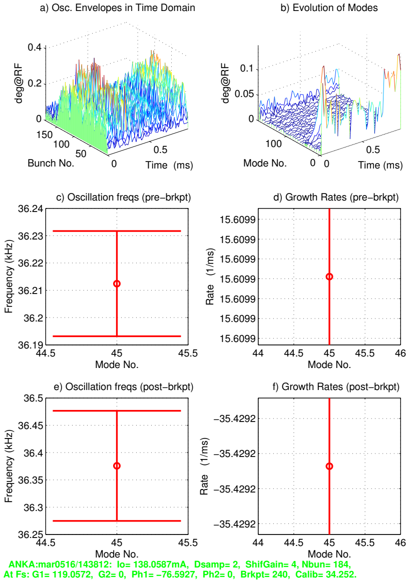
Longitudinal Damping at ANKA



ANKA:mar0516/143812: Io= 138.0587mA, Dsamp= 2, ShifGain= 4, Nbun= 184,
At Fs: G1= 119.0572, G2= 0, Ph1= −76.5927, Ph2= 0, Brkpt= 240, Calib= 34.252.

- Measured while cavity tuning walks an HOM onto a synchrotron sideband;
- Growth time is $2.3\,T_s$, damping time is T_s;
- Filter is $2/3$ of a synchrotron period, processing every other turn;
- Close to maximum achievable damping.

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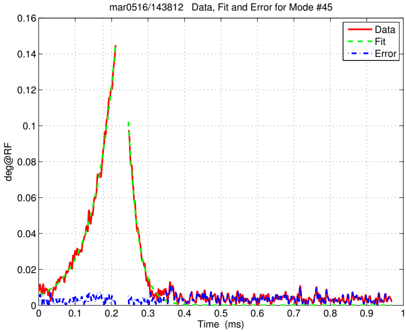

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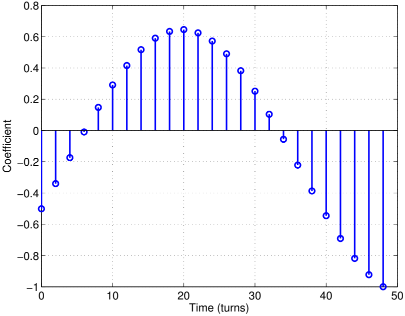

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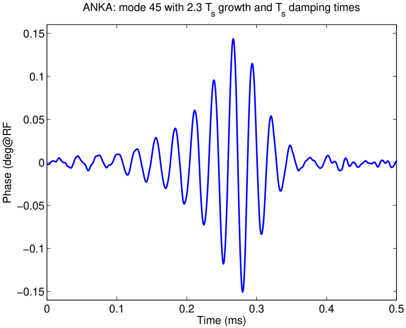

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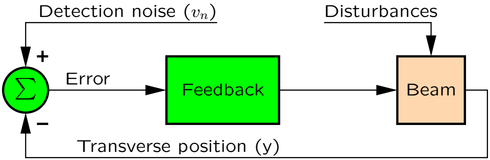
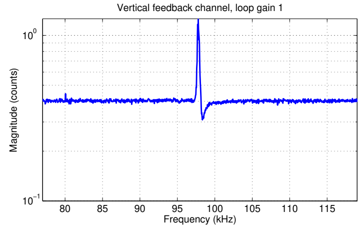
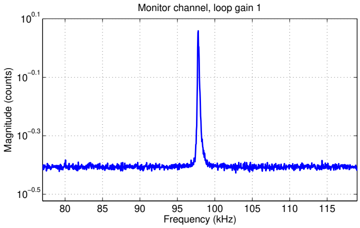
Sensitivity and Noise



- 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 → higher noise sensitivity;
- Rule of thumb: closed loop damping rate should be of the same magnitude as open-loop growth rate.

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;
- Significant residual motion line due to ion excitation;
- Double the feedback gain;
- Again;
- Again;
- Once more;
- Wider bandwidth.

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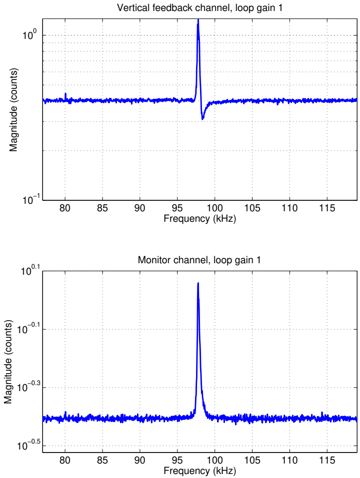

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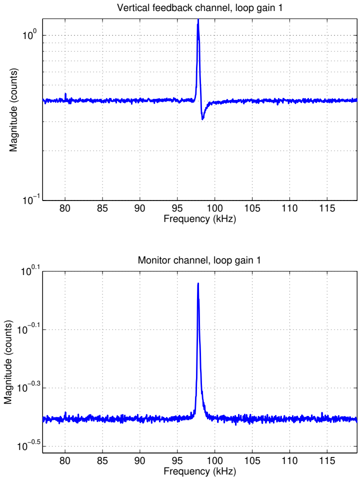

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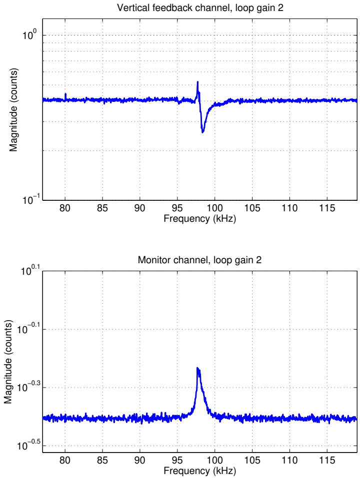

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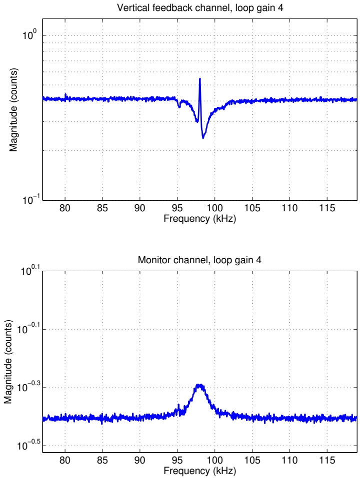

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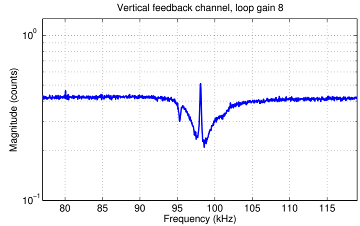

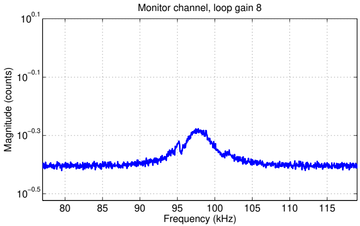

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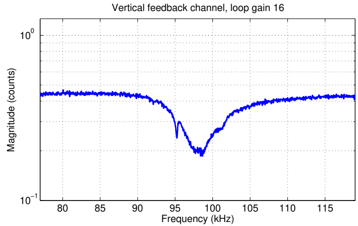
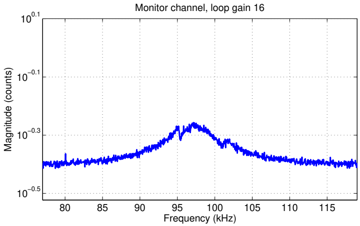

Vertical feedback channel, loop gain 16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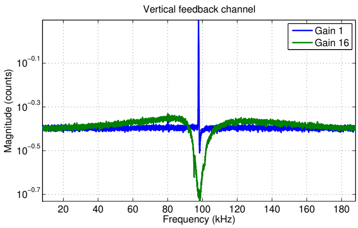

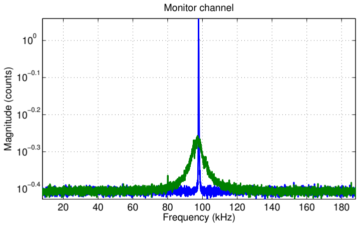

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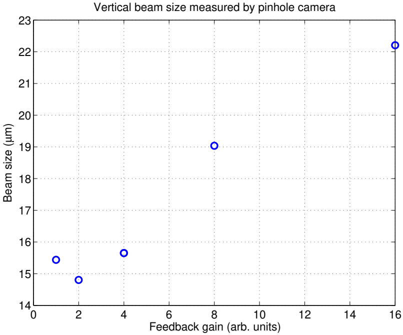

- Vertical beam size from pinhole camera;
- A superposition of true beam size and residual dipole motion;
- Vertical emittance, calculated from pinhole camera data;
- Lifetime is correlated with beam size measurements, suggesting vertical size blow-up as well.

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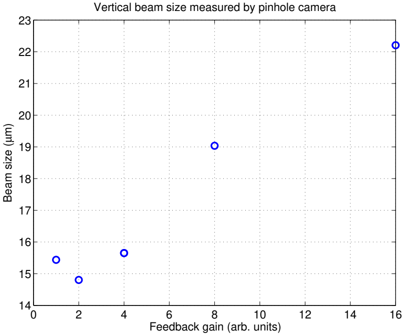

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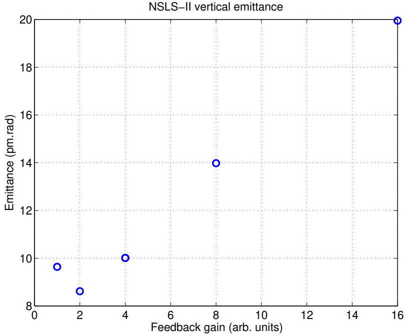

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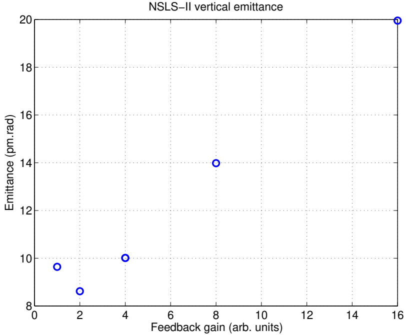

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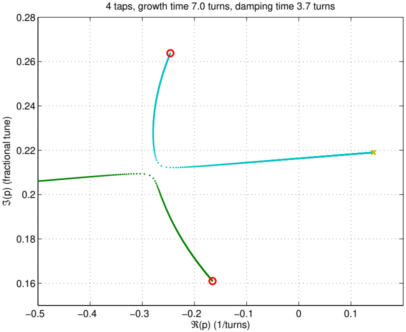

- Root locus — growth/damping rate on the real axis, tune on the imaginary;
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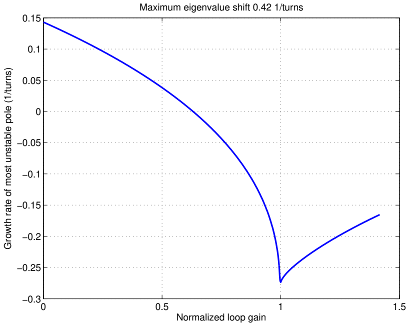

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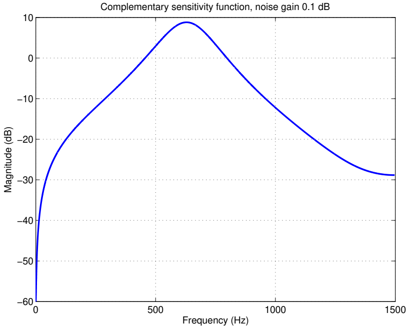
Complementary sensitivity function, noise gain 0.1 dB

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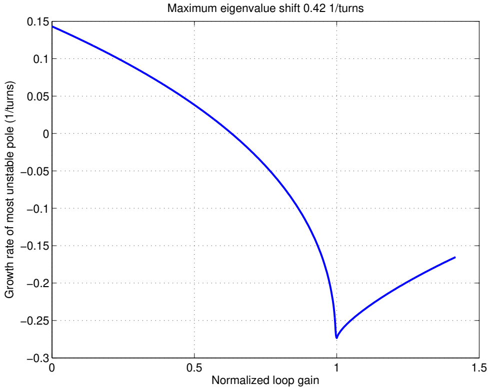
Damping and Tune Variation



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- At shifted betatron tunes the feedback is no longer optimal — less damping;
- Allowable tune shift range vs. growth time.

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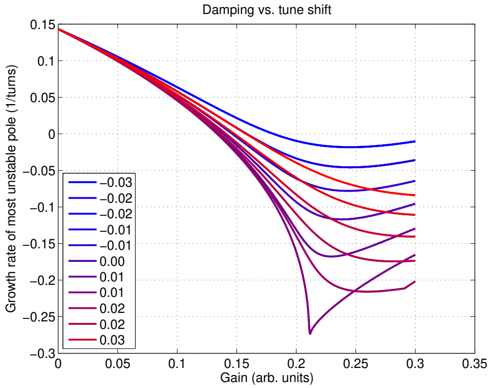

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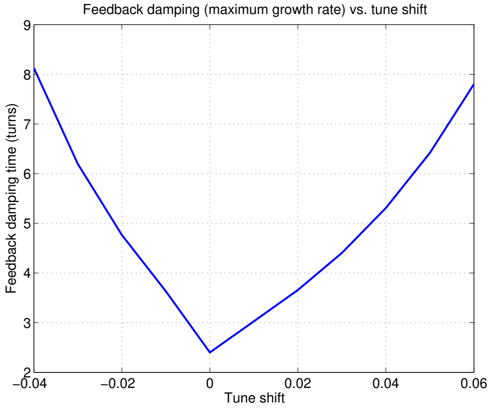

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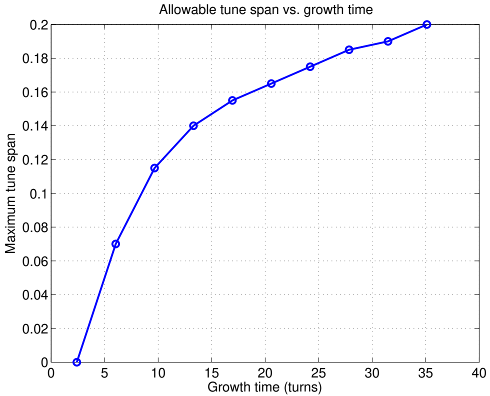

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Examples of Front-End Sensitivities Achieved

Vertical Plane

Machine	Attenuation	At nominal current
SPEAR3	0 dB	0.96 counts/µm
MAX IV 3 GeV	0 dB	2.8 counts/µm
ASLS	2 dB	0.83 counts/µm
NSLS-II[a]	0 dB	0.75 counts/µm

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[a] Older front-end design with lower sensitivity

- Systems optimized for low noise and bunch-to-bunch isolation at 2 ns bunch spacing;
- Input sensitivities around 1–3 counts/µm, steady-state RMS of 2 counts.

Feedback Sensitivity at the FCC-ee

- Integrated sensitivity function around 0 dB;
- Front-end at 2 counts/µm, 2 counts noise floor — 1 µm residual motion;
- Pickup at $\beta_y = 100$ m gives $\sigma_y = 10$ µm.
- Residual motion is at 10% of the beam size, too high;
- Sensitivities above are for 2 ns bunch spacing;
- Bandwidth reduction for 17.5 ns spacing — a factor of 3 improvement;
- Going to $\beta_y = 1$ km at the pickup provides another factor of 3;
- Residual motion at 1% level — what's the effect on luminosity?

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Outline

1. Introduction
2. Fundamental Limits
    - Damping and Delay
    - Residual Motion
3. FCC-ee Considerations
    - Transverse Damping
    - Sensitivity
    - Disturbance Sources
4. Extra Slides

Transverse Perturbations

- Original goal for bunch-by-bunch feedback — suppression of instabilities;
- In most electron and positron machines, there are no disturbance sources with frequencies high enough to excite betatron motion;
  - Ion and electron cloud driven instabilities are different — these generate instability growth as well as drive the beam at betatron frequencies.
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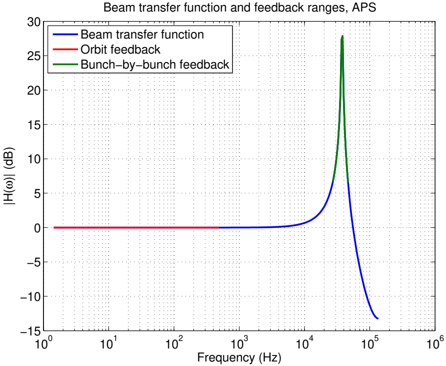
Instability and Orbit Feedback Overlap



- APS, 1104 m;
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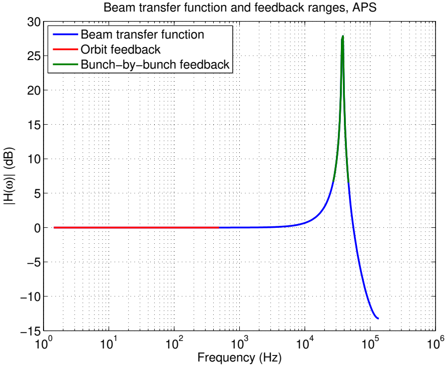

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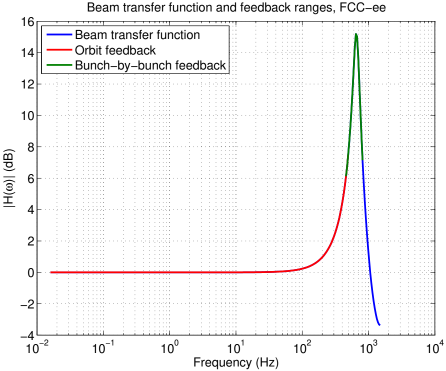

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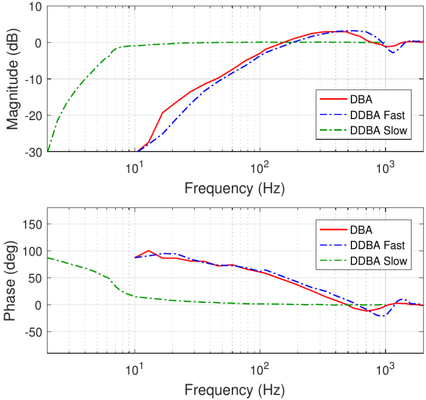

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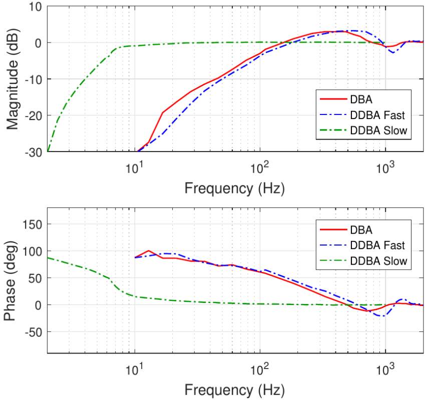

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Summary

- Control of coupled-bunch instabilities in FCC-ee is challenging;
- Fast transverse growth rates can be stabilized using the conventional topology;
- Relatively clear path to residual motion at 1% level;
- Beam-beam tune shift can worsen the transverse stability;
    - Tune spread (intra- and inter-bunch) also produces Landau damping;
    - Needs study!
- Beam-ion interaction can lead to emittance blowup;
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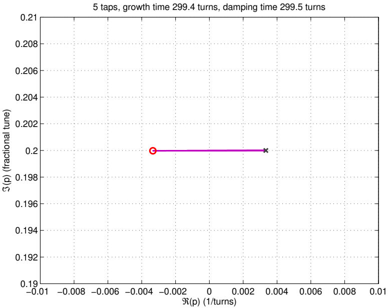
Acknowledgments

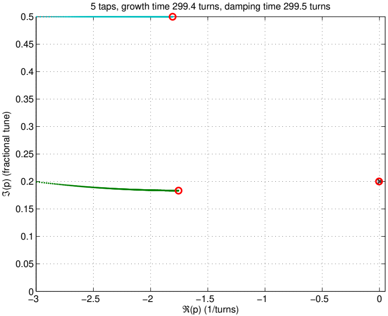
- Thank you for your attention!
- I would also like to thank physicists, engineers, and operators at many machines around the world who directly or indirectly contributed to measurements presented here.
- Special thanks to Weixing Cheng for fruitful discussions and NSLS-II measurements.

Root Locii in Complex Plane: Close Zoom



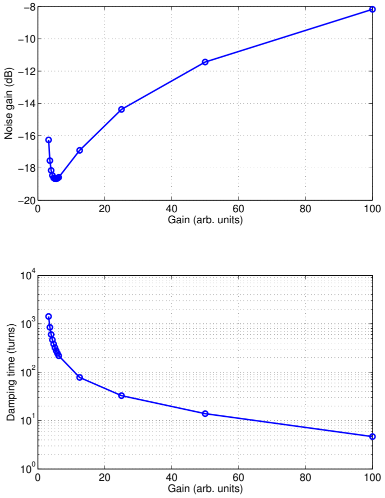
- Root locus on the complex plane:
  - Starts at the open-loop pole (×), ends at the highest gain setting (o);
  - Real part corresponds to growth (positive, right half plane) or damping (negative, left half plane) rate;
  - Imaginary part is the frequency.
- Zoomed in around the dominant pole, all filters look the same.

Root Locii in Complex Plane: Wider View



- Zooming out we see additional poles;
- These are due to the additional delay of the feedback controller;
- Added poles account for increasing noise sensitivity.

Sensitivity vs. Feedback Gain



- 300 turns growth time, fractional tune of 0.2, 5-turn feedback filter;
- No excitation, purely flat noise floor;
- Minimum integrated sensitivity at $\tau_{\rm ol} = \tau_{\rm cl}$;
- Highly peaked $T(\omega)$ at low gains, very wide at high gains.

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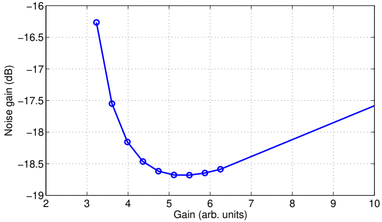

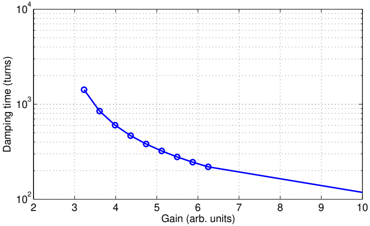

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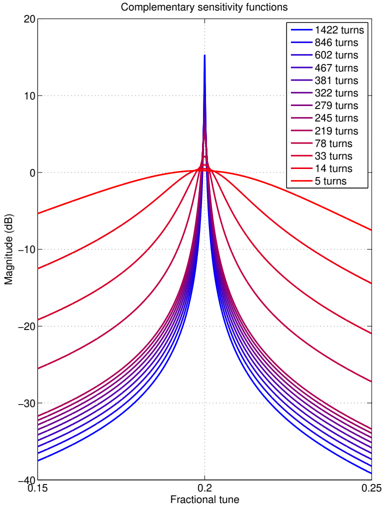

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