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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- 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

- 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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Sensitivity and Noise

- Complementary sensitivity function
  \[ T(\omega) = \frac{L(\omega)}{1 + L(\omega)} \] 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.
Introduction

Fundamental Limits

FCC-ee Considerations

Extra Slides

Averaged Bunch Spectra vs. Feedback Gain

- 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.

1Measurements courtesy of Weixing Cheng of NSLS-II.
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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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Vertical Setup

- Root locus — growth/damping rate on the real axis, tune on the imaginary;
- Configured for maximum damping;
- Damping vs. gain;
- Complementary sensitivity function describes the closed-loop response to measurement noise.
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Damping and Tune Variation

- Well configured for the nominal tune;
- What about tune shifts?
- At shifted betatron tunes the feedback is no longer optimal — less damping;
- Allowable tune shift range vs. growth time.
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Examples of Front-End Sensitivities Achieved

**Vertical Plane**

<table>
<thead>
<tr>
<th>Machine</th>
<th>Attenuation</th>
<th>At nominal current</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEAR3</td>
<td>0 dB</td>
<td>0.96 counts/µm</td>
</tr>
<tr>
<td>MAX IV 3 GeV</td>
<td>0 dB</td>
<td>2.8 counts/µm</td>
</tr>
<tr>
<td>ASLS</td>
<td>2 dB</td>
<td>0.83 counts/µm</td>
</tr>
<tr>
<td>NSLS-II(^a)</td>
<td>0 dB</td>
<td>0.75 counts/µm</td>
</tr>
</tbody>
</table>

\(^a\)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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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.
- FCC-ee circumference places betatron tunes very low in the spectrum (660 and 2340 Hz lowest vertical lines);
- Mechanical and electrical perturbations can be problematic;
- Fast orbit feedback overlap?
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Instability and Orbit Feedback Overlap

- APS, 1104 m;
- Good separation between fast orbit feedback and coupled-bunch instability feedback;
- A different story in the FCC-ee;
- Orbit feedback and betatron dynamics;
- High-end disturbance amplification, nowhere to hide\(^3\).

\(^3\)S. Gayadeen et al, in 2017 IPAC proceedings, pp. 189–191, TUPIK113
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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;
- Low frequency overlap with orbit feedback is worrisome.
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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.
• 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 $\tau_{ol} = \tau_{cl}$;
- Highly peaked $T(\omega)$ at low gains, very wide at high gains.
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