Experience with feedback systems in modern synchrotron light sources

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Dimtel, Inc., San Jose, CA, USA

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Experience with feedback systems in modern synchrotron light sources

Outline

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  ANKA Detective Story
  NSLS-II Residual Motion Story

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  Transverse Feedback and Noise
  Longitudinal Instabilities and Harmonic Cavities

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▶ A definite learning opportunity!

▶ Helped me gain some understanding of feedback limiting factors;

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Steady State Spectra Under Feedback Control

- In transverse planes there are very few steady-state disturbances;
- Instabilities are damped to the noise floor;
- Spectrum is determined by the detection noise and the feedback loop response;
- Open loop transfer function $L(\omega)$ peaks at beam resonance;
- Transfer gain from detection noise to the feedback input is $\frac{1}{1+L(\omega)}$ — a notch.
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Examples of Steady State Spectra

- Averaged spectra of all bunches under closed-loop feedback control;
  - BESSY II\(^1\) Y at 298 mA;
  - Zoomed in;
  - Aichi SR\(^2\) X at 300 mA;
  - Zoomed in;
  - TLS\(^3\) at 200 mA;
  - Two notches - dual plane (X and Y) feedback;
  - Clean horizontal notch;
  - A line poking through the vertical notch — evidence of ion-driven instabilities.

\(^1\) \(h = 400\), \(C = 240\) m
\(^2\) \(h = 120\), \(C = 72\) m
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Initial Assessment

- A ramping machine, 500 MeV injection, 2.5 GeV operation;
- Historically operated with only transverse feedback, with moderate longitudinal instabilities at injection energy;
- After a shutdown had problems injecting more than 100–120 mA, limited by sudden partial beam loss.
Initial Assessment

- A ramping machine, 500 MeV injection, 2.5 GeV operation;
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Feedback in All Three Planes

- Turned on feedback in the longitudinal plane;
- Still hitting a limit during injection, with partial beam losses;
- Feedback tuned near absolute limit, growth time $2.3 \times T_s$, damping time $T_s$;
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Capturing the Beam Loss Event

- Noticed significant activity in the vertical plane during beam loss events;
- Used baseband processor output to trigger acquisition in all planes;
- Vertical correction signals are normally small, only reaching full-scale during beam loss;
- Longitudinal and vertical signals for bunch 140.
Capturing the Beam Loss Event

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- Longitudinal and vertical signals for bunch 140.
Deciphering the Beam Loss Event

- Which plane came first?
  - Zoom in, still too close;
  - Zoom more — looks like longitudinal starts first, but could be trigger error;
  - Longitudinal oscillation amplitude exceeds $30^\circ$;
  - Modal analysis in Z shows mode 46 rapidly running away under full feedback control.
Deciphering the Beam Loss Event

- Which plane came first?
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ANKA:mar0416/015147; Io=94.174mA, Dsamps=1, ShifGain=4, Nbins=184,
At ∆: G1=76.0692, G2=76.0692, Ph1=15.1664, Ph2=15.1664, Brkpt=1600, Calib=34.252.
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Deciphering the Beam Loss Event, Continued

► Spectrogram of vertical bunch signal settles it!

► Longitudinal motion starts first, seen mostly as second harmonic in the amplitude detector channel;

► At beam phase excursions exceeding 90° at detection frequency, vertical feedback gain flips;

► Positive feedback excites vertical motion, causes beam loss.
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Deciphering the Beam Loss Event, Continued

- Spectrogram of vertical bunch signal settles it!
- Longitudinal motion starts first, seen mostly as second harmonic in the amplitude detector channel;
  - At beam phase excursions exceeding 90° at detection frequency, vertical feedback gain flips;
  - Positive feedback excites vertical motion, causes beam loss.
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- RF cavities in ANKA are compression tuned;
- During injection, LLRF adjusts cavity tuning to compensate for beam loading;
- All cavity HOMs tune at the same time;
- By adjusting cavity temperature we shifted the problematic HOM enough so that synchrotron sideband crossing happened at much lower beam current;
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- After adjusting cavity temperature we were able to keep the beam stable in X, Y, and Z;
  - New problem — with all planes stable, injection saturated around 110 mA due to poor Touschek lifetime;
  - Streak camera, stabilized beam;
  - Applied quadrupole excitation through the LFB;
  - Bunch lengthening leads to Touschek lifetime improvement;
  - With both feedback and modulation injected 160 mA and ramped to 2.5 GeV.
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ANKA Summary

- Historically operated with only transverse feedback, relied on moderate longitudinal instabilities at injection energy to provide sufficient lifetime to accumulate beam;
- Changes during a shutdown prevented injection above 100–120 mA
- Investigation showed:
  - Longitudinal HOM in RF cavity crossed synchrotron sideband around 110 mA;
  - Vertical beam loss mechanism — large longitudinal oscillation moved vertical bunch-by-bunch feedback into positive range;
  - Longitudinal growth rates unfeasible to control with feedback;
  - Adjusted cavity temperature to move sideband crossing to lower current, could run with full feedback control in all three planes;
  - With fully stabilized beam, lifetime dropped, injection saturated at 110–115 mA;
  - Used swept quadrupole excitation to control bunch length and lifetime, injected to 160 mA, successfully ramped.
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- 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.

Measurements courtesy of Weixing Cheng of NSLS-II.
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- Vertical beam size measured by a pinhole camera;
- A superposition of true beam size and residual dipole motion;
- Vertical emittance, calculated from pinhole camera data;
- Beam lifetime is correlated with beam size measurements, suggesting vertical size blow-up;
- Could get a better estimate of true beam size by subtracting known dipole motion term.

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New Machines and Challenges

- Transversely, new light sources and colliders are going become more and more sensitive to residual dipole motion;
  - Rule of thumb: residual dipole motion should be kept below 10% of the transverse beam size;
  - Usually more critical in the vertical plane;
  - Low-noise techniques in RF front end and digitizer design are required;
  - Most system designers do not care about spurs 100 dB below ADC full scale;
  - Since bunch-by-bunch feedback settles to the front end/digitizer noise floor, any spur can potentially ruin performance.

- Longitudinally, harmonic cavities used for lifetime improvement create major difficulties for bunch-by-bunch feedback:
  - HCs result in low synchrotron tune with large tune spread;
  - Conventional topology can handle tune spread of 2:1 at most.
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Bunch-by-bunch Feedback

- Sensor (pickup);
- Analog front-end;
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- Actuator (kicker).
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First stage of BPM signal processing — separating X/Y/Z signals

Since we are digitizing in the end, why not digitize raw signals?

For X and Y we are dealing with small differences of large signals;

If we can reject the common-mode at 20–30 dB level, that is also the gain of low-noise amplifier we can use to improve sensitivity.
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BPM Hybrid Network

First stage of BPM signal processing — separating $X/Y/Z$ signals

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Analog Front-end Design

Front-end requirements:
- Low amplitude and phase noise;
- Wideband to ensure high isolation between neighboring bunches.

Input bandpass filter is an analog FIR filter that replicates BPM pulse with spacing, matched to detection frequency period;

Detection frequency choice:
- High frequencies for sensitivity;
- Must stay below the propagation cut-off frequency of the vacuum chamber.

Local oscillator adjusted for amplitude (transverse) or phase (longitudinal) detection.
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Examples of Front-End Sensitivities Achieved

<table>
<thead>
<tr>
<th>Machine</th>
<th>Atten.</th>
<th>Calibration</th>
<th>At nominal current</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEAR3</td>
<td>0 dB</td>
<td>0.54 counts/mA/µm</td>
<td>0.96 counts/µm</td>
</tr>
<tr>
<td>MAX IV 3 GeV</td>
<td>0 dB</td>
<td>0.98 counts/mA/µm</td>
<td>2.8 counts/µm</td>
</tr>
<tr>
<td>ASLS</td>
<td>2 dB</td>
<td>1.24 counts/mA/µm</td>
<td>0.83 counts/µm</td>
</tr>
<tr>
<td>NSLS-II(^6)</td>
<td>0 dB</td>
<td>1.5 counts/mA/µm</td>
<td>0.75 counts/µm</td>
</tr>
</tbody>
</table>

- LSB of the 12-bit ADC in Dimtel iGp12 is only 5 times larger than thermal noise in the ADC bandwidth (wide for good isolation down to 2 ns bunch spacing);
- Not a lot of room for improved sensitivity, need to be smart with pickup selection, feedback algorithms.

\(^6\)Older front-end design with lower sensitivity
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Sensitivity and Noise

Detection noise ($v_n$)

Disturbances

Error

Feedback

Beam

Transverse position ($y$)

- 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.
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Growth and damping times in turns;

- $\tau_{ol} = \tau_{cl} = 300: -18.7$ dB
- $\tau_{ol} = \tau_{cl} = 30: -8.1$ dB
- $\tau_{ol} = 30, \tau_{cl} = 3.2: -6.0$ dB
- $\tau_{ol} = 5.4, \tau_{cl} = 5.4: 3.8$ dB
- Fast growth rates result in higher noise sensitivity.

Sensitivity Functions Compared
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- 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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- Conventional wisdom — shorter filter can generate faster damping, longer filter is quieter due to narrower bandwidth;
- Let’s see what complementary sensitivity function tells us.
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- Moderate increase of the integrated noise gain with filter length;
- Effect of the group delay;
- $T(\omega)$ shapes very similar near the tune — reflect identical closed-loop damping pole;
- As an added bonus, shorter filters are less sensitive to tune variation.
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Residual Noise vs. Filter Length

![Complementary sensitivity functions graph]

- 5 taps
- 6 taps
- 7 taps
- 8 taps
- 9 taps
- 10 taps
- 12 taps
- 15 taps
- 18 taps
- 21 taps
- 24 taps
- 32 taps
- 64 taps

Fractional tune
Magnitude (dB)
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Direct Energy Sensing

- Basic method: use horizontal signal from a pickup in a high dispersion location to sense energy oscillation directly;
- Eliminates the need to generate a 90° phase shift between longitudinal position measurement and energy kick;
- Feedback filter is just a gain plus two constraints:
  - High-pass transition below the synchrotron frequency band to filter out DC orbit offsets;
  - Low-pass transition above the synchrotron frequency band to remove horizontal signals.
- Can’t handle full lengthening (synchrotron frequency band extends to DC);
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APS-U Example

- Possible filter response for APS-U energy sensing;
  - $f_s = 620$ Hz without harmonic cavities;
  - Drops to $100 \pm 100$ Hz under optimal bunch lengthening;
  - 2 dB gain and $12.5^\circ$ phase ripple in 20–800 Hz range.
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- Bunch-by-bunch feedback can make different machines look alike, but it takes good system design and thorough understanding of driving terms;
- Never trust a “mild” instability — you never know when it will turn into a showstopper;
- Characterization of instabilities is a definite must for robust feedback operation;
- New low-emittance machines demand noise-figure optimized RF front-ends and digitizers;
- Simplified models are very helpful in understanding feedback algorithm trade-offs;
- Longitudinal feedback in presence of harmonic cavities is challenging, new (so far untested) energy sensing technique might help.
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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.
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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.