Coupled-bunch Instabilities and the Anna Karenina Principle

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Next Generation Beam Position Acquisition and Feedback Systems

Outline

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Many Ways to Fail, One Way to Succeed

Leo Tolstoy, "Anna Karenina"

All happy families are alike; each unhappy family is unhappy in its own way.

- Deficiency in any one of a large number factors can lead to failure;
- For success one must avoid all of these deficiencies;
- A slight variation in the context of accelerators and feedback:
  - Coupled bunch instabilities are excited by a wide variety of sources:
  - Instabilities exhibit a wide variety of behaviors;
  - Consequently, each storage ring presents unique set of challenges for feedback stabilization;
  - Under proper feedback control all storage rings look more or less the same.

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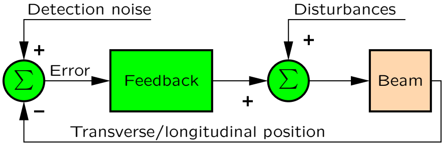
Steady State Spectra Under Feedback Control



- In transverse planes there are very few steady-state disturbances;
- Instabilities are damped to the noise floor;
- Spectrum is determined by feedback channel measurement noise, feedback gain, plus inevitable spur lines;
- Transfer gain from measurement noise to the feedback input is $\frac{1}{1+L(\omega)}$
- Maximum attenuation at the beam resonance produces a notch.

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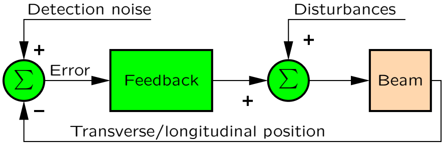

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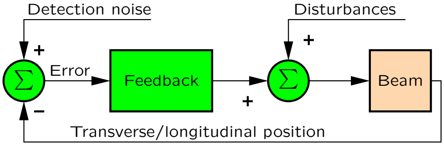

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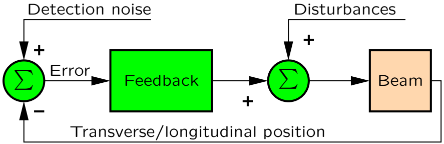

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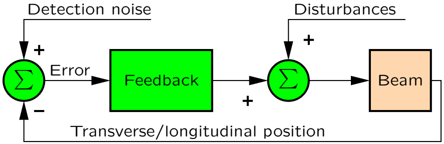

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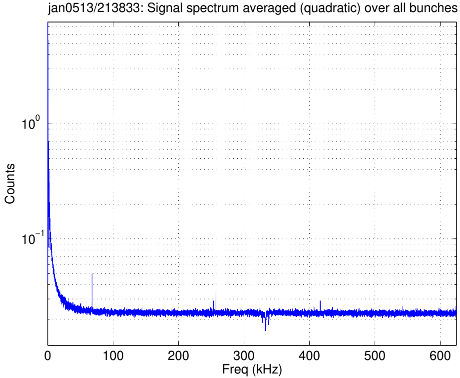

- Averaged spectra of all bunches under closed-loop feedback control;
  - BESSY II[1] Y at 298 mA;
  - Zoomed in;
  - Aichi SR[2] X at 300 mA;
  - Zoomed in;
  - TLS[3] at 200 mA;
  - Two notches - dual plane (X and Y) feedback;
  - Clean horizontal notch;
  - A line poking through the vertical notch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

[1] $h = 400$, $C = 240$ m
[2] $h = 120, C = 72$ m
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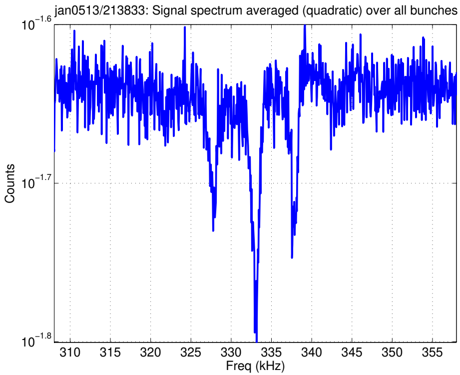

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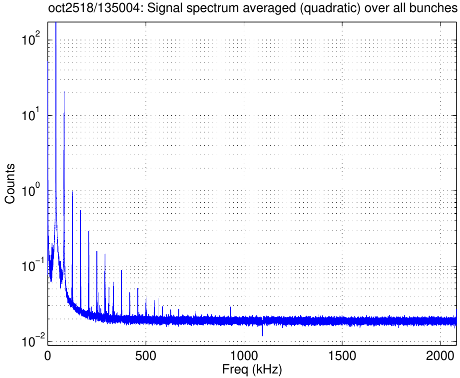

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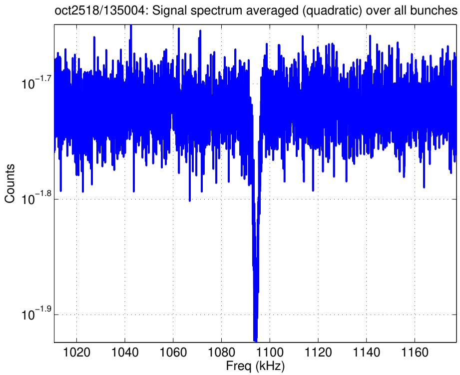

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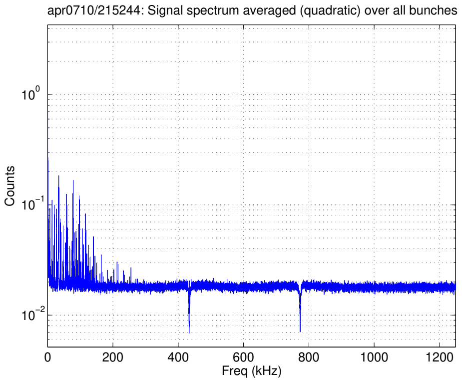

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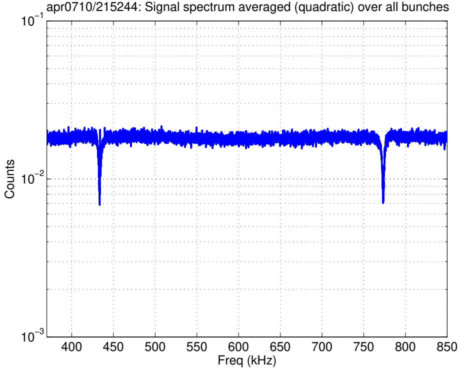

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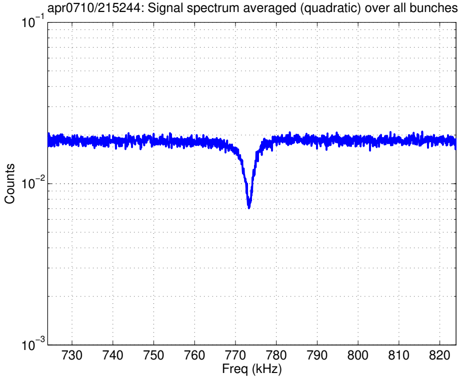

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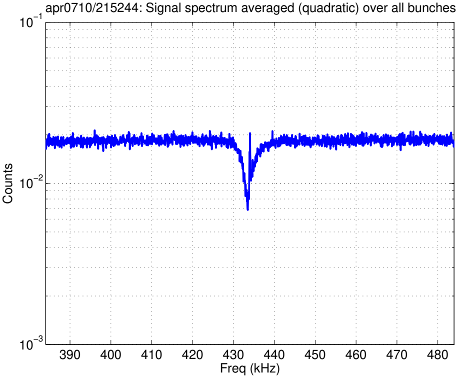

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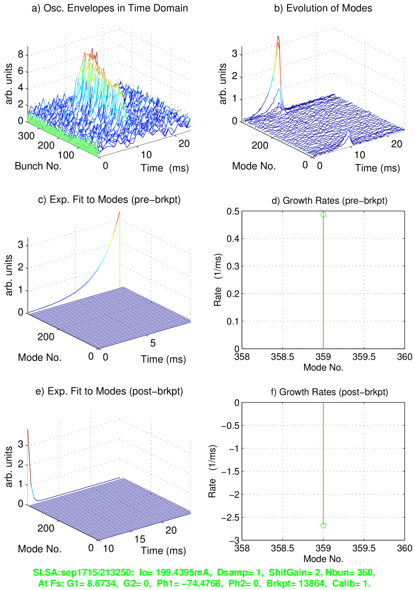
Resistive Wall and HOMs



- Australian Synchrotron has 3 in vacuum undulators (IVUs);
- With IVU gaps open vertical instabilities are dominated by the resistive wall;
- When the gaps are closed, much faster modes appear;
- Scanned vertical growth rates vs. IVU gap to quantify the resonance.

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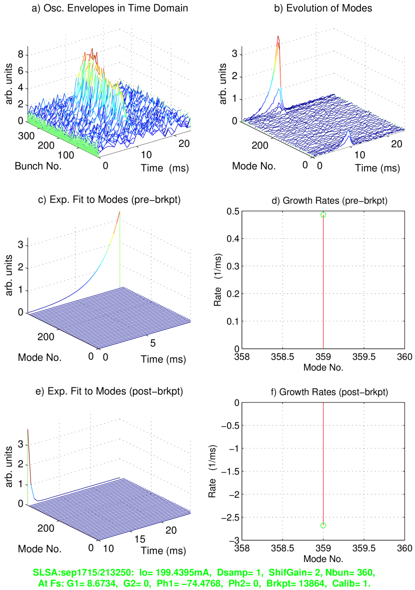

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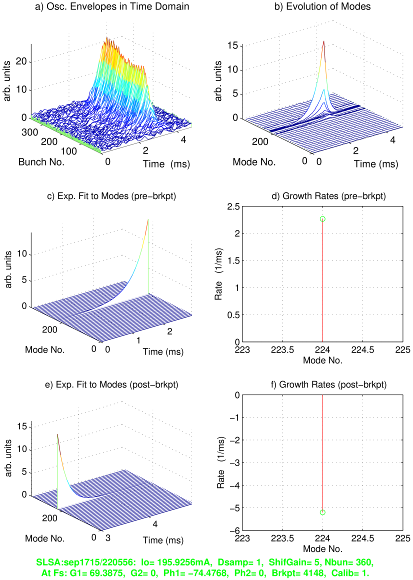

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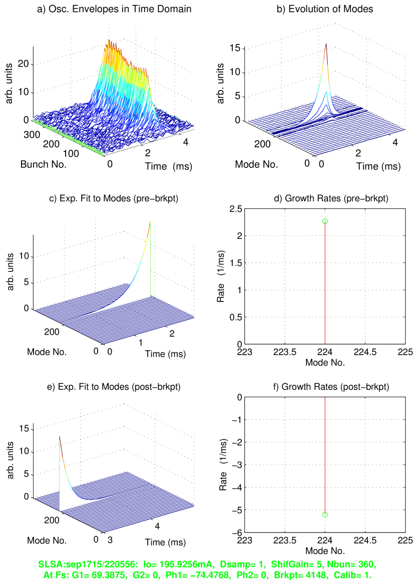

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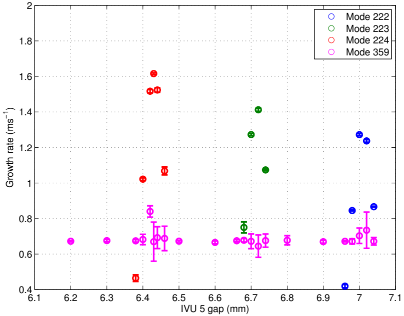
Vertical Growth Rates vs. IVU Gap



- Moved the resonance over 3 revolution harmonics;
- Resistive wall mode is more or less constant;
- Fit second order responses to each mode;
- Consistent results: bandwidth 75–78 µm;
- Impedance seems to increase as we get closer to the beam.

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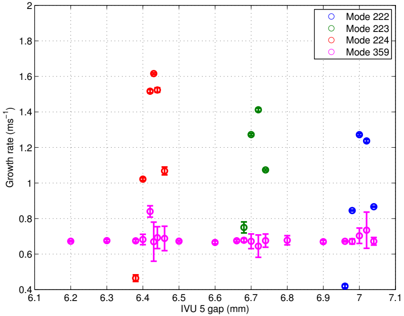

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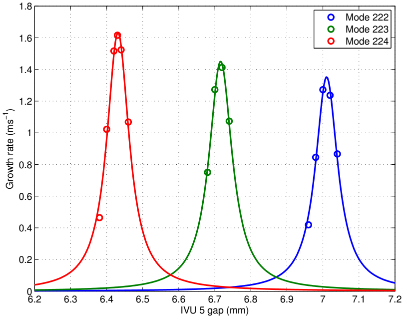

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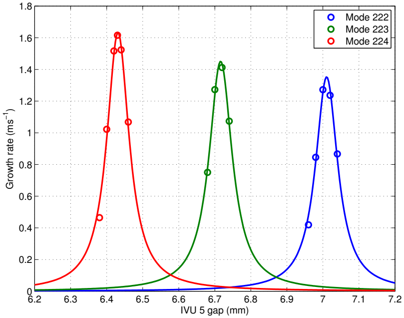

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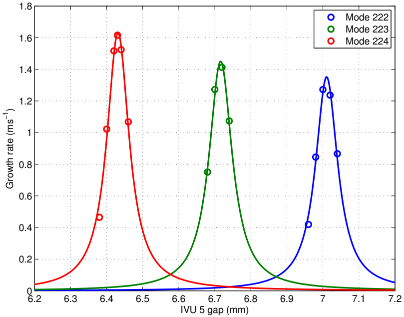

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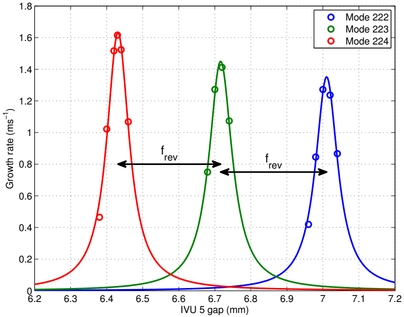

- Resonant frequency seems to change linearly with the gap position:
  - Two revolution harmonic distances are within 3%;
- Tuning sensitivity 4.8 MHz mm^{-1};
- Bandwidth of 76 µm translates to 365 kHz;

Parameter	Measurement	Model
Tuning sensitivity, MHz mm^{-1}	4.8	4.8
Bandwidth, kHz	360–374	239
CF @ 6 mm gap, MHz	186.4	194.4

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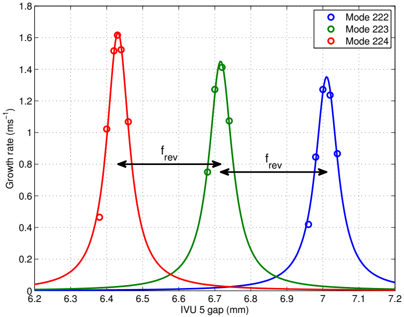

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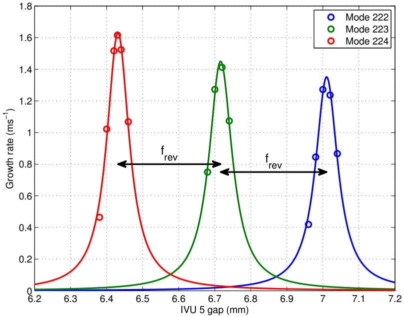

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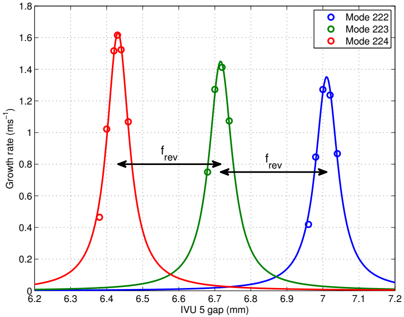

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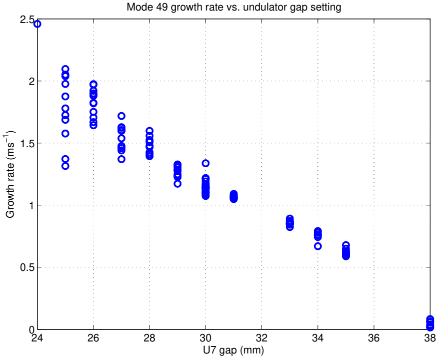

- APPLE II undulator;
- Instability threshold at 38 mm gap is 300 mA;
- Growth rates are going up monotonically with decreasing undulator gap;
- Betatron tune moves from 1105 to 1180 kHz during this scan;
- At some point in the range, low frequency (resistive wall?) modes pop up;
- All modes are easily suppressed by feedback, but the mechanism is still unclear.

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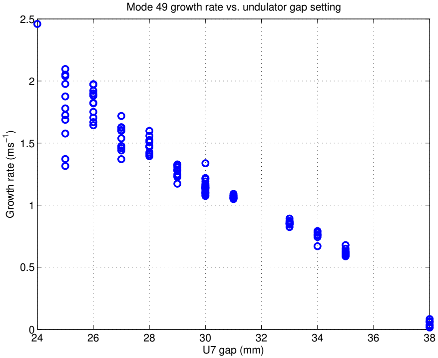

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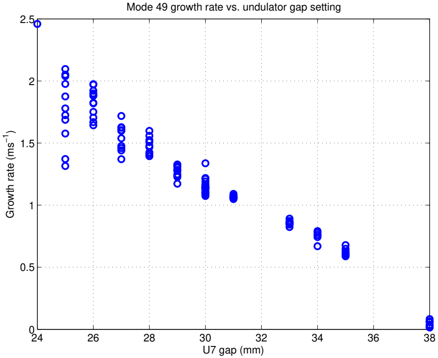

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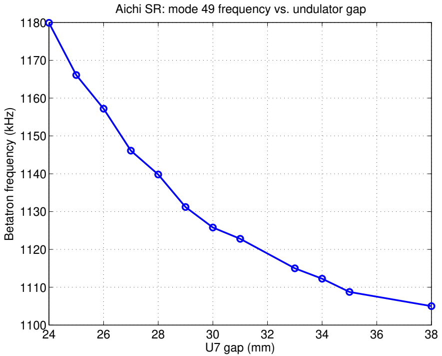

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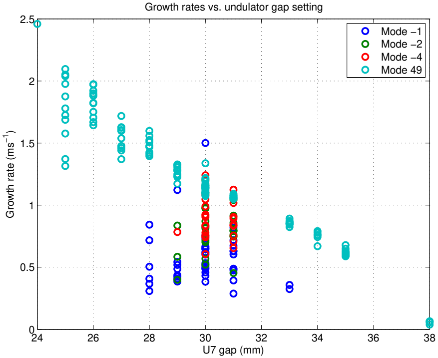

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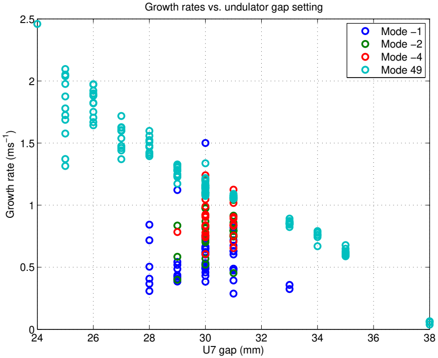

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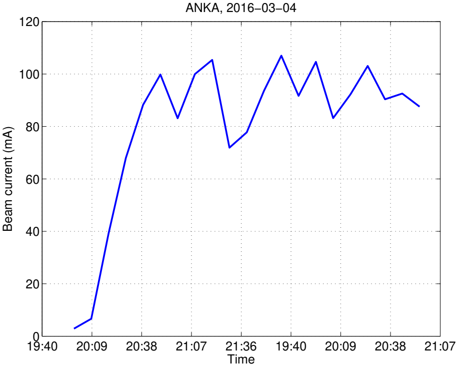
- Instability threshold at 38 mm gap is 300 mA;
- Growth rates are going up monotonically with decreasing undulator gap;
- Betatron tune moves from 1105 to 1180 kHz during this scan;
- At some point in the range, low frequency (resistive wall?) modes pop up;
- All modes are easily suppressed by feedback, but the mechanism is still unclear.

Outline

Initial Assessment



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

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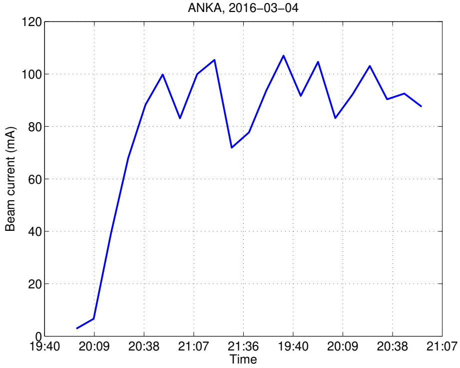

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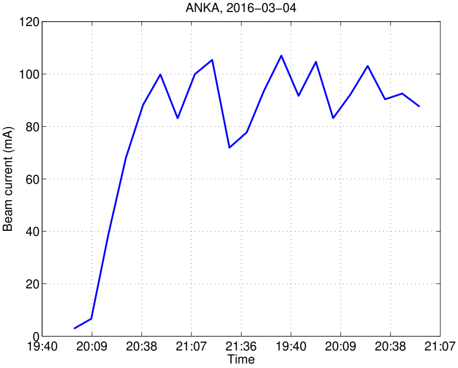

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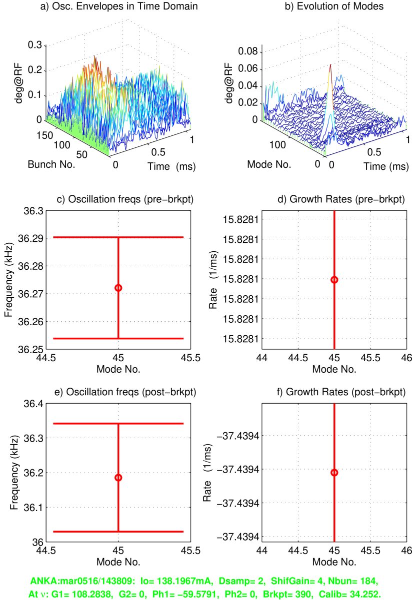
Feedback in All Three Planes



- 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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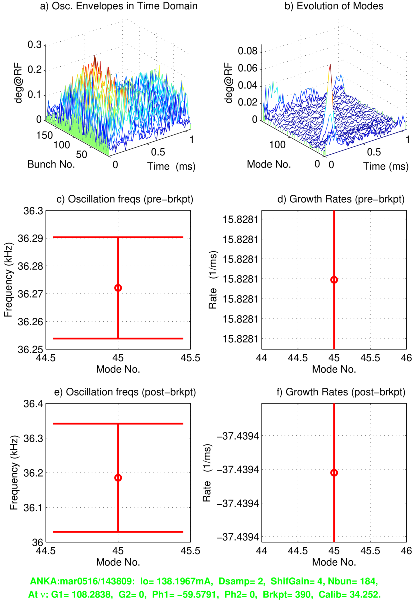

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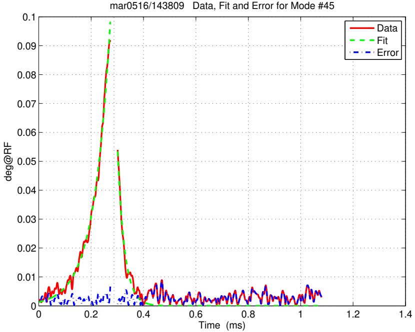

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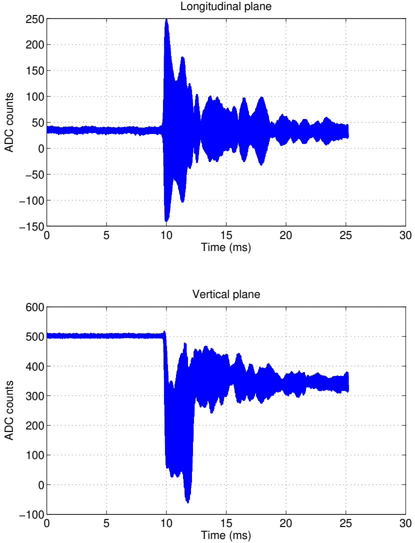
Capturing the Beam Loss Event



- 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.

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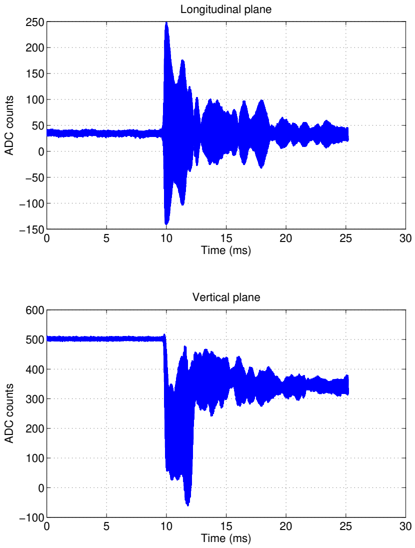

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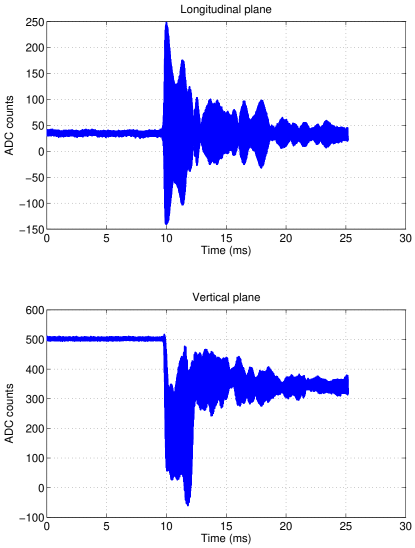

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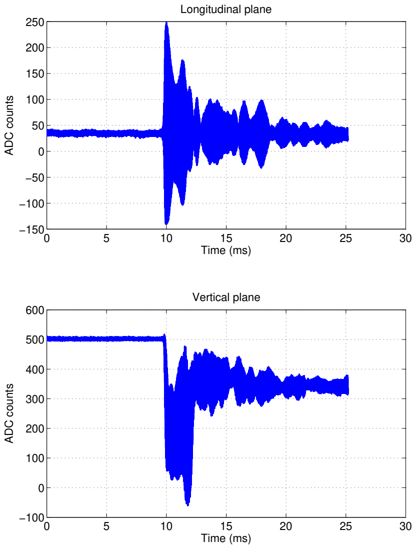

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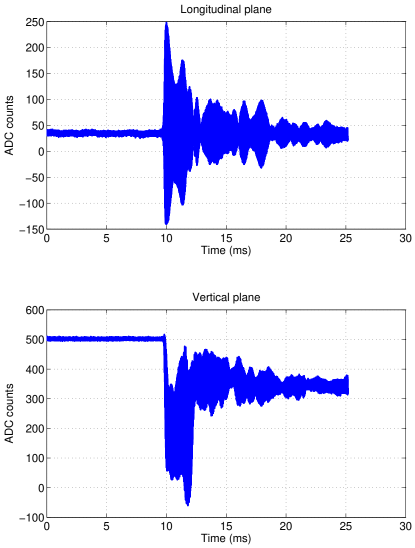

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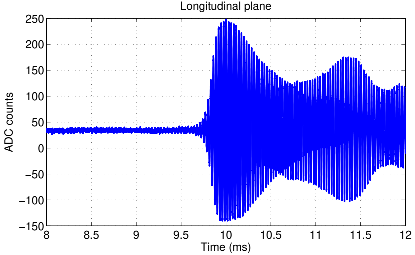

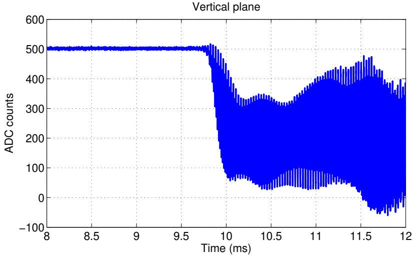

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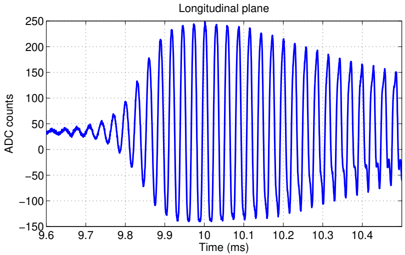

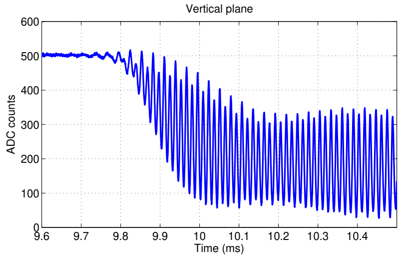

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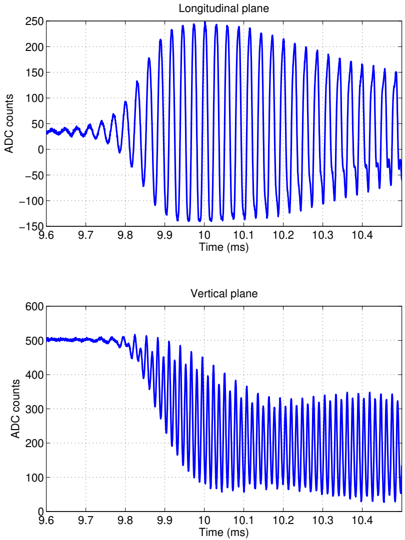

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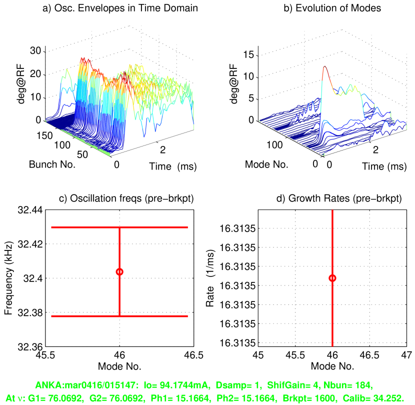

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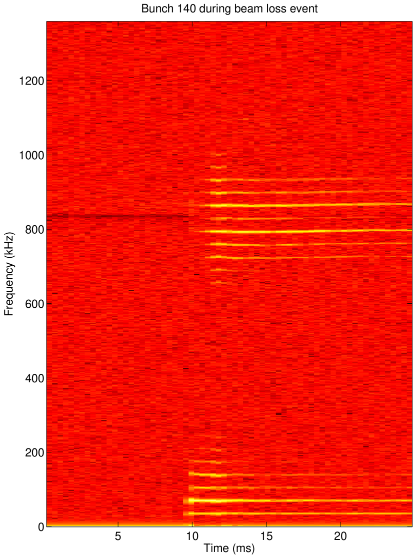

- Spectrogram of vertical bunch signal settles it!
- Longitudinal motion starts first, seen mostly as second harmonic in the amplitude detector channel;
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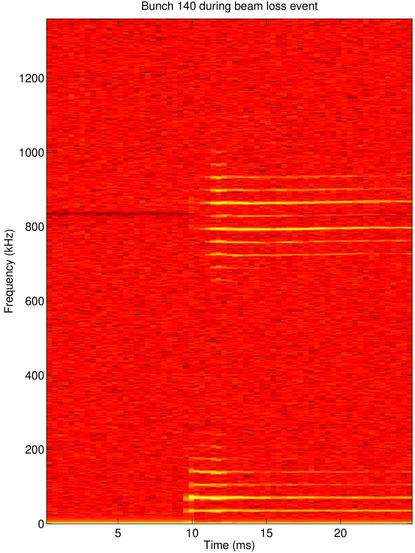

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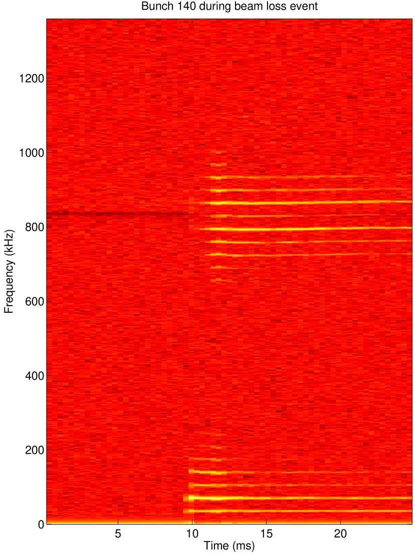

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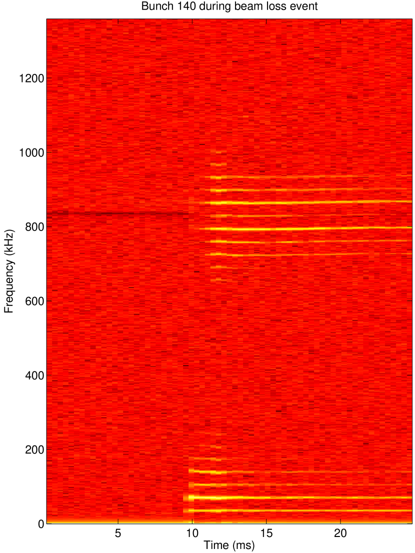

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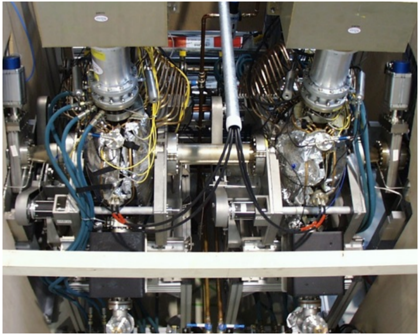

- RF cavities in ANKA are compression tuned;
- During injection, LLRF adjusts cavity tuning to compensate for beam loading;
- All cavity HOMs tune at the same time;
- By adjusting cavity temperature we shifted the problematic HOM enough so that synchrotron sideband crossing happened at much lower beam current;
- Growth rates scale with current, feasible to control!

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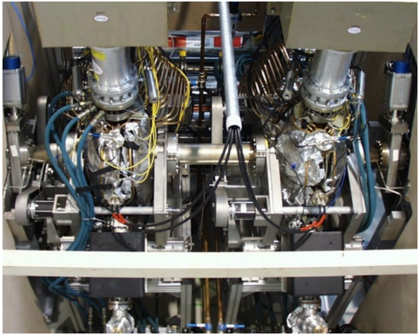

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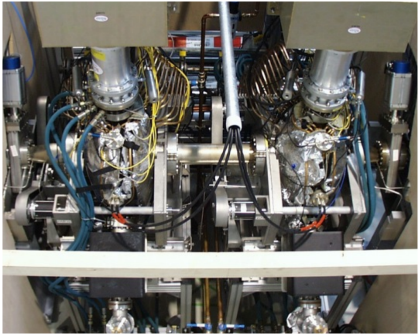

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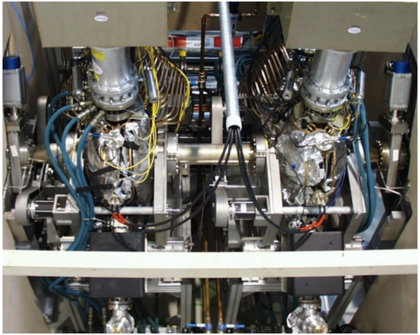

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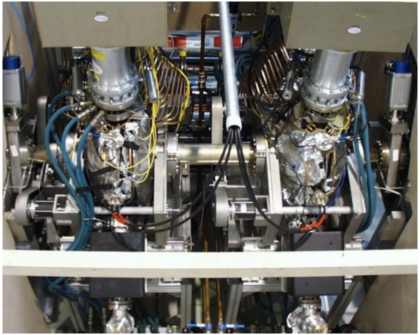

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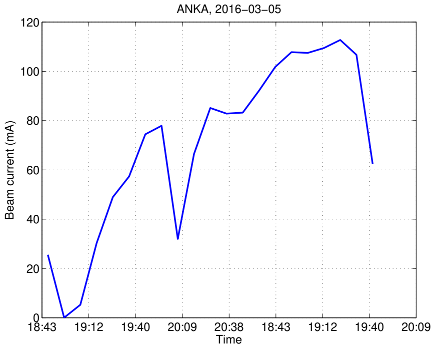

- After adjusting cavity temperature we were able to keep the beam stable in X, Y, and Z;
- New problem — with all planes stable, injection saturated around 110 mA due to poor Touschek lifetime;
- Streak camera, stabilized beam;
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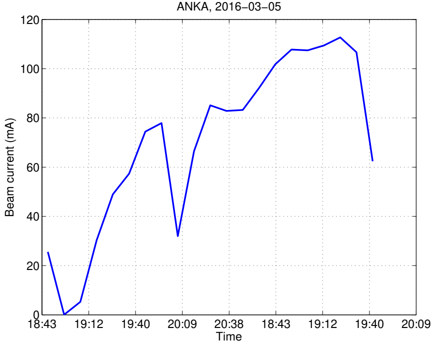

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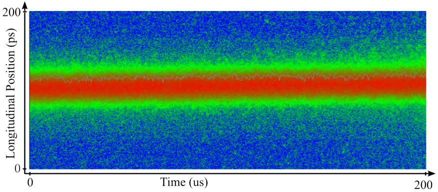

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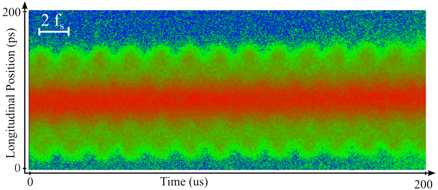

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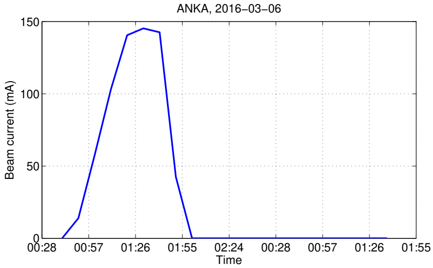

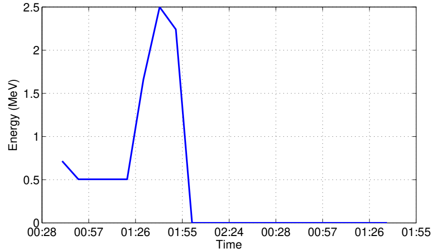

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ANKA Summary

- 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.

New Machines and Challenges

- Transversely, new light sources and colliders are going become more and more sensitive to residual dipole motion;
  - For low-emittance machines, residual motion should be below 10% of transverse beam size;
  - Usually more critical in the vertical plane;
  - Low-noise techniques in RF front end and digitizer design are required;
  - Most 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 ruin performance.
- Longitudinally, harmonic cavities used for lifetime improvement create major difficulties for bunch-by-bunch feedback:
  - Synchrotron tune is pushed down and tune spread increases;
  - Conventional topology can handle tune spread of 2:1 at most.

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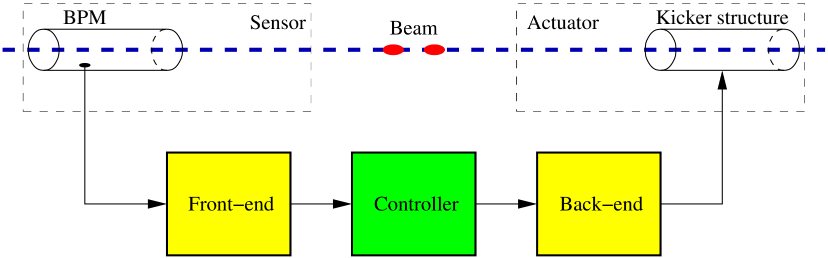
Bunch-by-bunch Feedback



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- Analog front-end;
- Controller;
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- Actuator (kicker).

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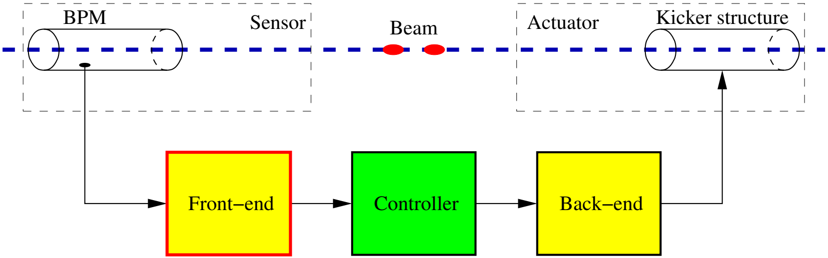

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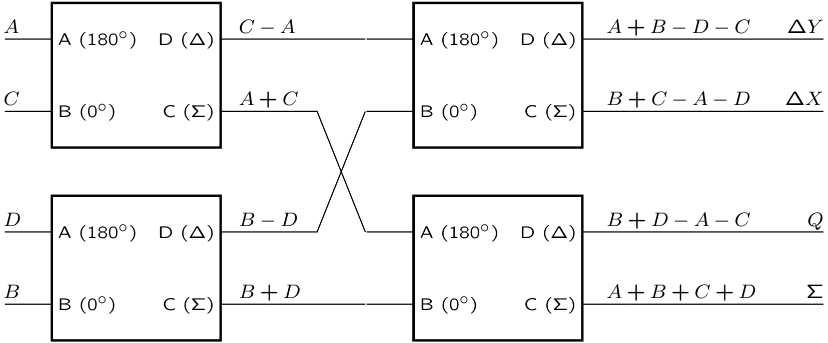
BPM Hybrid Network



- 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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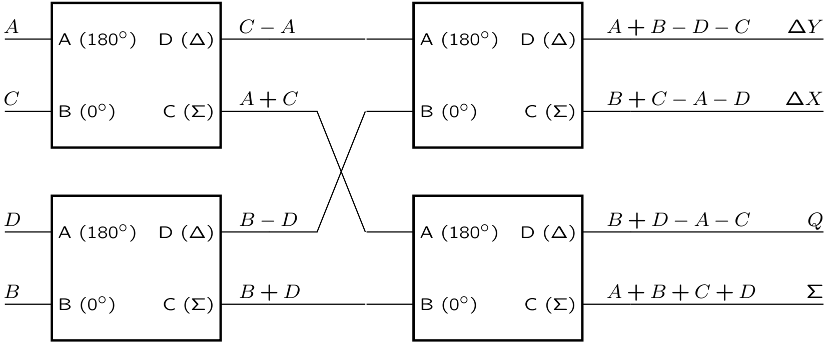

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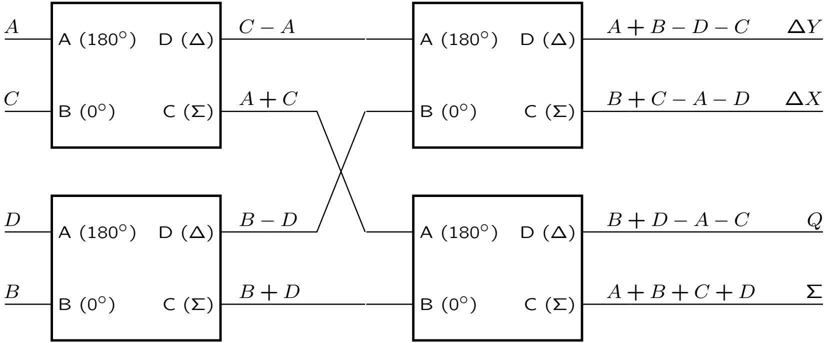

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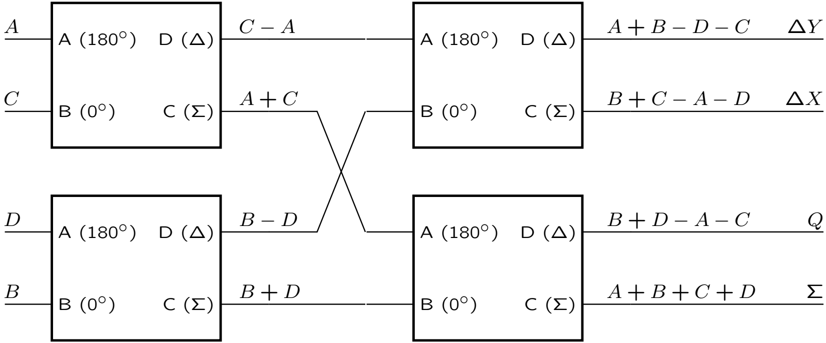

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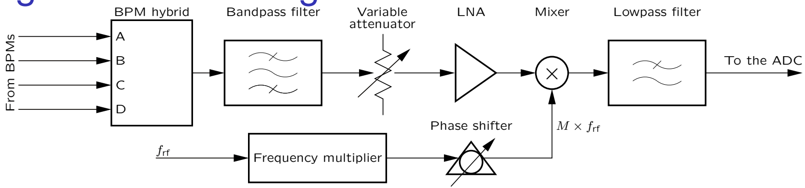

- Front-end requirements:
  - Low amplitude and phase noise;
  - Wideband to ensure high isolation between neighboring bunches.
- Input bandpass filter is an analog FIR filter that replicates BPM pulse with spacing, matched to detection LO period;
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  - Must stay below the propagation cut-off frequency of the vacuum chamber.
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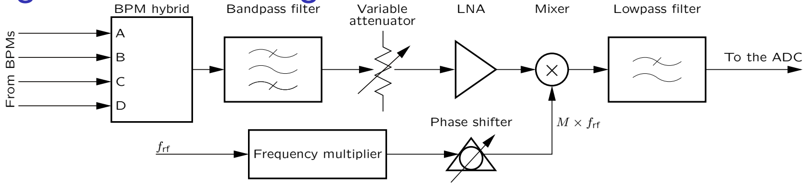

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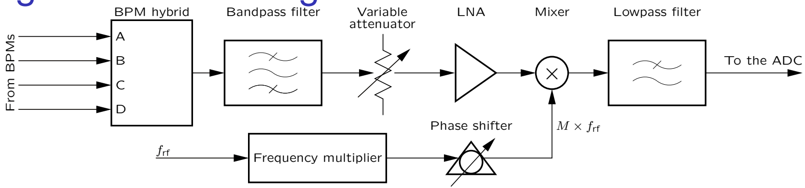


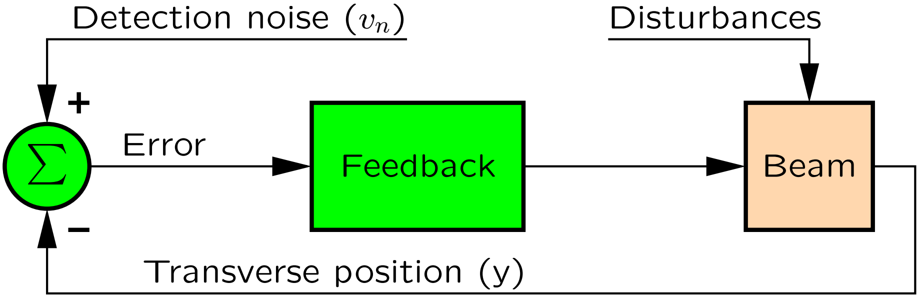
- Front-end requirements:
  - Low amplitude and phase noise;
  - Wideband to ensure high isolation between neighboring bunches.
- Input bandpass filter is an analog FIR filter that replicates BPM pulse with spacing, matched to detection LO period;
- Detection frequency choice:
  - High frequencies for sensitivity;
  - Must stay below the propagation cut-off frequency of the vacuum chamber.
- Local oscillator adjusted for amplitude (transverse) or phase (longitudinal) detection.

Examples of Front-End Sensitivities Achieved

Vertical Plane

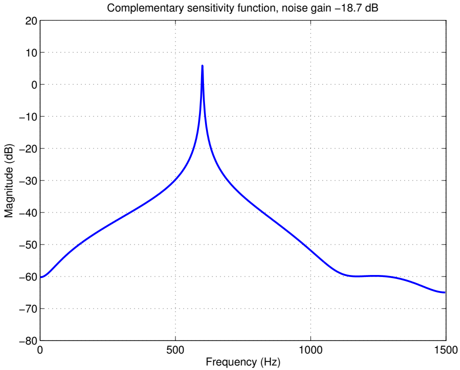
Machine	Atten.	Calibration	At nominal current
SPEAR3	0 dB	0.54 counts/mA/µm	0.96 counts/µm
MAX IV 3 GeV	0 dB	0.98 counts/mA/µm	2.8 counts/µm
ASLS	2 dB	1.24 counts/mA/µm	0.83 counts/µm

Sensitivity and Noise



- Complementary sensitivity $S(\omega)$ 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
- $\tau_{\mathrm{ol}} = \tau_{\mathrm{cl}} = 30$: −8.1 dB
- $\tau_{\mathrm{ol}} = 30$, $\tau_{\mathrm{cl}} = 3.2$: −6.0 dB
- $\tau_{\mathrm{ol}} = 5.4$, $\tau_{\mathrm{cl}} = 5.4$: 3.8 dB
- Fast growth rates result in higher noise sensitivity.

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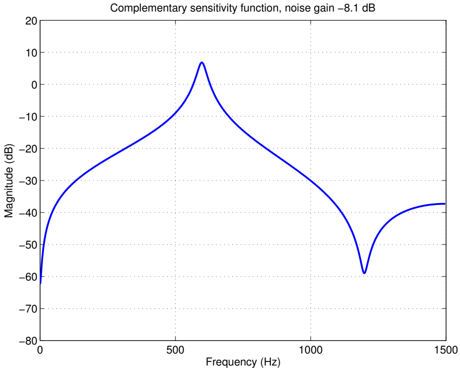

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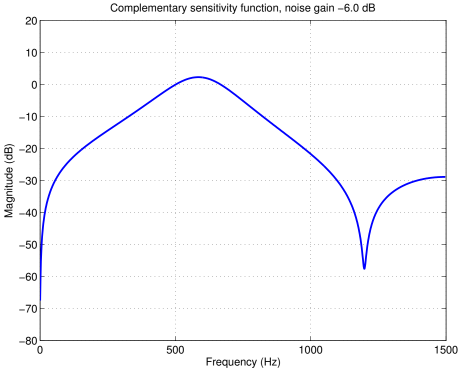

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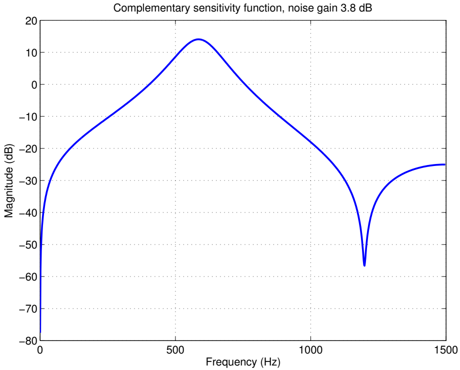

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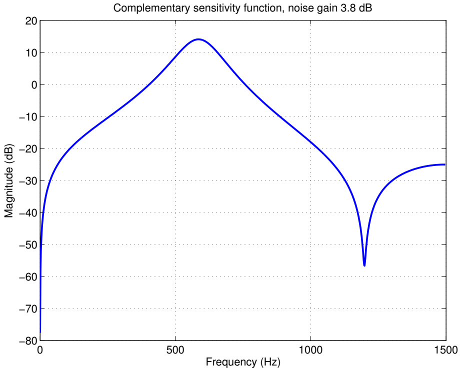

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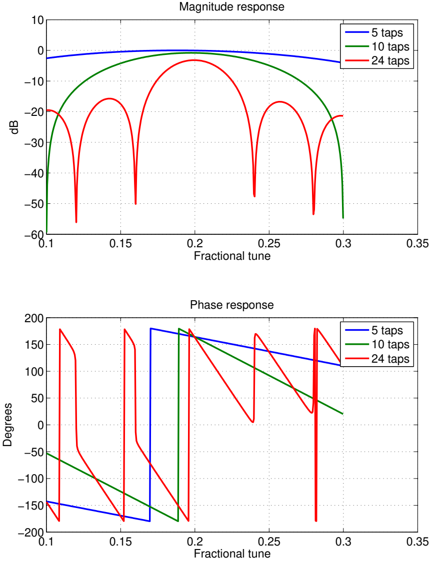
Feedback Filter Design



- Transverse feedback FIR filters, tune of 0.2, adjusted for the same closed-loop damping time ($\tau_{\rm cl} = \tau_{\rm ol} = 30$ turns);
- 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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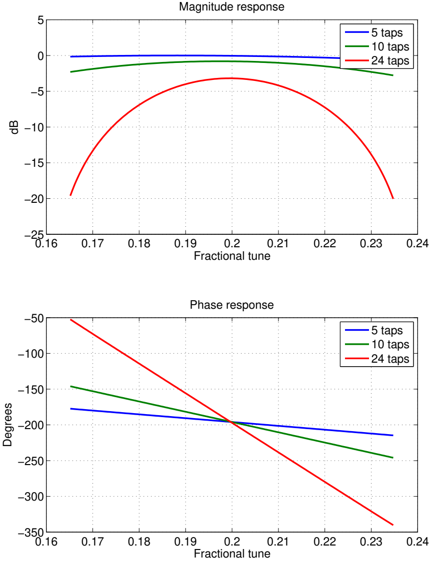

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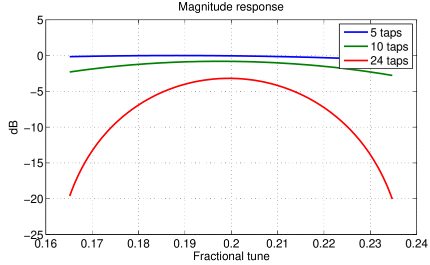

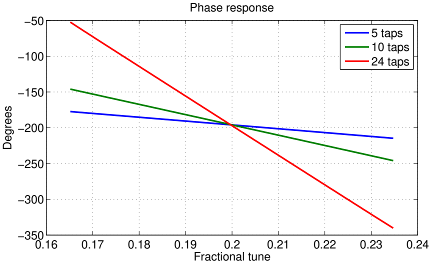

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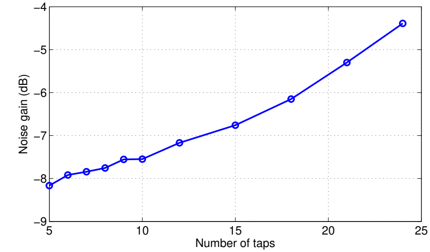
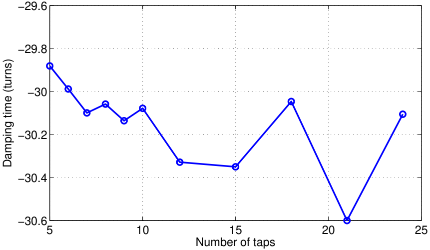
Residual Noise vs. Filter Length





- Integrated noise gain increases with filter length;
- Effect of the group delay;
- $S(\omega)$ get more peaked with larger group delay;
- Only applicable in white noise situation, with narrowband spurs/interferers response notches can be helpful.

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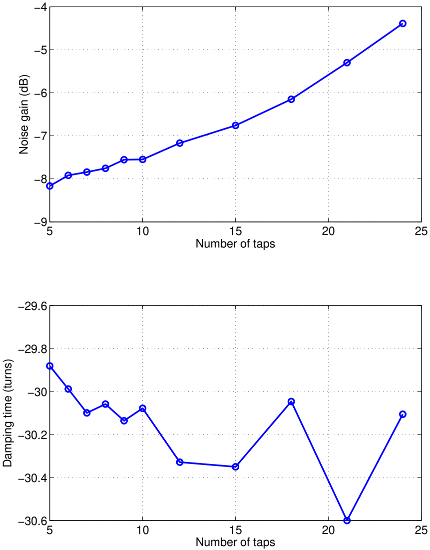

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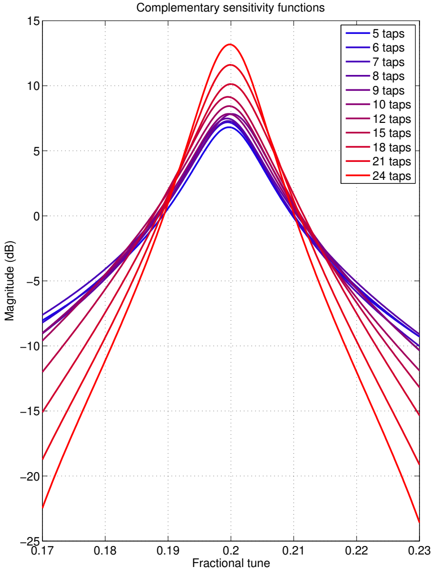

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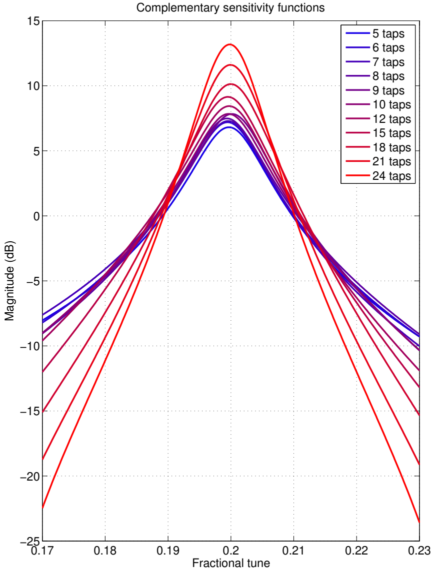

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Outline

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, when synchrotron frequency band extends to DC;
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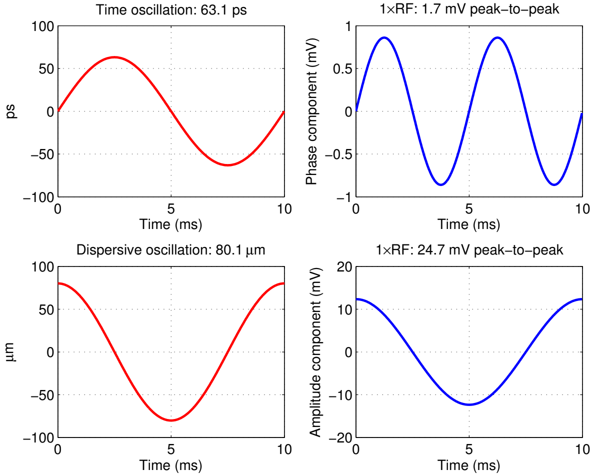
APS-U Example



- 352 MHz;
- 704 MHz;
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- Linear scaling for amplitude, quadratic for phase, just as expected.

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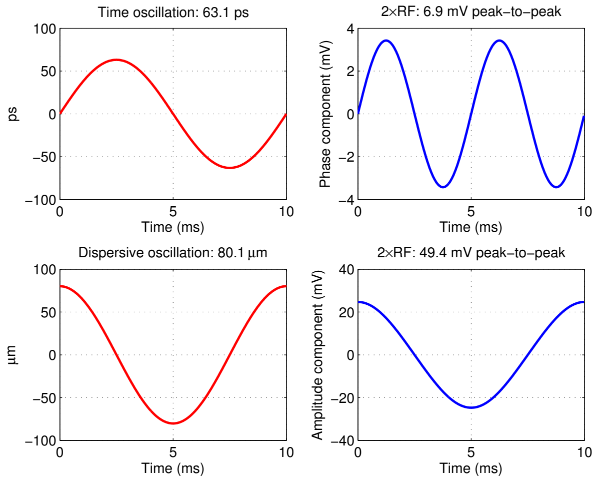

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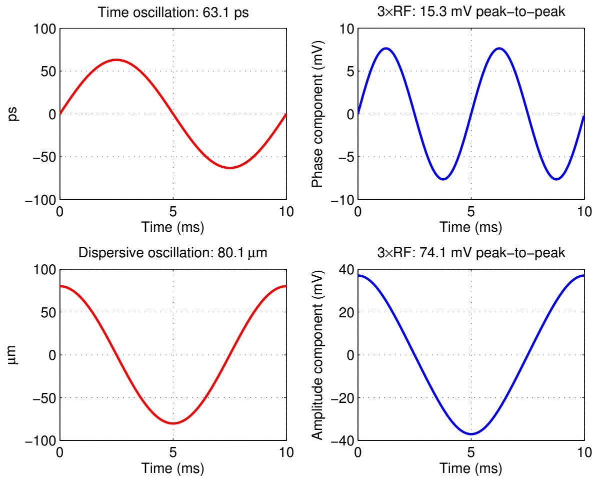

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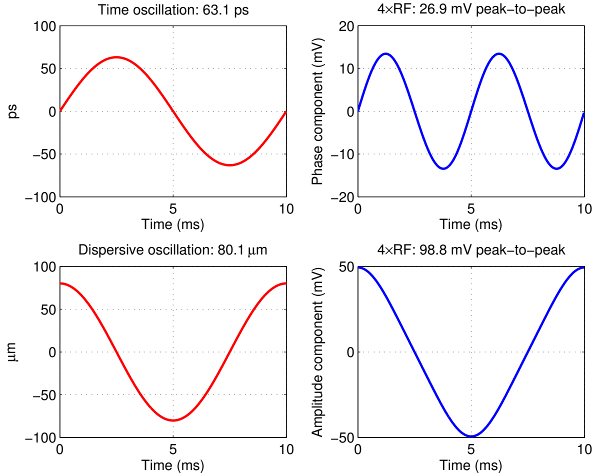

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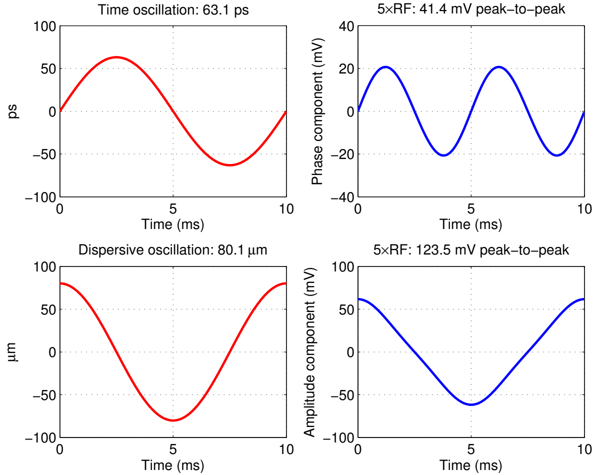

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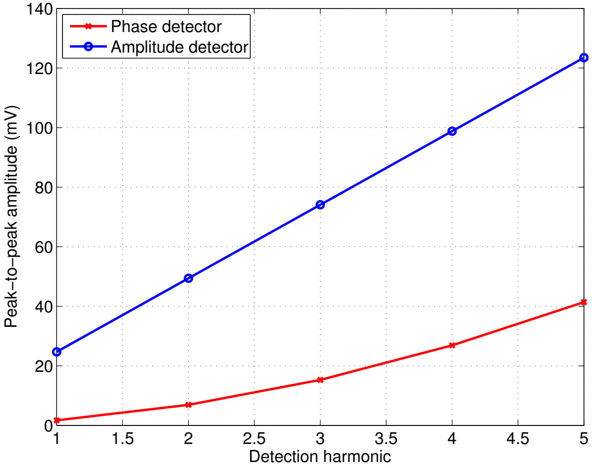

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Summary

- 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;
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