Experience with feedback systems in modern synchrotron light sources

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Dimtel, Inc., San Jose, CA, USA

Accelerator Performance and Concepts Workshop
Frankfurt, December 10-12, 2018

Outline

Learning From Many Facilities

Machines

Ring	C, m	E, GeV
MLS	48	0.1–0.6
HLS	66	0.8
LNLS UVX	93	0.5–1.37
MAX IV 1.5 GeV	96	1.5
DAΦNE	98	0.51
Duke SR-FEL	108	0.2–1.2
ANKA	110	0.5–2.5
DELTA	115	1.5
TLS	120	1.5
ELSA	164	1.2–3.2
Indus-2	173	0.55–2.5
Photon Factory	187	2.5
ALS	197	1.9
Australian Synchrotron	216	3
SPEAR3	234	3
BEPC-II	238	1.89
BESSY II	240	1.7
TPS	518	3
MAX IV 3 GeV	528	3
CESR-TA	768	1.5–6
NSLS-II	792	3
SuperKEKB	3016	4/7

- Over the last 12 years I had a pleasure of directly or indirectly participating in commissioning bunch-by-bunch feedback in 22 machines;
- A definite learning opportunity!
- Helped me gain some understanding of feedback limiting factors;
- Becoming more important in future accelerators.

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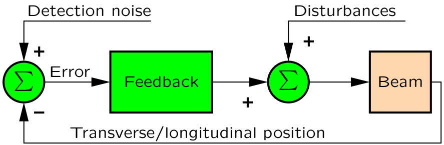
Steady State Spectra Under Feedback Control



- 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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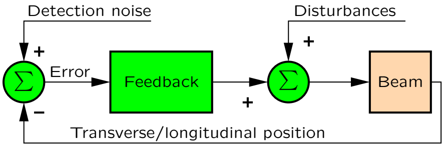

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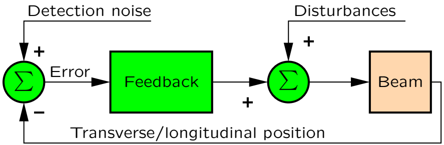

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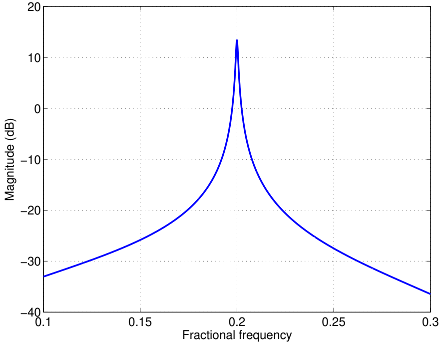

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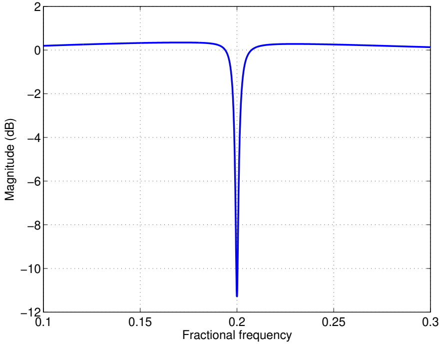

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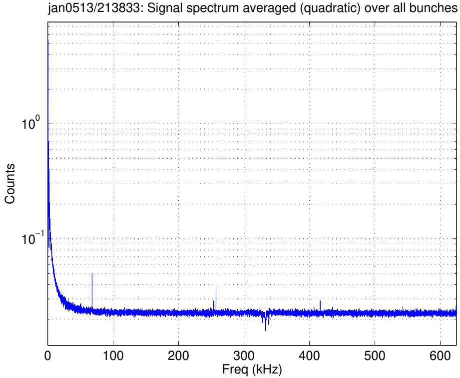

- Averaged spectra of all bunches under closed-loop feedback control;
  - BESSY II[1] Y at 298 mA;
  - Zoomed in;
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  - TLS[3] at 200 mA;
  - Two notches - dual plane (X and Y) feedback;
  - Clean horizontal notch;
  - A line poking through the vertical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

[1] $h = 400$, $C = 240$ m
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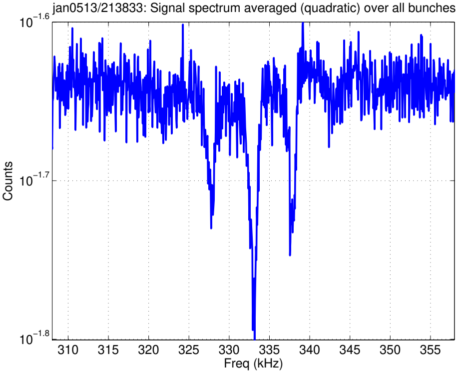

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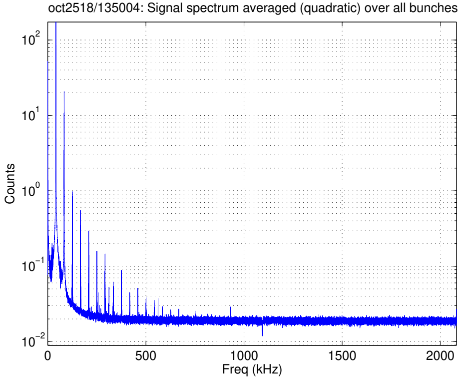

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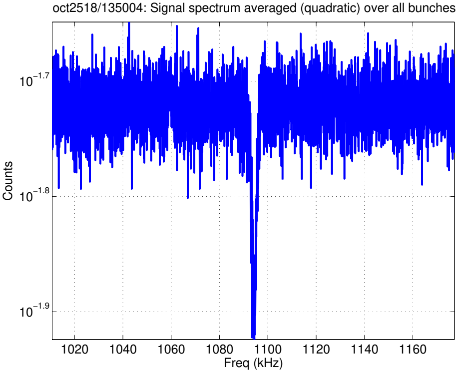

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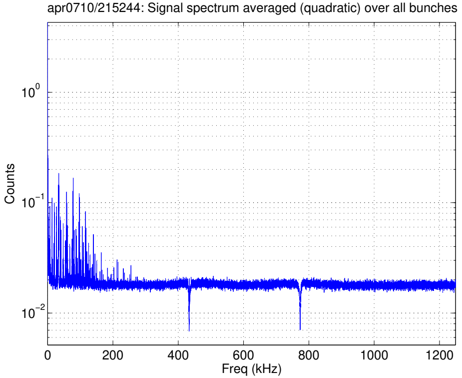

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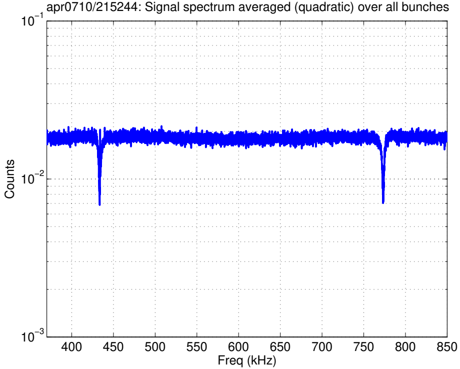

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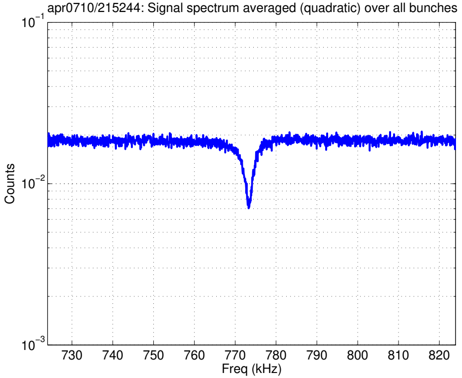

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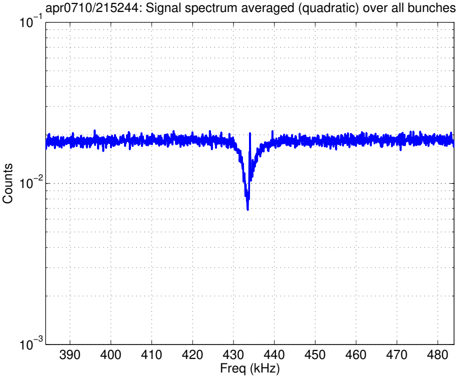

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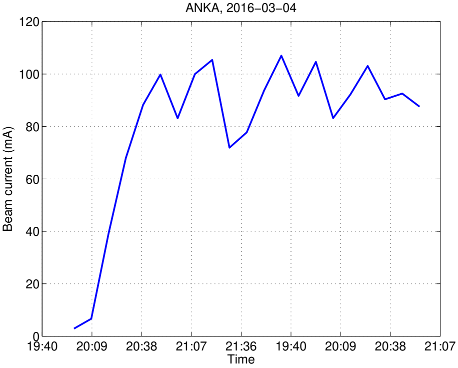
Initial Assessment



- 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.

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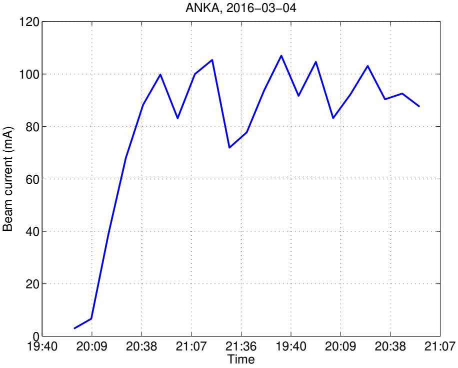

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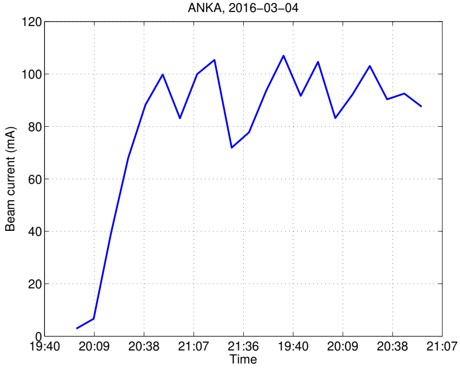

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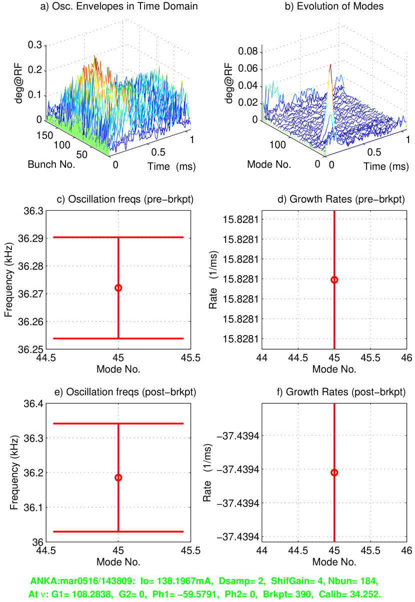
Feedback in All Three Planes



- 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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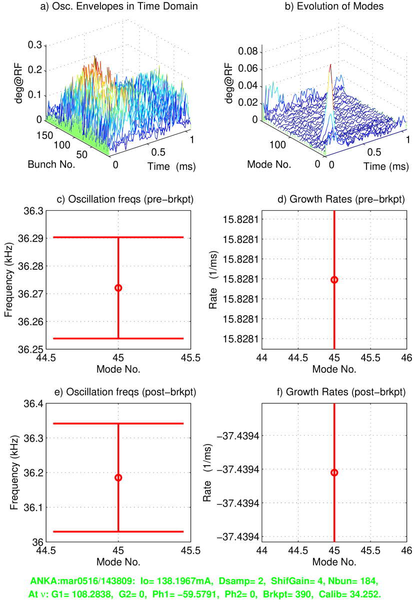

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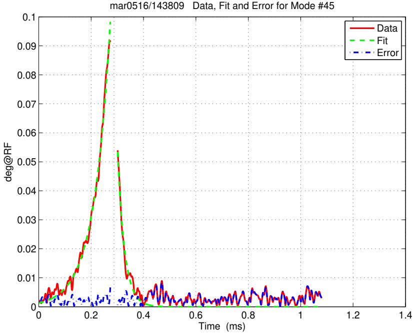

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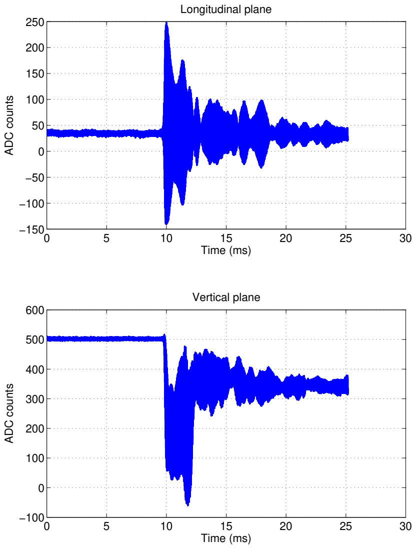

- Noticed significant activity in the vertical plane during beam loss events;
- Used baseband processor output to trigger acquisition in all planes;
- Vertical correction signals are normally small, only reaching full-scale during beam loss;
- Longitudinal and vertical signals for bunch 140.

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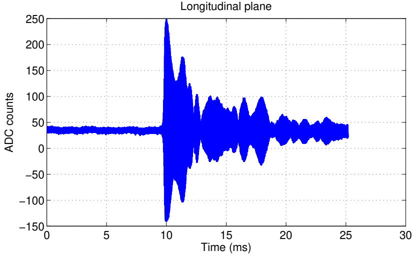

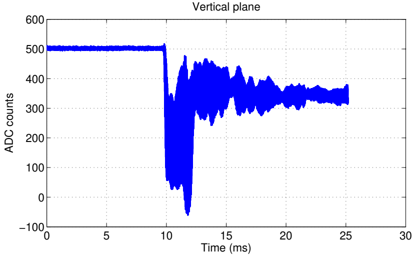

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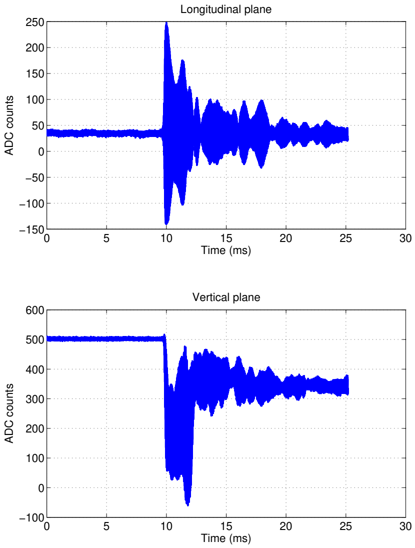

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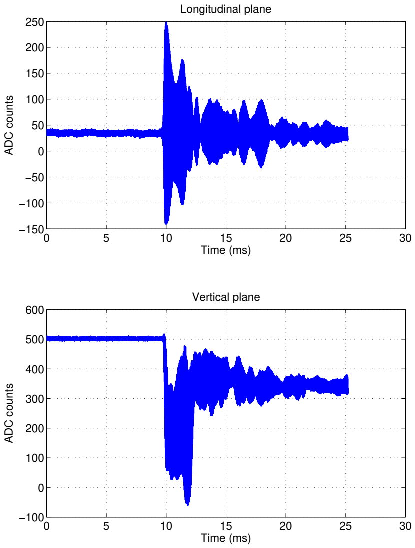

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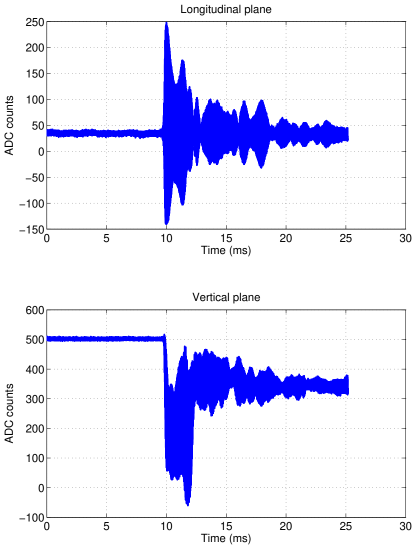

- Which plane came first?
- Zoom in, still too close;
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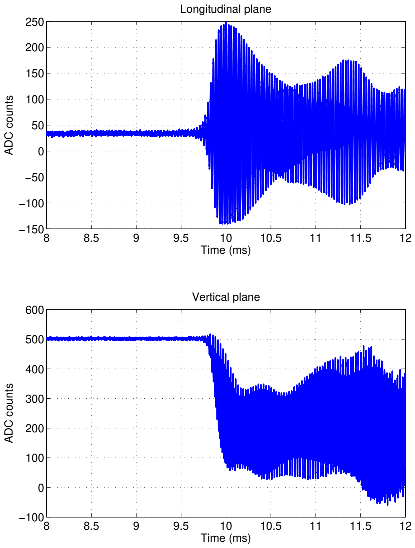

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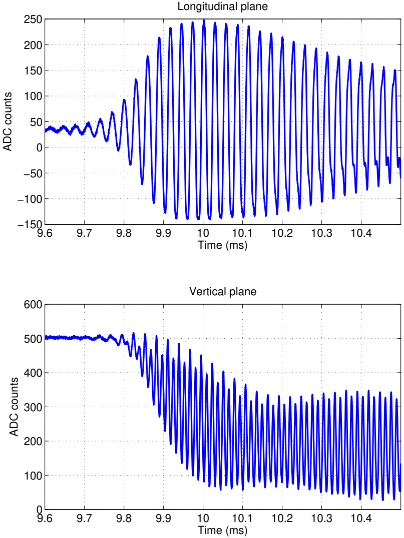

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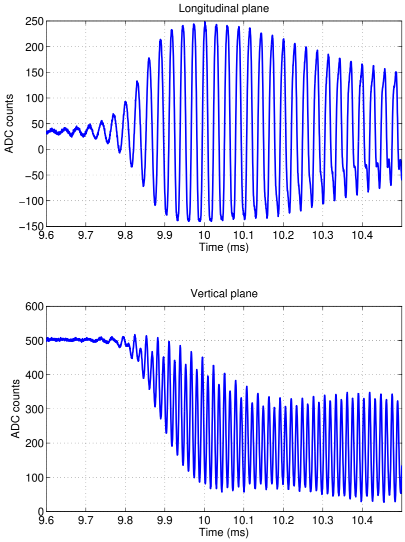

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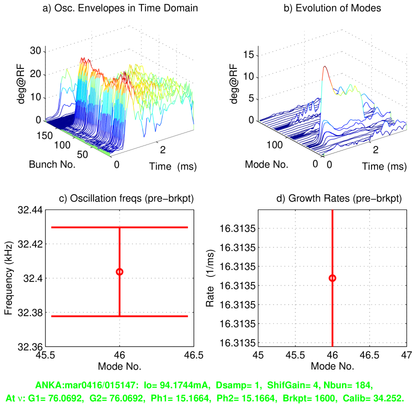

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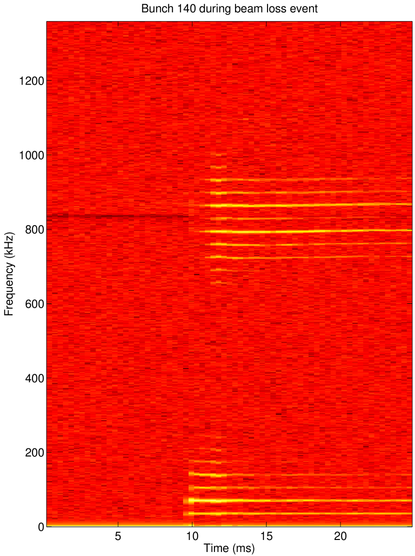

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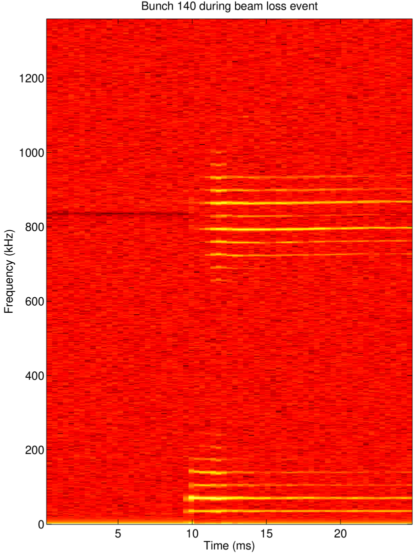

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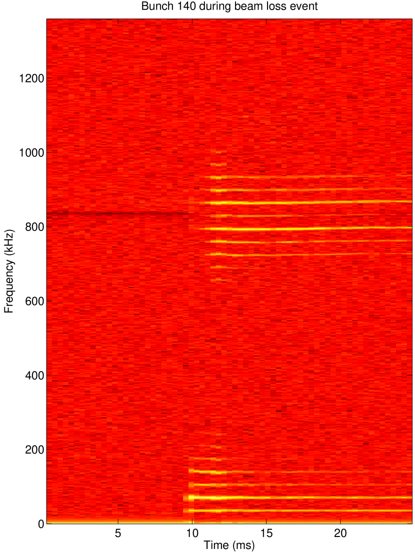

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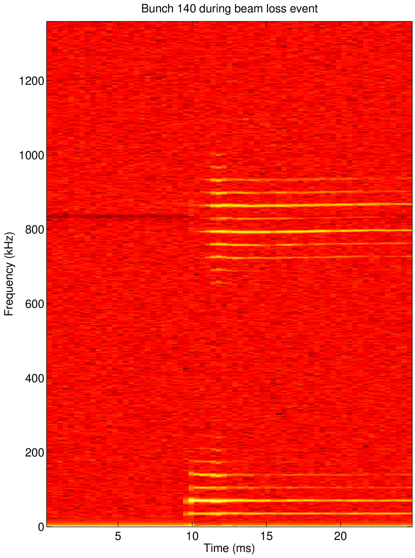
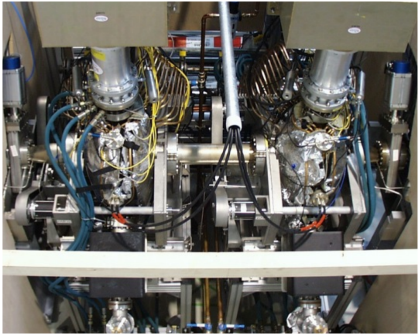


- Spectrogram of vertical bunch signal settles it!
- Longitudinal motion starts first, seen mostly as second harmonic in the amplitude detector channel;
- At beam phase excursions exceeding 90° at detection frequency, vertical feedback gain flips;
- Positive feedback excites vertical motion, causes beam loss.

Fixing the Issue



- 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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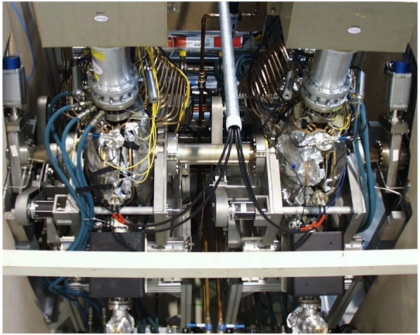

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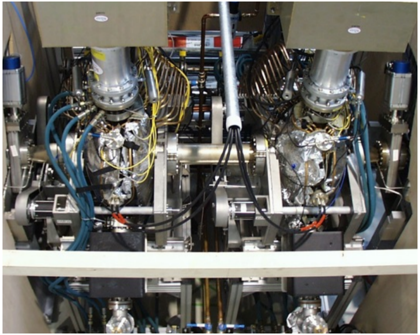

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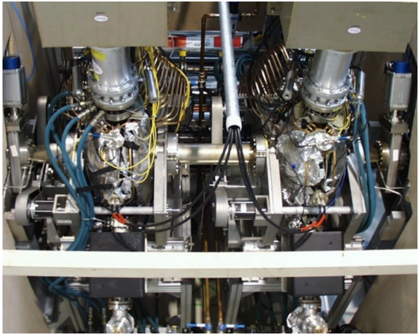

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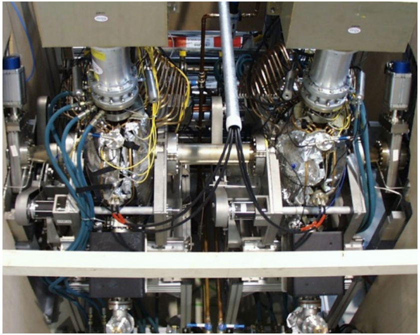

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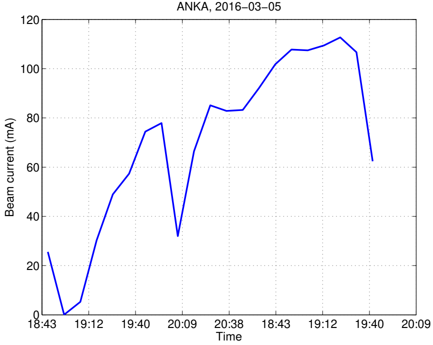
The Final Problem



- 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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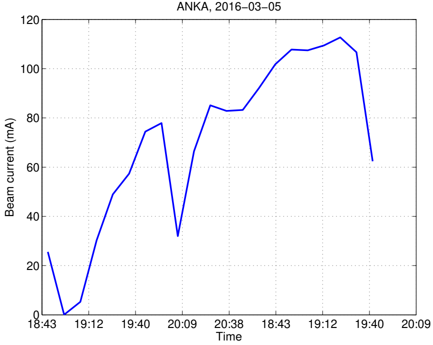

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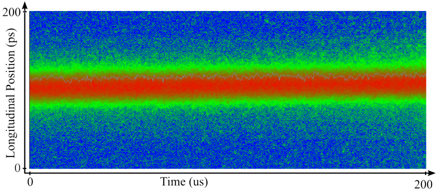

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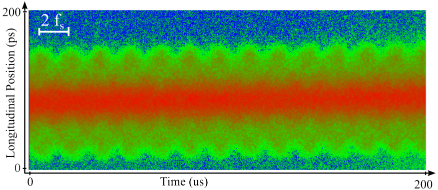

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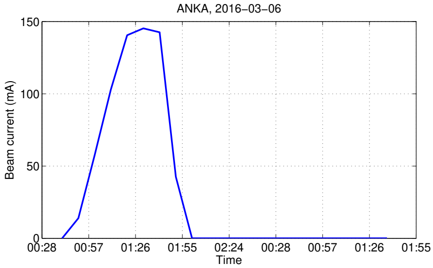

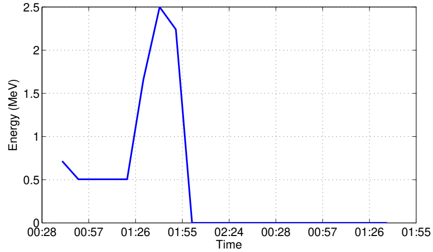

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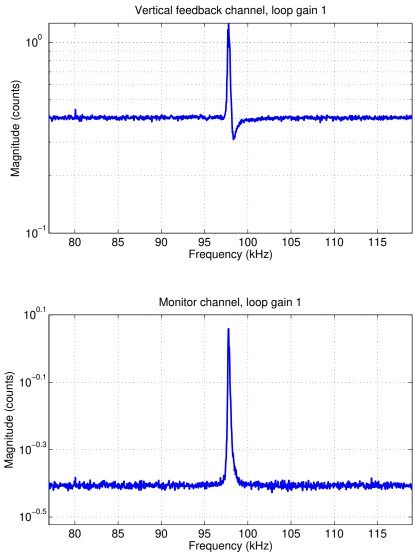
ANKA Summary

- 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.

Outline

Averaged Bunch Spectra vs. Feedback Gain [4]



- 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.

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

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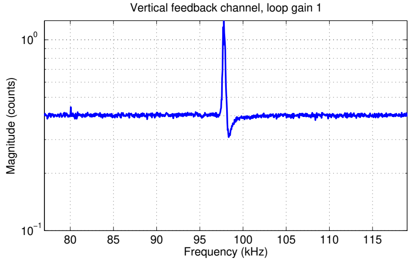

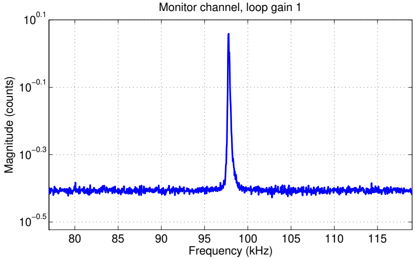

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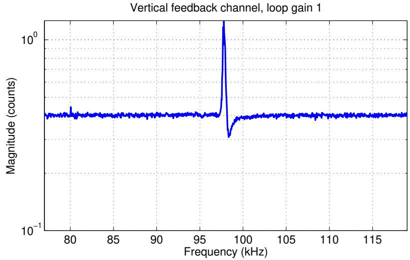

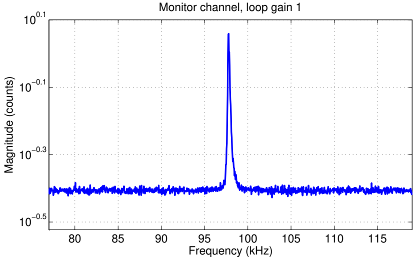

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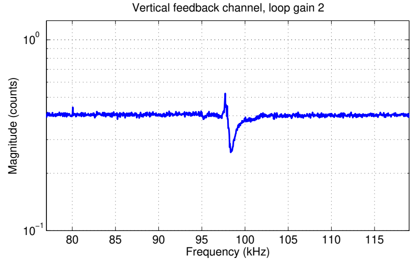

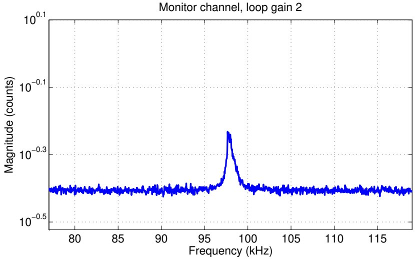

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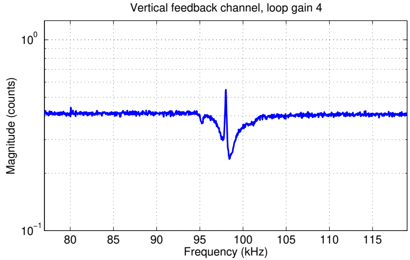

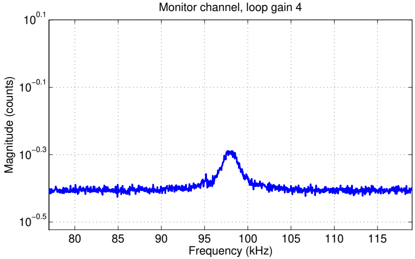

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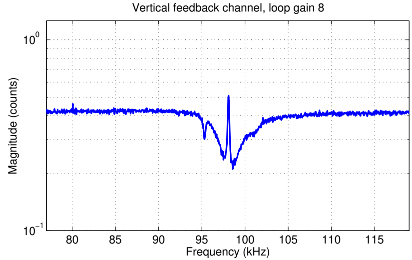

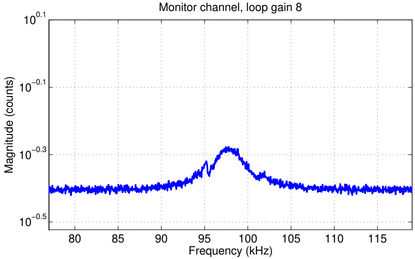

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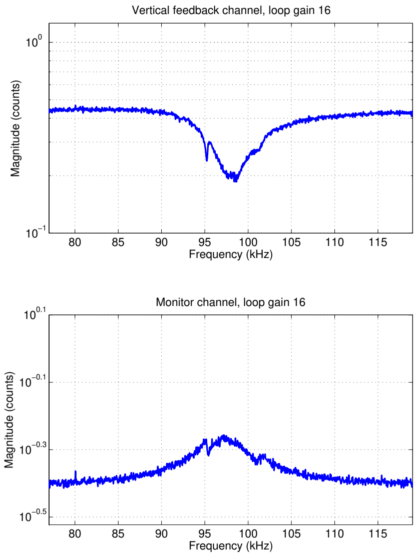

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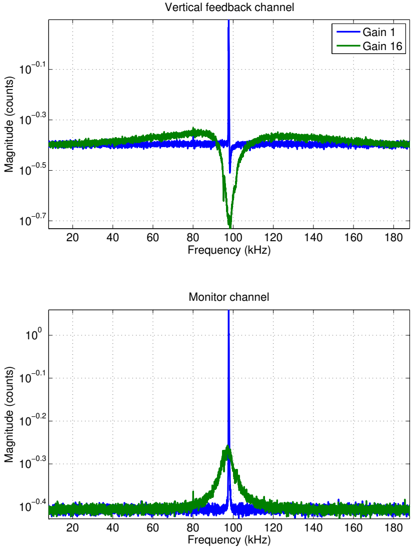

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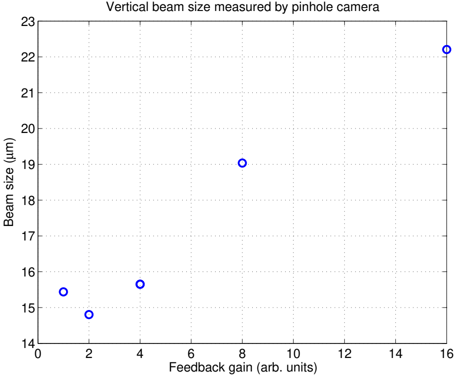
Beam Size vs. Feedback Gain [5]



- 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;
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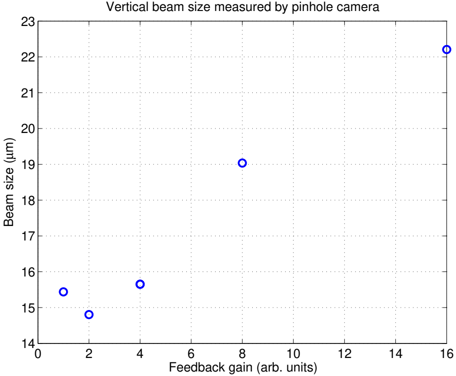

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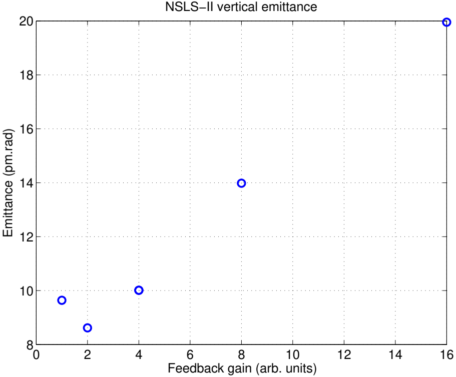

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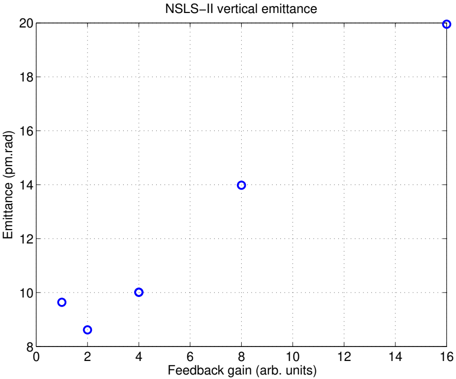

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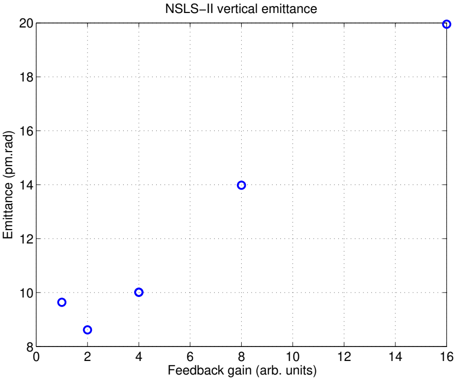

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Outline

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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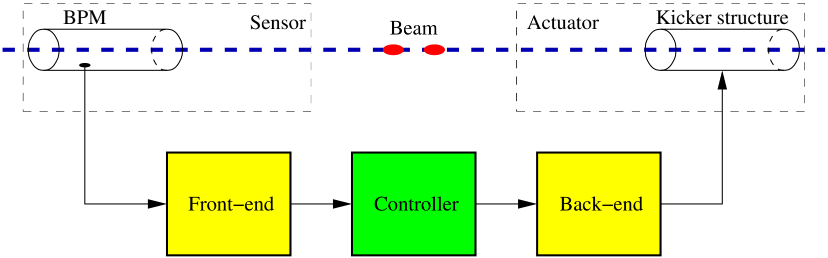
Bunch-by-bunch Feedback



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- Analog front-end;
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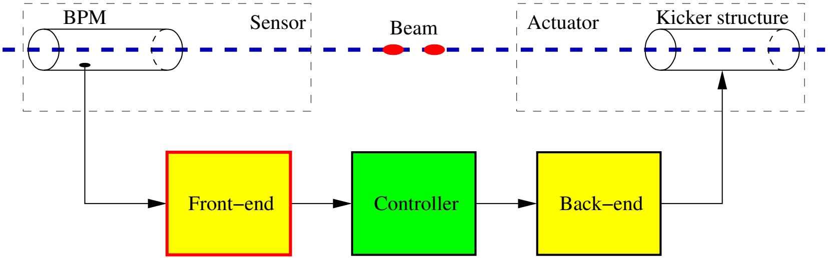

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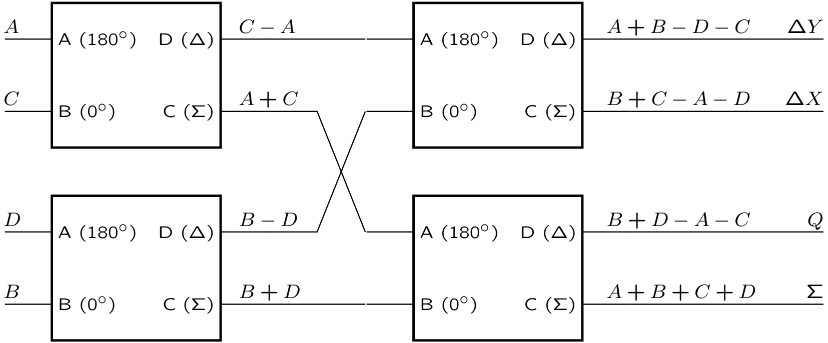
BPM Hybrid Network



- First stage of BPM signal processing — separating X/Y/Z signals
- Since we are digitizing in the end, why not digitize raw signals?
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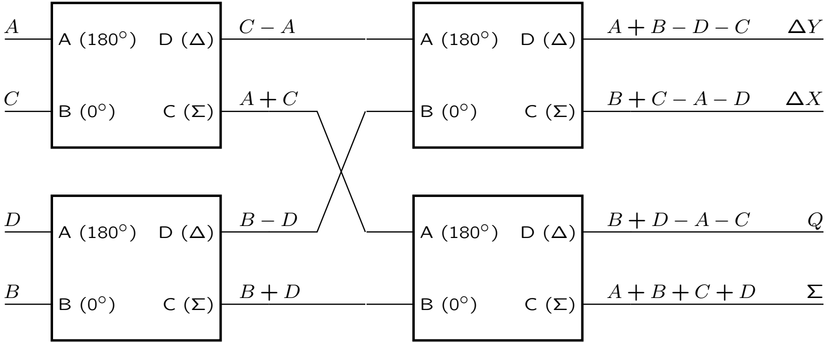

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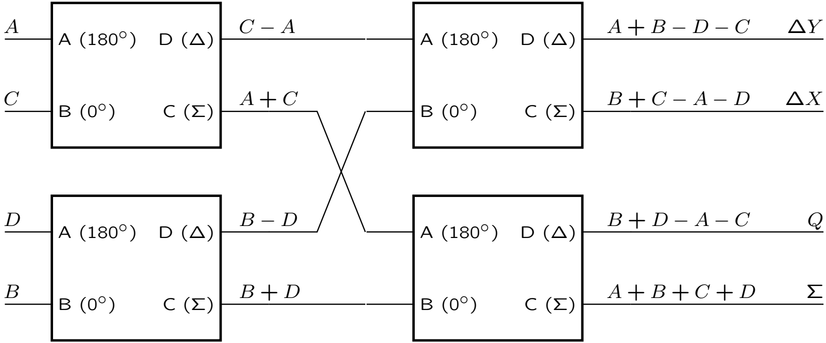

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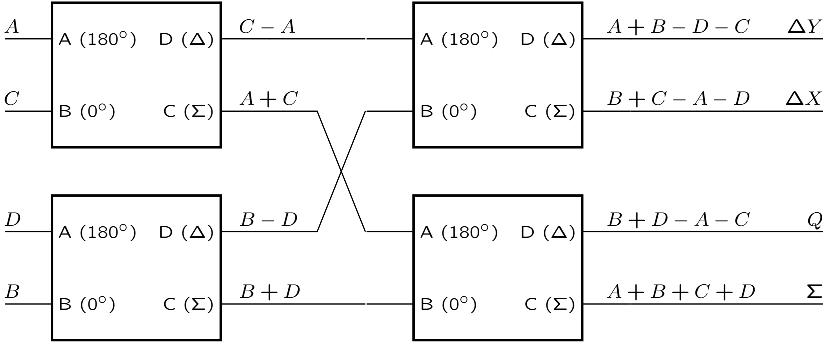

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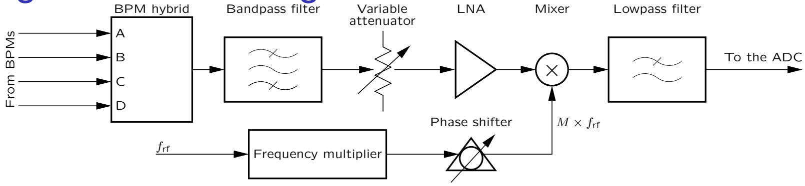

- Front-end requirements:
  - Low amplitude and phase noise;
  - Wideband to ensure high isolation between neighboring bunches.
- Input bandpass filter is an analog FIR filter that replicates BPM pulse with spacing, matched to detection frequency period;
- Detection frequency choice:
  - High frequencies 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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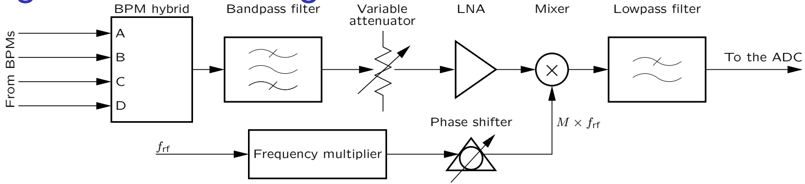

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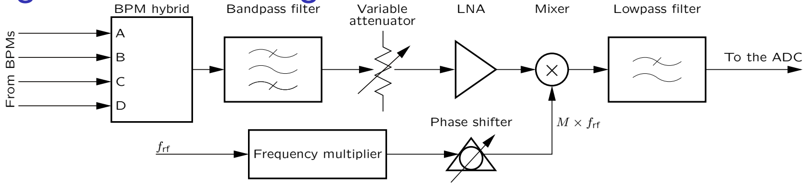

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- Local oscillator adjusted for amplitude (transverse) or phase (longitudinal) detection.

Examples of Front-End Sensitivities Achieved

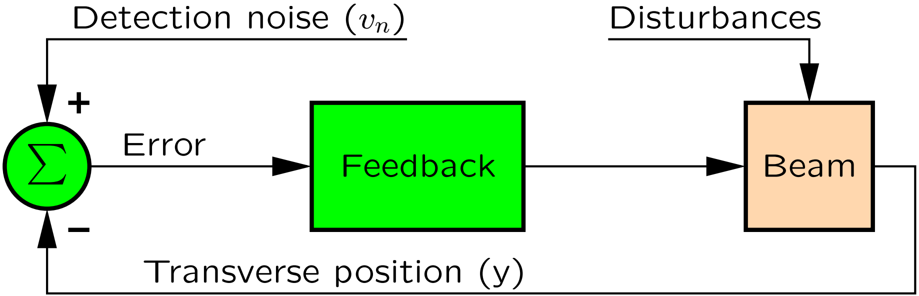
Vertical Plane

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
NSLS-II[6]	0 dB	1.5 counts/mA/μm	0.75 counts/μm

- 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.

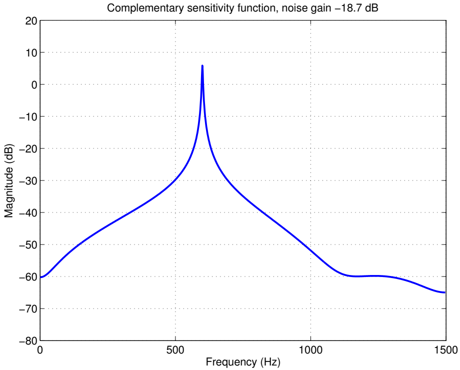
[6] Older front-end design with lower sensitivity

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
- $\tau_{\mathrm{ol}} = \tau_{\mathrm{cl}} = 30$: −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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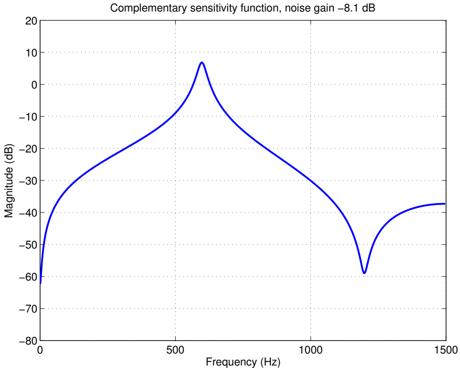

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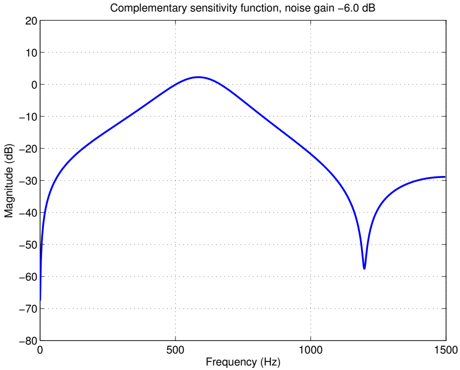

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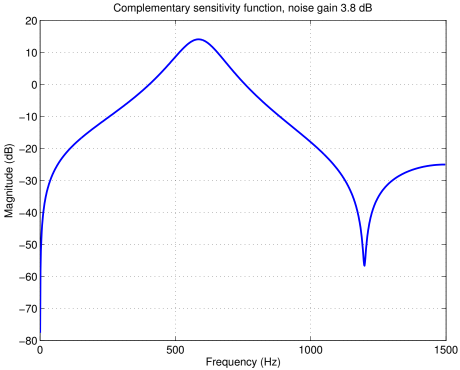

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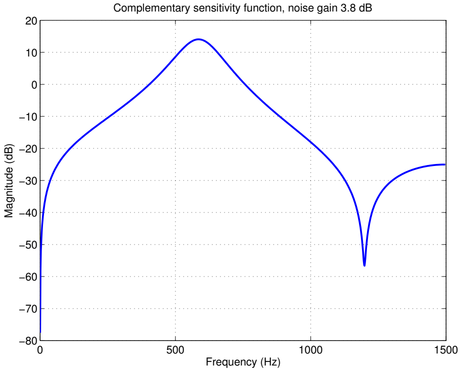

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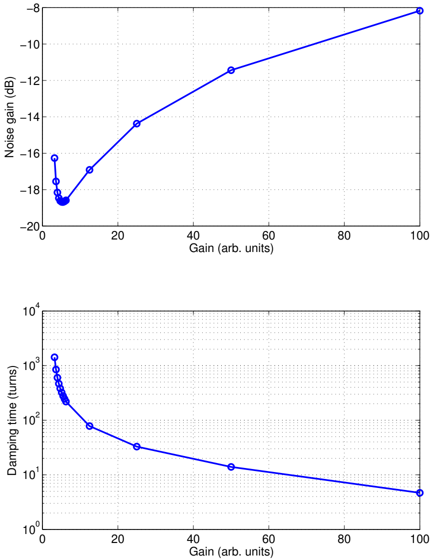
Sensitivity vs. Feedback Gain



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

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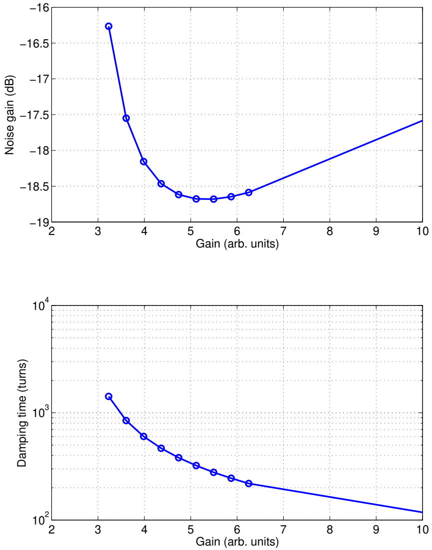

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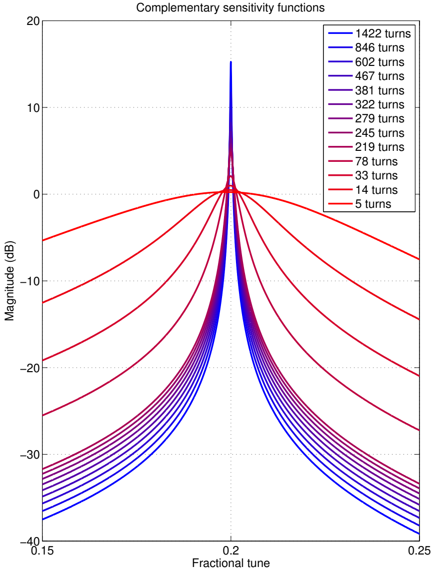

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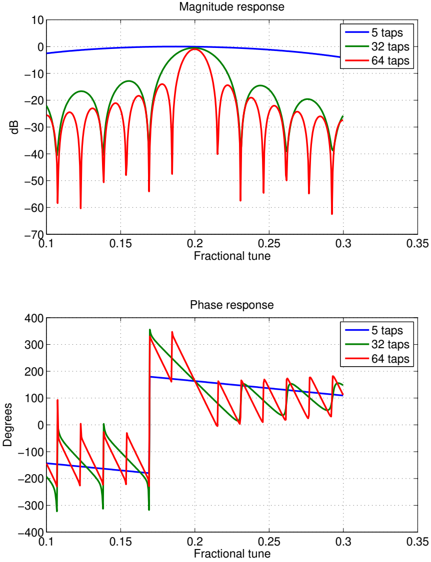
Feedback Filter Design



- Transverse feedback FIR filters, tune of 0.2, adjusted for the same closed-loop damping time ($\tau_{\mathrm{cl}} = \tau_{\mathrm{ol}} =$ 300 turns);
- Conventional wisdom — shorter filter can generate faster damping, longer filter is quieter due to narrower bandwidth;
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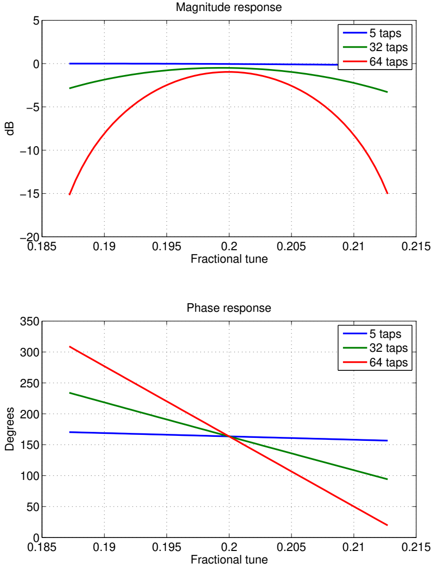

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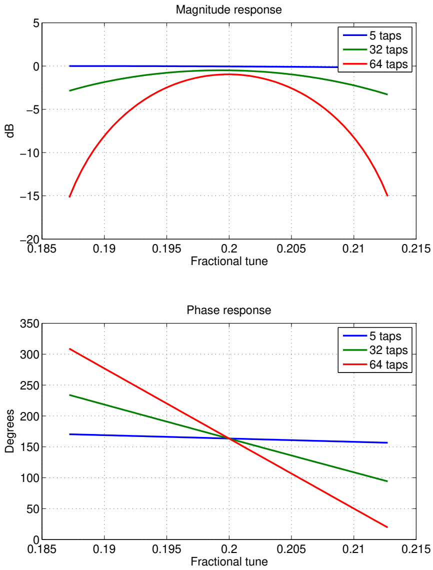

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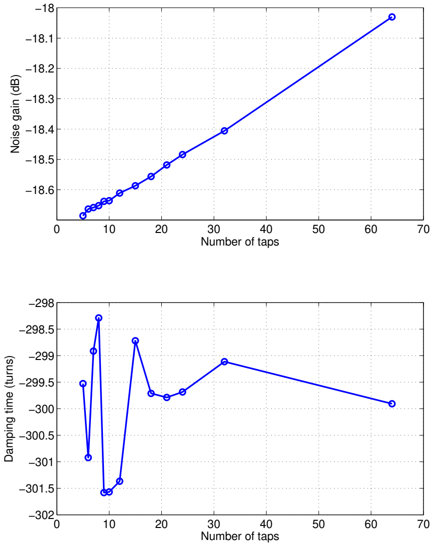
Residual Noise vs. Filter Length



- 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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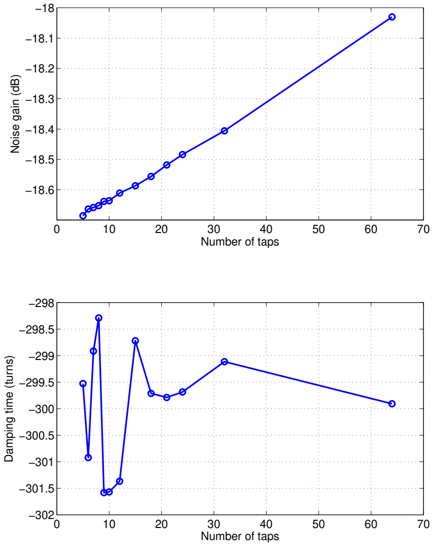

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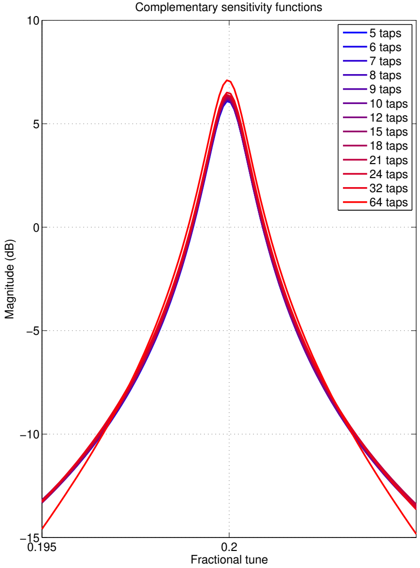

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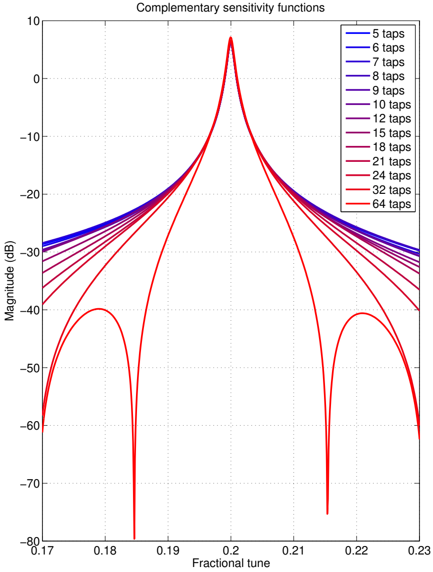

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Outline

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 (synchrotron frequency band extends to DC);
- Use two pickups with 0° or 180° relative phase advance to eliminate horizontal signals?

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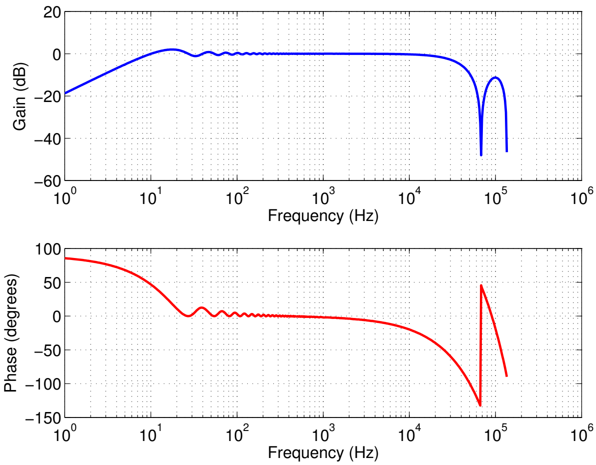
APS-U Example



- Possible filter response for APS-U energy sensing;
- $f_s = 620$ Hz without harmonic cavities;
- Drops to 100 ± 100 Hz under optimal bunch lengthening;
- 2 dB gain and 12.5° phase ripple in 20–800 Hz range.

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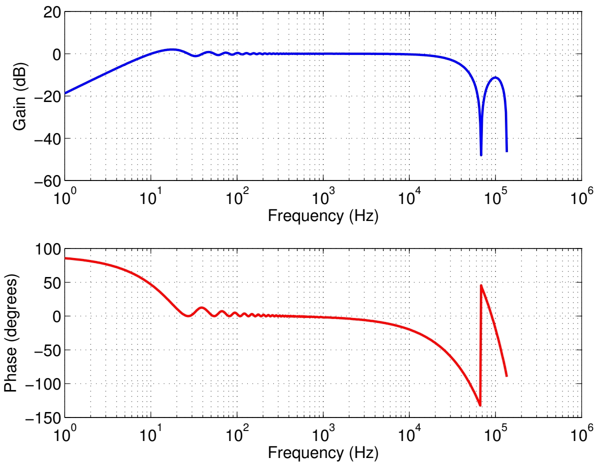

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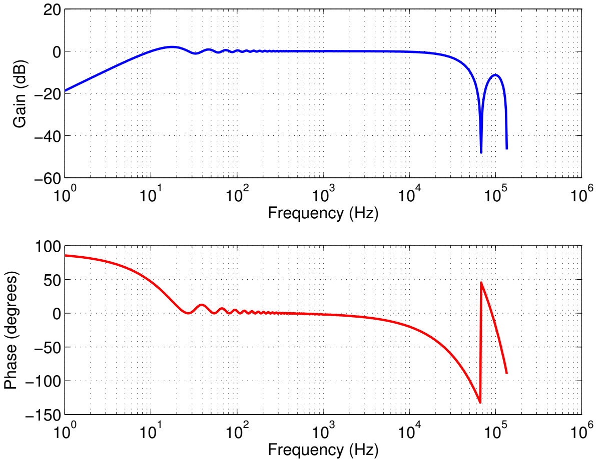

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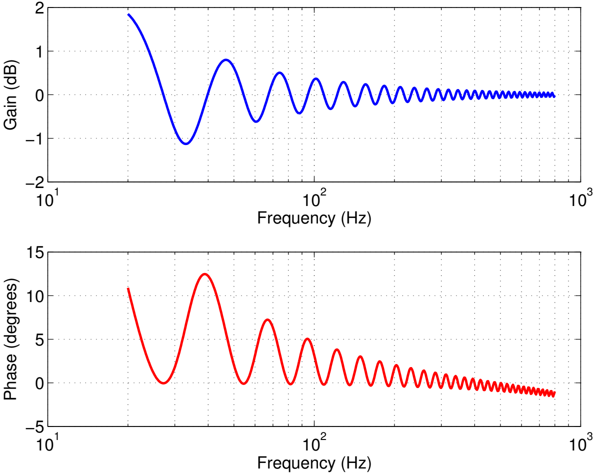

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Summary

- 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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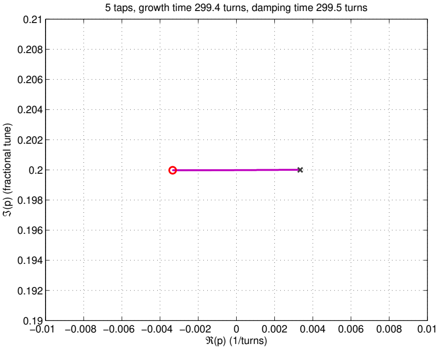
Acknowledgments

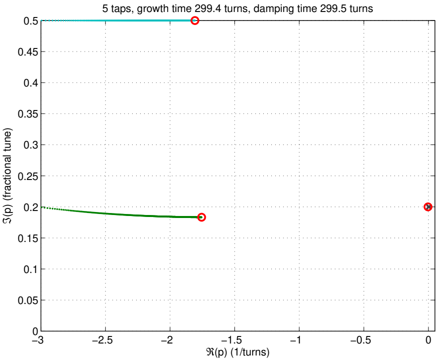
- Thank you for your attention!
- I would also like to thank physicists, engineers, and operators at many machines around the world who directly or indirectly contributed to measurements presented here.
- Special thanks to Weixing Cheng for fruitful discussions and NSLS-II measurements.

Root Locii in Complex Plane: Close Zoom



- Root locus on the complex plane:
  - Starts at the open-loop pole ($\times$), 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.