Feedback System Specifications

Transverse Feedback

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JLEIC Spring Collaboration Meeting

Introduction
Bunch-by-bunch Feedback: Concepts and Models
Coupled-bunch instabilities and feedback
Beam and feedback models
Technology
Feedback Design Process
Loop Gain
Residual Motion
Summary

Outline

Introduction

Bunch-by-bunch Feedback: Concepts and Models
- Coupled-bunch instabilities and feedback
- Beam and feedback models
- Technology

Feedback Design Process
- Loop Gain
- Residual Motion

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Coupled-bunch Instabilities

- Instability control systems require the designers to make a large number of choices:
  - Overall topology;
  - Pickups — location, requirements;
  - Front end(s) — technology, limitations;
  - Feedback controller;
  - Back end(s) — power amplifiers, kicker design;
- This talk will attempt to reduce the search space and to simplify the design process;
- Of course, there are limits to applicability of such simplified process — these will be pointed out.

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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
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Photon Factory	187	2.5
ALS	197	1.9
Australian Synchrotron	216	3
SPEAR3	234	3
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TPS	518	3
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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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Coupled-bunch Instabilities

- Focusing on electron/positron machines here;
- Consider a single bunch in a storage ring;
- Centroid motion has damped harmonic oscillator dynamics;
- Multiple bunches couple via wakefields (impedances in the frequency domain);
- At high beam currents this coupling leads to instabilities;
- Active feedback is used to suppress such instabilities above the threshold.

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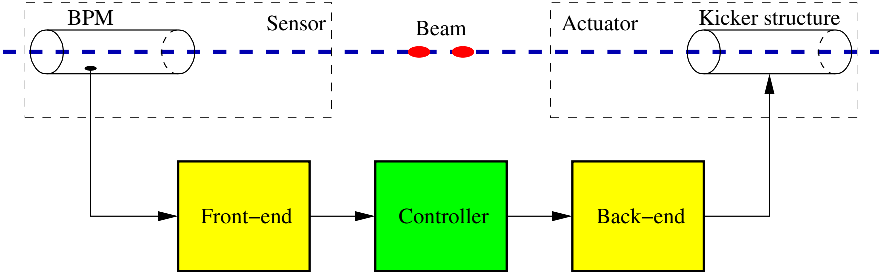
Bunch-by-bunch Feedback

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 or more turns later;
- Diagonal feedback — computationally efficient;
- Extremely popular in storage rings — well understood.

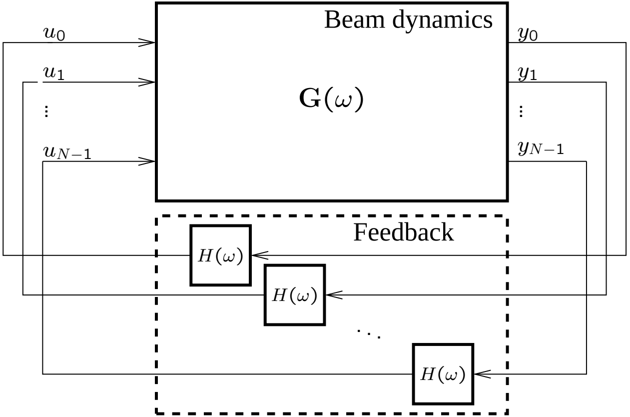
Conventional Topology — Applicability

- Conventional topology:
  - Single pickup;
  - Single kicker;
  - Purely bunch-by-bunch processing.
- Good performance for moderate growth times (above 20 turns);
- Reduced damping rates for betatron tunes near half integer;
- Sensitivity limits for very small beams.

Coupled-bunch Instabilities: Eigenmodes and Eigenvalues

- If we consider bunches as coupled harmonic oscillators, a system of N bunches has N eigenmodes;
- Without the wakefields these modes have identical eigenvalues determined by the tune and the radiation damping;
- Impedances shift the modal eigenvalues in both real part (damping rate) and imaginary part (oscillation frequency);
- For an even fill pattern the eigenmodes are at the synchrotron or betatron sidebands of revolution harmonics from DC to $f_{\mathrm{RF}}/2$.

MIMO Model of Bunch-by-bunch Feedback



- N bunch positions and feedback kicks;
- Diagonal feedback matrix $H(\omega)\mathbf{I}$;
- Invariant under coordinate transformations.

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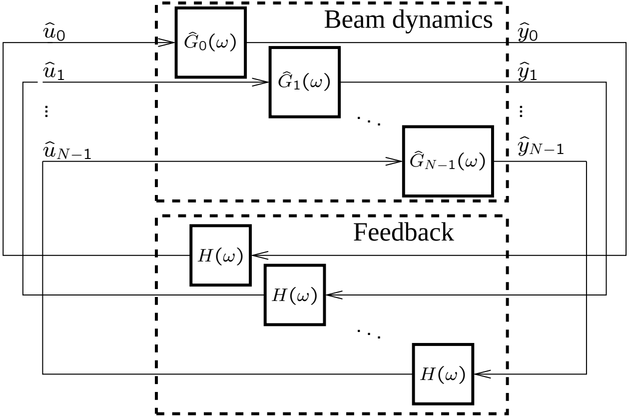
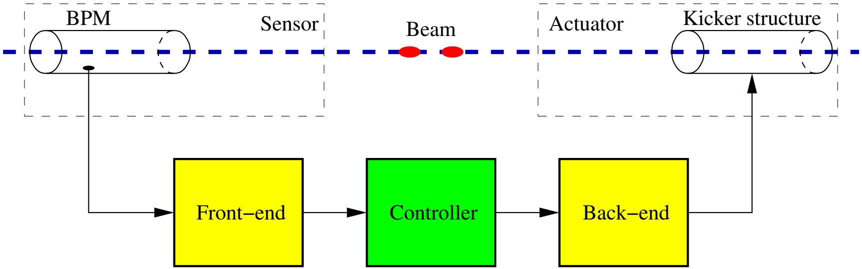


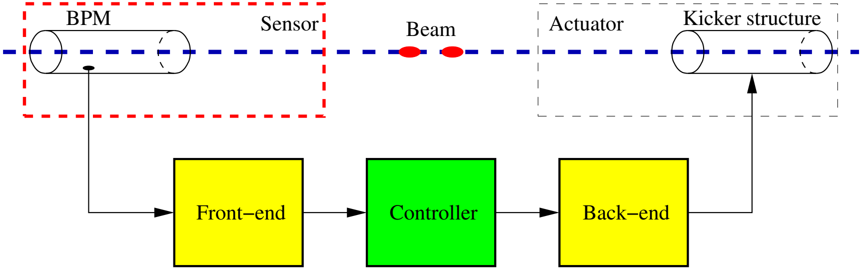
- Coordinate transformation to eigenmode basis;
- *N* feedback loops - one per mode;
- Identical feedback applied to each mode.

Bunch-by-bunch Feedback



- Sensor (pickup);
- Analog front-end;
- Controller;
- Analog back-end;
- Actuator (kicker).

Bunch-by-bunch Feedback



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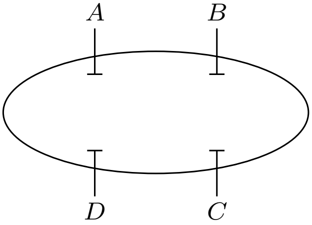
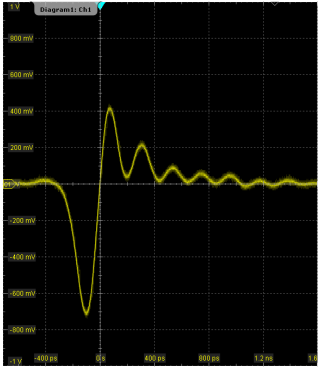
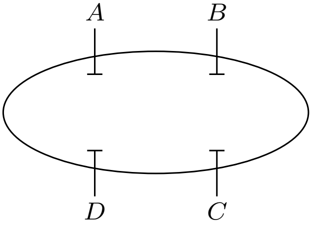
Beam Position Sensor

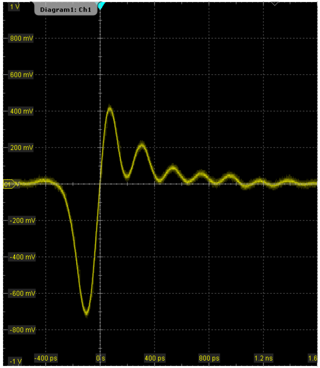




- To sense beam position we typically use capacitive button beam position monitors (BPMs);
- Buttons couple capacitively to the beam, differentiating bunch current shape;
- BPM signals are wideband differentiated pulses with 100–400 ps duration;
- Differentiation means sensor gain increases with frequency.

Beam Position Sensor





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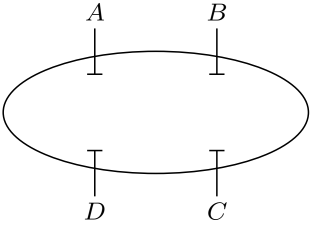

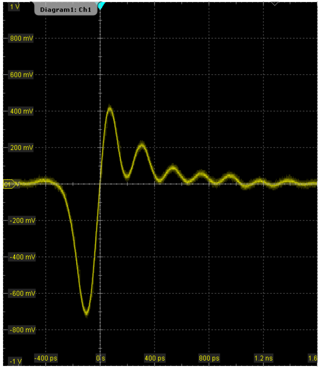

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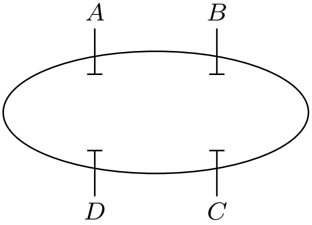

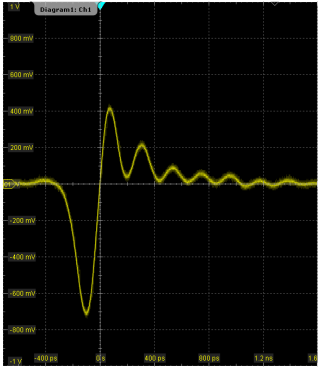

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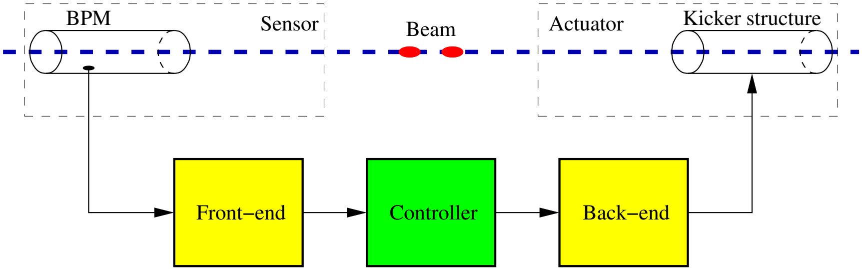

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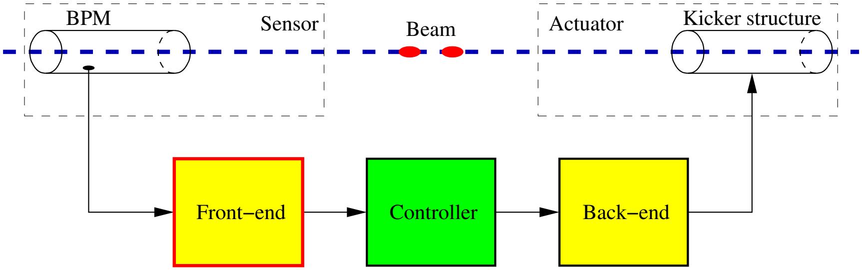

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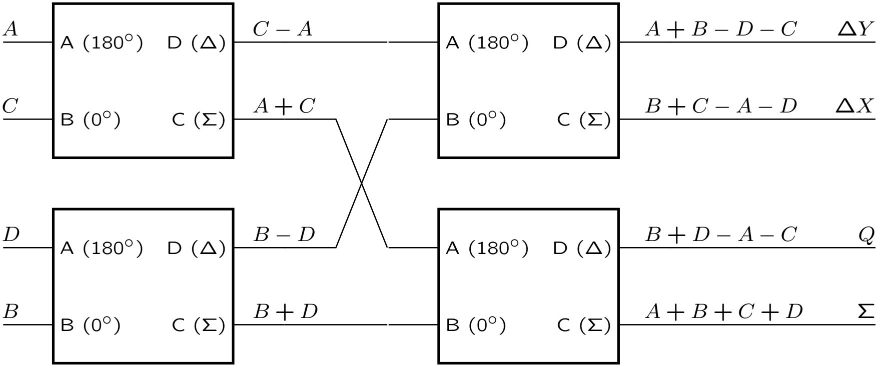
BPM Hybrid Network



- 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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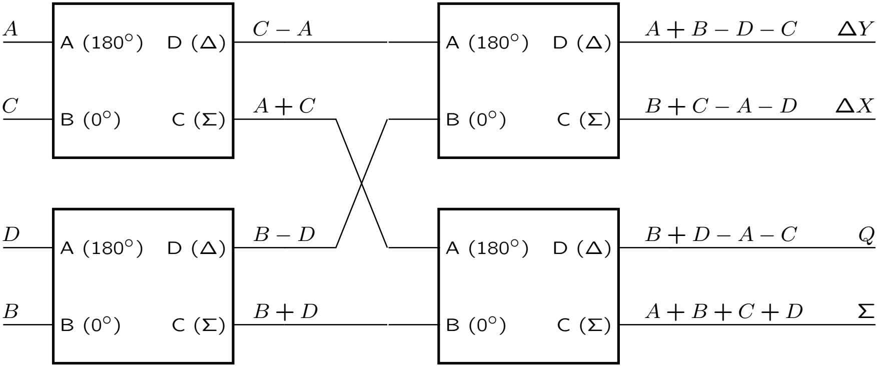

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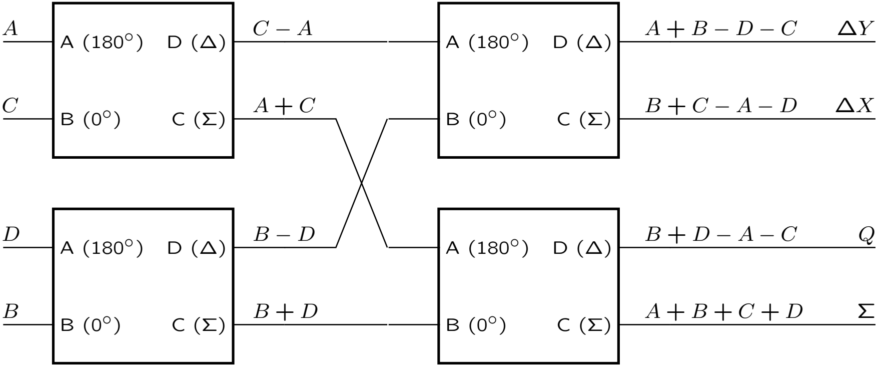

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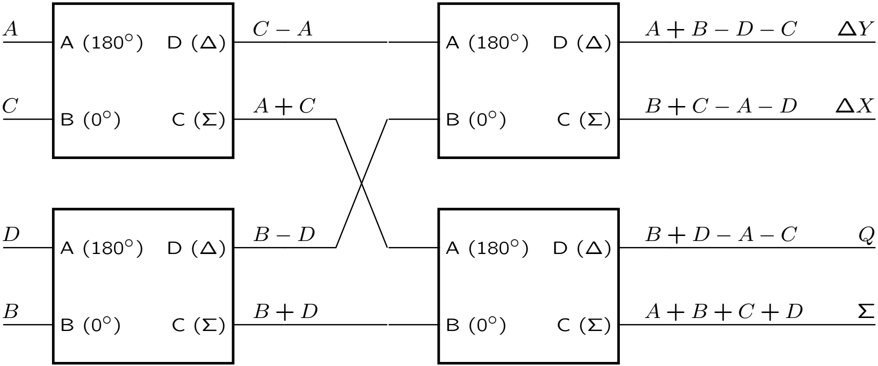

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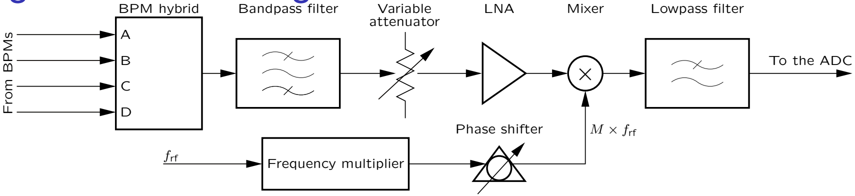

- Front-end requirements:
  - Low amplitude and phase noise;
  - Wideband to ensure high isolation between neighboring bunches.
- Input bandpass filter is an analog FIR filter that replicates BPM pulse with spacing, matched to detection LO period;
- Detection frequency choice:
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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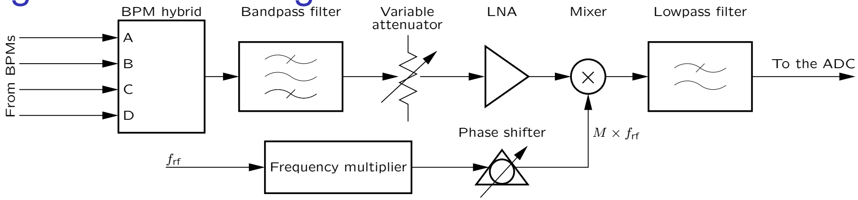

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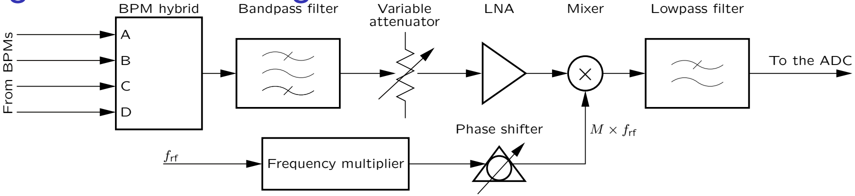

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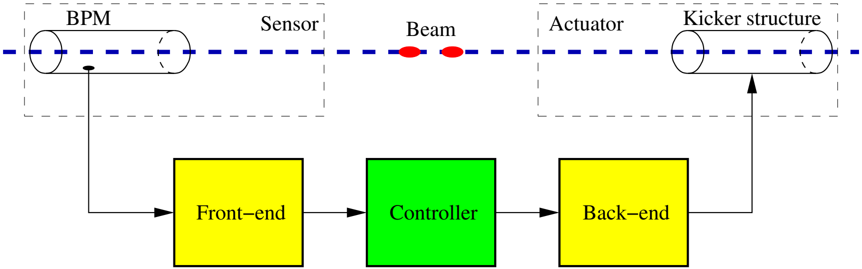

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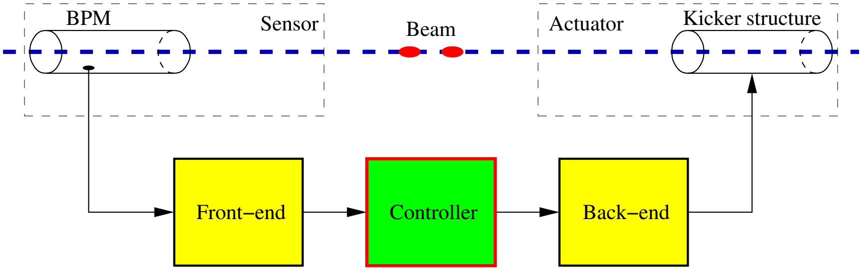

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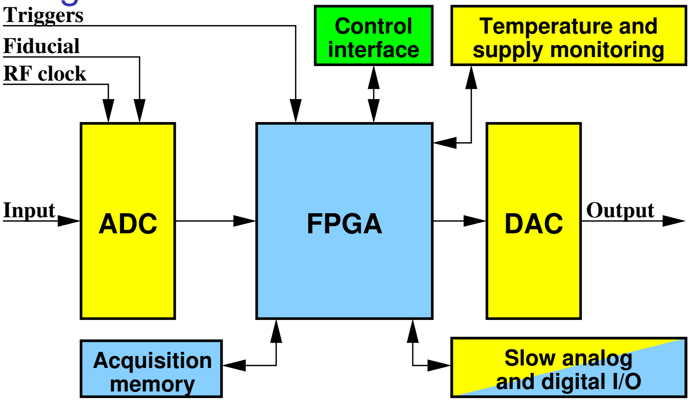
Baseband Signal Processor



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- ADC, DAC: 12–14 bit, 500–600 MSPS, 400 ps rise/fall times;
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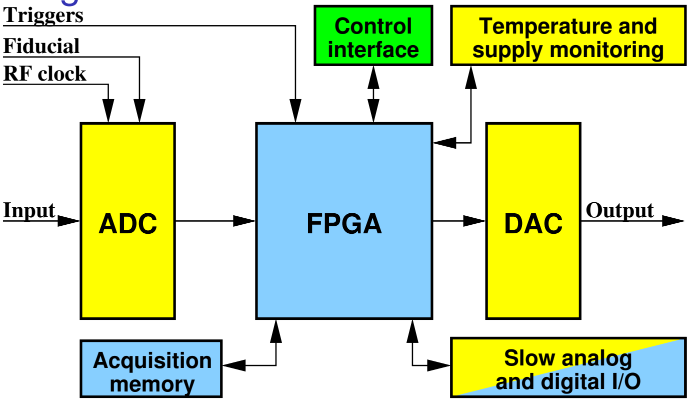

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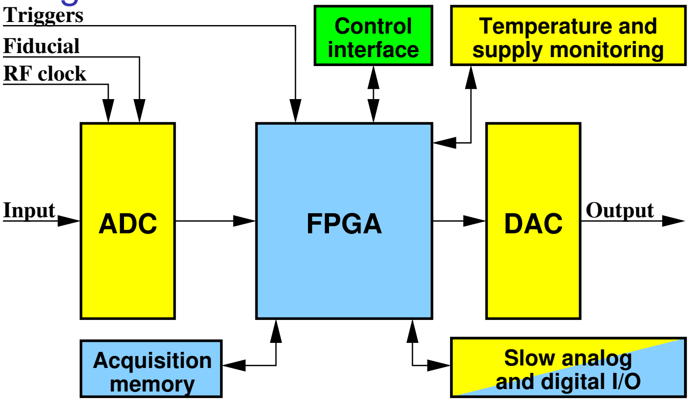

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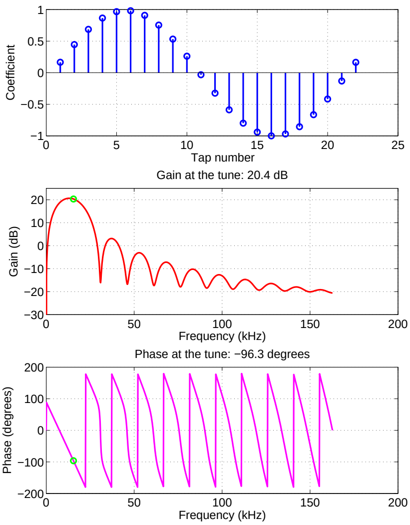
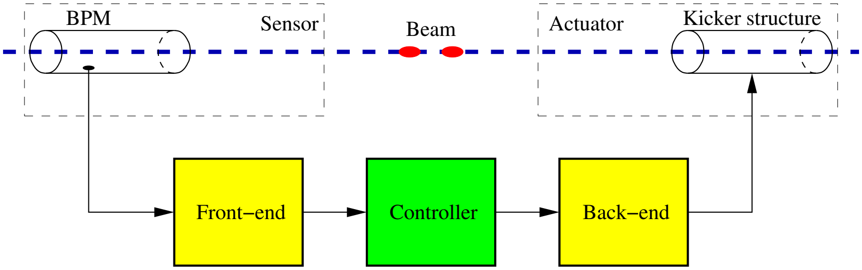
Feedback Filter



- Requirements:
  - Adjustable phase shift at the tune frequency;
  - DC rejection to get rid of constant orbit offsets;
  - Low group delay.
- Filter design approach — sample one period of a sine wave at tune frequency;
  - Group delay is $\frac{1}{2}$ of oscillation period;
  - Nicely parameterized, often close to optimal.
- More sophisticated design methods are required when large perturbations are present or with variable beam dynamics, etc.

Bunch-by-bunch Feedback



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

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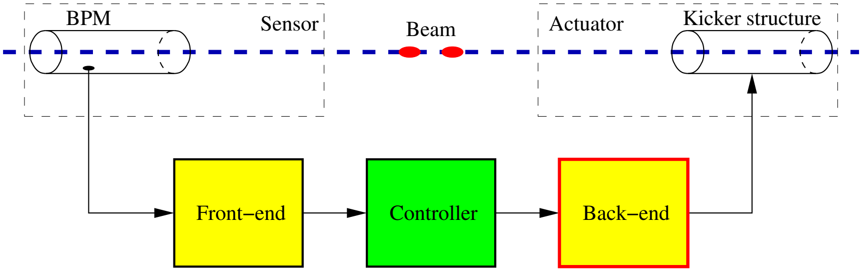

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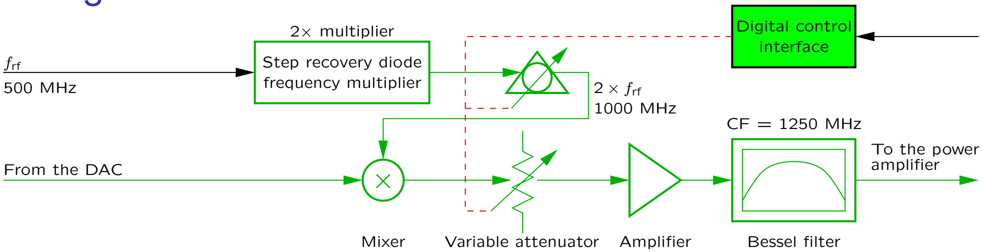

- Longitudinal kickers are usually built as highly damped (low Q, wideband) cavities at 1–1.5 GHz;
- Baseband kick must be upconverted to the right frequency to drive these;
- Phase linearity is critical to maintain the same feedback for different modes;
- Constant group-delay filters are used to create single-sideband modulation to efficiently drive kicker cavity.

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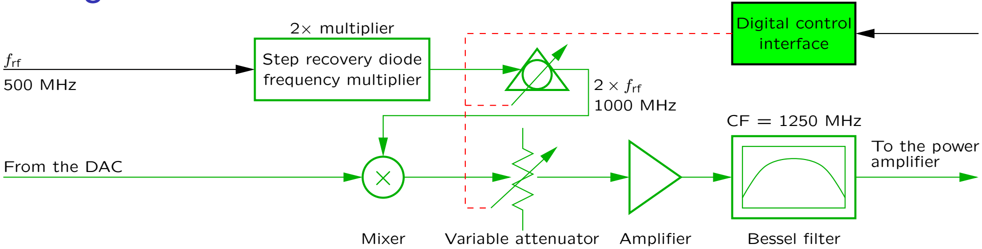

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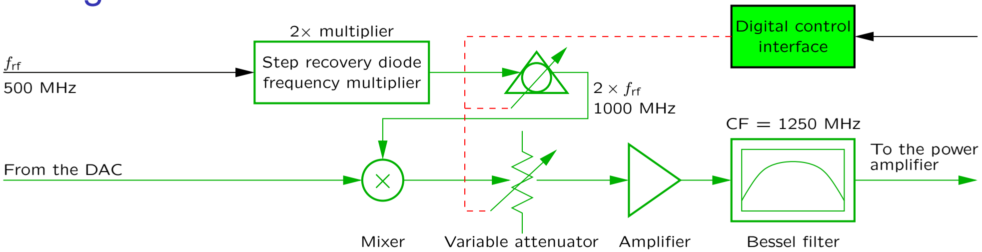

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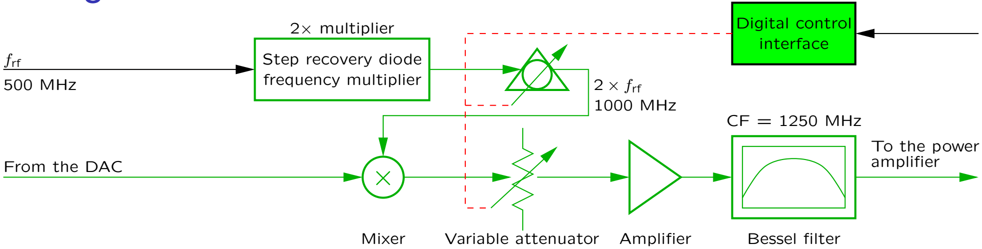

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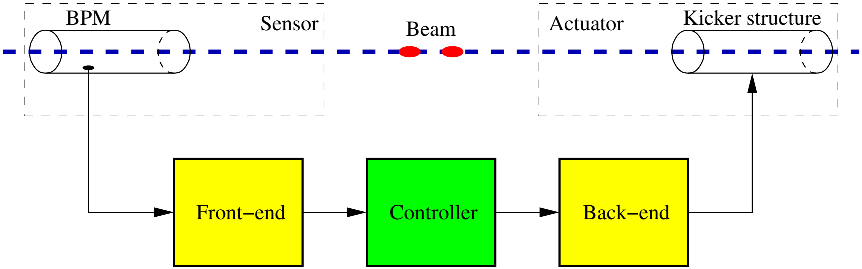

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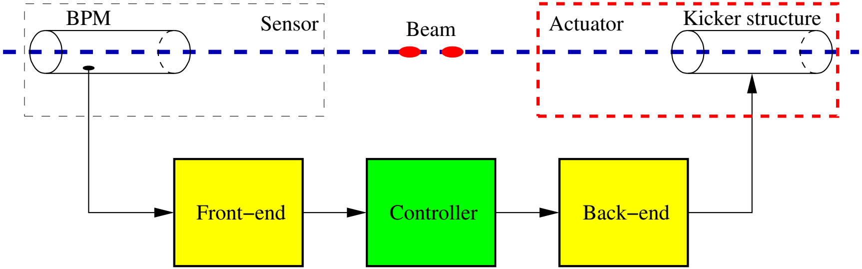

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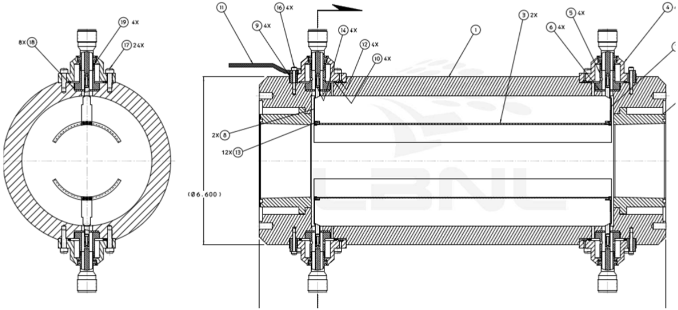
Transverse Kicker



- 50 Ω striplines driven differentially;
- Counter-propagating beam and kick signals;
- For 2 ns bunch spacing maximum/optimal stripline length is 1 ns:
  - Fill time of 1 ns;
  - Beam propagation time of 1 ns;
- Longer striplines will couple the kick to neighboring bunches.
- Shorter striplines provide better isolation, lower shunt impedance.

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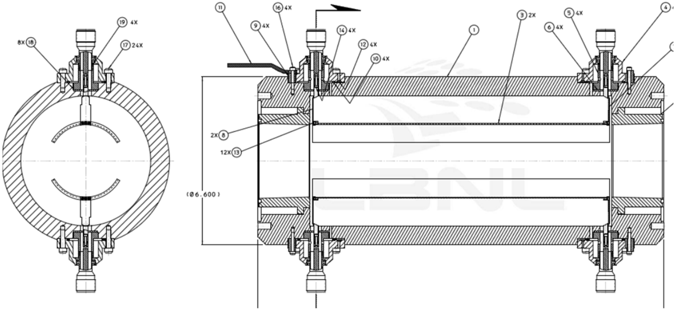

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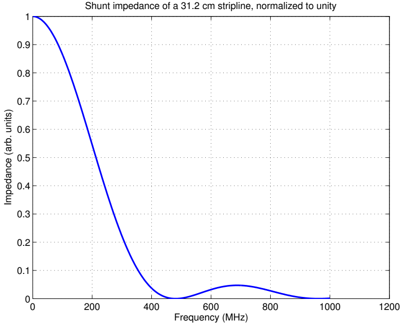

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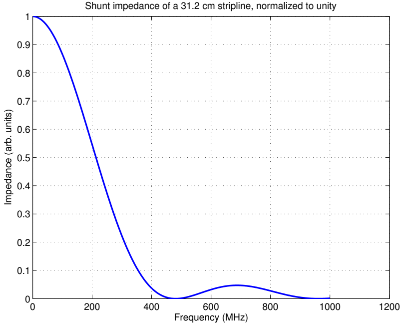

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Design Procedure

- For a given fractional tune and pickup/kicker placement there is a maximum instability growth rate that can be stabilized;
- If your expected growth rate is faster, a different approach is needed:
  - Reduce impedances;
  - Move pickup/kicker, adjust tunes;
  - Change feedback topology.
- Determine the minimum required loop gain — to get closed-loop damping rate equal to the open-loop growth rate;
- Once the gain is defined, required maximum kick angle can be computed based on the expected perturbations;
- Maximum kick angle determines the actuator setup — amplifier power, kicker shunt impedance, number of kickers.

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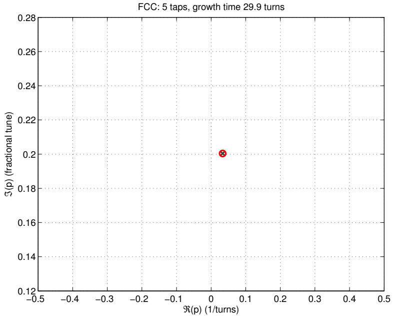

- At zero gain we see the open-loop eigenvalue;
- With increasing gain the eigenvalue moves left, towards stability;
- At some point another eigenvalue shows up from the left — due to the delay;
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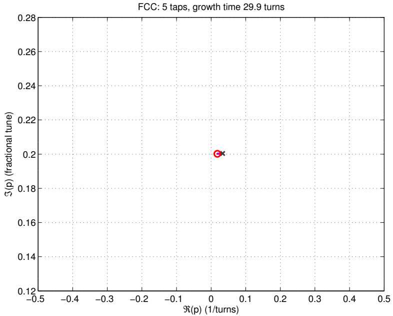

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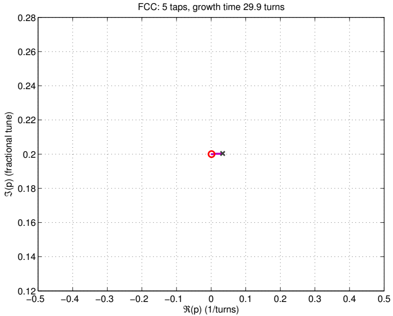

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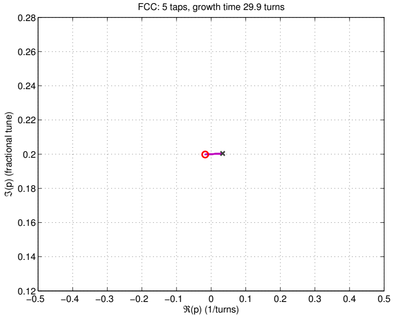

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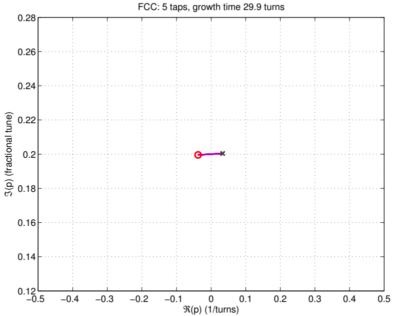

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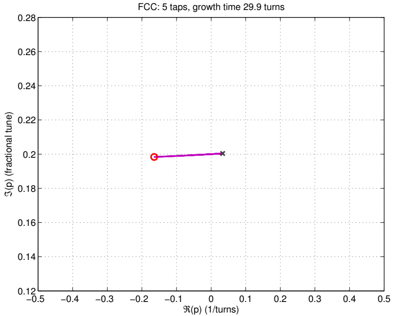

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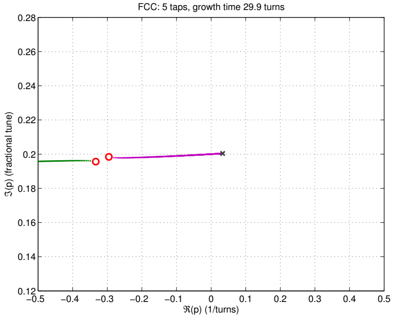

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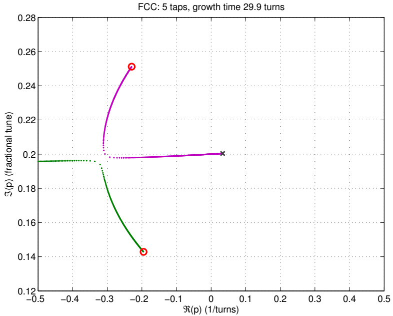

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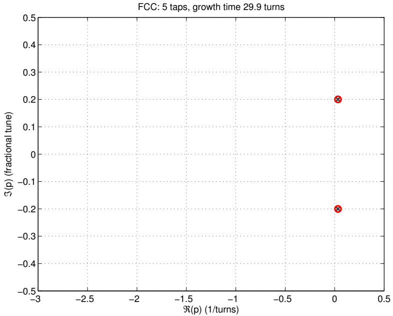

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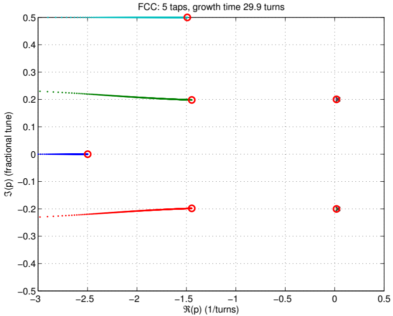

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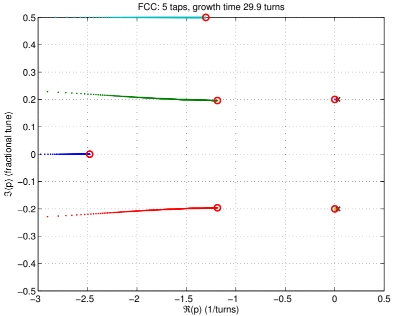

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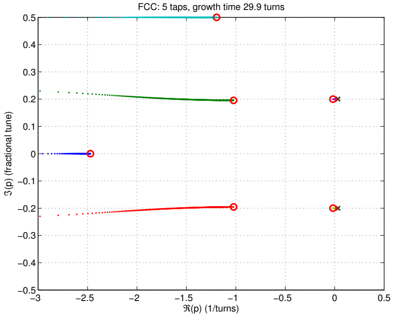

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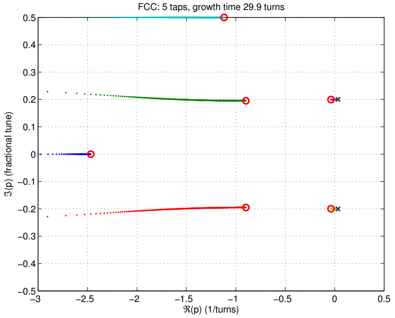

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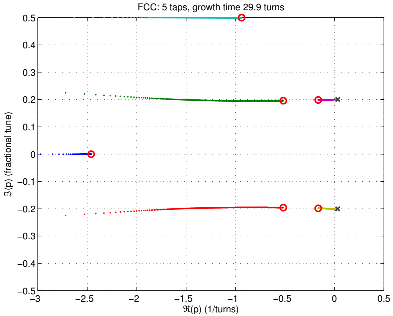

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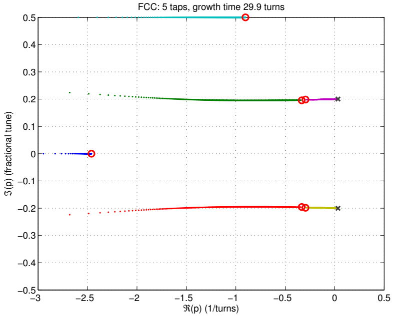

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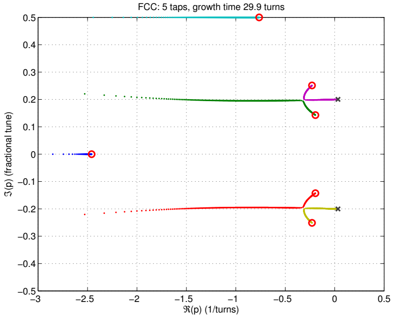

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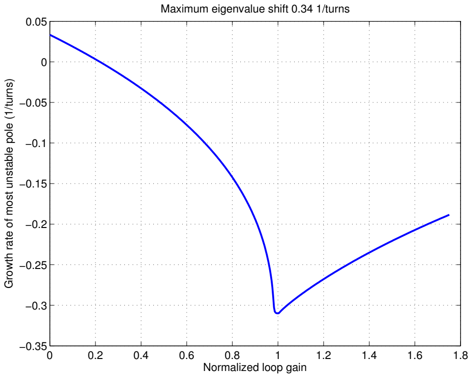

- At each gain point in the root locus we plot the real part of the rightmost (least stable) eigenvalue;
- Starts at open-loop growth rate, minimum shows achievable feedback damping rate;
- Rule of thumb — closed loop damping should be at least as fast as the open-loop growth rate;
- Damping is roughly linear with gain at moderate damping rates, eigenvalue shift is $\lambda = g_{\rm fb}\sqrt{\beta_B \beta_K} f_{\rm rev}/2$.
- For $\tau_{\rm ol} = -\tau_{\rm cl}$, $g_{\rm fb} = \frac{4 T_{\rm rev}}{\sqrt{\beta_B \beta_K}\tau_{\rm ol}}$;

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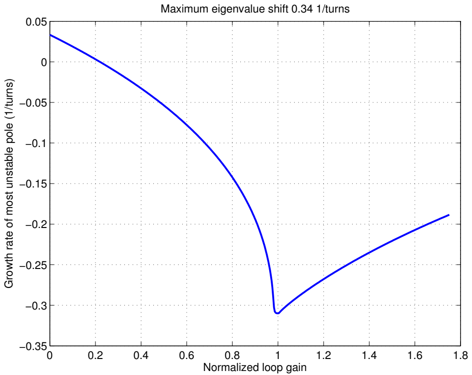

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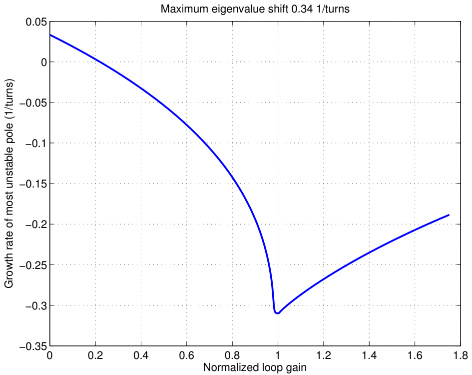

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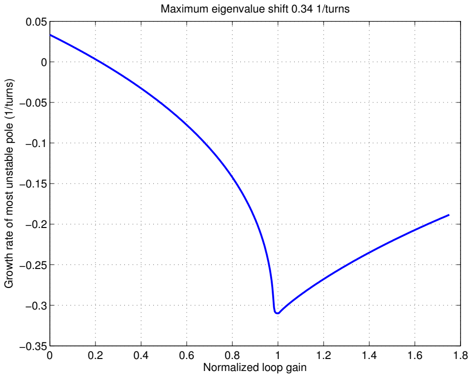

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Examples of Front-End Sensitivities Achieved

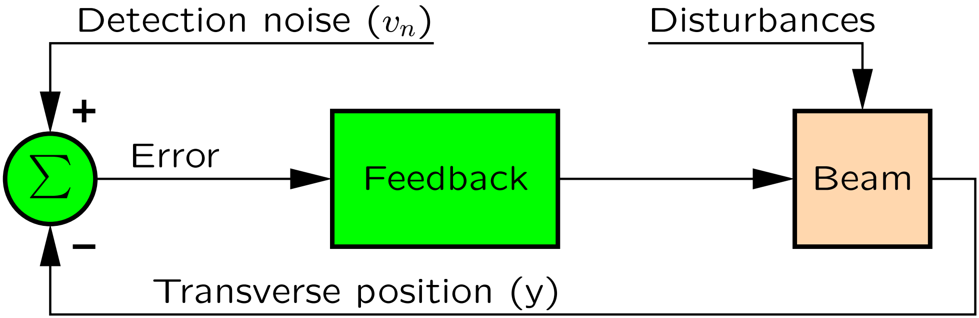
Vertical Plane

Machine	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[1]	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.

[1] 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.

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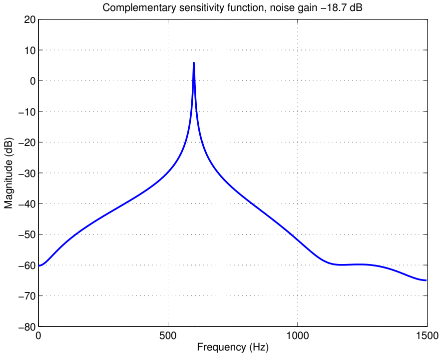
Sensitivity Functions Compared



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

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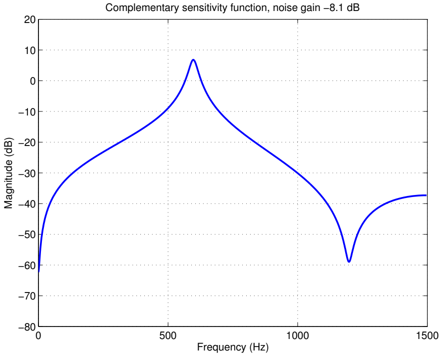

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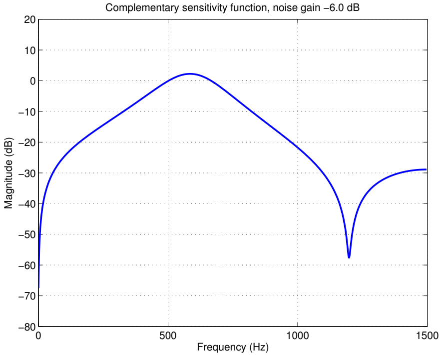

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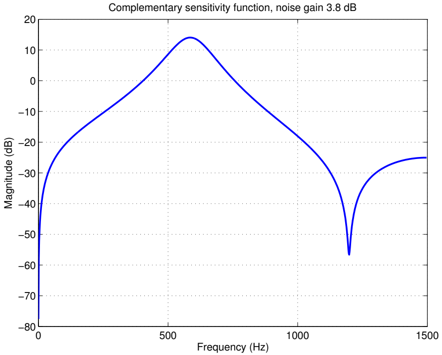

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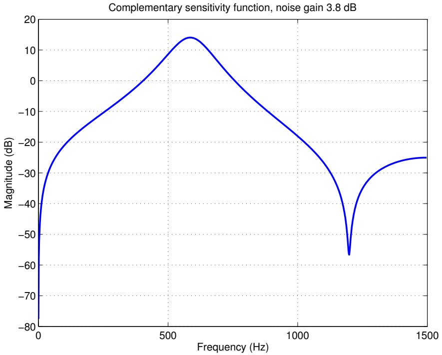

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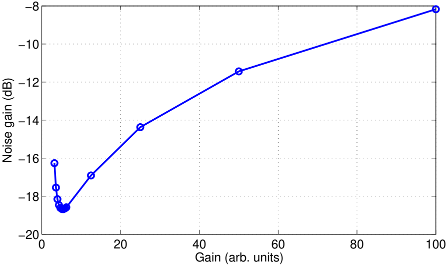

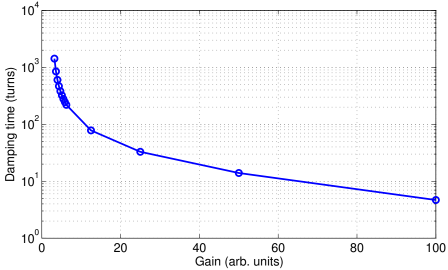

- 300 turns growth time, fractional tune of 0.2, 5-turn feedback filter;
- No excitation, purely flat noise floor;
- Minimum integrated sensitivity at $\tau_{\mathrm{ol}} = -\tau_{\mathrm{cl}}$;
- Highly peaked $T(\omega)$ at low gains, very wide at high gains.

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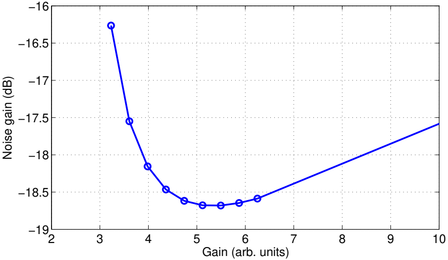

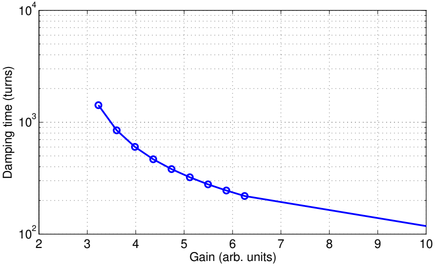

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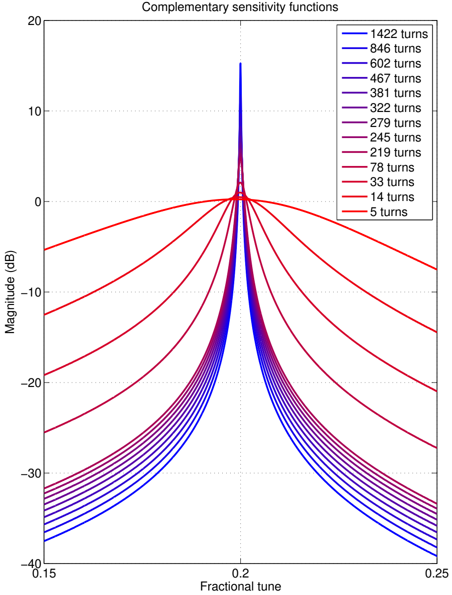

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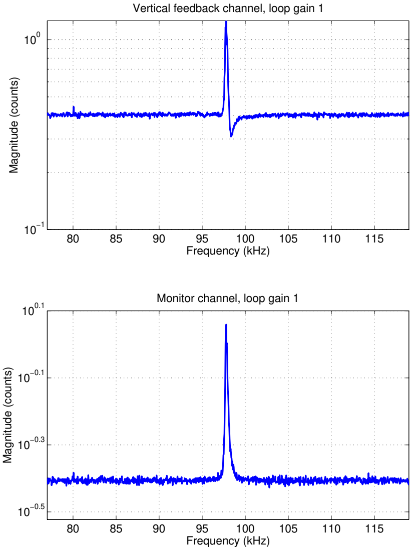
NSLS-II: Averaged Bunch Spectra vs. Feedback Gain [2]



- 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.

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

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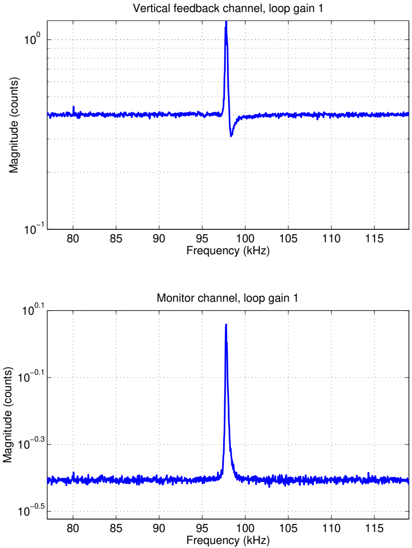

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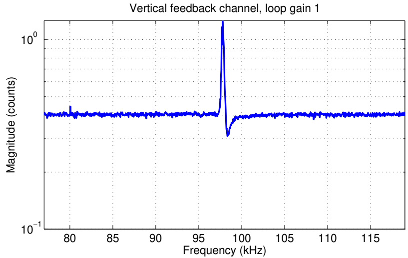

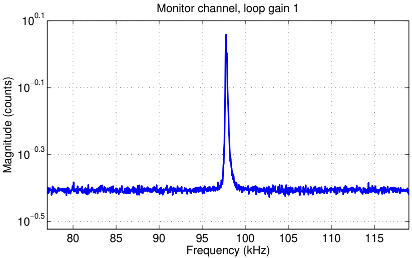

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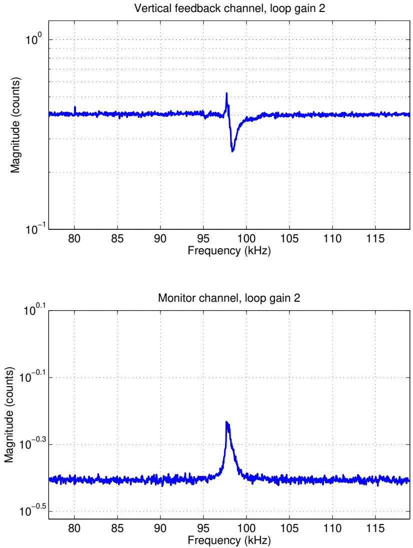

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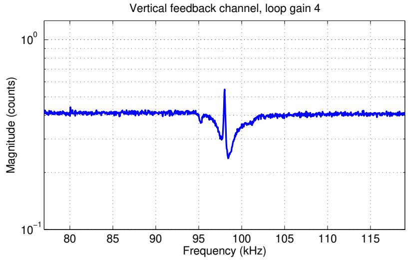

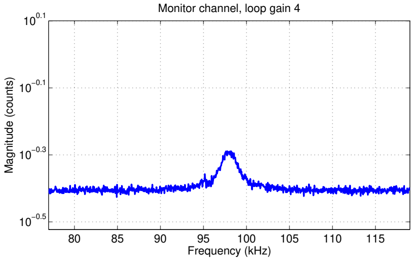

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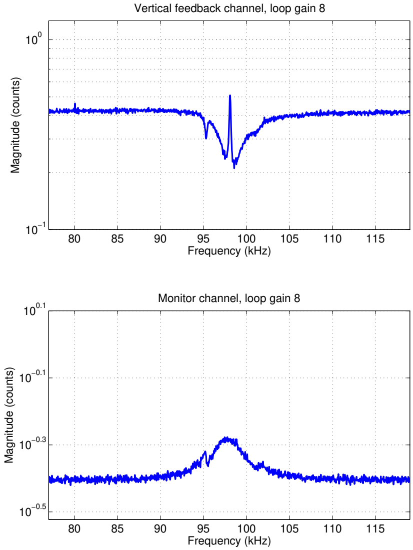

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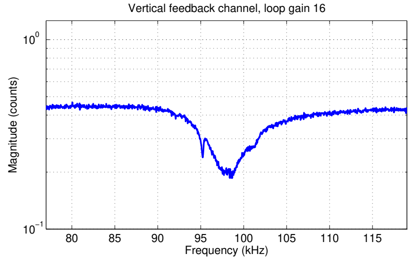

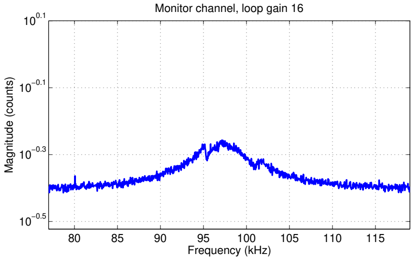

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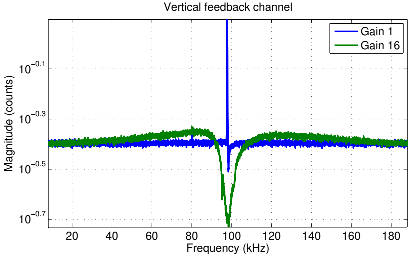

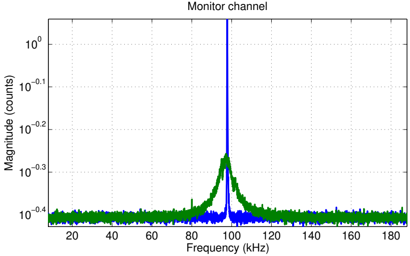

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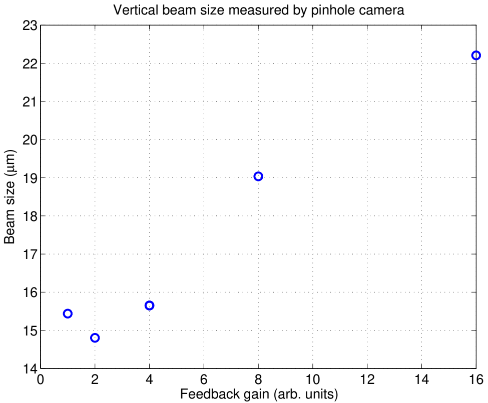

- Vertical beam size measured by a pinhole camera;
- A superposition of true beam size and residual dipole motion;
- Vertical emittance, calculated from pinhole camera data;
- Beam lifetime is correlated with beam size measurements, suggesting vertical size blow-up;
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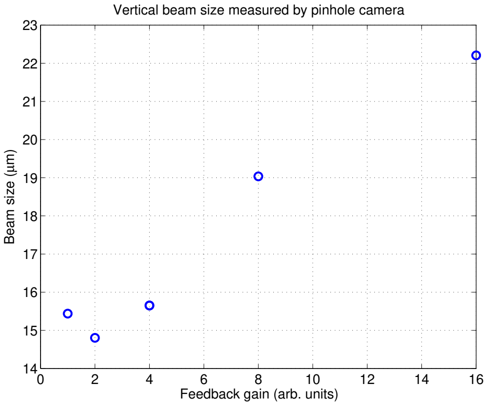

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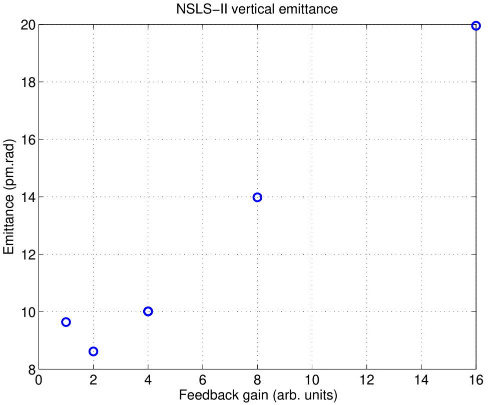

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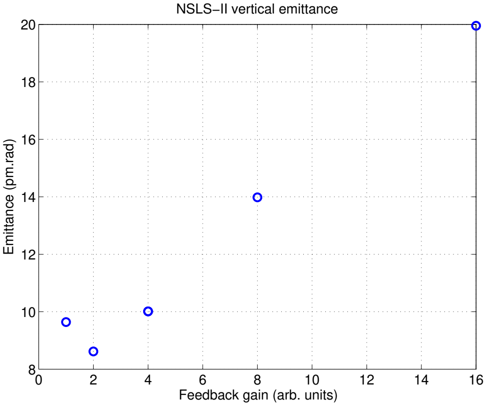

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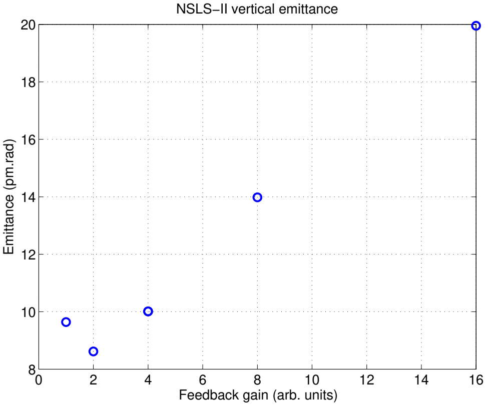

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- There are both theoretical and practical limits to the instabilities that can be controlled;
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