

Closed-loop Feedback Control of Coupled-bunch Instabilities

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October 13, 2026

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- A Few Examples of Storage Rings
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Thresholds

Machine	$I_{\text{nom}}/I_{\text{th}}$ (mA)
ALS	500/50
HLS	300/5
ANKA	200/10

- ▶ Applications of charged-particle circular accelerators:
 - ▶ Colliders
 - ▶ Synchrotron light sources
- ▶ In both of these applications beam stability is crucial for achieving design performance (collider luminosity, light source brilliance);
- ▶ Coupled-bunch instabilities cause beam loss or reduce performance;
- ▶ In the past, machines were designed to operate below the instability threshold;
- ▶ Modern storage rings often operate far above the threshold level and require feedback stabilization.

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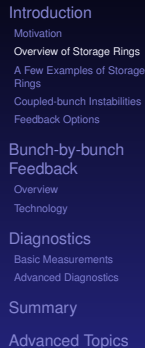
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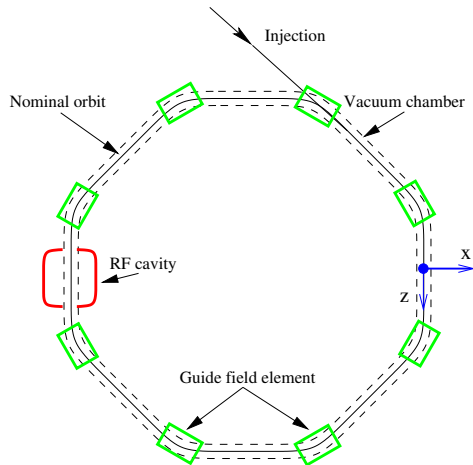
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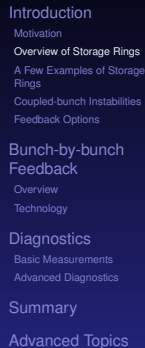


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- ▶ Particles are accelerated to desired energy and injected into a storage ring;
- ▶ Vacuum chamber around a closed trajectory;
- ▶ Magnetic guide field elements deflect charged particles to follow the nominal orbit;
- ▶ Charged particles under acceleration radiate, leading to energy loss;
 - ▶ Angular acceleration only!
- ▶ Energy lost in one turn is replenished in one or more RF cavities.

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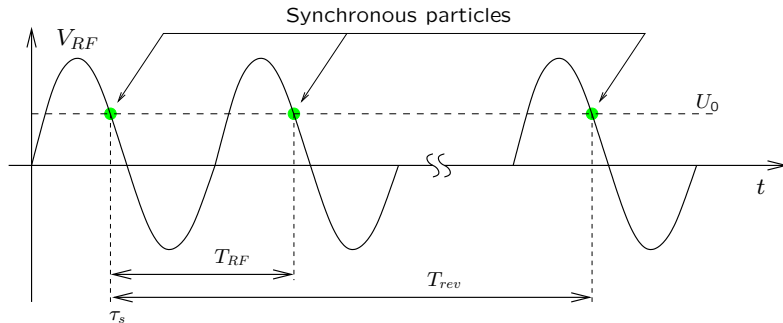
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RF and Longitudinal Focusing



- ▶ Periodic RF voltage restores the energy lost via radiation;
- ▶ Synchronous particle gains exactly the energy lost in one turn;
- ▶ Particles above nominal energy take a longer path — positive momentum compaction;
- ▶ RF voltage slope creates a potential well (longitudinal focusing);
- ▶ Integer ratio T_{rev}/T_{RF} (harmonic number) is the number of stable RF buckets where bunches of charged particles can be stored.

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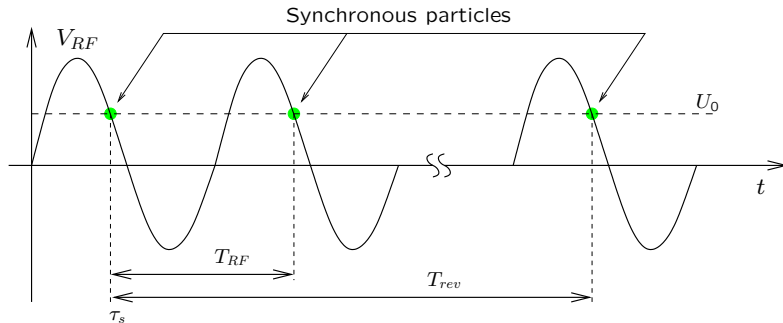
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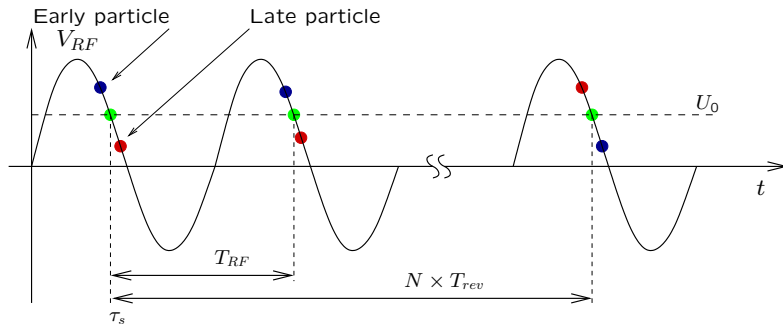
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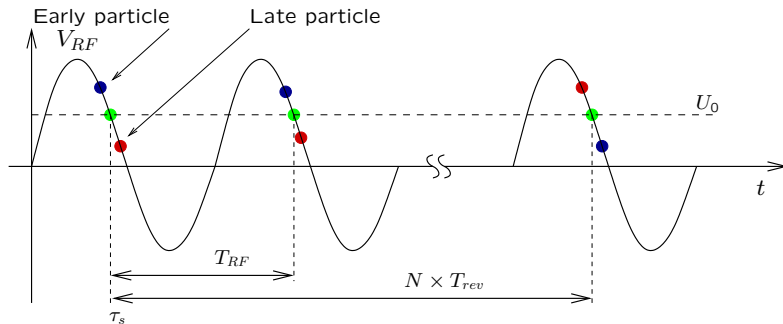
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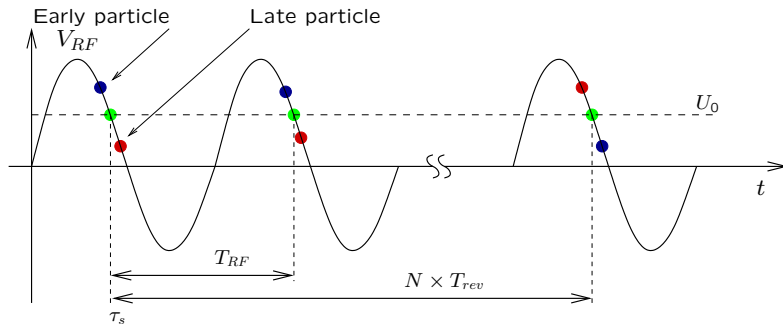
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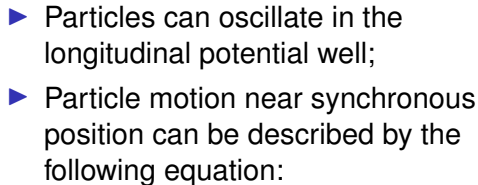
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- ▶ d_r is the radiation damping rate;
- ▶ ω_s is the synchrotron frequency;

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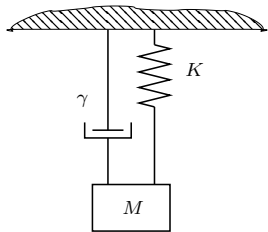
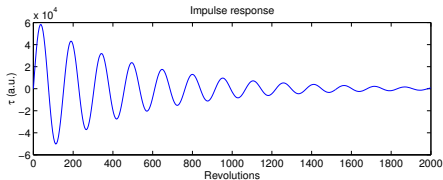
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Longitudinal Equation of Motion



- ▶ Particles can oscillate in the longitudinal potential well;
- ▶ Particle motion near synchronous position can be described by the following equation:
$$\ddot{\tau} + 2d_r\dot{\tau} + \omega_S^2\tau = 0$$
 - ▶ d_r is the radiation damping rate;
 - ▶ ω_S is the synchrotron frequency;
- ▶ This equation describes a damped harmonic oscillator;
- ▶ When many particles are stored in one RF bucket, the same equation describes center-of-mass motion.

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Betatron oscillation

- ▶ In addition to dipoles, magnetic lattice of a storage ring includes focusing elements;
- ▶ Similarly to longitudinal plane, horizontal and vertical motions at low amplitudes behave as damped harmonic oscillators;
- ▶ One major difference between longitudinal and transverse motion:
 - ▶ Synchrotron period is 50–1000 revolutions;
 - ▶ Transversely, particles execute multiple betatron cycles in one revolution.
- ▶ When betatron motion is observed at a single point in the ring, it is aliased;
- ▶ Only fractional part of betatron frequency (tune) is observed.

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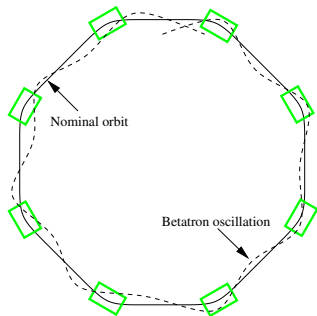
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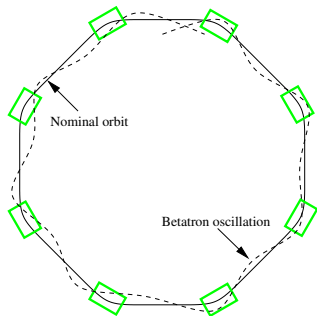
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Transverse Motion



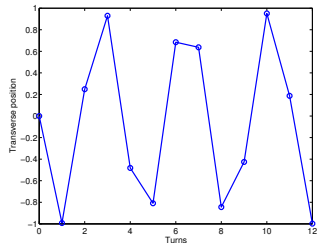
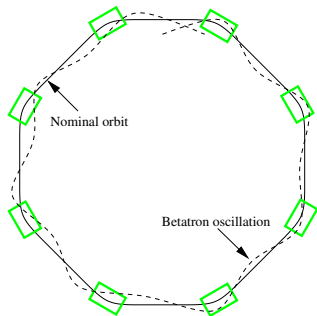
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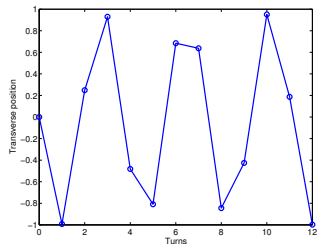
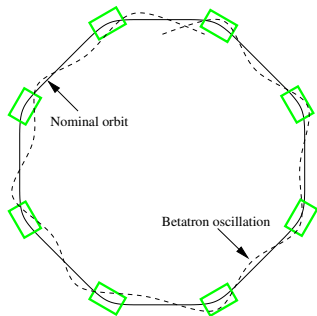
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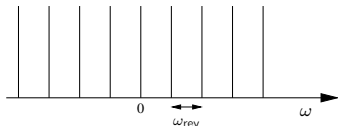
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- ▶ Single particle in a ring has time domain signal $i(t) = \sum_{n=-\infty}^{\infty} \delta(t - nT_{\text{rev}})$
- ▶ Frequency domain:

$$I(\omega) = \omega_{\text{rev}} \sum_{p=-\infty}^{\infty} \delta(\omega - p\omega_{\text{rev}})$$
- ▶ Placing identical particles in all RF buckets:
 - ▶ $i(t) = \sum_{n=-\infty}^{\infty} \delta(t - nT_{\text{RF}})$
 - ▶ $I(\omega) = \omega_{\text{RF}} \sum_{p=-\infty}^{\infty} \delta(\omega - p\omega_{\text{RF}})$
- ▶ Assumption of infinitely short bunches produces unphysically wide spectrum;
- ▶ For Gaussian bunch with RMS bunch length σ_{τ} : $I(\omega) = Q\omega_{\text{RF}} e^{-\omega^2 \sigma_{\tau}^2 / 2} \sum_{p=-\infty}^{\infty} \delta(\omega - p\omega_{\text{RF}})$

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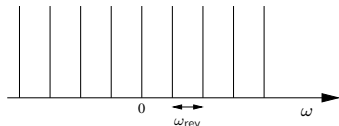
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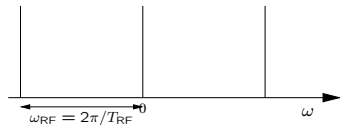
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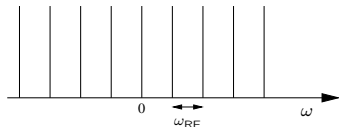
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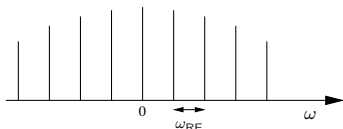
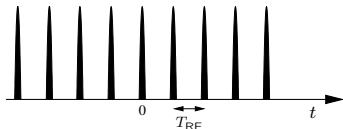
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Synchrotron and Betatron Oscillation

- ▶ Synchrotron oscillation is a phase modulation of beam signal;
- ▶ At low amplitudes of motion, synchrotron sidebands appear around the harmonics of the revolution frequency;
- ▶ At larger amplitudes of motion (higher phase modulation index), harmonics of synchrotron frequency become significant;
- ▶ Signal repeats at multiples of RF frequency, with increasing phase modulation index, i.e. larger synchrotron harmonics;
- ▶ Betatron oscillation causes the beam to pass closer to or farther from the detector;
- ▶ Amplitude modulation;
- ▶ Aliased betatron frequency sidebands of the revolution harmonics;
- ▶ For rigid bunch centroid motion, full information appears in $f_{\text{RF}}/2$ band above or below each RF harmonic.

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Synchrotron and Betatron Oscillation

- ▶ Synchrotron oscillation is a phase modulation of beam signal;
- ▶ At low amplitudes of motion, synchrotron sidebands appear around the harmonics of the revolution frequency;
- ▶ At larger amplitudes of motion (higher phase modulation index), harmonics of synchrotron frequency become significant;
- ▶ Signal repeats at multiples of RF frequency, with increasing phase modulation index, i.e. larger synchrotron harmonics;
- ▶ Betatron oscillation causes the beam to pass closer to or farther from the detector;
- ▶ Amplitude modulation;
- ▶ Aliased betatron frequency sidebands of the revolution harmonics;
- ▶ For rigid bunch centroid motion, full information appears in $f_{\text{RF}}/2$ band above or below each RF harmonic.

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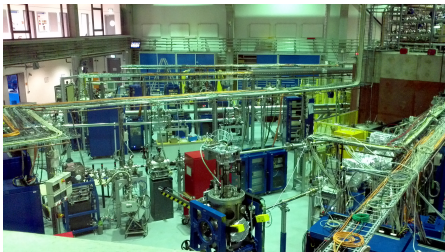
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Parameters

Parameter	Value
Circumference	48 m
RF frequency	500 MHz
Harmonic number	80
Energy	105–629 MeV
Design current	100 mA

Application: Synchrotron Light Source,
Primary Radiation Standard.



Hefei Light Source



Image courtesy of USTC NSRL

Parameters

Parameter	Value
Circumference	66 m
RF frequency	204 MHz
Harmonic number	45
Energy	800 MeV
Design current	300 mA

Application: Synchrotron Light Source.

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Australian Synchrotron



Image courtesy of Australian Synchrotron

Parameters

Parameter	Value
Circumference	216 m
RF frequency	500 MHz
Harmonic number	360
Energy	3 GeV
Design current	200 mA

Application: Synchrotron Light Source.

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MAX IV 3 GeV



Image from Lund University Media Bank

Parameters

Parameter	Value
Circumference	528 m
RF frequency	100 MHz
Harmonic number	176
Energy	3 GeV
Design current	500 mA

Application: Synchrotron Light Source.

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KEK B-Factory

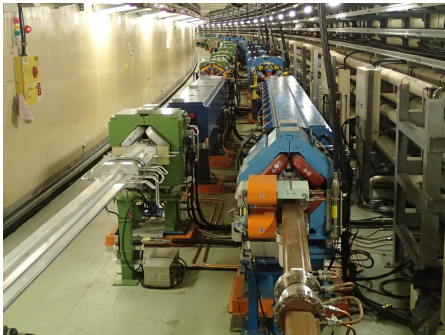


Image credit: KEK

Parameters

Parameter	Value
Circumference	3016 m
RF frequency	509 MHz
Harmonic number	5120
Energy	4/7 GeV
Design current	3.6/2.6 A

Application: Two ring e^+/e^- collider.

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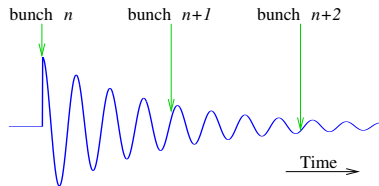
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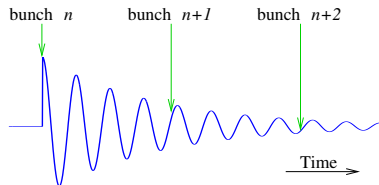
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- ▶ Bunch passing through a resonant structure excites a wakefield which is sampled by the following bunches — a coupling mechanism;
- ▶ In practice the wakefields have much longer damping times than illustrated here;
- ▶ Longitudinal bunch oscillation $\rightarrow$ phase modulation of the wakefield $\rightarrow$ slope of the wake voltage sampled by the following bunches determines the coupling.
- ▶ For certain combinations of wakefield amplitudes and frequencies the overall system becomes unstable.

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Coupled-bunch Instabilities: Eigenmodes and Eigenvalues

- ▶ A system of N bunches (coupled harmonic oscillators) has N eigenmodes;
- ▶ From symmetry considerations we find that the eigenmodes correspond to Fourier vectors;
- ▶ Mode number m describes the number of oscillation periods over one turn;
- ▶ Wakefields affect the modal eigenvalues in both real (growth rate) and imaginary (oscillation frequency) parts;
- ▶ Motion of bunch k oscillating in mode m is given by: $A_m e^{i2\pi km/N} e^{\Lambda_m t}$
 - ▶ A_m — modal amplitude;
 - ▶ Λ_m — complex modal eigenvalue.

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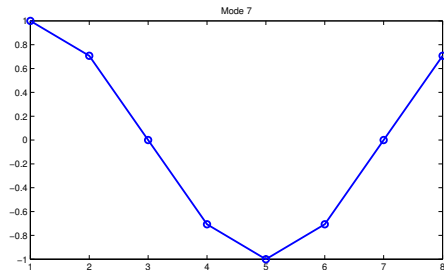
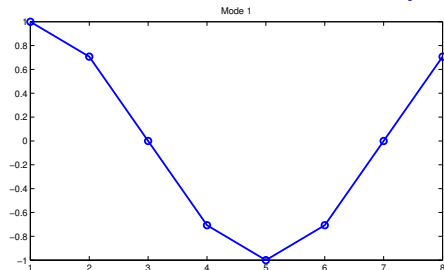
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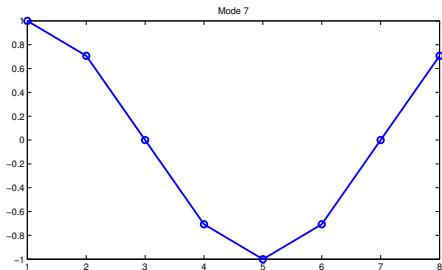
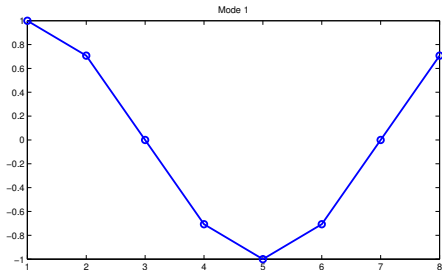
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Modal Oscillation Example



- ▶ Harmonic number of 8;
- ▶ Top plot — mode 1;
- ▶ Bottom — mode 7;
- ▶ All bunches oscillate at the same amplitude and frequency, but different phases;
- ▶ Cannot distinguish modes m and $N - m$ (or $-m$) from a single turn snapshot.

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- ▶ Same modes with damping.

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Coupled-bunch Instabilities: Eigenvalues and Impedances

- ▶ Beam interacts with wakefields (impedances in frequency domain) at synchrotron or betatron sidebands of revolution harmonics;
- ▶ Impedance functions are aliased, since they are sampled by the beam;
- ▶ Longitudinal: $\Lambda_m = (-\lambda_{\text{rad}}^{\parallel} + i\omega_s) + \frac{\pi \alpha e f_{\text{rf}}^2 I_0}{E_0 h \omega_s} Z^{\parallel \text{eff}}(m\omega_0 + \omega_s)$;
- ▶ Effective impedance: $Z^{\parallel \text{eff}}(\omega) = \sum_{p=-\infty}^{\infty} \frac{p\omega_{\text{rf}} + \omega}{\omega_{\text{rf}}} Z^{\parallel}(p\omega_{\text{rf}} + \omega)$
- ▶ Transverse: $\Lambda_m = (-\lambda_{\text{rad}}^{\perp} + i\omega_{\beta}) - \frac{c e f_{\text{rev}} I_0}{2\omega_{\beta} E_0} Z^{\perp \text{eff}}(m\omega_0 + \omega_{\beta})$
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Feedback Topologies

- ▶ Historically, people started fighting coupled-bunch instabilities in the frequency domain by building mode-by-mode systems;
 - ▶ Driven by relatively small number of bunches in the early machines;
 - ▶ Correspondingly, few modes and even fewer unstable modes.
- ▶ Such systems rapidly became impractical in storage rings with hundreds or thousands of bunches;
- ▶ In the mid-1980s first time-domain systems started to appear, performing bunch-by-bunch processing;
- ▶ Progress of DSP technology in 1990s and 2000s led to the development of programmable digital systems;
- ▶ Pioneered at SLAC by Dr. John D. Fox.

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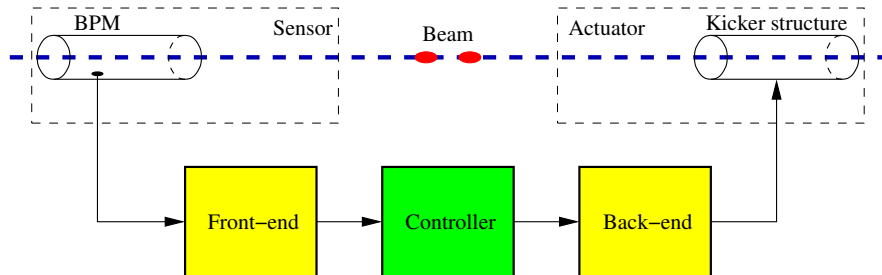
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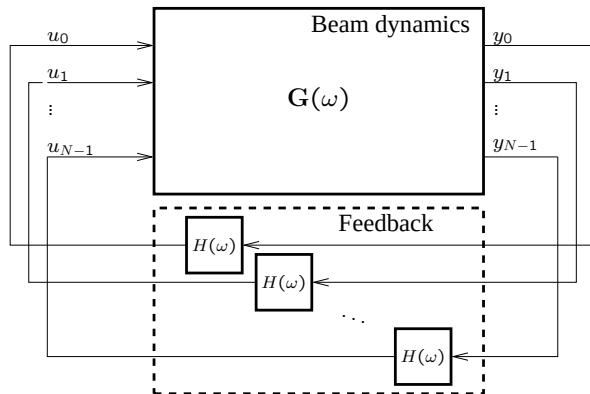
Definition

In **bunch-by-bunch feedback approach** the actuator signal for a given bunch depends only on the past motion of that bunch.



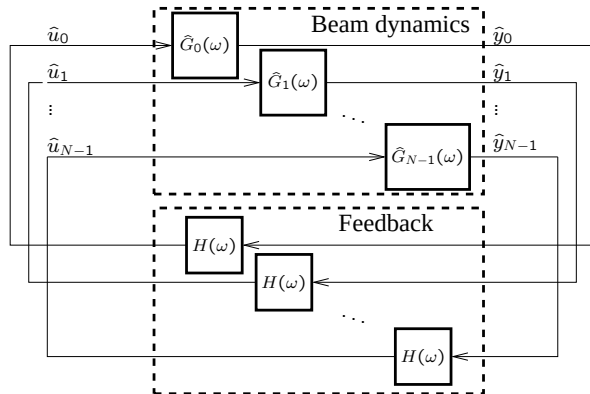
- ▶ Bunches are processed sequentially;
- ▶ Correction kicks are applied one or more turns later;
- ▶ Diagonal feedback — computationally efficient;
- ▶ Extremely popular in storage rings — why?

MIMO Model of Bunch-by-bunch Feedback



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

MIMO Model of Bunch-by-bunch Feedback



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

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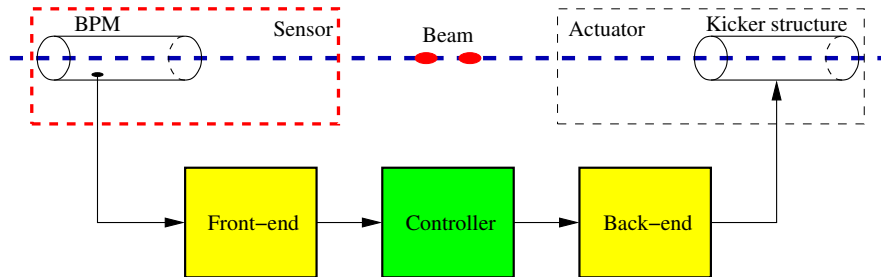
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Bunch-by-bunch Feedback



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

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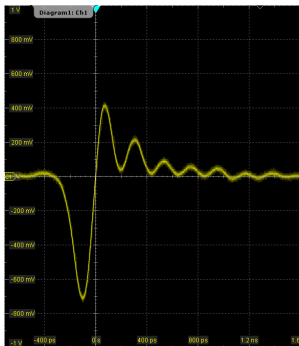
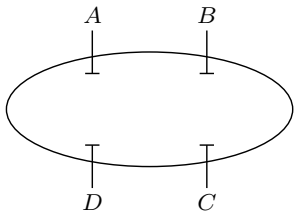
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- ▶ To sense beam position we typically use capacitive button beam position monitors (BPMs);
- ▶ Arrangement of pickups is driven by the need to avoid synchrotron radiation fan;
 - ▶ Horizontal/vertical buttons are easier to process.
- ▶ Buttons couple 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.

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Coupled-bunch Instabilities

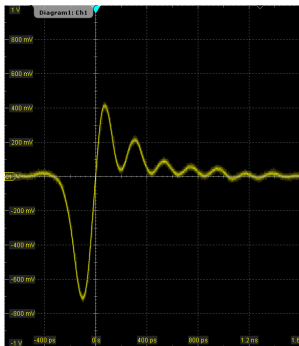
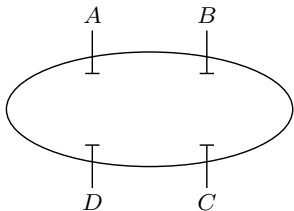
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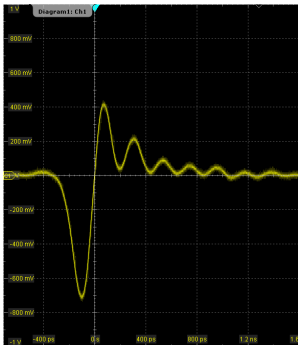
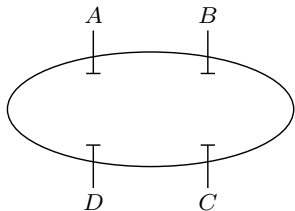
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- ▶ To sense beam position we typically use capacitive button beam position monitors (BPMs);
- ▶ Arrangement of pickups is driven by the need to avoid synchrotron radiation fan;
 - ▶ Horizontal/vertical buttons are easier to process.
- ▶ Buttons couple 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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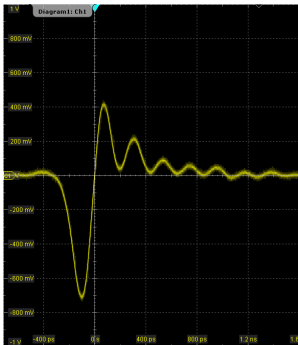
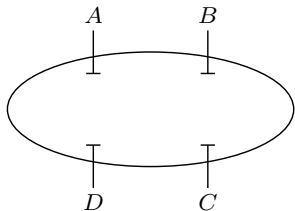
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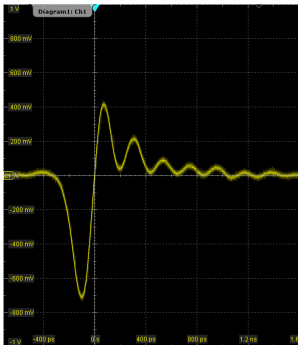
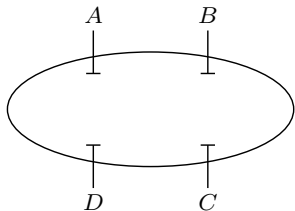
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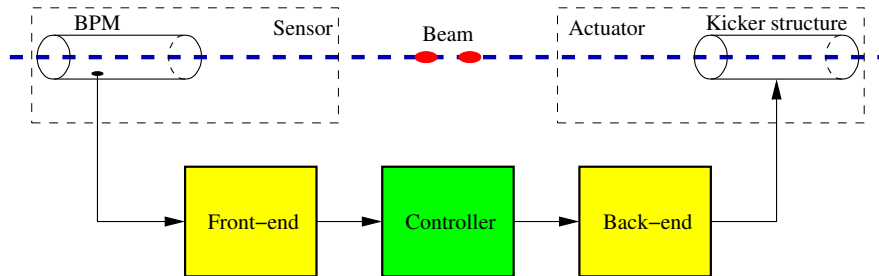
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Bunch-by-bunch Feedback



- ▶ Sensor (pickup);
- ▶ Analog front-end;
- ▶ Controller;
- ▶ Analog back-end;
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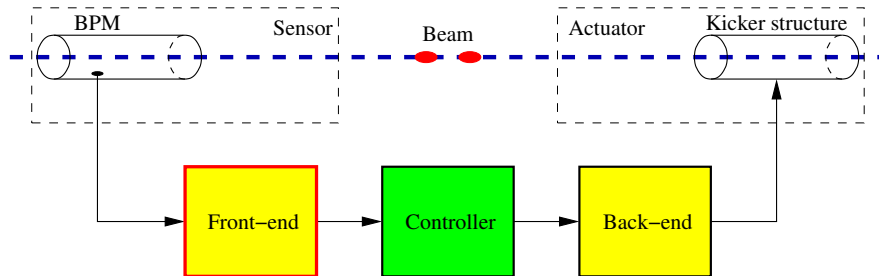
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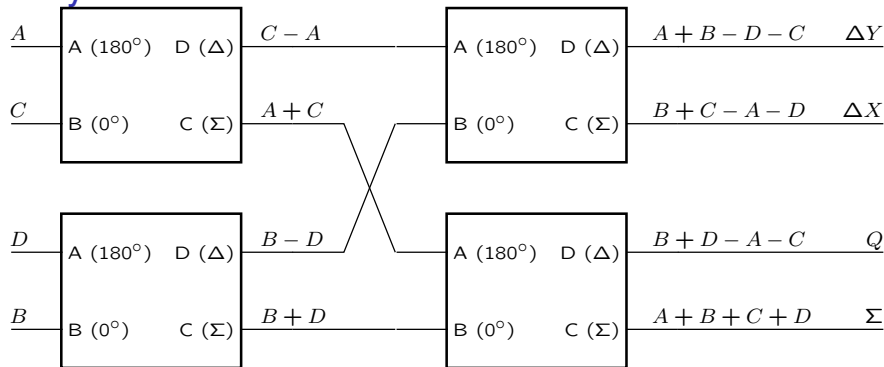
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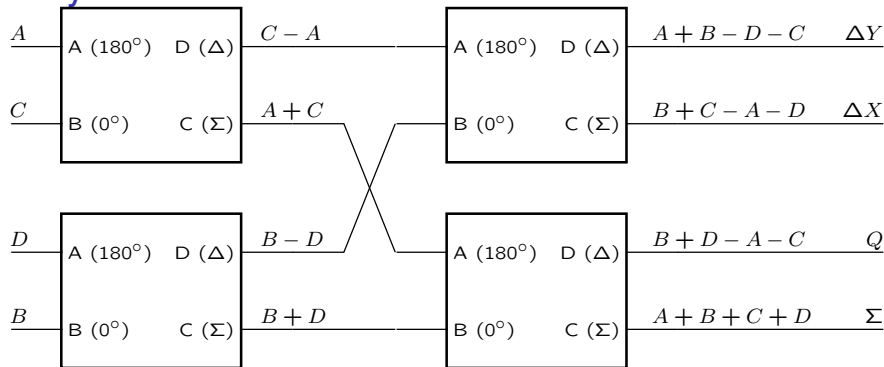
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BPM Hybrid Network



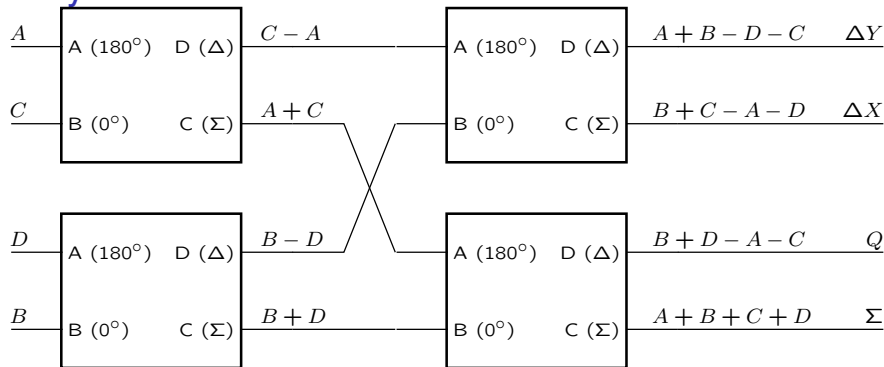
- ▶ First stage of BPM signal processing — separating X/Y/Z signals (some of you might recognize the monopulse comparator structure);
- ▶ Since we are digitizing in the end, why not digitize raw signals?
- ▶ For X and Y we are dealing with small differences of large signals;
- ▶ If we can reject the common-mode at 20–30 dB level, that is also the gain of low-noise amplifier we can use to improve sensitivity.

BPM Hybrid Network



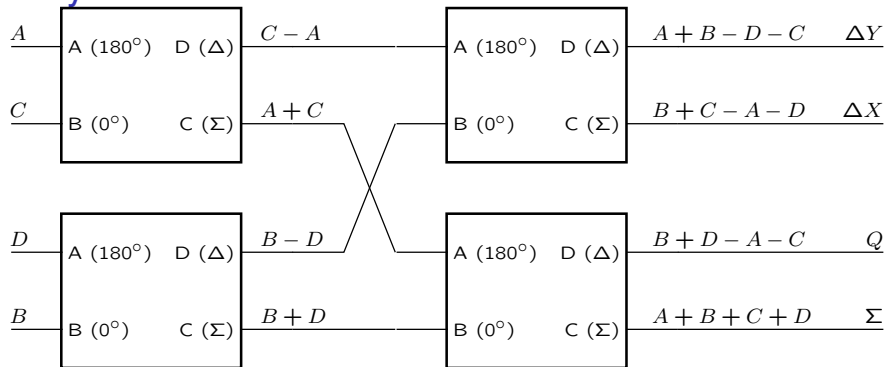
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Feedback



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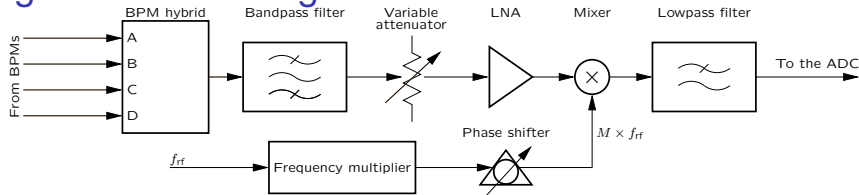
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- ▶ Front-end requirements:
 - ▶ Low amplitude and phase noise;
 - ▶ Wideband to ensure high isolation between neighboring bunches.
- ▶ Input bandpass filter is an analog FIR filter that replicates BPM pulse with spacing, matched to the detection LO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

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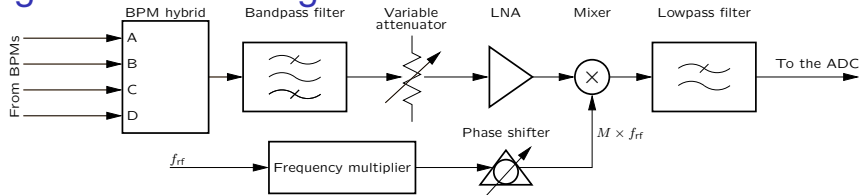
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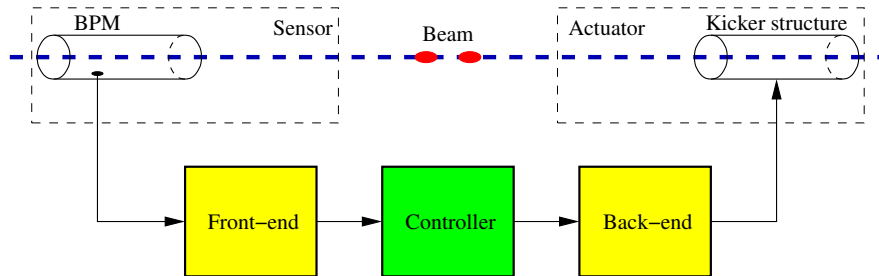
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- ▶ Sensor (pickup);
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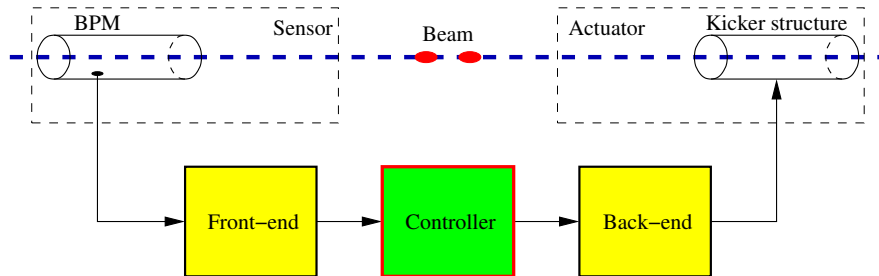
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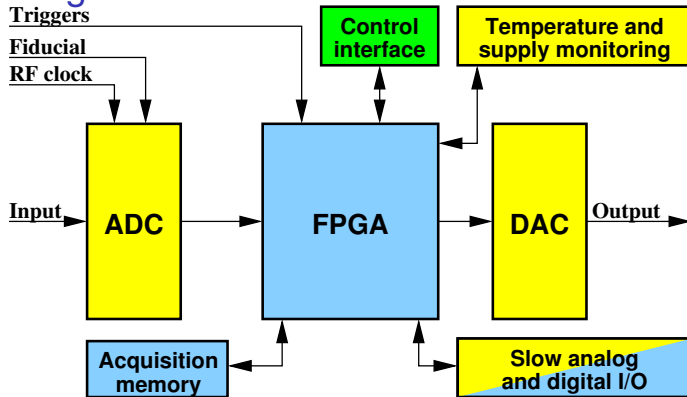
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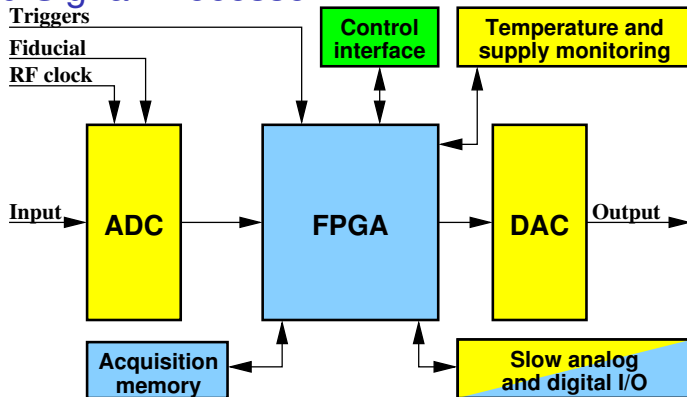
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Baseband Signal Processor



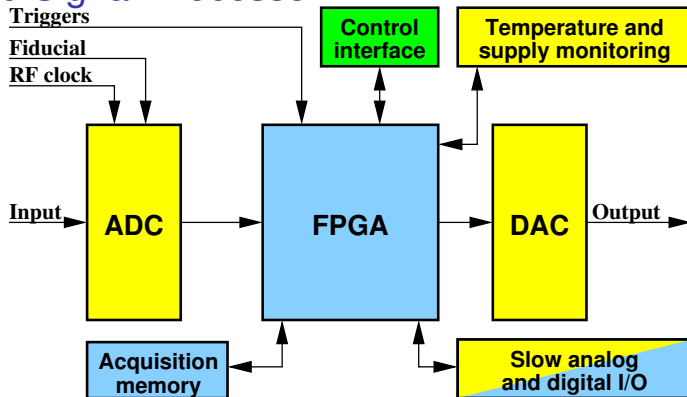
- ▶ Block diagram of a type frequently seen in accelerator context: ADC, FPGA, and DAC;
- ▶ ADC, DAC: 12–14 bit, 500–600 MSPS, 400 ps rise/fall times;
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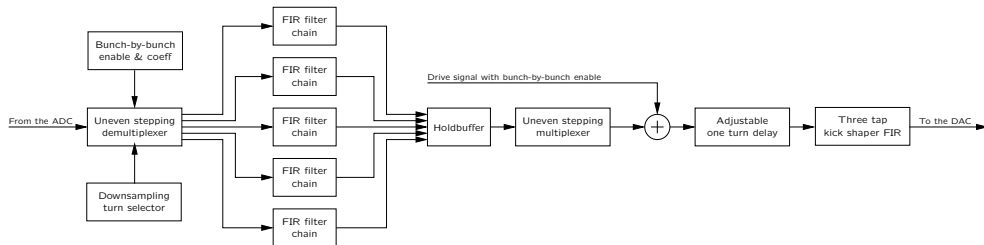
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Inside the FPGA



- ▶ Multiple filter chains to match FPGA processing rate to the bunch crossing rate;
- ▶ Uneven stepping scheme — use groups of n and $n + 1$ bunches to make sure signal from a given bunch ends up in the same filter chain on consecutive turns;
- ▶ Bunch-by-bunch excitation and feedback enables;
- ▶ Back-end compensation.

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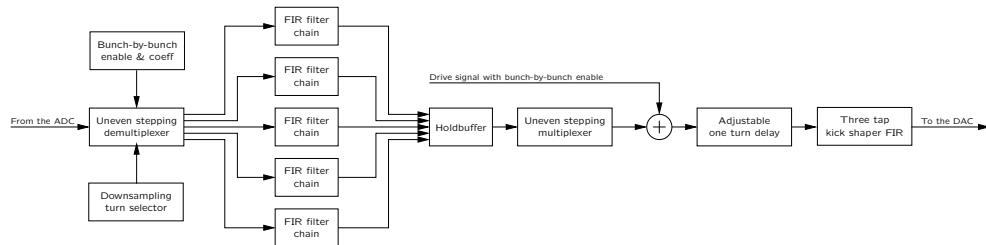
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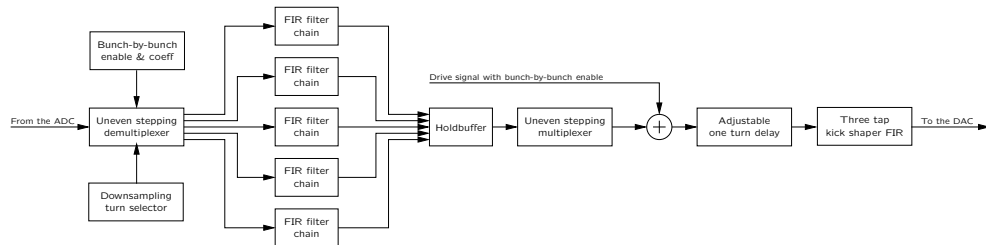
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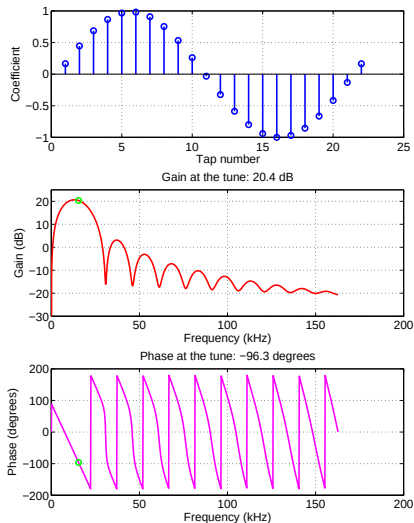
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Feedback Filter



- ▶ 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;
 - ▶ 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.

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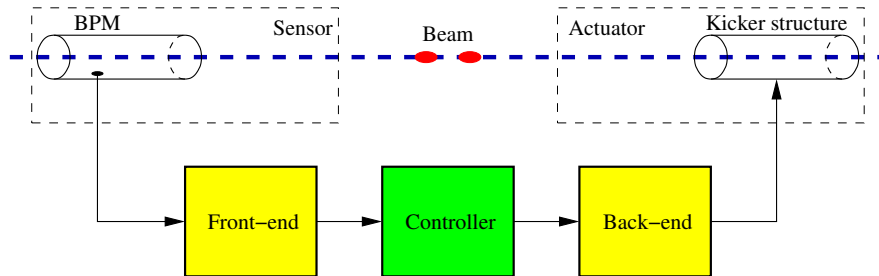
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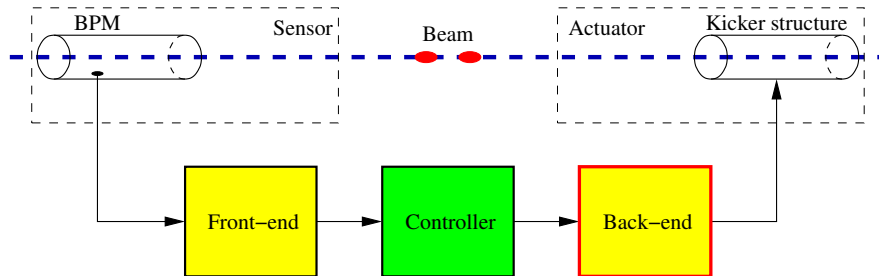
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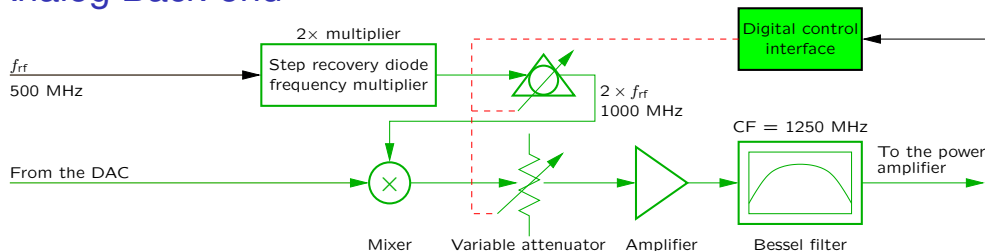
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Analog Back-end



- ▶ 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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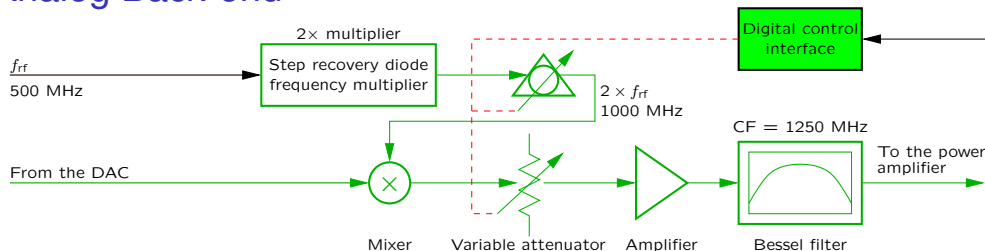
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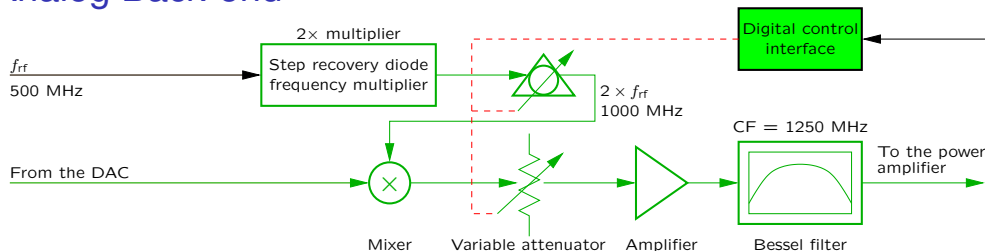
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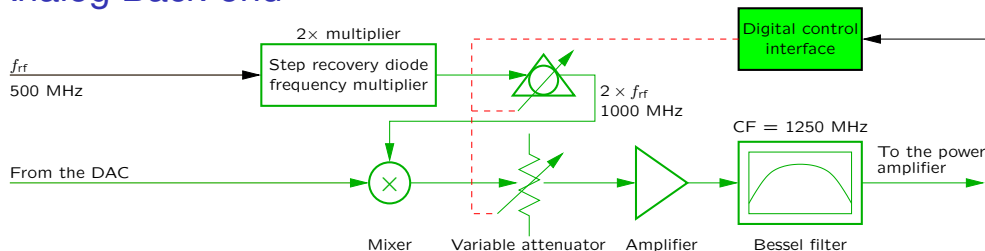
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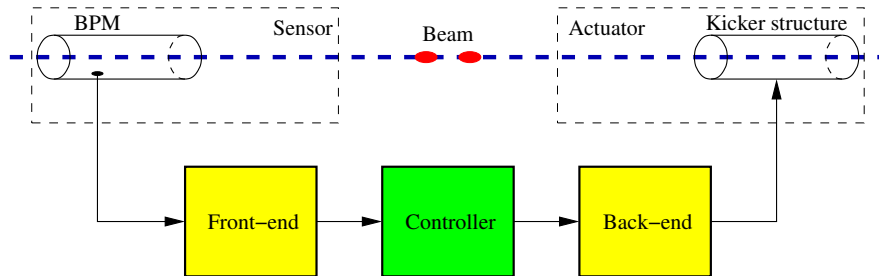
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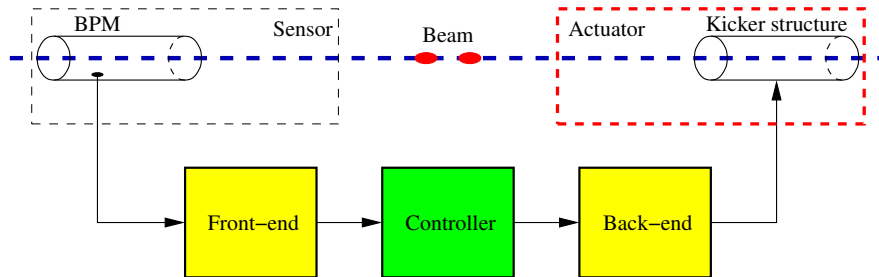
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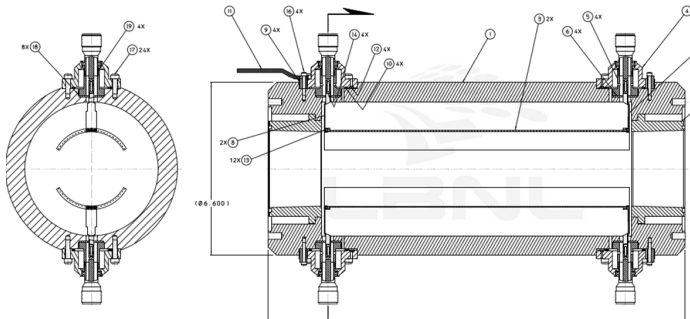
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Transverse Kicker



- ▶ 50 Ω striplines driven differentially;
- ▶ Counter-propagating beam and kick signals;
- ▶ For 2 ns bunch spacing maximum 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 do better in frequency domain, have smaller kick.

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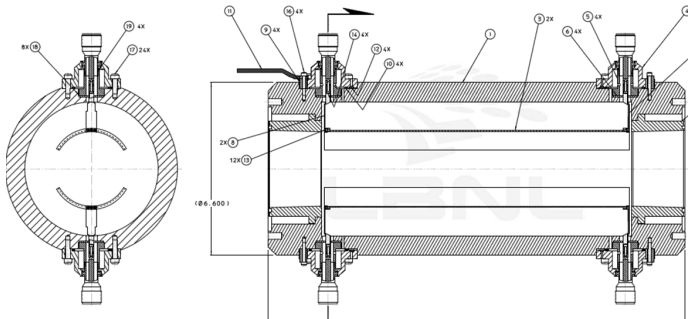
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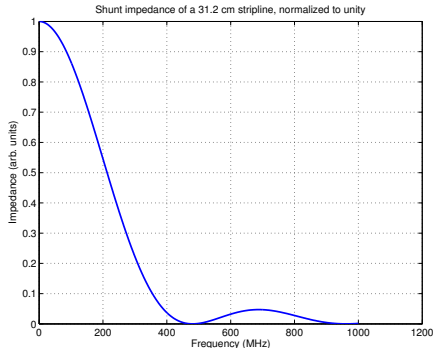
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How Does One Characterize an Unstable System?

- ▶ Standard methods of characterization:
 - ▶ Frequency domain — transfer function;
 - ▶ Time domain — step/pulse response.
- ▶ These methods fail for unstable beam;
- ▶ In 1990s our group at SLAC developed so-called transient diagnostics:
 - ▶ Upon some trigger, turn off feedback and start recording beam motion;
 - ▶ Unstable motion grows from ever-present noise-floor level excitation;
 - ▶ After an adjustable open-loop time period, turn feedback on;
- ▶ Resulting data set captures open-loop growth of the fastest unstable modes and closed-loop damping;
- ▶ Used to characterize driving terms (impedances) and feedback performance, optimize tuning.

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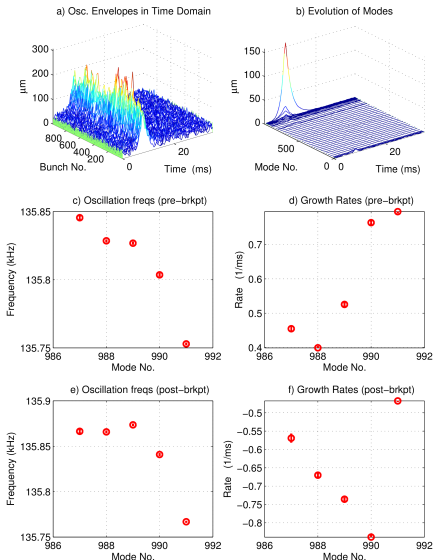
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Grow/damp Measurements from ESRF



ESRF: apr2517/123303: Io= 100.44mA, Dsamp= 1, ShifGain= 6, Nbnun= 992,
At Fs: G1= 137.054, G2= 0, Ph1= 83.6019, Ph2= 0, Brkpt= 2900, Calib= 0.36.

- ▶ Grow/damp at 100 mA, 8 ms growth time;
- ▶ Only resistive wall modes;
- ▶ Damping rates non-uniform — low frequency response of the amplifier?
- ▶ Fits look very clean, textbook exponential transients;
- ▶ Filled to 200 mA, not limited by instabilities;
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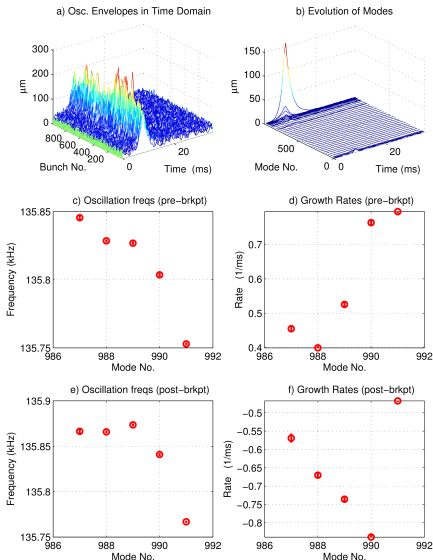
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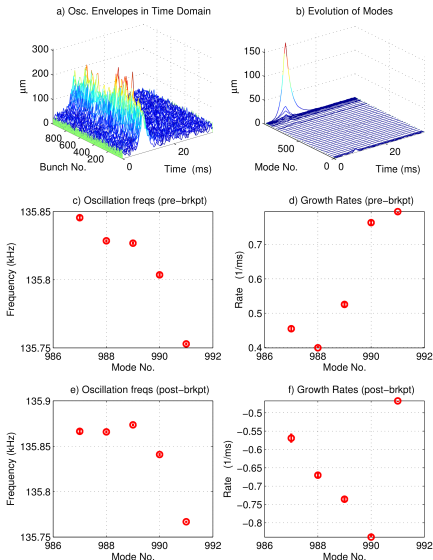
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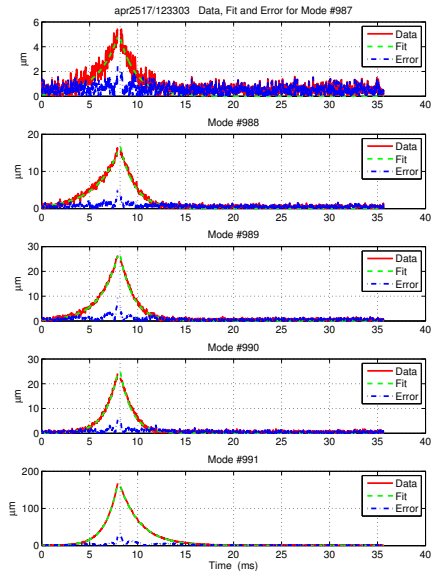
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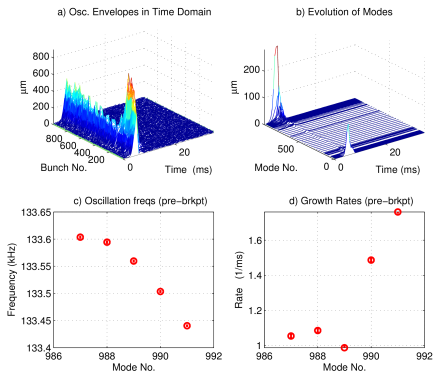
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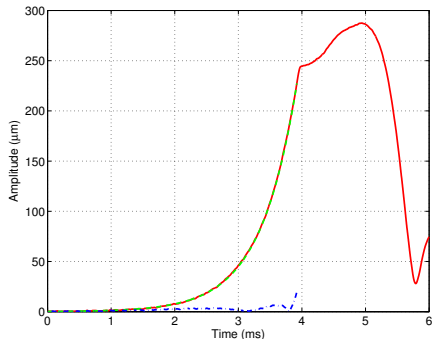
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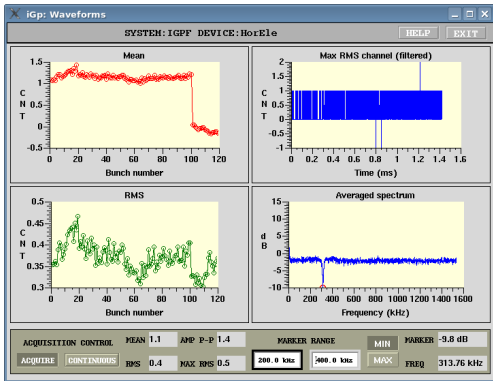
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Parasitic Tune Measurement



- ▶ Transverse feedback in DAΦNE operating in the X plane;
- ▶ Averaged beam spectrum (lower right) shows a notch;
- ▶ This notch is a key to the parasitic tune measurement capability.

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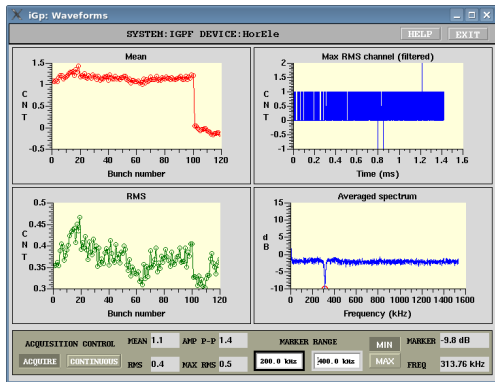
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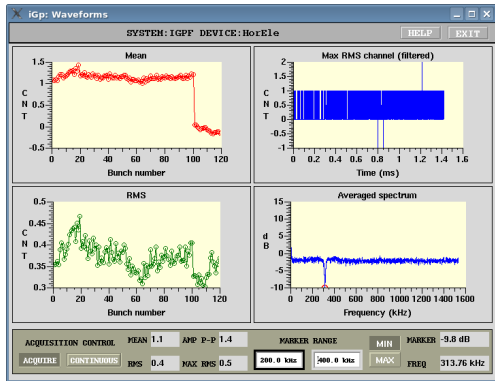
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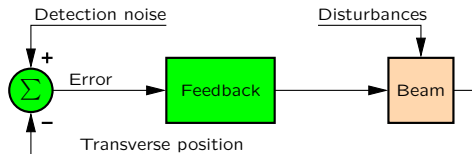
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Steady State Spectra Under Feedback Control



- ▶ 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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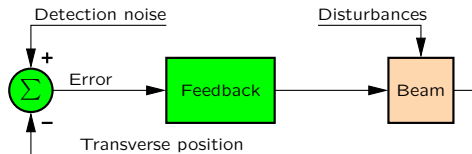
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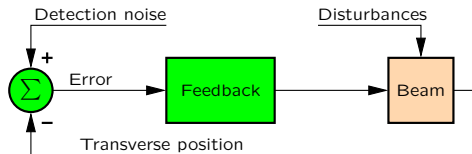
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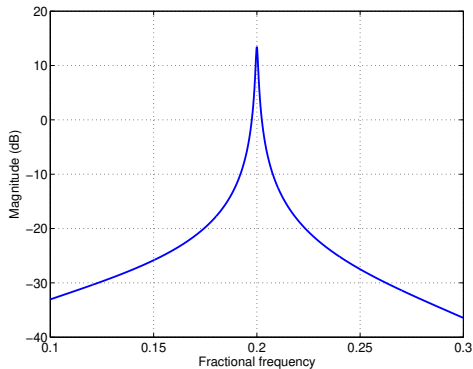
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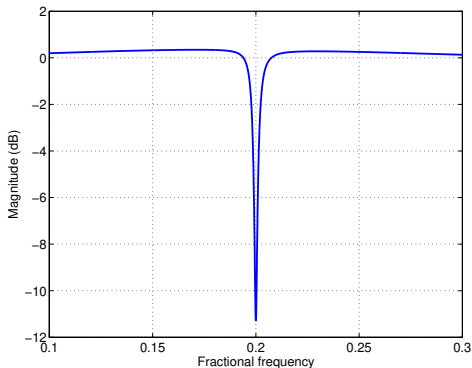
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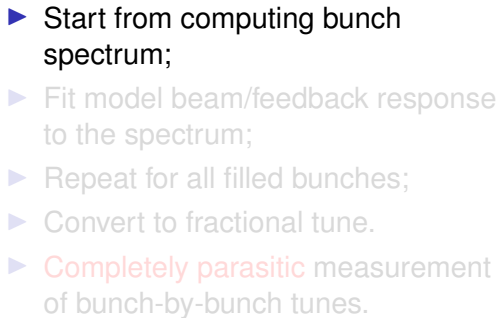
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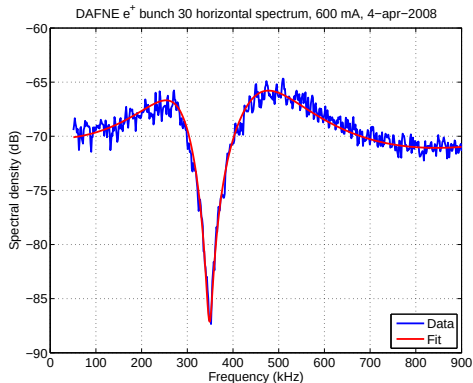
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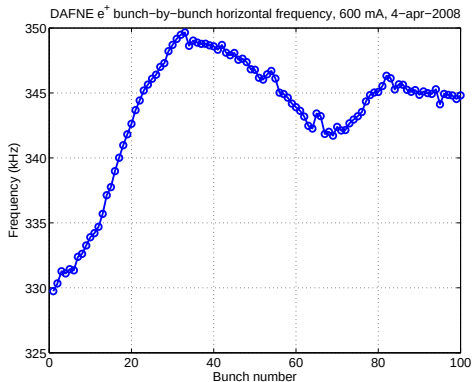


Bunch-by-bunch Tunes in DAΦNE



- ▶ Start from computing bunch spectrum;
- ▶ Fit model beam/feedback response to the spectrum;
- ▶ Repeat for all filled bunches;
- ▶ Convert to fractional tune.
- ▶ Completely parasitic measurement of bunch-by-bunch tunes.

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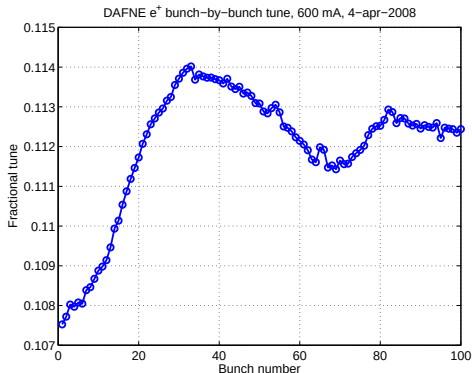
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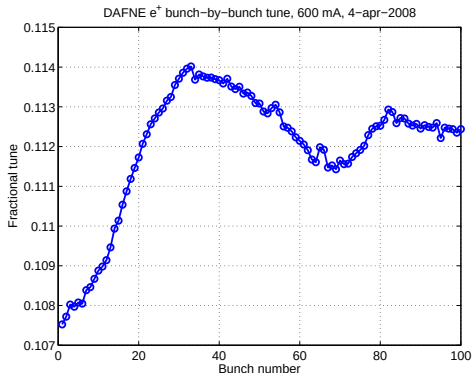
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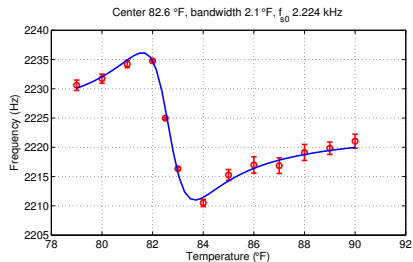
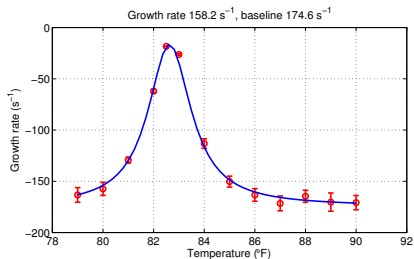
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Using Beam to Measure Impedances



- ▶ Advanced Photon Source at Argonne National Laboratory;
- ▶ Longitudinal instabilities driven by parasitic higher-order modes in RF cavities;
- ▶ Use cavity temperature to scan the impedance across a synchrotron sideband:
 - ▶ Mode 36;
 - ▶ Mode 144;
 - ▶ Mode 146.

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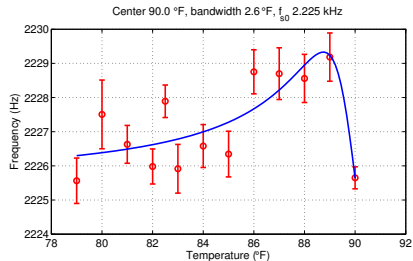
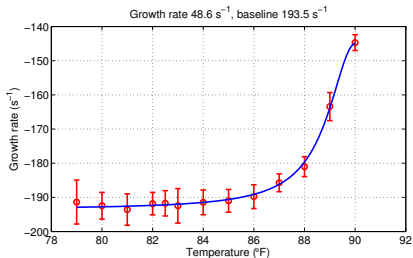
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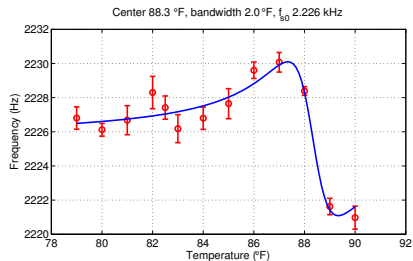
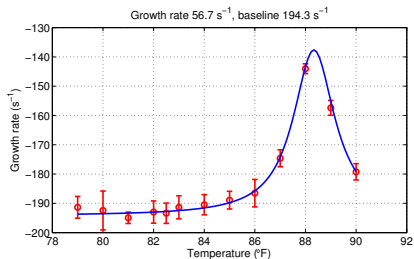
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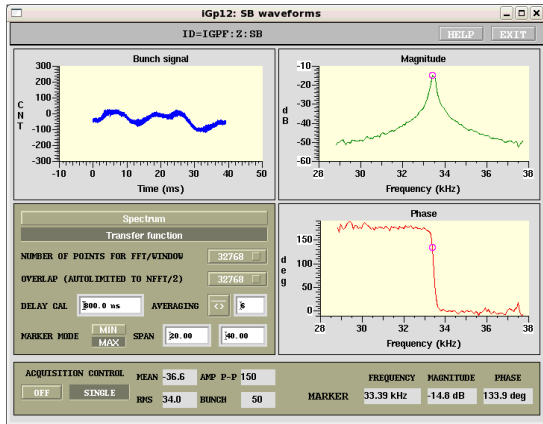
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Beam Transfer Function: Measurement Approach

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- ▶ Single-bunch acquisition engine captures 96k samples for one bunch together with excitation signal;
- ▶ From excitation and response signals, frequency domain transfer function can be estimated.

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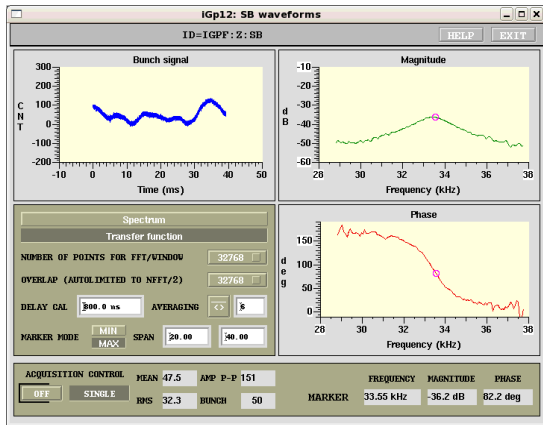
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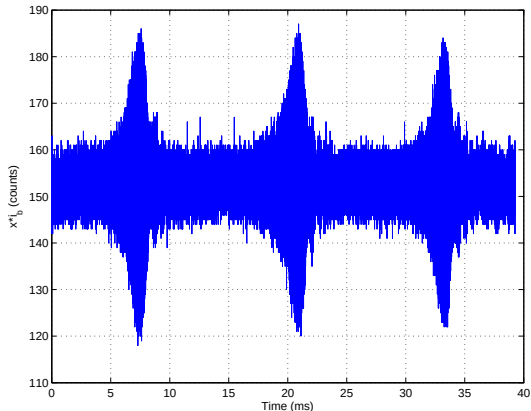
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A Few Examples from the Taiwan Light Source

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- ▶ Time-domain response, horizontal, open loop
- ▶ Frequency domain transfer function
 - ▶ Horizontal
 - ▶ Vertical
 - ▶ Longitudinal

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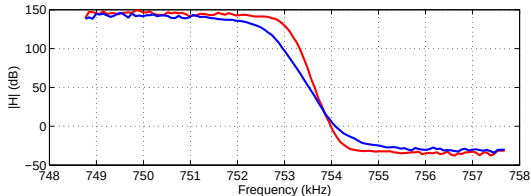
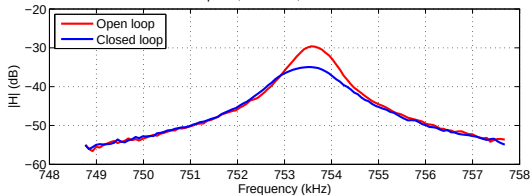
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Horizontal plane, bunch 50, standard fill at 50 mA



- ▶ Time-domain response, horizontal, open loop
- ▶ Frequency domain transfer function
 - ▶ Horizontal
 - ▶ Vertical
 - ▶ Longitudinal

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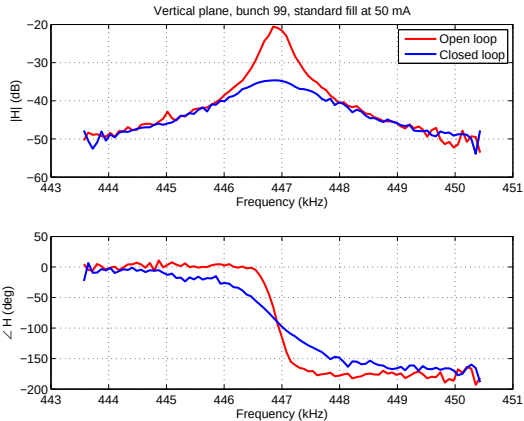
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- ▶ Time-domain response, horizontal, open loop
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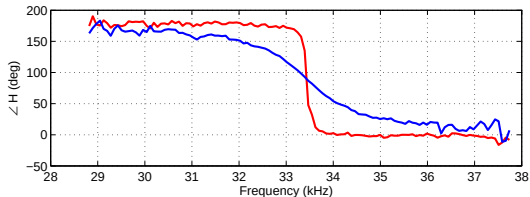
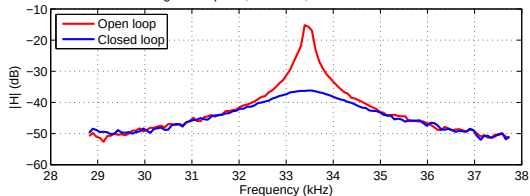
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Longitudinal plane, bunch 50, standard fill at 50 mA



- ▶ Time-domain response, horizontal, open loop
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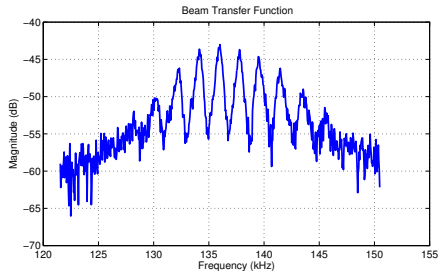
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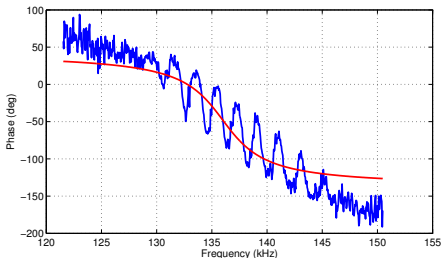
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Single Bunch Transfer Function at ESRF



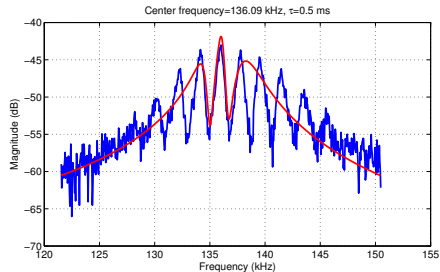
- ▶ Turn off feedback for bunch 40;
- ▶ Apply swept sinusoidal excitation;
- ▶ Measure beam transfer function;
- ▶ A simple-minded fit of a resonant response;
- ▶ Fit a linear combination of 3 resonances;
- ▶ 5 resonances;
- ▶ 7 resonances;
- ▶ 9 resonances;
- ▶ 11 resonances.

Feedback

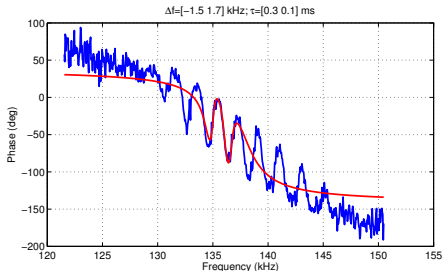


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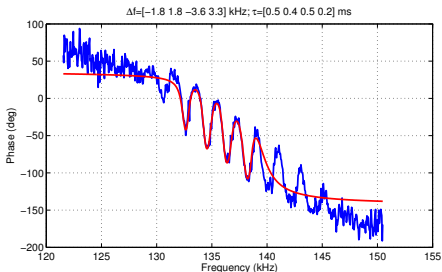
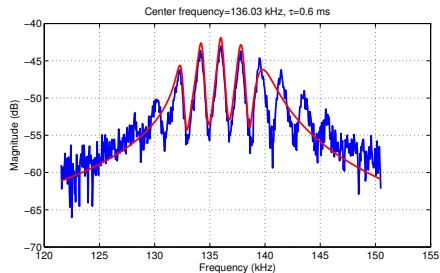
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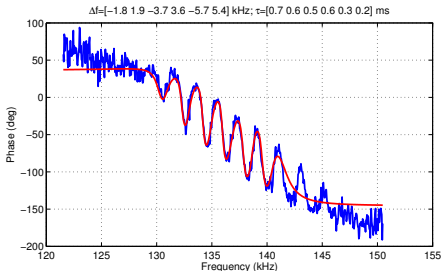
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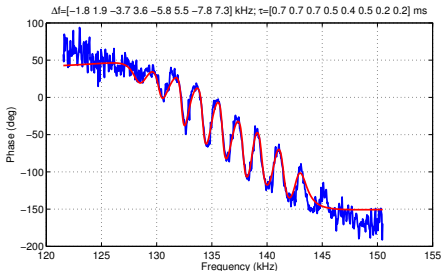
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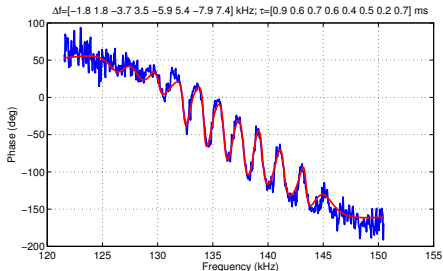
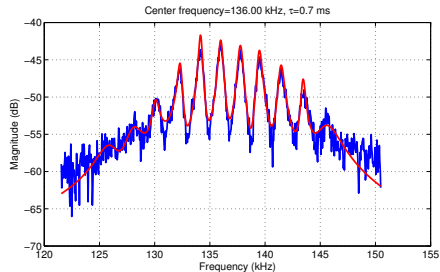
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- ▶ For stable operation of modern storage rings, control of coupled-bunch instabilities is a must;
- ▶ Bunch-by-bunch feedback is a powerful and well understood tool for such control;
- ▶ Good understanding of beam dynamics and feedback control is needed to successfully operate these systems;
- ▶ Digital signal processing techniques in modern bunch-by-bunch feedback systems enable a wealth of beam and system diagnostics.

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Acknowledgments

- ▶ Big thanks to my (former) colleagues at Stanford Linear Accelerator Center for their wisdom, willingness to talk, and to offer advice and encouragement;
- ▶ A special thanks to my Ph.D. adviser and friend, John Fox, who taught me pretty much everything I know about particle accelerators;
- ▶ I also should mention physicists and engineers at many machines around the world who directly or indirectly contributed to measurements presented here.

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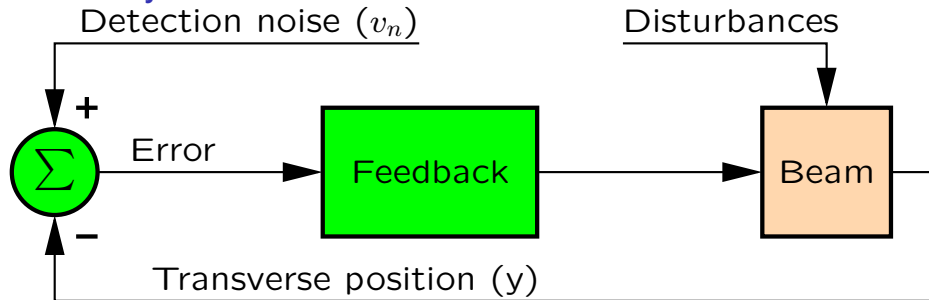
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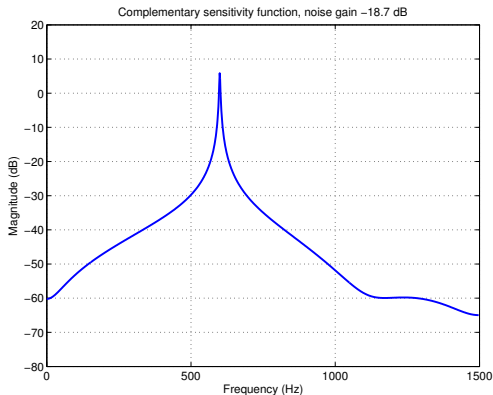
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Sensitivity and Noise



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

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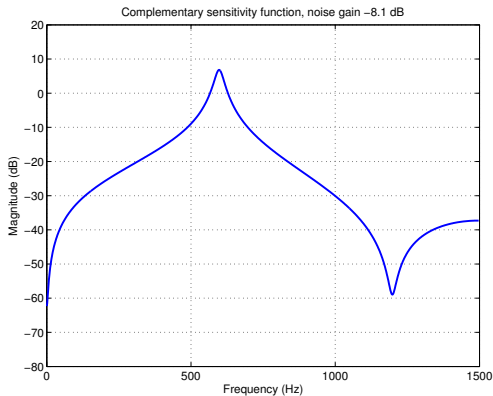
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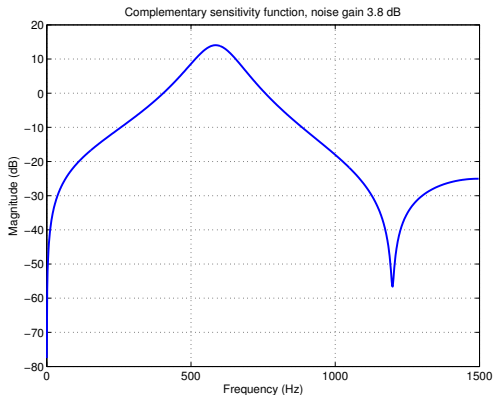
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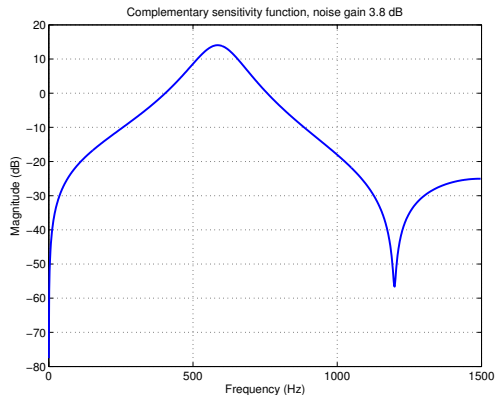
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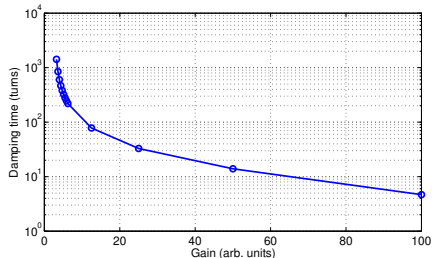
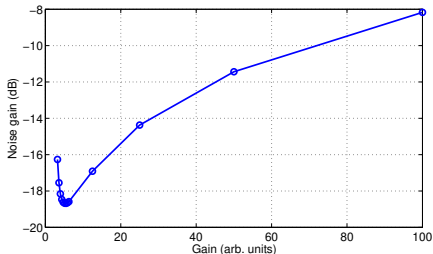
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Sensitivity vs. Feedback Gain



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

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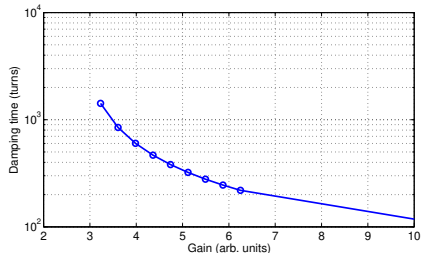
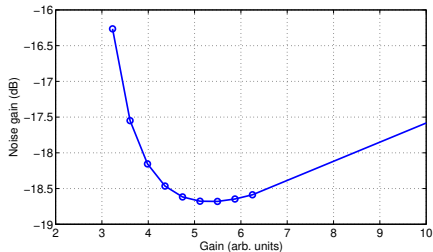
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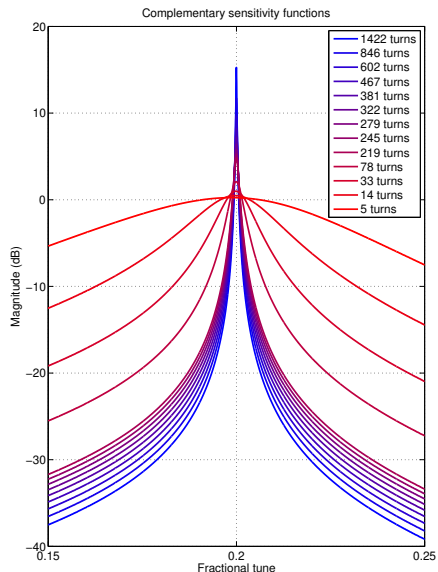
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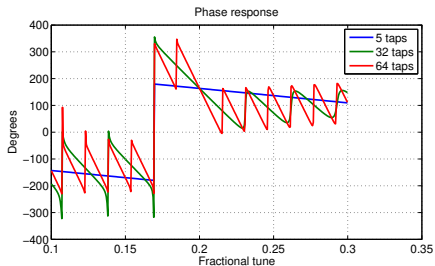
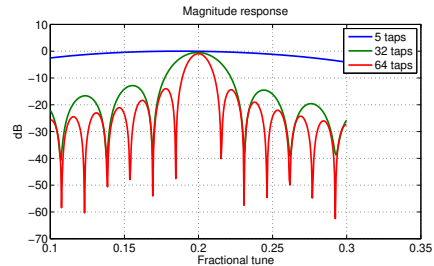
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Feedback Filter Design



- ▶ Transverse feedback FIR filters, tune of 0.2, adjusted for the same closed-loop damping time ($\tau_{cl} = \tau_{ol} = 300$ 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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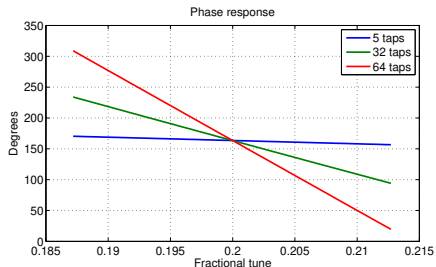
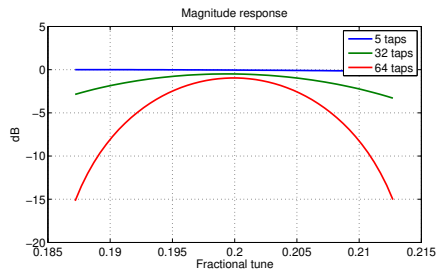
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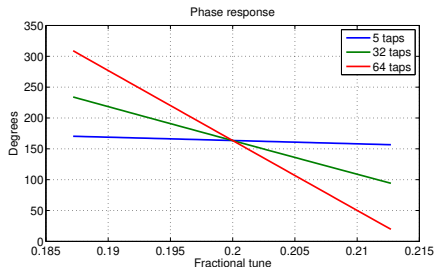
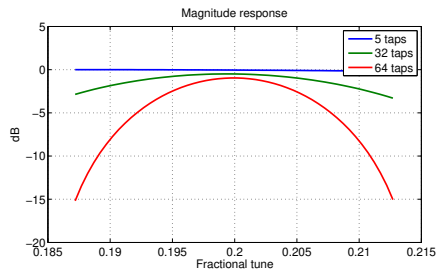
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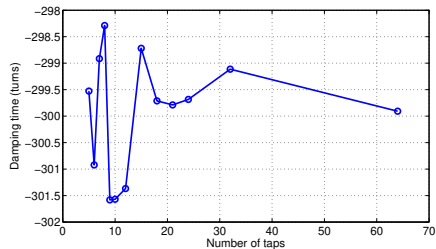
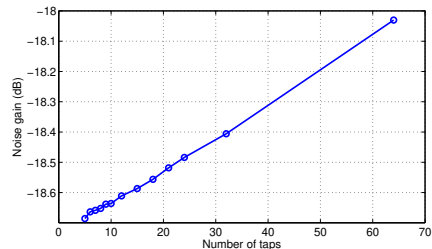
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Residual Noise vs. Filter Length



- 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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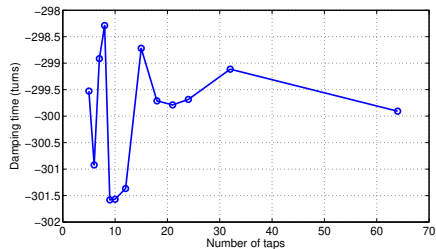
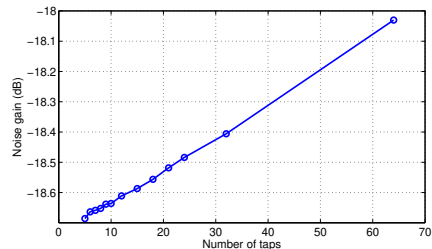
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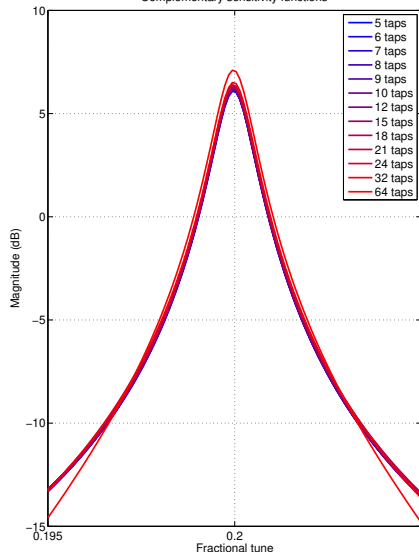
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Complementary sensitivity functions



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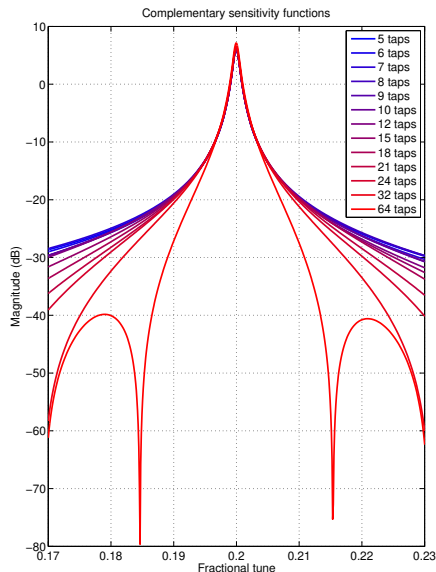
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