Closed-loop Feedback Control for Particle Accelerators

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Outline

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Motivation

- 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.

Thresholds

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

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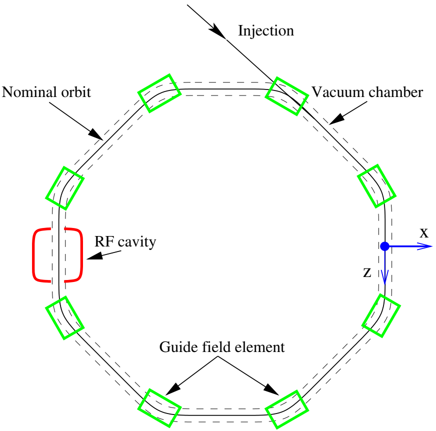

- Particles are accelerated to desired energy and injected into a storage ring;
- Vacuum chamber around a closed trajectory;
- Magnetic guide field elements deflect charged particles to follow the nominal orbit;
- Charged particles under acceleration radiate, leading to energy loss;
  - Angular acceleration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

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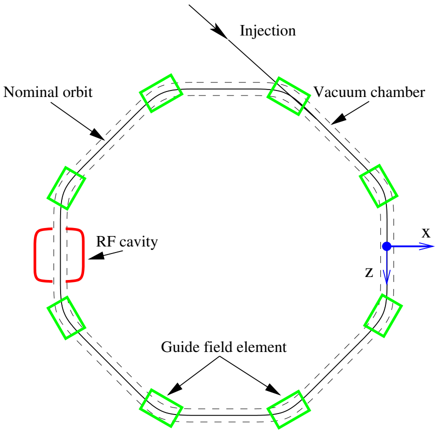

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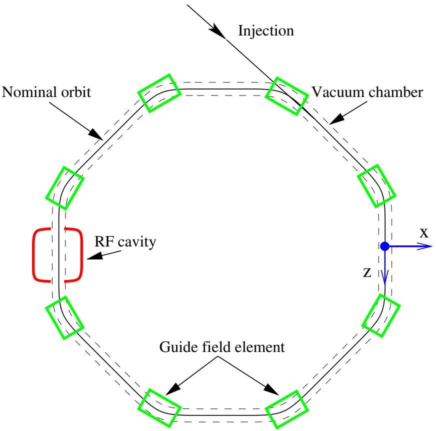

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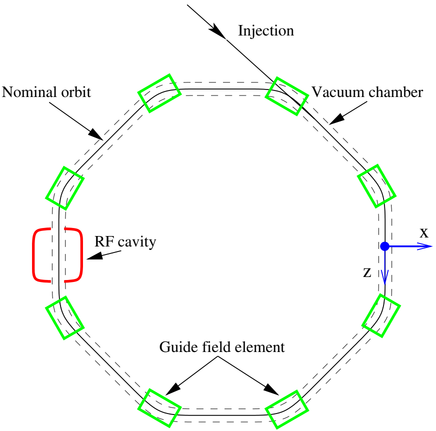

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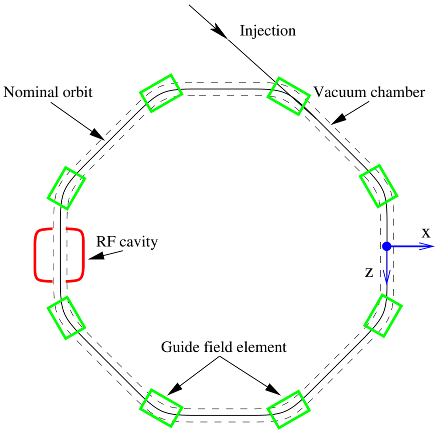

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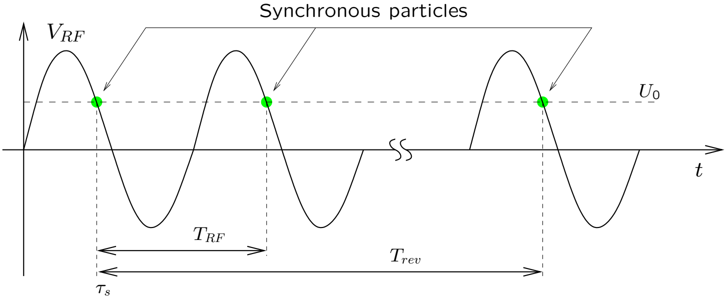
RF and Longitudinal Focusing



- 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 $T_{\mathrm{rev}}/T_{\mathrm{RF}}$ (harmonic number) is the number of stable RF buckets where bunches of charged particles can be stored.

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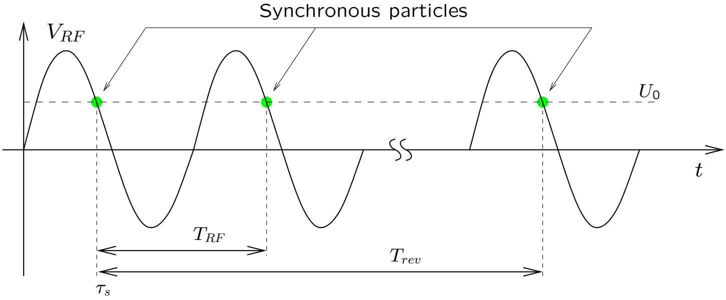

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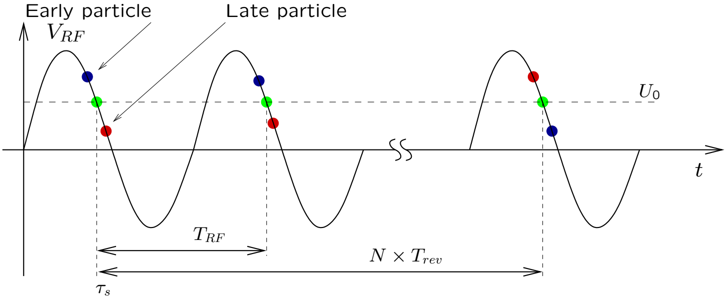

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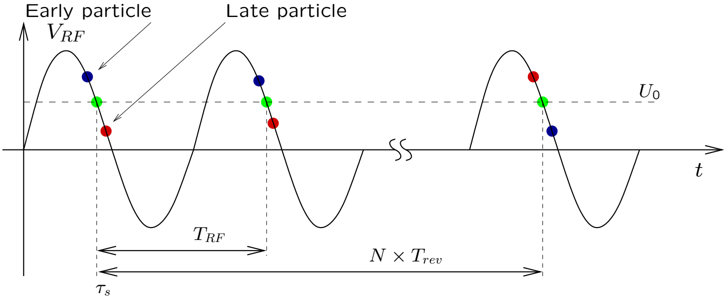

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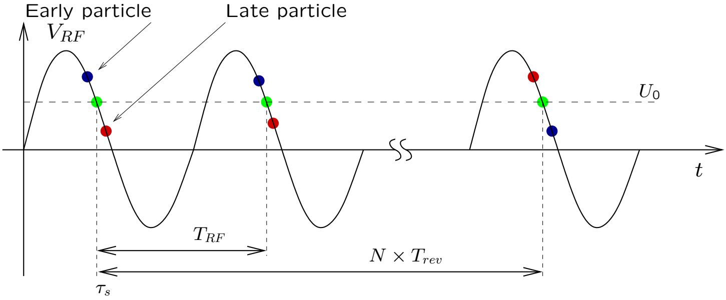

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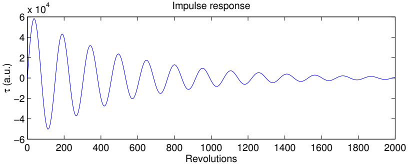
Longitudinal Equation of Motion



- 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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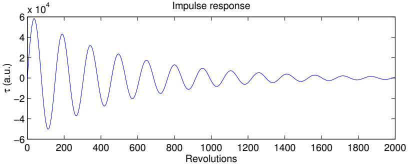

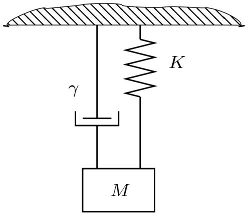

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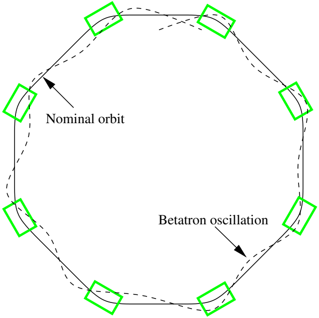
Transverse Motion



- 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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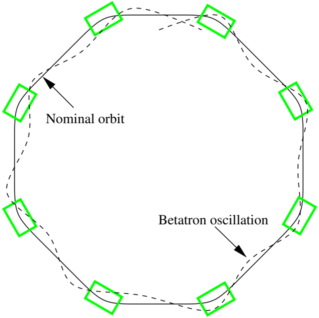

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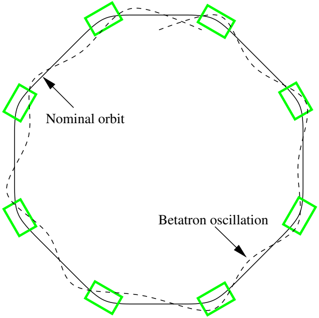

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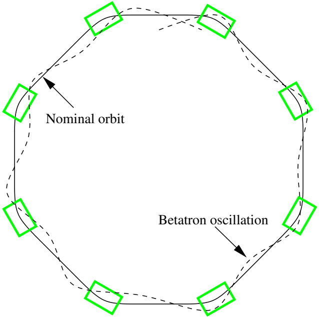

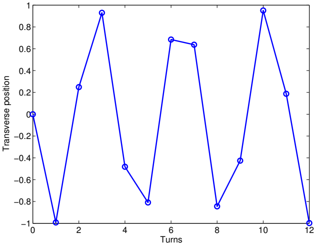

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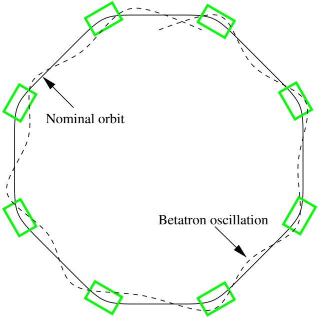

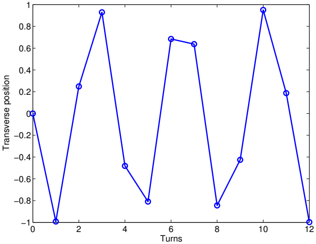

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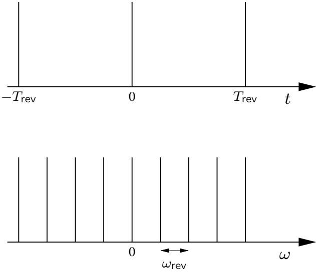
Beam Signals in Time and Frequency Domains



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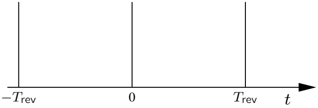

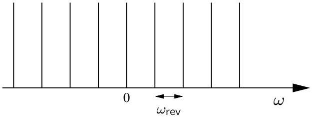

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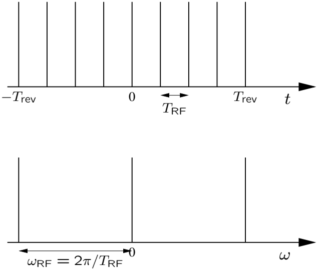

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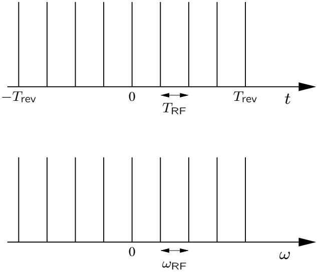

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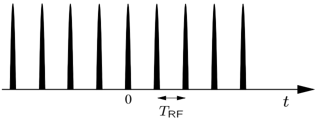

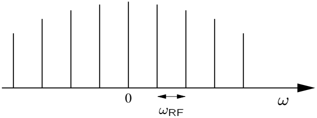

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Synchrotron and Betatron Oscillation

- 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 $f_{\mathrm{RF}}/2$ band above or below each RF harmonic.

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Metrology Light Source

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

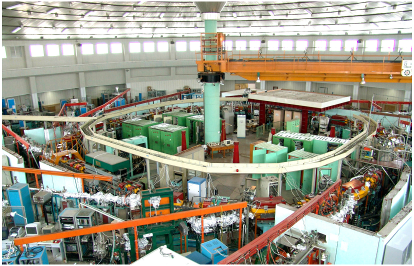


Image courtesy of USTC NSRL

Parameters

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

Application: Synchrotron Light Source.

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.

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.

KEK B-Factory

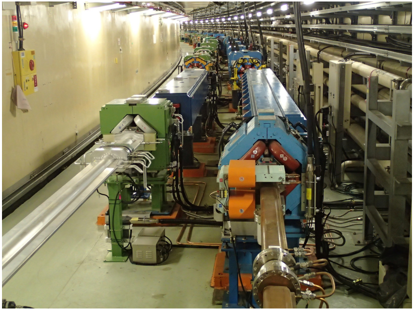


Image credit: KEK

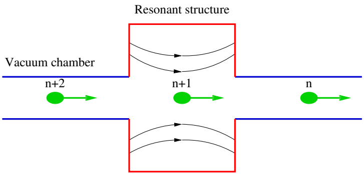
Parameters

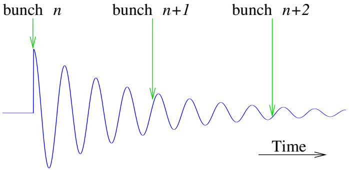
Parameter	Value
Circumference	3016 m
RF frequency	509 MHz
Harmonic number	5120
Energy	4/7 GeV
Design current	3.6/2.6 A

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

Outline

Coupled-bunch Instabilities





- 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 → phase modulation of the wakefield → 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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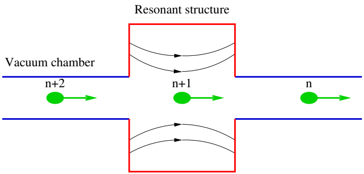

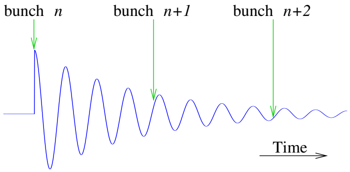

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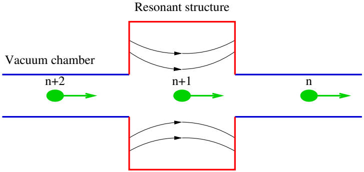

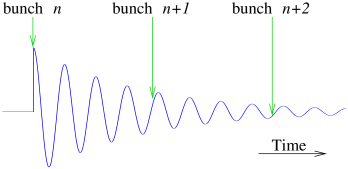

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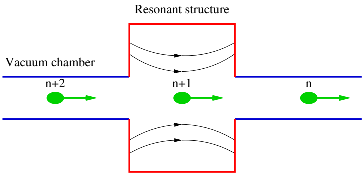

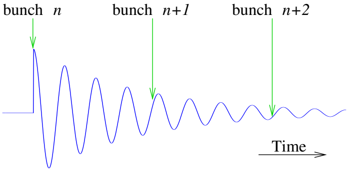

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Coupled-bunch Instabilities: Eigenmodes and Eigenvalues

- 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: $A_m e^{2\pi km/N} e^{\Lambda_m t}$
  - A_m — modal amplitude;
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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.

Modal Oscillation With Damping

- Same modes with damping.

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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Outline

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;
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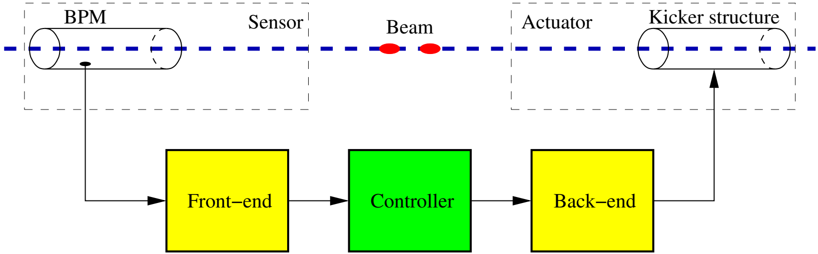
Bunch-by-bunch Feedback

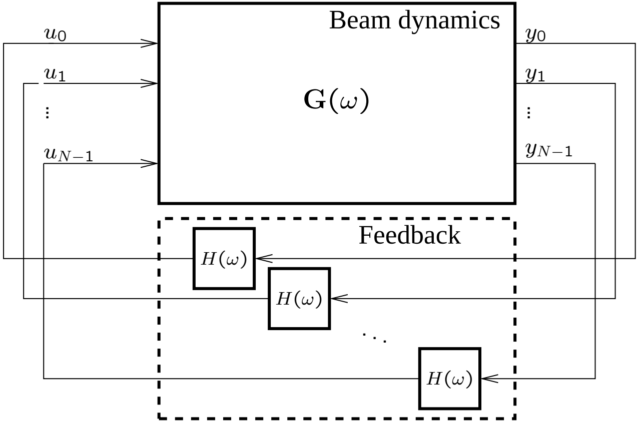
Definition

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 — 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.

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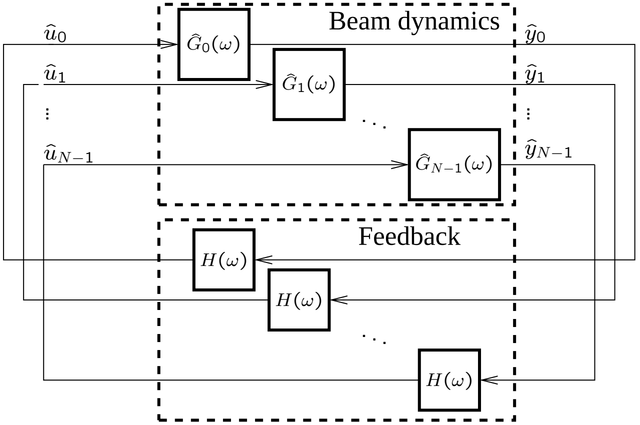
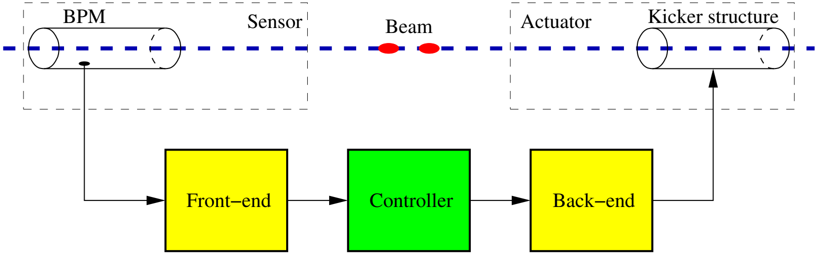


- Coordinate transformation to eigenmode basis;
- N feedback loops - one per mode;
- Identical feedback applied to each mode.

Outline

Bunch-by-bunch Feedback



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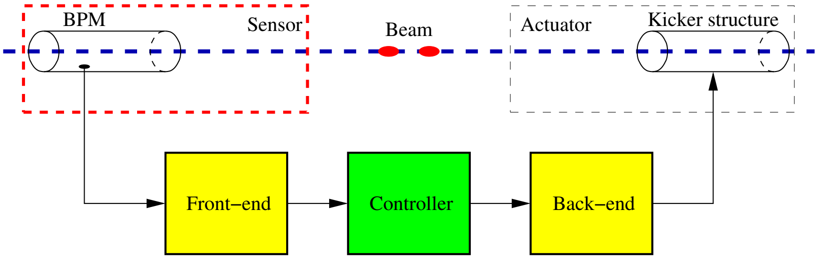
- Actuator (kicker).

Bunch-by-bunch Feedback



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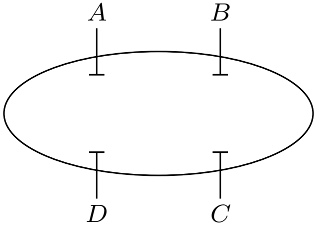
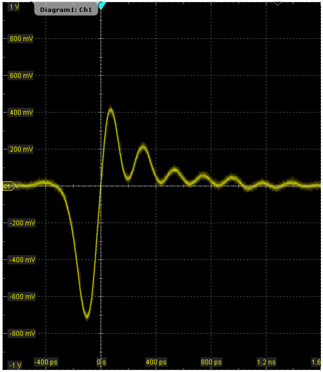
Beam Position Sensor





- To sense beam position we typically use capacitive button beam position monitors (BPMs);
- 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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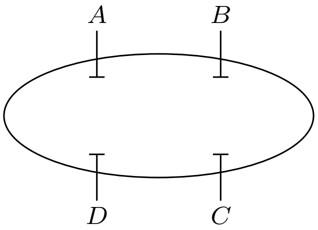

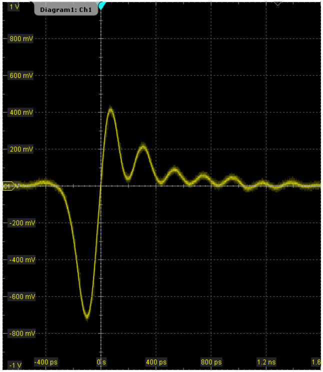

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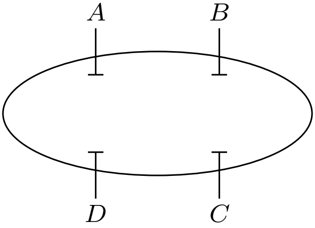

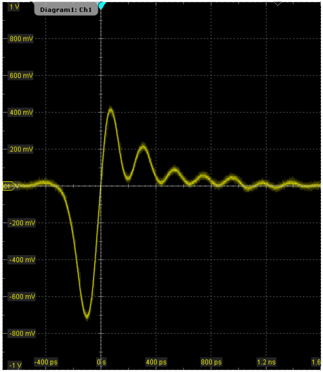

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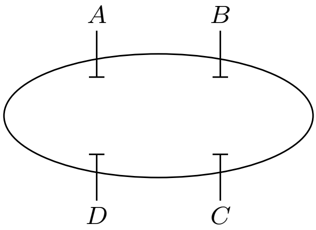

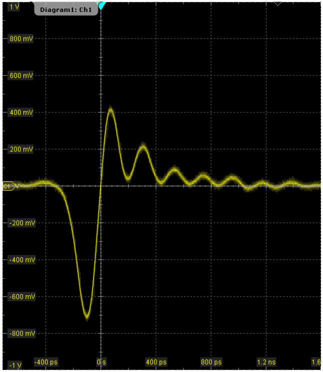

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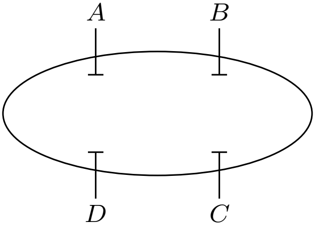

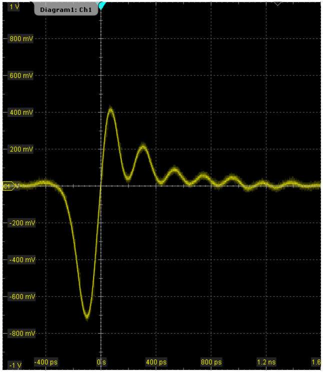

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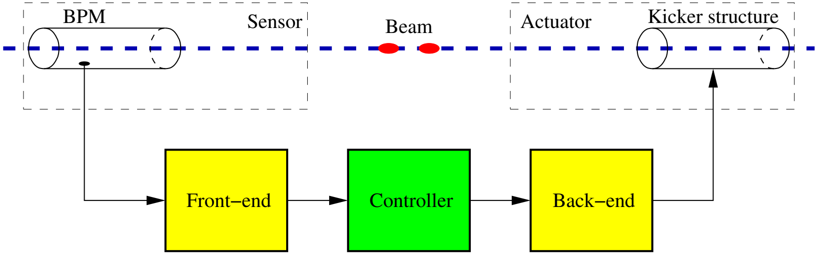
Bunch-by-bunch Feedback



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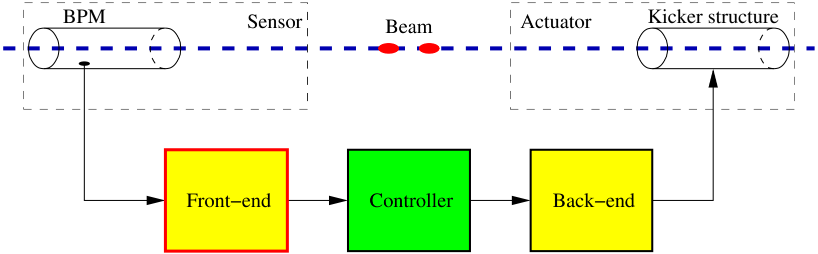

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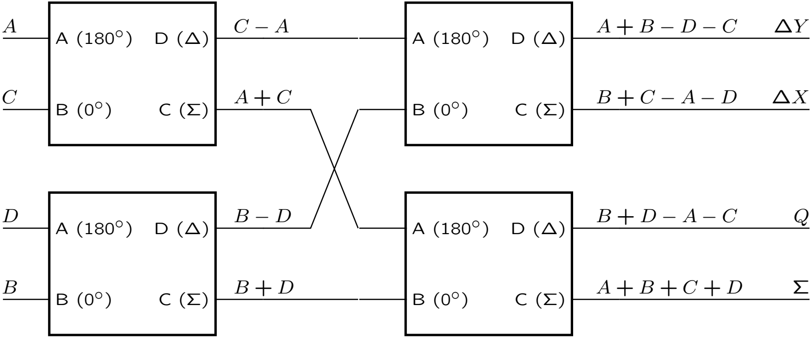
BPM Hybrid Network



- First stage of BPM signal processing — separating X/Y/Z signals (some of you might recognize 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.

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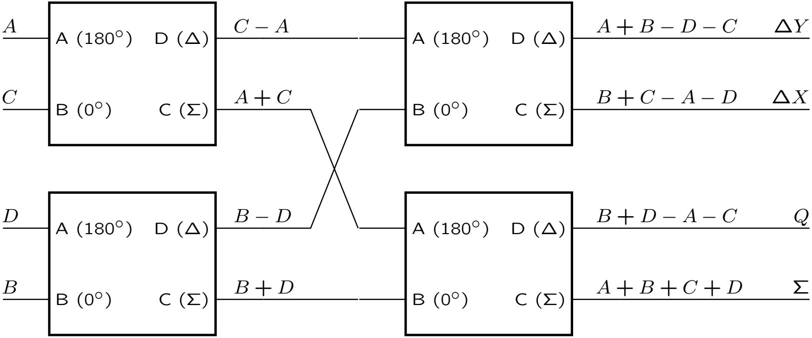

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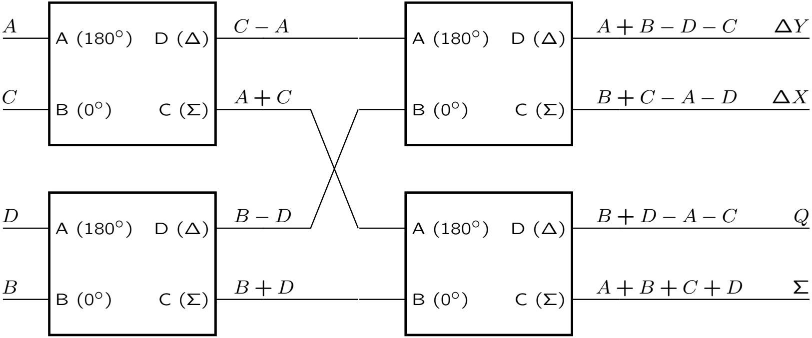

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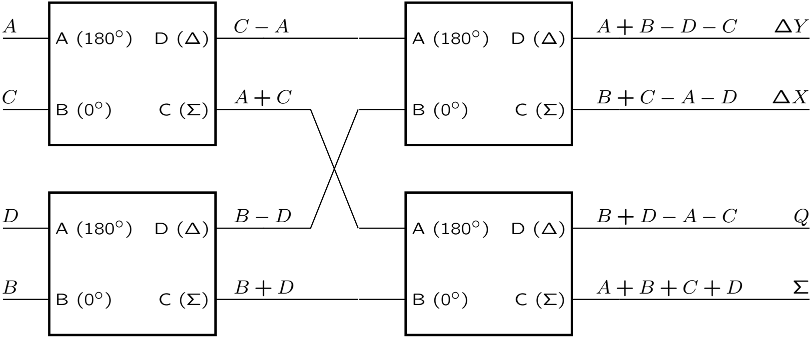

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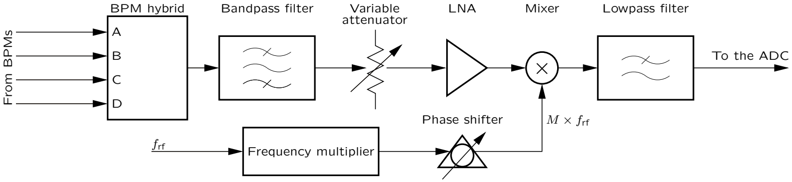
Analog Front-end Design



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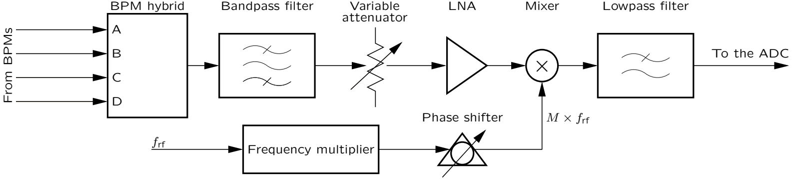

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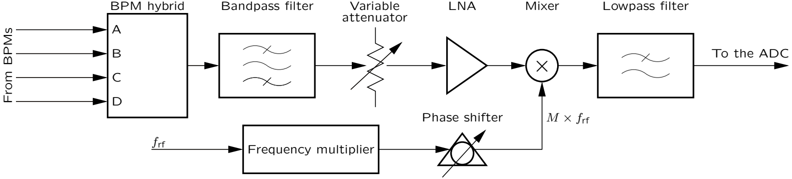

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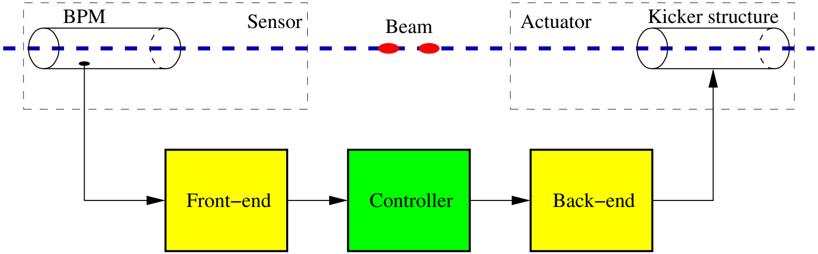

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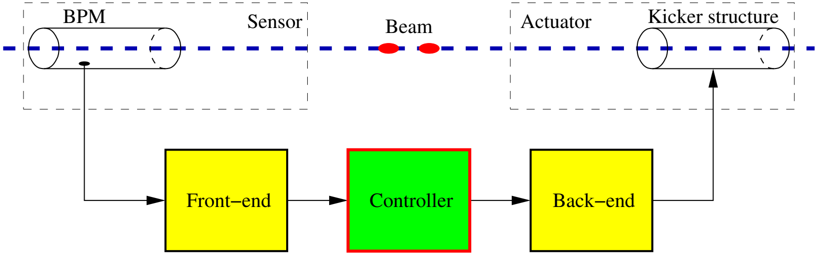

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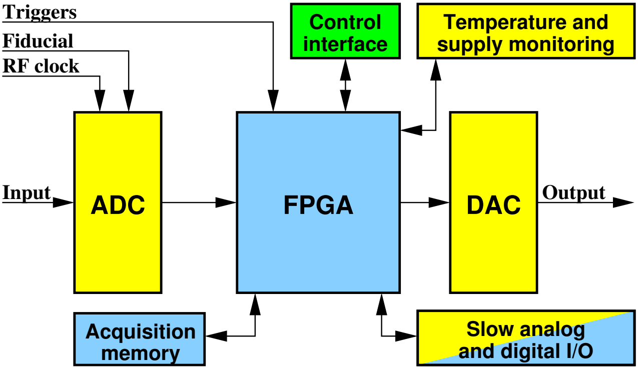

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- ADC, DAC: 12–14 bit, 500–600 MSPS, 400 ps rise/fall times;
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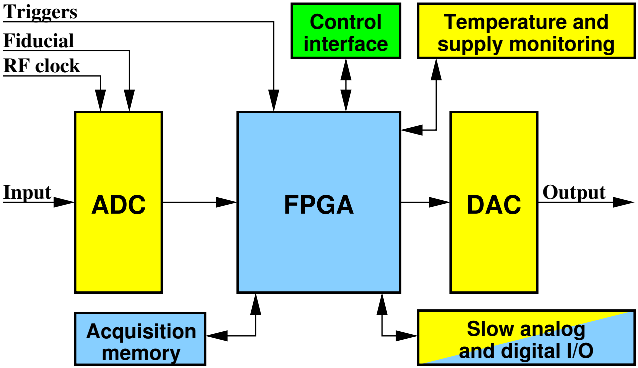

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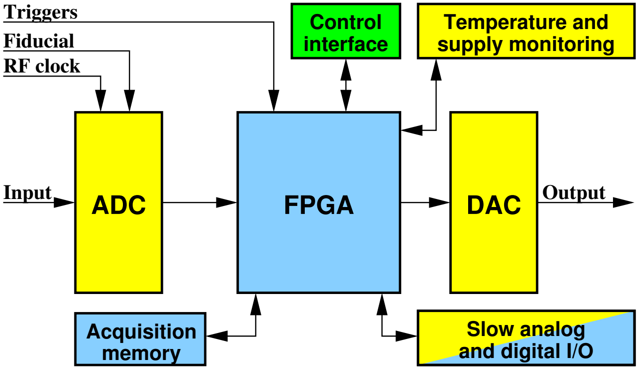

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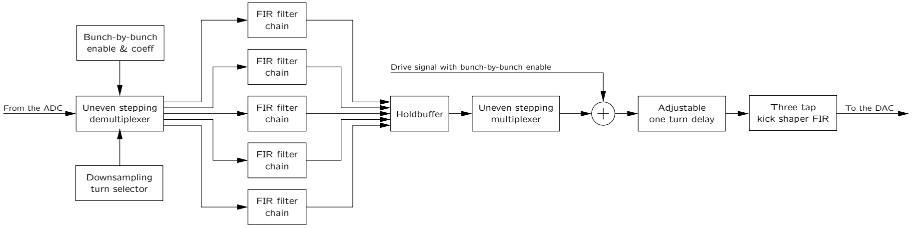

- Multiple filter chains to match FPGA processing rate to the bunch crossing rate;
- Uneven stepping scheme — use groups of n and $n+1$ bunches to make sure signal from a given bunch ends up in the same filter chain on consecutive turns;
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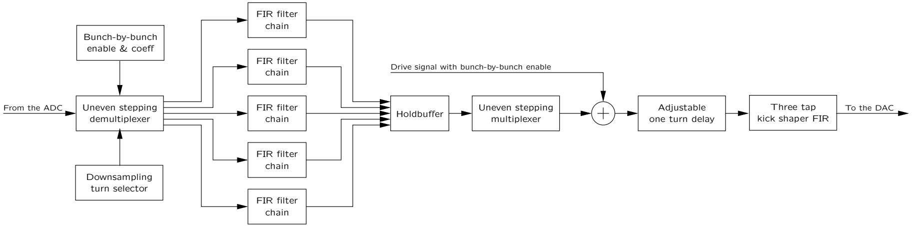

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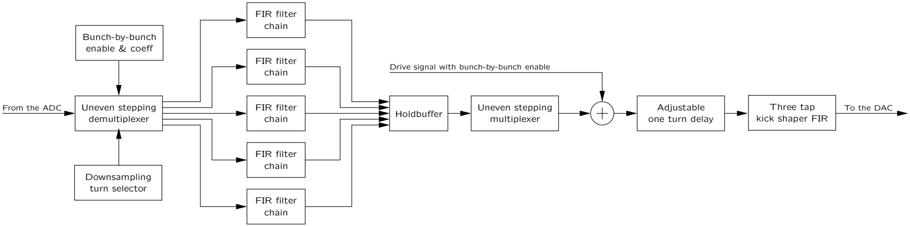

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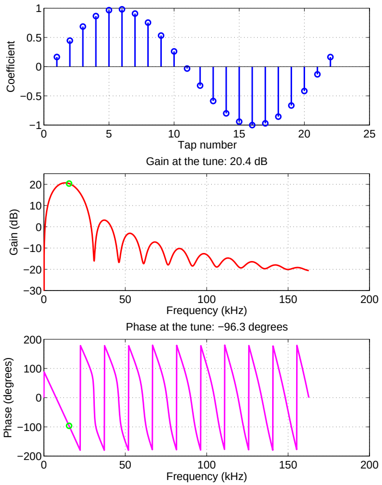
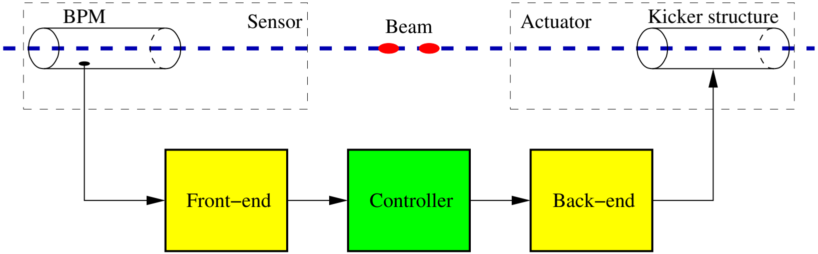
Feedback Filter



- 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.

Bunch-by-bunch Feedback



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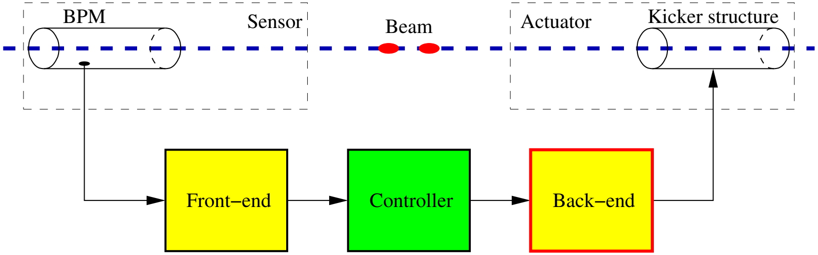

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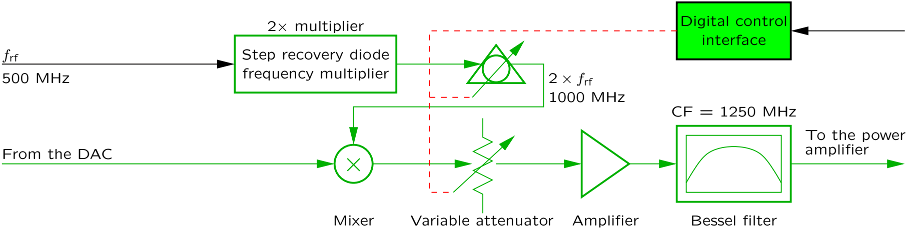

- Longitudinal kickers are usually built as highly damped (low Q, wideband) cavities at 1–1.5 GHz;
- Baseband kick must be upconverted to the right frequency to drive these;
- Phase linearity is critical to maintain the same feedback for different modes;
- Constant group-delay filters are used to create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

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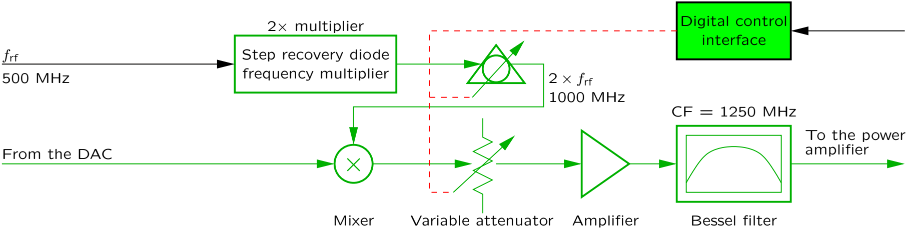

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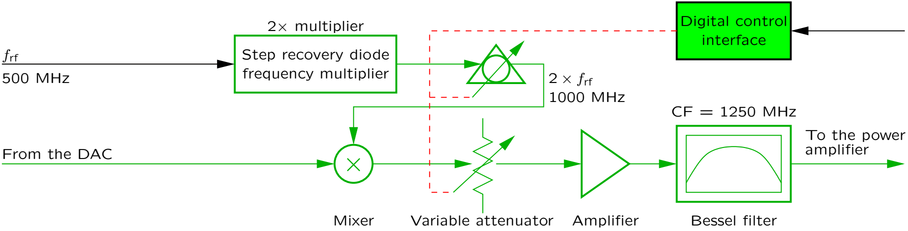

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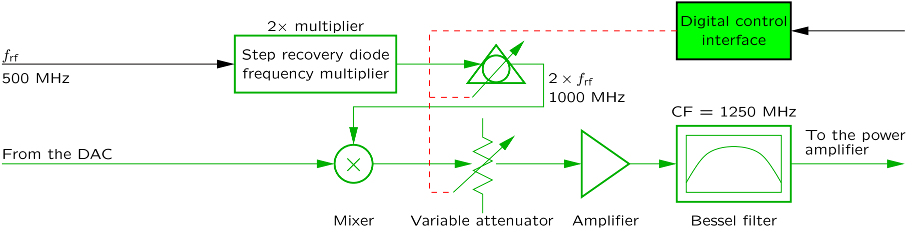

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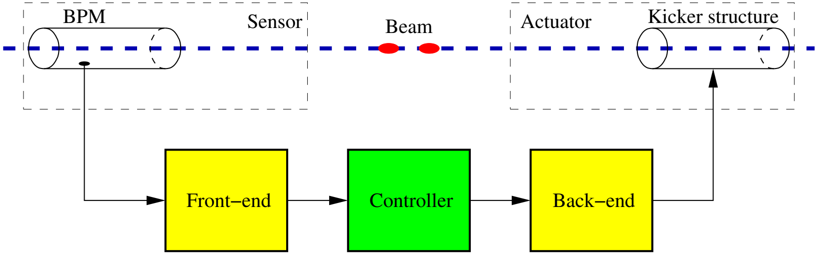

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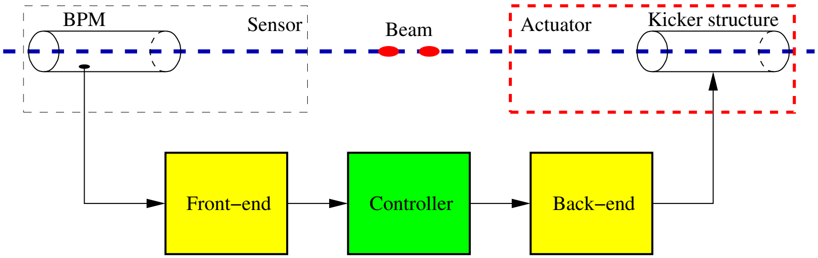

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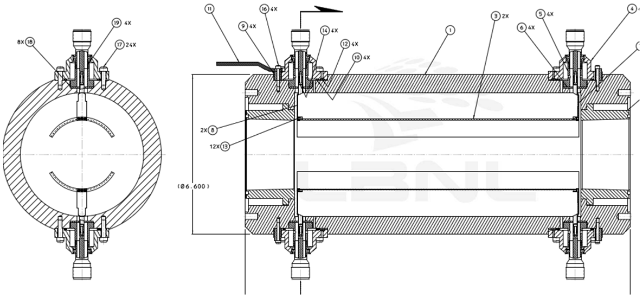

- 50 Ω striplines driven Differentially;
- Counter-propagating beam and kick signals;
- For 2 ns bunch spacing maximum stripline length is 1 ns:
  - Fill time of 1 ns;
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  - Longer striplines will couple the kick to neighboring bunches.
- Shorter striplines do better in frequency domain, have smaller kick.

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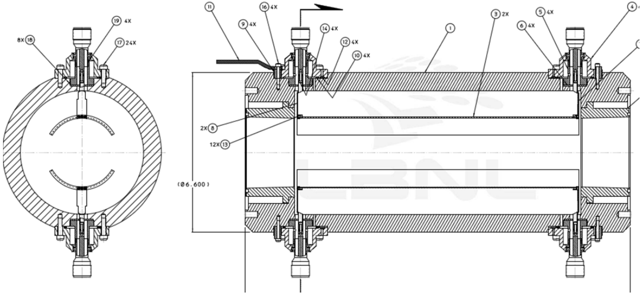

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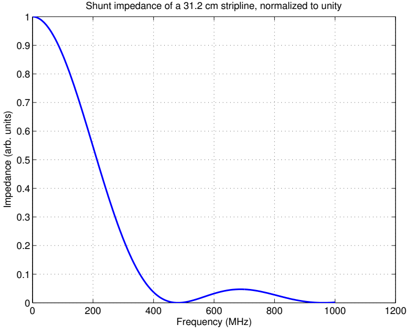

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How Does One Characterize an Unstable System?

- 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;
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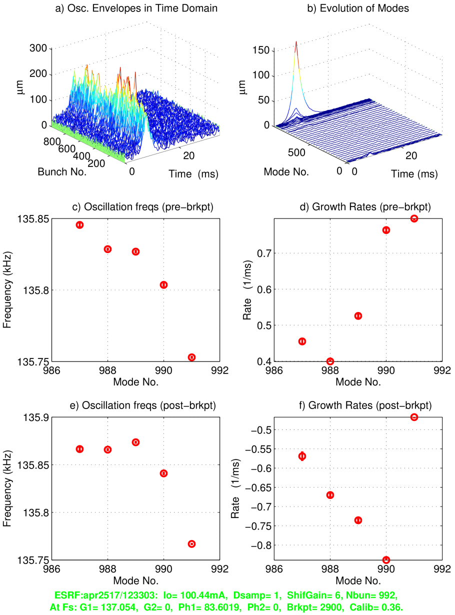

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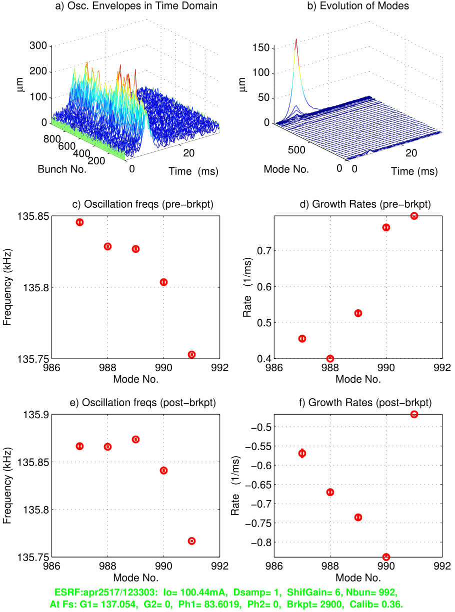

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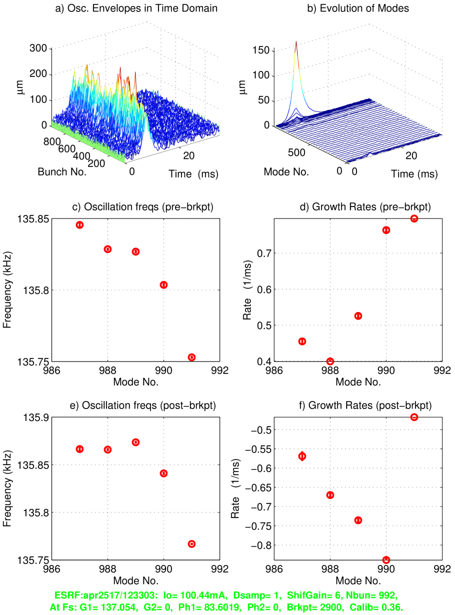

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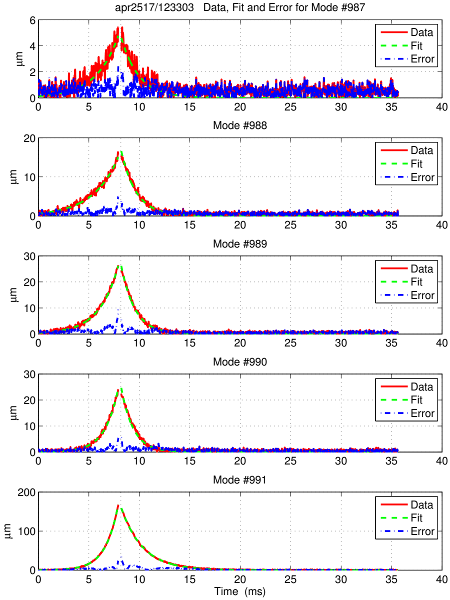

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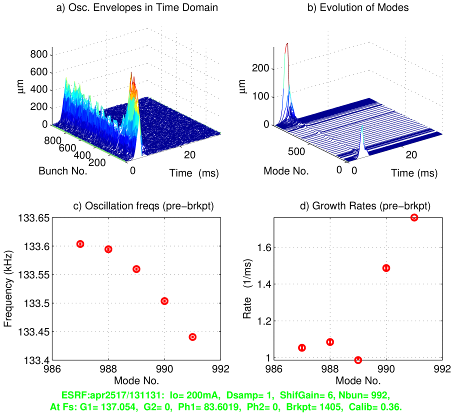

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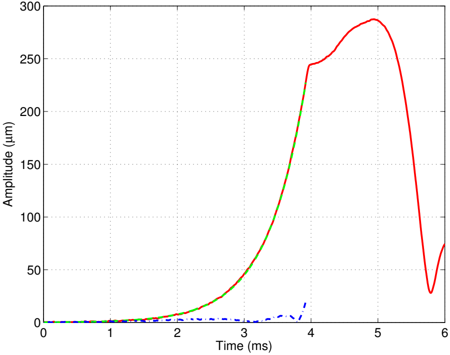

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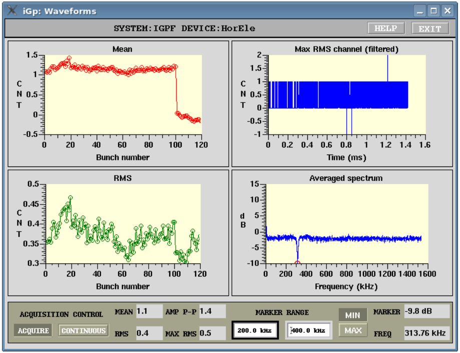
Parasitic Tune Measurement



- 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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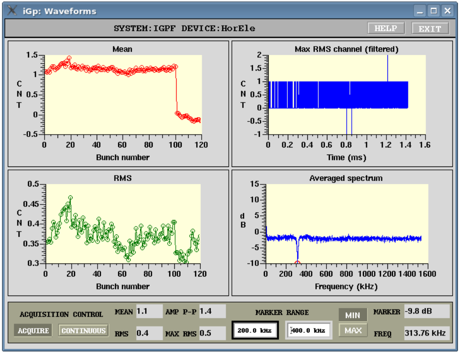

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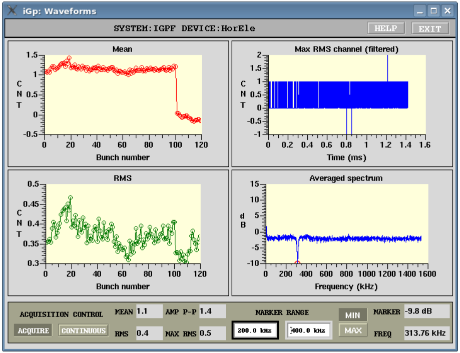

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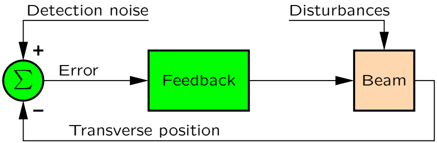

- Beam response is resonant at the tune frequency;
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- Transfer gain from noise to the feedback input is $\frac{1}{1+L(\omega)}$
- Maximum attenuation at the resonance, thus a notch.

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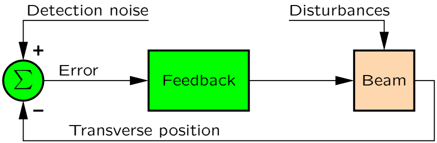

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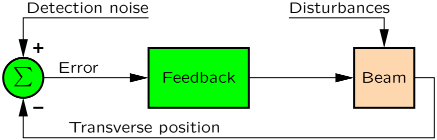

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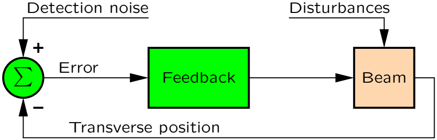

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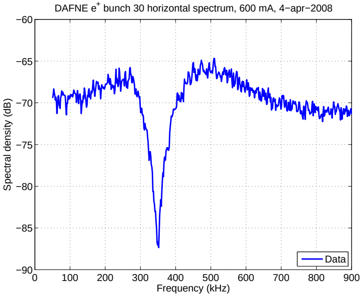
Bunch-by-bunch Tunes in DAΦNE



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- Repeat for all filled bunches;
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- Completely parasitic measurement of bunch-by-bunch tunes.

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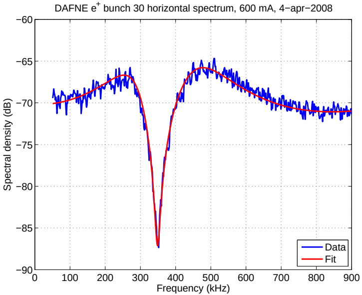

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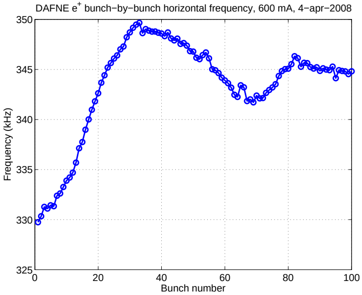

- Start from computing bunch spectrum;
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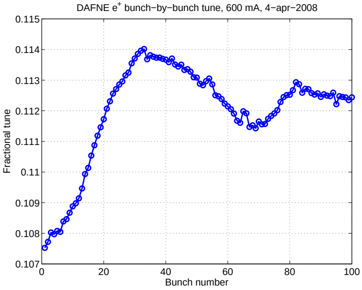

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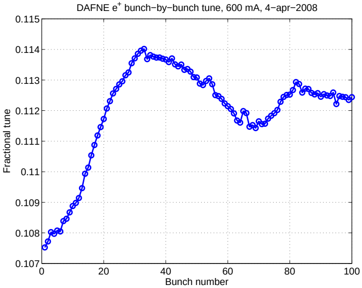

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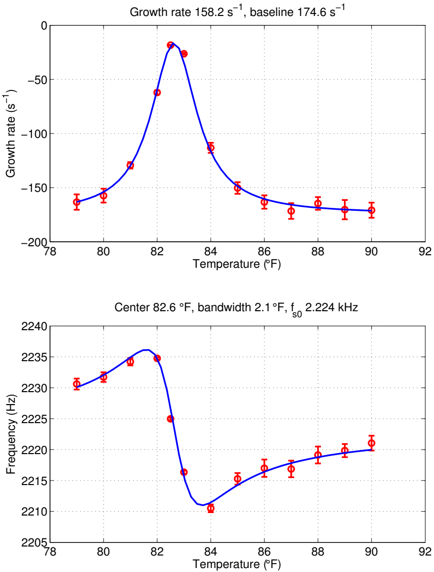
Using Beam to Measure Impedances



- 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:
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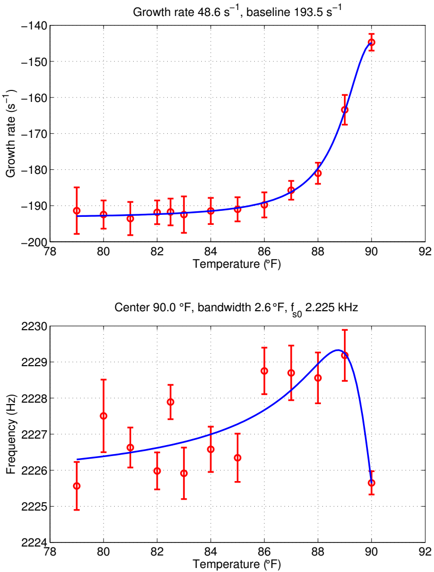

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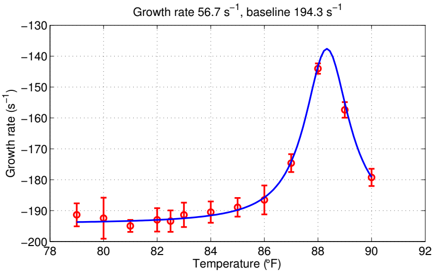

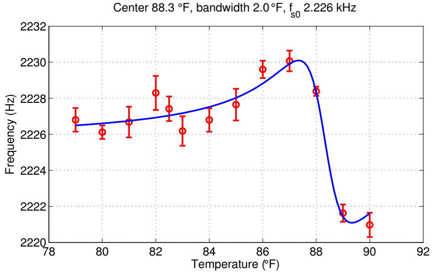

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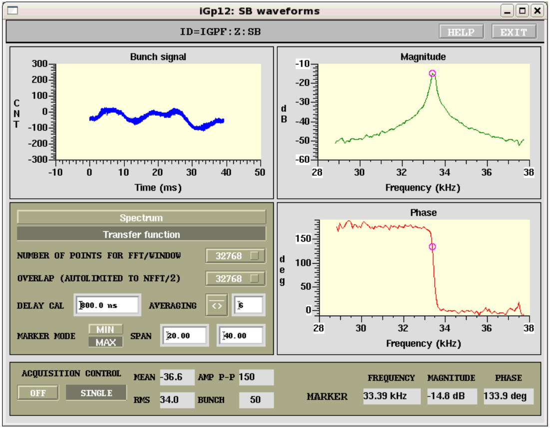
Measurement Approach



- 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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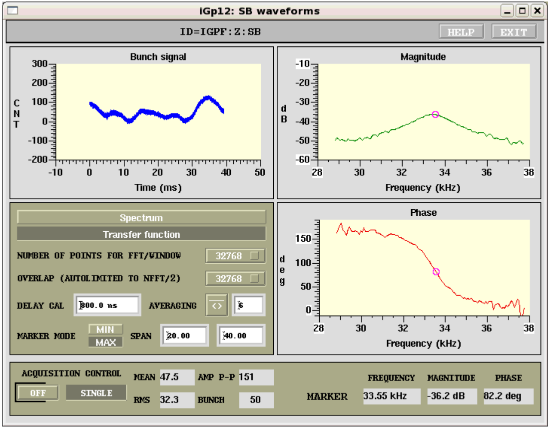

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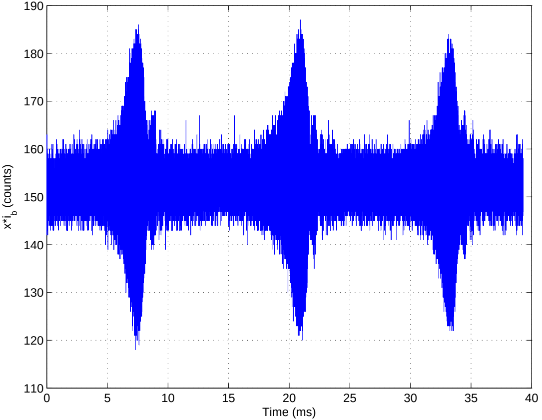
A Few Examples from Taiwan Light Source



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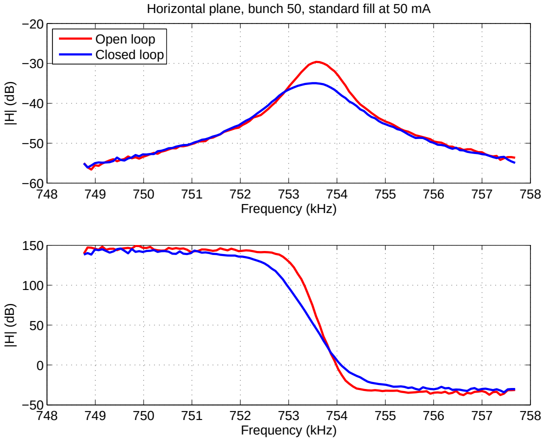

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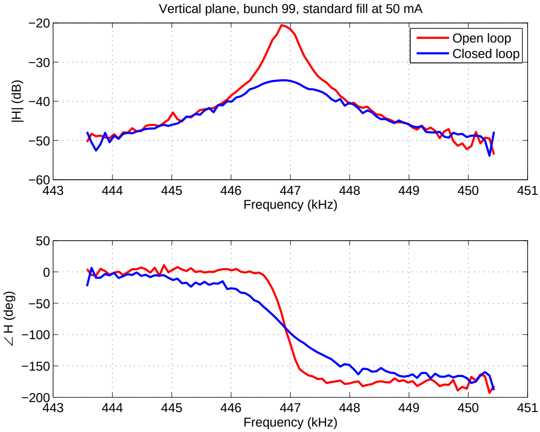

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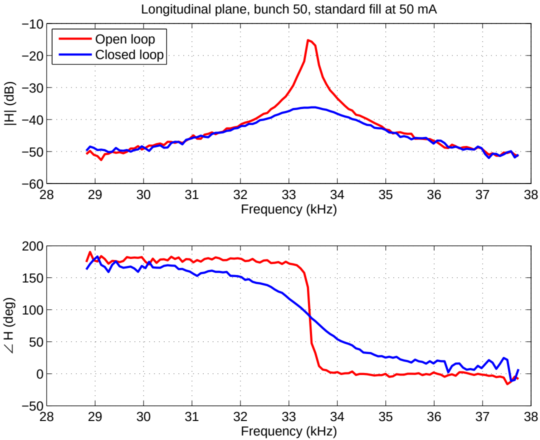

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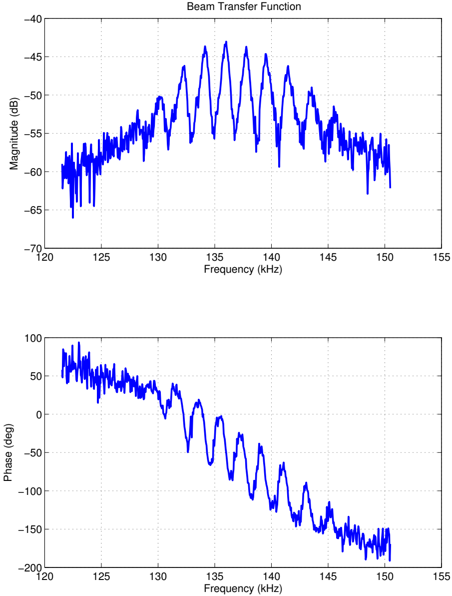
Single Bunch Transfer Function at ESRF



- Turn off feedback for bunch 40;
- Apply swept sinusoidal excitation;
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- Fit a linear combination of 3 resonances;
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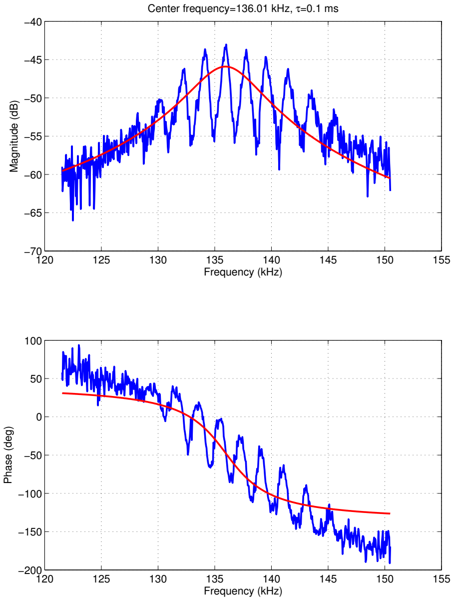

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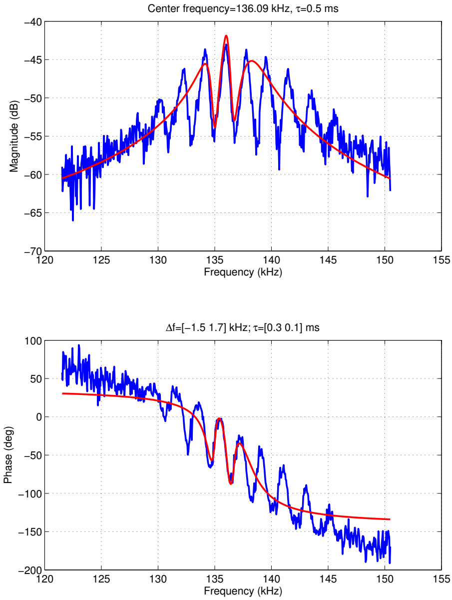

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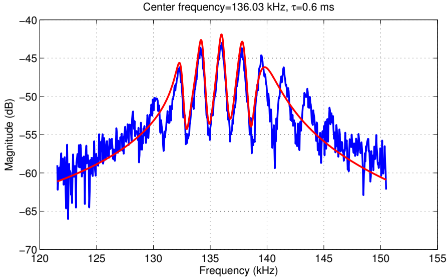

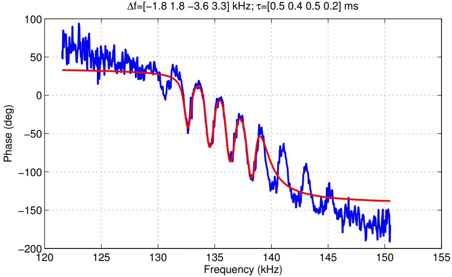

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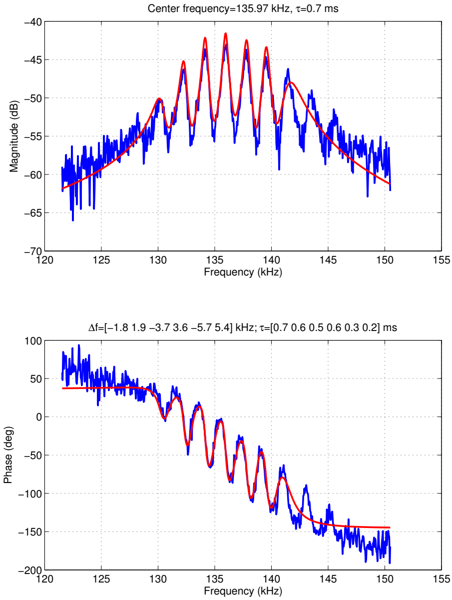

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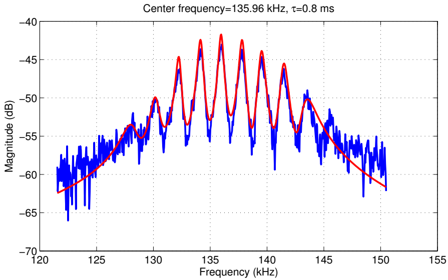

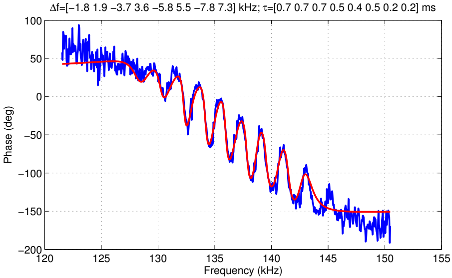

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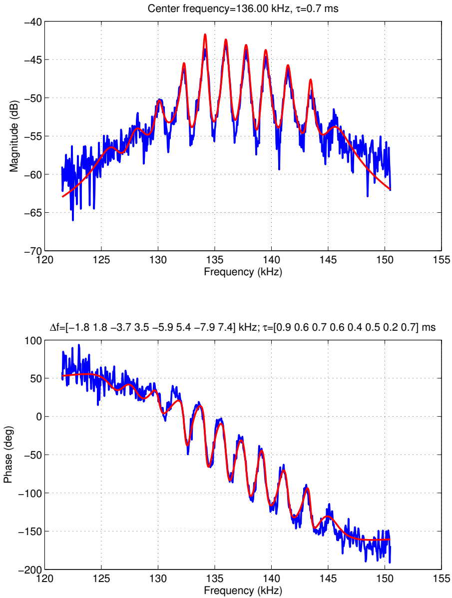

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Summary

- 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;
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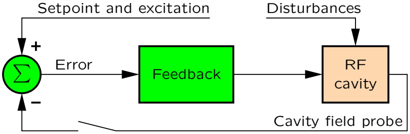
Acknowledgments

- I want to thank Santa Clara Valley Chapter of IEEE CSS for inviting me;
- Big thanks to my (former) colleagues at Stanford Linear Accelerator 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.

Open Loop Transfer Function



- Measured from setpoint to the cavity probe;
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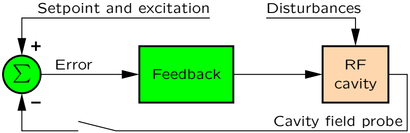

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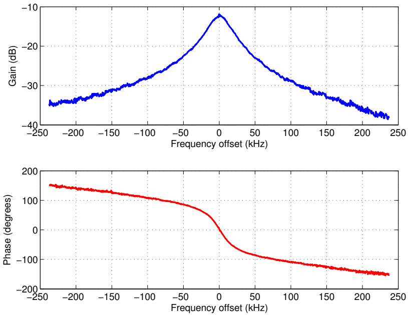

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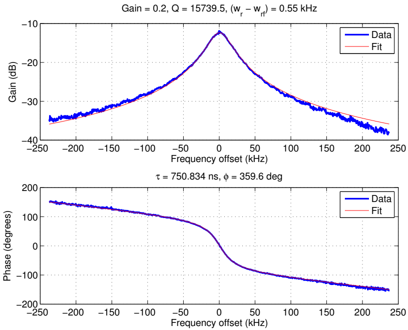

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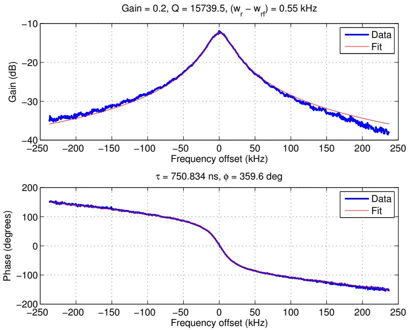

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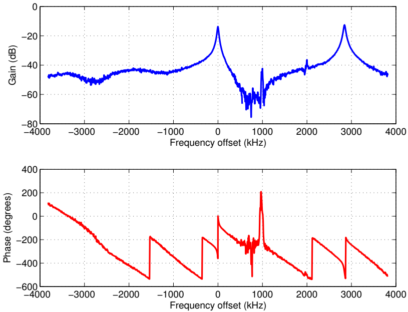
Wideband Open Loop Transfer Function



- Wider sweep reveals a parasitic mode at 2.8 MHz above the π mode;
- Negative feedback for the π mode is positive for the parasitic mode;
- This positive feedback limits direct loop gain;
- The simplest way around the issue is to use digital delay to equalize the modal phase shifts (230 ns).

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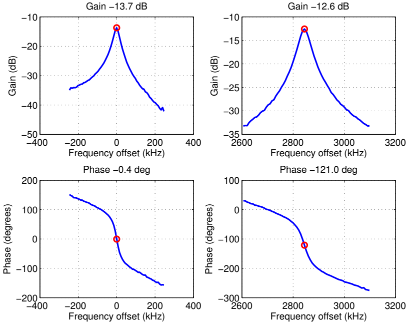

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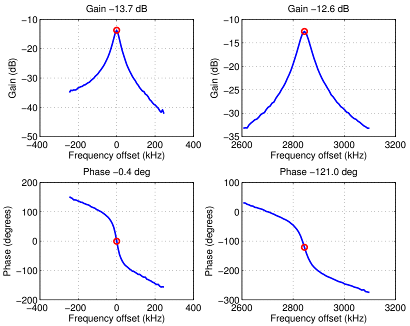

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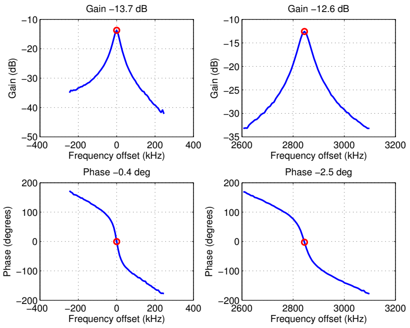

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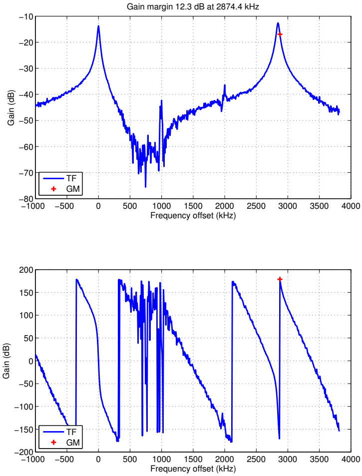
Proportional Loop Gain and Delay



- Set up minimum delay and equalized transfer functions for identical 3 dB closed-loop peaking.
  - Minimum delay: peak gain at RF is -9.2 dB, gain margin 12.3 dB
  - Equalized: peak gain at RF is $+8$ dB, gain margin 11.8 dB, phase margin 88 degrees
- More sophisticated parasitic mode suppression methods can improve the performance only slightly, around 2-3 dB.

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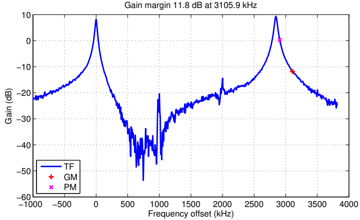

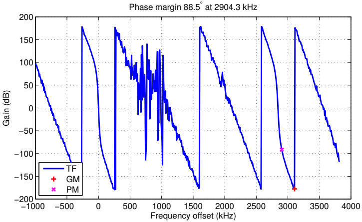

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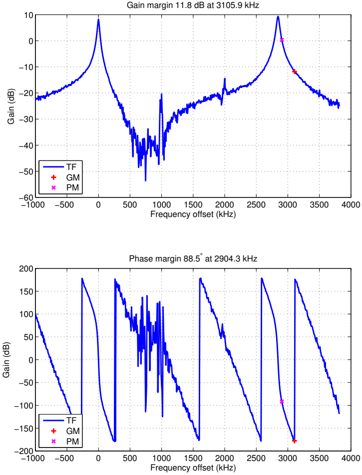

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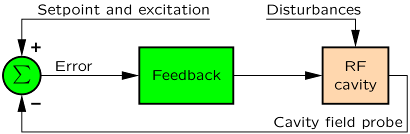

- Measured from setpoint to the error signal;
- Quantifies closed-loop disturbance rejection vs. frequency offset from f_{RF};
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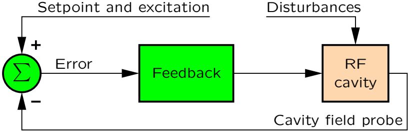

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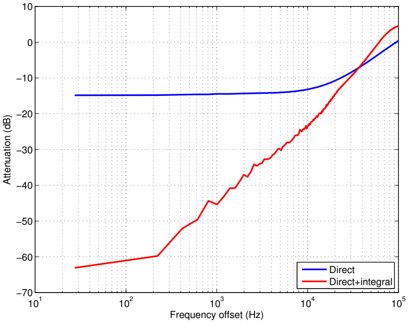

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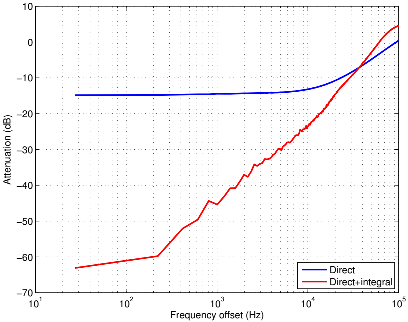

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