Overview of System Specifications for Bunch-by-Bunch Feedback Systems

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March 30, 2011

Outline

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Coupled-bunch Instabilities

- I will limit the discussion to lepton machines, but most material is applicable to hadron storage rings as well.
- Consider a single bunch in a lepton storage ring.
- Centroid motion has damped harmonic oscillator dynamics.
- Multiple bunches couple via wakefields (impedances in the frequency domain).
- At high beam currents this coupling leads to instabilities.
- In modern accelerators active feedback is used to suppress such instabilities.

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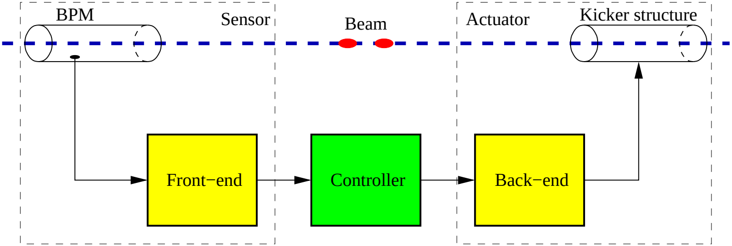
Bunch-by-bunch Feedback

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.

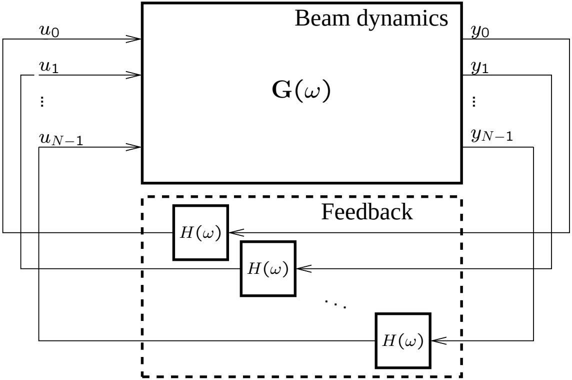
Outline

1. Bunch-by-bunch Feedback: Concepts and Models
   - Coupled-bunch instabilities and feedback
   - Beam and feedback models
2. Performance Limitations
   - Gain Window Concept
   - Bunch-to-bunch Coupling
3. Component Sizing
   - Feedback Gain and Maximum Kick
   - Estimating Necessary Kick Amplitudes
4. Summary

Coupled-bunch Instabilities: Eigenmodes and Eigenvalues

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

MIMO Model of Bunch-by-bunch Feedback



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

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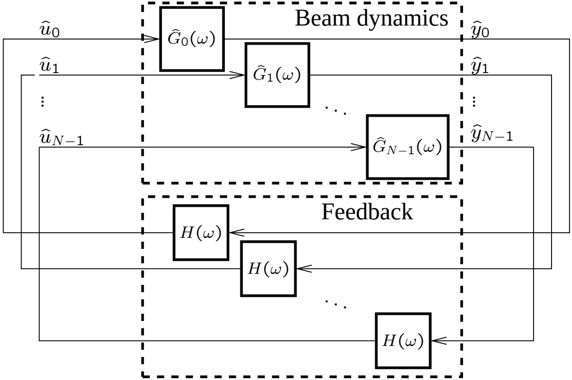
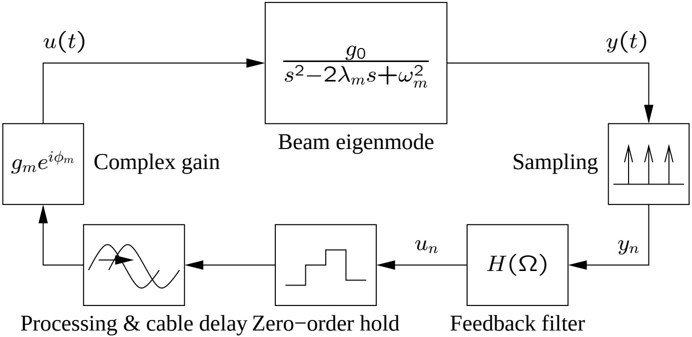


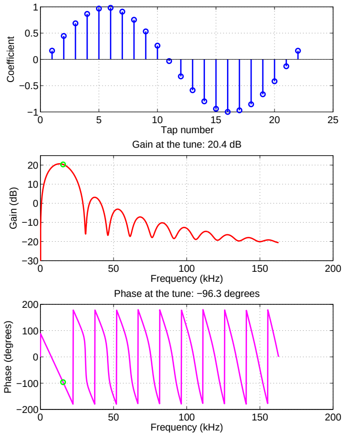
- Coordinate transformation to eigenmode basis;
- *N* feedback loops - one per mode;
- Identical feedback applied to each mode.

Detailed Scalar Feedback Model



- Eigenmode m with eigenvalue $\lambda_m + i\omega_m$;
- Per mode effective gain and phase errors: g_m and ϕ_m.

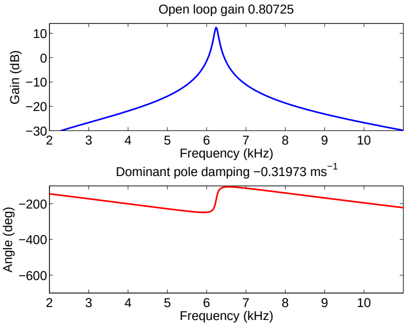
Feedback Filter



- Requirements:
  - 90° phase shift at the tune frequency;
  - DC rejection — gets rid of constant orbit;
  - Bandpass response;
- Filter design — sample one period of a sine wave;
- Group delay is $\frac{1}{2}$ of oscillation period;
- Achievable damping roughly linear with the tune up to 0.25.

Outline

Closed Loop Response Versus Gain



- Start from a low gain - the system is unstable.
- Raising the gain stabilizes the beam.
- Further increase improves the damping.
- There is a point of maximum damping.
- Increasing gain further produces less damping.

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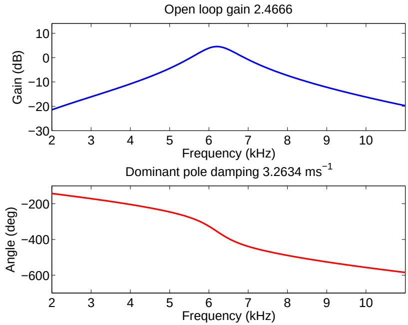

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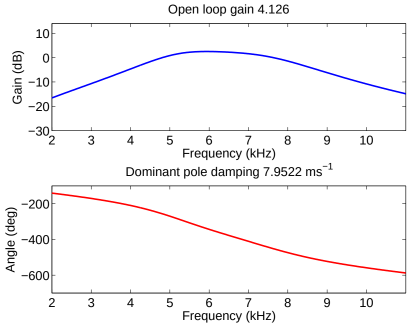

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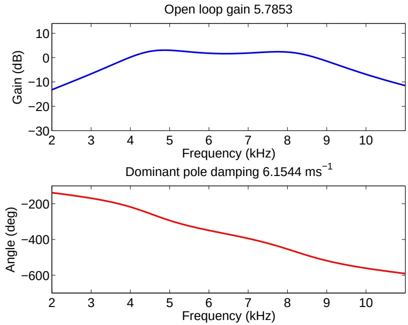

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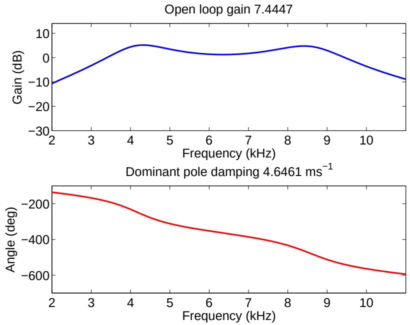

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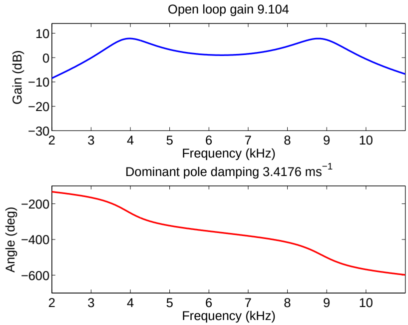

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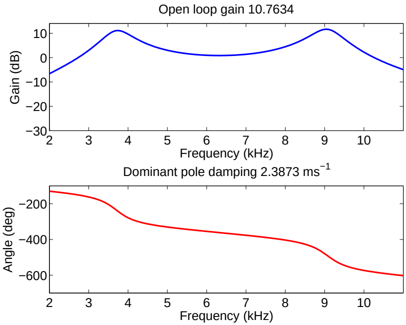

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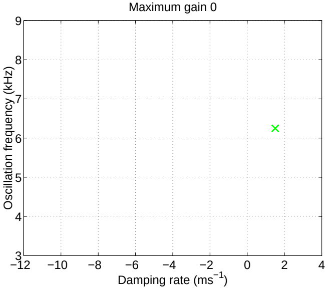

- Plot the eigenvalues on the complex plane versus loop gain.
- Real part - growth or damping rate.
- Imaginary part - oscillation frequency.
- Above certain gain the locus turns around.
- System poles approaching the imaginary axis generate the gain peaks in the frequency response.

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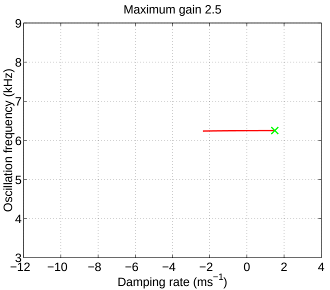

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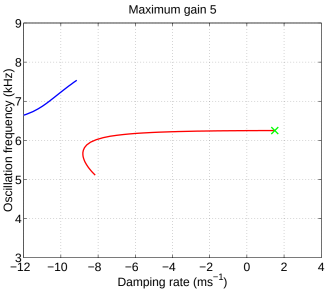

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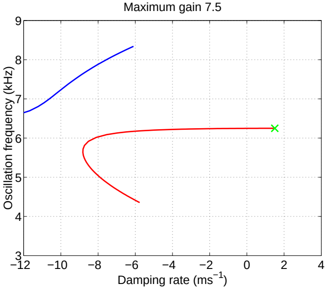

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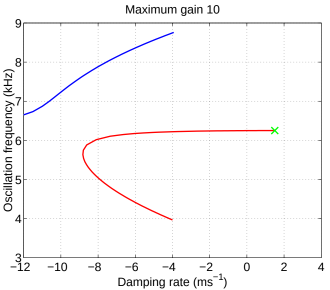

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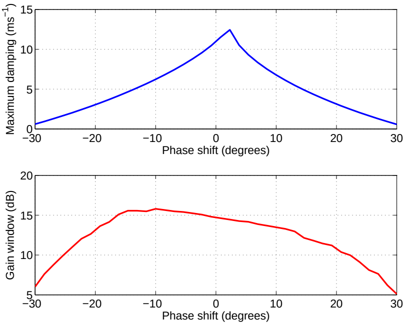
Gain Window: Definition

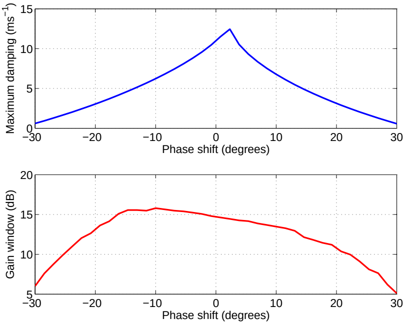
Definition

Gain window is the difference between maximum and minimum gains in decibels.



- Minimum gain $\propto$ to the fastest growth rate;
- Maximum gain decreases with feedback group delay;
- Imperfections — gain and phase errors — shrink the gain window from the ideal maximum value.

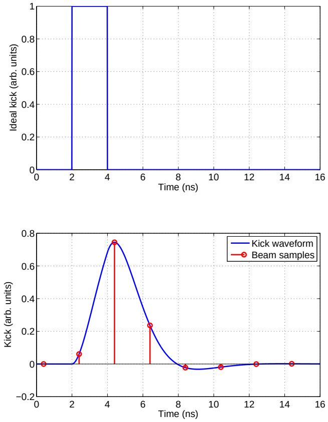
Gain Window: Usage



- Consider an error term of 50% at a given eigenmode;
- Can produce 6 dB of gain error or 26 degrees of phase error;
- Gain errors may or may not affect the gain window;
- Phase error always reduces the gain window;
- Typically, phase errors are more harmful than gain errors.

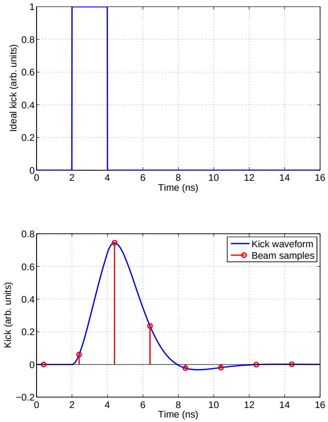
Outline

Sampling in the Feedback Loop



- Beam with a digital bunch-by-bunch feedback is a doubly sampled system.
  - Beam-derived front end signal is sampled by the feedback ADC;
  - Beam passing through the kicker samples the kick waveform.
- Not a time invariant system!
- Relative timing of the analog signals and the samplers changes the response.

Effective Coupling Filter



- Feedback kick and power amplifier output;
- Beam samples of the kick waveform create an effective FIR filter at RF frequency (500 MHz);
- Frequency response;
- Timing shift of 280 ps;
- Causes distortion filter to change.
- Trade off 1 dB of gain at 250 MHz for phase error reduction from 16 to 4 degrees.

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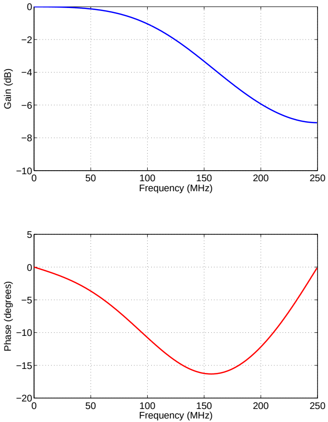

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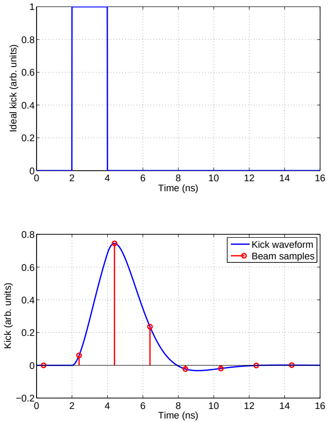

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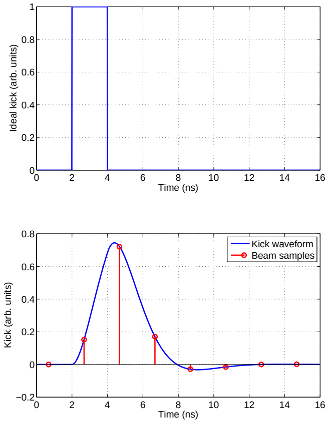

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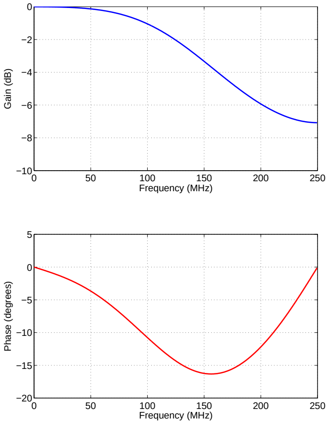

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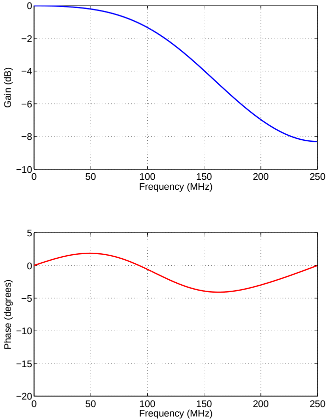

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Feedback Gain and Kick Amplitude

- Relationship of the feedback gain and maximum kick amplitude is often misunderstood;
- Feedback gain: the ratio of the feedback output kick amplitude to the amplitude of beam oscillation at the tune frequency;
- Maximum kick amplitude: largest kick voltage or angle that the power amplifier and kicker combination can deliver;
- There is no rigid relationship between the two;
- Feedback gain requirement is driven by instability growth rates;
- Maximum kick amplitude is related to the system perturbations due to injection, RF, etc.

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Gain Partitioning

- Feedback gain is partitioned into three sections:
  - Front end — limited by having to fit orbit offsets within the ADC range;
  - Back end — fixed by the amplifier power and kicker shunt impedance. Set up the back end to saturate at the full-scale of the DAC;
  - Digital processor — limited by front end and quantization noise;
- If the set up high gain in the digital section, small beam oscillation will cause saturation. Effective gain drops in saturation;
- Gain dropping below some minimum value produces instability.

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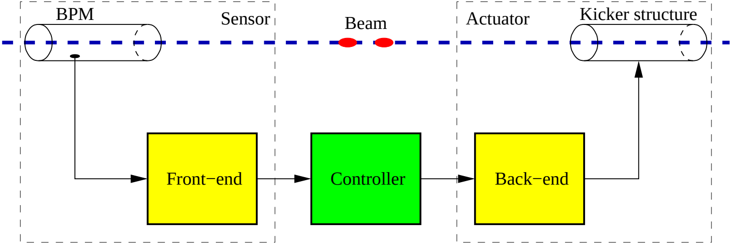
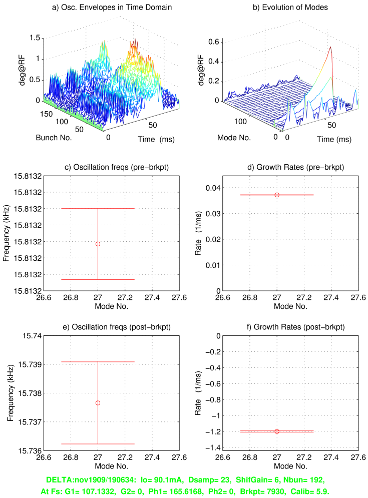
Sizing Up the Feedback



- The goal: adding feedback to an existing ring;
- Measure instability parameters in an improvised setup;
  - Typically low kicker shunt impedance;
  - Low amplifier power.
- Measure the growth rates to determine the necessary gain;
- Measure the steady-state noise and perturbations to determine the required kick;
- Match an off-line model to the measurements, extrapolate.

DELTA: Grow/Damp



- Grow/damp measurement with an improvised longitudinal kicker;
- Used a stripline as a weak longitudinal kicker;
- Clean growth and damping rate measurement.

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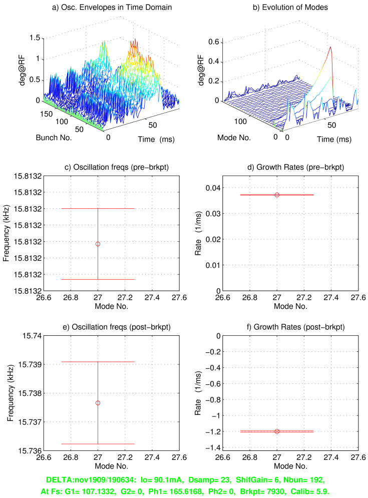

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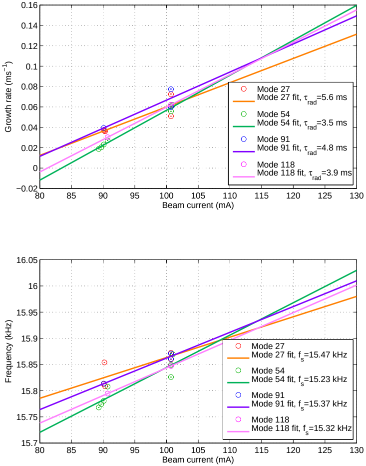
Growth Rates vs. Beam Current



- Measure the growth rates over a range of beam currents (DELTA);
- Get the slope (proportional to the impedance);
- Can extrapolate to higher currents;
- Many measurements over as wide a current range as possible is key (ELSA).

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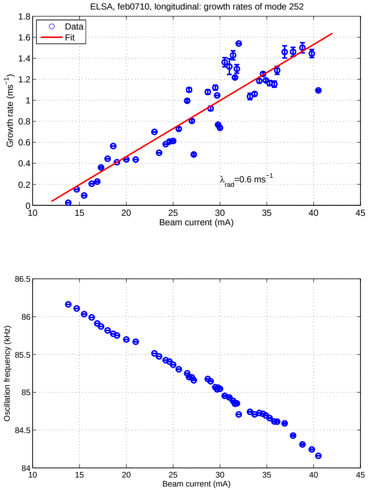

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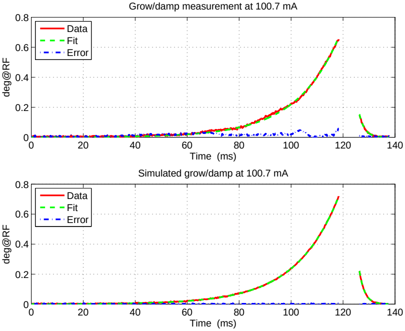

- Using measured growth and damping rates verify beam/feedback model;
- DELTA: Measured and simulated transients at 100 mA;
- ELSA: A simulated transient at 26.7 mA.

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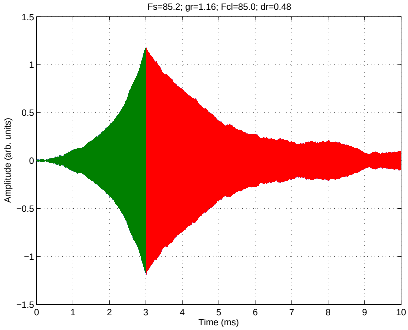

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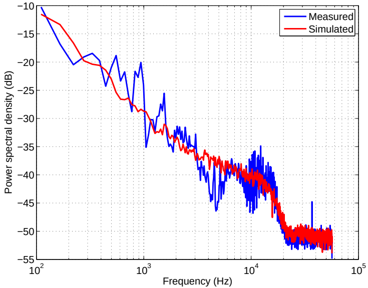
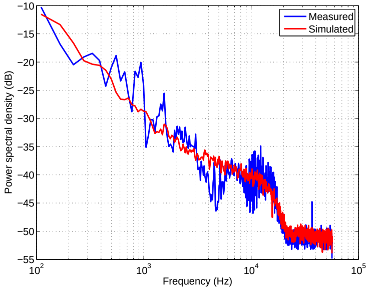


- Closed-loop measurement to quantify the steady-state noise;
- Match the noise spectrum in the model;
- Given an acceptable average saturation level we can compute the necessary kick voltage;
- Translate that into amplifier power and kicker shunt impedance.

Match the Noise Sources



- Closed-loop measurement to quantify the steady-state noise;
- Match the noise spectrum in the model;
- Given an acceptable average saturation level we can compute the necessary kick voltage;
- Translate that into amplifier power and kicker shunt impedance.

Summary

- Bunch-by-bunch feedback is an important tool in the accelerator physicist's toolbox.
- Understanding the relationship between time and frequency domains is critical for successfully designing and configuring bunch-by-bunch feedback.
- Combination of experimental measurements and modeling helps optimize critical system elements — power amplifiers and kickers.

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