Use of Bunch-by-bunch Feedback Systems for Advanced Beam Control and Diagnostics

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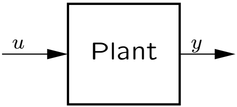
Outline

Closed-loop Feedback: Structure and Example



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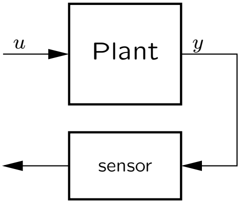

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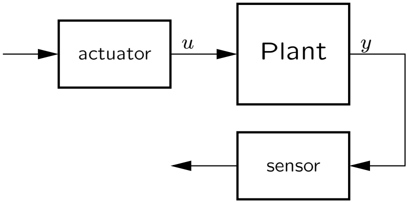

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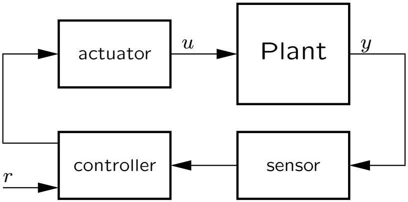

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- Feedback loop is completed by a controller.

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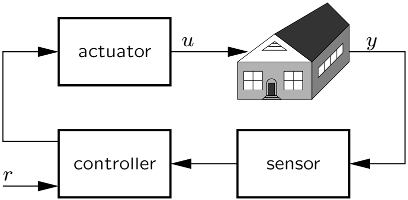

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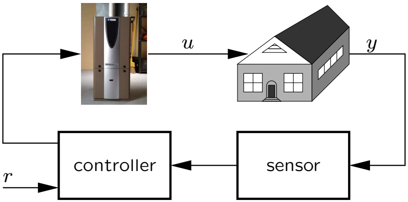

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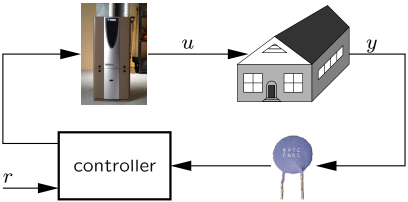

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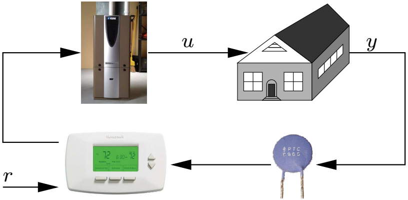

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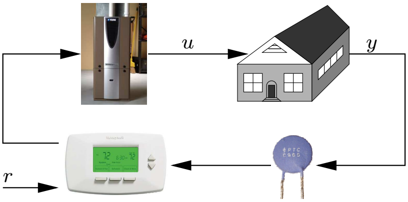
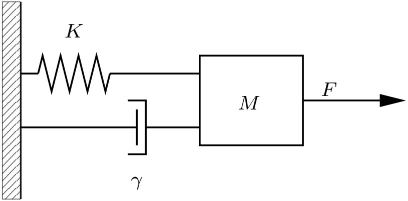


- Take a household heating system as an example.
  - Our plant is the house.
  - Actuator - furnace.
  - Sensor - thermistor.
  - Controller - thermostat.
- Loop signals
  - Output y - temperature;
  - Input u - heated air from the furnace;
  - Reference r - temperature setpoint.

Dynamic System Descriptions and Models



- Mechanical system: mass on a spring with a damper.
- Described by $M\ddot{x} + \gamma\dot{x} + Kx = F$.
- Differential equation is a time-domain description.
- Frequency domain - Laplace transform.
- Frequency response evaluated at $s = i\omega$.

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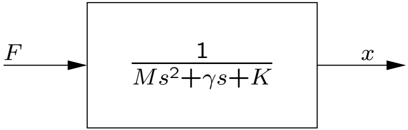

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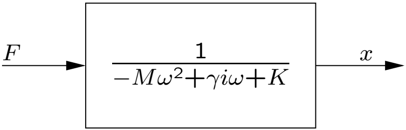

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Coupled-bunch Instabilities

- 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.
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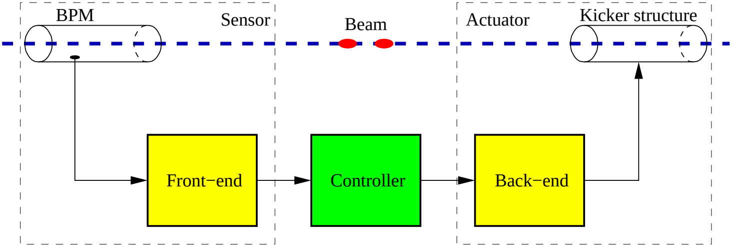
Bunch-by-bunch Feedback

Definition

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

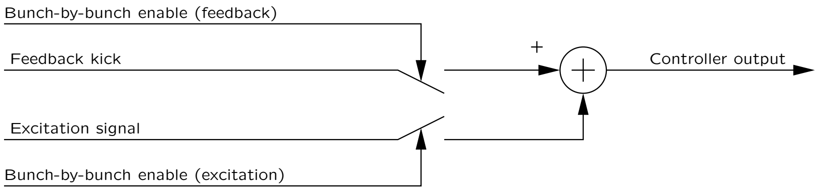


- Bunches are processed sequentially.
- Correction kicks are applied one or more turns later.

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.
- wakefields (impedances) shift the modal eigenvalues in both real part (damping rate) and imaginary part (oscillation frequency).

System Flexibility



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- Bunch-by-bunch masking;
- Opens up a wealth of control and diagnostic techniques that are difficult, if not impossible, with other means.

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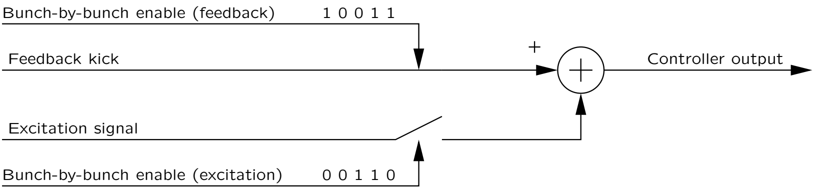

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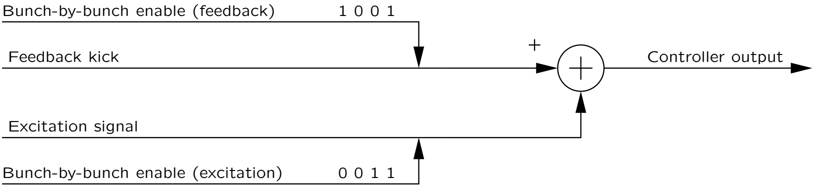

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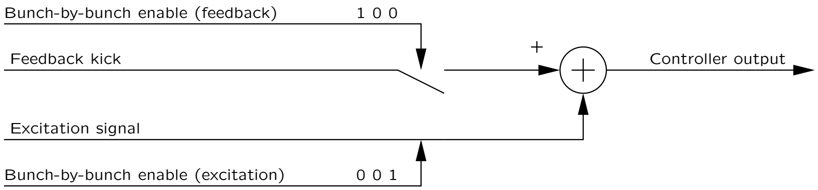

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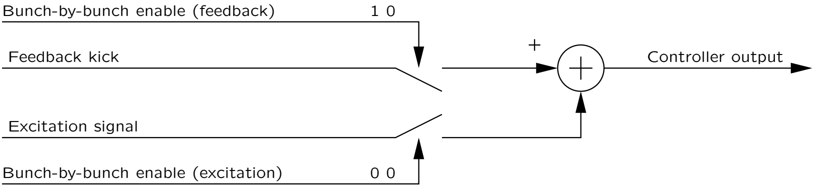

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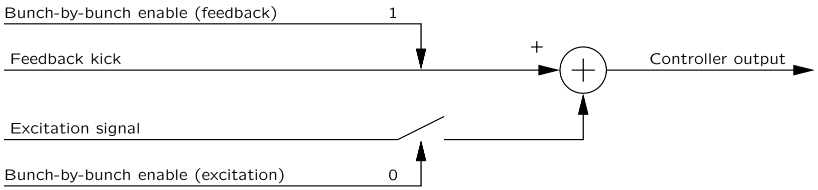

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Definition and Applications

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Bunch cleaning capability in a lepton storage ring is a way to remove all charge from an arbitrary subset of RF buckets, without disturbing bunches excluded from such a subset.

Many applications:

- Cleaning up injection errors;
- Controlling diffusion from filled to empty buckets;
- Creating single-bunch fill patterns in storage rings without single-bunch injection capability;
- Creating arbitrary fill patterns for studying detector responses, etc.

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General Approach

- Keep negative feedback on the bunches to retain;
- Turn off the feedback on the bunches to clean;
- Apply to these bunches a swept sinewave excitation centered on the tune frequency;
- When excitation sweeps across the betatron resonance, bunches are driven to large transverse amplitudes and scraped off;
- Excitation frequency sweep must cover the full range of tune variations with beam current and amplitude.

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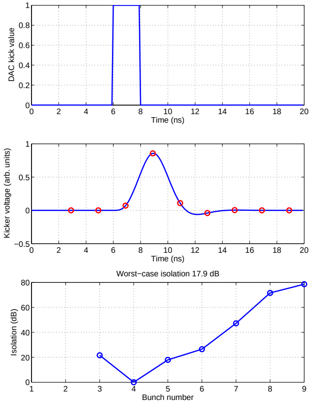

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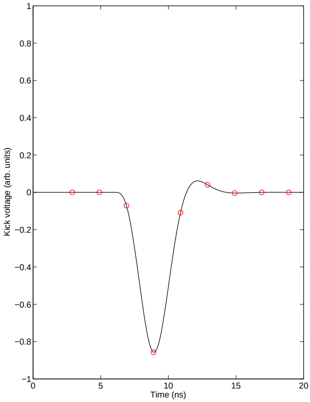

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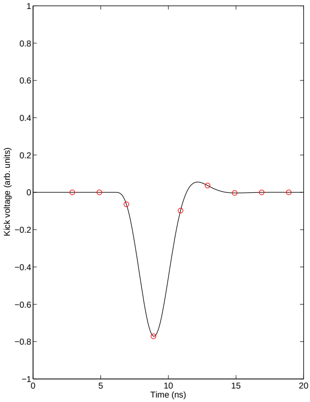

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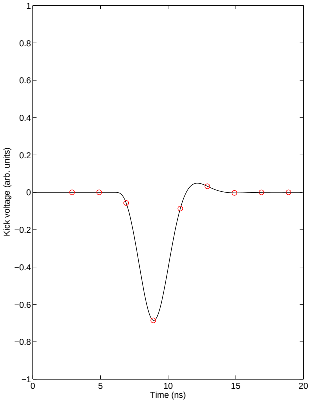

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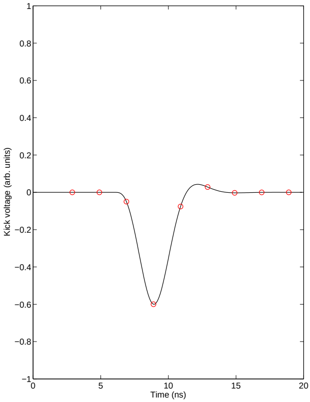

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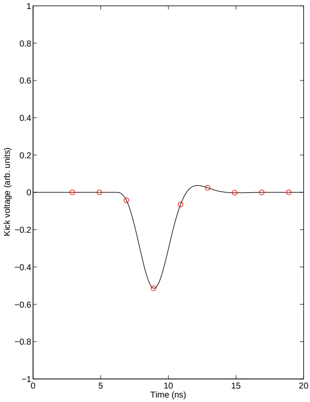

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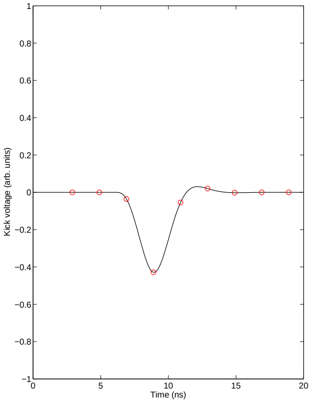

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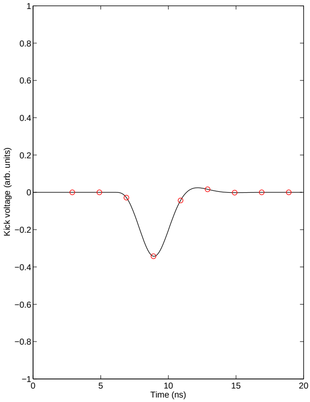

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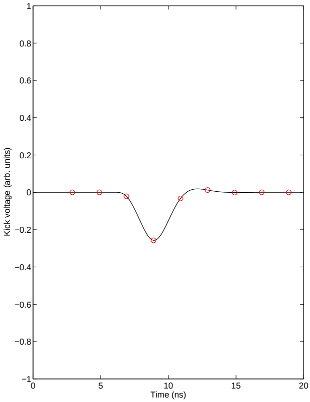

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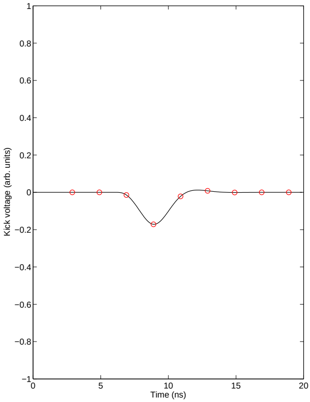

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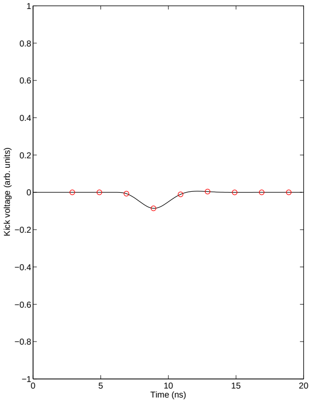

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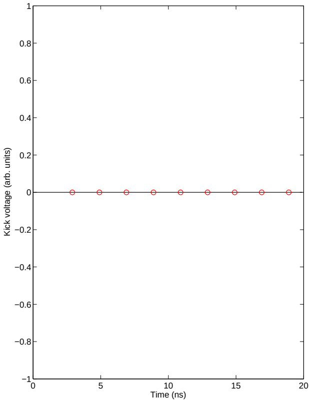

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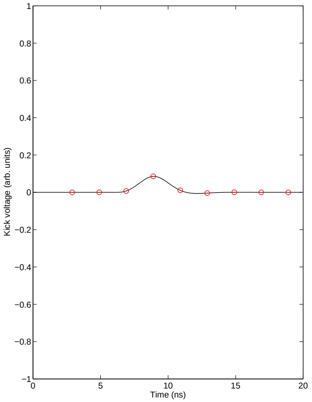

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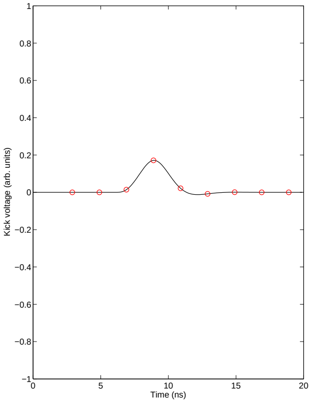

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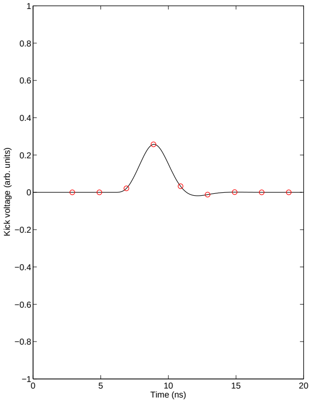

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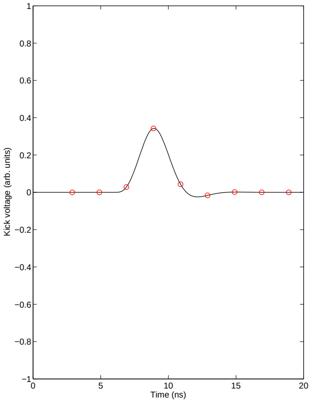

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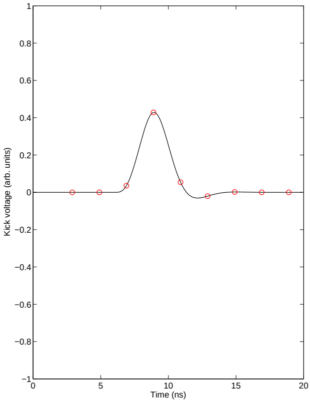

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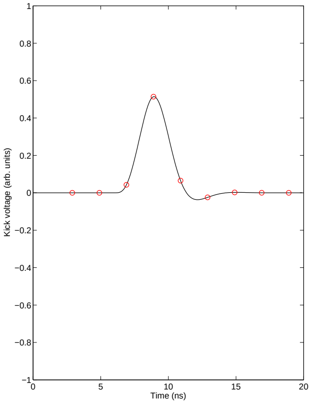

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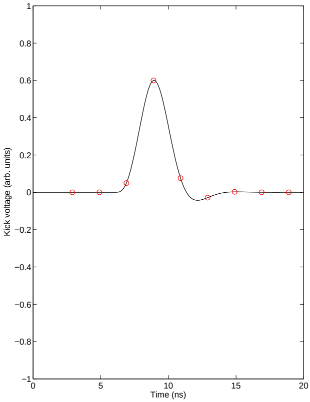

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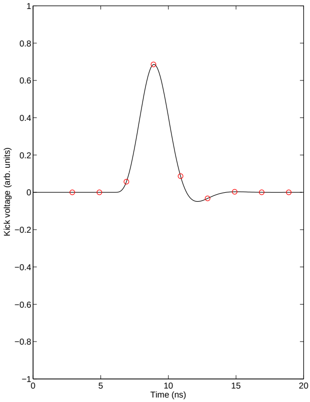

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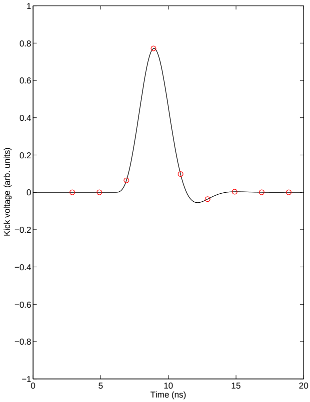

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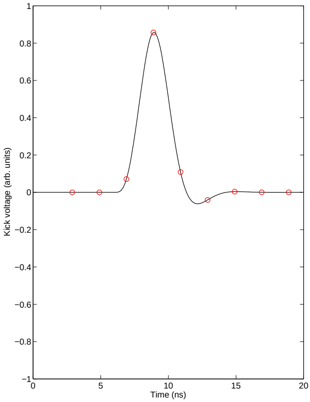

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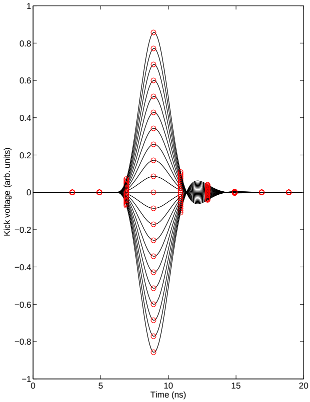

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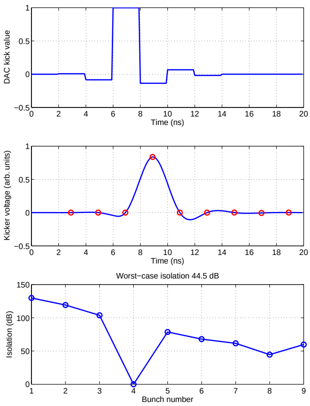

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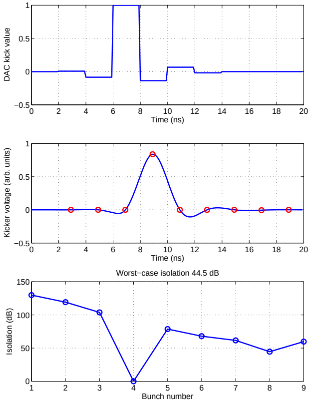

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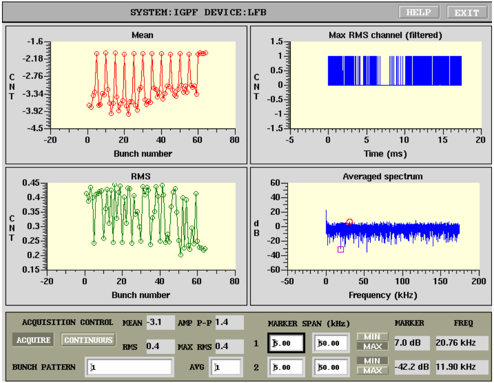
Duke SR-FEL: Removing Every Fifth Bunch



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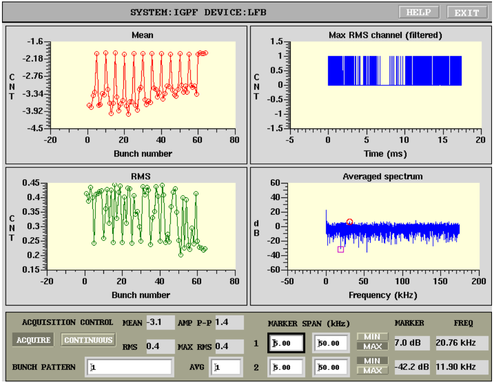

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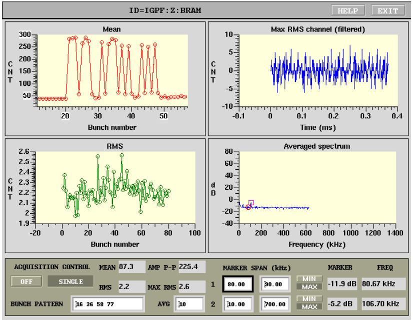
MLS: Custom Pattern



- With the back-end optimized see good isolation bunch-to-bunch;
- Spelling MLS in Morse code here.

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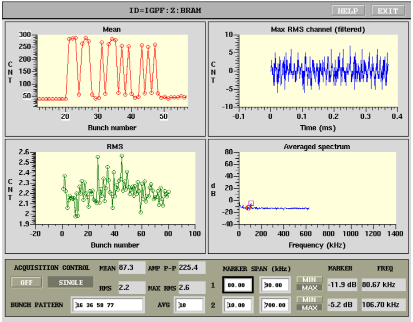

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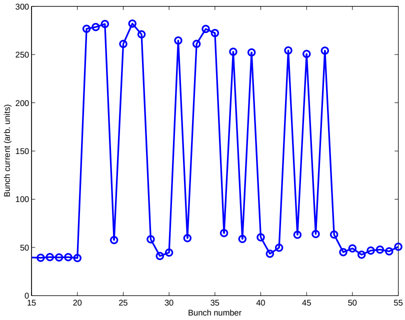

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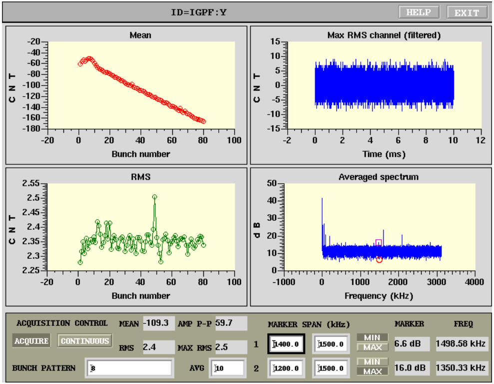
MLS: Arbitrary Fill Patterns



- Adjust the excitation to achieve relatively slow bunch cleaning rate;
- A Matlab script trims the bunches in a controlled manner.

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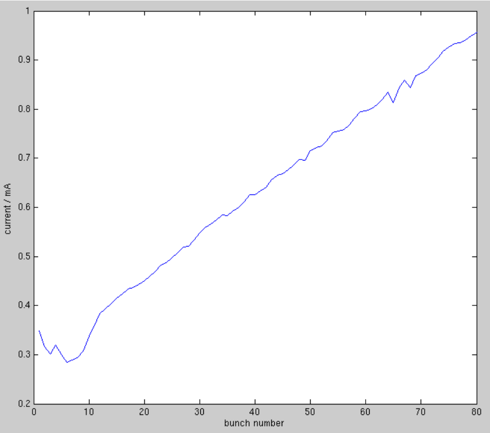

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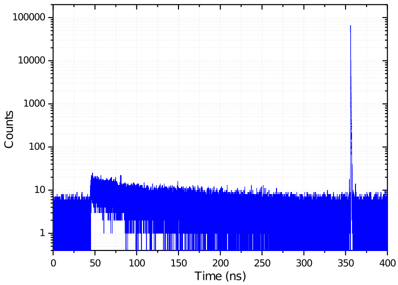
TLS: Bunch Purity Measurements



- Use optical methods (single photon counting) to characterize the purity after bunch cleaning;
- Small peaks are due to multiple light reflections, not sattelite bunches.

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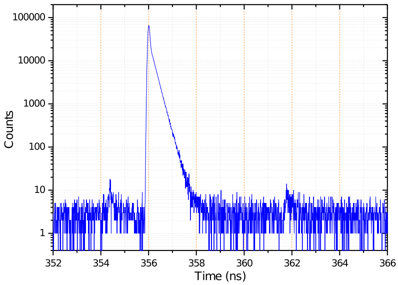

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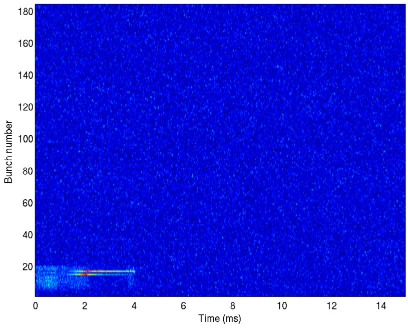
Outline

General Approach



- Modulate excitation signal on/off together with transient measurements;
- Example from ANKA: 20 bunches driven for 4 ms with feedback turned off;
- Bunch 15 spectrogram;
- Excitation sweeps through the betatron frequency.

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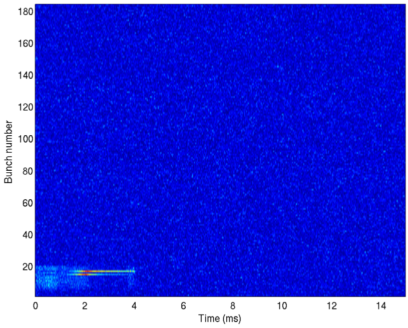

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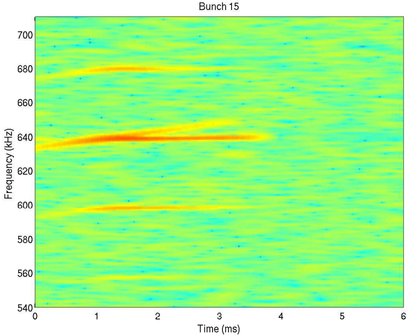

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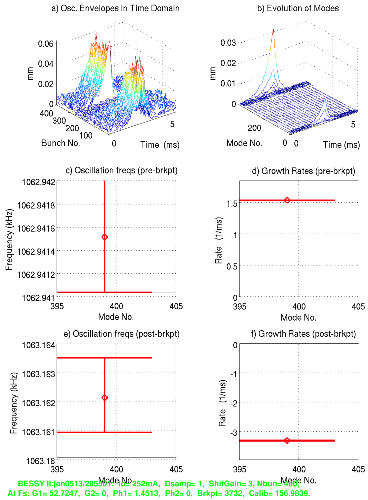
BESSY II Horizontal Grow/Damp Measurement



- Horizontal grow/damp at -3.0 units, 245 mA, no camshaft;
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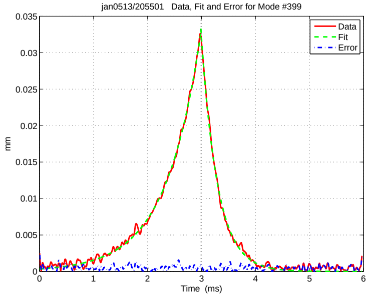

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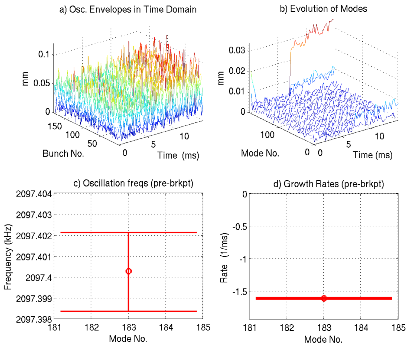
Measuring Stable Eigenmodes: ANKA X, 2.5 GeV



- Set up constant frequency excitation to drive mode -1;
- Excitation is on during normal running, off during growth period;
- Feedback is also off — measuring open loop trajectory of one mode;
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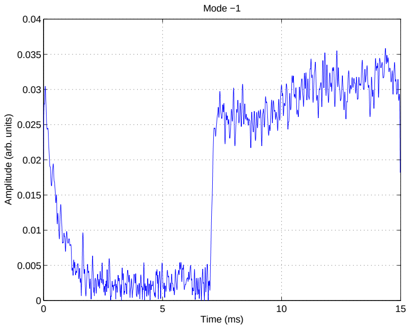

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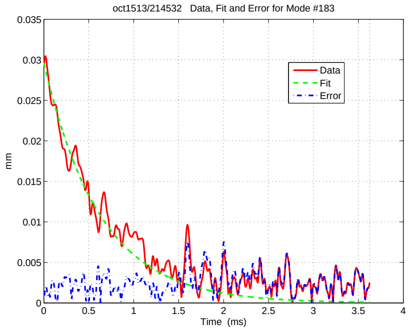

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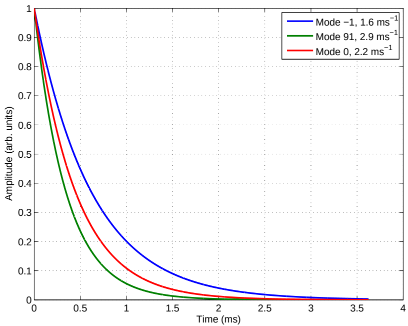

- Three transients, modes 0, 91, and -1;
- Fits scaled to the same starting point;
- Expect slower damping for mode -1, driven by the resistive wall impedance;
- Actual data are fairly noisy.

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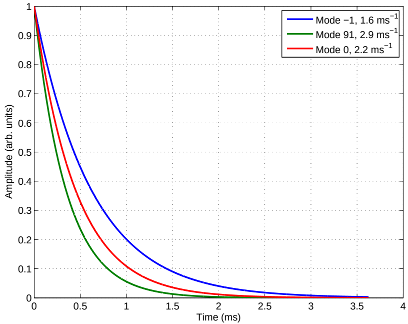

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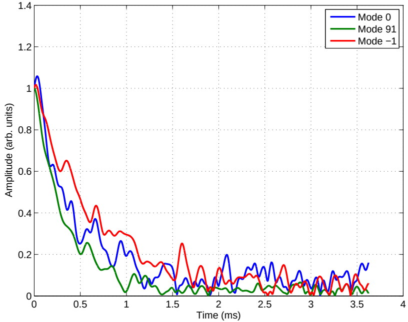

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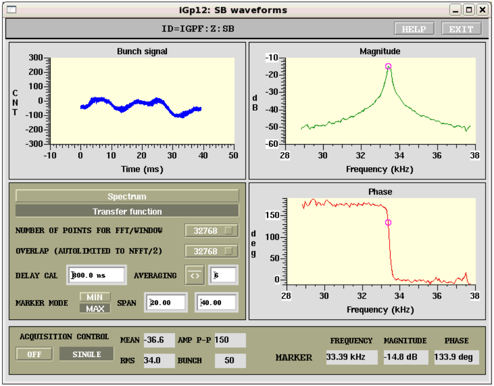

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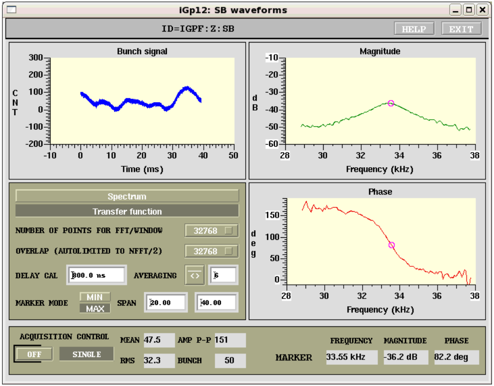

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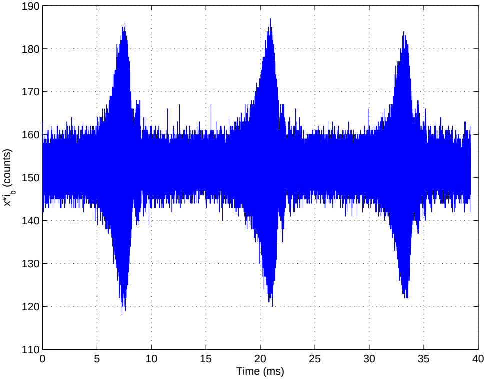

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- Frequency domain transfer function
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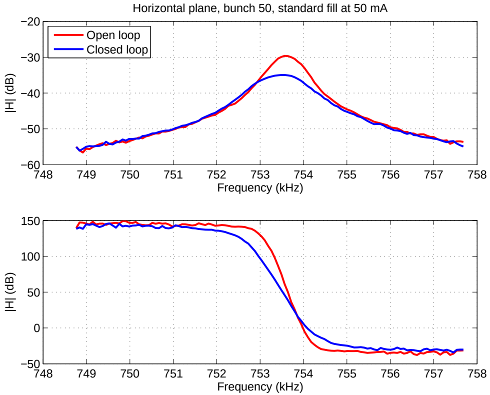

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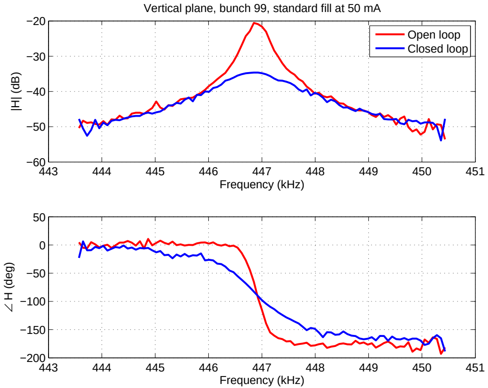

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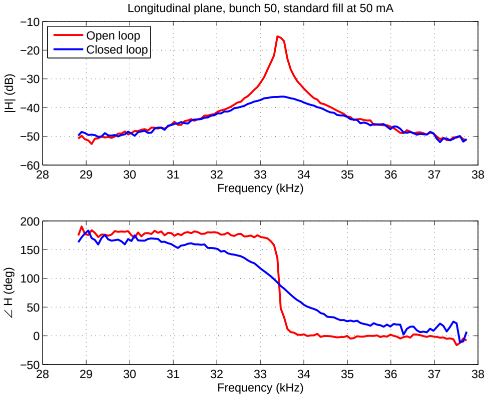

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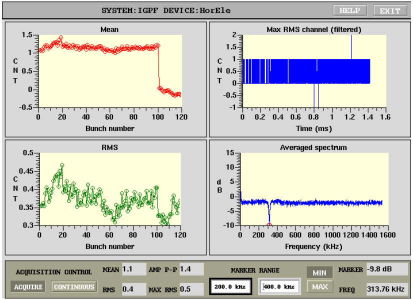
Parasitic Tune Measurement



- 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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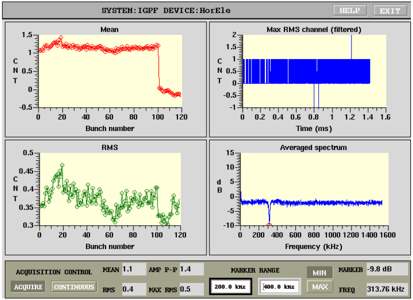

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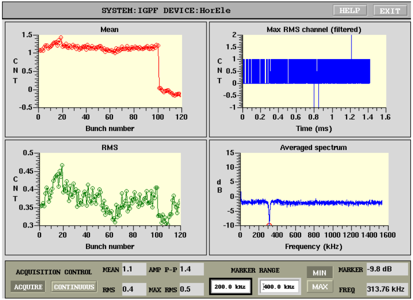

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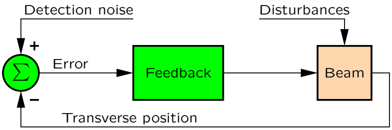
Why Is There a Notch?



- Beam response is resonant at the tune frequency;
- Attenuation of detection noise by the feedback is proportional to the loop gain;
- 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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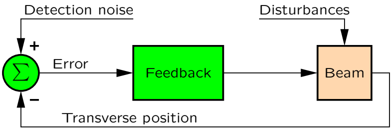

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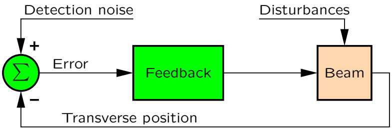

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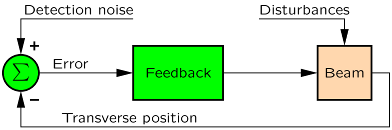

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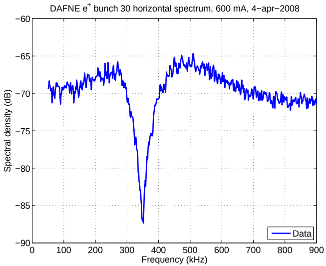
Bunch-by-bunch Tunes in DAΦNE



- 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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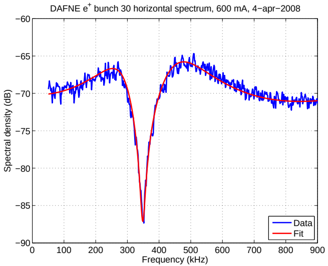

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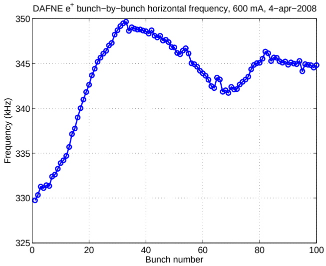

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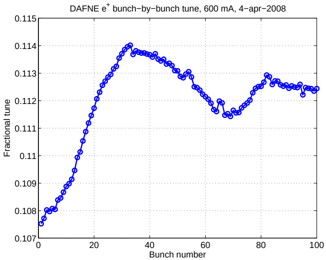

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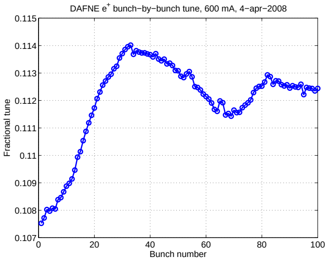

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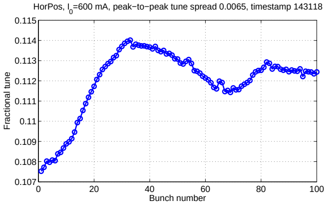

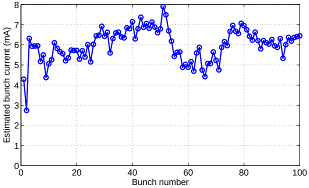

- Two measurements at 420 mA;
- Horizontal tune spread is 6.5×10^{-3};
- Vertical tune spread is 2.8×10^{-3}.
- Horizontal plane shows evidence of strong electron-cloud instabilities.

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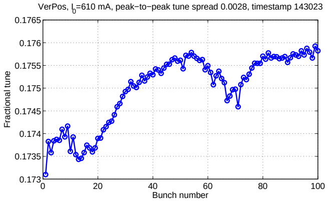

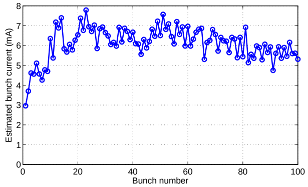

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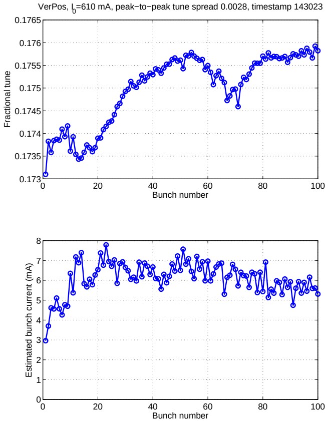
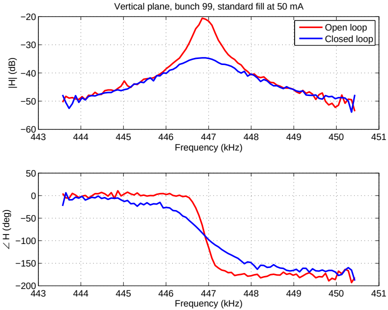


- Two measurements at 420 mA;
- Horizontal tune spread is 6.5×10^{-3};
- Vertical tune spread is 2.8×10^{-3}.
- Horizontal plane shows evidence of strong electron-cloud instabilities.

Tune Tracker: General Approach

- Turn off feedback for one selected bunch;
- Apply low amplitude sinusoidal excitation to that bunch;
- Measure the response and extract phase shift between excitation and response;
- Adjust excitation frequency to keep the phase shift constant;
- At some value of the phase shift we will excite the beam on resonance;
- If the tune changes, closed-loop tune tracker follows;
- Tune tracking can be slow (1-10 Hz) or fast (kHz).

Beam Transfer Function and Tracking



- Open loop response has steep phase slope;
- At -90 degrees phase shift excitation is on resonance;
- Negative phase slope — negative phase tracker gain.

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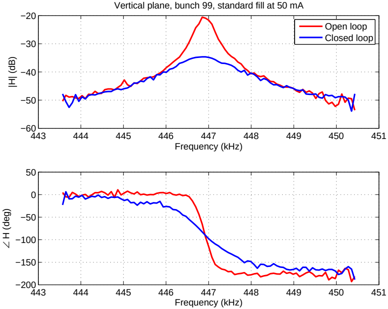

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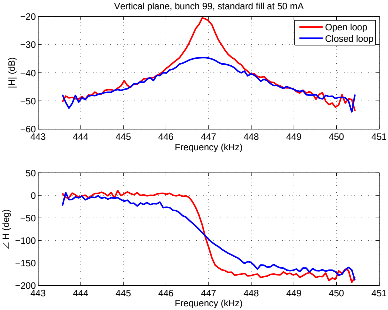

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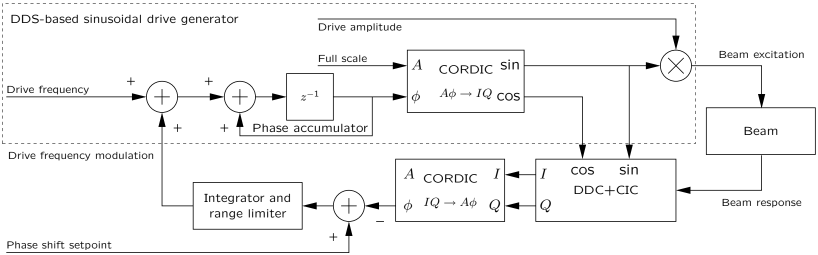
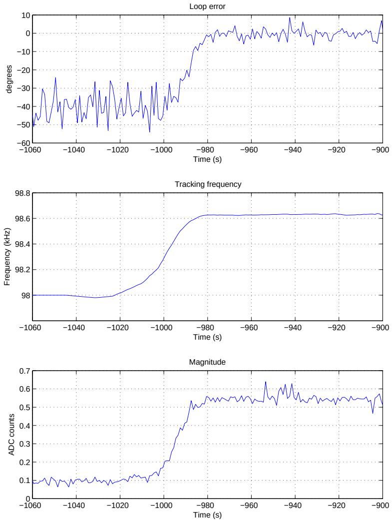
Tune Tracker: Block Diagram



Slow Tune Tracking in NSLS-II



- Tune tracking loop closed around -1000 seconds;
- Low gain — slow settling;
- Once settled, the loop maintains stable oscillation amplitude by tracking the variations in the tune.

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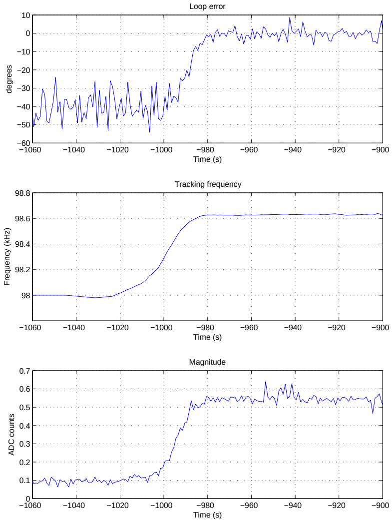

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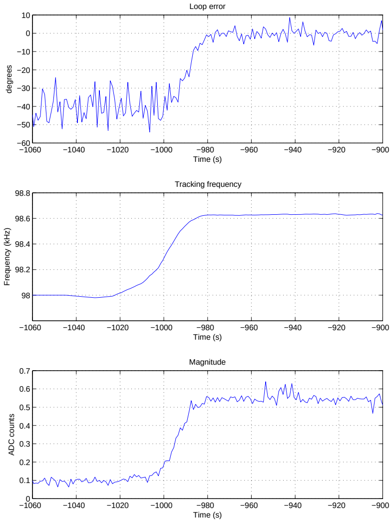

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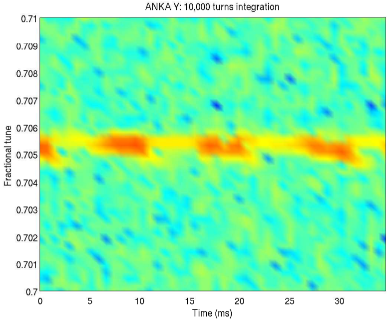
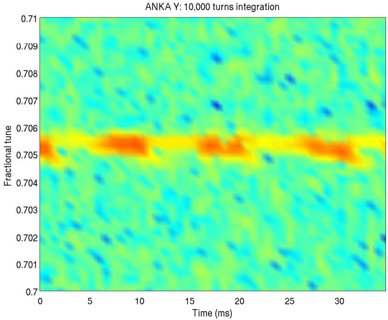
Slow Tune Tracking in ANKA



- Slow tracking — 10^4 turns integration, 120 Hz measurement bandwidth;
- Spectrogram of the bunch under tracking control;
- Suggestive of periodic tune variation.

Slow Tune Tracking in ANKA



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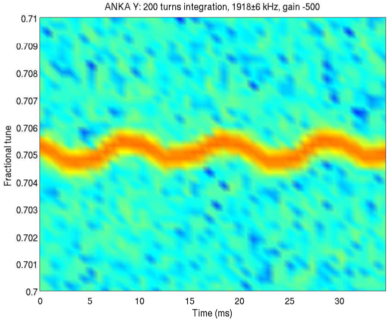
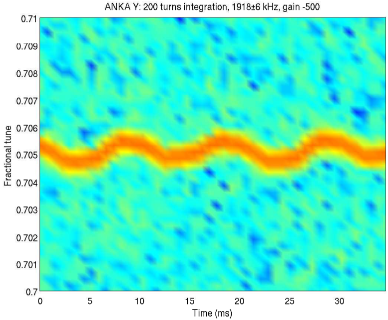
Fast Tune Tracking in ANKA



- Fast tracking — 200 turns integration, 6 kHz measurement bandwidth;
- Spectrogram of the bunch under tracking control;
- 100 Hz tune variation (quadrupole supply ripple).

Fast Tune Tracking in ANKA



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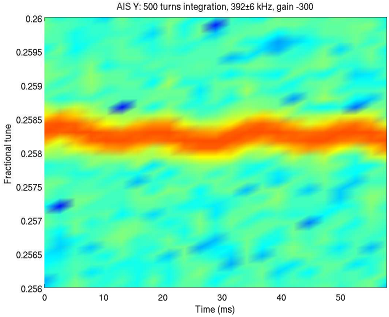
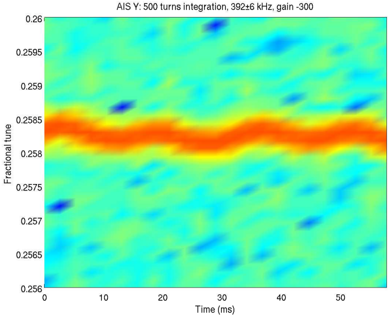
Fast Tune Tracking in the ALS



- Fast tracking — 500 turns integration, 1.3 kHz measurement bandwidth;
- Spectrogram of the bunch under tracking control;
- 60 Hz tune variation.

Fast Tune Tracking in the ALS



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Summary

- Modern bunch-by-bunch feedback system is capable of much more than just keeping the beam stable;
- Programmable hardware enables a number of experimental techniques for controlling bunch positions and currents;
- Modern feedback systems provide multiple ways of monitoring beam dynamics in real time.

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