Bunch-by-bunch feedback and diagnostics

Dmitry Teytelman

Dimtel, Inc., San Jose, CA, USA

DELTA Seminar

Outline

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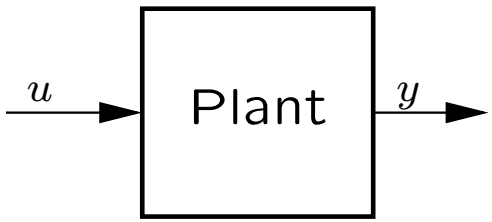
Closed-loop Feedback: Structure and Example



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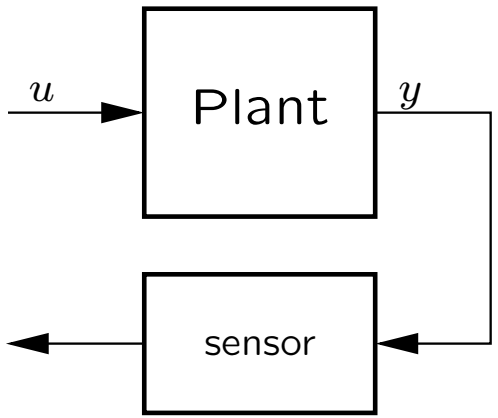

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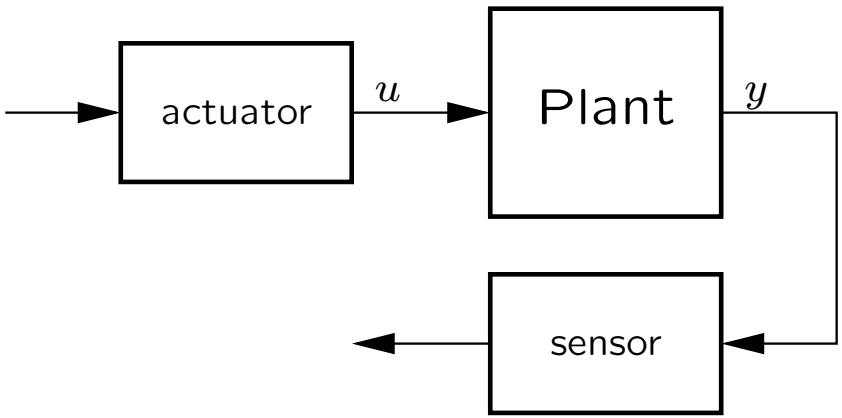

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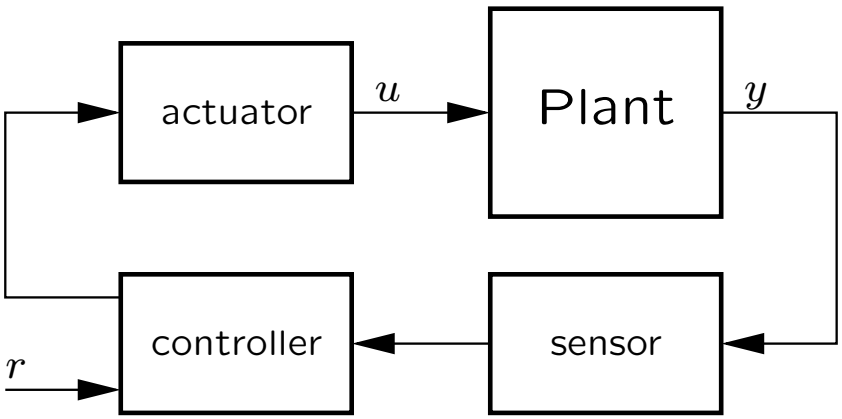

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- Plant behavior (state) can be affected by an actuator.
- Feedback loop is completed by a controller.

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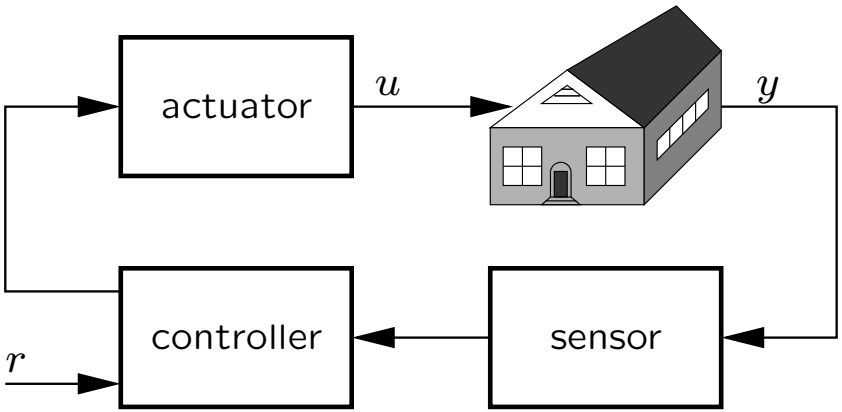

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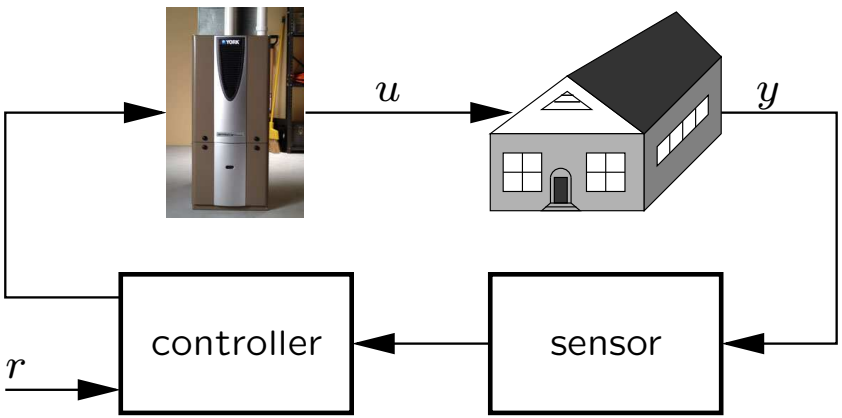

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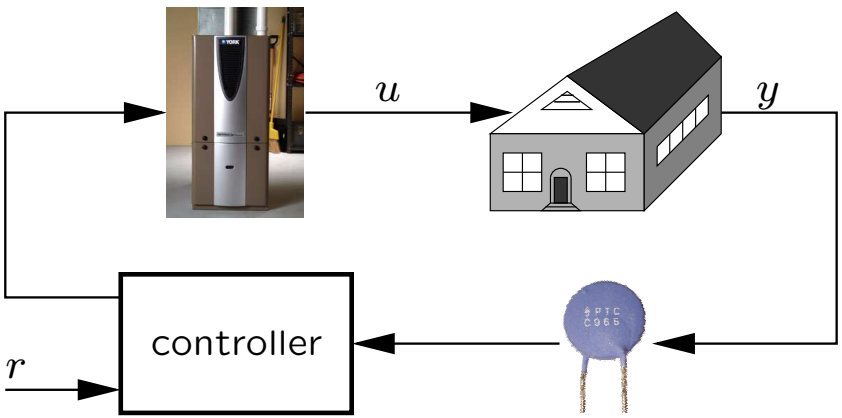

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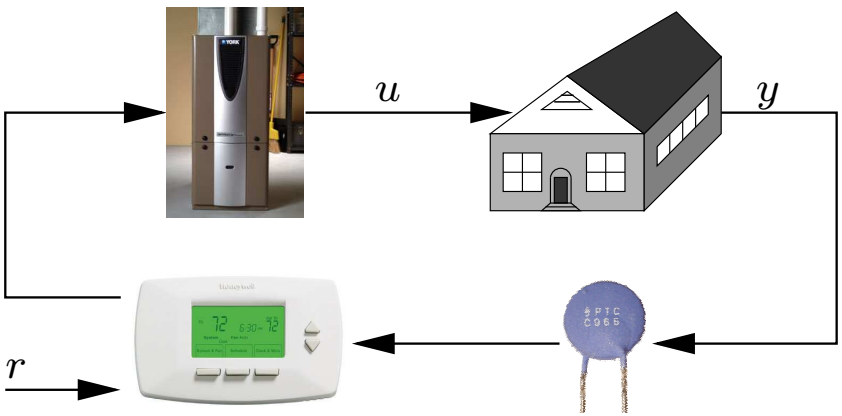

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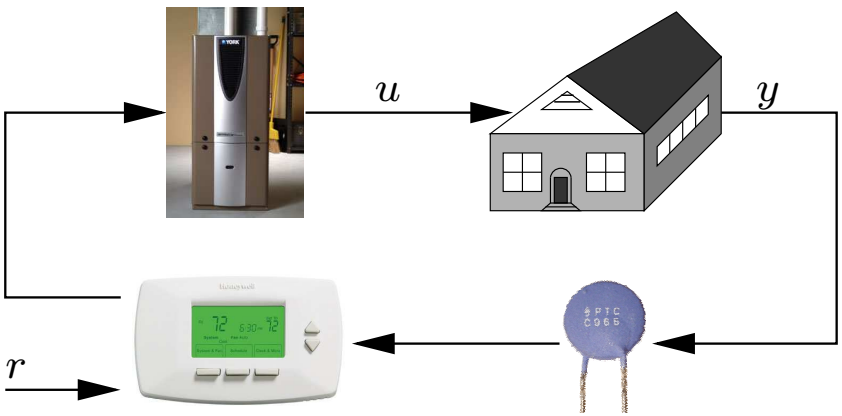
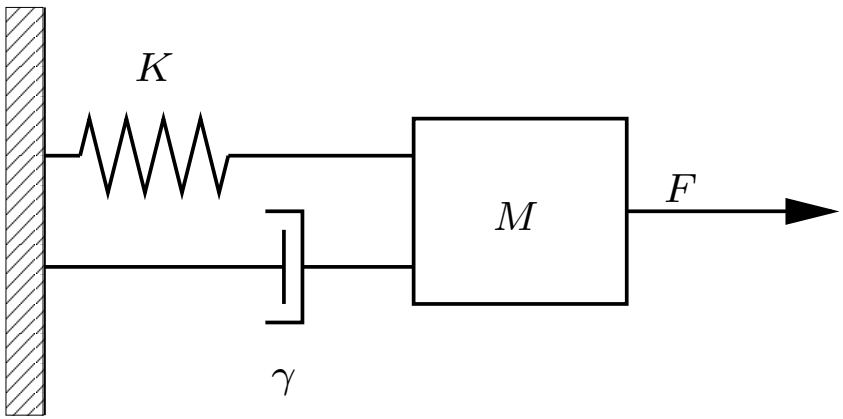


- Take a household heating system as an example.
  - Our plant is the house.
  - Actuator - furnace.
  - Sensor - thermistor.
  - Controller - thermostat.
- Loop signals
  - Output *y* - temperature;
  - Input *u* - heated air from the furnace;
  - Reference *r* - temperature setpoint.

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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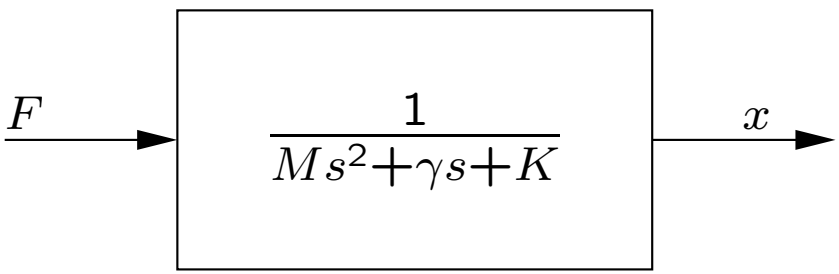

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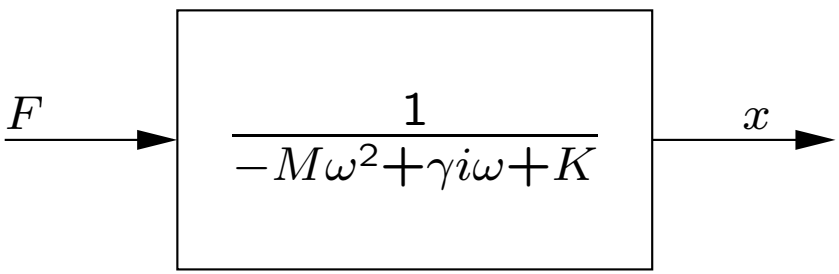

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Outline

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.
- In modern accelerators active feedback is used to suppress such instabilities.

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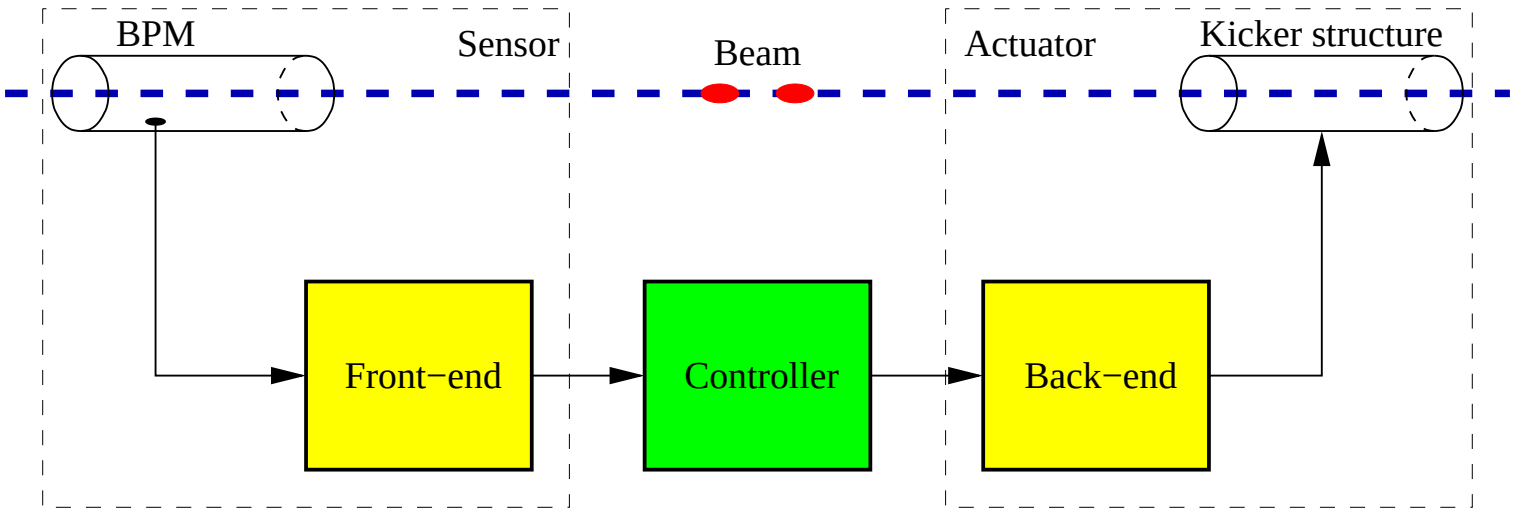
Bunch-by-bunch Feedback

Definition

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



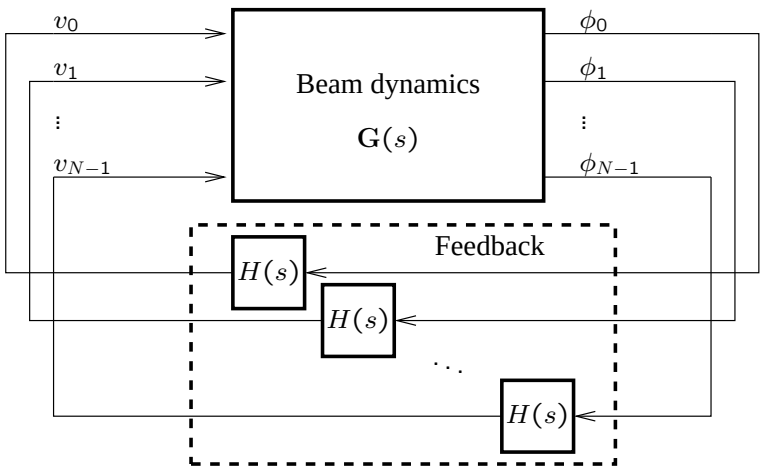
- Bunches are processed sequentially.
- Correction kicks are applied one or more turns later.

Outline

Coupled-bunch Instabilities: Eigenmodes and Eigenvalues

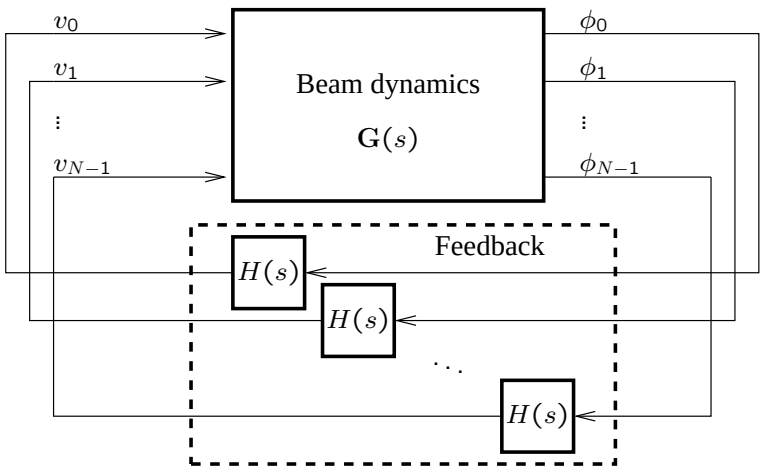
- If we consider bunches as coupled harmonic oscillators, a system of N bunches has N eigenmodes.
- Without the wakefields these modes have identical eigenvalues determined by the tune and the radiation damping.
- Impedances shift the modal eigenvalues in both real part (damping rate) and imaginary part (oscillation frequency).
- Modeling all eigenmodes is computationally intensive.

MIMO model of the bunch-by-bunch feedback



- Beam is a multi-input multi-output (MIMO) system.
- For *N* bunches there are *N* inputs and outputs.
  - Individual bunch kicks are the inputs.
  - Bunch positions are the outputs.
- Sequential processing, parallel analysis.

MIMO model of the bunch-by-bunch feedback



- If feedback is the same for all bunches, it is invariant under coordinate transformations.
- Bunch-by-bunch feedback applies the same feedback $H(s)$ to each eigenmode.
- Consequently it is sufficient to consider the most unstable eigenmode for modeling.

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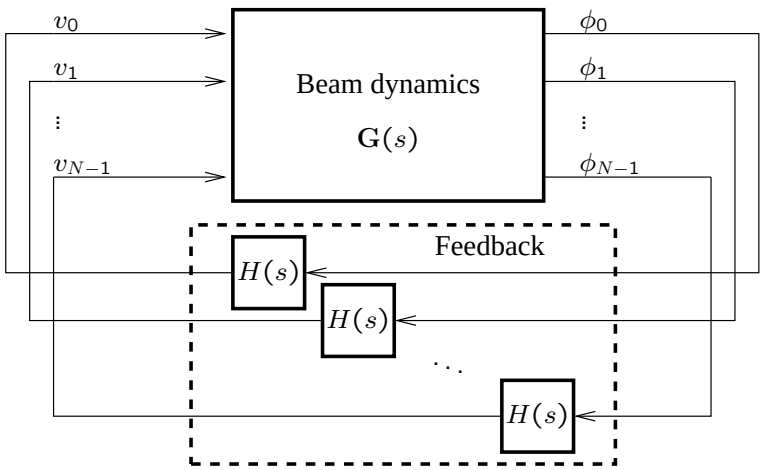

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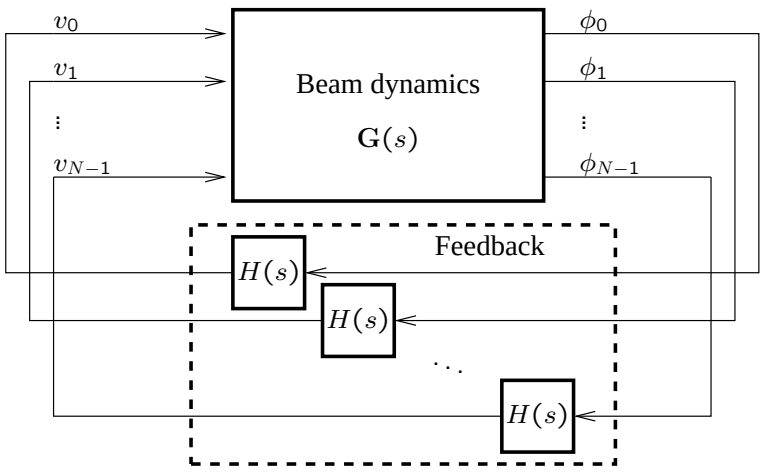

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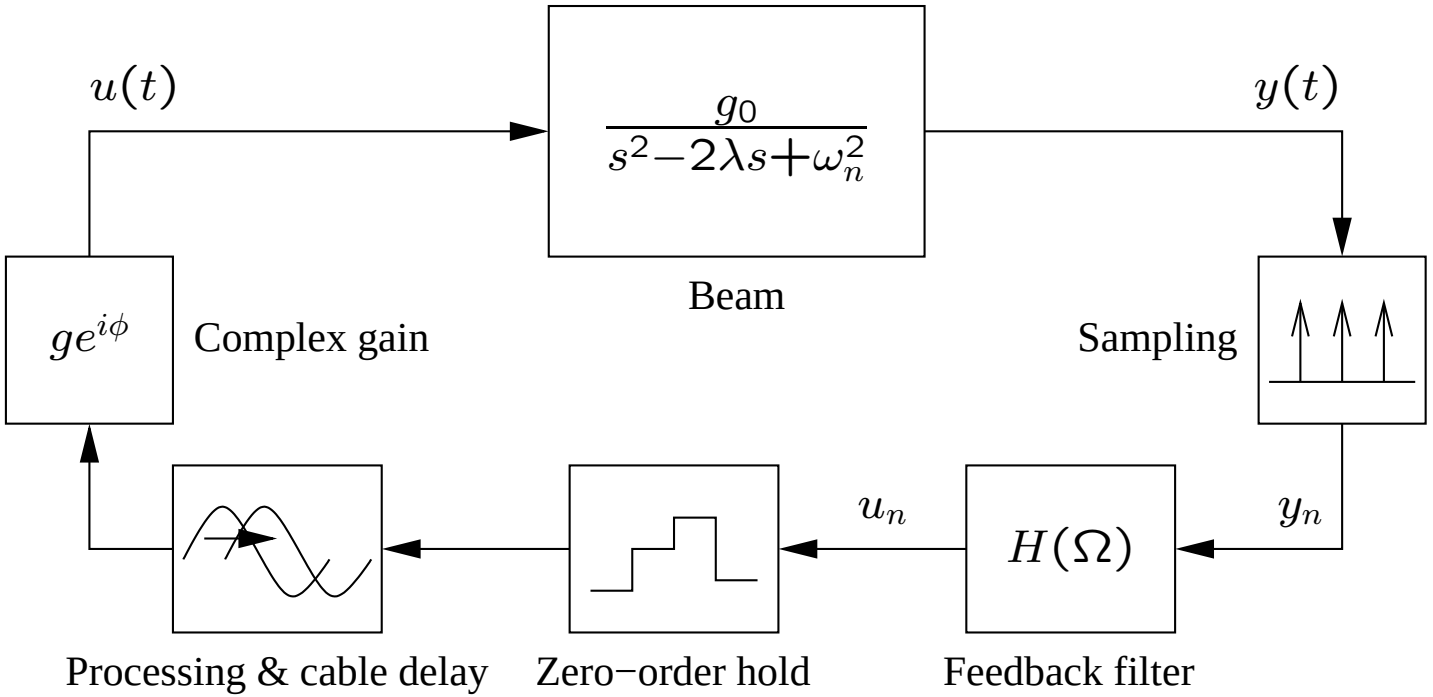
Detailed Scalar Feedback Model



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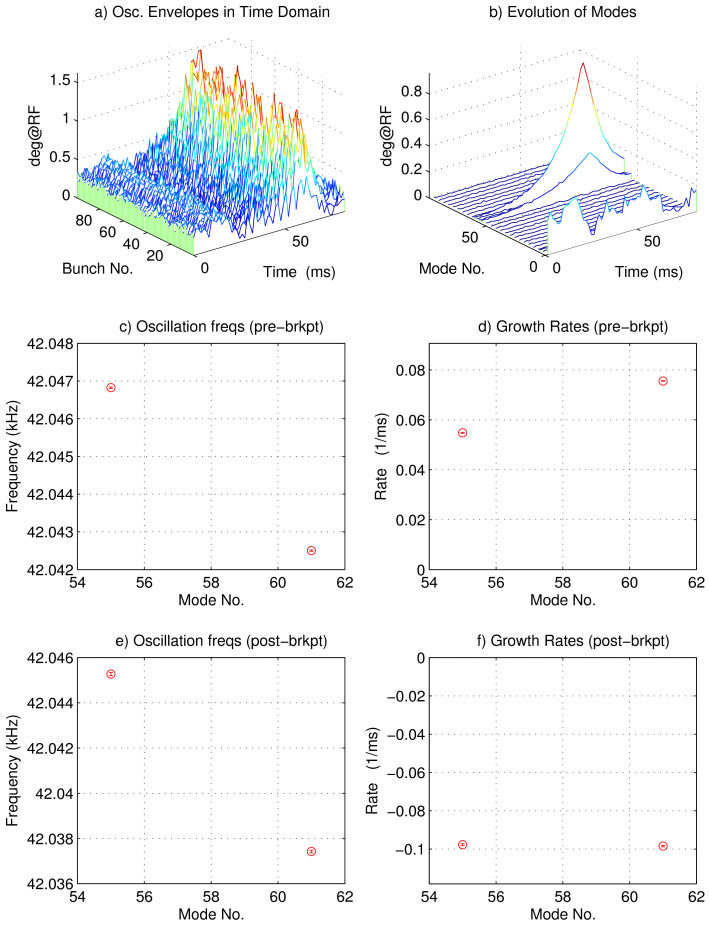
Grow/Damp Measurements



BEPC−II E−:nov0708/024925: Io= 273.063mA, Dsamp= 10, ShifGain= 4, Nbun= 99,
At Fs: G1= 6.3492, G2= 0, Ph1= −62.2095, Ph2= 0, Brkpt= 8000, Calib= 1.4207.

- Unstable systems are difficult to characterize.
- Transient measurements - open the loop for a short time to allow the unstable modes to grow.
- Record coordinates of all bunches.
- Longitudinal grow/damp in BEPC-II - HOMs in various vacuum structures.
- Vertical grow/damp in CESR-TA - electron cloud.

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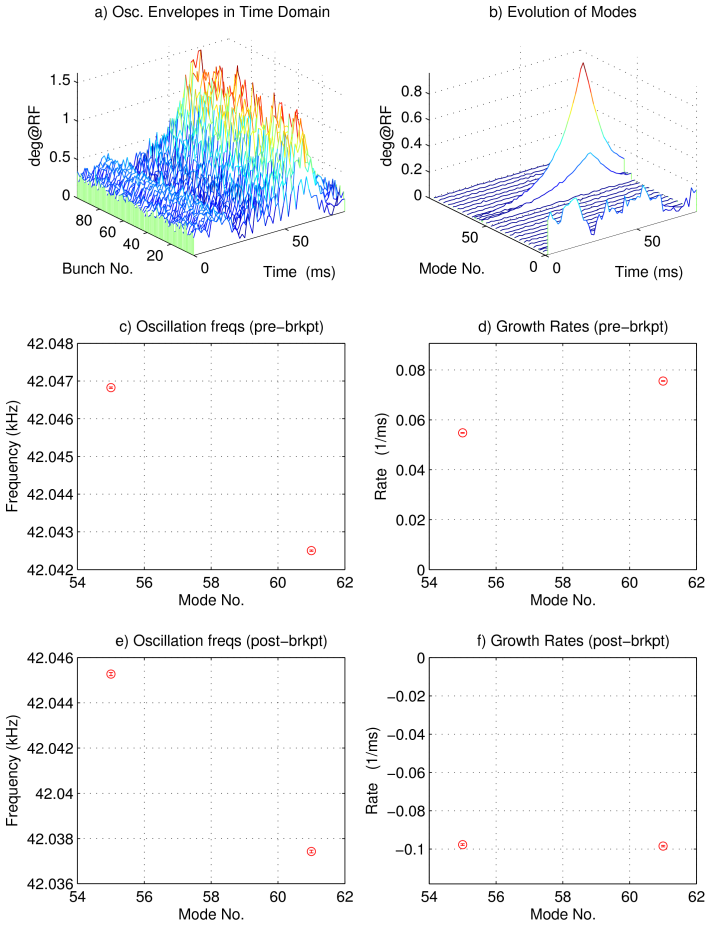

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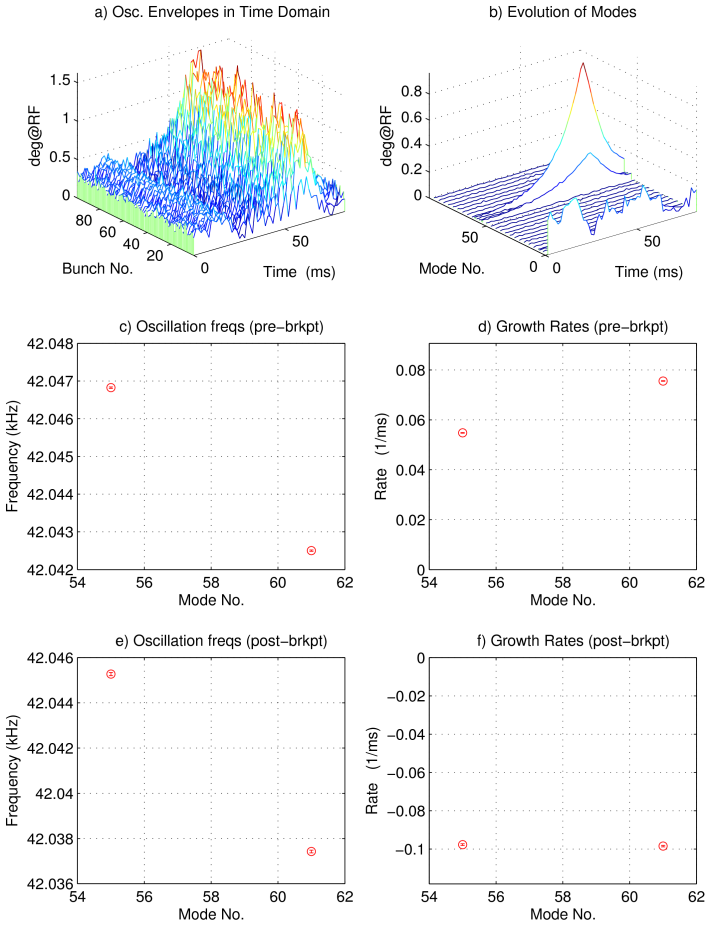

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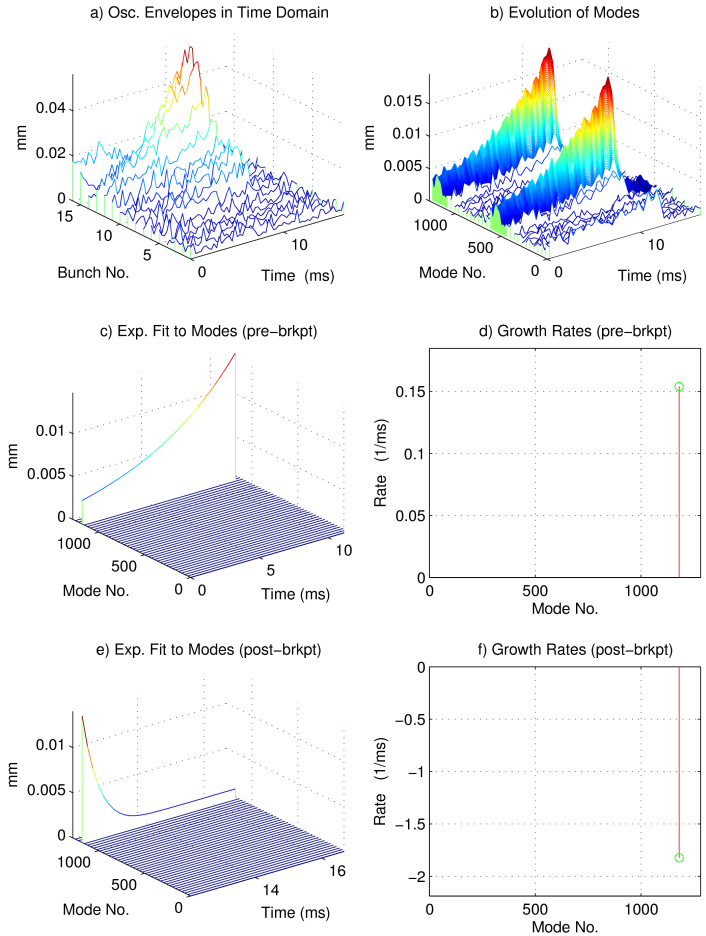

CESR TA:may2009/235030: Io= 12mA, Dsamp= 1, ShifGain= 2, Nbun= 16,
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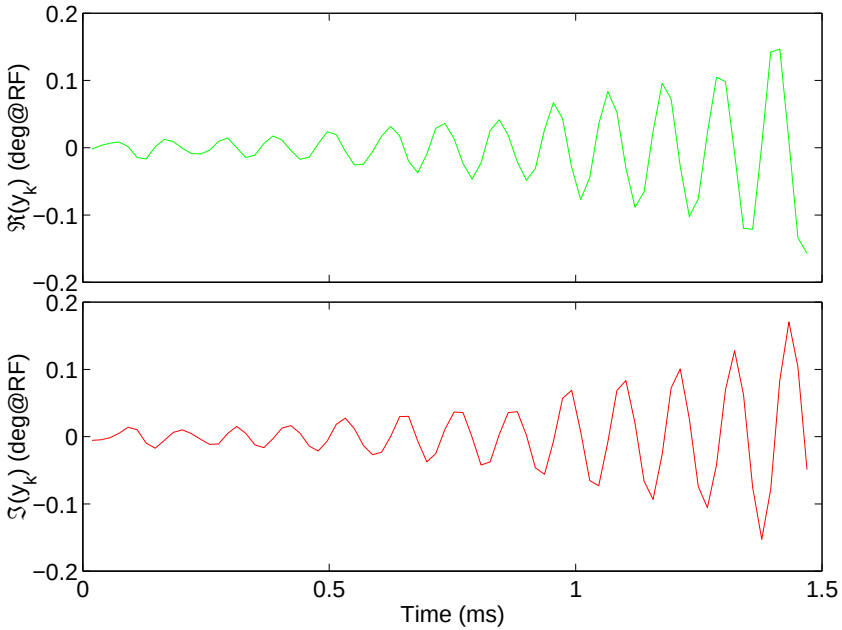
Estimating Eigenvalues



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- Longitudinal mode 233 at the ALS is shown.
- Complex exponentials are fitted to the data to estimate the eigenvalues.

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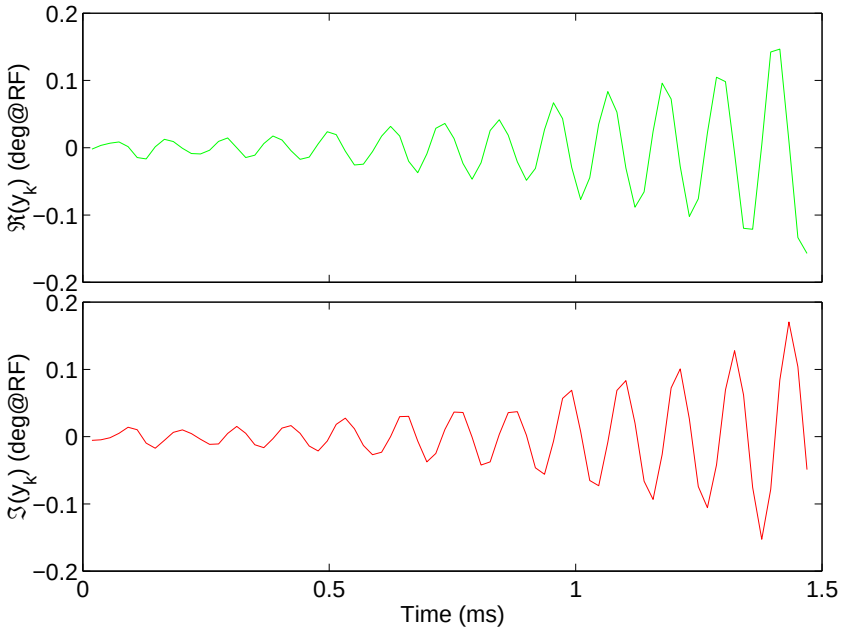

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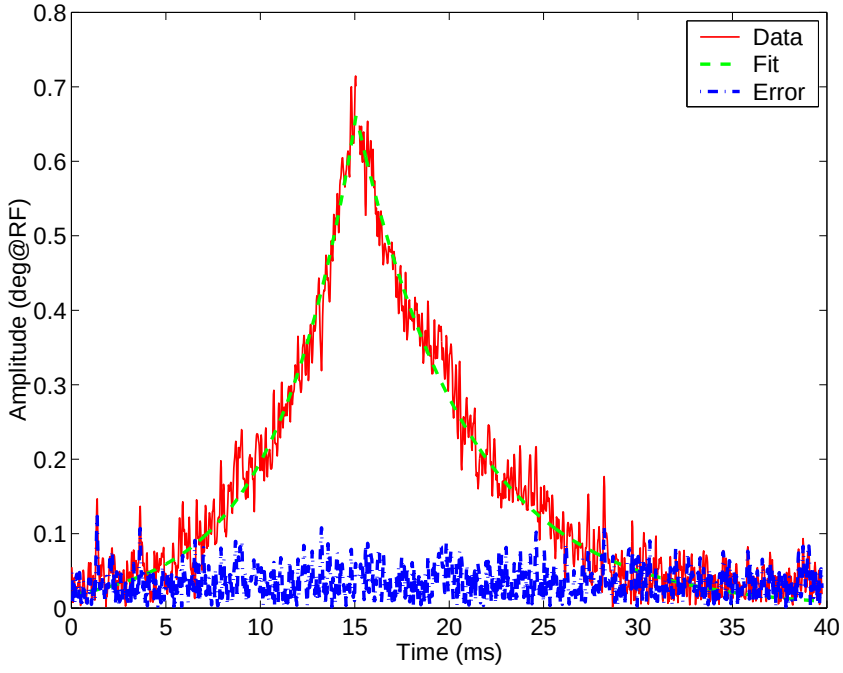

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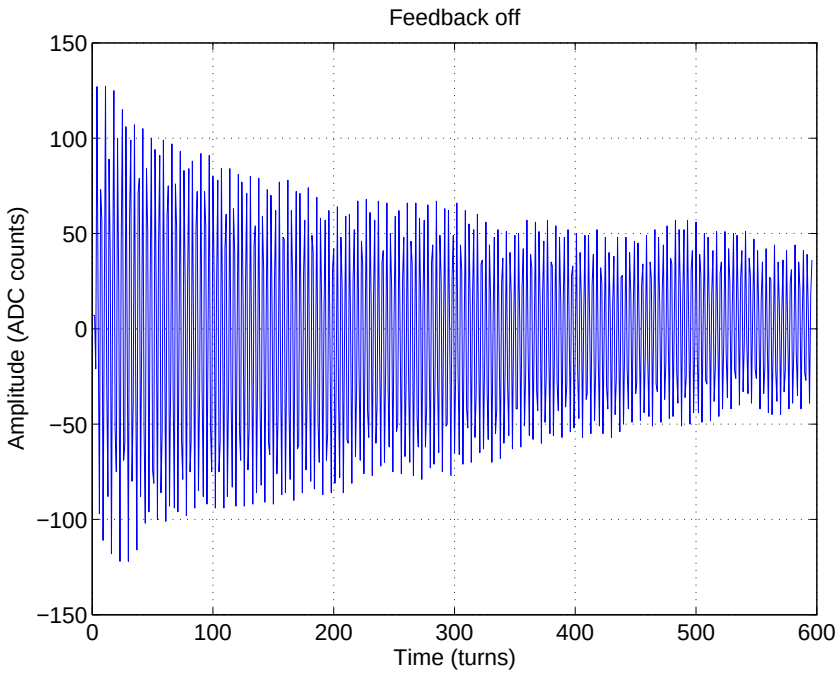

- Data acquisition can be externally triggered;
- Typically used to observe the motion of the injected bunch turn-by-turn;
- Longitudinal oscillations in the ATF (KEK) after injection;
- ... and with longitudinal feedback on.

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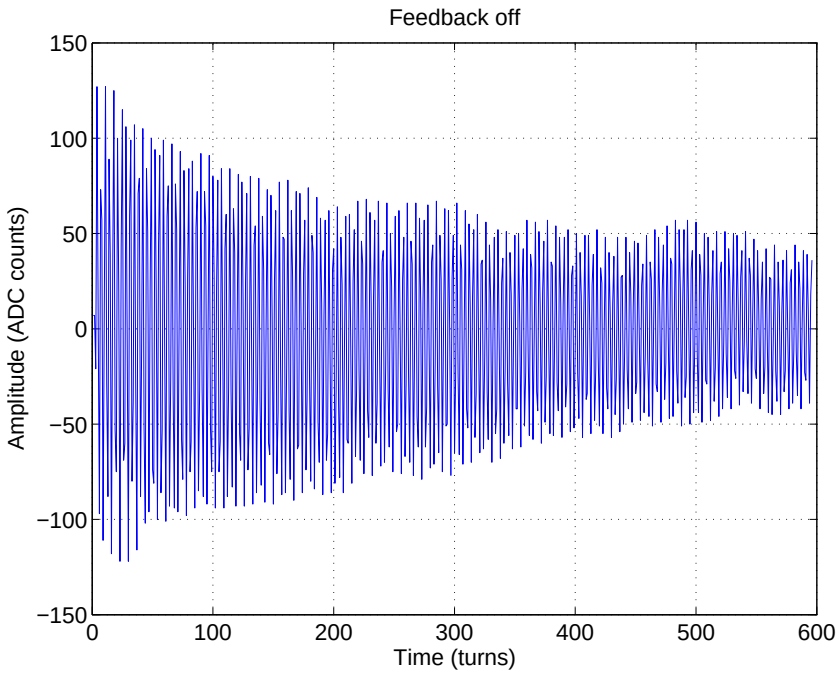

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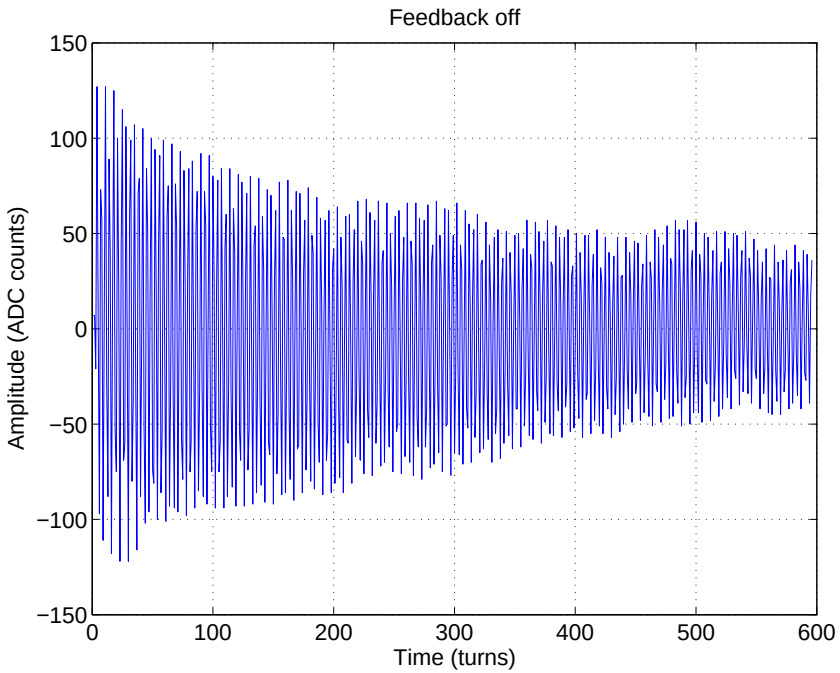

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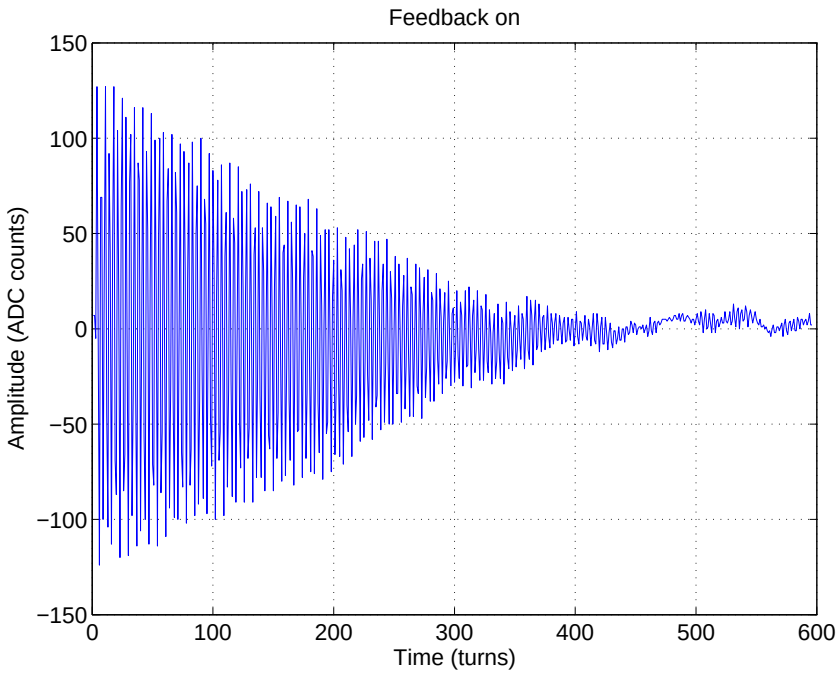

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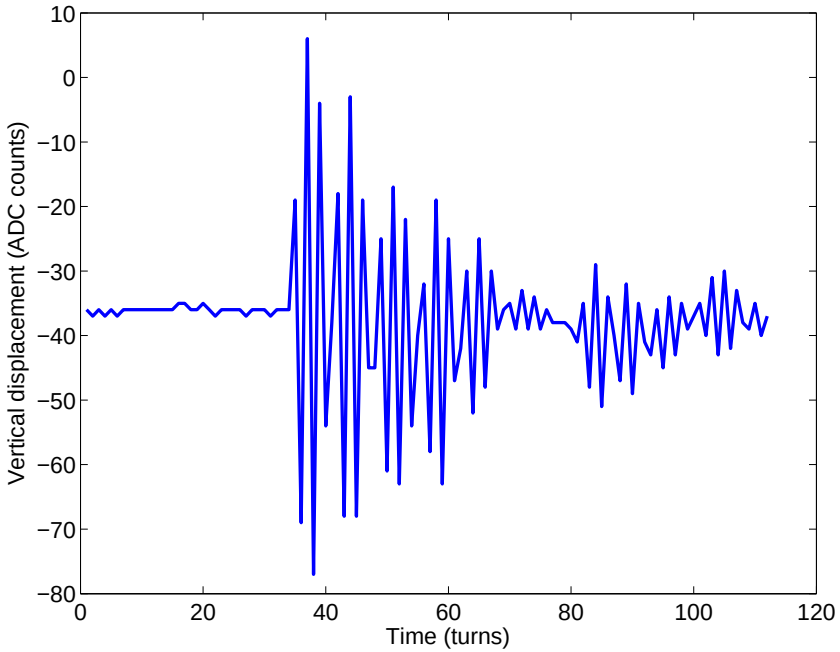

- Acquire PEP-II LER vertical motion data on injection trigger;
- Plot bunch-by-bunch RMS, align on the bunch with max. RMS;
- Plot turn-by-turn RMS;
- Use data before injection to compute steady-state detector offsets;
- Plot orbit perturbation on the first turn after injection.

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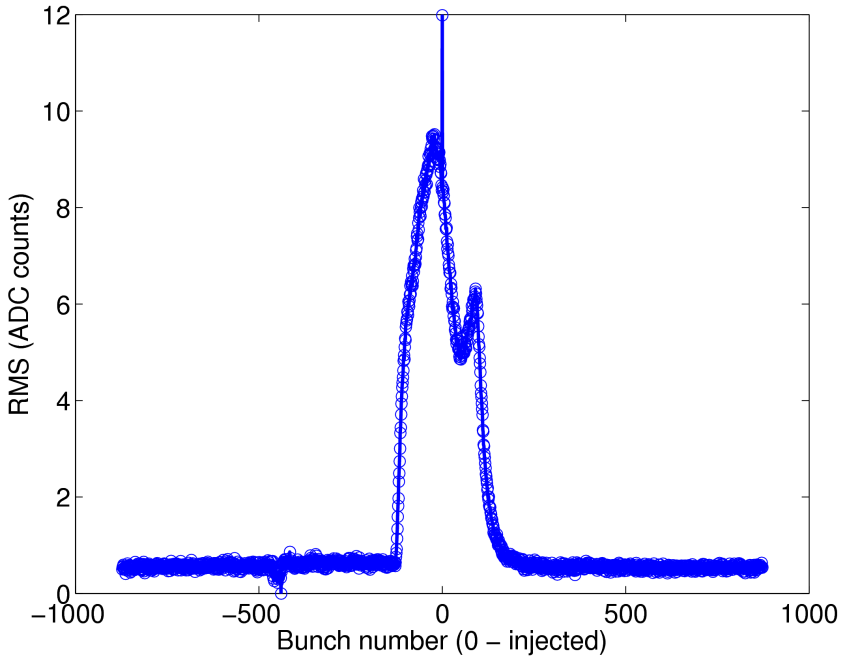

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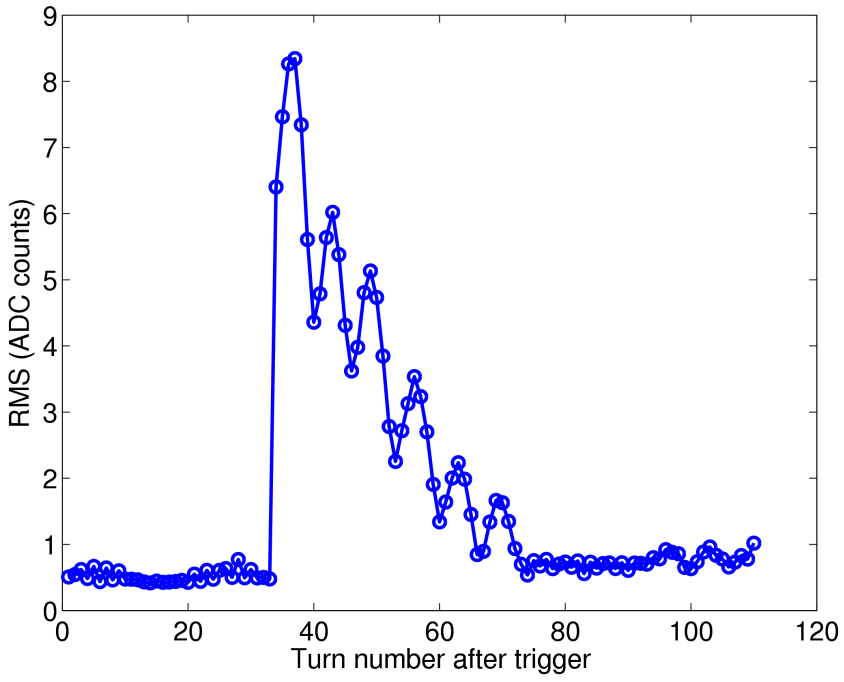

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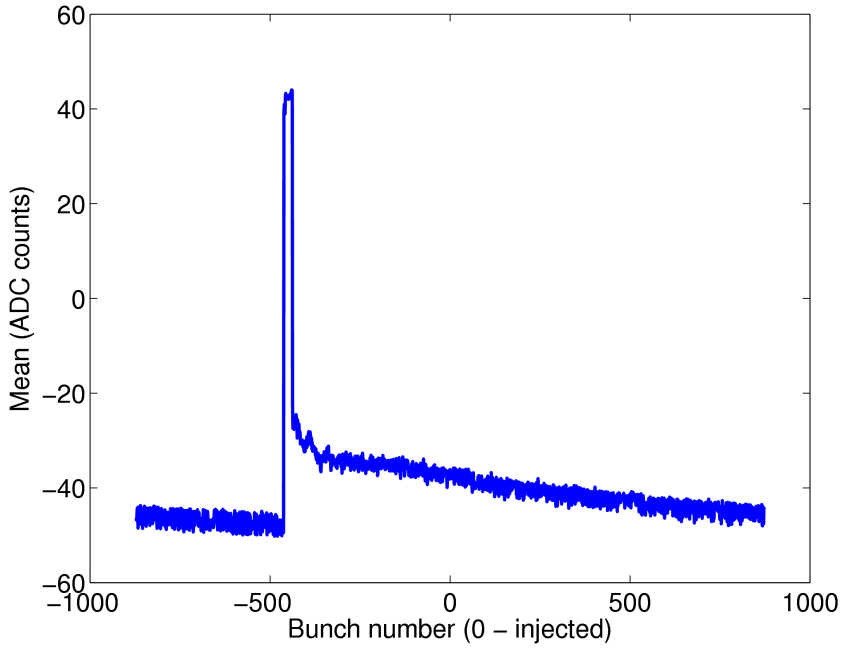

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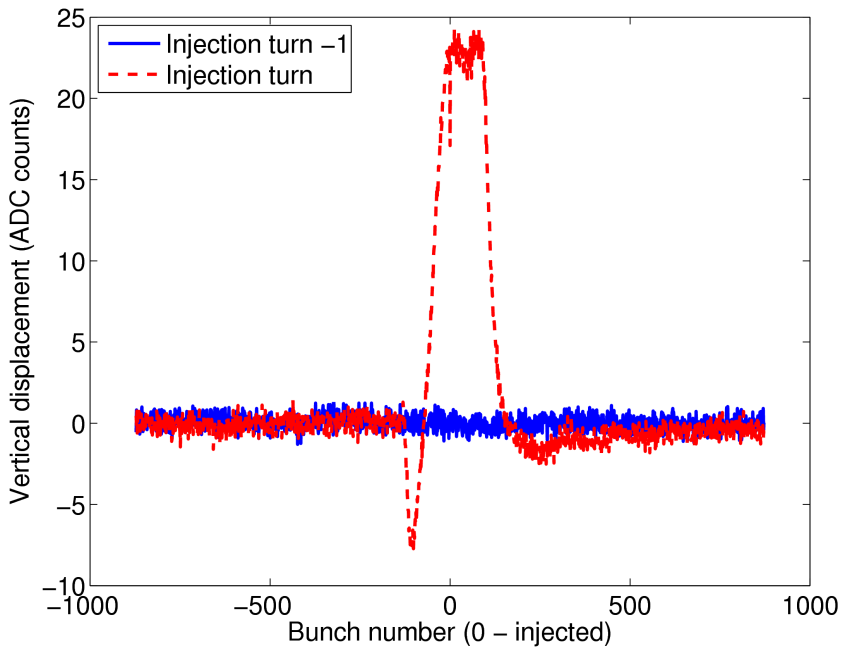

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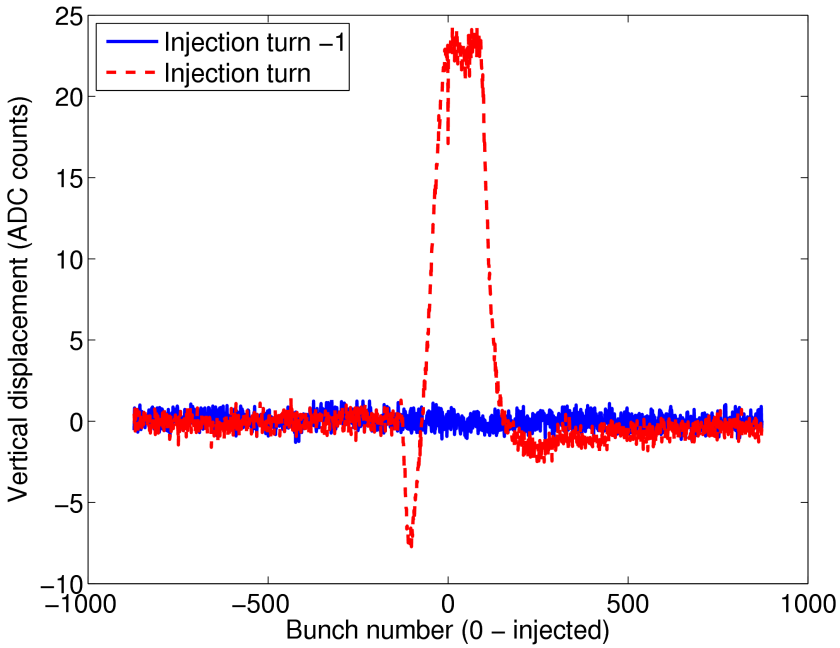

- Orbit perturbation shows relative and absolute kicker timing error;
- Adjust the timing;
- Next we adjust kicker 2 amplitude;
- EPICS waveform display shows the injection quality in real time.

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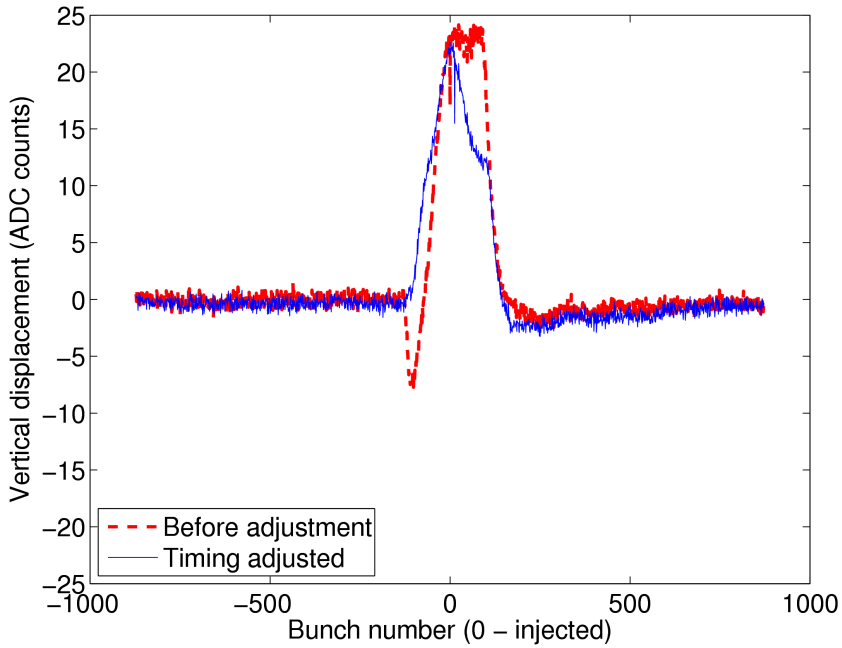

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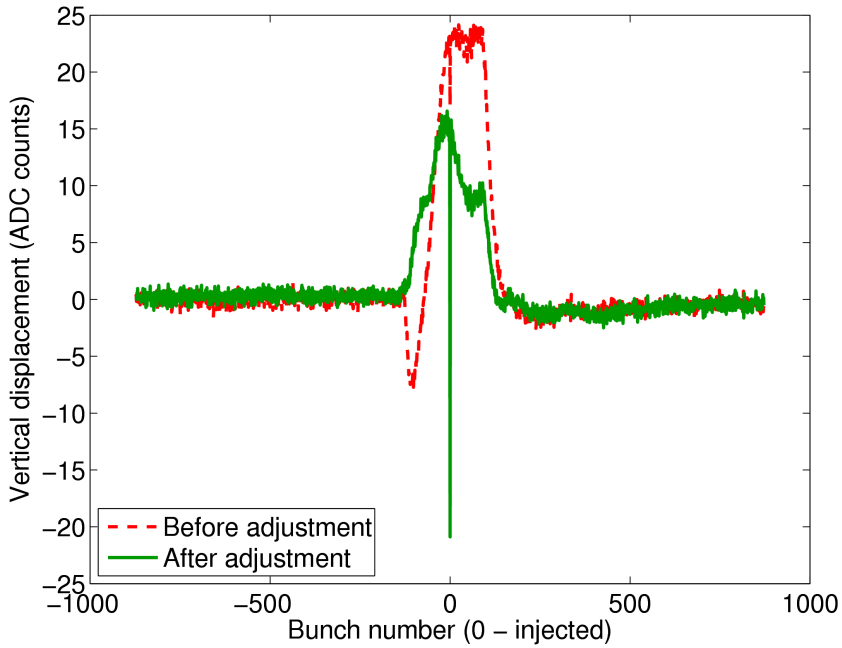

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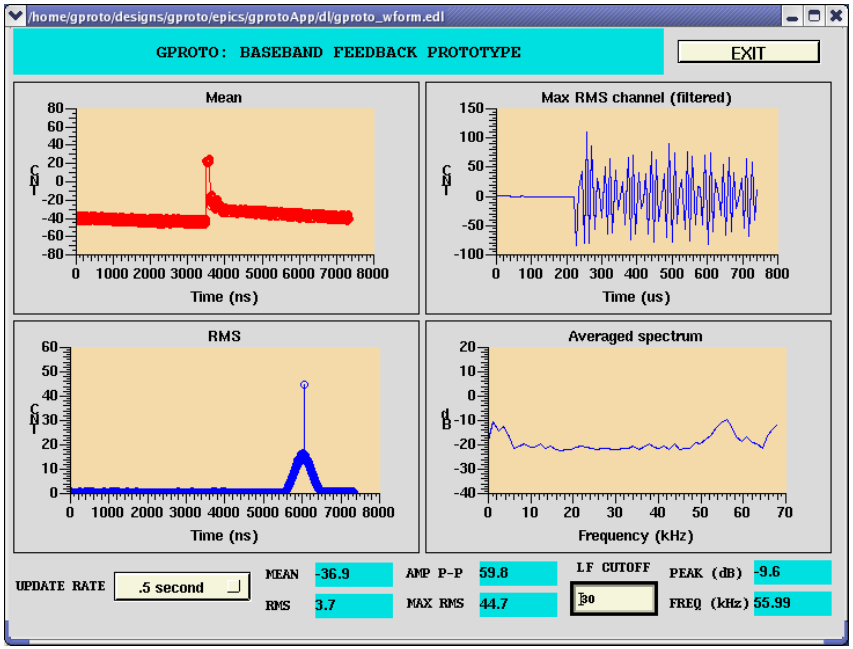
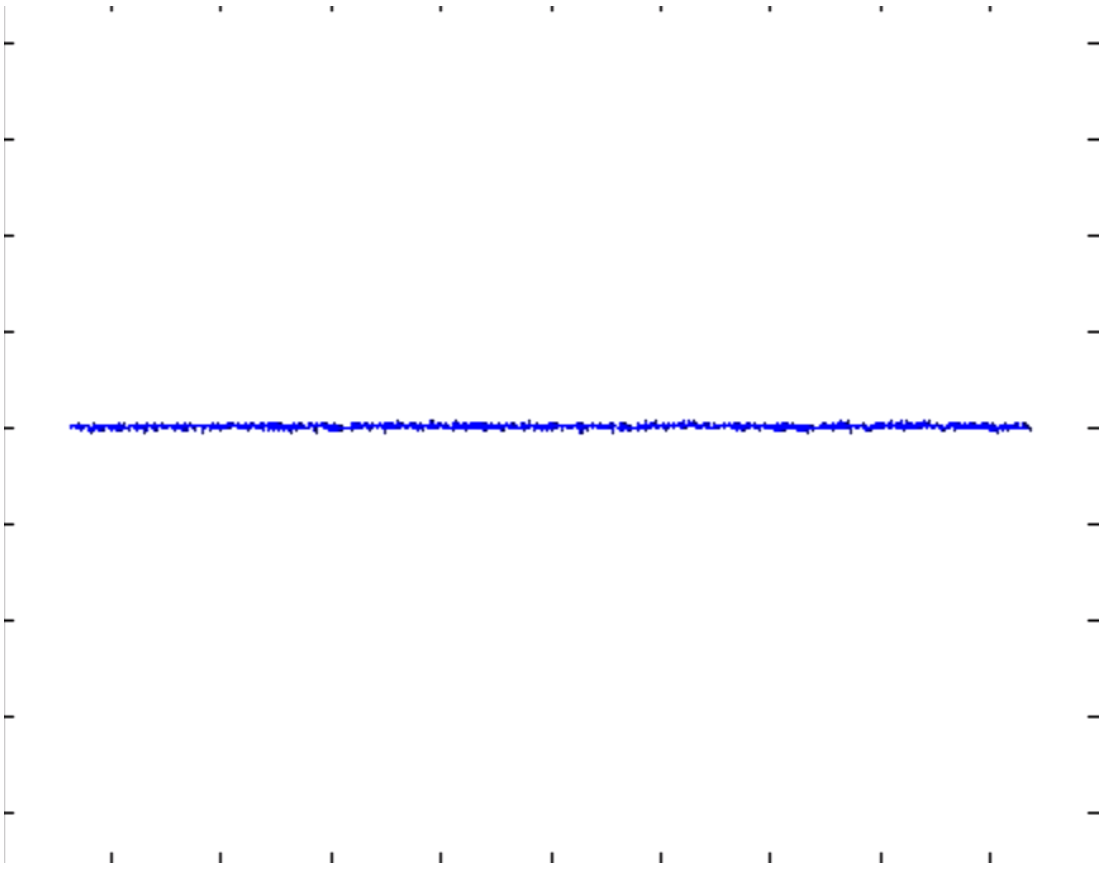


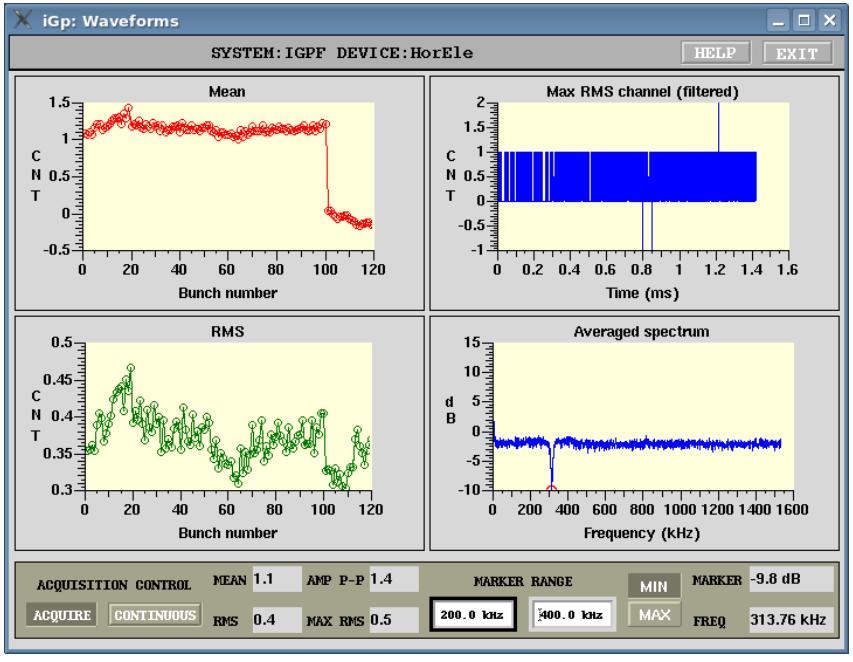
- Orbit perturbation shows relative and absolute kicker timing error;
- Adjust the timing;
- Next we adjust kicker 2 amplitude;
- EPICS waveform display shows the injection quality in real time.

PEP-II LER Injection Movie



Outline

Parasitic Tune Measurement



- In 2005–2008 DAΦNE upgraded to Dimtel, Inc. bunch-by-bunch feedback systems with integrated diagnostics;
- This upgrade created new measurement possibilities;
- Key to these measurements is a curious notch in the beam spectrum.

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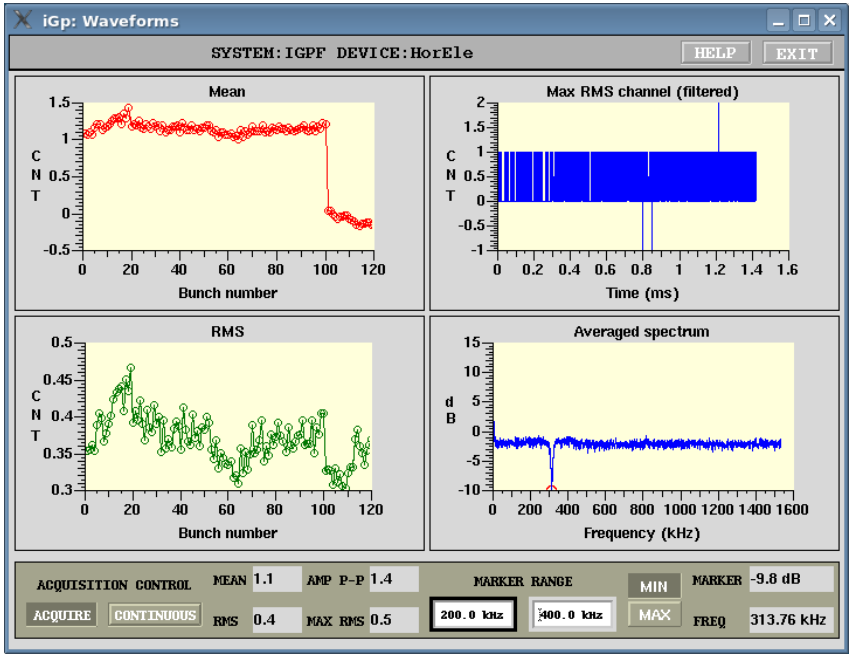

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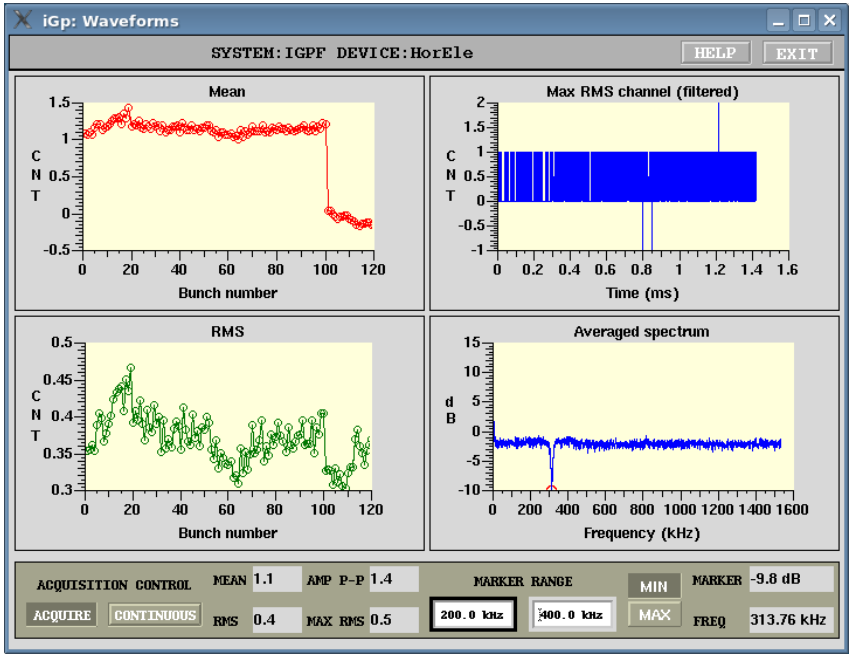

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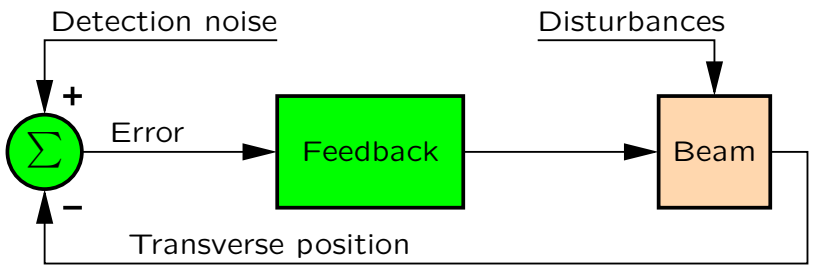
Why Is There a Notch?



- 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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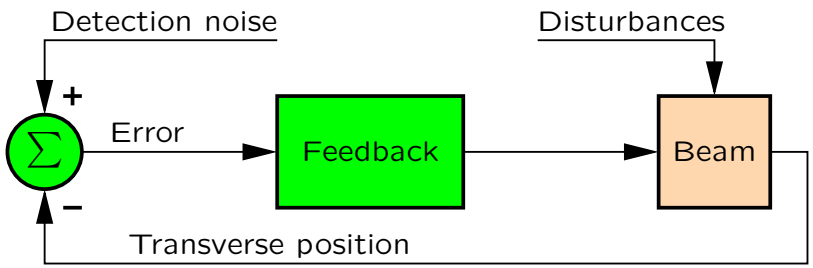

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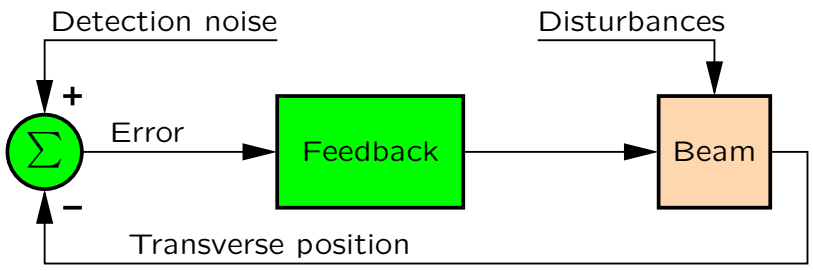

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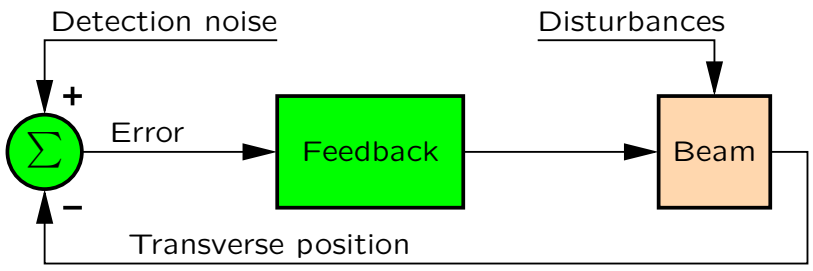

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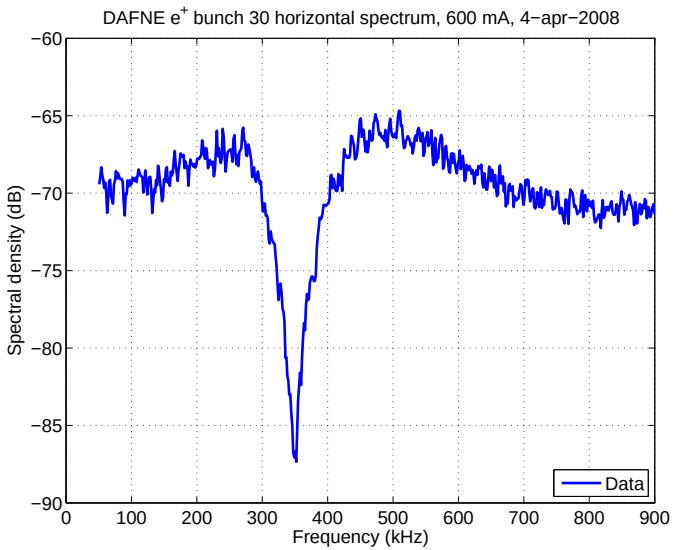
Bunch-by-bunch Tunes



- 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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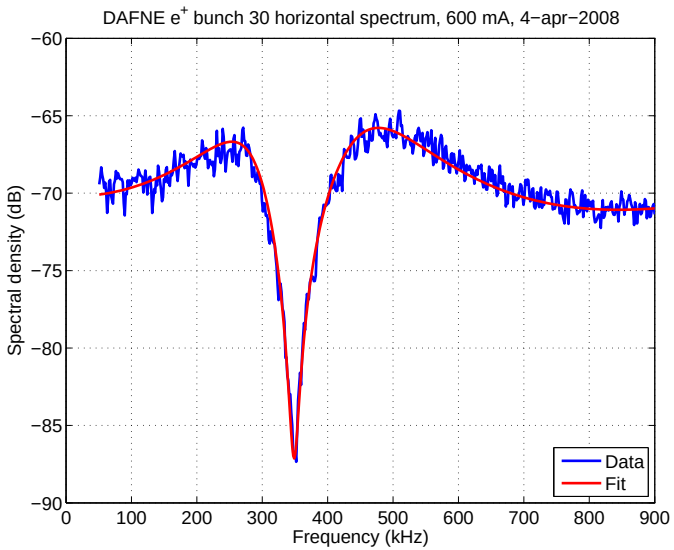

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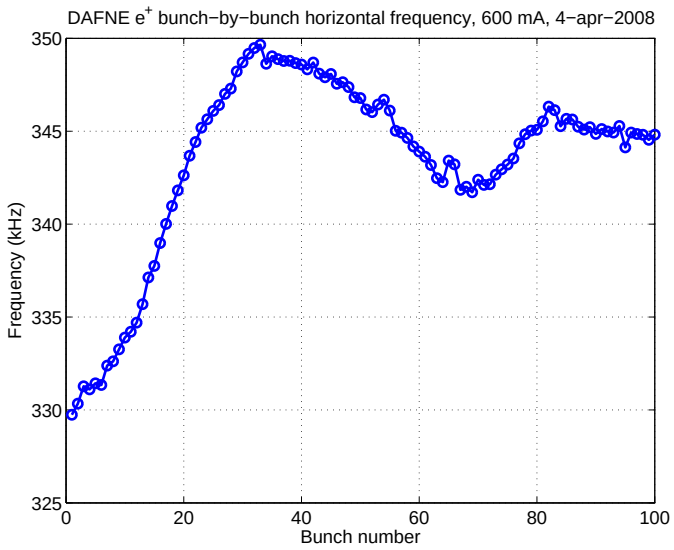

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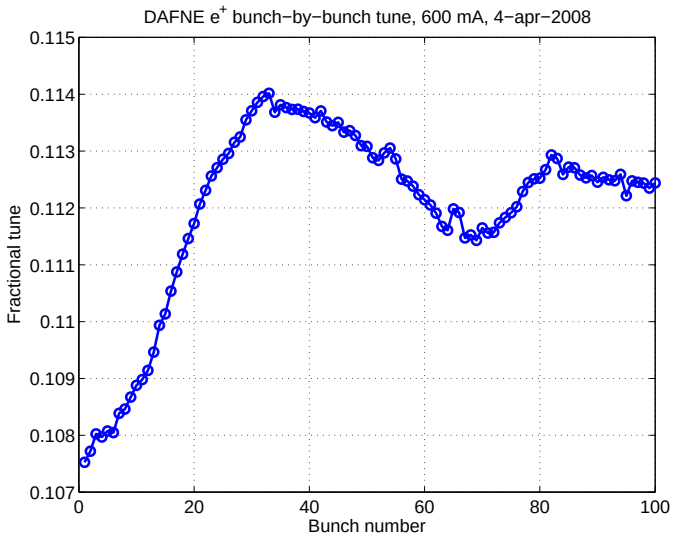

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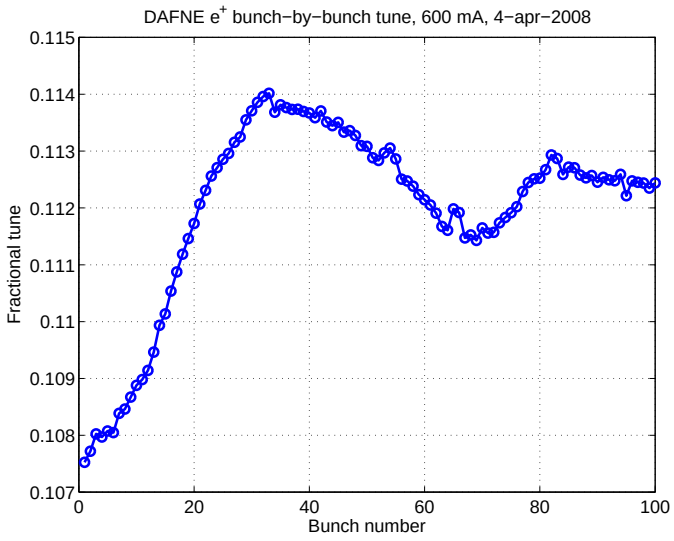

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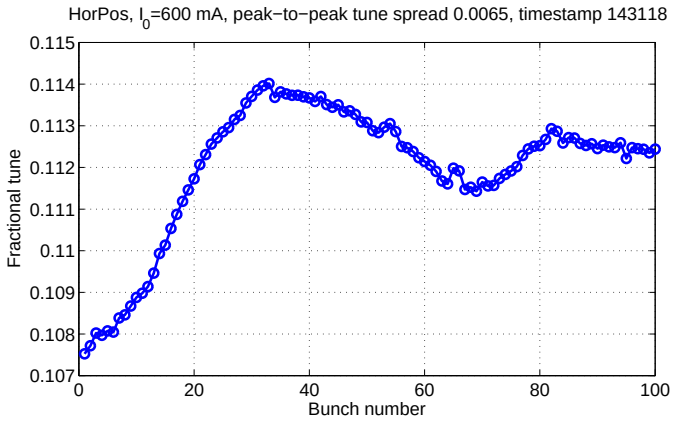

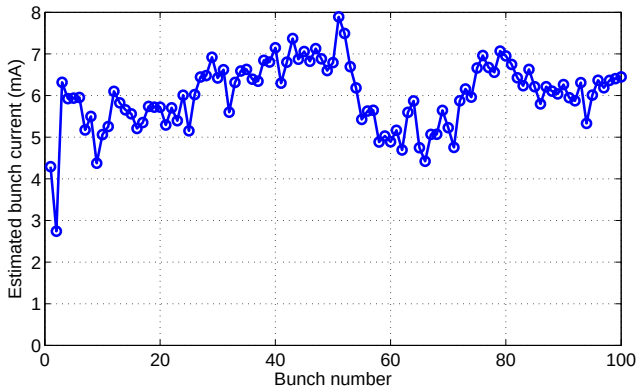

- Two measurements at 420 mA;
- Horizontal tune spread is 6.5×10^{-3};
- Vertical tune spread is 2.8×10^{-3}.

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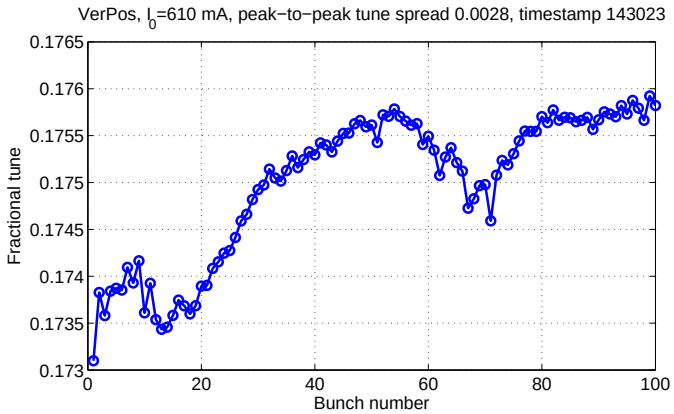

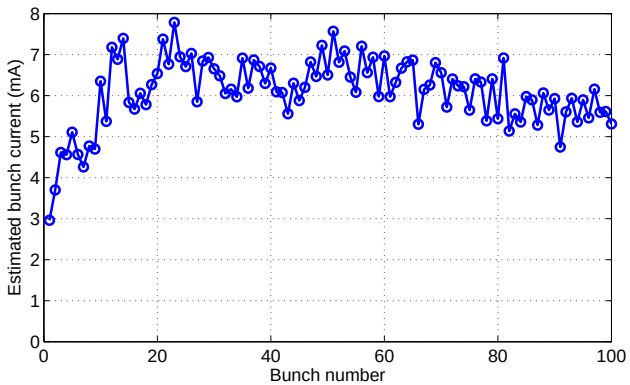

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Summary

- Bunch-by-bunch feedback is a well-understood powerful tool.
- Sophisticated beam and feedback modeling tools are critical for successful and reliable instability control.
- Bunch-by-bunch data acquisition yields a lot of diagnostic information.
- Some diagnostics are only possible within the feedback loop.

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