Bunch-by-bunch feedback and LLRF at ELSA

Dmitry Teytelman

Dimtel, Inc., San Jose, CA, USA

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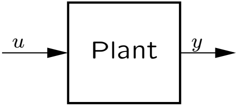
Outline

1. Feedback
   - Feedback basics
   - Coupled-bunch instabilities and feedback
   - Beam and feedback models
2. Diagnostics
   - Grow/Damp Measurements
3. ELSA Measurements
   - Hardware
   - Horizontal
   - Vertical
   - Longitudinal
   - Digital LLRF

Outline

Closed-loop Feedback: Structure and Example



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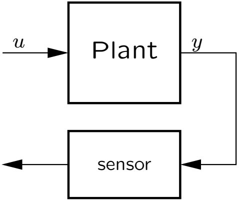

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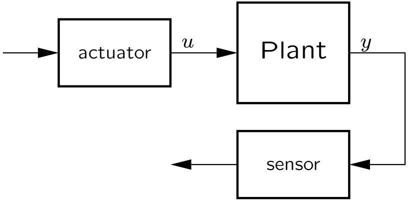

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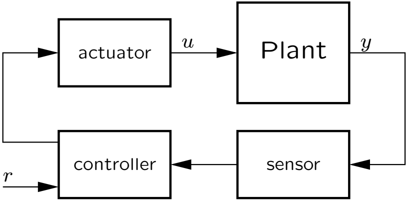

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- Feedback loop is completed by a controller.

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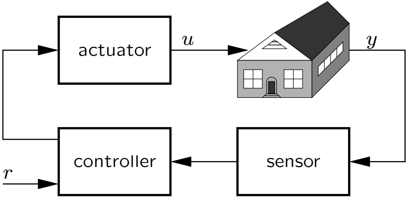

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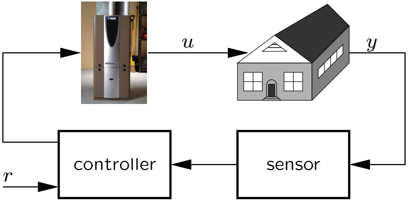

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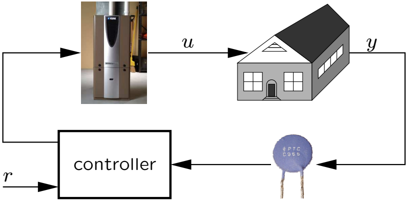

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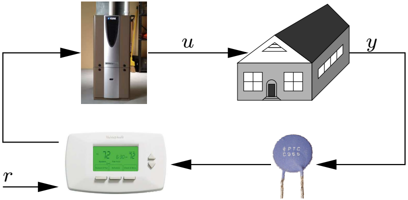

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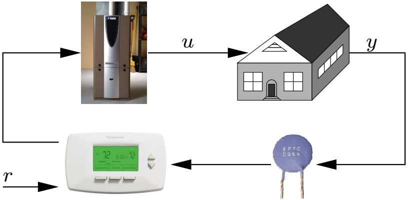
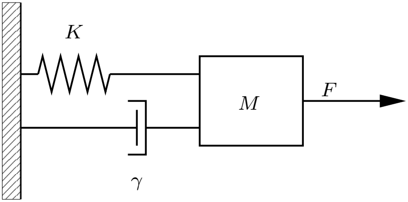


- Take a household heating system as an example.
  - Our plant is the house.
  - Actuator - furnace.
  - Sensor - thermistor.
  - Controller - thermostat.
- Loop signals
  - Output y - temperature;
  - Input u - heated air from the furnace;
  - Reference r - temperature setpoint.

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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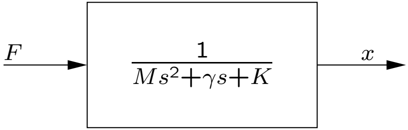

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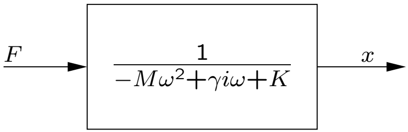

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Coupled-bunch Instabilities

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

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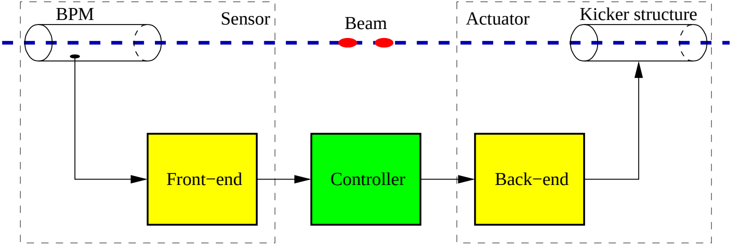
Bunch-by-bunch Feedback

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.

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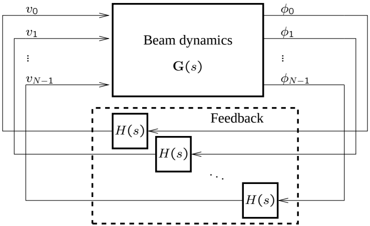
Coupled-bunch Instabilities: Eigenmodes and Eigenvalues

- 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.

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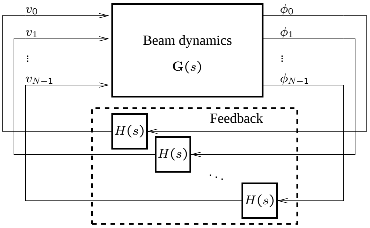

- If feedback is the same for all bunches, it is invariant under coordinate transformations.
- Bunch-by-bunch feedback applies the same feedback $H(s)$ to each eigenmode.
- Consequently it is sufficient to consider the most unstable eigenmode for modeling.

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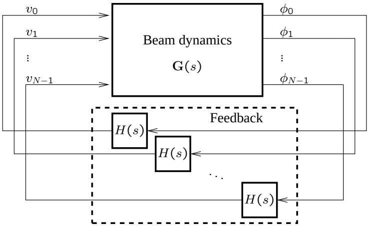

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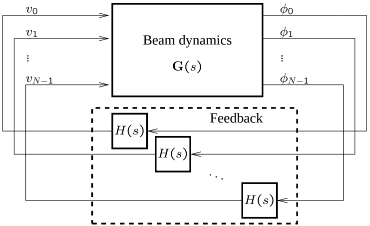

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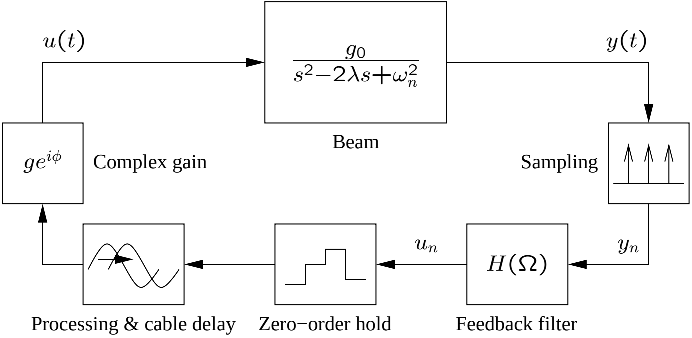
Detailed Scalar Feedback Model



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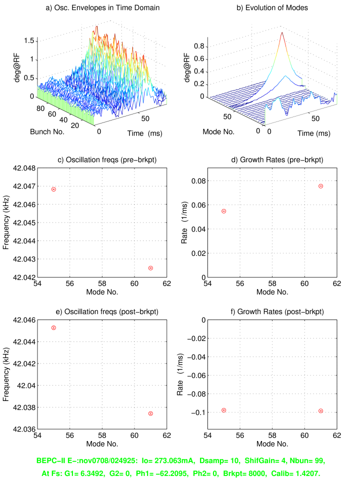
Grow/Damp Measurements



- 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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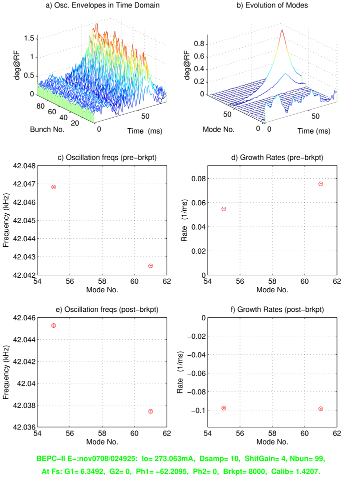

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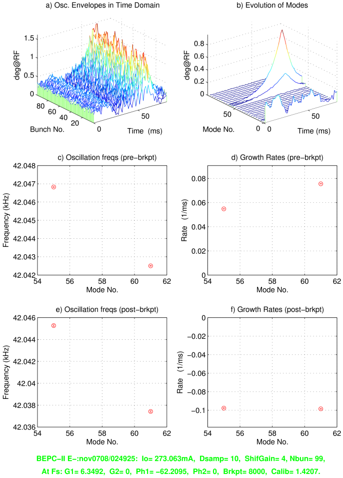

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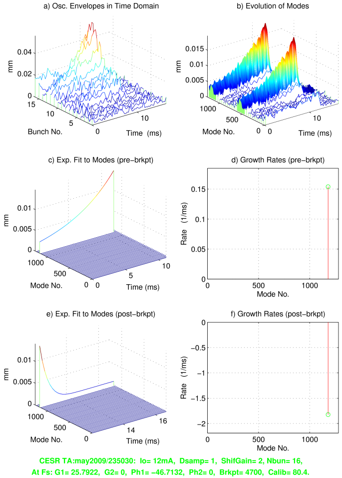

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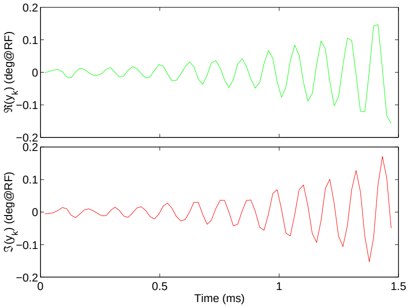
Estimating Eigenvalues



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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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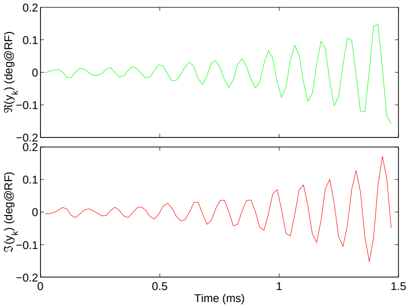

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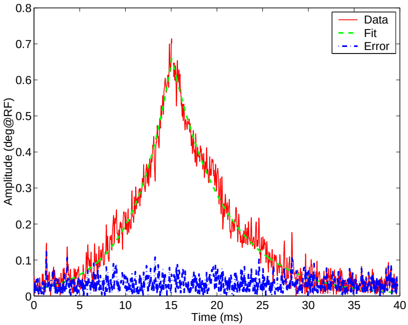

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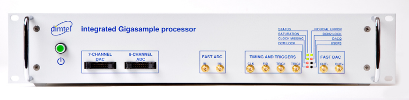
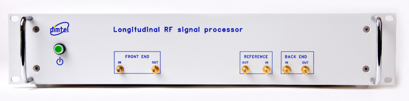
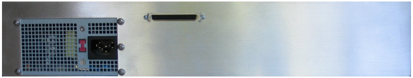
iGp Highlights



- A 500+ MHz processing channel.
- Finite Impulse Response (FIR) bunch-by-bunch filtering for feedback.
- Control and diagnostics via EPICS soft IOC on Linux.
- External triggers, fiducial synchronization, low-speed ADCs/DACs, general-purpose digital I/O.

Front/Back-end Unit





- 1.5 GHz front-end detection frequency.
- 2-cycle comb generator.
- 1 GHz back-end frequency.
- Integrated control via iGp GPIO:
  - Front and back-end LO phase shifters;
  - Front and back-end attenuators.

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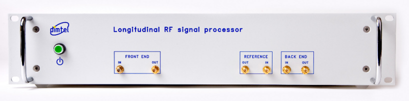

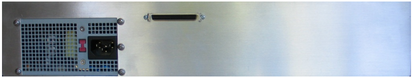

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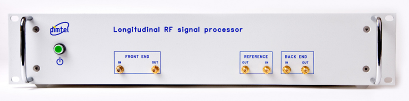

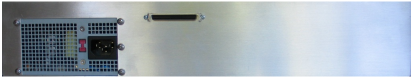

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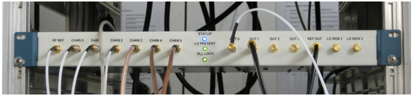

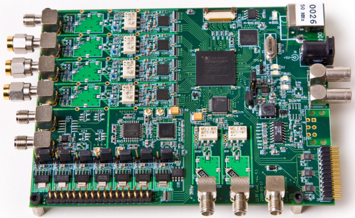

- Full cavity control and monitoring;
- 6 RF inputs: forward, reflected, and probe signals;
- Klystron drive in open or closed-loop mode;
- Calibrated monitoring of channel amplitude and phase;
- Interlock options, digital I/O (tuners), EPICS controls.

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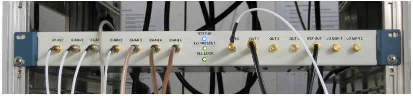

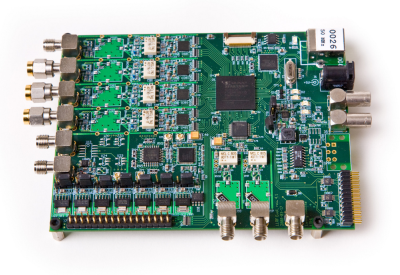

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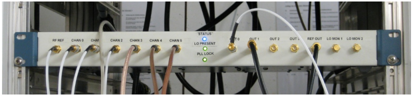

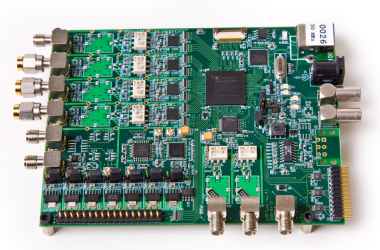

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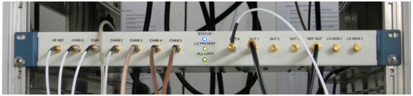

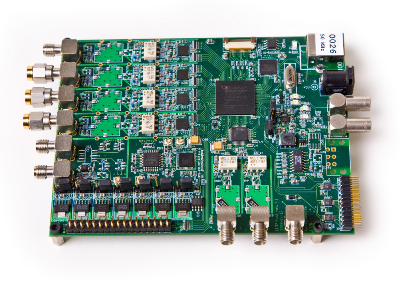

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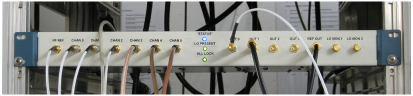

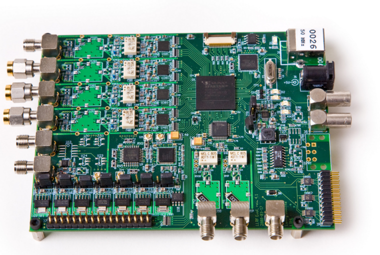

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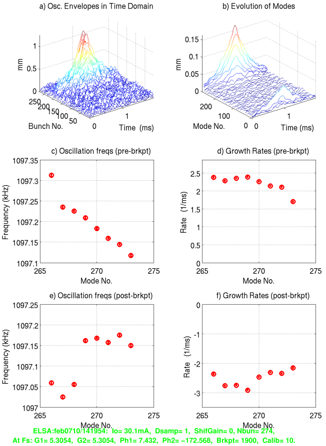
Horizontal Drive/Damp



- Measurement at 30 mA, 2.3 GeV;
- Beam is stable, had to apply positive feedback;
- Band of modes centered at 270 (-4);
- Suggestive of ion-driven instability.

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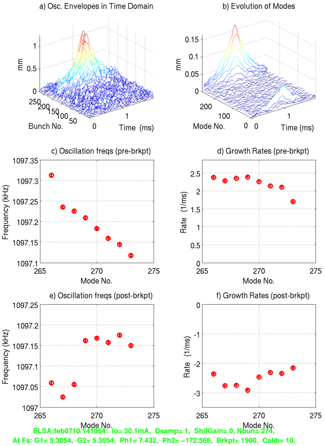

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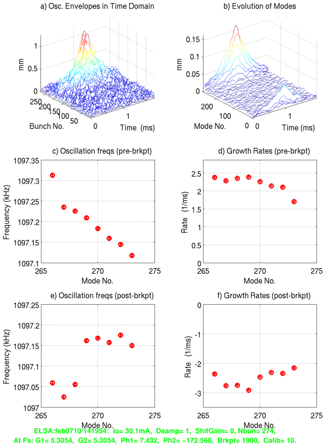

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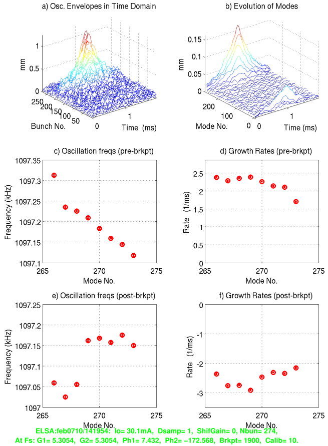

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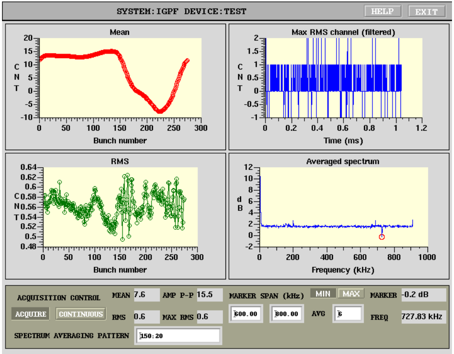
Horizontal Closed-loop Spectrum



- Measurement at 7 mA, 2.3 GeV;
- Feedback loop is closed;
- Notch at the betatron frequency;
- Can be used for parasitic tune measurement at 1 Hz rate.

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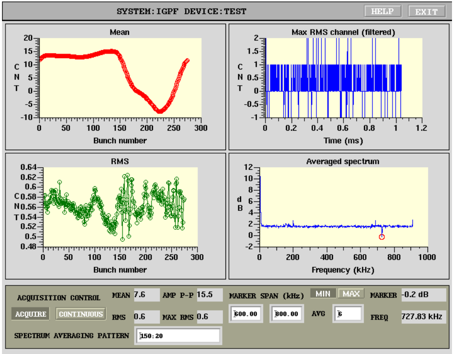

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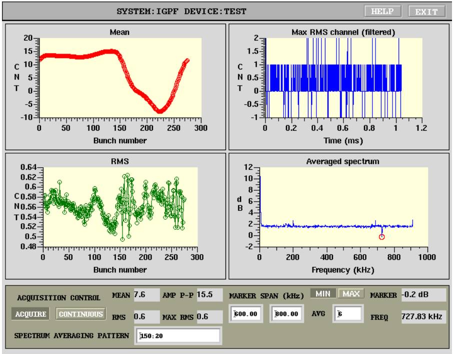

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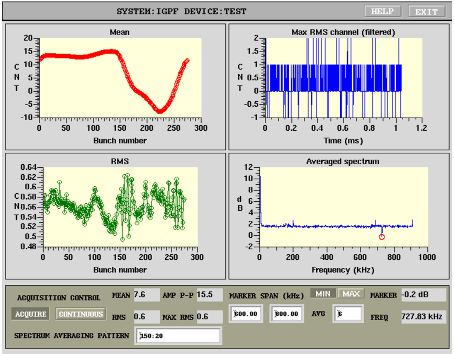

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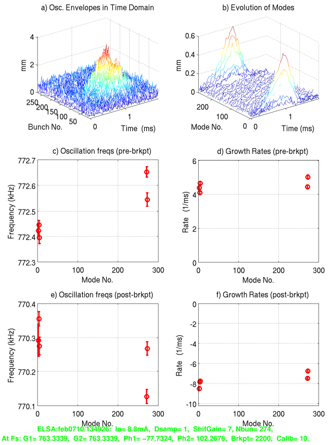
Outline

Vertical Drive/Damp



- Measurement at 8.8 mA, 2.3 GeV;
- Two bands of modes: around -1 and 4;
- Combination of resistive wall and ions?

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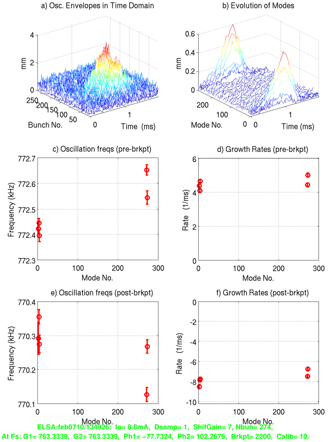

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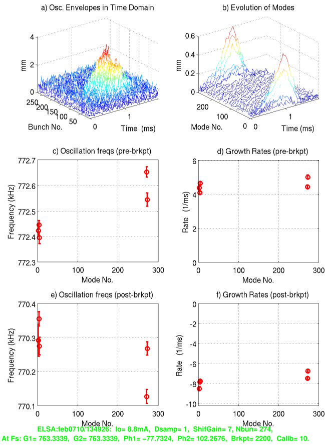

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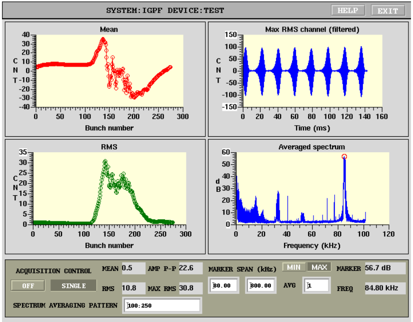
Outline

Bursting Longitudinal Motion



- Large amplitude (more than 30 degrees @ RF) longitudinal motion;
- Bursting at almost periodic intervals which change with beam current and energy;
- Time-domain plot of longitudinal position of one bunch;
- Spectrogram shows large tune shifts.

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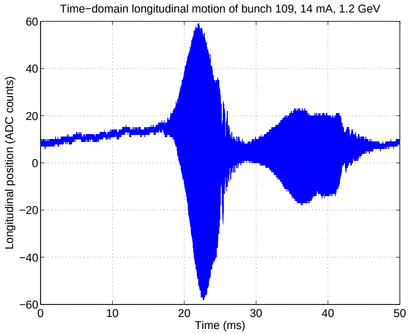

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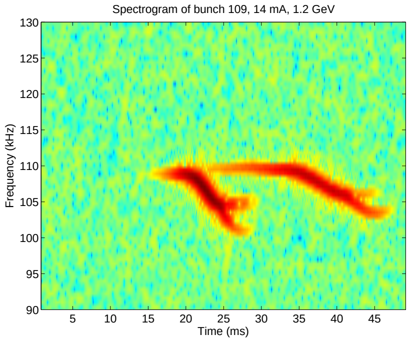

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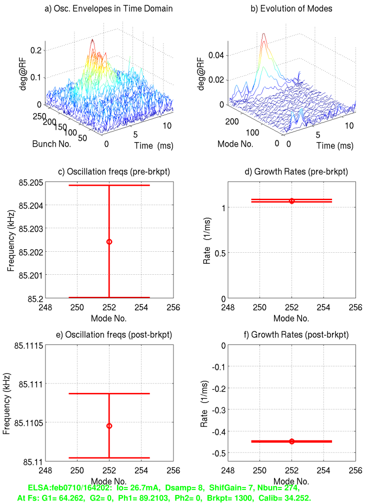
Longitudinal Stabilization



- Ramping to 2.3 GeV allowed us to stabilize the motion;
- Used a stripline as a weak longitudinal kicker;
- Mode 252 dominates;
- Good growth and damping fits with no tune shifts.

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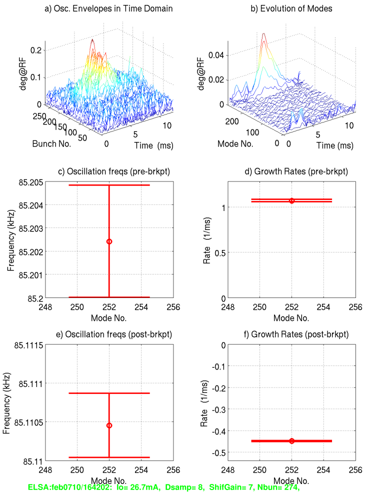

ELSA:feb0710/164202: Io= 26.7mA, Dsamp= 8, ShifGain= 7, Nbun= 274,
At Fs: G1= 64.262, G2= 0, Ph1= 89.2103, Ph2= 0, Brkpt= 1300, Calib= 34.252.

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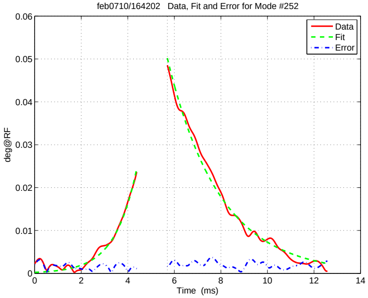

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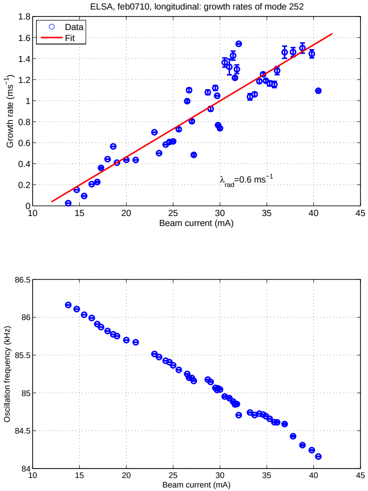
Growth Rates



- Extract growth and damping rates from multiple transients;
- Fairly linear behavior versus beam current;
- Estimated radiation damping time of 1.66 ms;
- Added measurements below instability threshold (excite the motion, record open-loop decay);
- Most likely there are higher-order dynamics in play.

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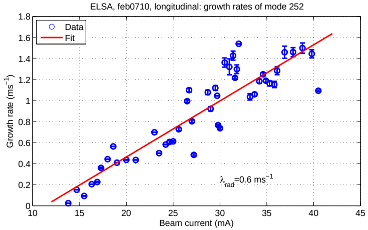

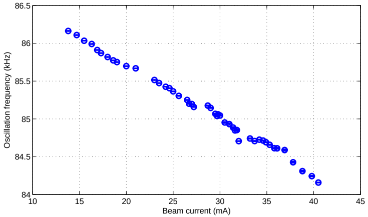

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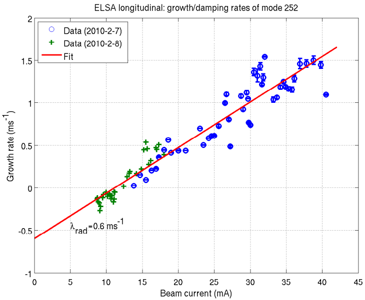

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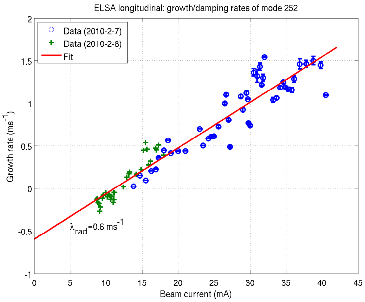

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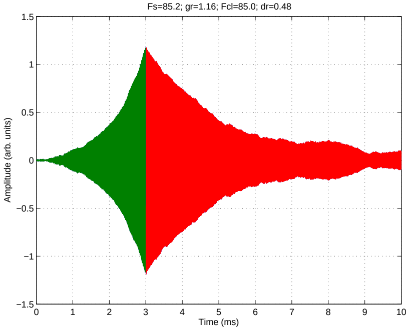

- Using measured growth and damping rates verify beam/feedback model;
- Simulated transient matches measurement at 26.7 mA;
- Extrapolate growth rate to 200 mA (10 ms^{-1}), assume 200 W power amplifiers with 450 Ω kicker;
- Excellent damping performance.

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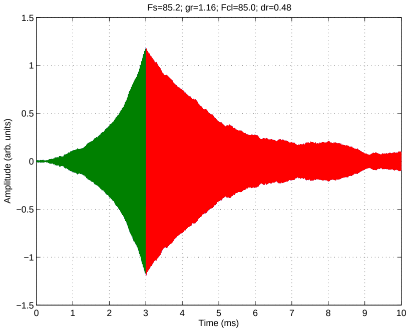

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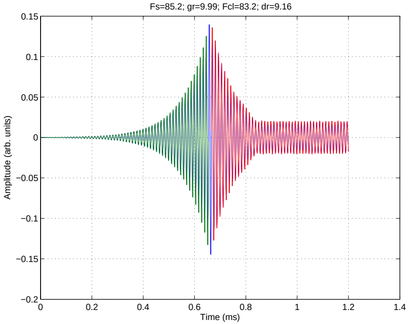

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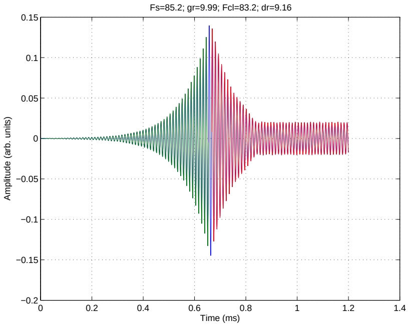

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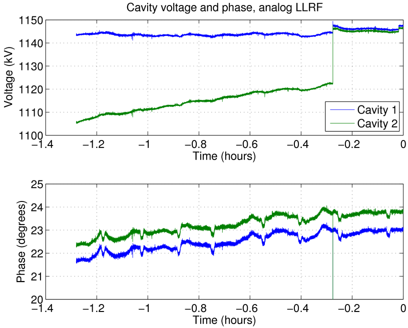
LLRF Testing Results



- Used the prototype to monitor cavity signals when running with the existing analog LLRF;
- Switched to prototype LLRF system for driving the klystron;
- Several hours running with beam (open-loop);
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dimtel

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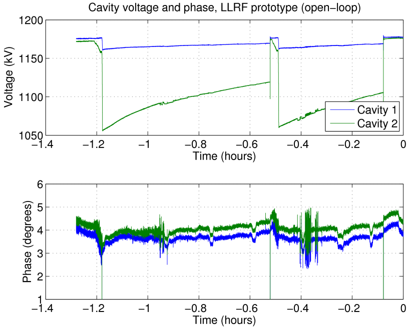

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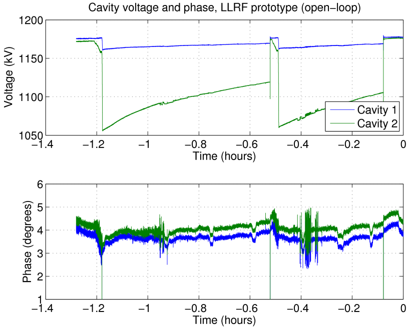

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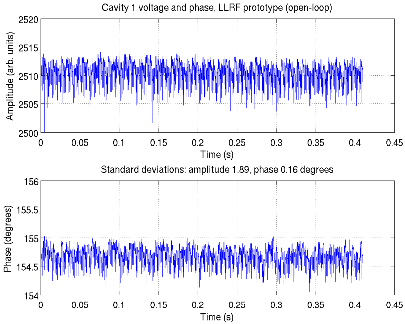

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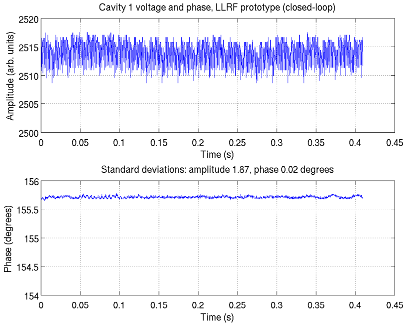

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- Interesting longitudinal dynamics at large amplitudes;
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