Bunch-by-bunch Feedback and Diagnostics

PLS-II

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Dimtel, Inc., San Jose, CA, USA

September 25, 2024

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- Coupled-bunch Instabilities

Bunch-by-bunch Feedback
- Overview
- Technology

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- Activities
- Comparison With SPring-8 Setup
- Grow/Damp Measurements
- Tune Measurements
- Bunch Cleaning

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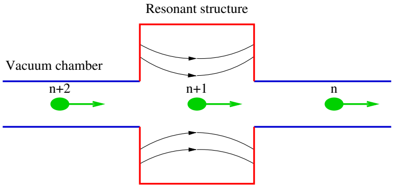
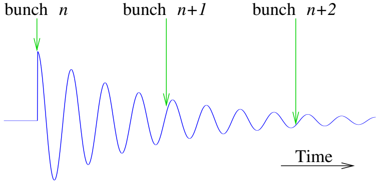
Coupled-bunch Instabilities





- Bunch passing through a resonant structure excites a wakefield which is sampled by the following bunches — a coupling mechanism;
- In practice the wakefields have much longer damping times than illustrated here;
- Longitudinal bunch oscillation → phase modulation of the wakefield → slope of the wake voltage sampled by the following bunches determines the coupling.
- For certain combinations of wakefield amplitudes and frequencies the overall system becomes unstable.

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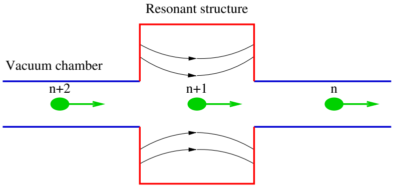

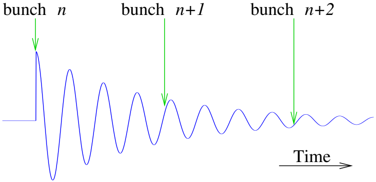

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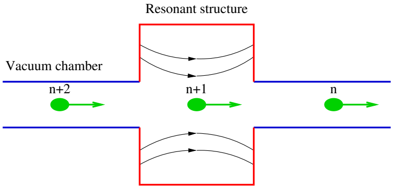

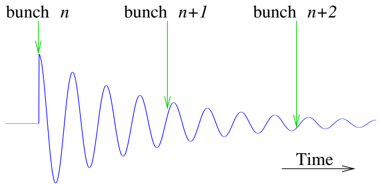

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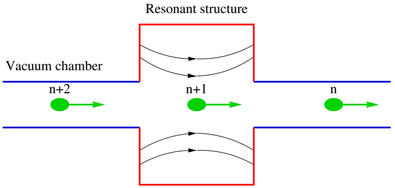

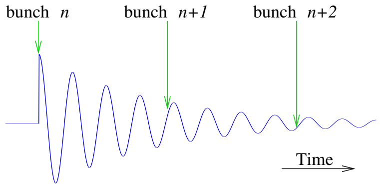

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Coupled-bunch Instabilities: Eigenmodes and Eigenvalues

- A system of N bunches (coupled harmonic oscillators) has N eigenmodes;
- From symmetry considerations we find that the eigenmodes correspond to Fourier vectors;
- Mode number m describes the number of oscillation periods over one turn;
- Wakefields affect the modal eigenvalues in both real (growth rate) and imaginary (oscillation frequency) parts;
- Motion of bunch k oscillating in mode m is given by: $A_m e^{i2\pi km/N} e^{\Lambda_m t}$
  - A_m — modal amplitude;
  - Λ_m — complex modal eigenvalue.

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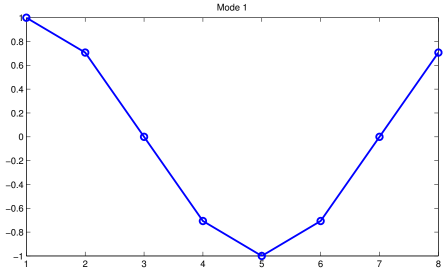
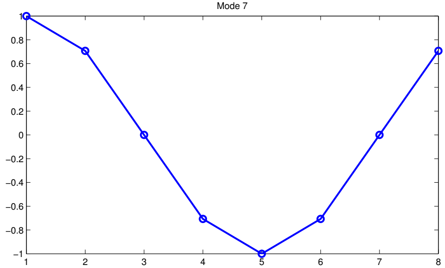
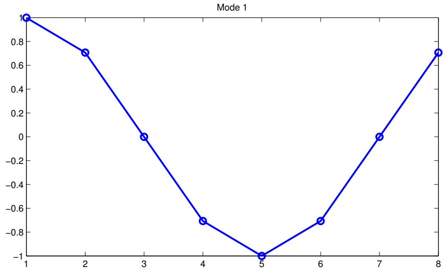
Modal Oscillation Example

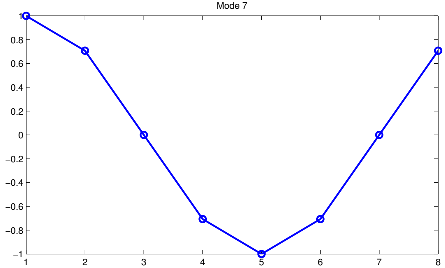




- Harmonic number of 8;
- Top plot — mode 1;
- Bottom — mode 7;
- All bunches oscillate at the same amplitude and frequency, but different phases;
- Cannot distinguish modes m and $N - m$ (or $-m$) from a single turn snapshot.

Modal Oscillation With Damping





- Same modes with damping.

Coupled-bunch Instabilities: Eigenvalues and Impedances

- Beam interacts with wakefields (impedances in frequency domain) at synchrotron or betatron sidebands of revolution harmonics;
- Impedance functions are aliased, since they are sampled by the beam;
- Longitudinal: $\Lambda_m = (-\lambda_{\text{rad}}^{\|} + i\omega_s) + \frac{\pi\alpha e f_{\text{rf}}^2 I_0}{E_0 h \omega_s} Z^{\|\text{eff}}(m\omega_0 + \omega_s)$;
- Effective impedance: $Z^{\|\text{eff}}(\omega) = \sum_{p=-\infty}^{\infty} \frac{p\omega_{\text{rf}}+\omega}{\omega_{\text{rf}}} Z^{\|}(p\omega_{\text{rf}} + \omega)$
- Transverse: $\Lambda_m = (-\lambda_{\text{rad}}^{\perp} + i\omega_\beta) - \frac{c e f_{\text{rev}} I_0}{2\omega_\beta E_0} Z^{\perp\text{eff}}(m\omega_0 + \omega_\beta)$
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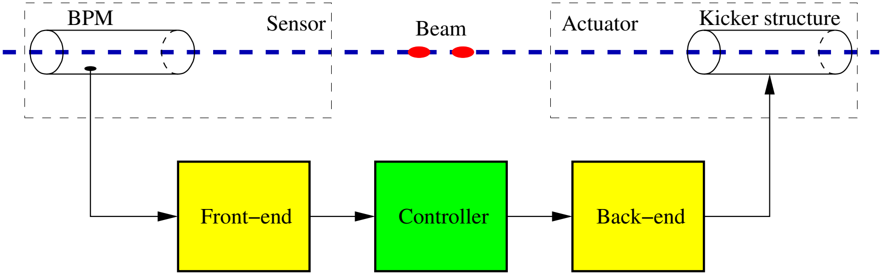
Bunch-by-bunch Feedback

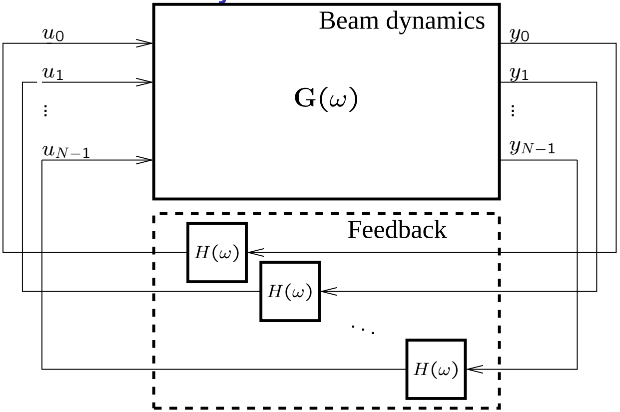
Definition

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



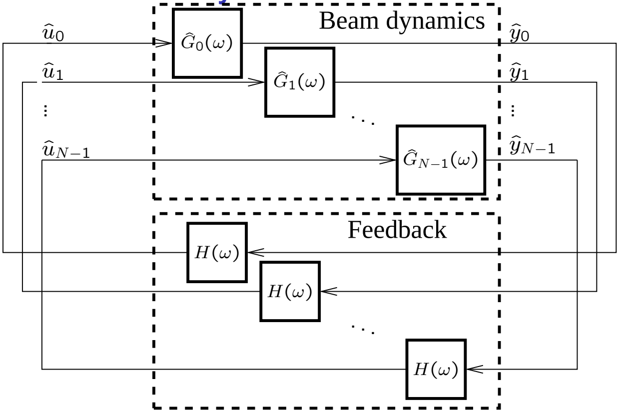
- Bunches are processed sequentially;
- Correction kicks are applied one or more turns later;
- Diagonal feedback — computationally efficient;
- Extremely popular in storage rings — why?

MIMO Model of Bunch-by-bunch Feedback



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

MIMO Model of Bunch-by-bunch Feedback



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

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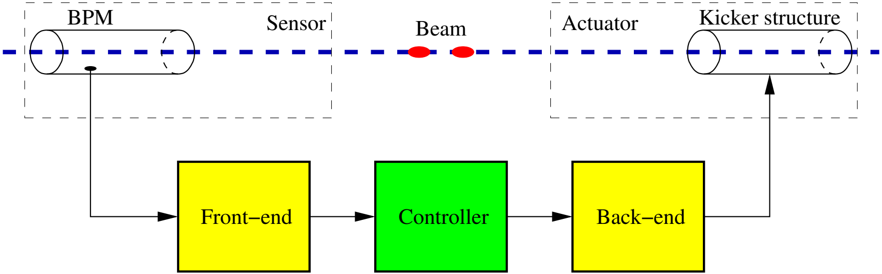

- Sensor (pickup);
- Analog front-end;
- Controller;
- Analog back-end;
- Actuator (kicker).

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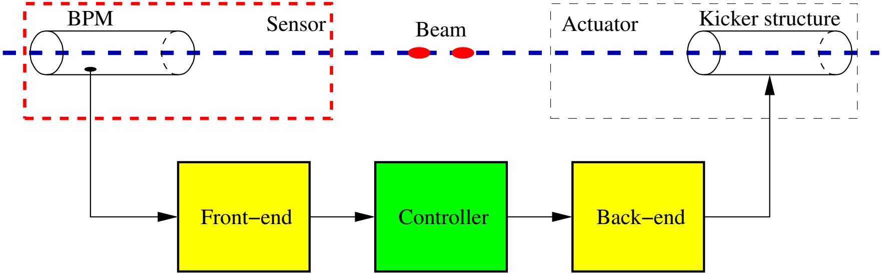

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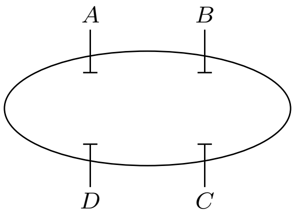
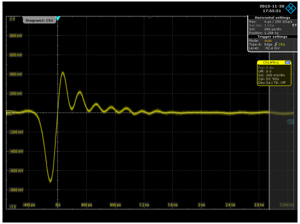
Beam Position Sensor





- To sense beam position we typically use capacitive button beam position monitors (BPMs);
- Buttons couple capacitively to the beam, differentiating bunch current shape;
- BPM signals are wideband differentiated pulses with 100–400 ps duration;
- Differentiation means sensor gain increases with frequency.

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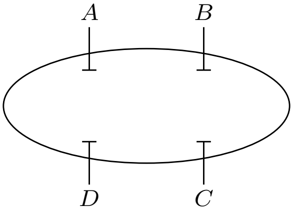

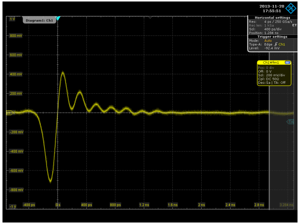

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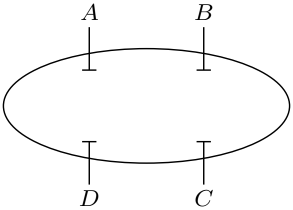

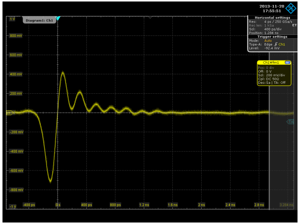

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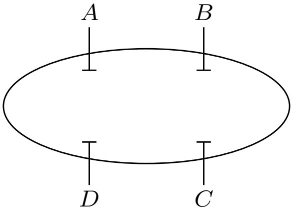

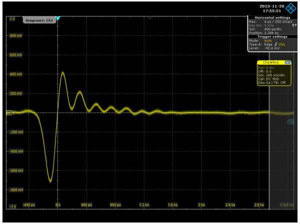

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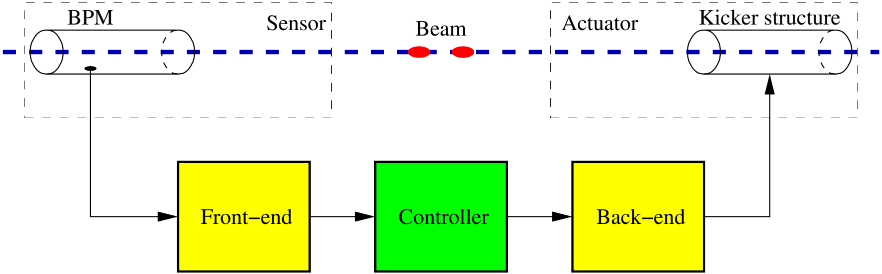

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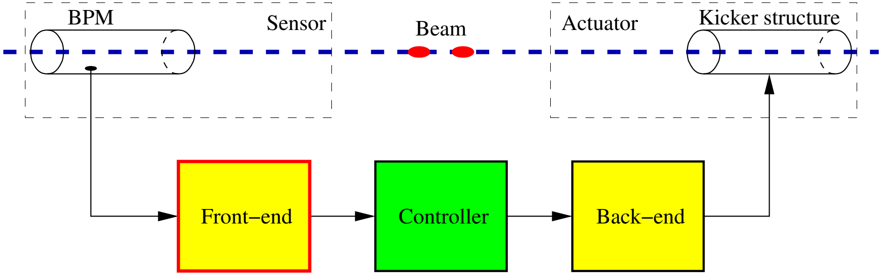

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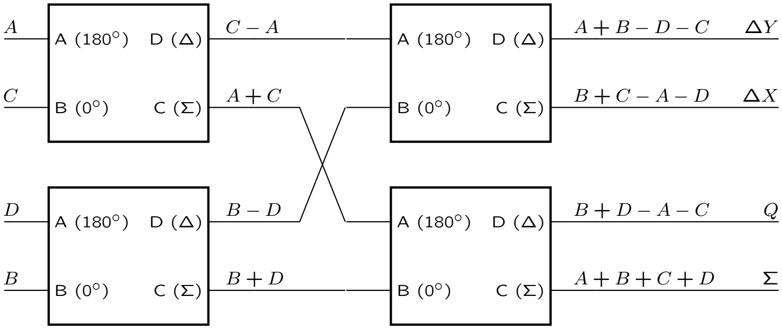

- First stage of BPM signal processing — separating X/Y/Z signals;
- Since we are digitizing in the end, why not digitize raw signals?
- For X and Y we are dealing with small differences of large signals;
- If we can reject the common-mode at 20–30 dB level, that is also the gain of low-noise amplifier we can use to improve sensitivity.

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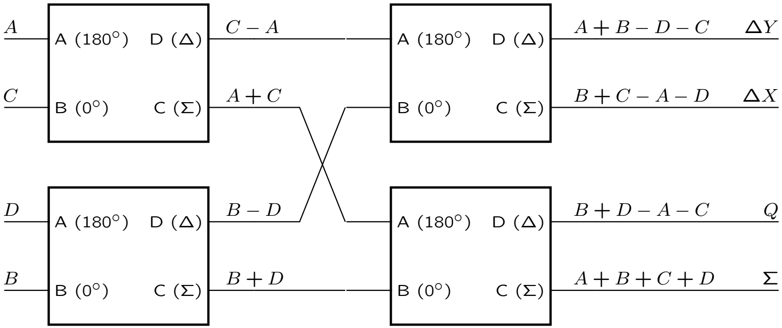

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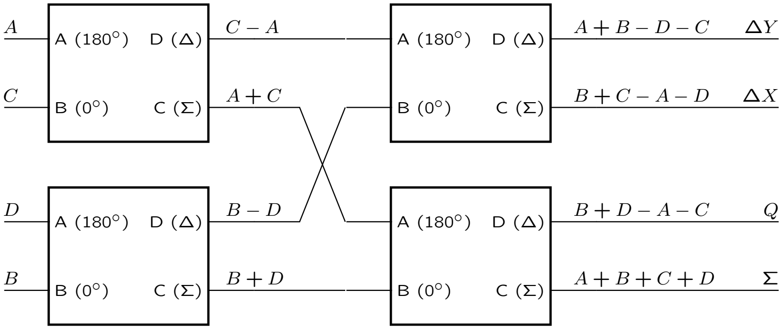

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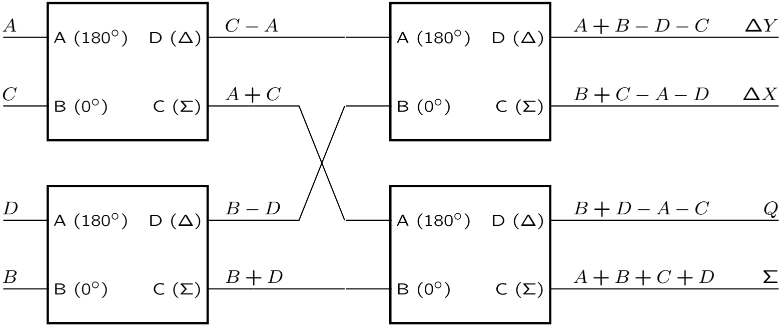
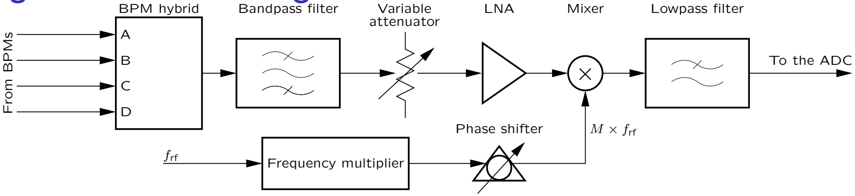
BPM Hybrid Network



- First stage of BPM signal processing — separating X/Y/Z signals;
- Since we are digitizing in the end, why not digitize raw signals?
- For X and Y we are dealing with small differences of large signals;
- If we can reject the common-mode at 20–30 dB level, that is also the gain of low-noise amplifier we can use to improve sensitivity.

Analog Front-end Design



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

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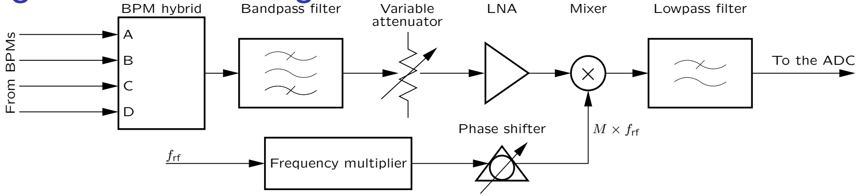

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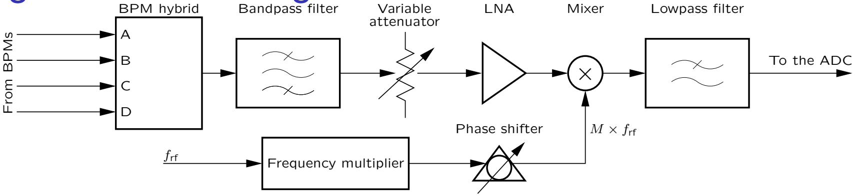

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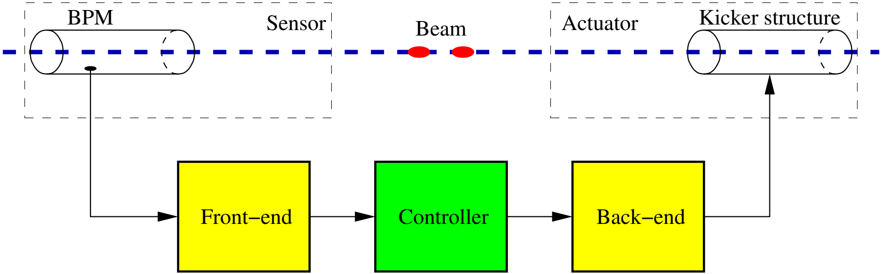

- Sensor (pickup);
- Analog front-end;
- Controller;
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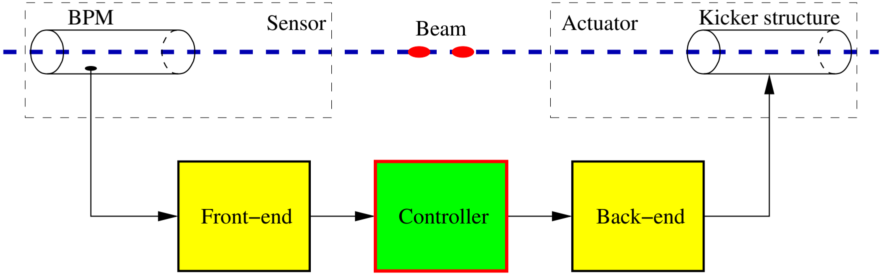

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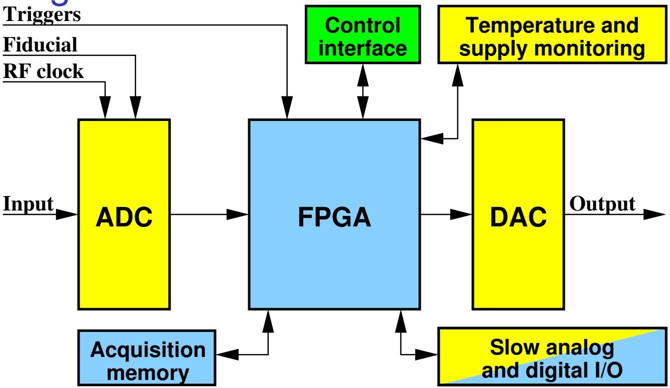
Baseband Signal Processor



- Block diagram of a type frequently seen in accelerator context: ADC, FPGA, and DAC;
- ADC, DAC: 12–14 bit, 500–600 megasamples per second, 400 ps rise/fall times;
- FPGA implements algorithmically simple, but computationally intensive processing.

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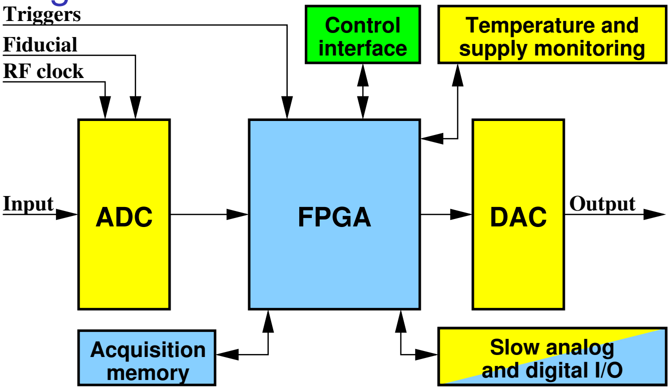

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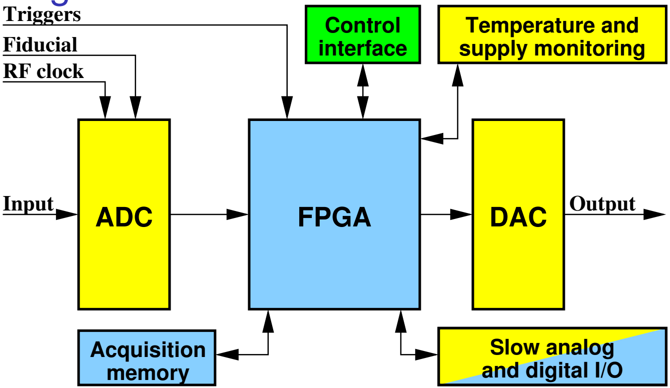

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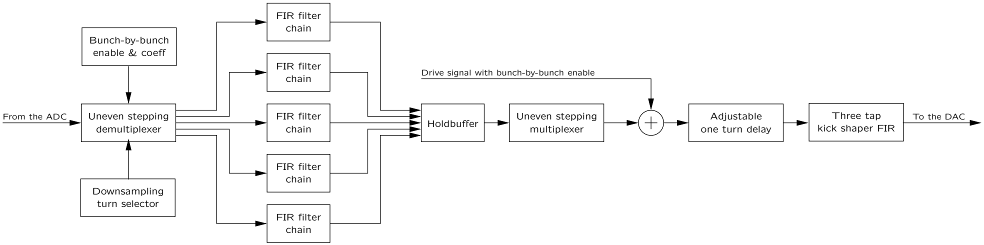
Inside the FPGA



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

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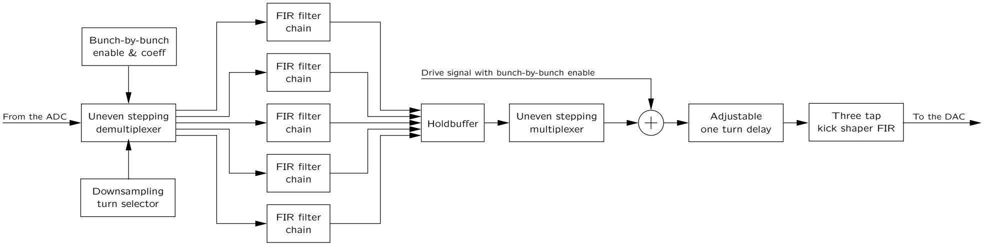

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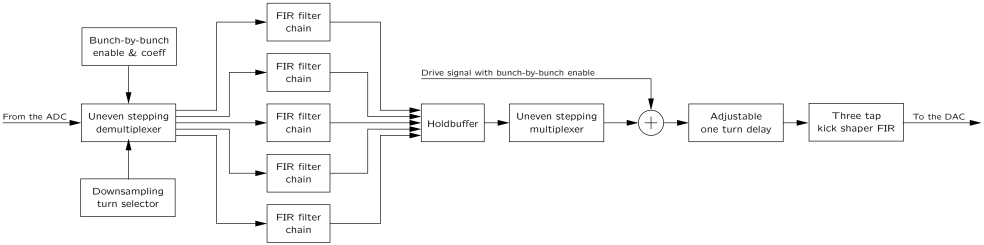

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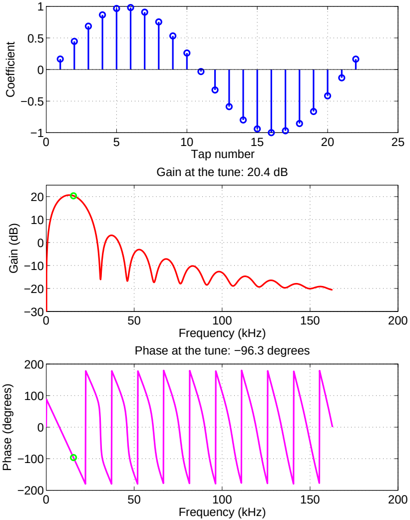
Feedback Filter



- Requirements:
  - Adjustable phase shift at the tune frequency;
  - DC rejection to get rid of constant orbit offsets;
  - Low group delay.
- Filter design approach — sample one period of a sine wave;
  - Group delay is $\frac{1}{2}$ of oscillation period;
  - Nicely parameterized, often close to optimal.
- More sophisticated design methods are required when large perturbations are present or with variable beam dynamics, etc.

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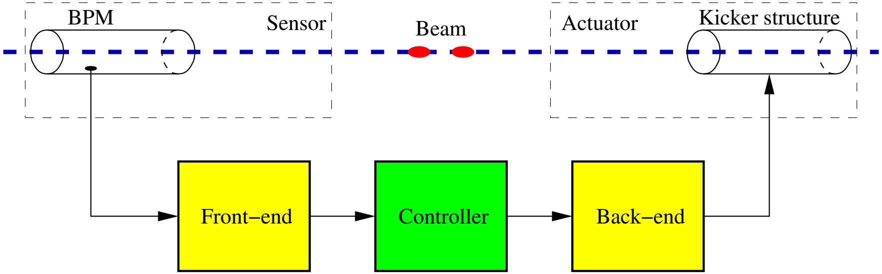

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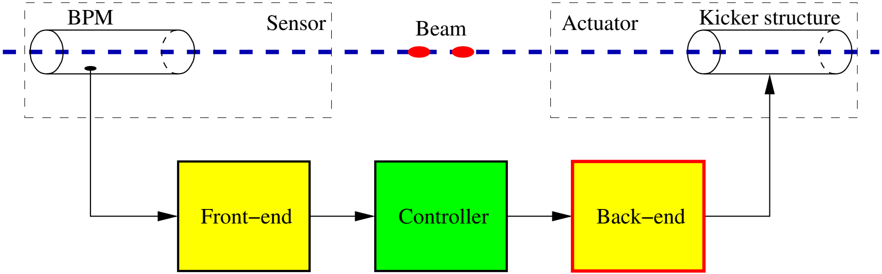

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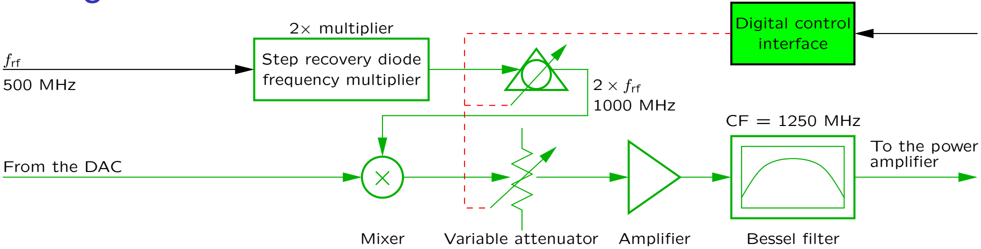

- Longitudinal kickers are usually built as highly damped (low Q, wideband) cavities at 1–1.5 GHz;
- Baseband kick must be upconverted to the right frequency to drive these;
- Phase linearity is critical to maintain the same feedback for different modes;
- Constant group-delay filters are used to create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

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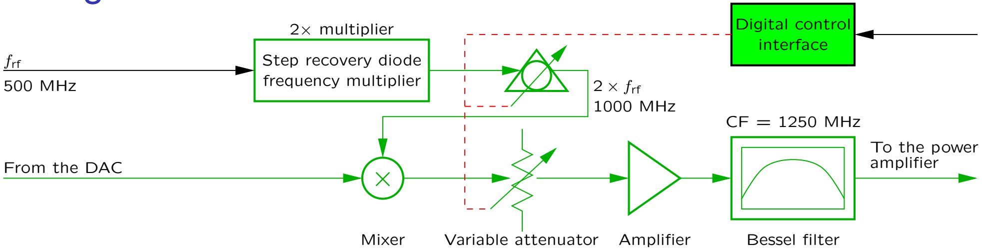

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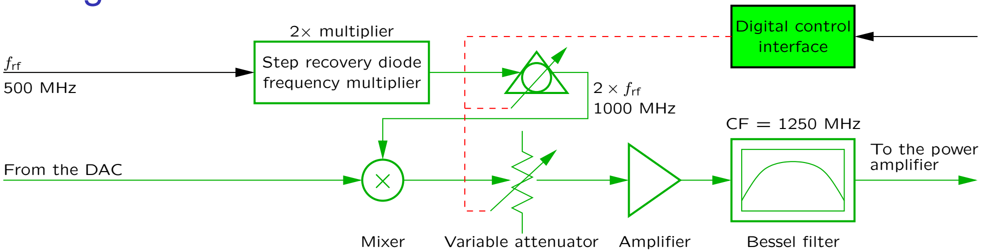

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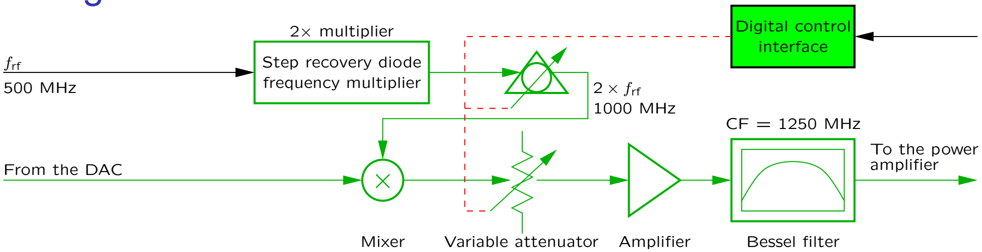

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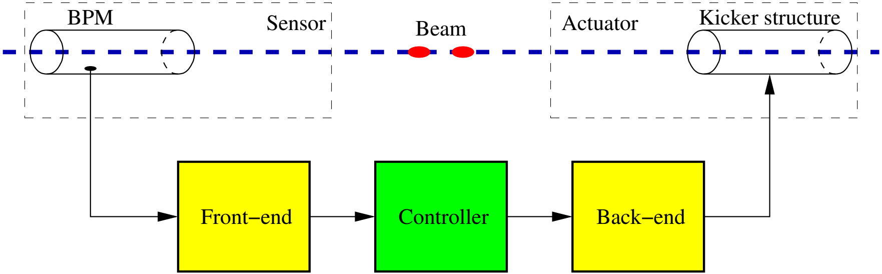

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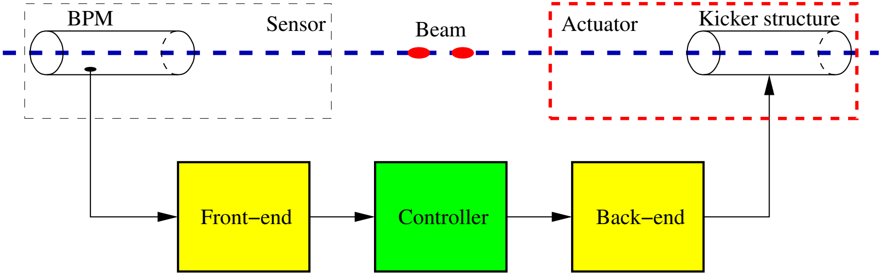

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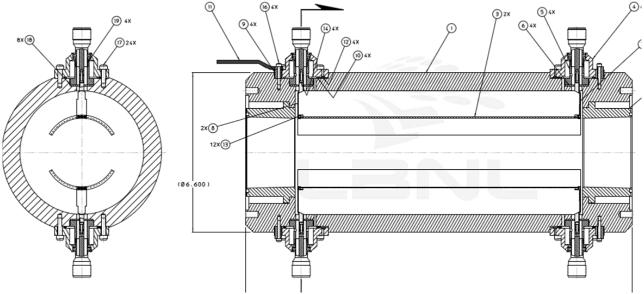
Transverse Kicker



- 50 Ω striplines driven differentially;
- Counter-propagating beam and kick signals;
- For 2 ns bunch spacing maximum stripline length is 1 ns:
  - Fill time of 1 ns;
  - Beam propagation time of 1 ns;
  - Longer striplines will couple the kick to neighboring bunches.
- Shorter striplines — better isolation, have smaller kick.

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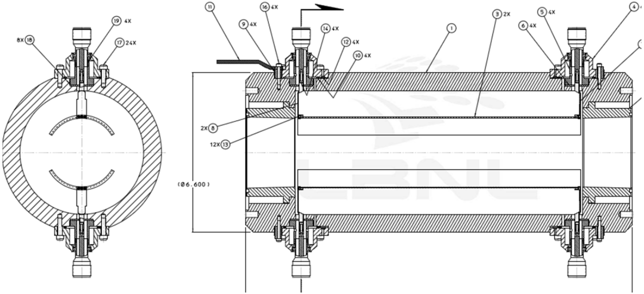

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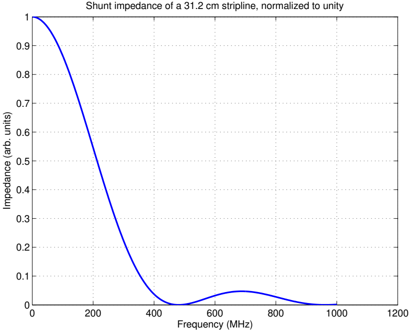

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Demonstration Summary

- Saturday, September 21:
  - Started from unpacking hardware around 11:15;
  - Connected $A - C$ hybrid output to the front-end, iGp12 outputs to amplifiers A and C;
  - Set up transverse feedback in X and Y by 14:00;
  - After lunch set up fast tune tracking to characterize tune variation;
  - Investigated observed offsets between spectrum analyzer and feedback notch tune measurement methods.
- Sunday, September 22:
  - Reconfigured for an A/B comparison with the SPring-8 system;
  - Performed vertical and horizontal calibration;
  - Reconfigured the feedback input chain, recalibrated;
  - Spent the rest of the day demonstrating bunch cleaning.
- Monday, September 23:
  - Configured the feedback to increase camshaft bunch current;
  - Investigated transverse stability as a function of insertion device gaps;
  - Left ring running overnight with 7 mA camshaft bunch.

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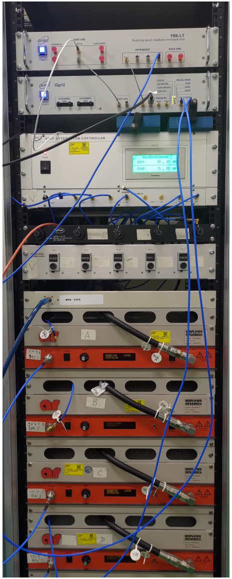

- Three Dimtel units:
  - iGp12 baseband processor;
  - FBE-500LT analog front/back-end;
  - BPMH-20-2G BPMH hybrid network.
- Used buttons A and C, adjustable delays to compensate for cable length errors;
- Only two amplifiers driven differentially: A and C.

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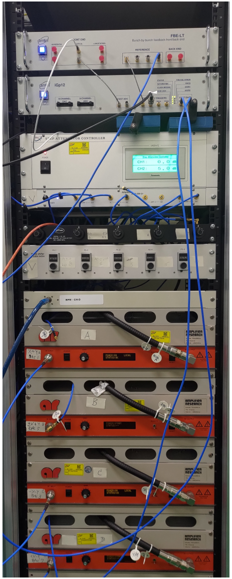

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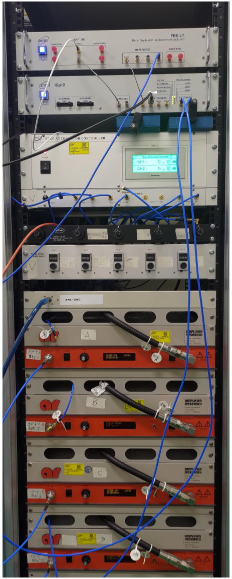

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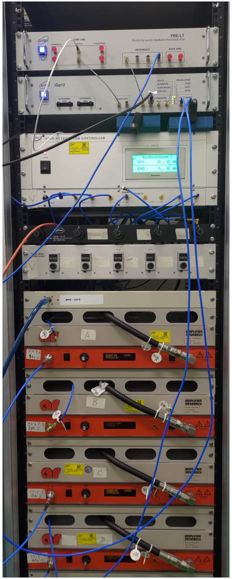

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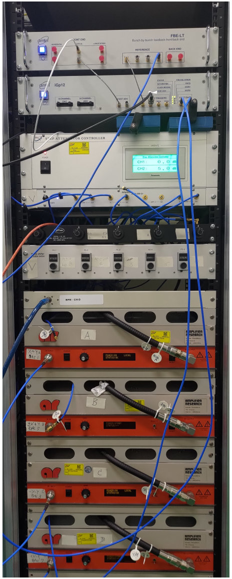

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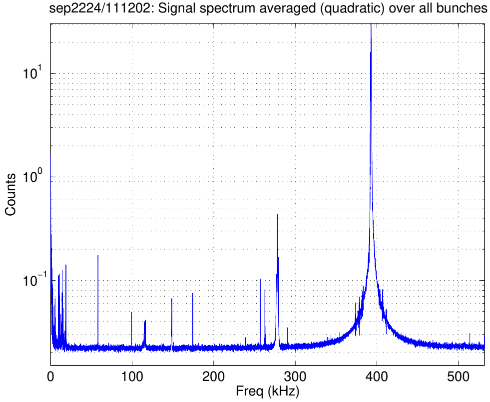
Setup and Spectra



- SPring-8 system in normal configuration;
- Dimtel system monitoring unused button D;
- Open-loop measurement, large X motion;
- Another open-loop dataset, quiet;
- SPring-8 system operational, little effect in the vertical plane;
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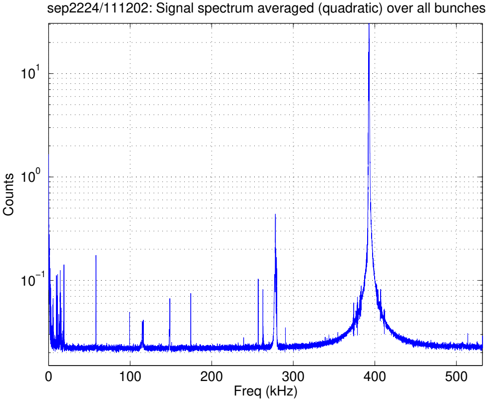

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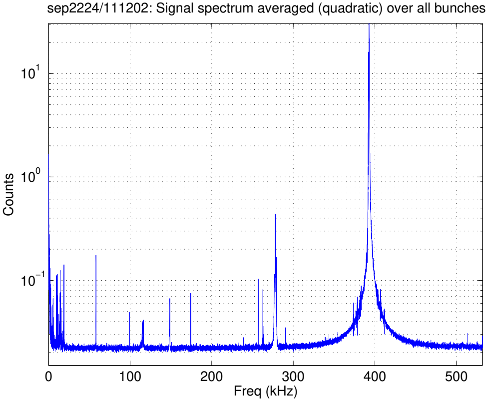

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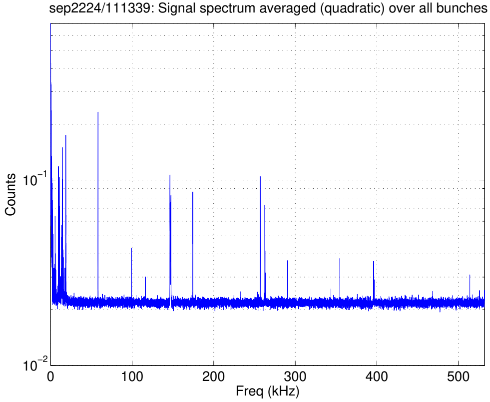

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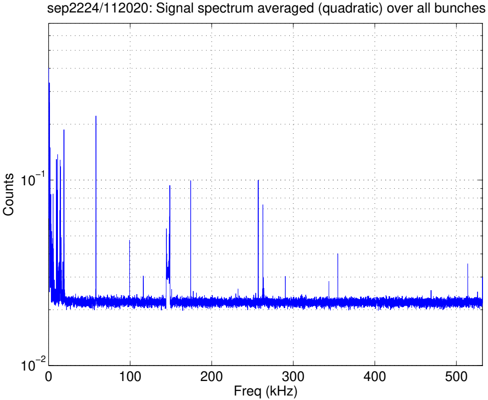

- SPring-8 system in normal configuration;
- Dimtel system monitoring unused button D;
- Open-loop measurement, large X motion;
- Another open-loop dataset, quiet;
- SPring-8 system operational, little effect in the vertical plane;
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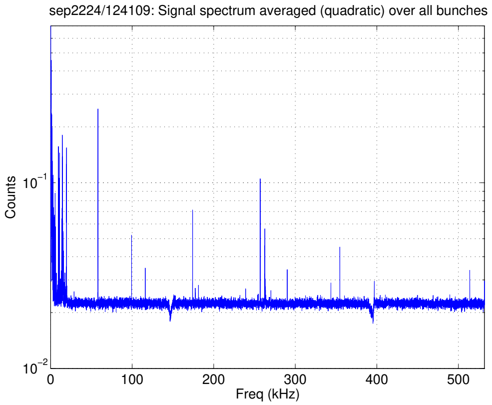

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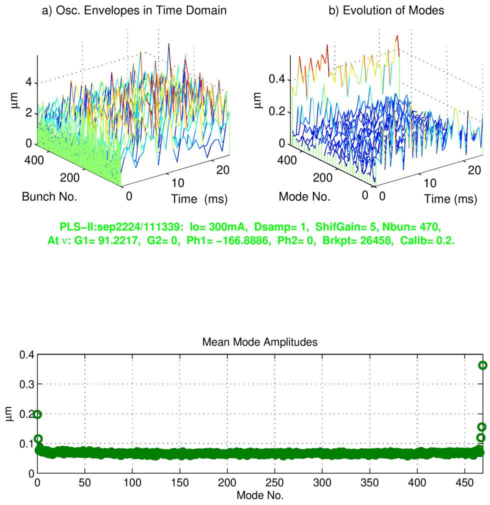
Modal Amplitudes, Horizontal Plane



- Data filtered around ν_x, calibration applied;
- Open-loop;
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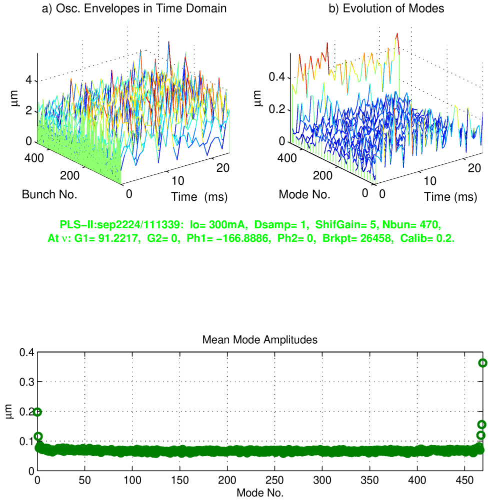
Modal Amplitudes, Horizontal Plane



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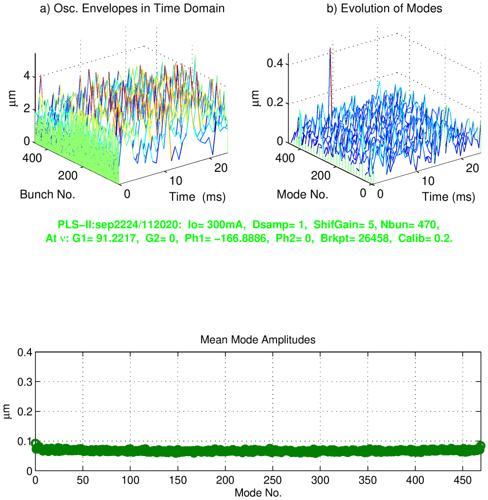

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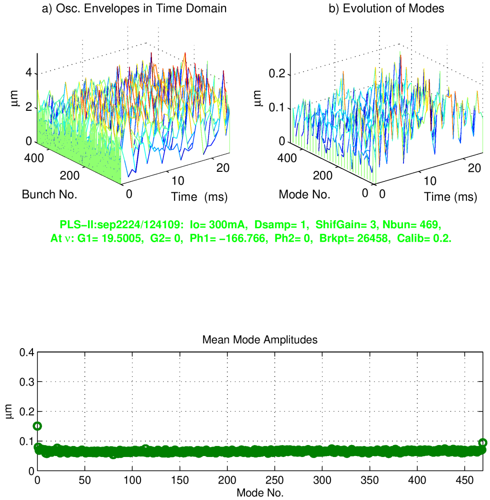

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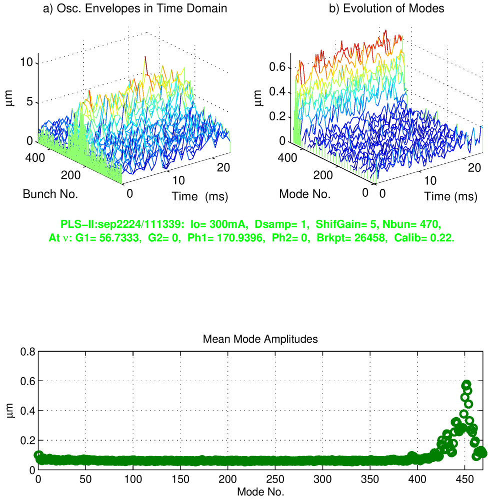

- Data filtered around ν_y, calibration applied;
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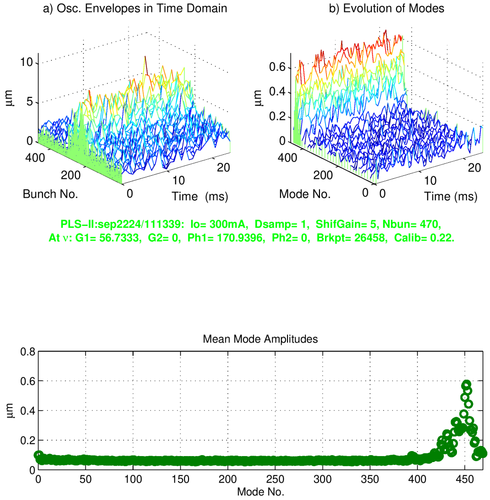

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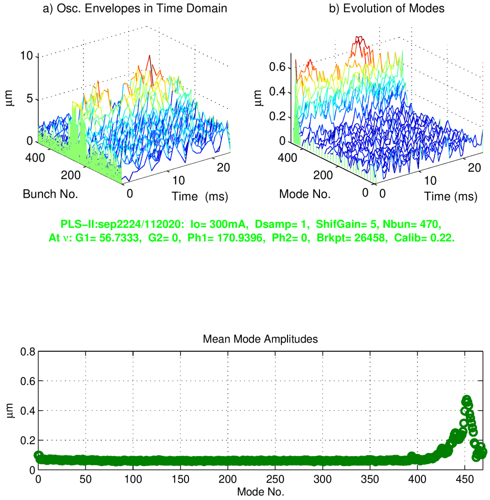

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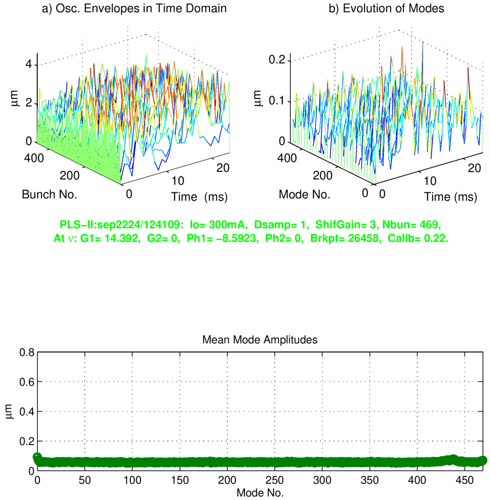

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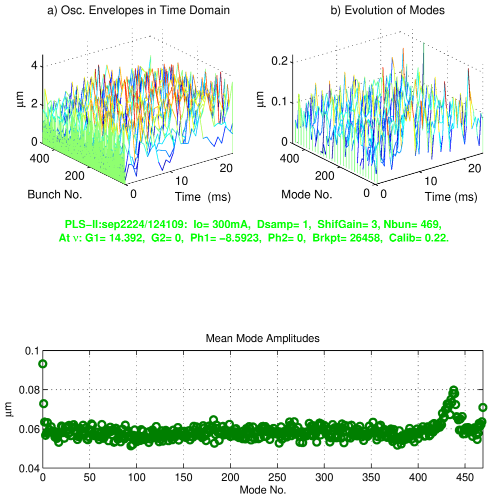

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How Does One Characterize an Unstable System?

- Standard methods of characterization:
  - Frequency domain — transfer function;
  - Time domain — step/pulse response.
- These methods fail for unstable beam;
- In 1990s our group at SLAC developed so-called transient diagnostics:
  - Upon some trigger, turn off feedback and start recording beam motion;
  - Unstable motion grows from ever-present noise-floor level excitation;
  - After an adjustable open-loop time period, turn feedback on;
- Resulting data set captures open-loop growth of the fastest unstable modes and closed-loop damping;
- Used to characterize driving terms (impedances) and feedback performance, optimize tuning.

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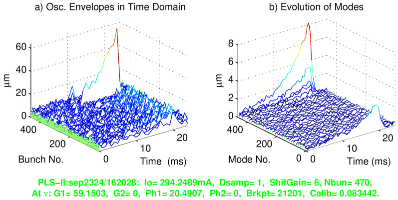
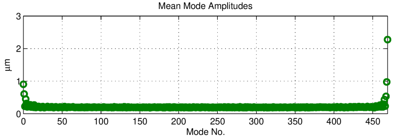
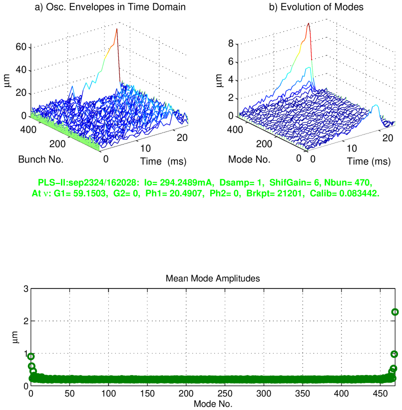




- At nominal ID gaps PLS-II is at the threshold of horizontal resistive wall instability;
- Taken with 4A EPU at 20 mm gap;
- Grow/damp at 300 mA, 40 ms growth time;
- Only a resistive wall mode;
- Fit exponentials to growth and damping amplitudes, fairly clean fits.

Horizontal Grow/damp Measurement



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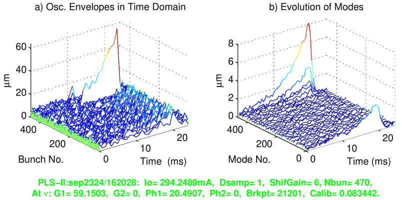

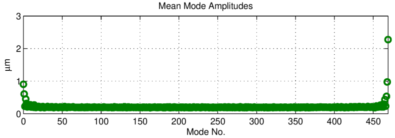

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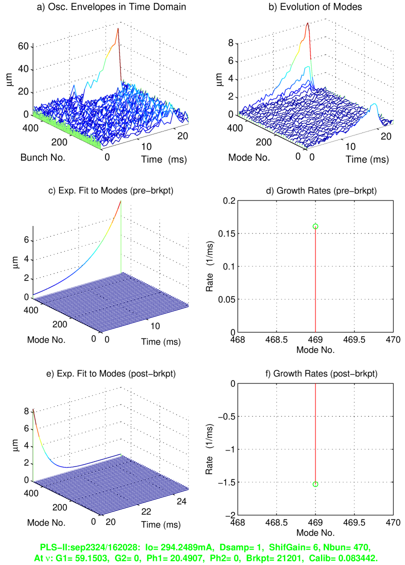

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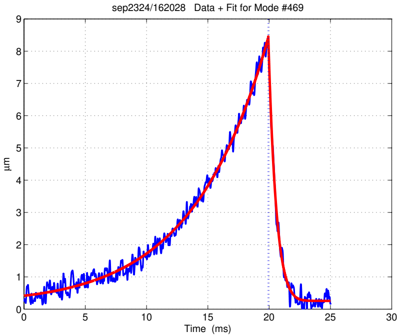

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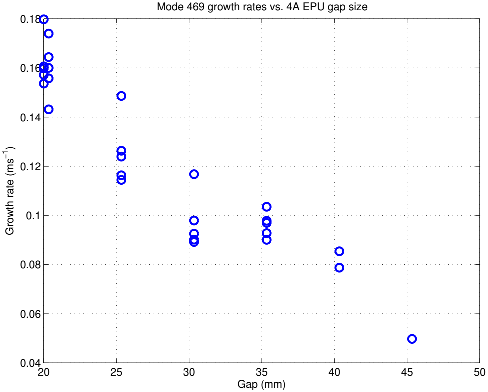
Growth Rate vs. EPU Gap



- Adjust 4A EPU from 45.34 to 20 mm gap;
- Resistive wall growth rates vs. gap setting;
- Moderate growth rates, damping is an order of magnitude faster;
- Taken with 7C SFA and 5C SFA at minimal gap.

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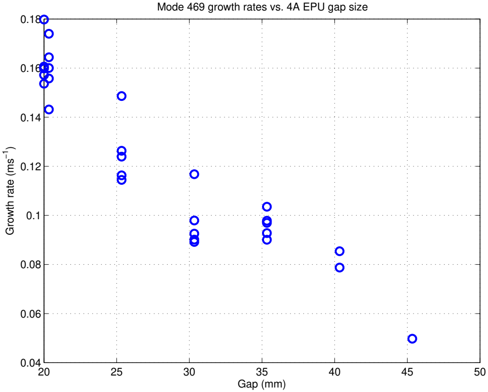

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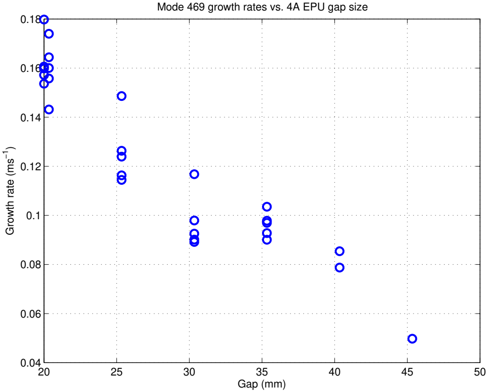

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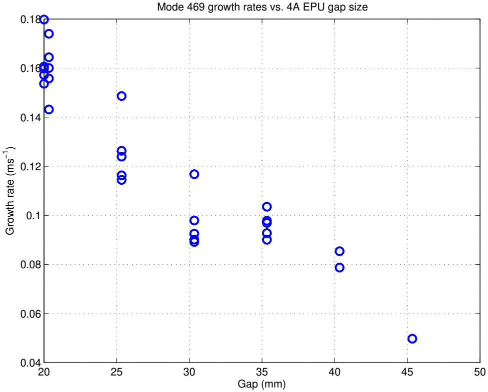

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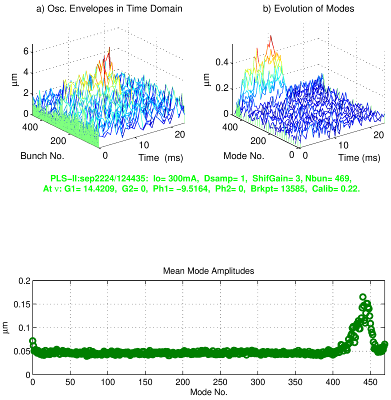
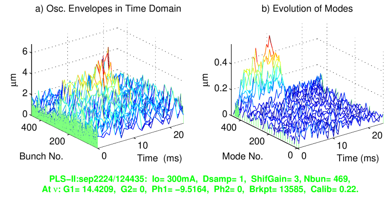
Vertical Grow/damp Measurement

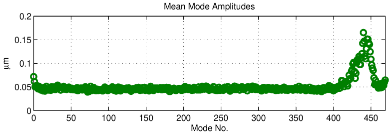


PLS–II:sep2224/124435: Io= 300mA, Dsamp= 1, ShifGain= 3, Nbun= 469,
At ν: G1= 14.4209, G2= 0, Ph1= −9.5164, Ph2= 0, Brkpt= 13585, Calib= 0.22.

- Grow/damp at 300 mA, 13 ms open loop;
- Increasing amplitudes towards the end of the train, a wide band of modes point to ion instability;
- A beating mess in time domain;
- RMS average of the envelopes make more sense;
- Can even fit growth and damping rates;
- Short section at the start is roughly exponential;
- Open loop time of 22 ms shows typical ion behavior — motion saturates at low amplitudes.

Vertical Grow/damp Measurement





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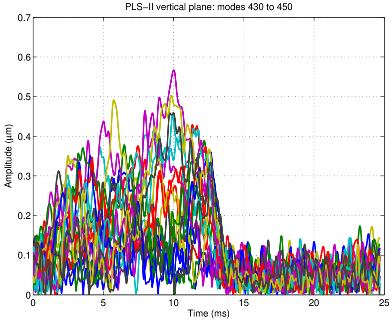

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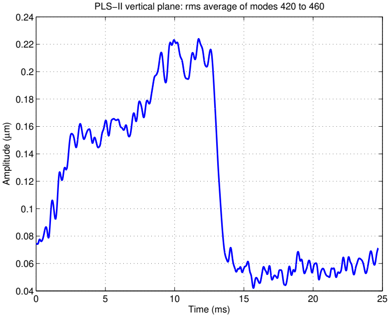

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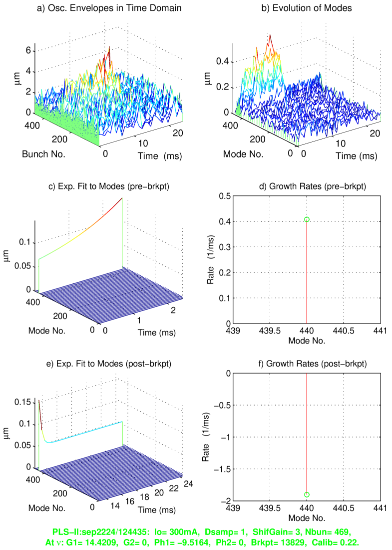

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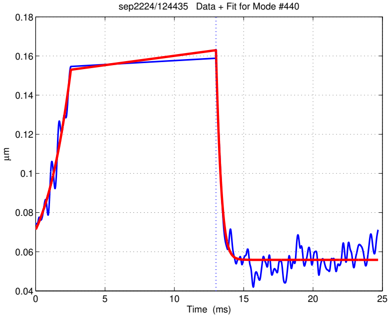

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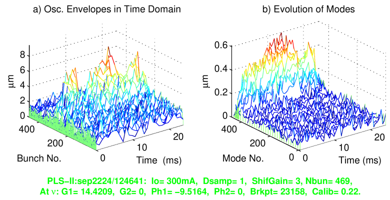

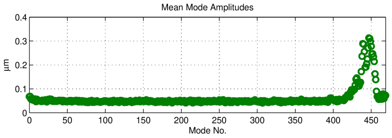

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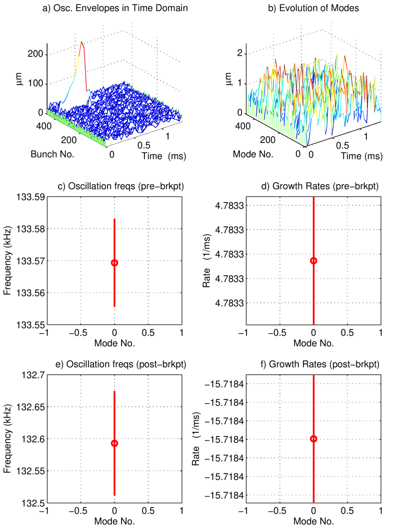
Single Bunch Instability



PLS−II:sep2324/124733: Io= 254.7903mA, Dsamp= 1, ShifGain= 7, Nbun= 470,
At ν: G1= 164.7166, G2= 164.7166, Ph1= 1.0239, Ph2= 1.0239, Brkpt= 451, Calib= 0.04143.

- High single bunch current leads to coupling of dipole and head-tail modes — transverse mode coupling instability (TMCI);
- PLS-II vertical TMCI threshold is 4.3 mA;
- Feedback cannot affect the head-tail modes, but damping of the dipole mode is enough;
- A single-bunch grow/damp — feedback turned off for camshaft bunch only;
- Fast growth, 0.5 ms open-loop time;
- High feedback gain means capture range is limited;
- Feedback on at 0.6 ms only slows down the growth.

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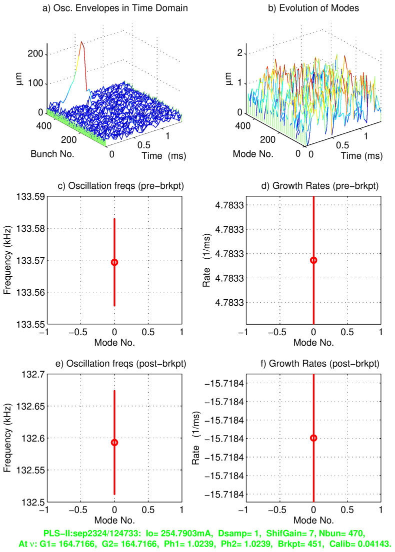

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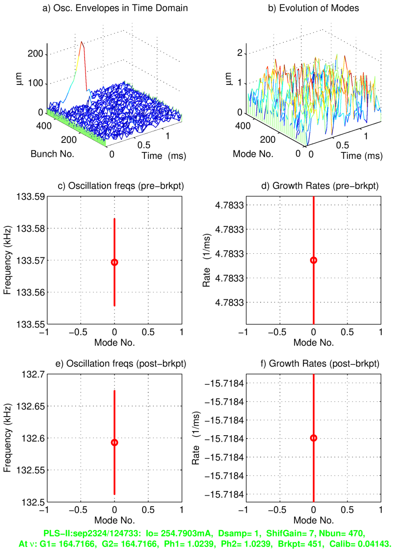

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- PLS-II vertical TMCI threshold is 4.3 mA;
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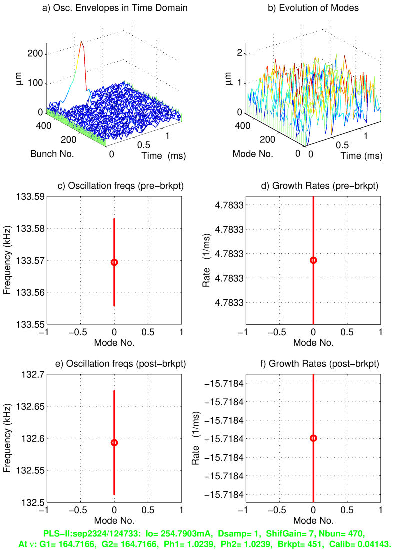
Single Bunch Instability



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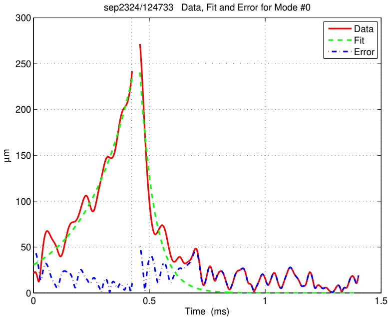

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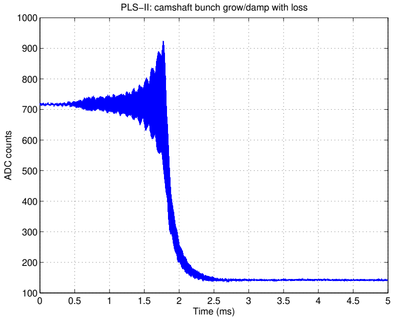

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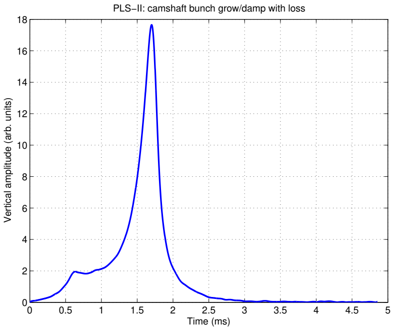

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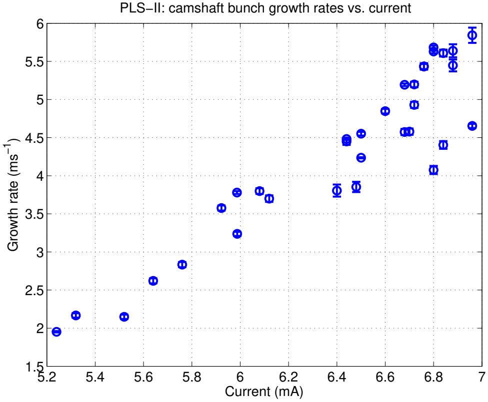
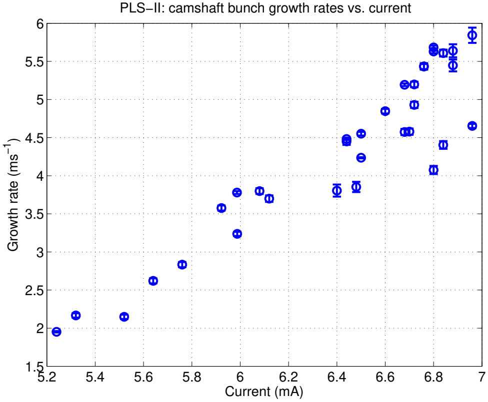
Growth Rate vs. Camshaft Current



- Growth rates vs. camshaft bunch current;
- Current is estimated from the scope peak-to-peak amplitude;
- Steep rise in growth rates, reaching 6 ms^{-1} at 7 mA — 180 turns;
- Reached 7.6 mA with the demonstration setup;
- With a separate X and Y processors (each driving four amplifiers) one can expect to reach even higher camshaft currents.

Growth Rate vs. Camshaft Current



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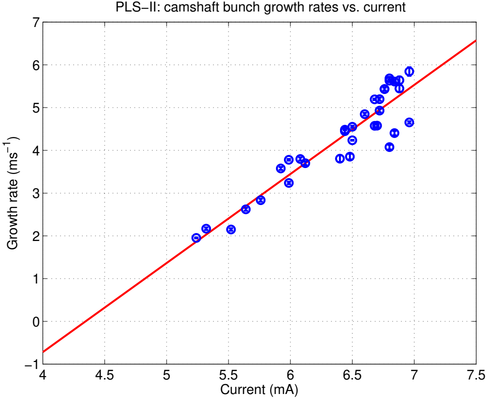

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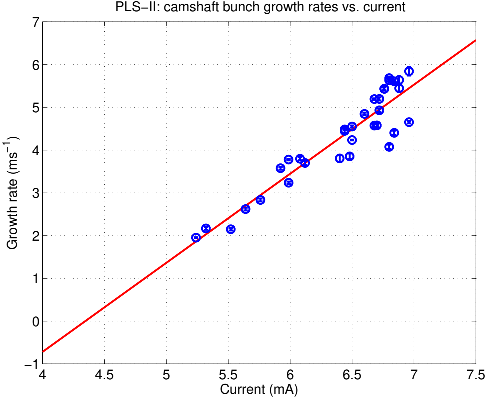

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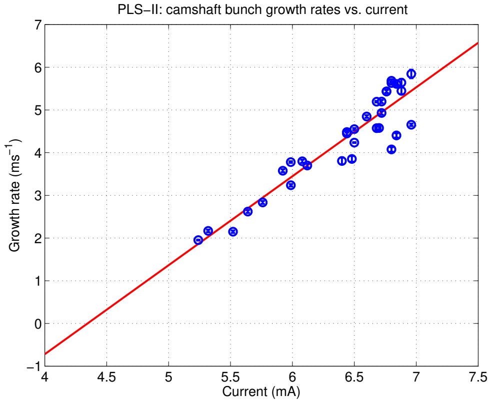

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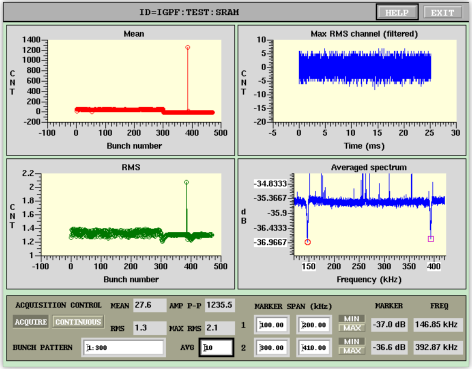
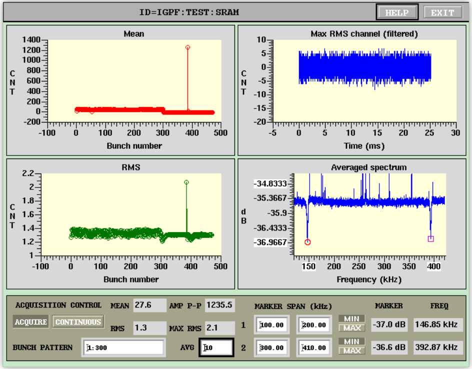


- Feedback in closed-loop operation, both X and Y;
- Averaged beam spectrum (lower right) shows two notches;
- These notches allows us to perform parasitic tune measurement.

Parasitic Tune Measurement



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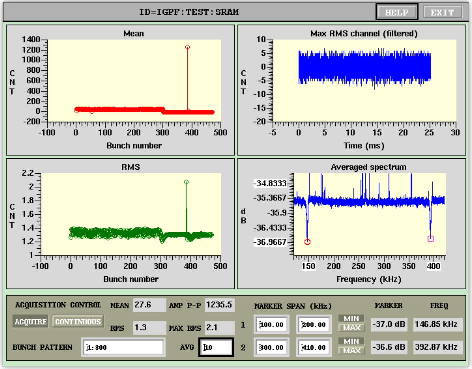

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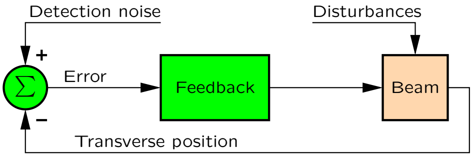

- In transverse planes there are very few steady-state disturbances;
- Instabilities are damped to the noise floor;
- Spectrum is determined by the detection noise and the feedback loop response;
- Open loop transfer function $L(\omega)$ peaks at beam resonance;
- Transfer gain from the detection noise to the feedback input is $\frac{1}{1+L(\omega)}$;
- Maximum attenuation at beam resonance — a notch.

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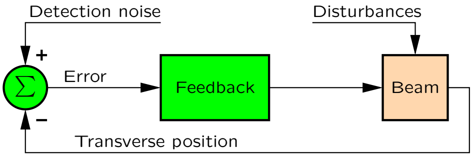

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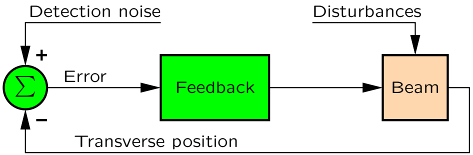

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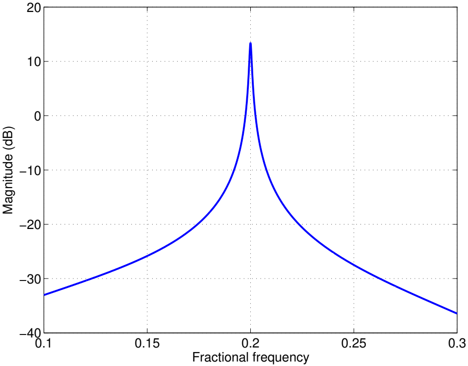

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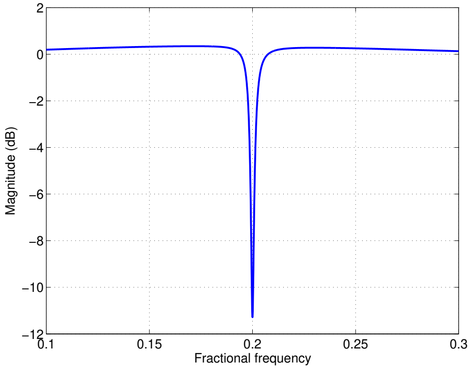

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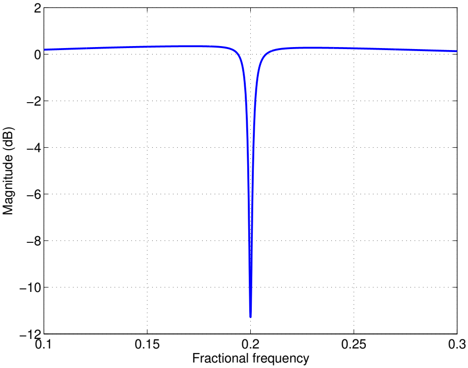

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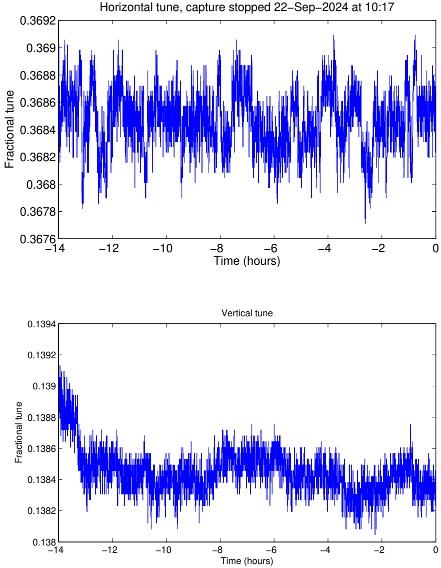

- Overnight capture of tune monitor at 1 Hz;
- Averaging time constant of around 30 s to mask injections;
- Observed an offset of ≈ 0.005 between the notch and the swept spectrum analyzer measurement;
- This offset is due to the amplitude-dependent tune shift, since notch measurement happens at much lower oscillation amplitudes.

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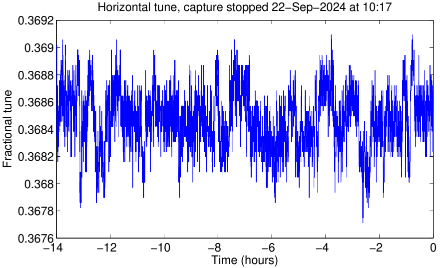

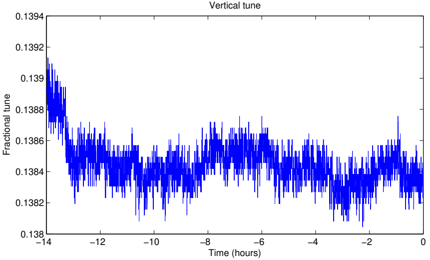

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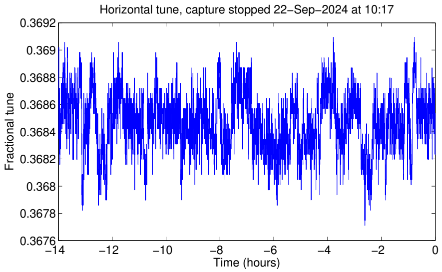

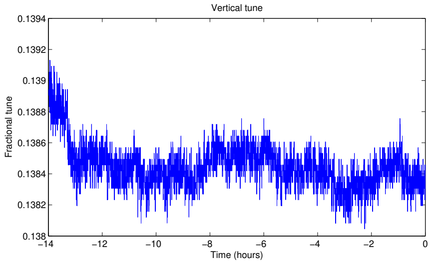

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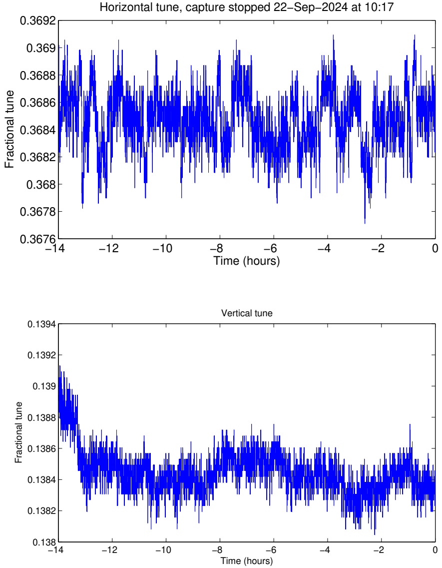

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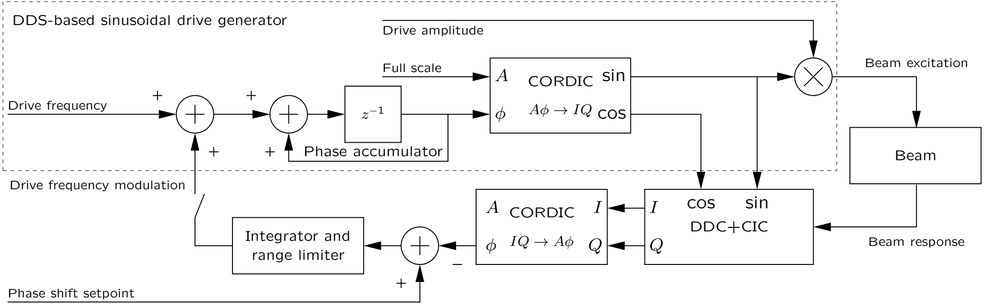
Single Bunch Phase Tracking



- A single bunch is excited with a sinusoidal excitation;
- Response is detected relative to the excitation to determine the phase shift;
- In closed loop, phase tracker adjusts the excitation frequency to maintain the desired phase shift value;
- Adjustable integration time, tracking range, loop gain.

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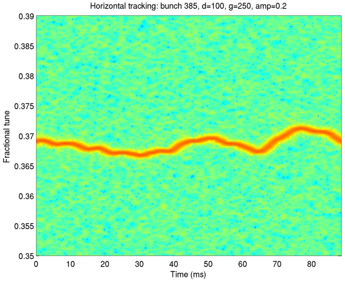
Fast Tune Tracking



- Optimized X tracking with 100 turns decimation;
- One more shot;
- And another one;
- Downconvert to baseband to separate amplitude and phase;
- We used fast tune tracking to establish calibration.

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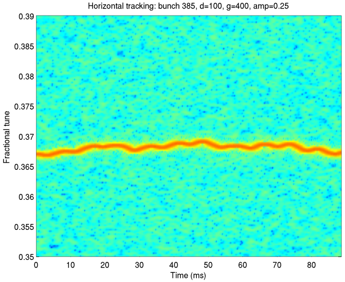

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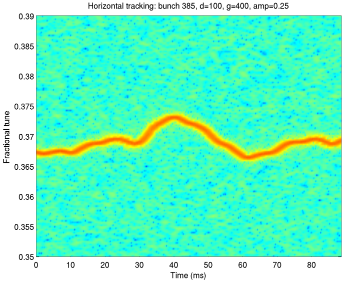

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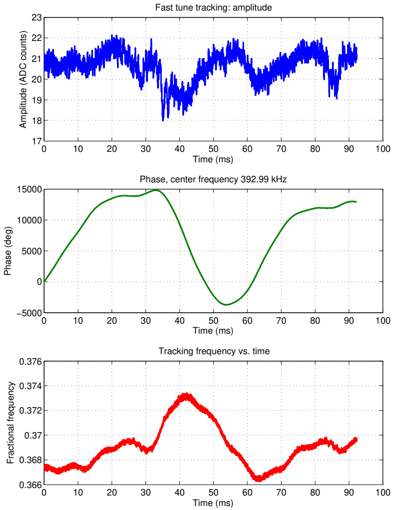

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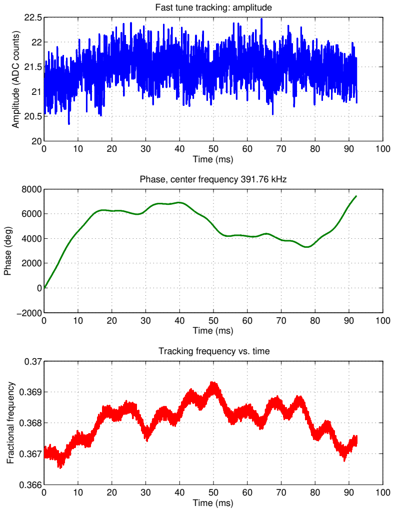

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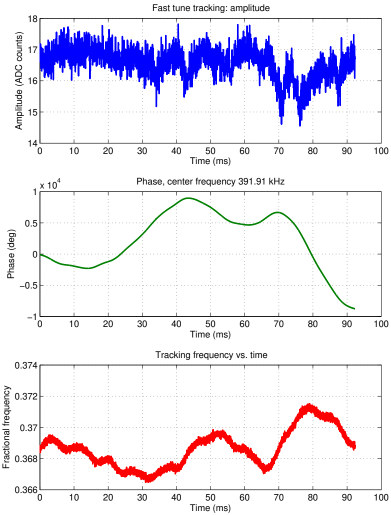

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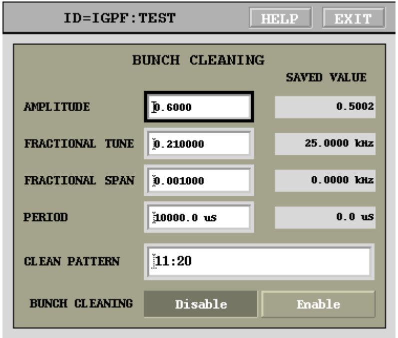
Bunch Cleaning



- Bunch cleaning is done by iGp12 as follows:
  - Apply normal negative feedback to the bunches we want to keep;
  - Turn off the feedback for the bunches to be removed;
  - Apply sine or square wave excitation with frequency sweeping to the bunches we are cleaning.
- With two power amplifiers we barely had enough kick to clean;
- Removed 3 bunches: 296, 299, 300;
- After cleaning optimization, with 9 bunches cleaned;
- Need optical diagnostics to characterize bunch purity.

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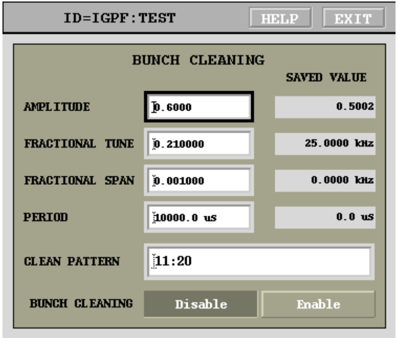

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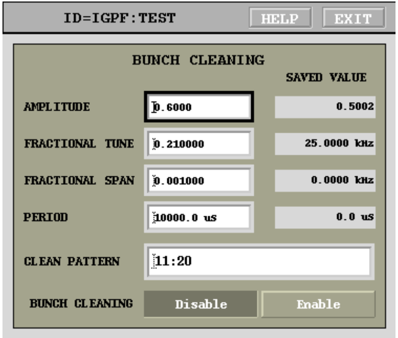

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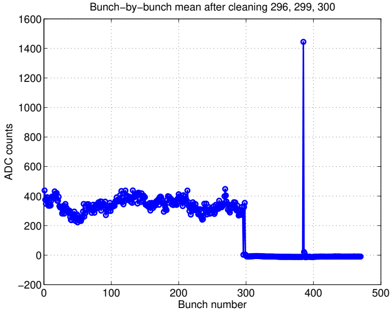

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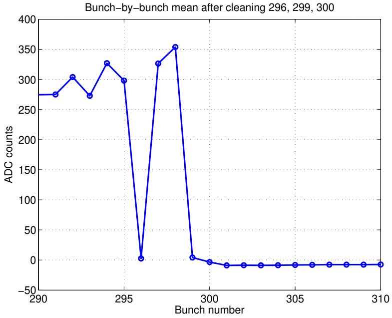

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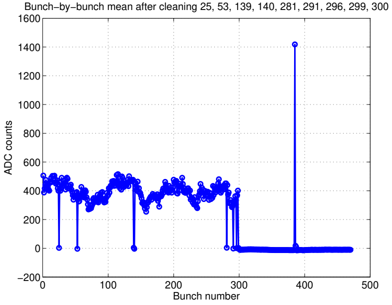
Bunch Cleaning



- Bunch cleaning is done by iGp12 as follows:
  - Apply normal negative feedback to the bunches we want to keep;
  - Turn off the feedback for the bunches to be removed;
  - Apply sine or square wave excitation with frequency sweeping to the bunches we are cleaning.
- With two power amplifiers we barely had enough kick to clean;
- Removed 3 bunches: 296, 299, 300;
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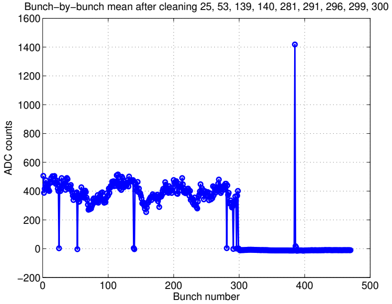

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- Used one unit to control both X and Y planes;
- Demonstrated control of resistive wall and ion coupled-bunch instabilities as well as control of TMCI (single-bunch instability);
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