Bunch-by-bunch feedback and diagnostics in CLS

Demonstration of iGp12 and FBE-LT

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Outline

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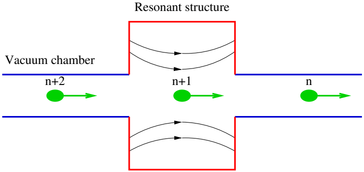
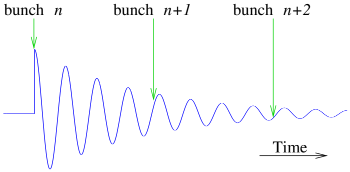
1. Introduction
   - Coupled-bunch Instabilities
   - Feedback Control
2. Hardware Overview
3. CLS Demo Results
   - Bunch Cleaning
   - Multibunch Measurements
   - Tune Measurement
   - Beam Loss at Low BXDS Gaps
4. Additional Measurement Examples

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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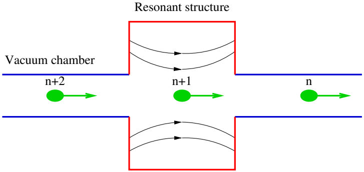

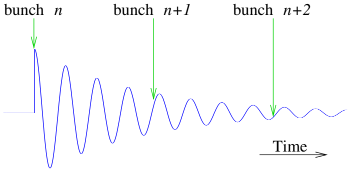

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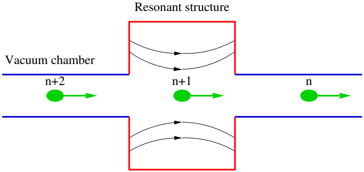

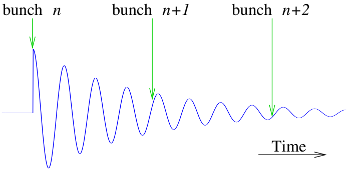

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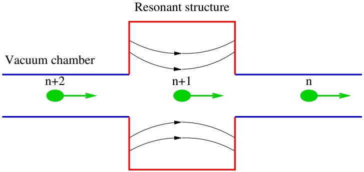

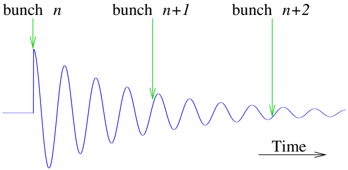

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Coupled-bunch Instabilities: Eigenmodes and Eigenvalues

- 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: $A_m e^{2\pi km/N} e^{\Lambda_m t}$
  - A_m — modal amplitude;
  - Λ_m — complex modal eigenvalue.

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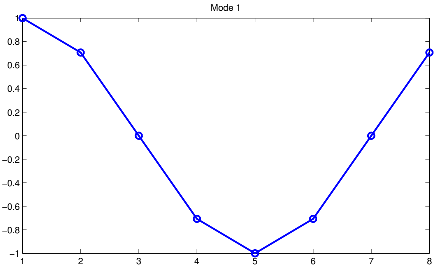
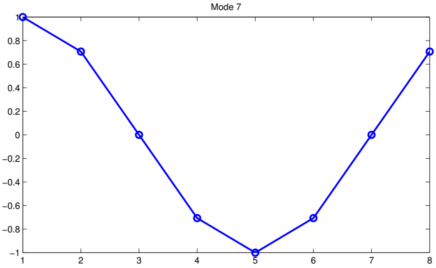
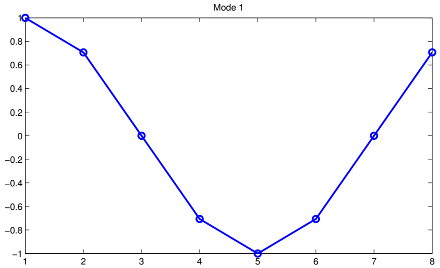
Modal Oscillation Example

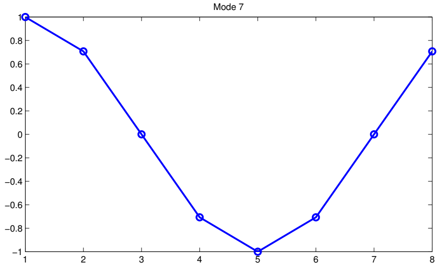




- Harmonic number of 8;
- Top plot — mode 1;
- Bottom — mode 7;
- All bunches oscillate at the same amplitude and frequency, but different phases;
- Cannot distinguish modes m and $N - m$ (or $-m$) from a single turn snapshot.

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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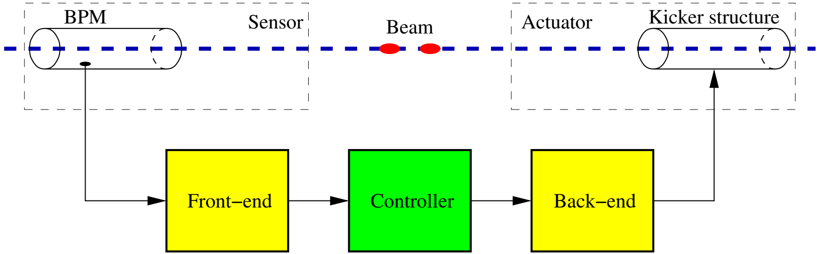
Bunch-by-bunch Feedback

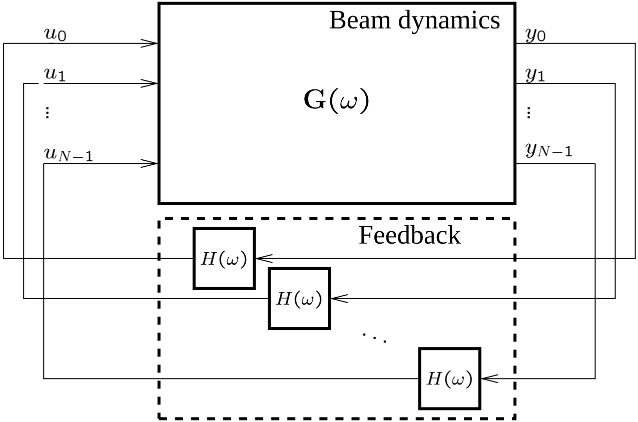
Definition

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.

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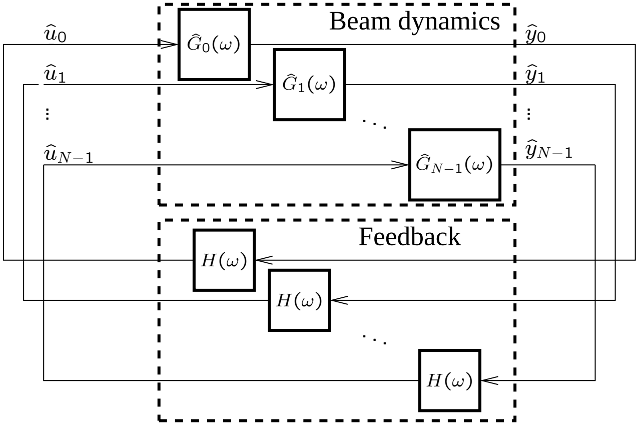


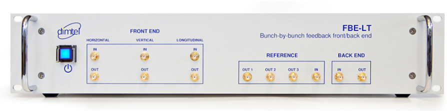
- Coordinate transformation to eigenmode basis;
- *N* feedback loops - one per mode;
- Identical feedback applied to each mode.

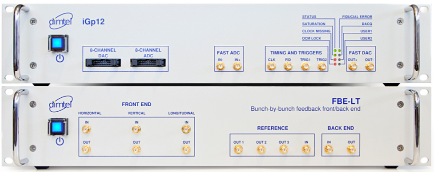
Outline

iGp12 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





- 3 front-end channels.
- 1–1.5 GHz front-end detection frequency.
- 2-cycle comb generator.
- 1–1.5 GHz back-end frequency.
- Integrated control via iGp:
  - LO phase shifters;
  - Attenuators;
  - Temperature measurement and stabilization.

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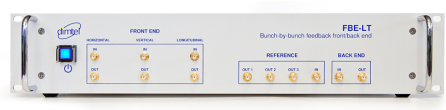

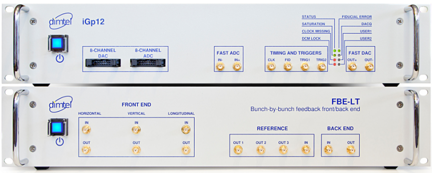

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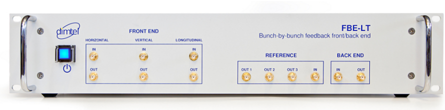

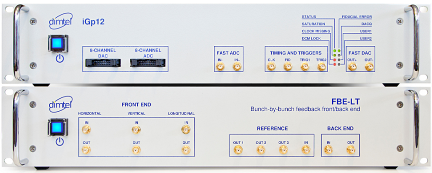

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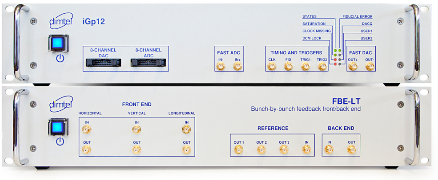

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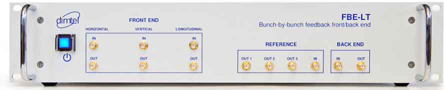

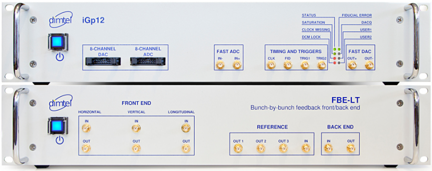

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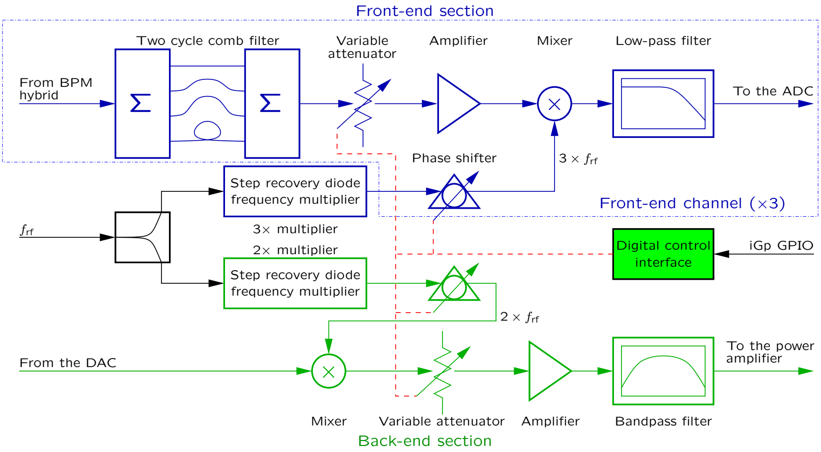
Front/Back-end Block Diagram



iGp12 Specifications

- Design goals:
  - Reliability;
  - Maintainability;
  - Ease of use;
  - Diagnostics.
- FPGA based processing:
  - Flexible;
  - Field upgradable.

Specifications

Bunch spacing	$\geq$ 1.9 ns
Harmonic number	32–5120
ADC resolution	12 bits
DAC resolution	12 bits
ADC bandwidth	1.35 GHz
Feedback filter	32-tap FIR
Downsampling	1-256
DAQ memory	12 MS
Triggers	2

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The Plan

- ✓ TFB in Y;
- ✓ Bunch cleaning;
- ✓ Tune measurement;
- ✓ TFB in X;
  - ✓ Covered during dual plane operation.
- ✓ Measurement of growth and damping times;
- ✓ Investigate BXDS ID beam loss problem;
- ✓ Feedback in both X and Y with one processor.

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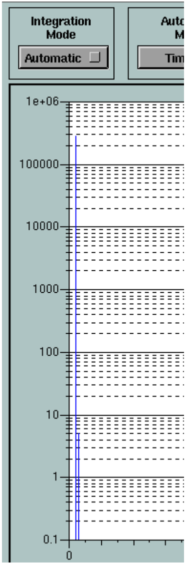
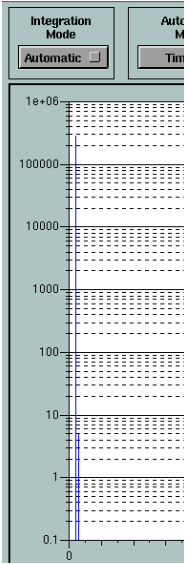
Single Bunch



- Cleaning approach:
  - Maintain feedback for bunches we want to keep;
  - Turn off feedback for bunches to be cleaned;
  - Apply swept frequency sinewave excitation to the bunches to be cleaned.
- Feedback action helps by rejecting excitation coupling;
- Power amplifiers currently in use are really marginal due to extreme phase non-linearity above 200 MHz;
- Fairly straightforward to achieve pure single bunch;
- Plots shows purity around 6×10^4, had better cleaning later on.

Single Bunch



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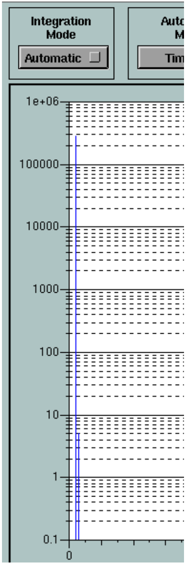

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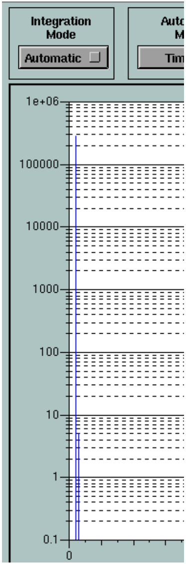

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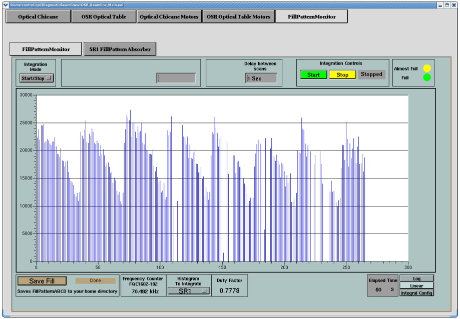
Middle of the Bunch Train



- Much more difficult to create a setup that can clean arbitrary patterns in the middle of the bunch train;
- Desired pattern: gap of 1, 1 bunch, gap of 2, 2 bunches, gap of 3, 3 bunches, gap of 4, 4 bunches, gap of 1;
- Achieved after some trial and error.

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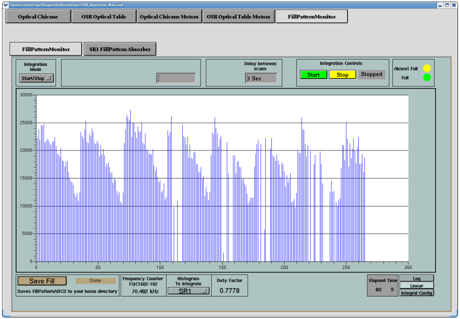

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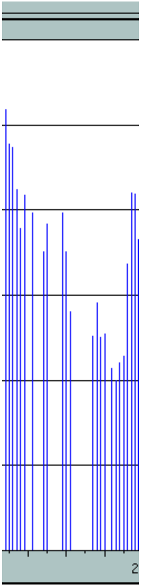
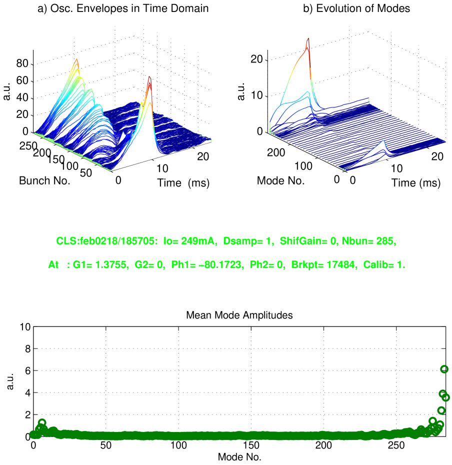


- Much more difficult to create a setup that can clean arbitrary patterns in the middle of the bunch train;
- Desired pattern: gap of 1, 1 bunch, gap of 2, 2 bunches, gap of 3, 3 bunches, gap of 4, 4 bunches, gap of 1;
- Achieved after some trial and error.

Outline

Grow/damp Measurements



- 280 bunches filled (short gap);
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- Dominated by low-frequency modes;
- Mode -1 is typically resistive wall, -2 and -3 are due to ions;
- Exponential growth of -1, linear/saturating growth of ion-drive modes;
- What if we let the oscillations grow a bit longer?
- 10 ms;
- 20 ms.

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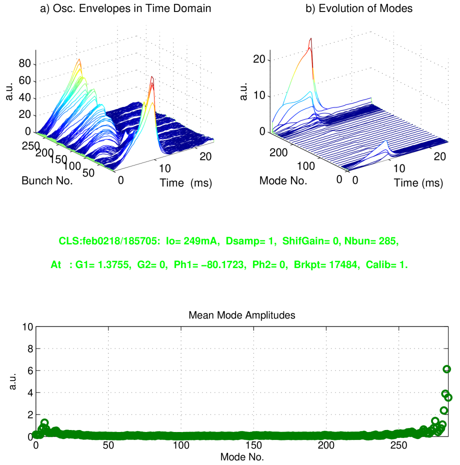

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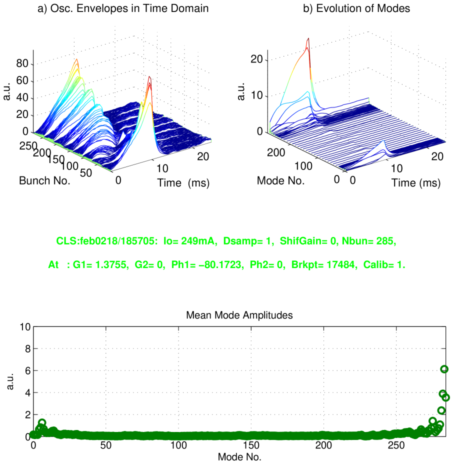

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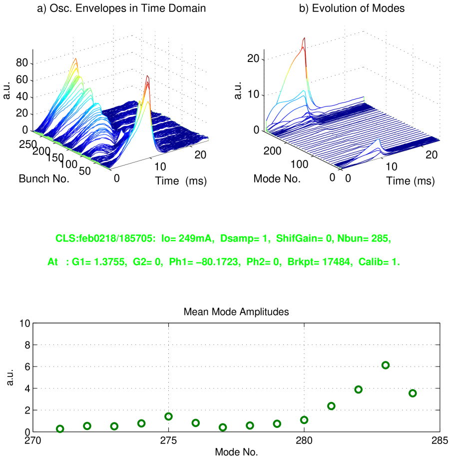

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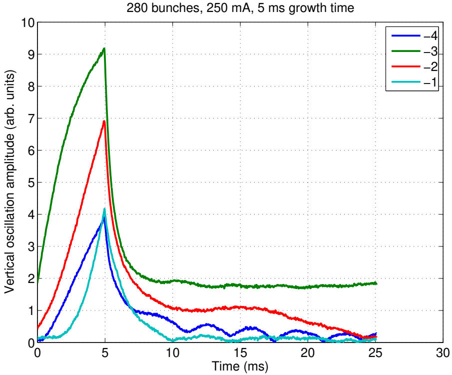

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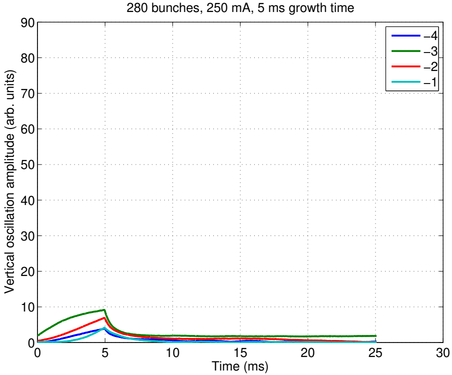

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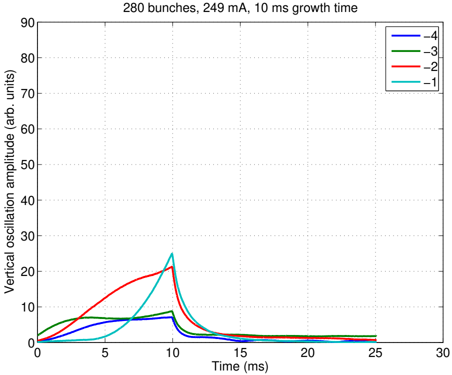

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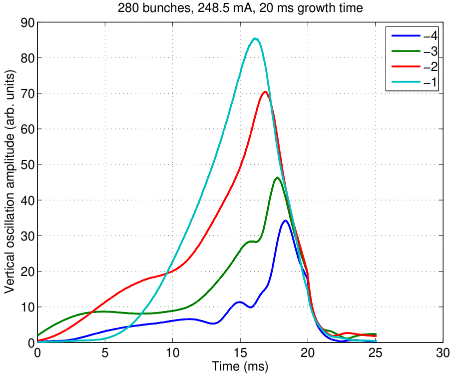

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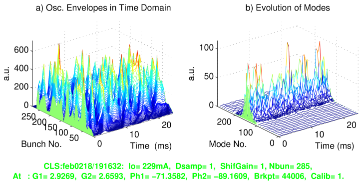
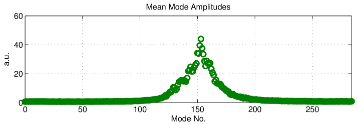
Power Amplifiers Limiting Feedback Gain





- Had a relatively low limit on feedback gain, leading to imperfect control of ion-driven motion;
- In 280 bunch fill assumed beam-ion interaction limited the gain;
- Limit persisted in 265 bunch pattern;
- At increased gain feedback drives modes 120–165 unstable;
- Used iGp12 shaper FIR to roll off feedback gain, allowing 12 decibel gain increase;
- Damping rate is 40 times faster than growth rate!

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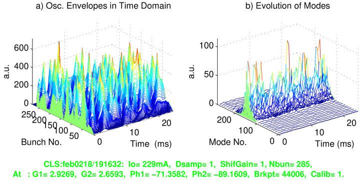

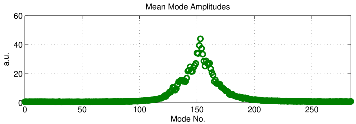

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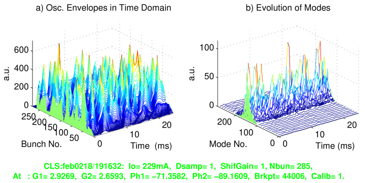

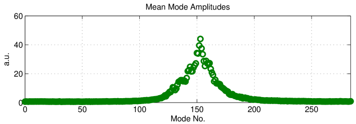

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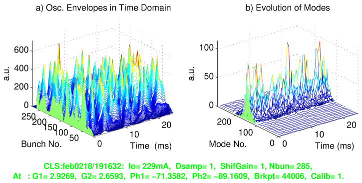

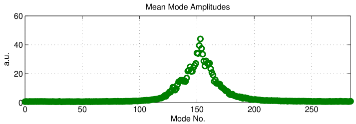

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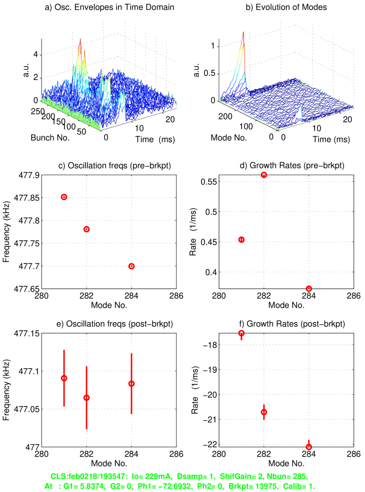

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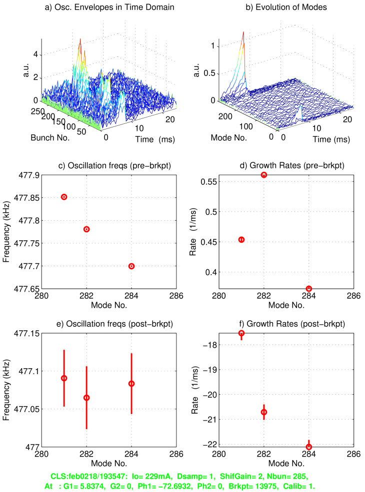

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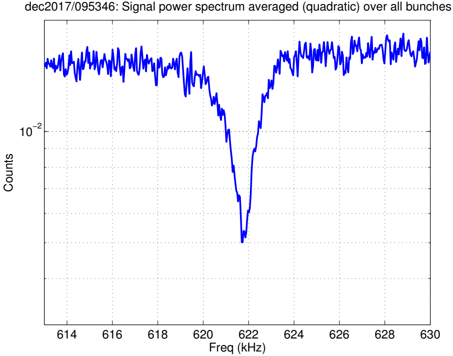
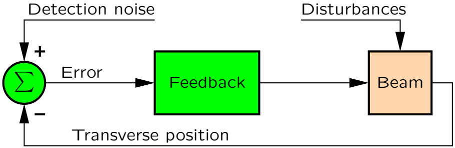
Outline

Spectral Notch Tune Monitoring



- In closed loop operation, feedback signals show a notch at the betatron frequency;
- 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.

Spectral Notch Tune Monitoring



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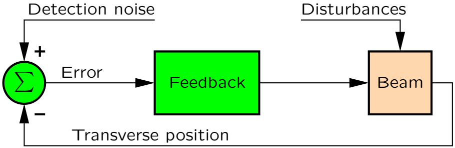

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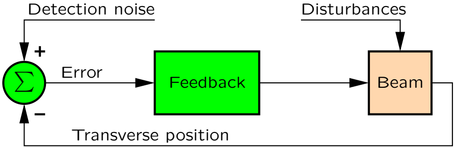

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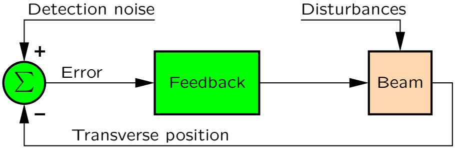

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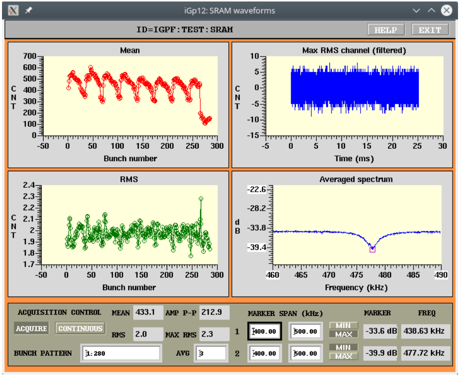
Tune Notch at the CLS



- Vertical feedback at 235 mA;
- A marker automatically tracks the minimum;
- Readout at 2 Hz in both frequency and fractional tune units;
- Notch can be washed out by external excitation;
- Can use external trigger to avoid known excitation source, e.g. injection.

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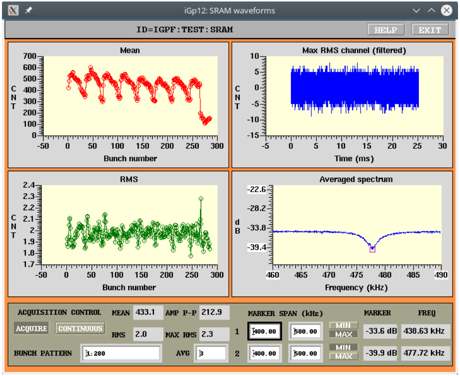

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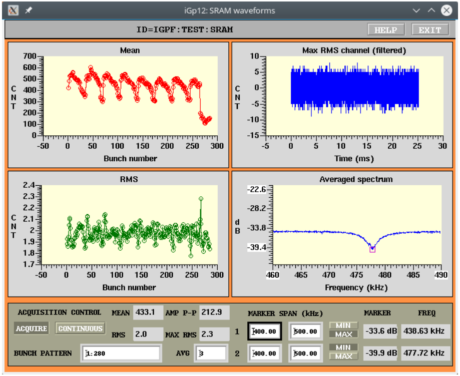

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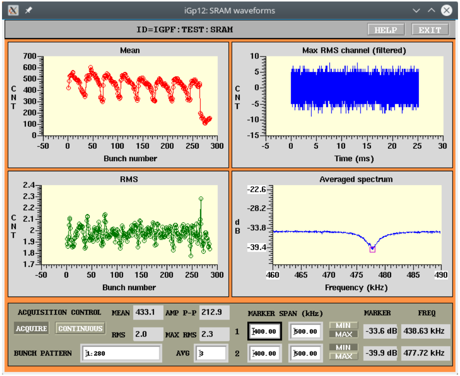

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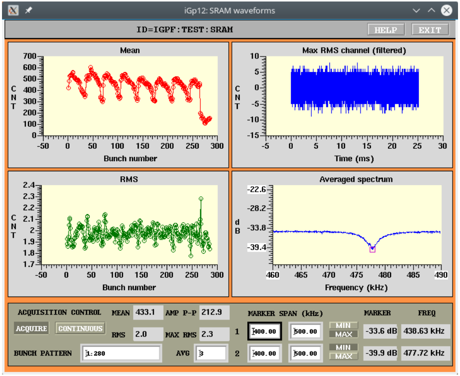

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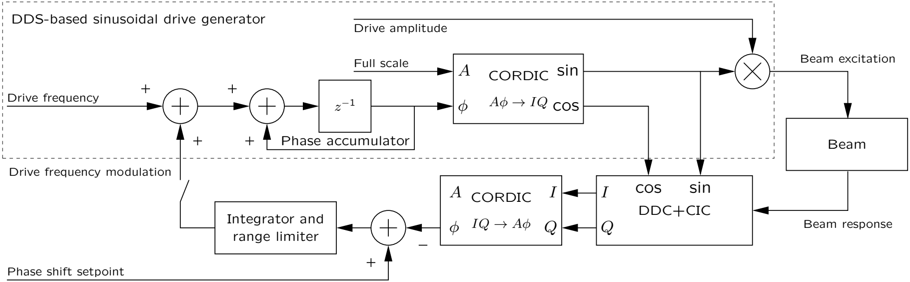
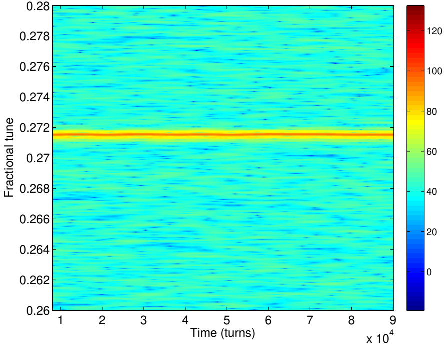
Single Bunch Phase Tracking



- A single bunch is excited with a sinusoidal excitation at low amplitude (20–40 µm);
- Response is detected relative to the excitation to determine the phase shift
- In closed loop, phase tracker adjusts the excitation frequency to maintain the correct phase shift value;
- Adjustable integration time, tracking range, loop gain.

Fast Phase Tracking



- Decimation factor in phase tracker controls tracking bandwidth;
- 2000 turns decimaton, 877 Hz feedback rate;
- Roughly 80 Hz closed loop tracking bandwidth;
- Tune variation in CLS is fairly slow, no ripple seen at 10–100 Hz range typical for other machines;
- Lower amplitudes with significant variation in open loop.

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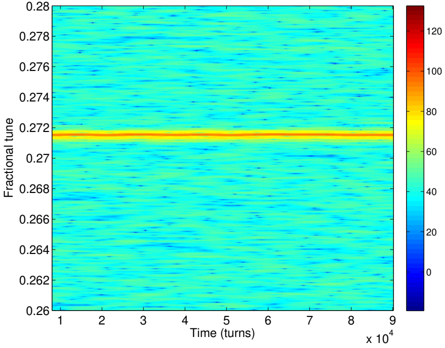

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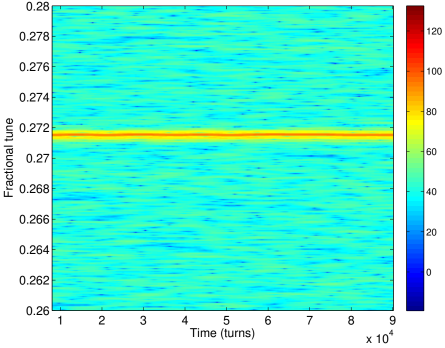

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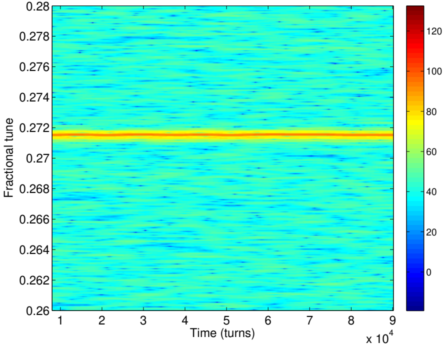

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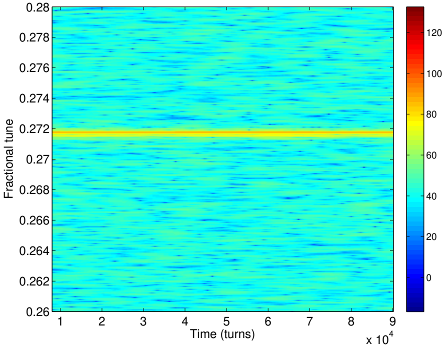

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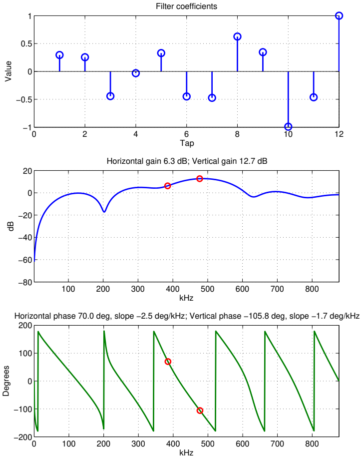
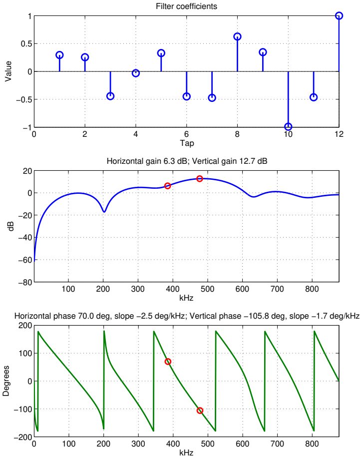


- Configured for feedback in both X and Y;
- Post-mortem acquisition with RF trip trigger;
- 24 ms before the trigger, 1.2 ms after.
- Captured one abort at 120 mA;
- No bunch-by-bunch feedback.

Setup



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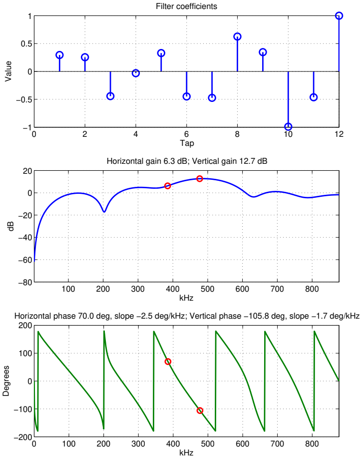

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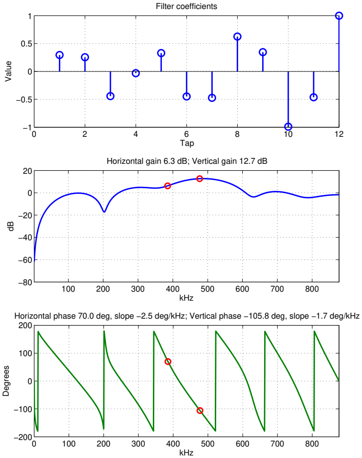

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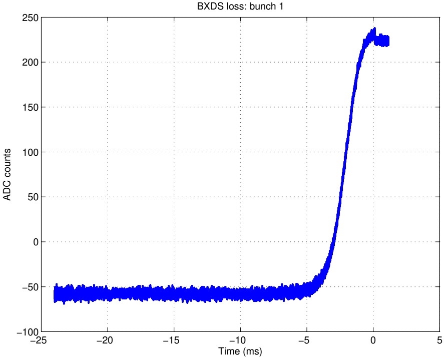

- Bunch 1 versus time;
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- Vertical plane;
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- Longitudinal.

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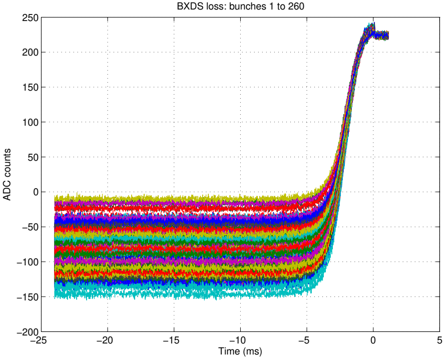

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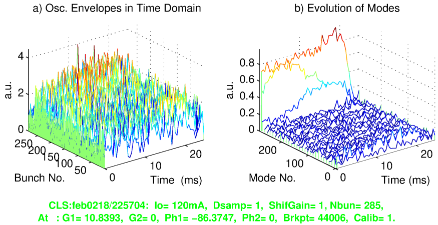

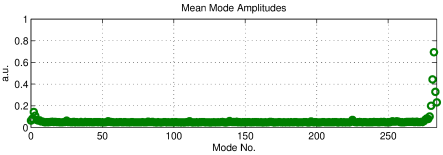

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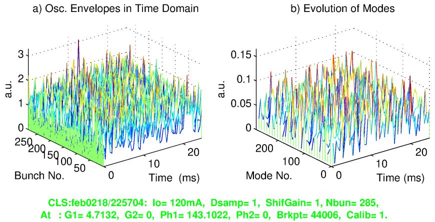

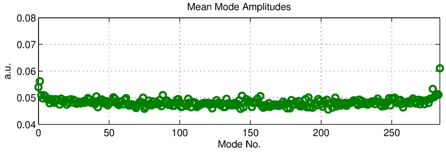

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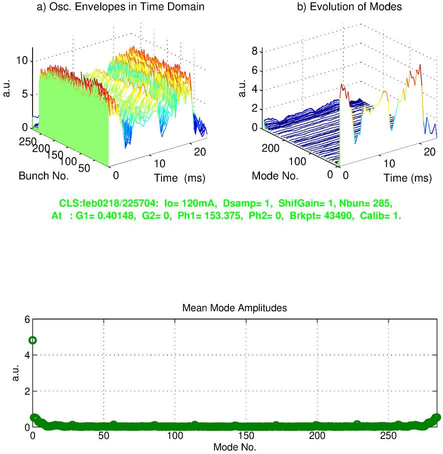
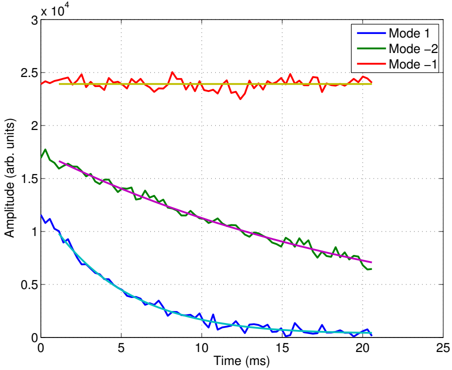


- Bunch 1 versus time;
- All bunches;
- Vertical plane;
- Horizontal plane;
- Longitudinal.

Outline

All Mode Scan: Technique



- Performed at 15.4 mA (under the threshold of instability);
- Each mode is excited to a small amplitude under feedback control;
- In a transient measurement excitation and feedback are turned off;
- Capturing 21 ms of beam motion twice a second, 16.5 minutes to scan all modes;
- 27 GiB data set.

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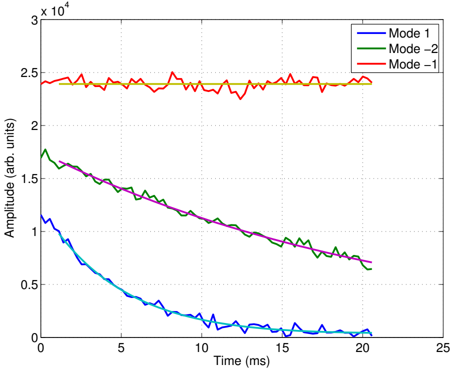

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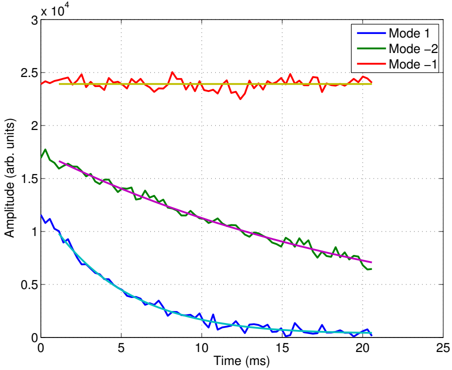

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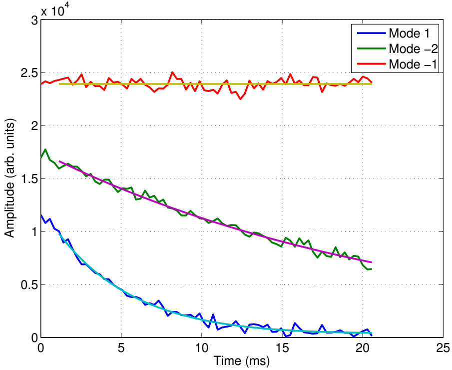

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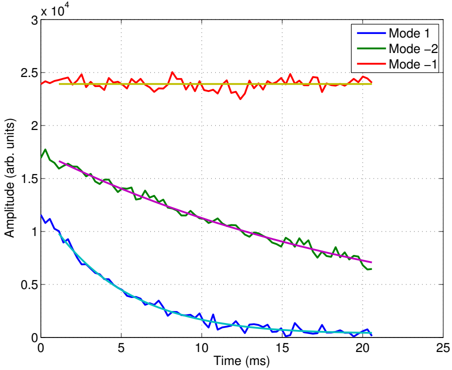

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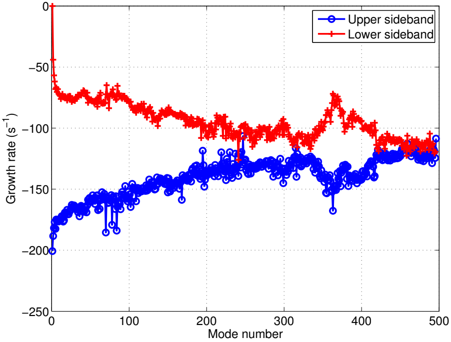

- Automated processing extracts growth or damping rates;
- Clear resistive wall signature;
- A band of higher order modes around mode -365 $(129 + N \times 352$ MHz);
- A smaller HOM band around -298 $(105 + N \times 352$ MHz);
- Radiation damping rate 118 s^{-1} (8.5 ms damping time).

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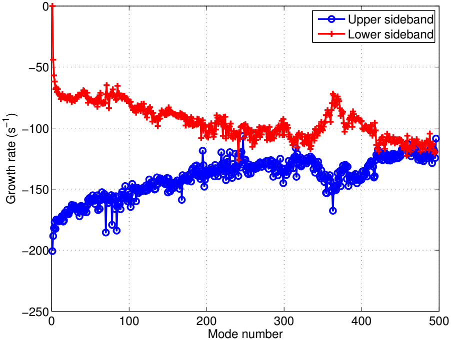

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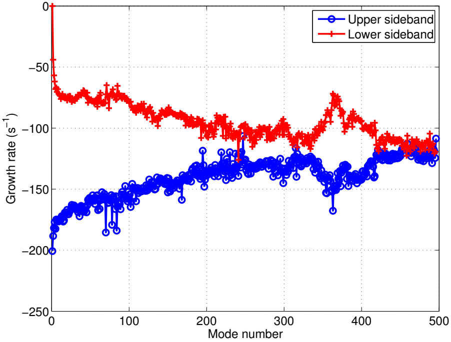

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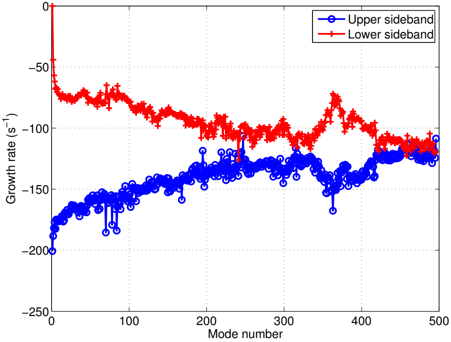

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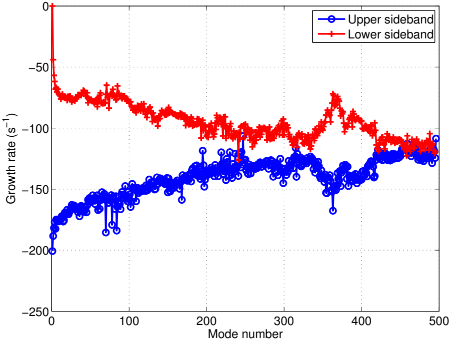

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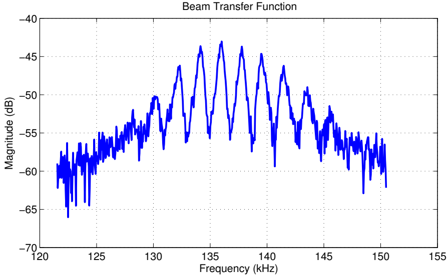
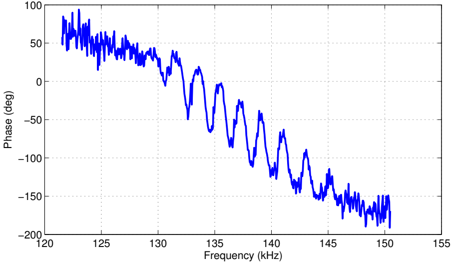
Single Bunch Transfer Function





- Turn off feedback for bunch 40;
- Apply swept sinusoidal excitation;
- Measure beam transfer function;
- A simple-minded fit of a resonant response;
- Fit a linear combination of 3 resonances;
- 5 resonances;
- 7 resonances;
- 9 resonances;
- 11 resonances.

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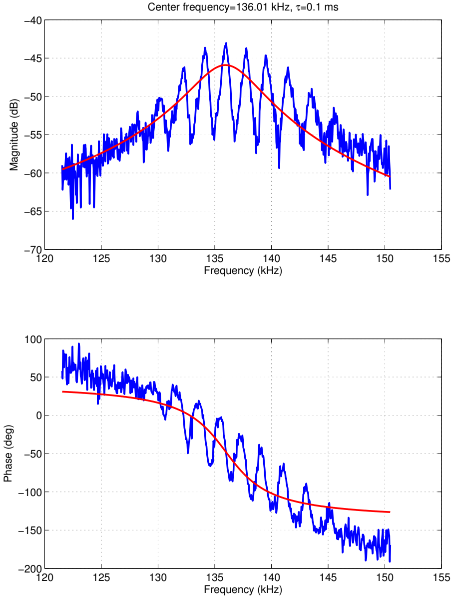

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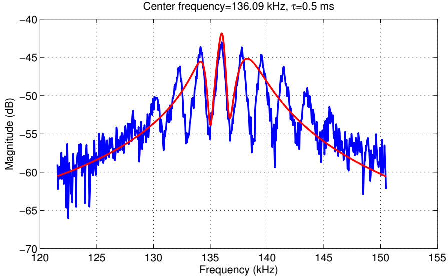

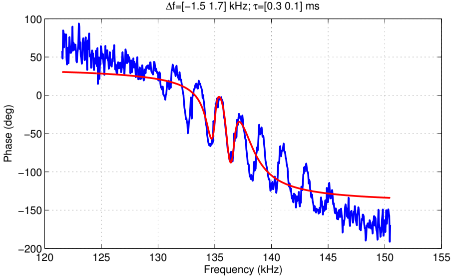

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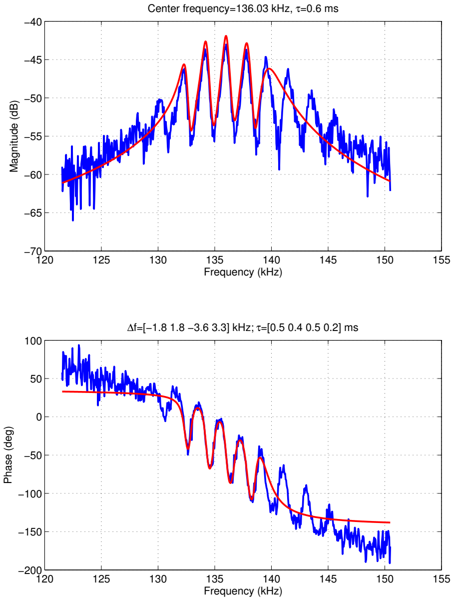

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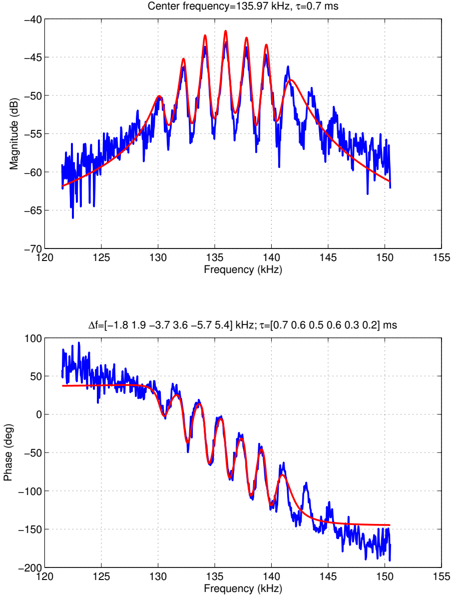

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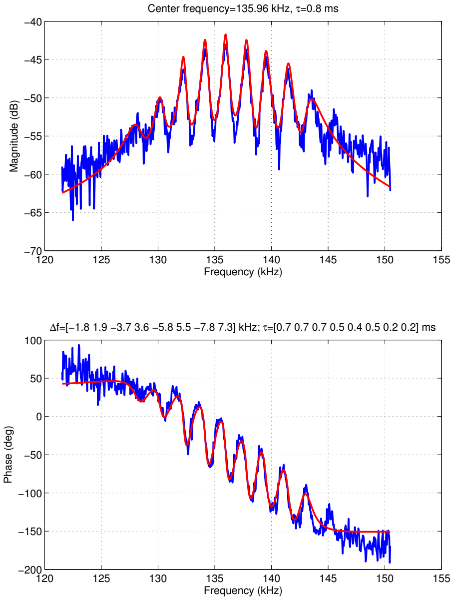

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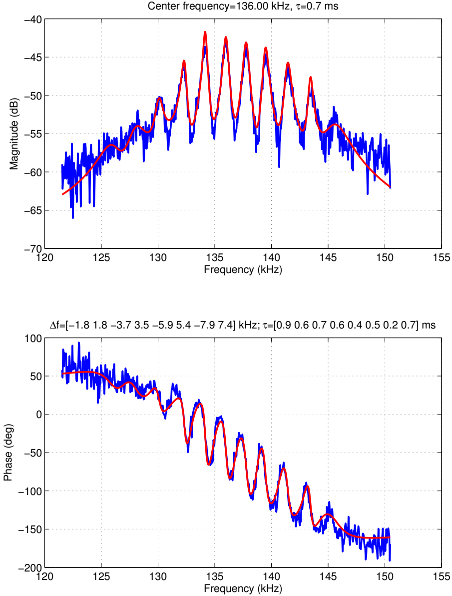

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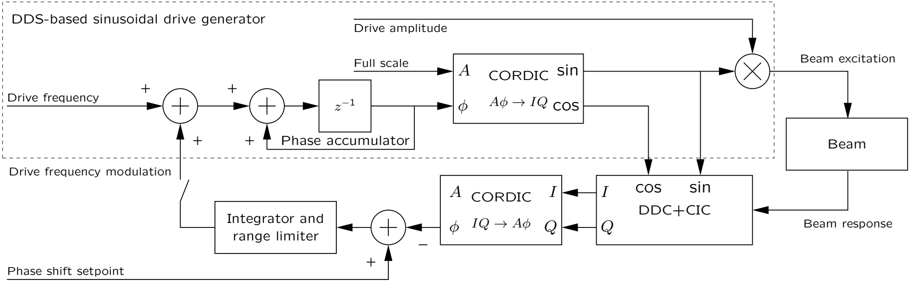
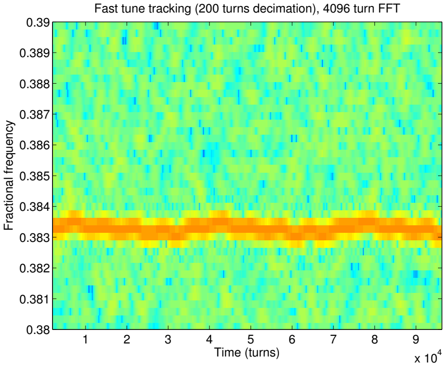
Single Bunch Phase Tracking



- A single bunch is excited with a sinusoidal excitation at low amplitude (20–40 µm);
- Response is detected relative to the excitation to determine the phase shift
- In closed loop, phase tracker adjusts the excitation frequency to maintain the correct phase shift value;
- Adjustable integration time, tracking range, loop gain.

Fast Phase Tracking



- Decimation factor in phase tracker controls tracking bandwidth;
- 200 turns decimaton, 1.77 kHz measurement bandwidth;
- 180 Hz closed loop tracking bandwidth;
- Use time-domain downconversion to better resolve tune modulation;
- Spectrum shows lines at 10 and 50 hertz.

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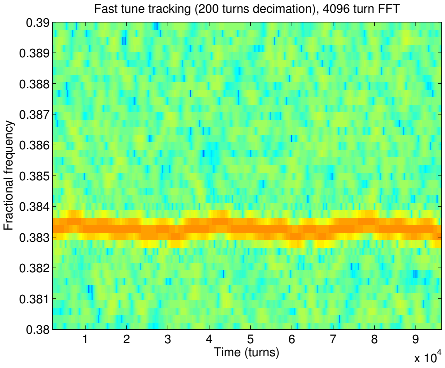

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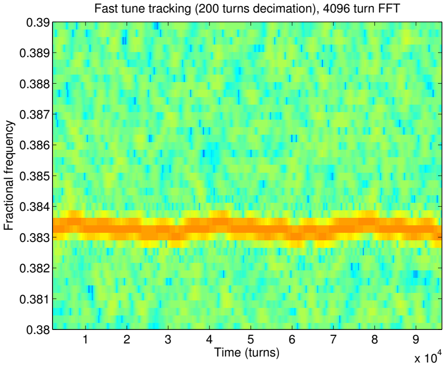

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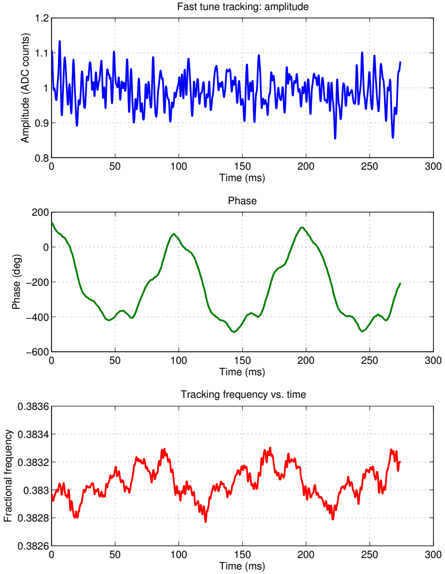

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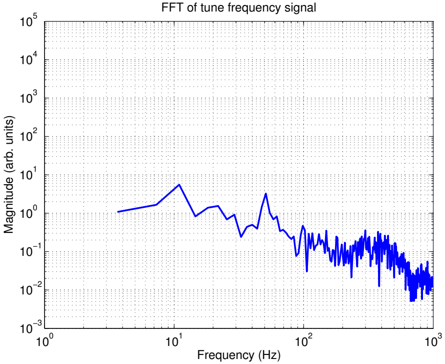

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Summary

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- Many diagnostic features have been demonstrated;
- With some balancing and optimization better performance is feasible;
- I'd like to thank everyone who helped to make this a successful test!

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