Bunch-by-bunch feedback and diagnostics in ESRF

Demonstration of iGp12 and LNFE

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Dimtel, Inc., San Jose, CA, USA

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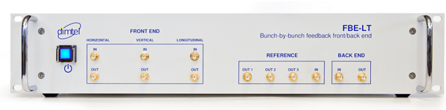
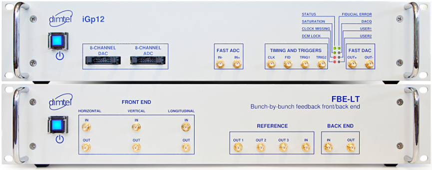
Outline

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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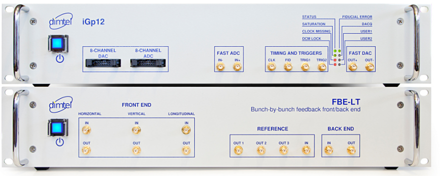

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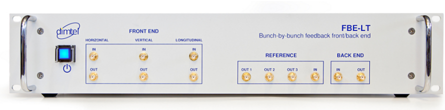

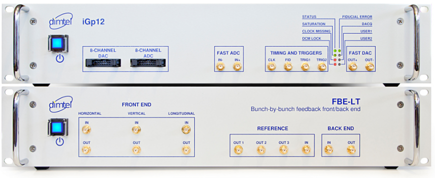

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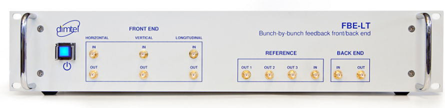

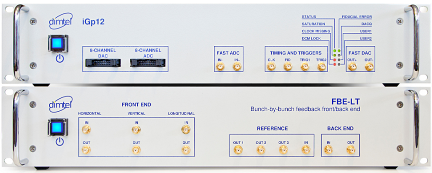

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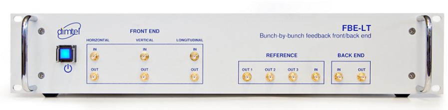

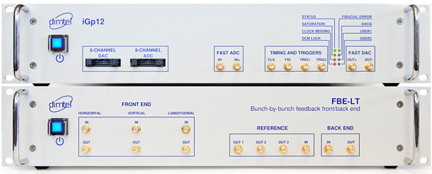

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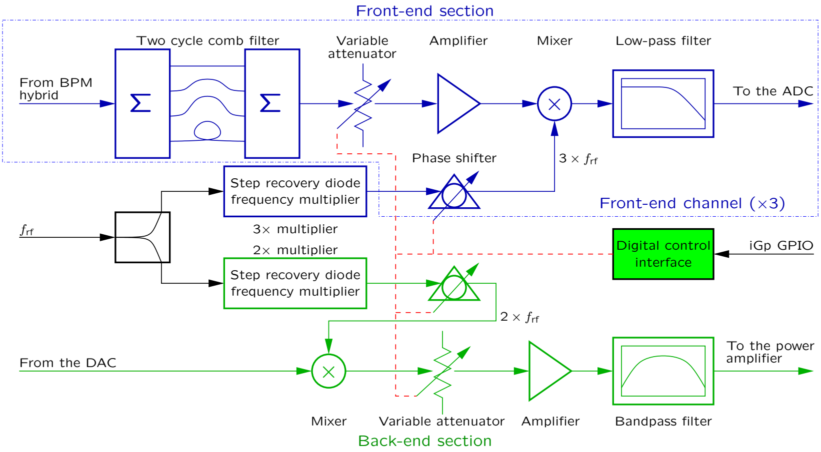
Front/Back-end Block Diagram



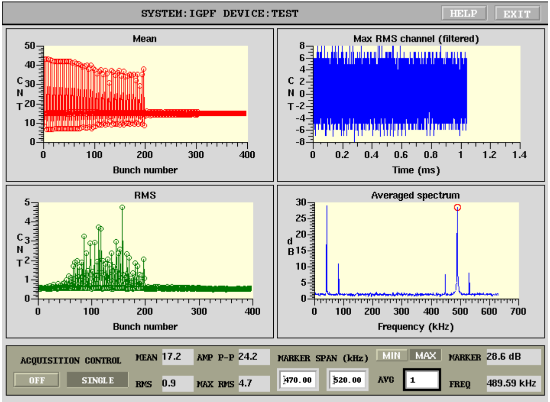
iGp12 Specifications

- 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

Waveform Panel



- Updates at 2 Hz
- Uses data from all bunches over many turns (12672 for ESRF).
- Four waveforms:
  - Mean;
  - RMS;
  - Bunch with largest RMS;
  - Averaged spectrum of all bunches.

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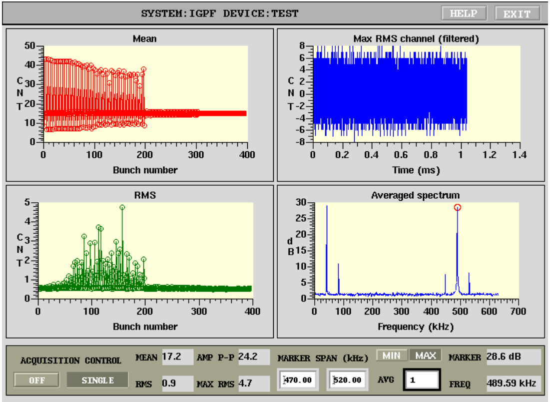

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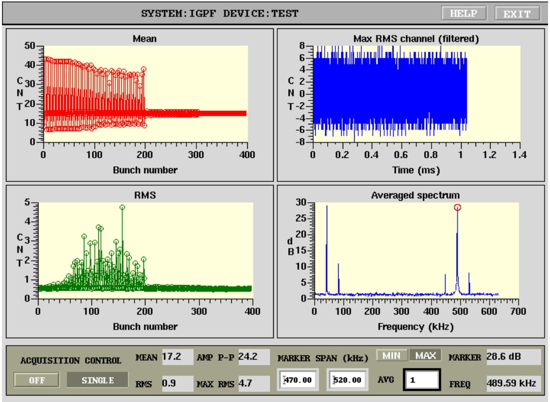

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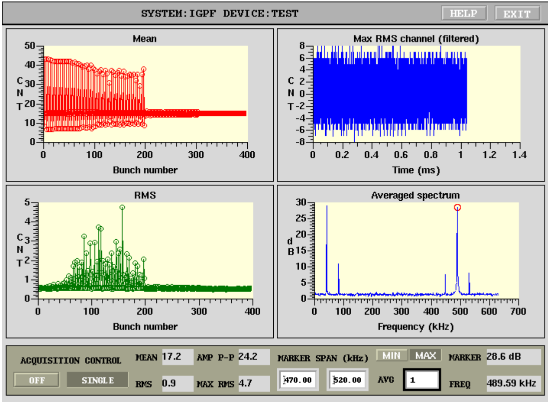

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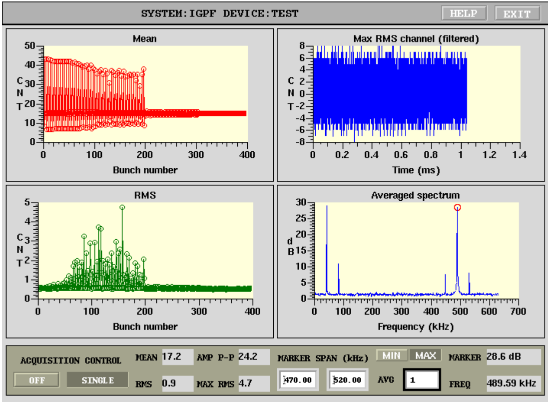

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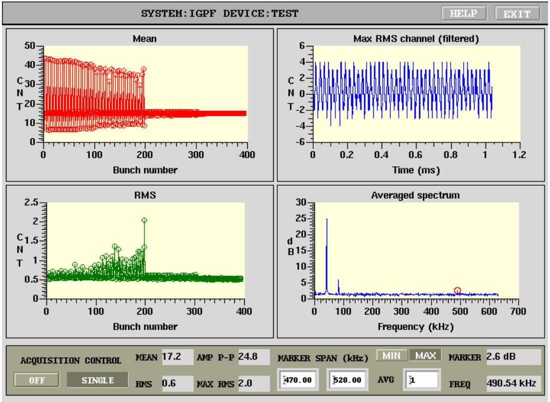

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Day by Day Summary

- Sunday (2017-04-23):
  - Unpacked the hardware;
  - Network and signal connections;
  - Passive monitoring with ESRF front-end;
  - Dimtel LNFE setup.
- Monday (2017-04-24):
  - Adjusted timing to the BPM hybrid to optimize common mode rejection;
  - Parasitically timed the front-end;
  - Using very low amplitude single bunch excitation timed the back-end;
  - Set up multibunch feedback;
  - Checked notch monitoring, tune tracking, single bunch transfer function.
- Tuesday (2017-04-25):
  - MDT shift from 8:00 to 19:00;
  - Covered 9 out of 10 items in the plan.

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Setup

- Baseband processor (iGp12) and 352 MHz low noise front-end (LNFE);
- Dimtel BPMH-20-2G hybrid processes 4 button signals to generate ΔY, ΔX, and Σ;
- Differential DAC output drives two power amplifiers directly.

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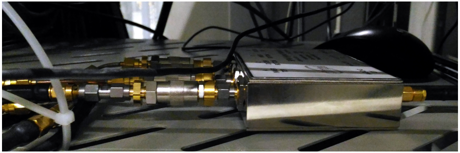

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The Plan

- ✓ Single bunch timing and calibration @ 8 mA, high chromaticity;
- ✓ Single bunch limits vs. chromaticity, gaps open and closed;
- ✓ Feedback operation: zero chromaticity, uniform fill;
  - ✓ Characterization of growth rates;
  - ✓ Bunch cleaning (zero chromaticity);
  - ✓ Parasitic tune monitoring.
- ✓ Standard 7/8 fill, high chromaticity
  - ✓ Tune monitoring tools
  - ✓ Bunch cleaning
- ✓ Injection studies;
- ✗ Operate with the current (ESRF) front end.

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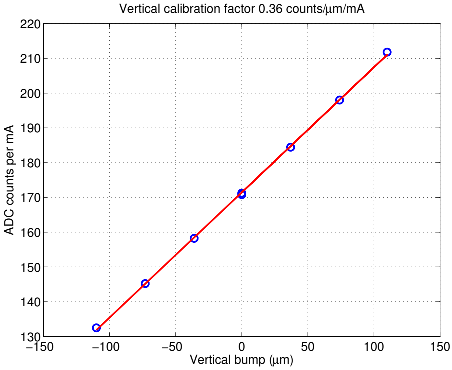

- Configured 9 dB of attenuation to handle apparent orbit offset;
- Calibration factor is 0.36 counts/µm/mA;
- Centering the beam requires a −476 µm bump;
- At this offset can support single bunch currents up to 12 mA;
- Much higher sensitivities are feasible with better pickup (β) and orbit offset trimming.

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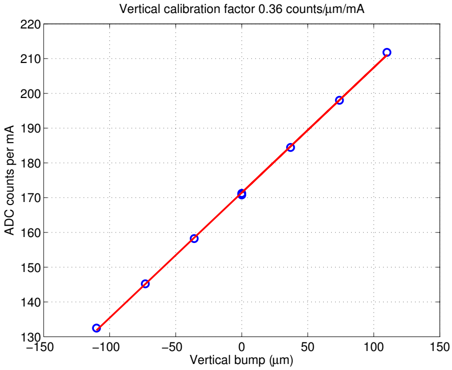

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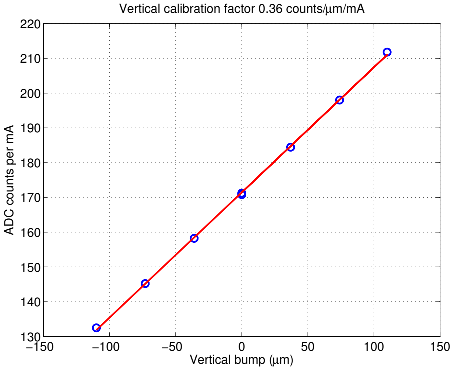

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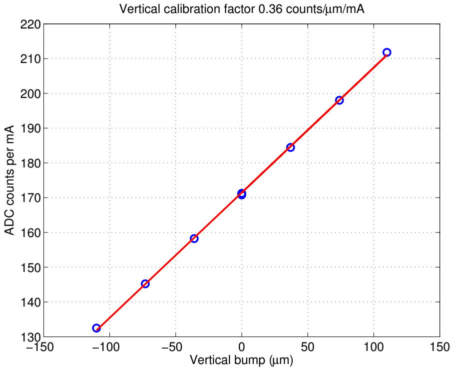

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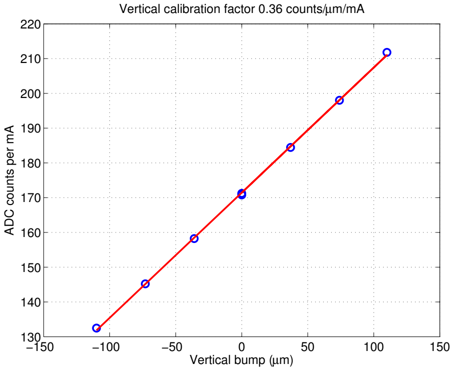

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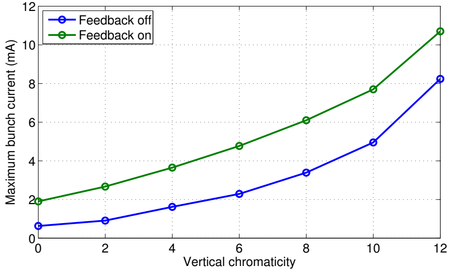

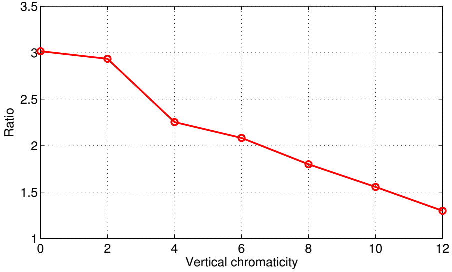

- A bit of feedback tuning at each point;
- Could definitely benefit from more tuning time;
- Roughly consistent with the results from the existing system;
- Modifying feedback during injection might help extend the limit.

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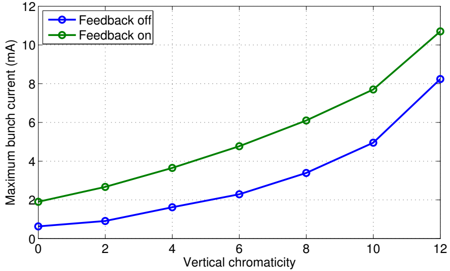

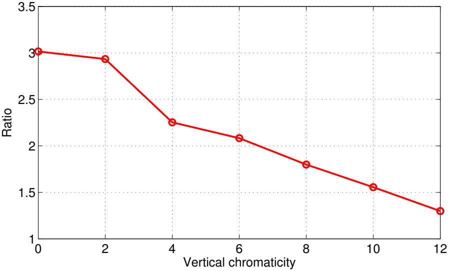

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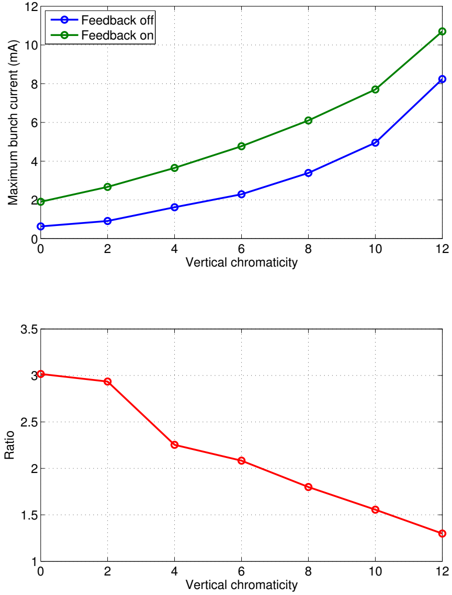

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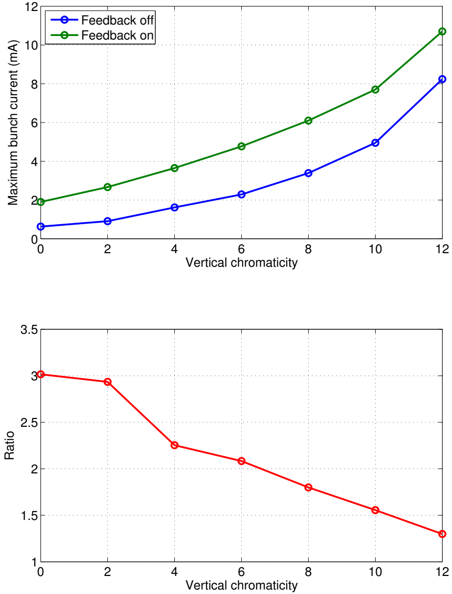

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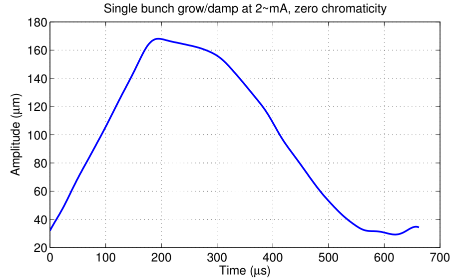

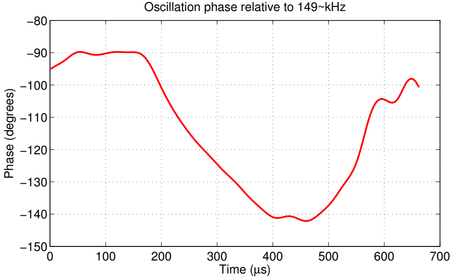

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- Feedback is turned off for 180 µs;
- Growth looks linear;
- Reactive feedback setup — closed loop induces frequency shift.

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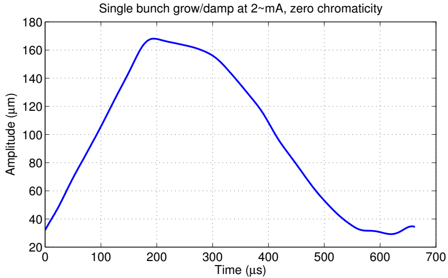

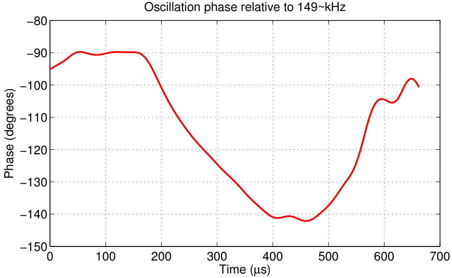

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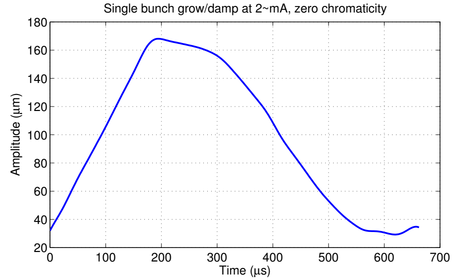

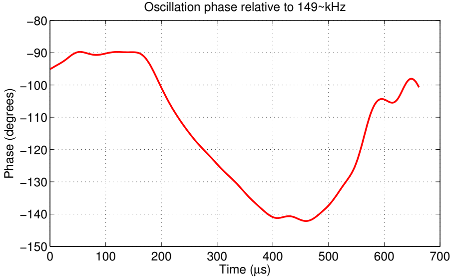

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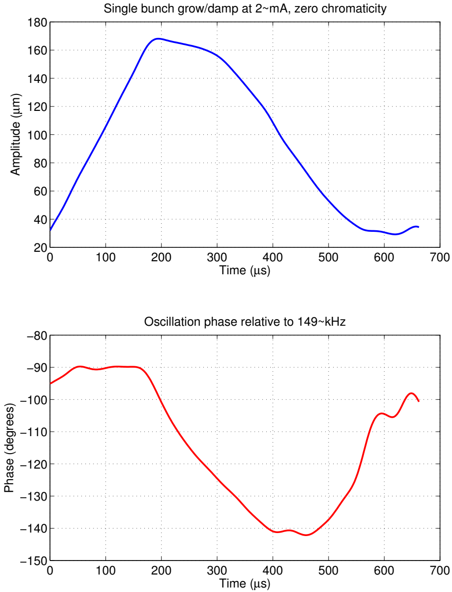

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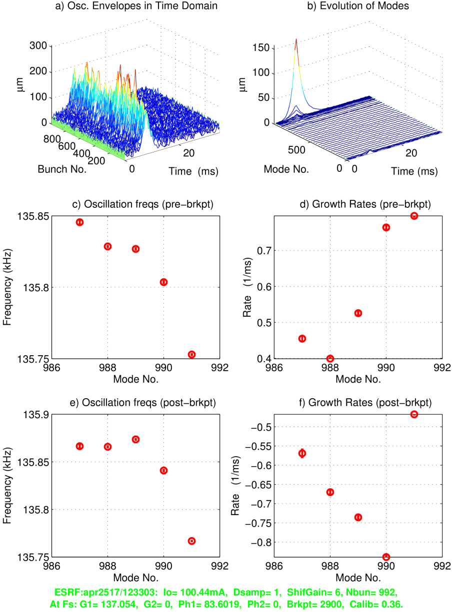

- Grow/damp at 100 mA, 8 ms growth time;
- Only resistive wall modes;
- Damping rates non-uniform — low frequency response of the amplifier?
- Fits look very clean, textbook exponential transients;
- Filled to 200 mA, not limited by instabilities;
- Growth time too long, when feedback turns on there is not enough gain to damp the motion.

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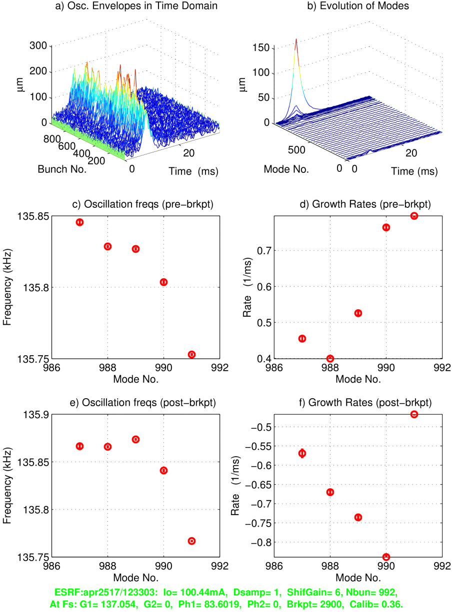

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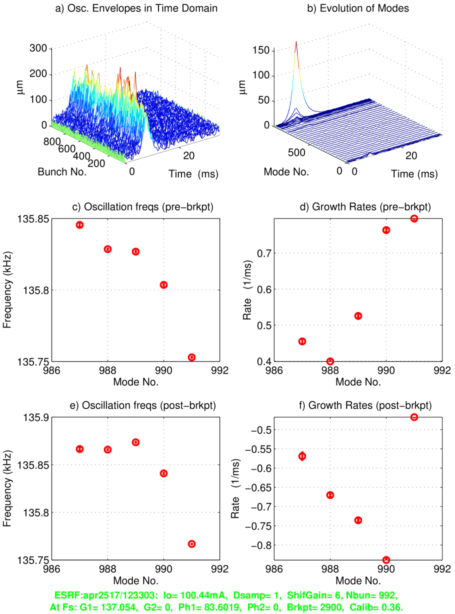

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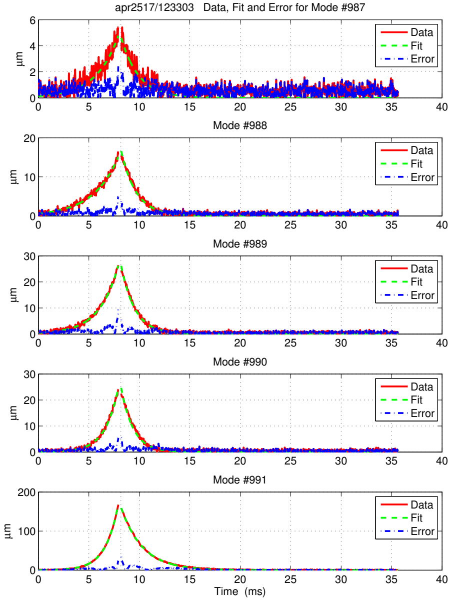

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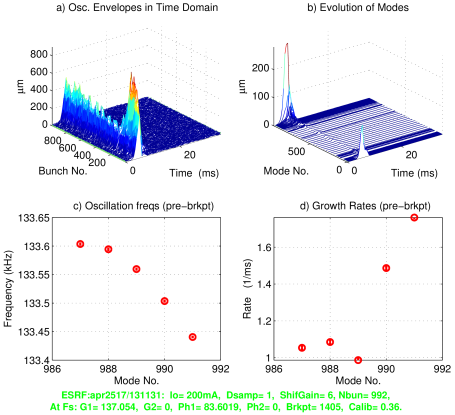

- Grow/damp at 100 mA, 8 ms growth time;
- Only resistive wall modes;
- Damping rates non-uniform — low frequency response of the amplifier?
- Fits look very clean, textbook exponential transients;
- Filled to 200 mA, not limited by instabilities;
- Growth time too long, when feedback turns on there is not enough gain to damp the motion.

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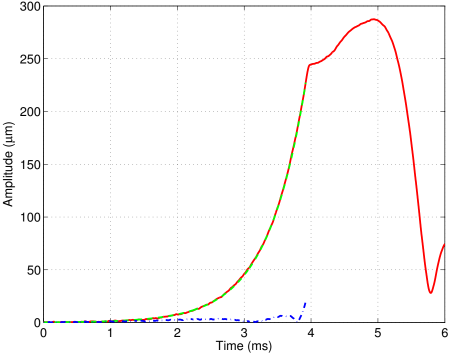

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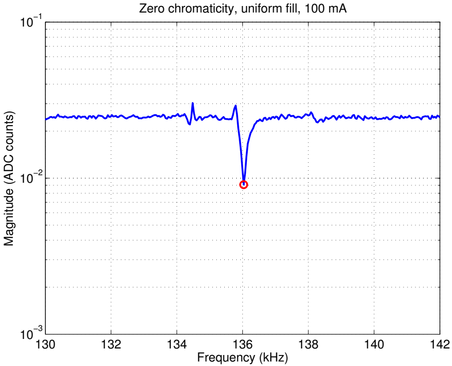
Spectral Notch Tune Monitoring



- 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.

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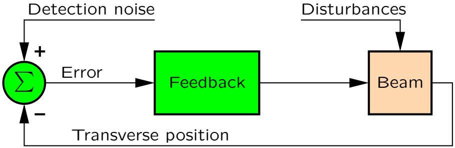

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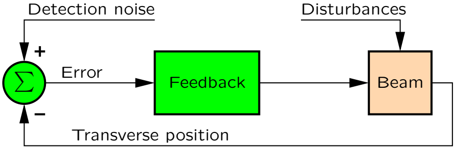

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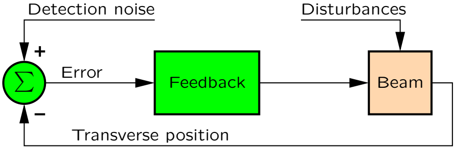

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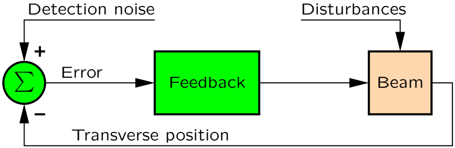

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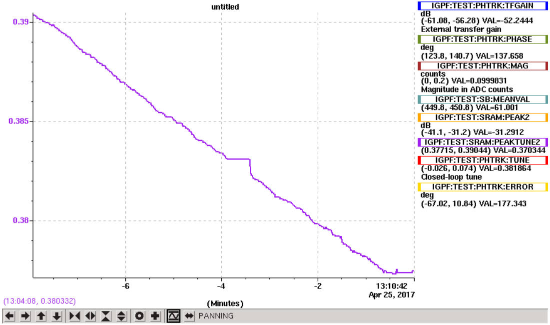

- Tune tracking during injection from 10 to 200 mA;
- Done by the iGp12 at 2 Hz update rate:
  - Exponential averaging of 5 sweeps (2.5 s time constant);
  - Minimum search in 120–150 kHz range.
- Network port change around −4 minute mark.

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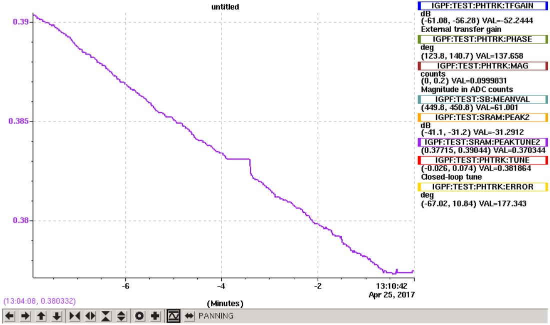

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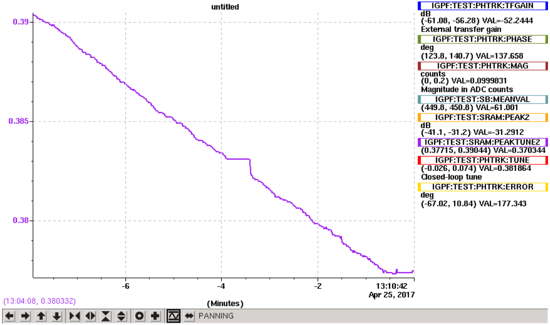

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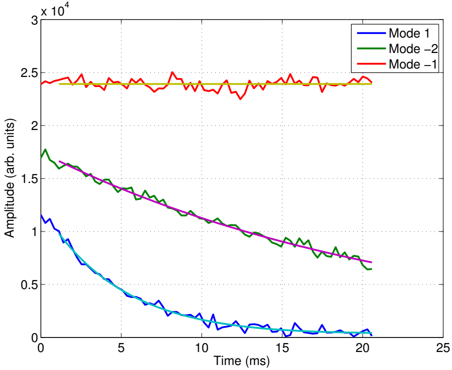
All Mode Scan: Technique



- 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;
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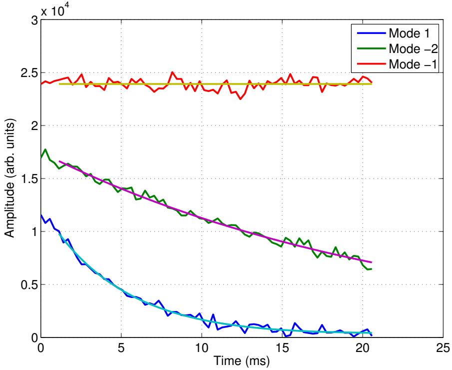

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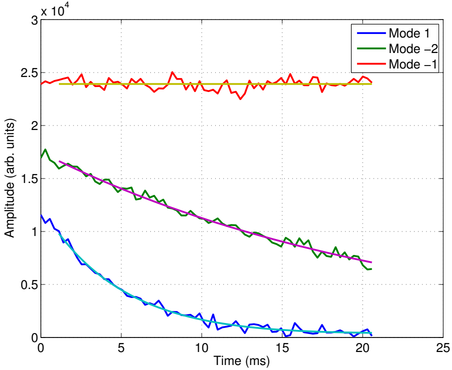

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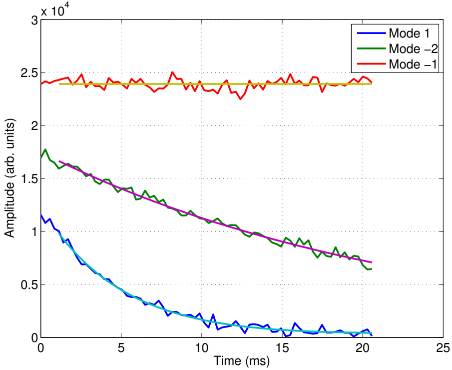

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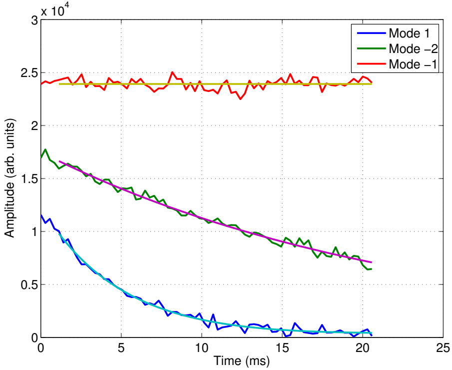

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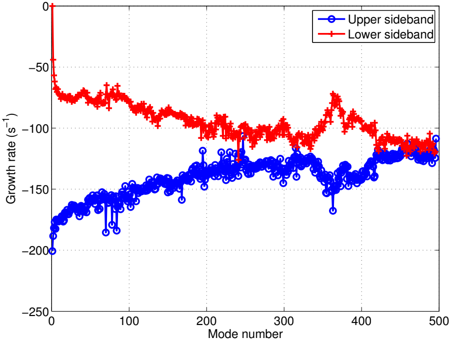

- Automated processing extracts growth or damping rates;
- Clear resistive wall signature;
- A band of higher order modes around mode -365 ($129 + N \times 352$ MHz);
- A smaller HOM band around -298 ($105 + N \times 352$ MHz);
- Radiation damping rate $118\ s^{-1}$ (8.5 ms damping time).

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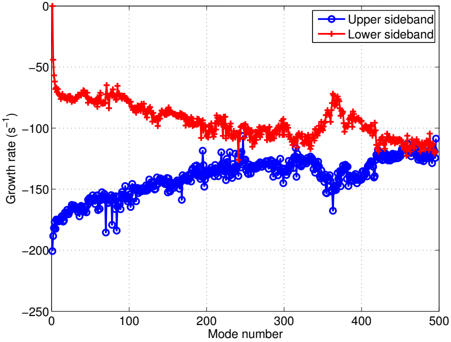

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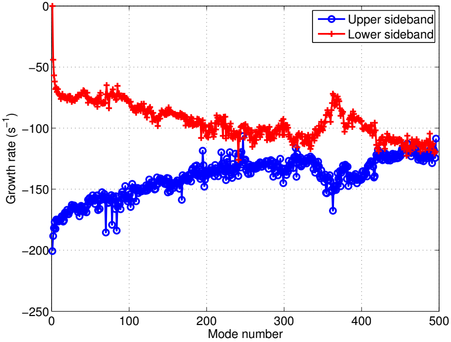

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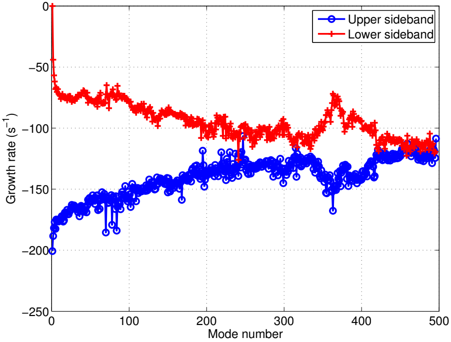

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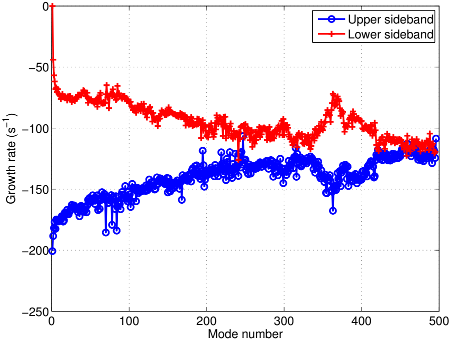

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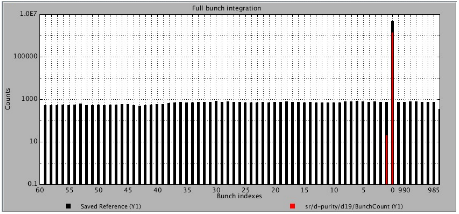
Outline

Bunch Cleaning



- Started with scraper at 1.5, tested at 3.0, then 4.5;
- Cleaning works fine at 1.5 and 3.0, somewhat touchy at 4.5;
- Need a bit of parameter optimization, most likely can support reliable cleaning at scraper gap of 3.5–4.5.

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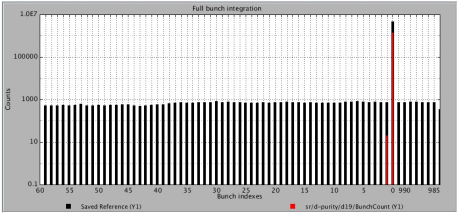

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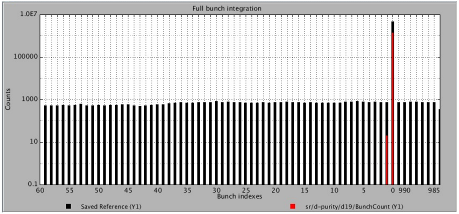

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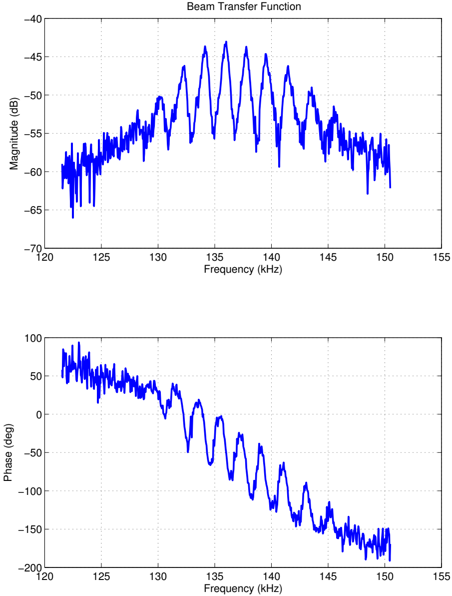
Single Bunch Transfer Function



- 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.

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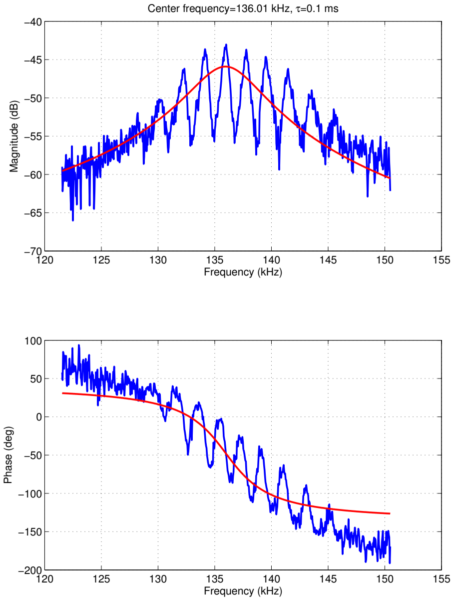

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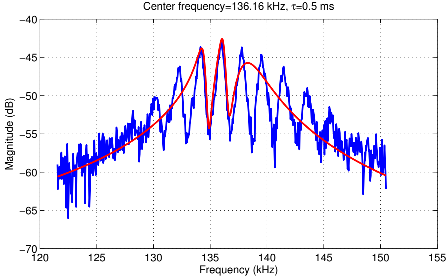

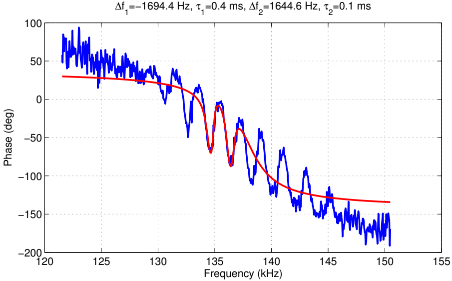

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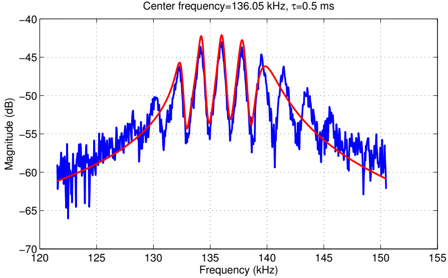

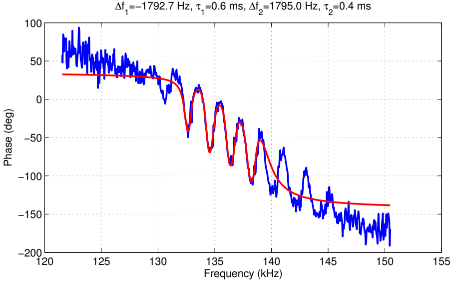

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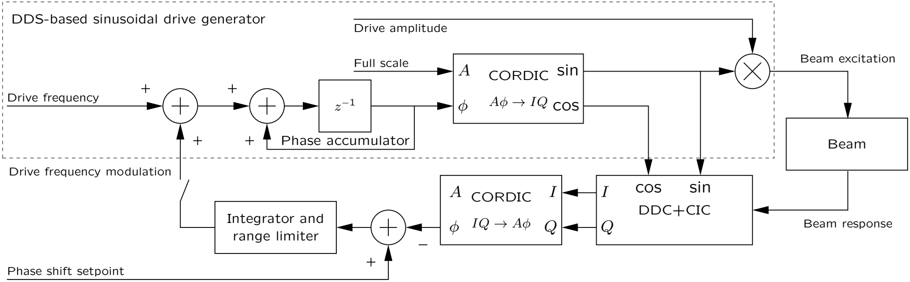
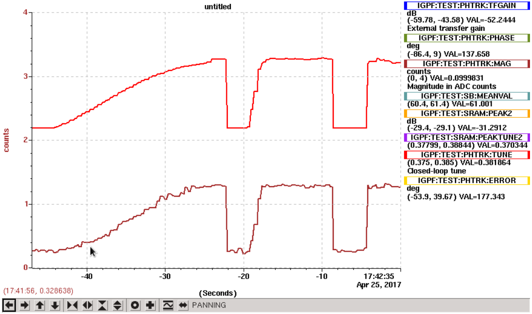
Single Bunch Phase Tracking



- 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.

Phase Tracking and Chromaticity Measurement



- Close the loop at -45 s;
- Slow settling at low gain, faster as the gain is raised;
- Chromaticity scan with 10 Hz steps;
- Return step of 40 Hz is too large, tracker locks at the wrong point;
- Open and close the loop to re-lock.

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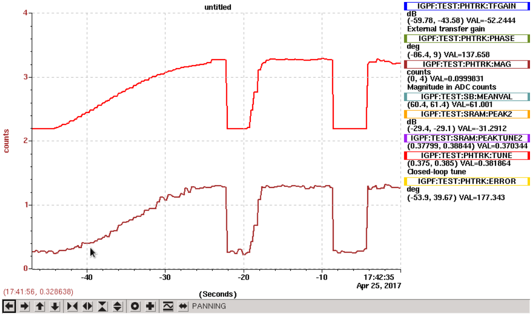

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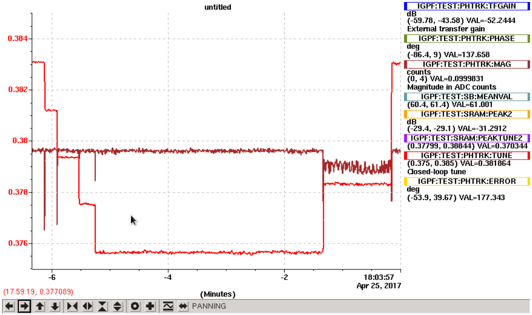

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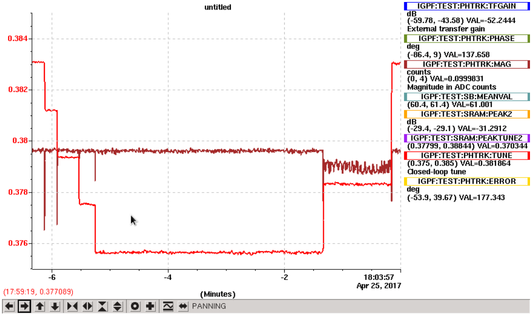

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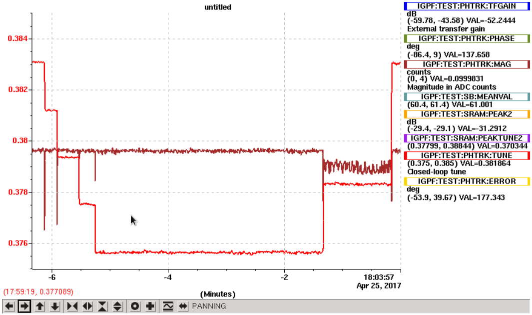

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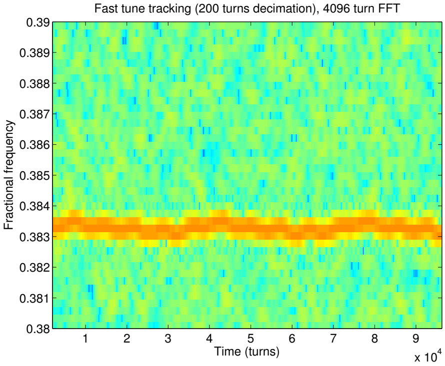

- Decimation factor in phase tracker controls tracking bandwidth;
- 200 turns decimaton, 1.77 kHz measurement bandwidth;
- 180 Hz closed loop tracking bandwidth;
- Use time-domain downconversion to better resolve tune modulation;
- Spectrum shows lines at 10 and 50 hertz.

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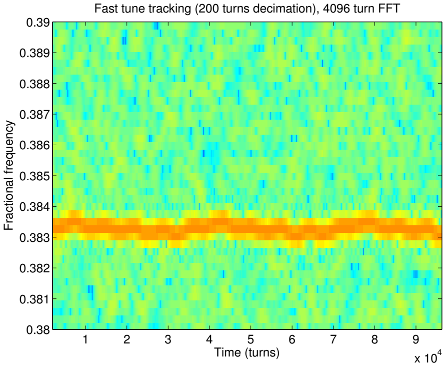

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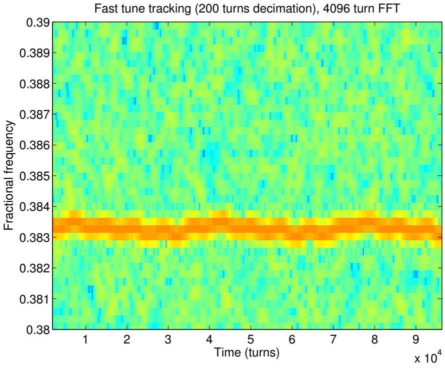

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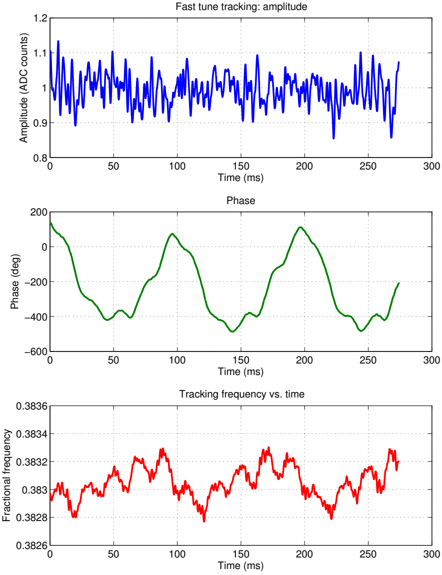

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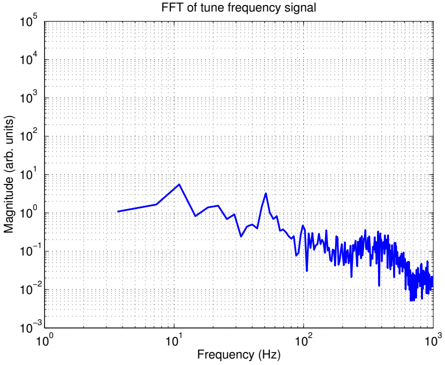

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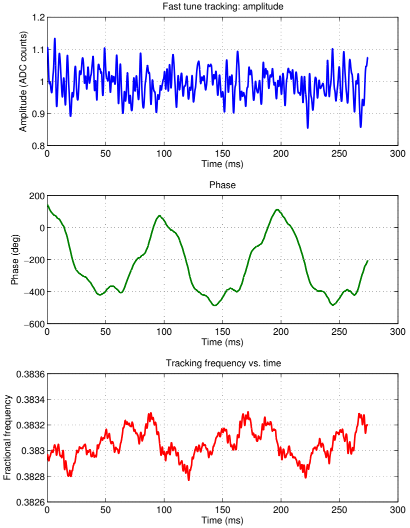

- Tune moves around by 5×10^{-4};
- Fitting complex phase space trajectories fails due to tune modulation;
- Modal scan runs at 2 Hz and aliases the modulation;
- Grow/damp transient shows tune shifts around 100 Hz (2.8×10^{-4}) at 100 mA;
- At 15 mA expect only 4.2×10^{-5}, completely obscured by this baseline modulation.

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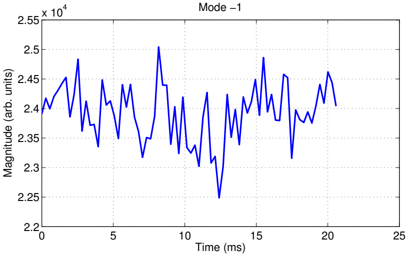

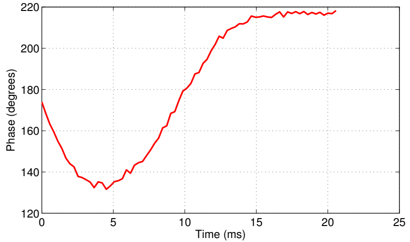

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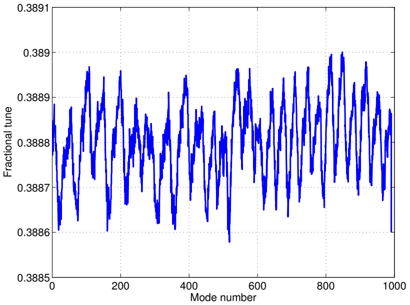

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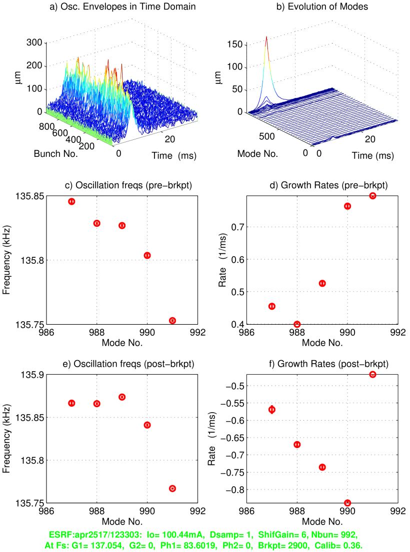

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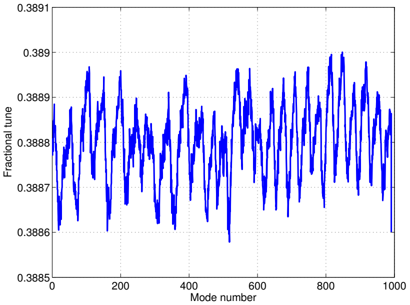
- Grow/damp transient shows tune shifts around 100 Hz (2.8×10^{-4}) at 100 mA;
- At 15 mA expect only 4.2×10^{-5}, completely obscured by this baseline modulation.

Tune Variation



- Tune moves around by 5×10^{-4};
- Fitting complex phase space trajectories fails due to tune modulation;
- Modal scan runs at 2 Hz and aliases the modulation;
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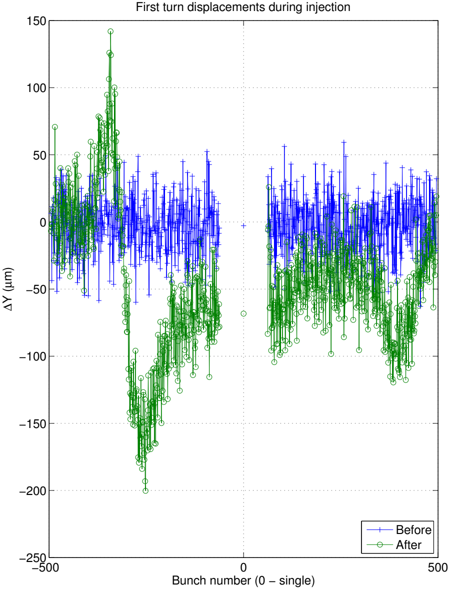
Injection Transient



- Captured beam transient due to the injection kickers firing;
- Automatic extraction of the difference orbit;
- Converted to physical units using bunch-by-bunch currents and measured calibration factor.

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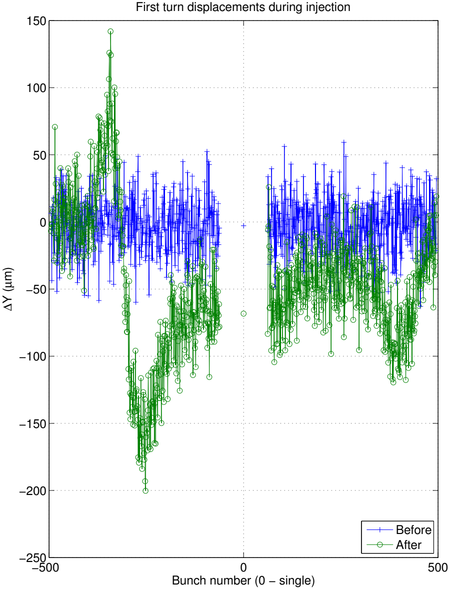

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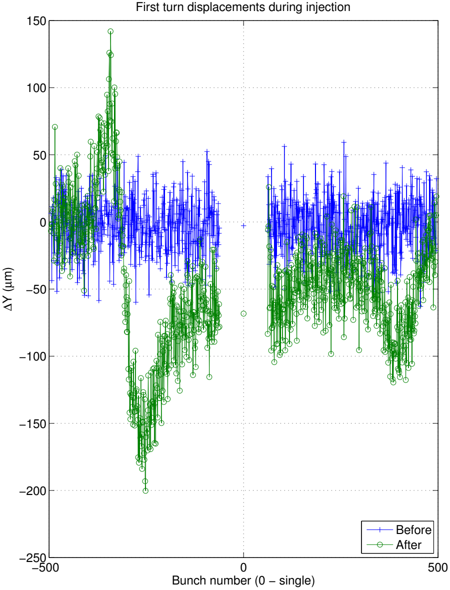

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- Successfully operated Dimtel bunch-by-bunch system in the ESRF;
- Many diagnostic features have been demonstrated;
- In the demo setup feedback pushes vertical emittance from 7.7 to 8 pm.
- With some balancing and optimization much lower noise floor is easily achievable.
- I'd like to thank everyone who helped to make this a successful test!

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