Bunch-by-bunch Feedback Studies in MAX IV 3 GeV

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June 13, 2016

Outline

1. Setup
2. Longitudinal Plane
   - System Characterization
   - Optimization of Cavity Temperatures
   - Stable Beam + Harmonic Cavities
3. Transverse Planes
   - System Characterization
   - Ion Instabilities
   - Resistive Wall Studies
   - Beam Transfer Functions and Radiation Damping

Day-by-Day Summary

- Thursday (2016-6-9):
  - Hardware setup and improvements;
- Friday (2016-6-10):
  - Set up all three planes at low current (1 mA);
  - Low current (up to 20 mA) measurements;
  - Attempted to run with harmonic cavities at 150 mA.
- Saturday (2016-6-11):
  - Mapped longitudinal HOMs vs. cavity temperature;
  - Pushed maximum stable current to 45 mA.

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  - Front-end calibrations;
  - Single bunch radiation damping;
  - Transverse studies at 40 mA;
  - Harmonic cavities at 40 mA.
- Monday (2016-6-13):
  - Zero chromaticity optics;
  - RF field control loops configured!!!
  - Measurements of transverse instabilities to 80 mA.

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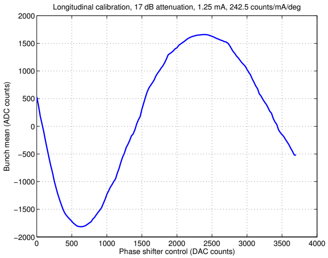
Longitudinal Calibration



- Sweep phase shifter over 360°;
- Record bunch signal (average);
- Calibration factor of 242.5 counts/mA/degree;
- At 1 mA per bunch ADC LSB is 4 milli-degrees (114 fs);
- At 80 mA residual RMS is 2 ADC counts or 18 milli-degrees (504 fs).

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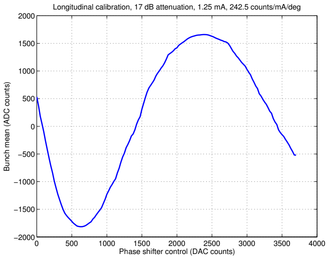

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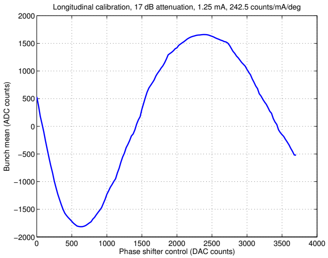

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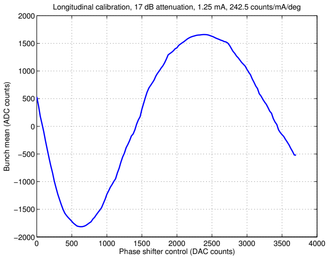

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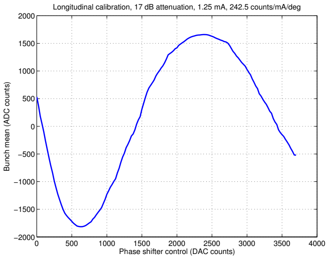

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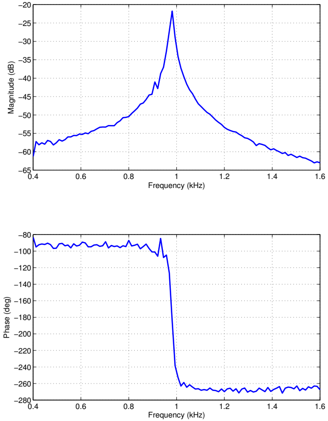

- Insufficient kick voltage to measure in time domain;
- Beam transfer function, single bunch, 1.25 mA;
- Zoom in: $f_s = 981$ Hz, $Q = 76.6$, $\tau_{rad} = 2Q/\omega_s = 24.9$ ms;
- Fit of the damped harmonic oscillator response gives similar values;
- As does the narrowband fit;
- Peak oscillation amplitude during measurement: 15 ps.

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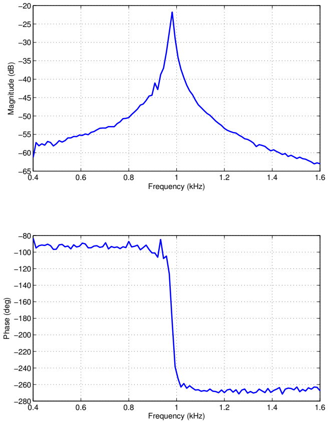

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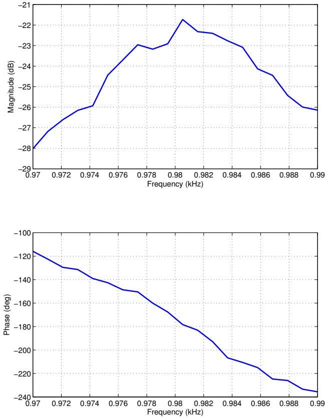

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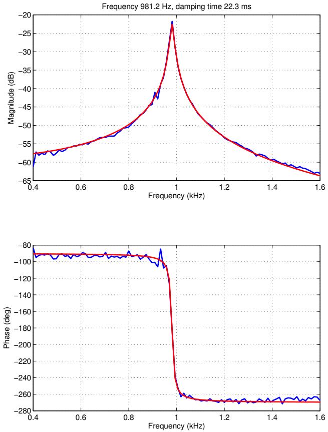

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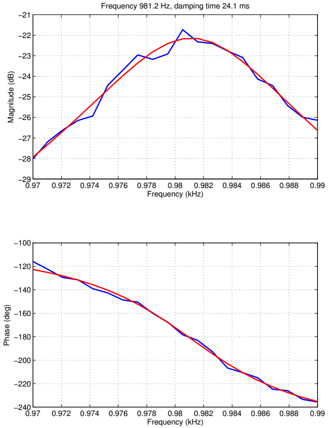

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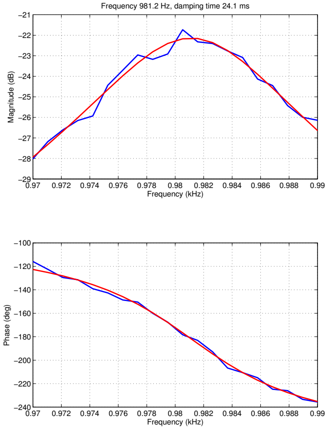

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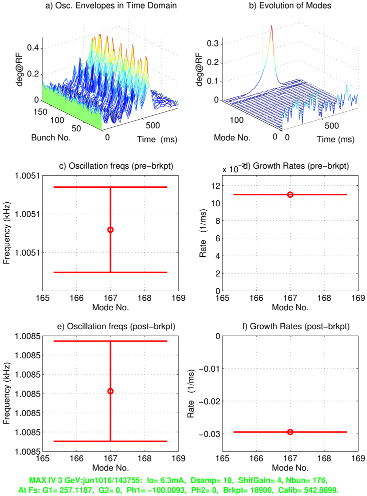

- Open loop measurement of fastest modes;
- Complex exponential fit to open and closed loop sections to extract the eigenvalues;
- Excellent fit to growth and damping.

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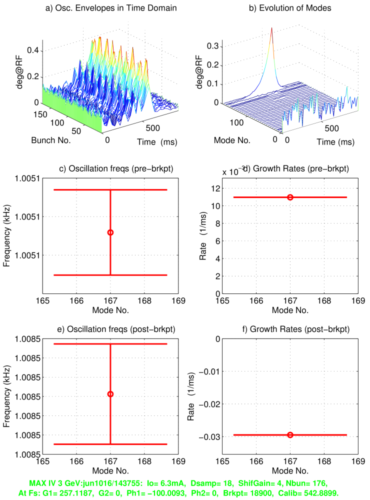

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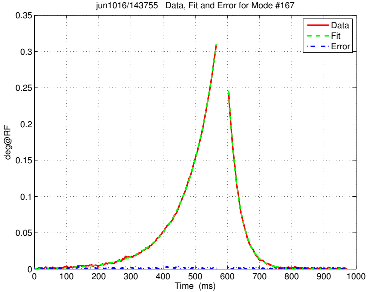

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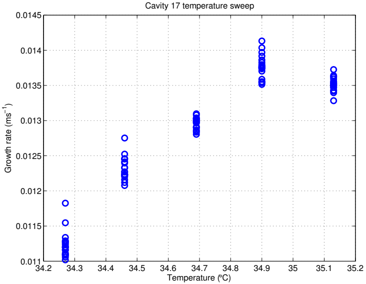
Cavity 17 Temperature Scan



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- Set cavity 17 to 33°C.

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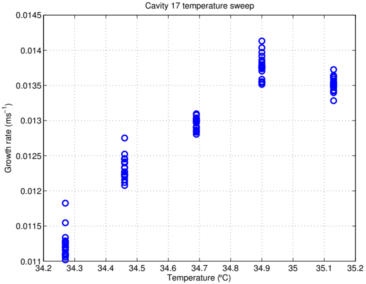

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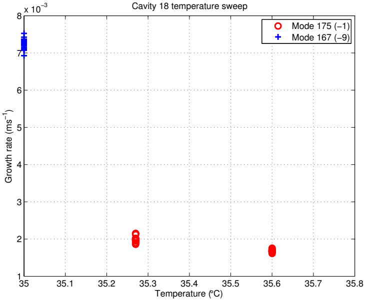
Cavity 18 Temperature Scan



- Lowering the temperature increases mode 167 growth rate (too fast to capture);
- Set cavity 17 to 35.9°C, moved to 33°C on Sunday.

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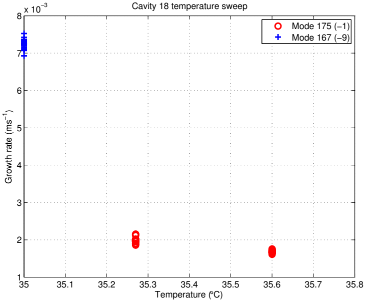

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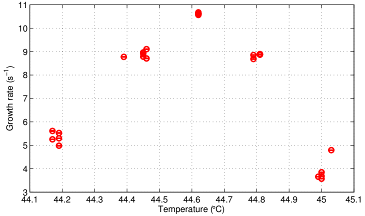
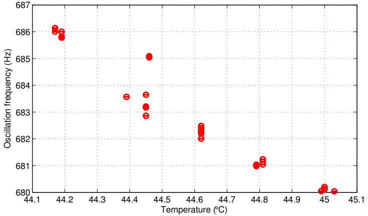
Cavity 20 Temperature Scan (February)





- Moved cavity temperature from nominal 35 °C;
- Growth rate peak seen around 45 °C — mode 167;
- Detailed scan at 0.2 °C steps reveals a clear resonance;
- Fit second-order resonator response:

Parameter	Value
T_{center}	44.56 °C
Bandwidth	2.64 °C
Rad. damping	18.5 ms

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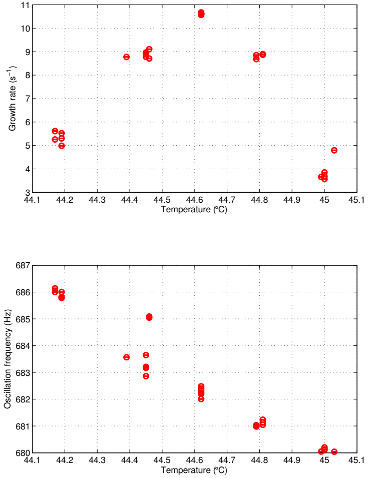

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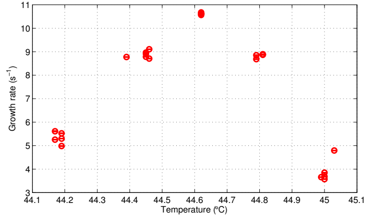

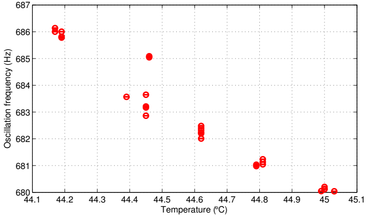

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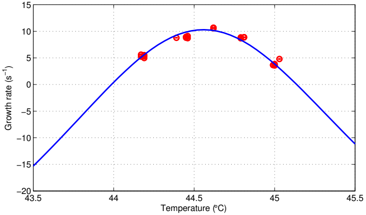

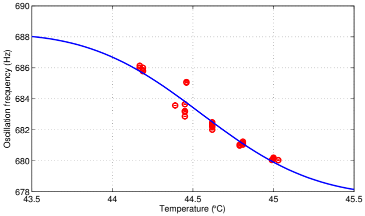

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Qualitative Analysis

- From cavity 20 temperature sweep we know that the tuning coefficient for the HOM driving mode 167 is negative;
- Detuning to compensate for beam loading lowers the frequency of the fundamental mode, as well as the HOMs;
- We lowered cavity temperatures to move the HOM away from the synchrotron sideband (tuned the mode to higher frequency);
- With beam current increasing the mode tunes back to drive the instabilities;
- Should do the opposite - move to higher temperature.

Cavities and HOMs

- We see the following eigenmodes dominating in the longitudinal plane: 119, 167, 172, 173, 175;
- Using cavity temperature tuning we can associate mode 167 with main RF cavities, the rest - with harmonic cavities;
- Most likely modes 172, 173, and 175 are driven by the same HOM in three individual cavities, with slightly different center frequencies.

Outline

Observations

- Filled to 40 mA with feedback in all planes;
- Found that tuning cavities 13 and 15 produced growth rate increases, used cavity 14;
- Tuned in in small steps, verified stability and recorded synchrotron frequency;
- When tuned in close to generate useful bunch lengthening, the cavity heats up due to beam induced power and tunes even closer to the third harmonic. Attention needed to avoid run-away (tuning loop?).
- Reached 73 kV (205 mV readback), bunch length 150 ps vs. 130 ps with cavities detuned;
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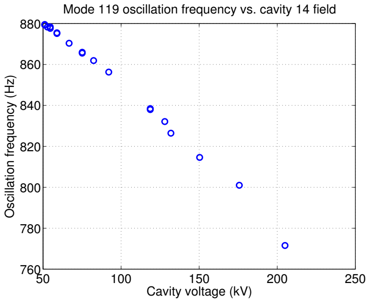
Synchrotron Frequency vs. Harmonic Voltage



- Voltage calculated from overheard conversion factor of 140 mV equal to 50 kV;
- Mode 119 frequency in growth transient, possible tune shifts;
- Measured with RF forward power stabilized, synchrotron frequency changes due to varying beam loading.

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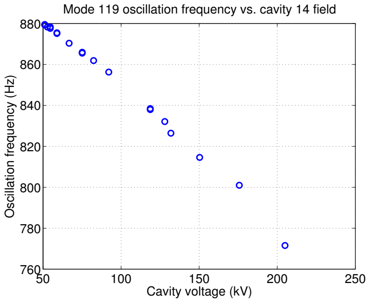

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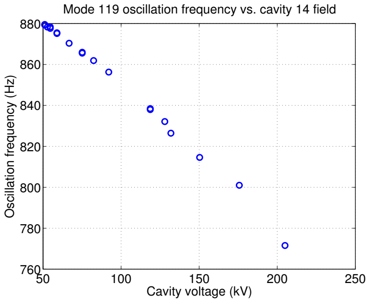

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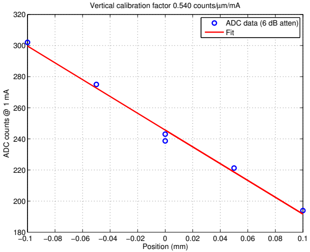

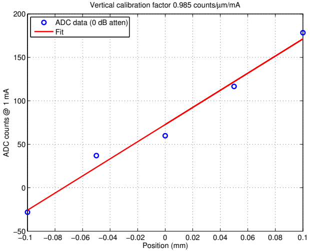

- Set up controlled orbit bumps in X and Y;
- Measure bunch signal displacement in ADC counts;
- At 2 mA per bunch ADC LSB corresponds to 0.9 and 0.5 μm in X and Y respectively;
- Calibration factors from February (1.5 GHz front end, different BPM): 0.688 counts/mA/μm and 0.764 counts/mA/μm (Y/X).

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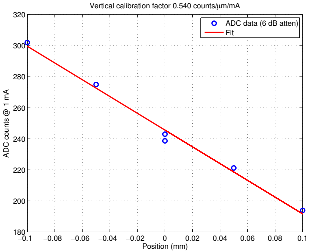

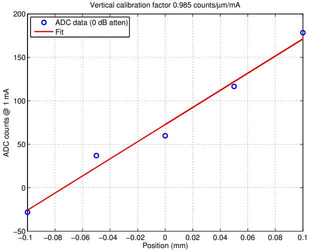

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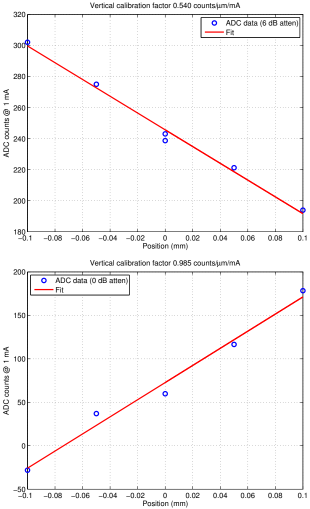

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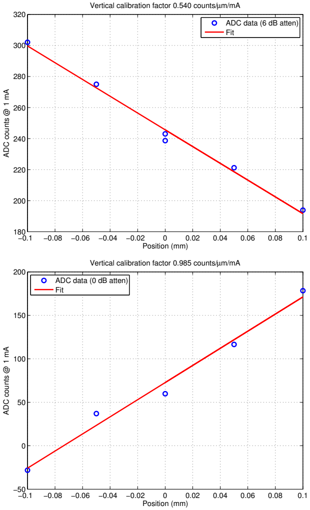

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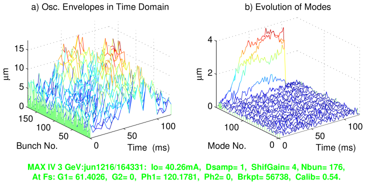
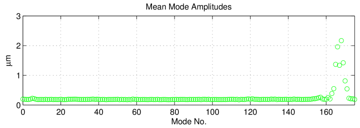
Outline

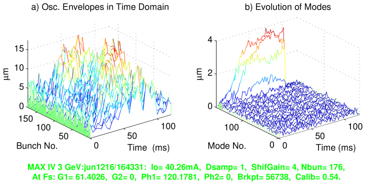
Horizontal Plane

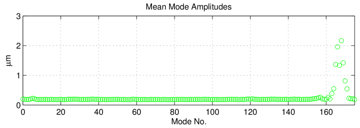




- Typical features of ion-driven instability:
  - Non-exponential growth;
  - Wide band of low frequency negative modes;
  - Low amplitude saturation
- Peak bunch amplitudes reach 14 μm.

Horizontal Plane





- Typical features of ion-driven instability:
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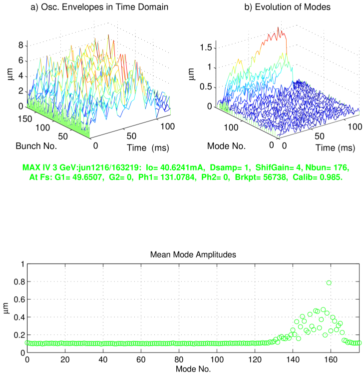
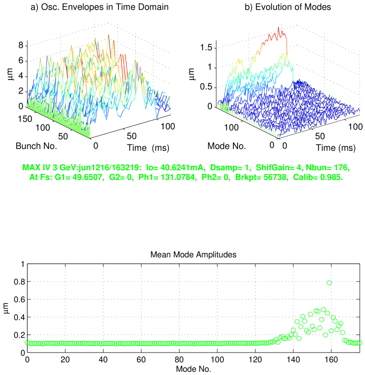
Vertical Plane



- Similar to X
- Much wider band of excited modes;
- Peak bunch amplitudes reach 11 μm.

Vertical Plane



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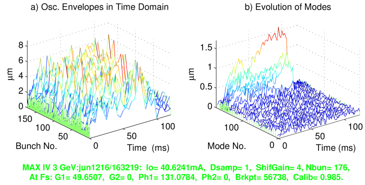
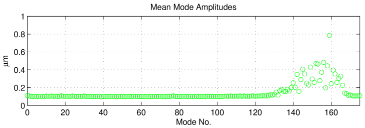
Vertical Plane





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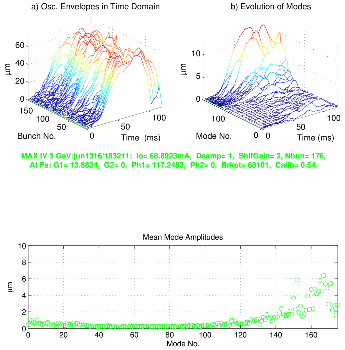
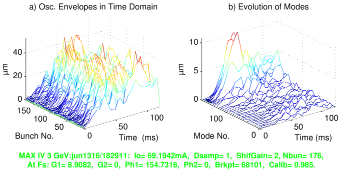
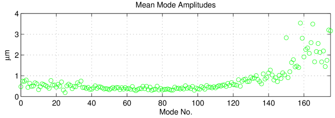
Measurements at 70 mA, Zero Chromaticity



- Still ions, 50–60 μm horizontally;
- 35-40 μm vertically;
- With vertical feedback off at 60 mA, blowup is seen clearly on the monitor (and has strong effect on the lifetime);
- Some evidence for resistive wall modes in the vertical plane, need a very uniform fill to investigate more carefully.

Measurements at 70 mA, Zero Chromaticity





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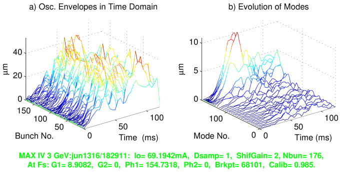

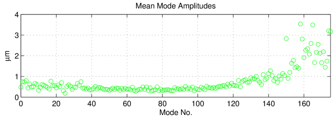

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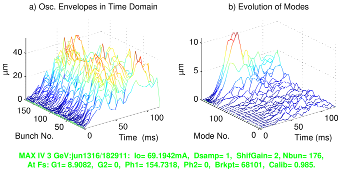

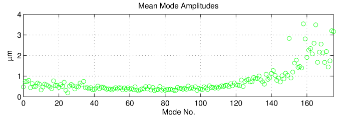

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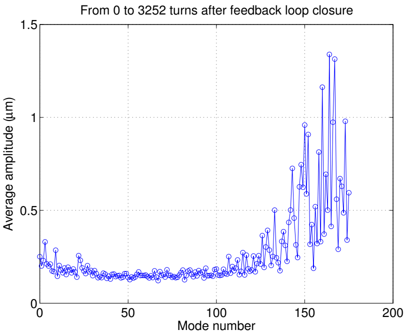
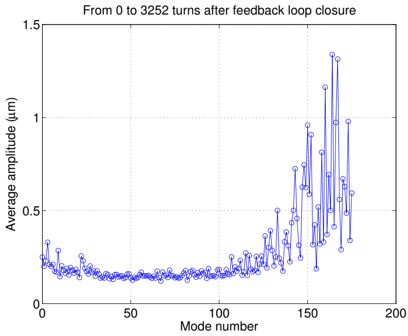
Residual Motion: X, Zero Chromaticity, 70 mA



- Average modal amplitudes, 10 kHz band around ν_x;
- Full damping transient;
- From 100 turns after transition;
- From 200 turns;
- From 400 turns;
- From 800 turns;
- From 1600 turns.

Residual Motion: X, Zero Chromaticity, 70 mA



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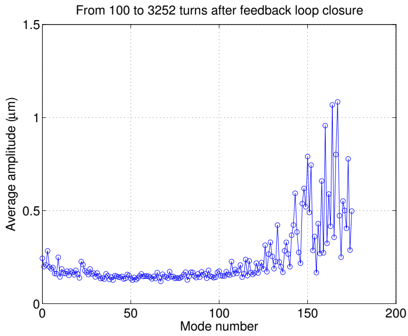
Residual Motion: X, Zero Chromaticity, 70 mA



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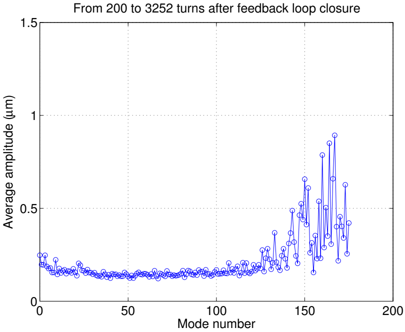

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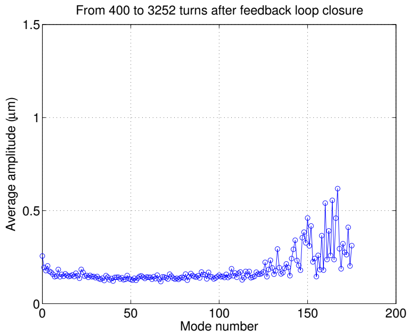

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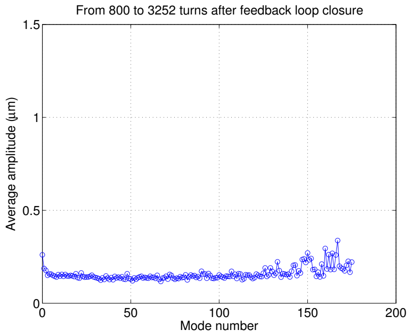

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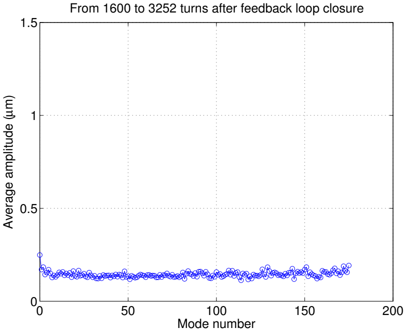
Residual Motion: X, Zero Chromaticity, 70 mA



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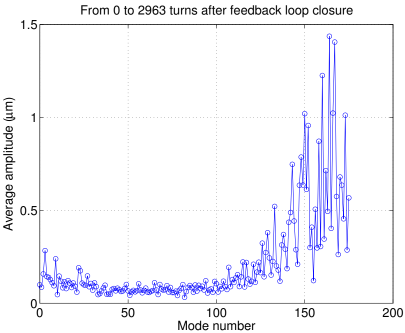
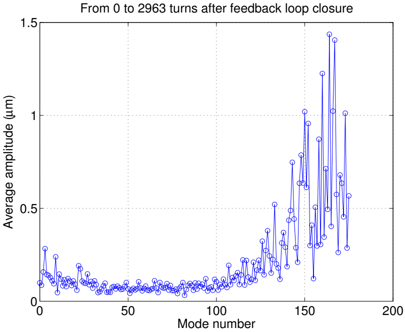
- From 200 turns;
- From 400 turns;
- From 800 turns;
- From 1600 turns.

Residual Motion: X, Zero Chromaticity, 70 mA (Cont.)



- Average modal amplitudes, 1.6 kHz band around ν_x;
- Full damping transient;
- From 100 turns after transition;
- From 200 turns;
- From 400 turns;
- From 800 turns;
- From 1600 turns.

Residual Motion: X, Zero Chromaticity, 70 mA (Cont.)



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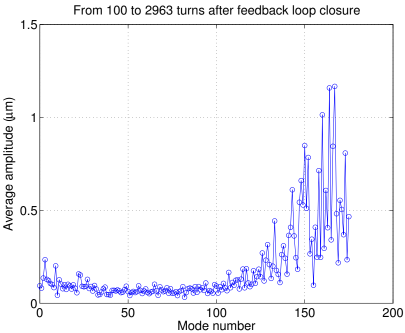
Residual Motion: X, Zero Chromaticity, 70 mA (Cont.)



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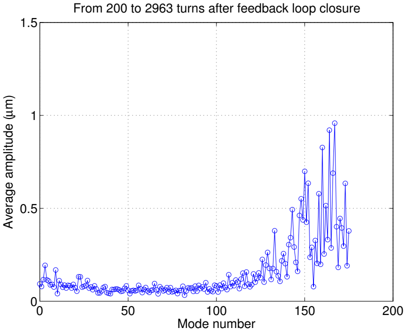
Residual Motion: X, Zero Chromaticity, 70 mA (Cont.)



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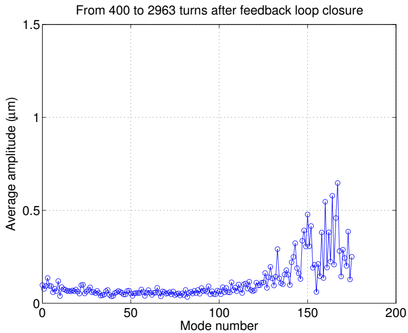
Residual Motion: X, Zero Chromaticity, 70 mA (Cont.)



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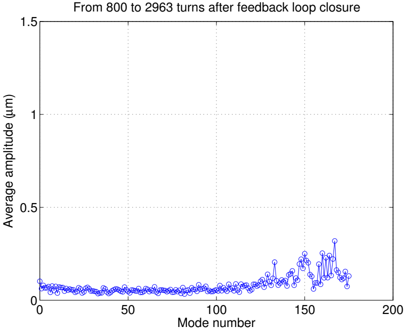
Residual Motion: X, Zero Chromaticity, 70 mA (Cont.)



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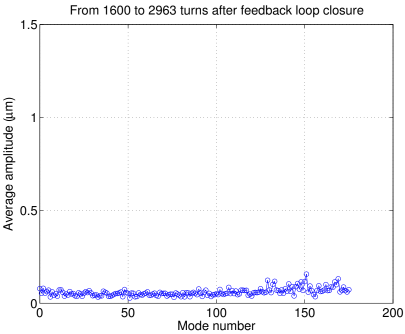
Residual Motion: X, Zero Chromaticity, 70 mA (Cont.)



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- Full damping transient;
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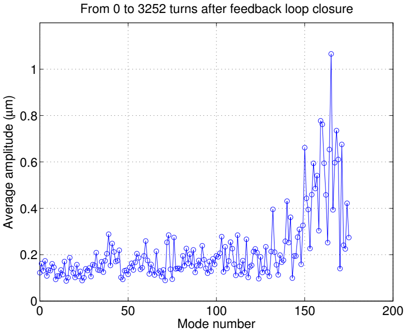
Residual Motion: Y, Zero Chromaticity, 70 mA



- Average modal amplitudes, 10 kHz band around ν_y;
- Full damping transient;
- From 100 turns after transition;
- From 200 turns;
- From 400 turns;
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- From 1200 turns;
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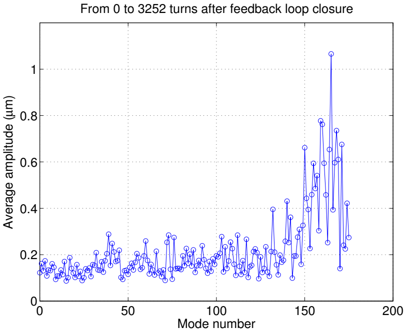
Residual Motion: Y, Zero Chromaticity, 70 mA



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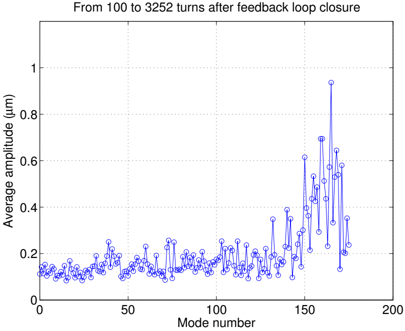
Residual Motion: Y, Zero Chromaticity, 70 mA



- Average modal amplitudes, 10 kHz band around ν_y;
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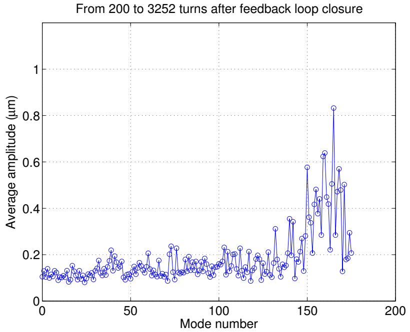
Residual Motion: Y, Zero Chromaticity, 70 mA



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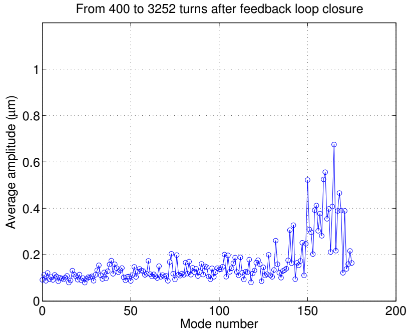

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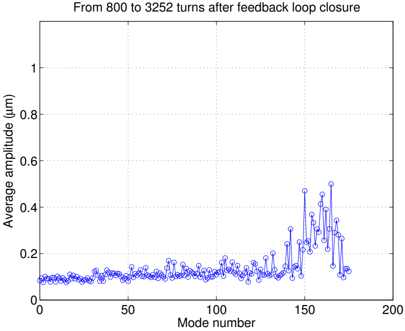

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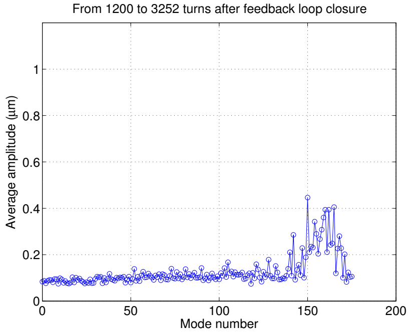

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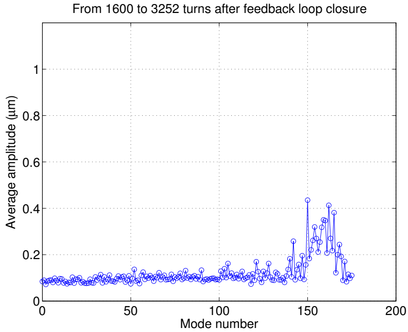

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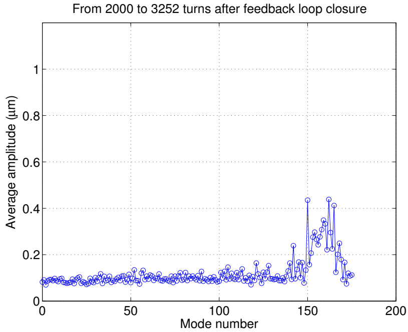

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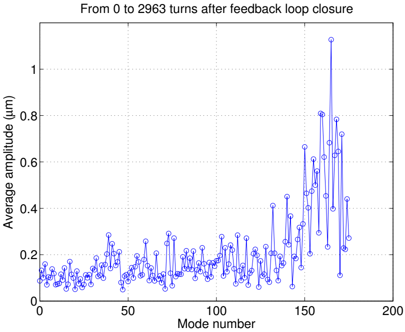
Residual Motion: Y, Zero Chromaticity, 70 mA (Cont.)



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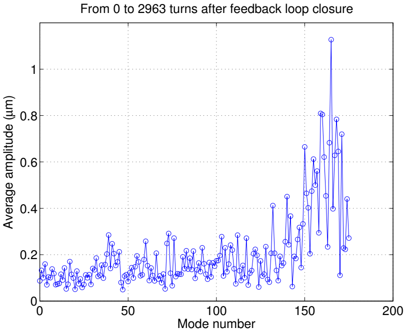
- From 2000 turns.

Residual Motion: Y, Zero Chromaticity, 70 mA (Cont.)



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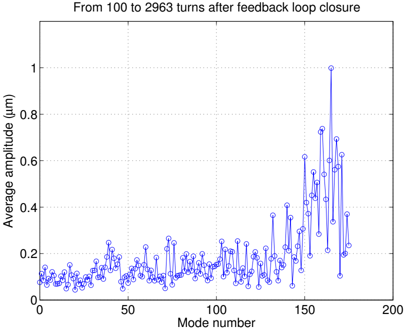

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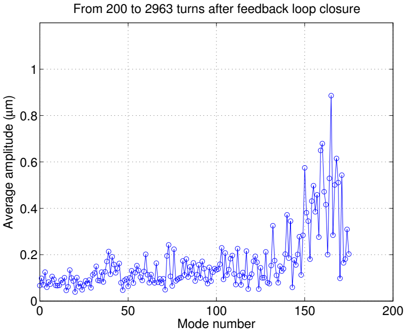

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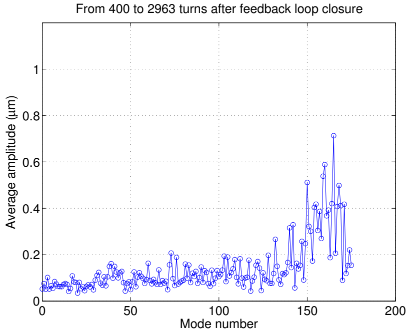
Residual Motion: Y, Zero Chromaticity, 70 mA (Cont.)



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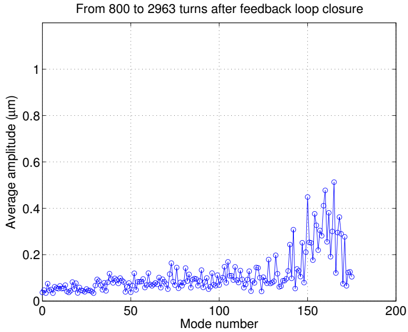
Residual Motion: Y, Zero Chromaticity, 70 mA (Cont.)



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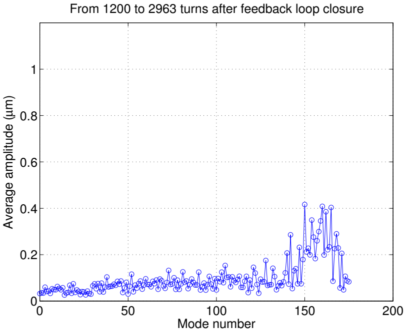
Residual Motion: Y, Zero Chromaticity, 70 mA (Cont.)



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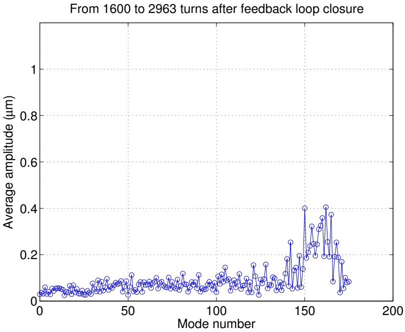
Residual Motion: Y, Zero Chromaticity, 70 mA (Cont.)



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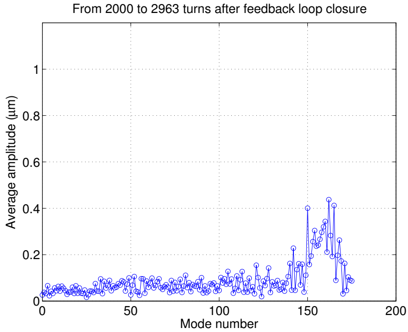
Residual Motion: Y, Zero Chromaticity, 70 mA (Cont.)



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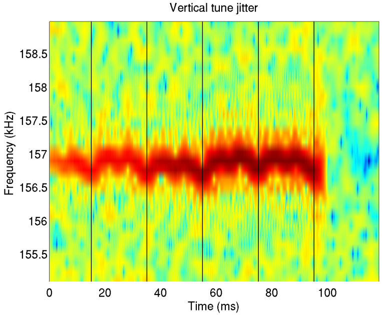
- From 1600 turns;
- From 2000 turns.

Tune Jitter



- Spectrogram: 4096 N_{FFT}, 4076 overlap;
- Every 20 ms vertical tune dips down more than 500 Hz;
- Dip amplitude is underestimated, FFT length is 7.2 ms;
- Upward dips in X, still 20 ms spacing.

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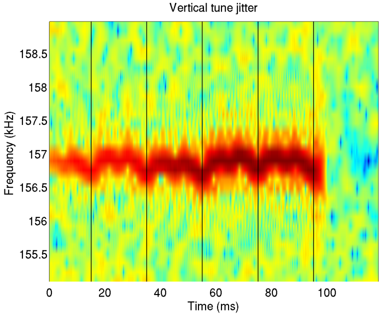

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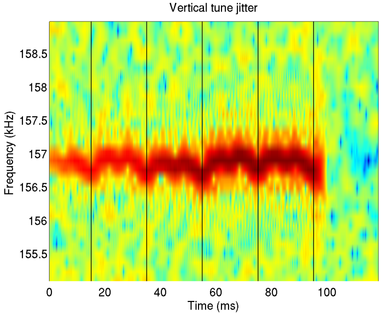

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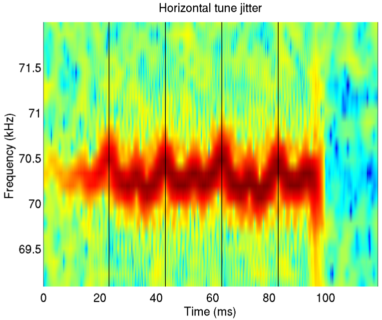

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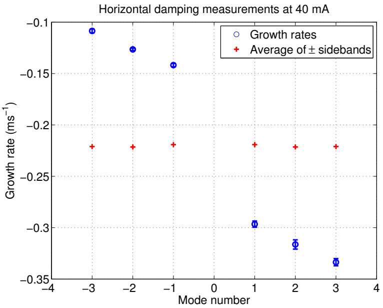
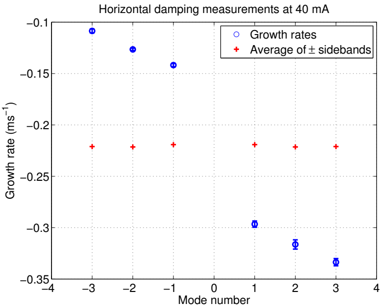
Outline

Horizontal Plane: Low Frequency Modes



- Selectively excite one mode, observe open-loop damping;
- Symmetric damping rate shifts for plus and minus modes;
- Estimated radiation damping time 4.5 ms;
- Damping rates decreasing from −1 to −3, likely towards a peak of ion-driven modes around −9 (open-loop amplitudes at 40 mA).

Horizontal Plane: Low Frequency Modes



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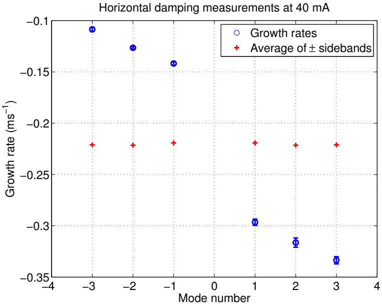

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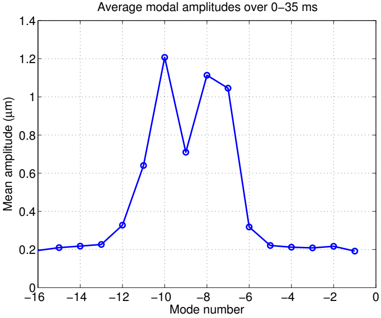

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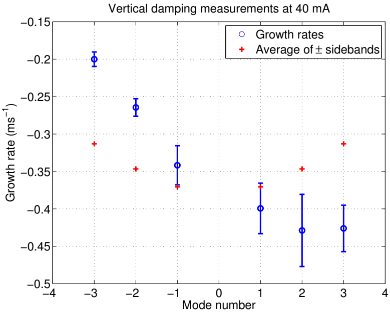

- Not as symmetric as X, considerable scatter for positive modes;
- Estimated radiation damping rate 0.37 ms^{-1} (2.7 ms damping time);
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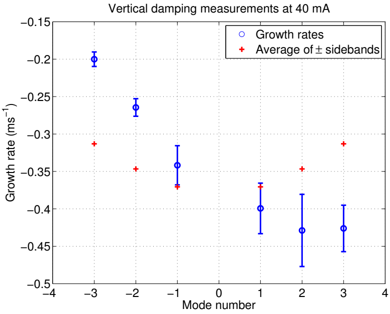
Vertical Plane: Low Frequency Modes



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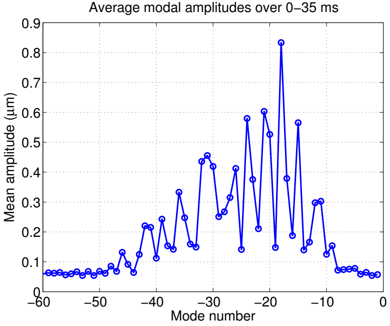

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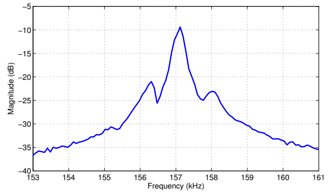
Outline

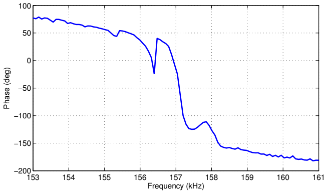
1 Setup

2 Longitudinal Plane
- System Characterization
- Optimization of Cavity Temperatures
- Stable Beam + Harmonic Cavities

3 Transverse Planes
- System Characterization
- Ion Instabilities
- Resistive Wall Studies
- Beam Transfer Functions and Radiation Damping

Vertical Beam Transfer Function





- Transfer function measured at 0.8 mA in a single bunch, production optics, excitation level at 0.007 of full scale;
- Peak motion amplitude is 6.2 μm.
- Synchro-betatron sidebands are clearly seen (more on that later);
- Fit the central peak, very fast damping time of 1.3 ms.

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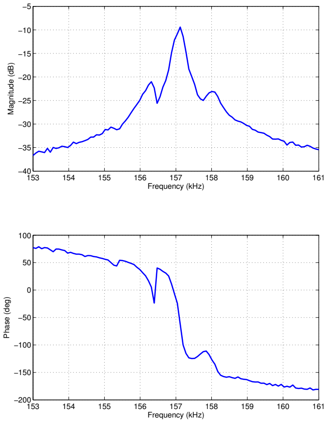

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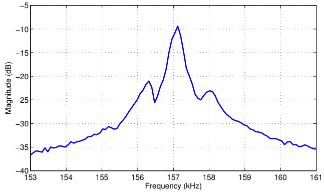

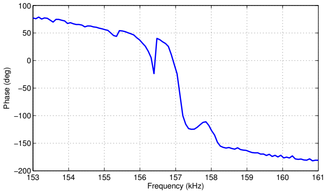

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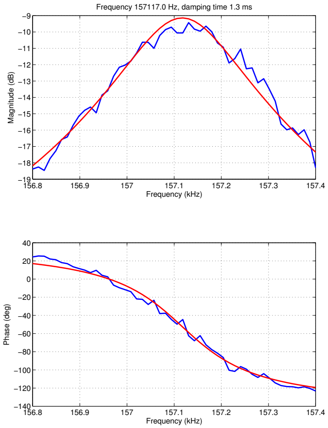

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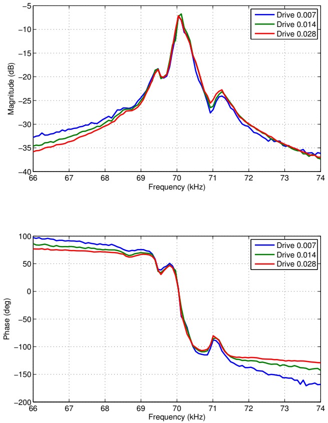

- 3 transfer functions measured at peak amplitudes of 13, 29, and 56 μm;
- No hint of amplitude dependent effects;
- Central peak fit, not very symmetric;
- Fit a linear combination of 3 harmonic oscillators, imperfect;
- Sidebands are clearly asymmetric, interesting physics to be learned.

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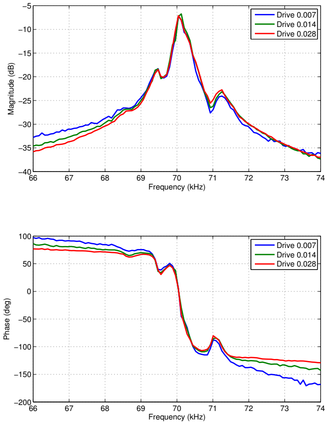

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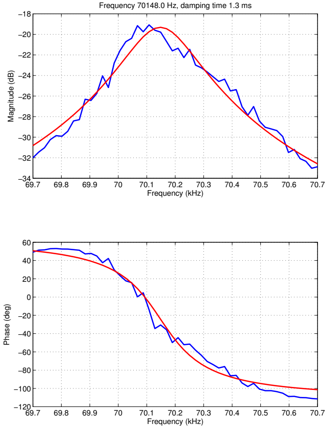

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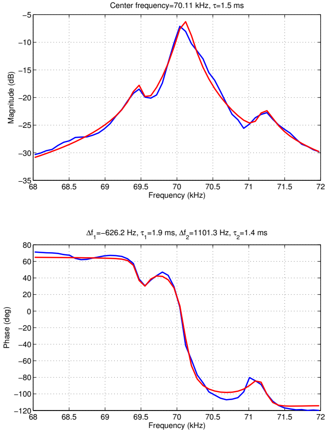

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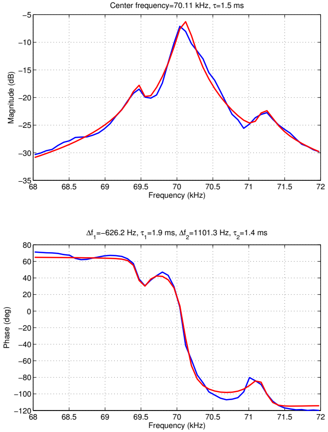

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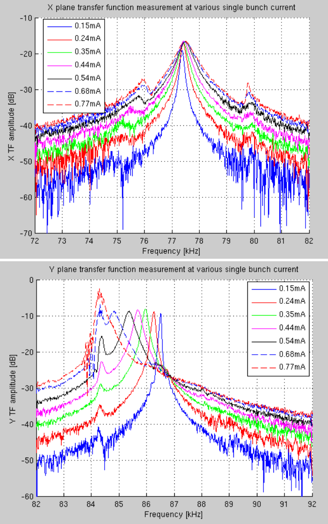
Transverse BTFs at NSLS-II



- Figures from “Commissioning of Bunch-by-bunch Feedback System for NSLS2 Storage Ring”, W. Cheng, et. al., IBIC14;
- Sidebands stay put, betatron peak shifts with current;
- Width also changes.

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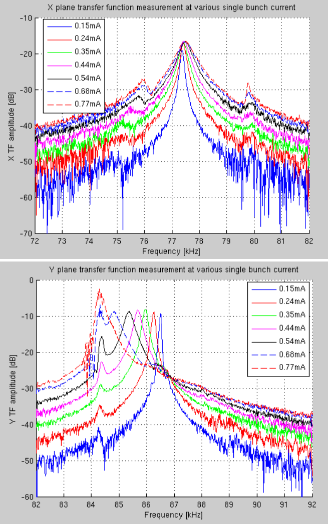

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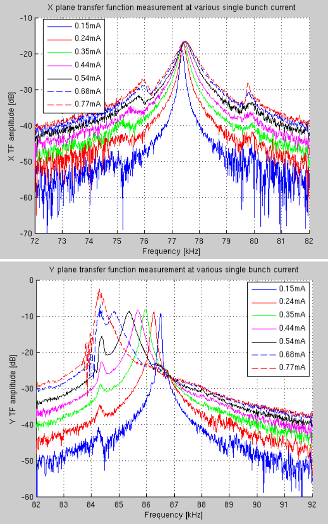

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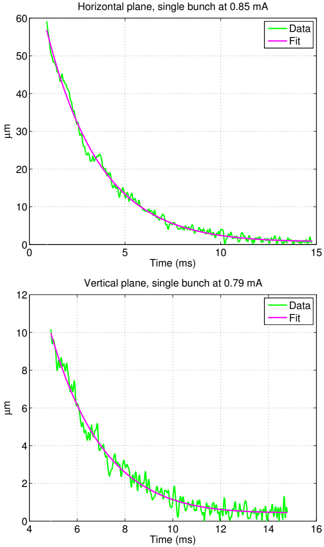
Single Bunch Damping Measurements



- Drive beam at betatron tune in closed loop, on trigger open the loop and turn off excitation;
- Horizontal damping time 2.8 ms;
- Vertical damping time 2.3 ms.

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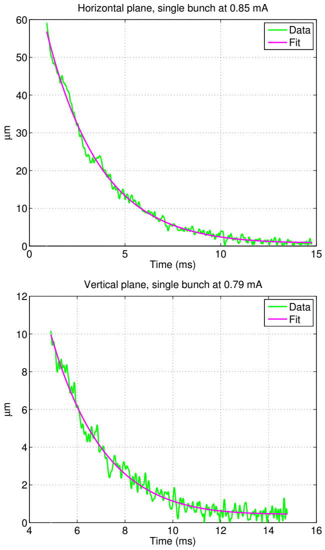

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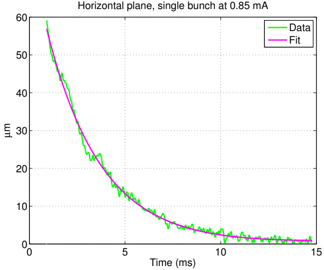

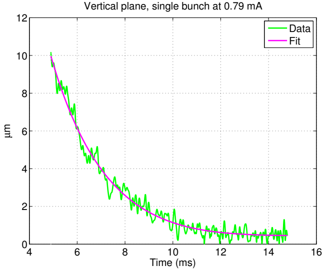

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Radiation Damping Measurements Summary

Horizontal

Measurement description	I_b (mA)	τ (ms)
Single bunch damping transient	0.85	2.8
Single bunch BTF	0.83	1.5
Even fill modal damping	0.23	4.5

Vertical

Measurement description	I_b (mA)	τ (ms)
Single bunch damping transient	0.79	2.3
Single bunch BTF	0.8	1.3
Even fill modal damping	0.23	2.7

Need to characterize damping time vs. bunch current.

Summary

- Reached 70 mA under feedback control, 80 mA in zero chromaticity (limited by heating);
- Cavity temperature tuning can be very helpful in improving longitudinal stability;
- Tuned in harmonic cavities with longitudinally stable beam, demonstrated some bunch lengthening;
- Front end at 1 GHz has good sensitivity, need longitudinally stable beam to properly run feedback;
- To investigate:
  - Transverse dipole damping vs. beam current;
  - Ion instabilities and uneven fill patterns;
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