RF and Instability Studies in SESAME

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Summary of Efforts

- Cavity temperature tuning for stability at 2.5 GeV;
- Precise calibrations — cavity voltage, phasing, power meters;
- Measurements of longitudinal instabilities at injection energy;
- RF system setup and improvements:
  - Updated FPGA design for wider dynamic range;
  - Reduced integral gain for better stability under heavy beam loading;
  - Configured cavity vacuum gauge monitoring in LLE1, setup interlock trip levels;
  - Activated klystron phase loop (compensates for slow phase shift changes between LLRF output and cavity forward);
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Cavity Temperature Tuning

- At 125 mA, 2.5 GeV, 400 kV per cavity.
- Cavity 1:
  - Original setpoint 54 °C;
  - Mode 53 onset at 56.7 °C, mode -24 unstable between 53.2–54.6 °C;
  - Horizontal mode 114 at 46 °C, set to 49.6 °C.
- Cavity 2:
  - Original setpoint 56 °C;
  - Downward adjustment shows instability at 50.5 °C;
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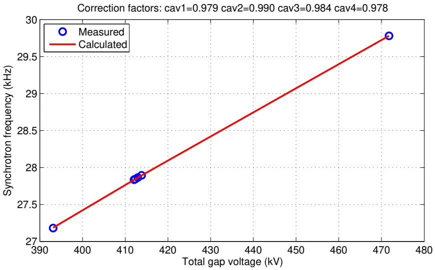

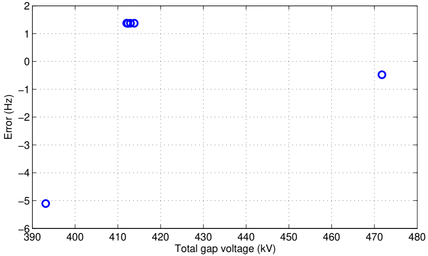

- Synchrotron frequency calculated from RF voltage:
$$\omega_s = \sqrt{-\frac{\alpha e \omega_{\mathrm{rf}}}{T_0 E} V_g \cos(\phi_b)}$$
- Assume that momentum compaction α and beam energy E are perfectly known ($\alpha = 0.0083$, $E = 790.14$ MeV);
- Calibration at injection energy more or less removes sensitivity to energy loss ($\cos(\phi_b) \approx -1 + 10^{-4}$)
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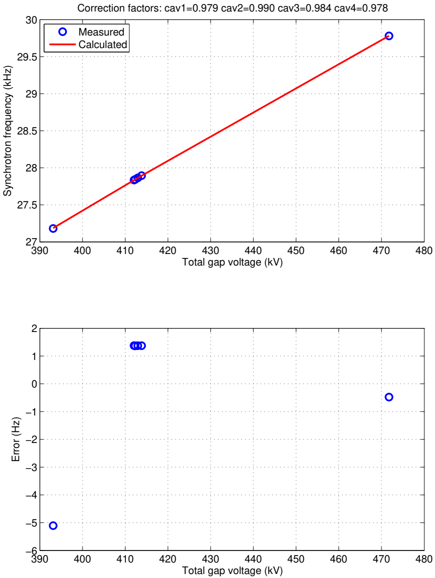

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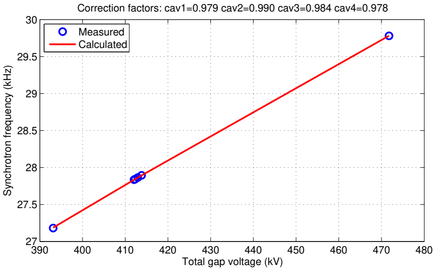

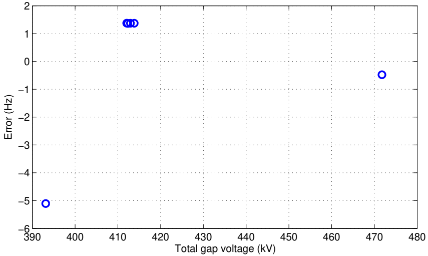

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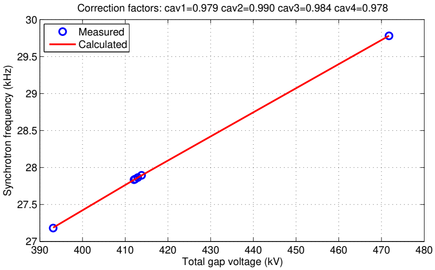

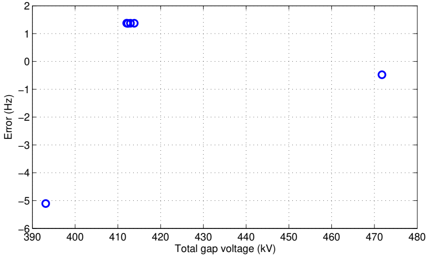

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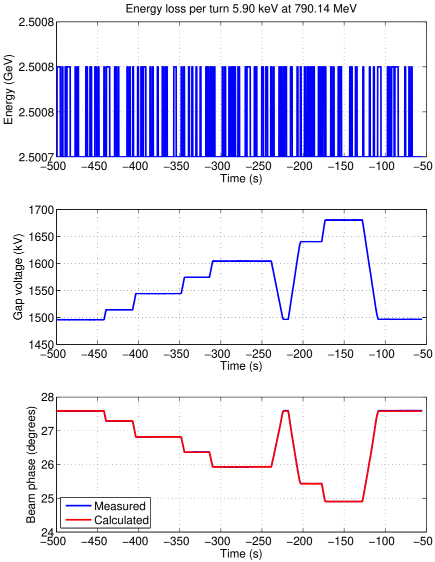

- Connected BPM signal to LLE1 spare input;
  - Ideally, a bandpass filter would be used to select 500 MHz component;
  - Without such filter have some parasitics due to aliasing of longitudinal oscillations;
  - Measurement at 2.5 GeV with stable beam.
- Beam phase responds to changes in gap voltage as $\sin^{-1}(U_0/V_g)$;
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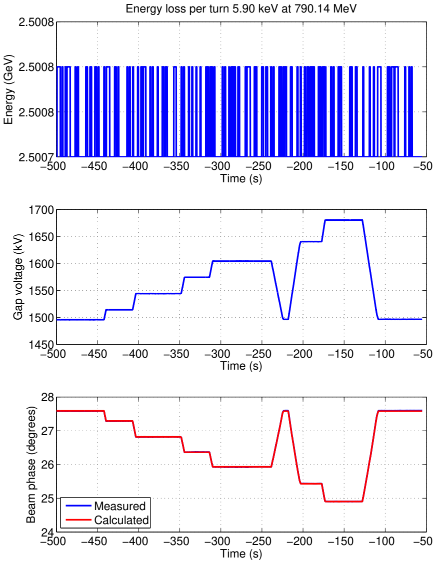

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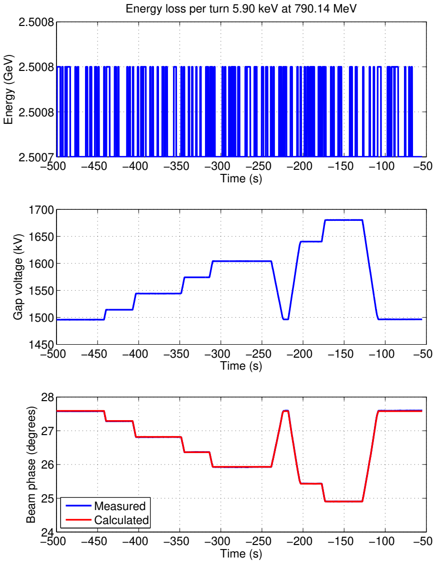

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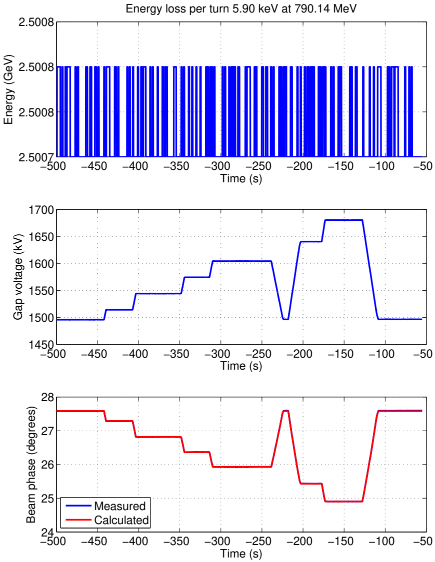

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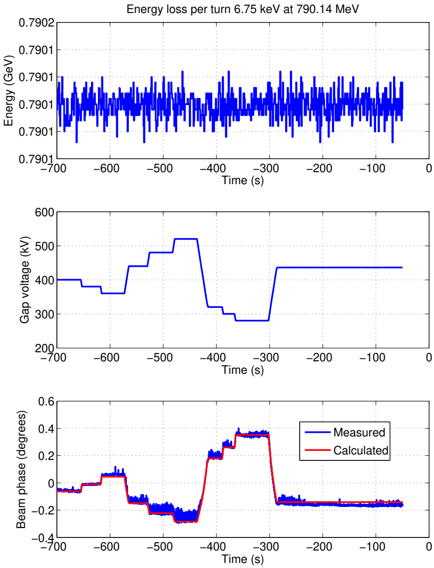

- Much smaller phase shifts — energy loss 100 times lower than at 2.5 GeV;
- Longitudinal instabilities causing apparent phase shifts in response to cavity voltage changes;
- Estimated energy loss per turn is 6.75 keV versus 5.9 keV from 2.5 GeV measurement;
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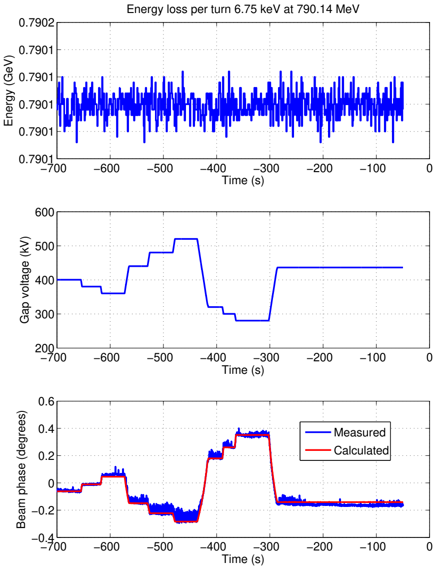

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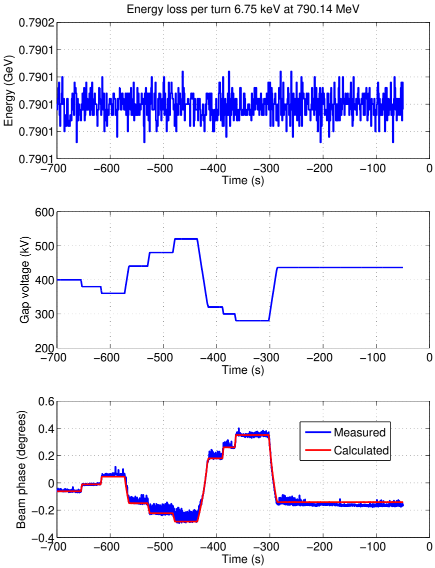

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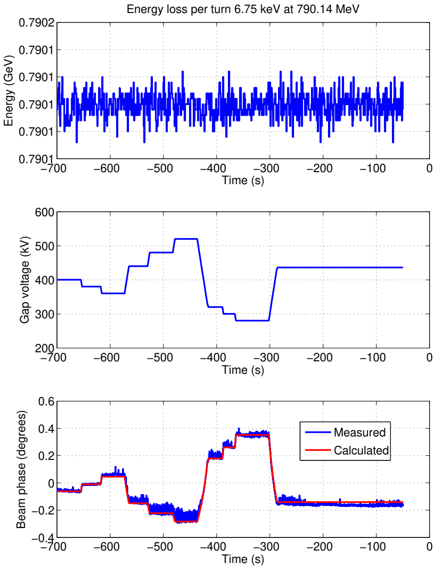

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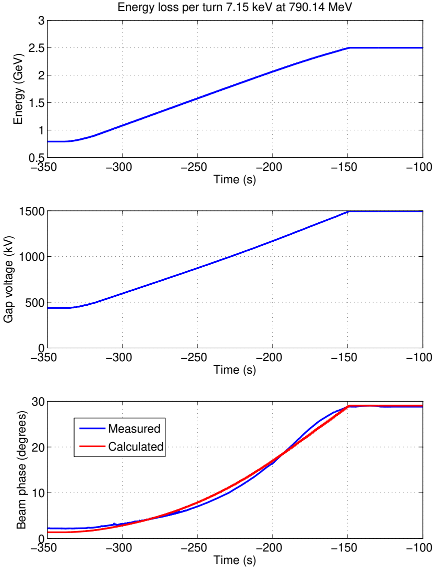

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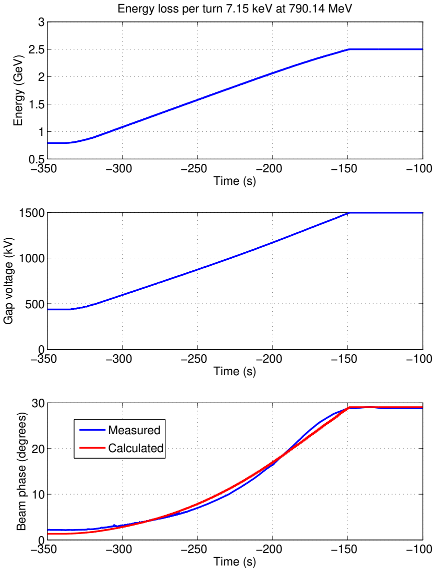

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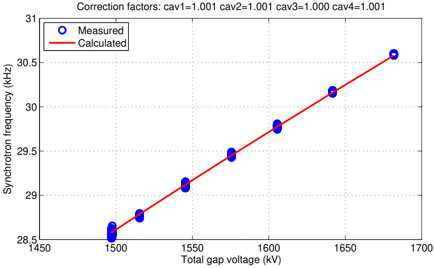

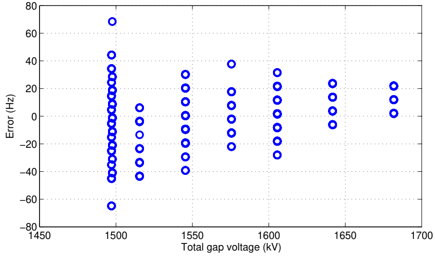

- Captured marker frequency from the bunch-by-bunch feedback during energy loss measurements at 2.5 GeV;
- Use that information to re-check voltage calibrations;
- Consistent within 0.1%.

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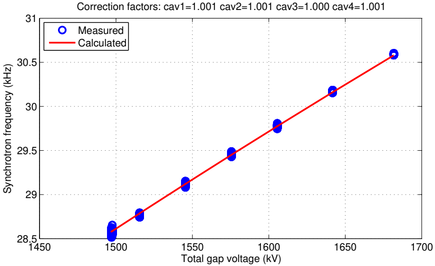

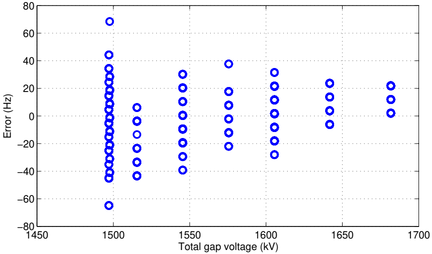

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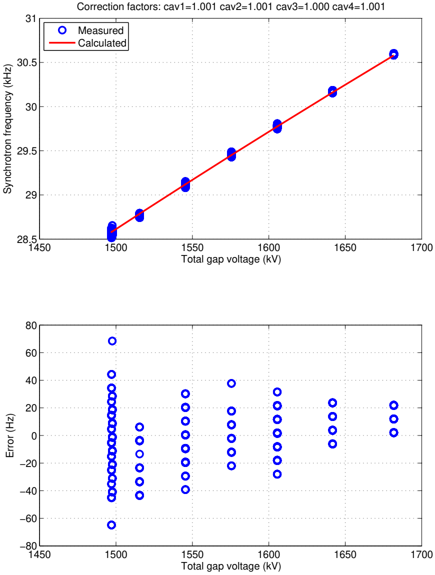

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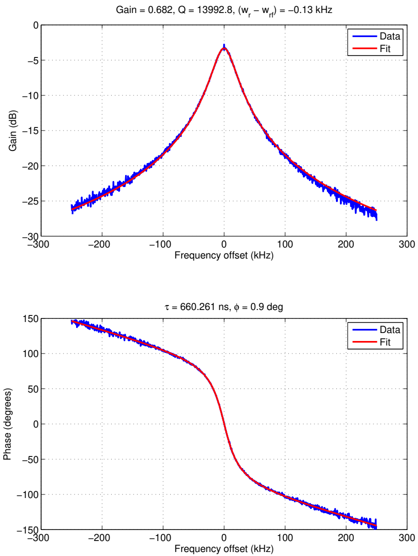

- Energy loss from 2.5 GeV measurement;
- Cavity $Q_0 = 41800$, $R_s = 3.3$ MΩ;
- Coupling factors adjusted to match measured loaded Q: 1.99, 2.06, 1.75, 2.28;
- At each point calculate RF operating point based on recorded cavity voltage, beam energy and current;
- Matching forward power (assume SSA calibration is correct) requires setting $R_s = 2.3$ MΩ;
- With 7.15 keV energy loss we get $R_s = 2.5$ MΩ.

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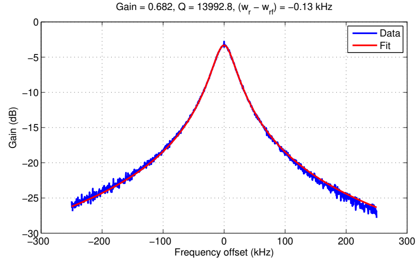

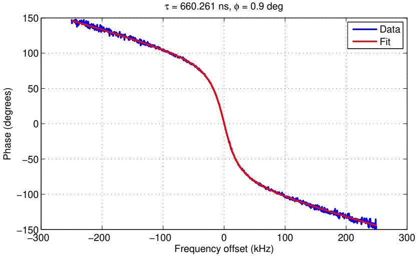

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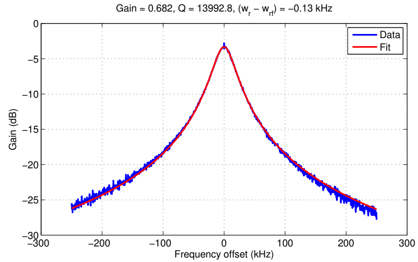

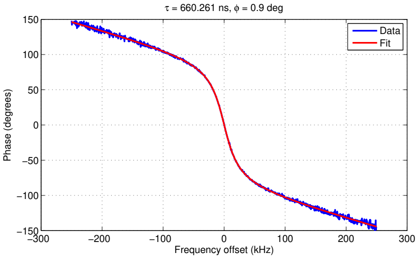

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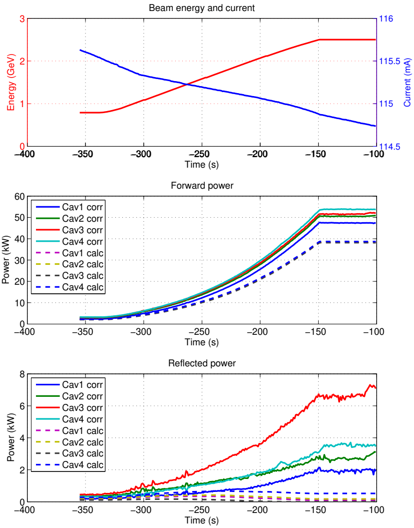

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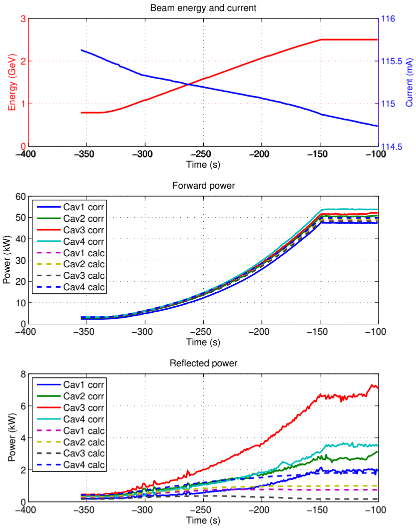

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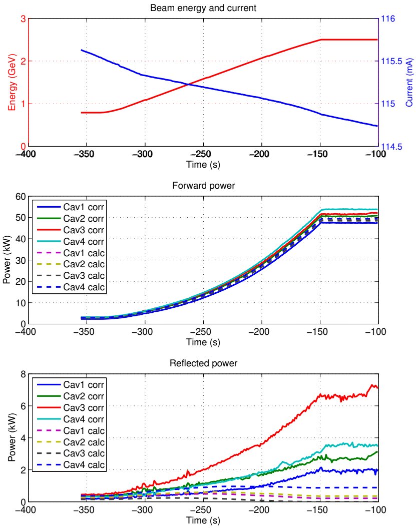

- Energy loss from 2.5 GeV measurement;
- Cavity $Q_0 = 41800$, $R_s = 3.3$ MΩ;
- Coupling factors adjusted to match measured loaded Q: 1.99, 2.06, 1.75, 2.28;
- At each point calculate RF operating point based on recorded cavity voltage, beam energy and current;
- Matching forward power (assume SSA calibration is correct) requires setting $R_s = 2.3$ MΩ;
- With 7.15 keV energy loss we get $R_s = 2.5$ MΩ.

Bunch-by-bunch Feedback and Diagnostics

- BPMH-20-2G BPM hybrid;
- FBE-500LT multi-channel front/back-end;
- iGp12 bunch-by-bunch feedback processor;
- Modified ENI 525LA power amplifier (25 W) driving one stripline.

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Bunch-by-bunch Studies — Summary

- 30 cm (1 ns) stripline can be used to provide weak longitudinal kick, requires 4 ns bunch spacing;
- Every other RF bucket fill pattern was created using bunch cleaning in transverse direction;
- iGp12 output setup to kick differentially ([1 -1]) in adjacent buckets, with proper timing the bunch receives a longitudinal kick of twice the line voltage.
- Bunch-by-bunch studies
  - Bunch cleaning;
  - Longitudinal front-end calibration;
  - Measurements of longitudinal coupled-bunch instabilities (growth rates, tune shifts, modal pattern);
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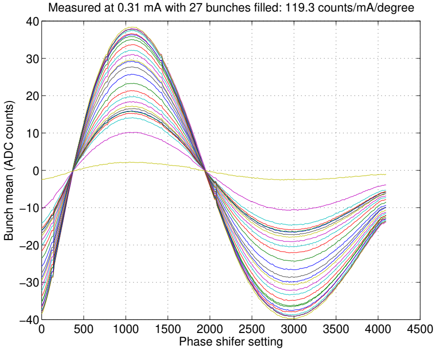
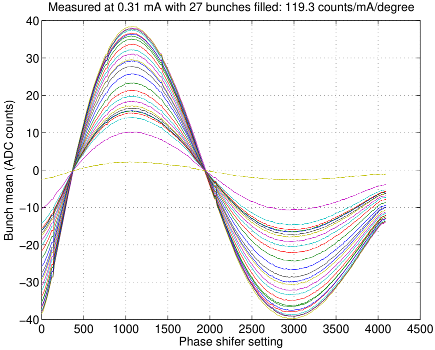
Front End Calibration



- 27 bunches, 0.31 mA total current;
- Local oscillator ($3 \times f_{\mathrm{rf}}$) phase sweep;
- Calculate front-end sensitivity.

Front End Calibration



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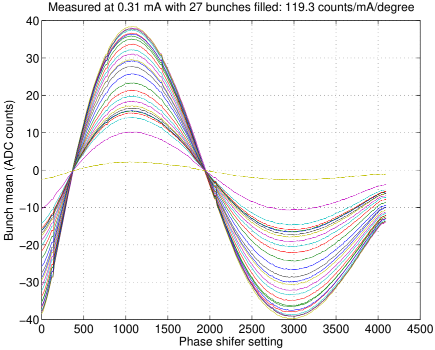

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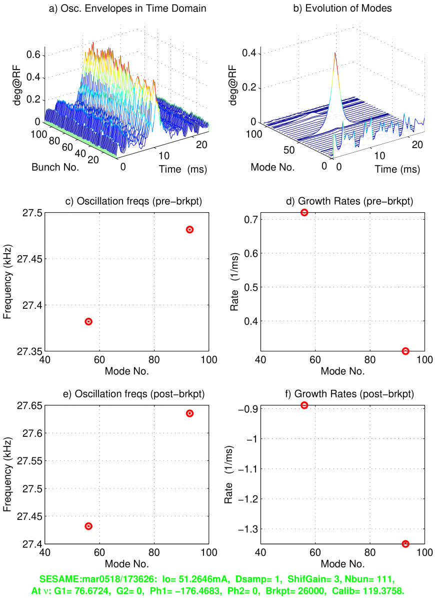
Longitudinal Grow/Damp Measurement



- 111 bunches, 51.3 mA total current;
- Two modes grow and damp, 56 (-55) and 93 (-18);
- Uniform damping rates, small tune shift — well configured feedback;
- Nicely exponential transients.

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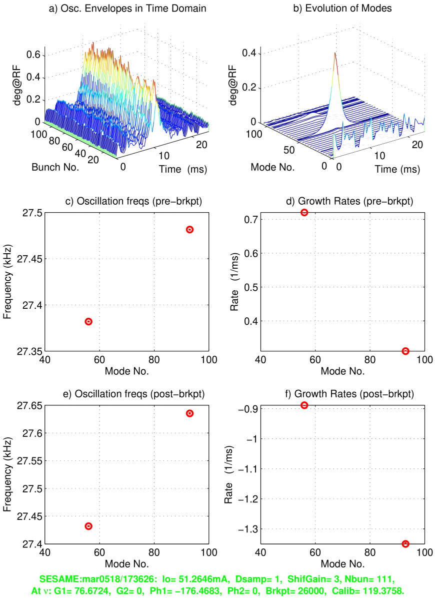

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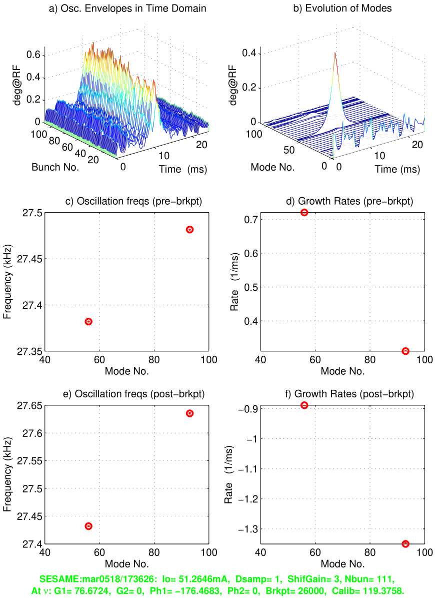

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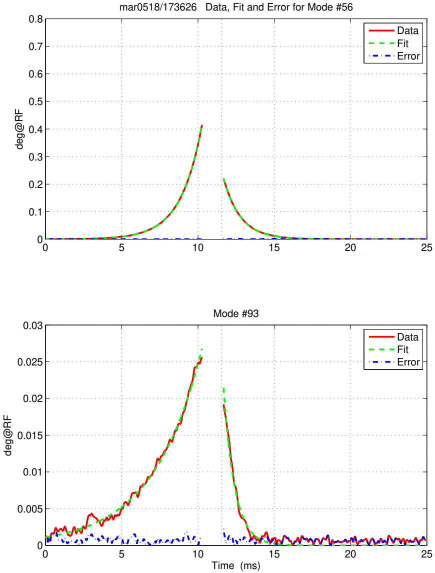

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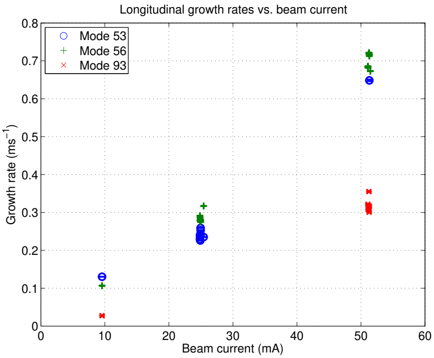

- Measurements at 10, 25, and 50 mA (filled to 20, 50, and 100 mA, then removed every other bunch);
- Collected multiple grow/damp measurements at each beam current;
- Impedance is not constant due to fundamental mode detuning, do not expect linear scaling with beam current;
- Frequency shift with current samples imaginary part of the HOM impedance.

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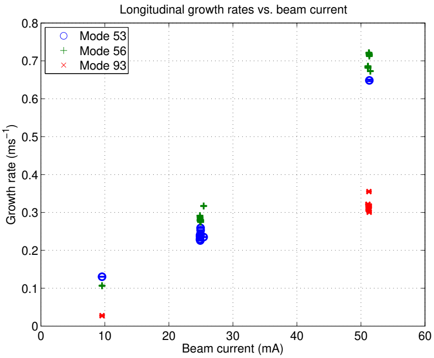

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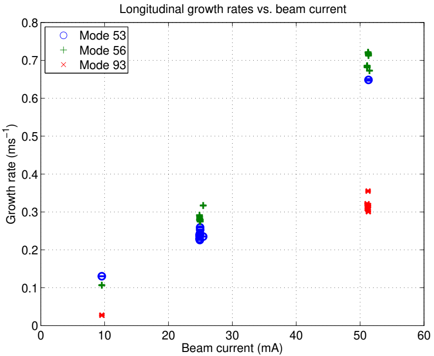

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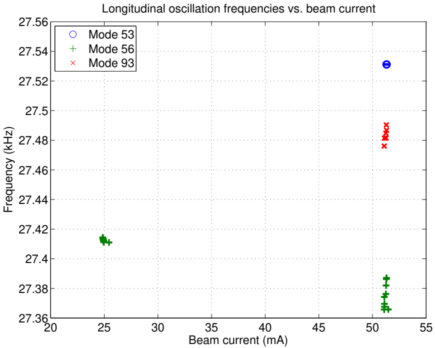

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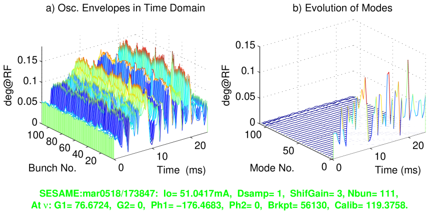
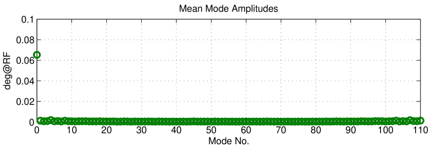
Residual Longitudinal Motion





- 111 bunches, 50.9 mA total current;
- At injection energy;
- Longitudinal motion suppressed by feedback;
- Residual motion of mode 0 is 0.06 ° (360 fs).

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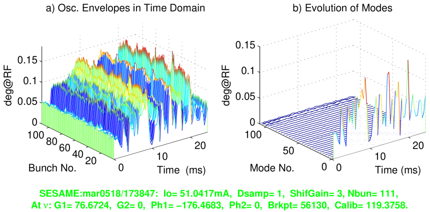

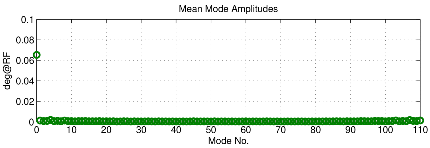

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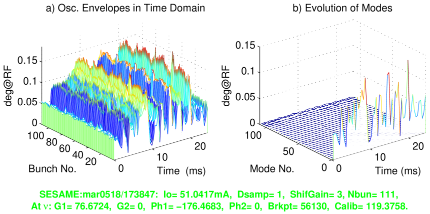

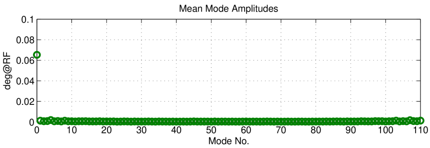

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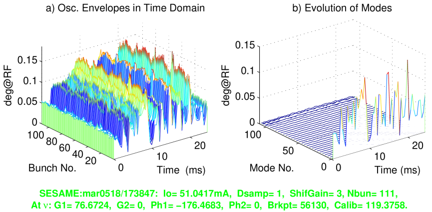

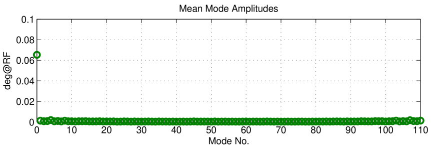

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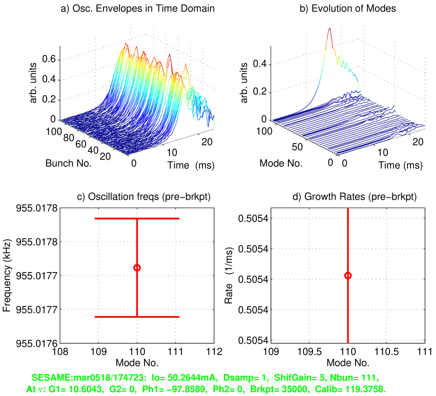

- At 50 mA observed horizontal bursting;
- Large mode -1 bursts;
- Repetition of a few hundred milliseconds;
- One more event;
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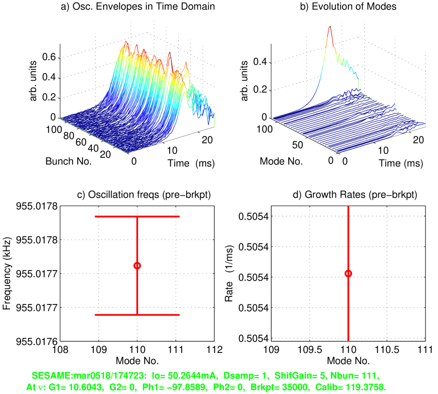

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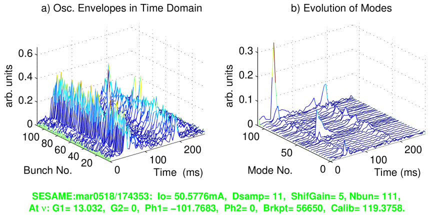

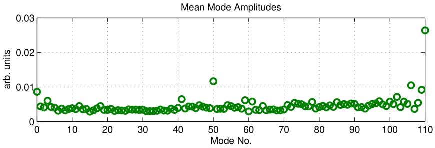

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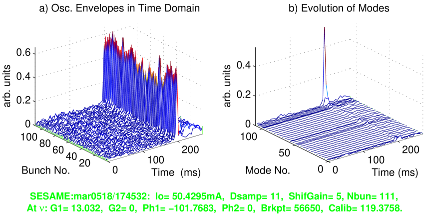

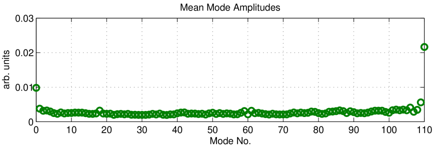

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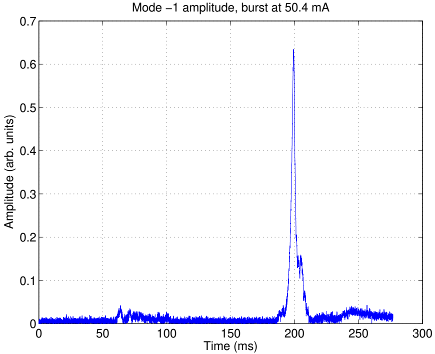

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Summary

- Many improvements in RF operation have been implemented;
- Created RF turn on script, automatically turns on RF, tunes cavities, and closes feedback loops;
- Precision measurements via LLRF and bunch-by-bunch feedback systems provide better calibrations, still more work to do to consistently estimate cavity and ring parameters;
- Demonstrated feedback and diagnostic capabilities of bunch-by-bunch feedback systems;
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