Beam Loading Studies in BEPC2

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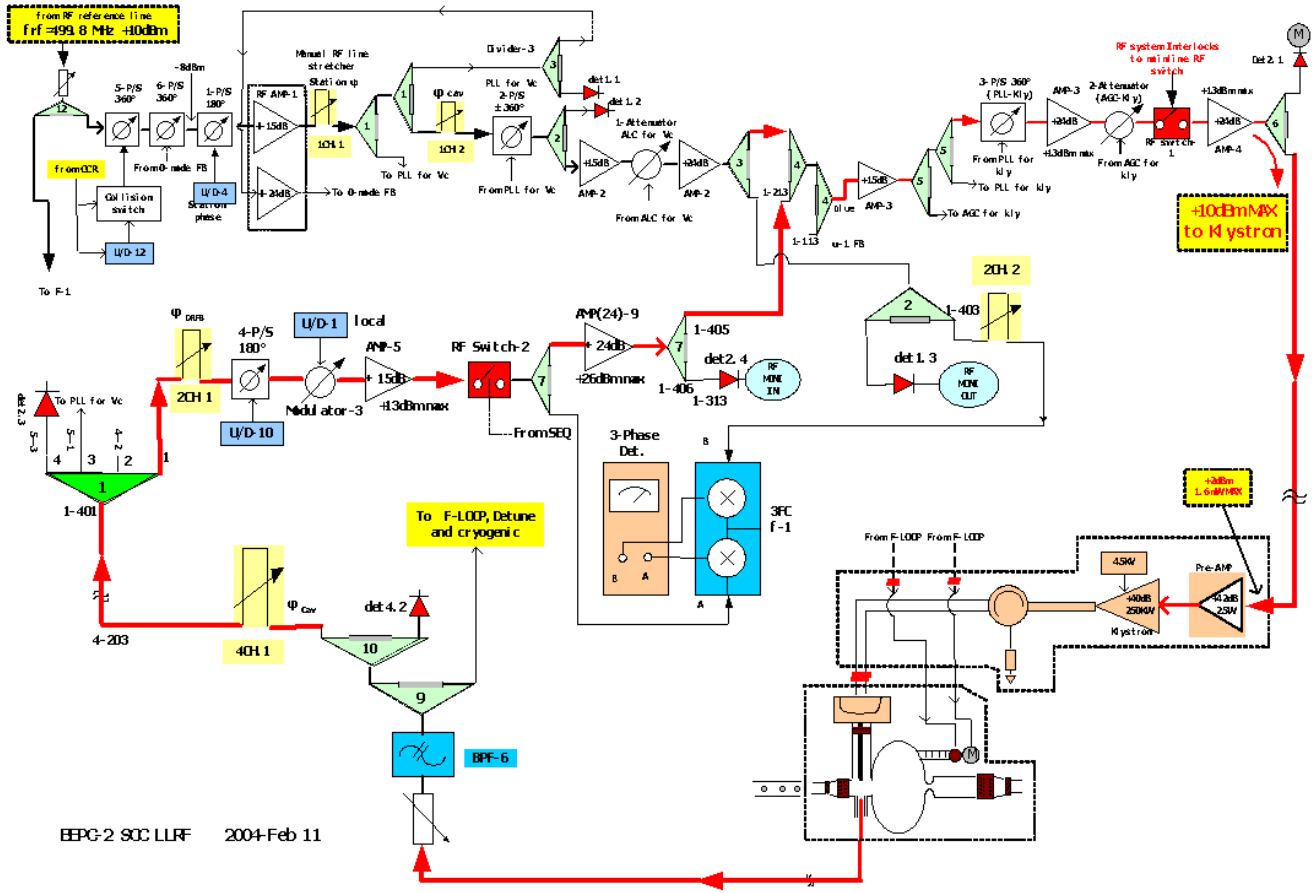
December 18, 2016

Cavity Transfer Functions



- Start from the last measurement we made (2016-12-11);
- Open and closed-loop transfer functions measured using a network analyzer.

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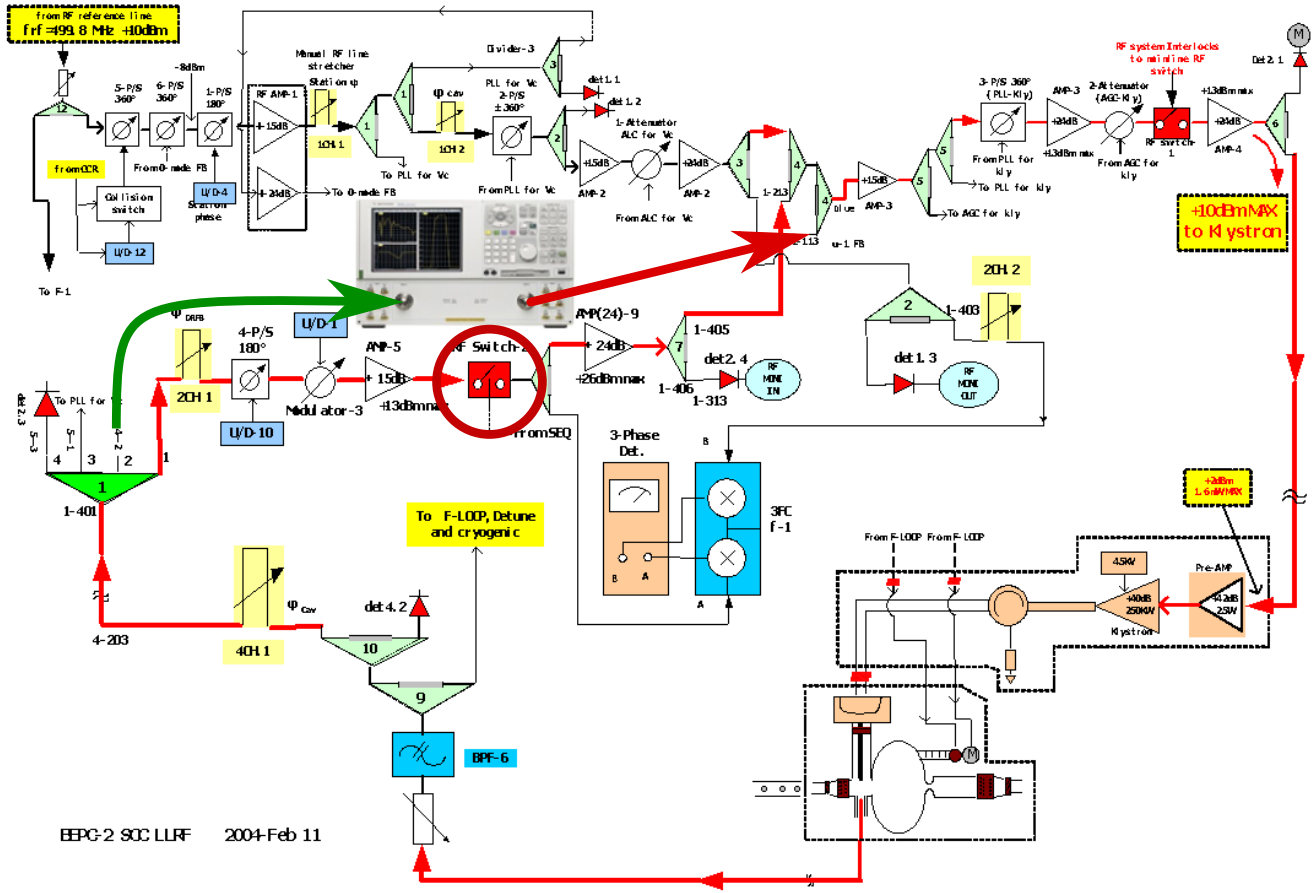

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Measurement Goal and Conditions

- The goal is to estimate direct loop gain at the nominal operating point;
- A difficult measurement — need to detect small NWA excitation in presence of large RF fundamental signal;
  - Field setpoint 222 kV — as low as possible to reduce fundamental signal;
  - Cavity detuned by setting load angle offset to $-40°$;
  - Amplitude and phase loops turned off;
  - Measurements with direct loop open and closed.
- No beam, of course.

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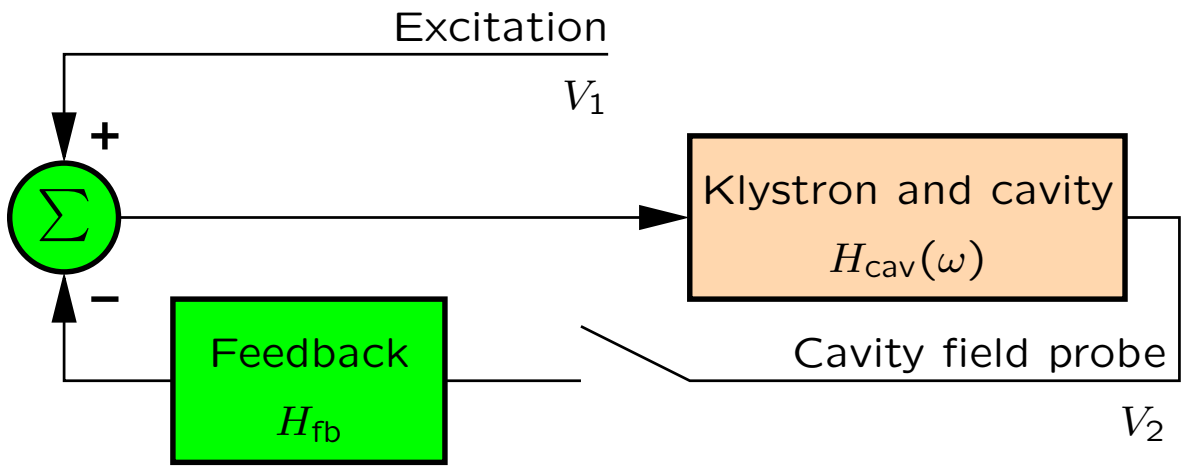
System Model



- Cavity response: $H_{\mathrm{cav}}(\omega) = \frac{2i\sigma\omega}{\omega^2 - 2i\sigma\omega - \omega_r^2} G e^{-i(\omega-\omega_{\mathrm{rf}})\tau} e^{i\phi_0}$
- Five parameters: gain G, damping rate σ, center frequency ω_r, delay τ, and phase shift ϕ_0;
- Feedback response is just gain and phase shift: $H_{\mathrm{fb}}(\omega) = G_{\mathrm{fb}} e^{i\phi_{\mathrm{fb}}}$;
- In open loop estimate the parameters of $H_{\mathrm{cav}}(\omega)$;
- Two parameter fit (G_{fb}, ϕ_{fb}) to the closed-loop $S_{21}(\omega)$.

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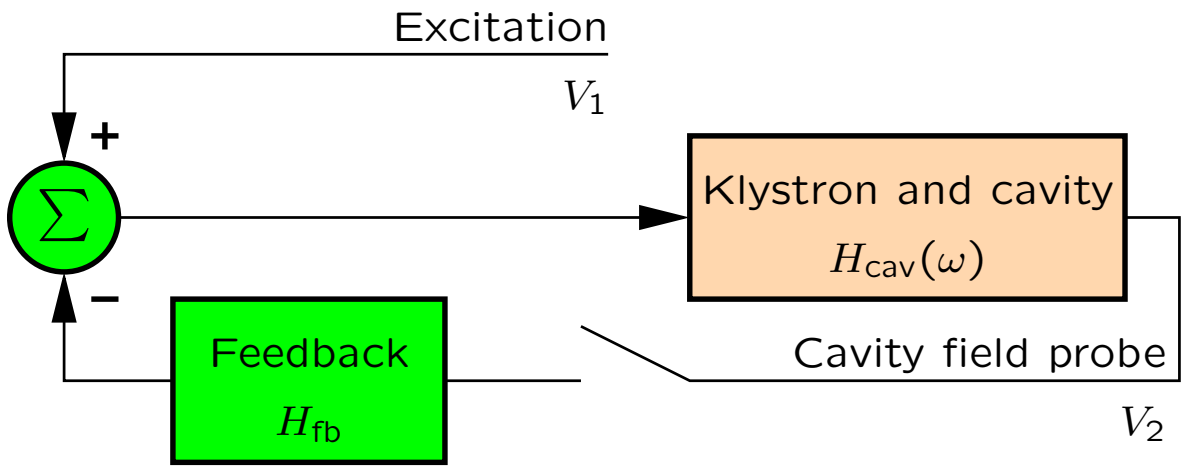

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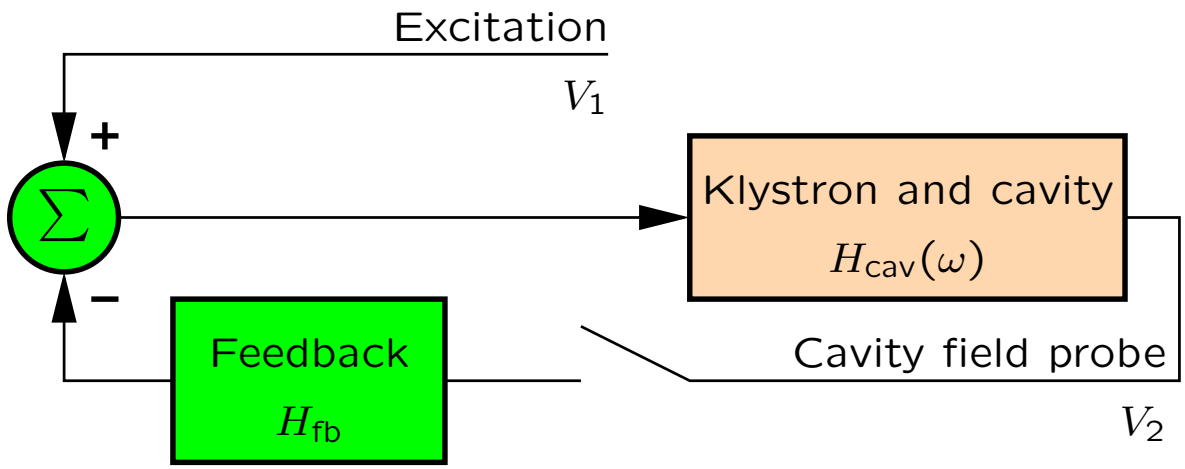

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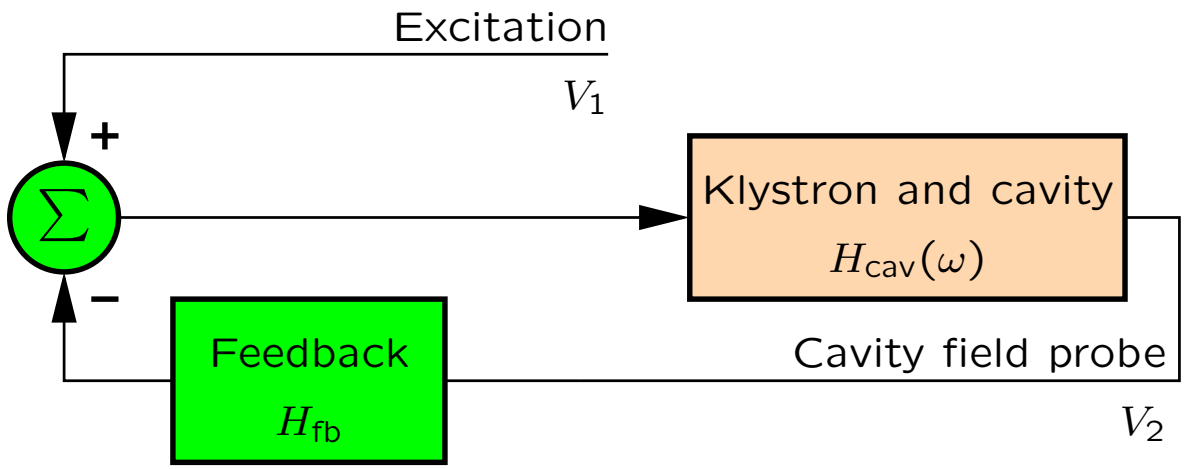

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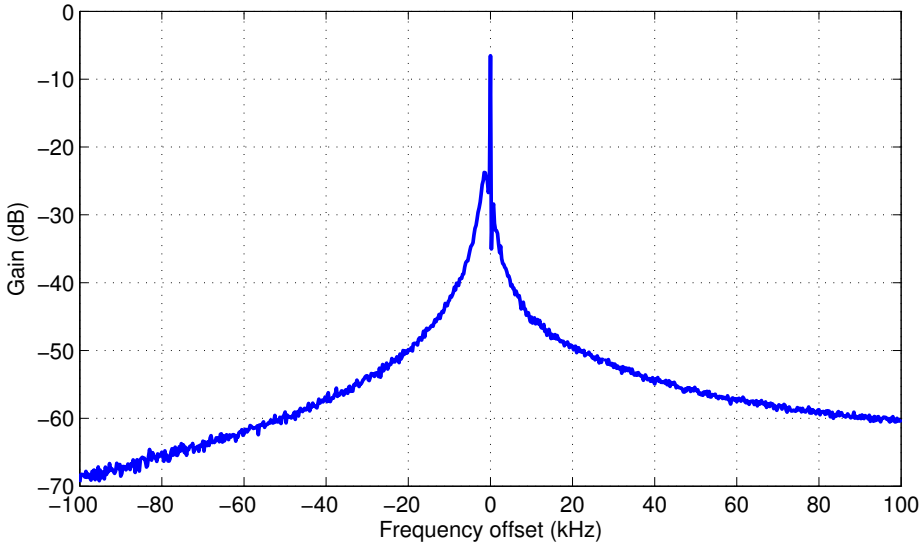
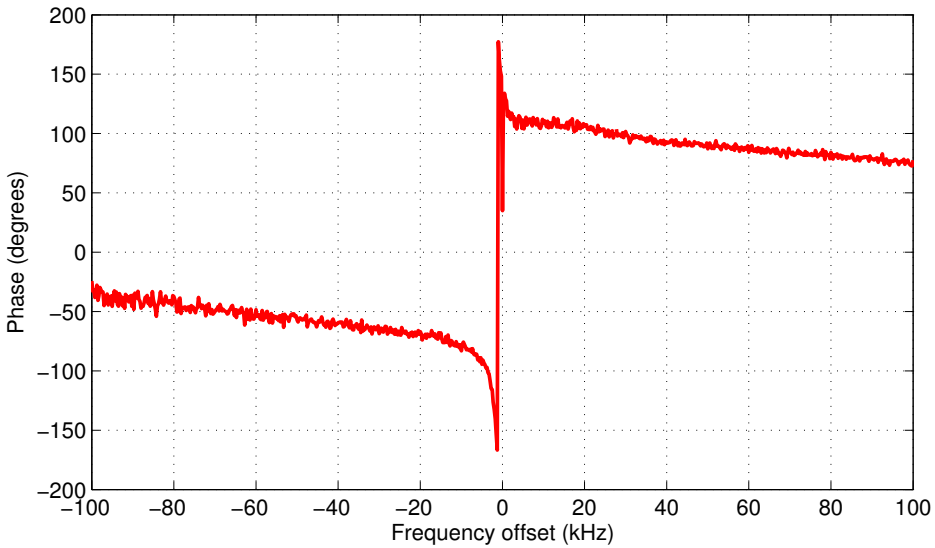
Wideband Open Loop Transfer Function





- 200 kHz span;
- Points near the RF frequency show significant scatter;
- For fitting, ignore points in −0.5–12.25 kHz range around RF;
- Increasing errors at large offsets;
- Near the resonance fit seems reasonable.

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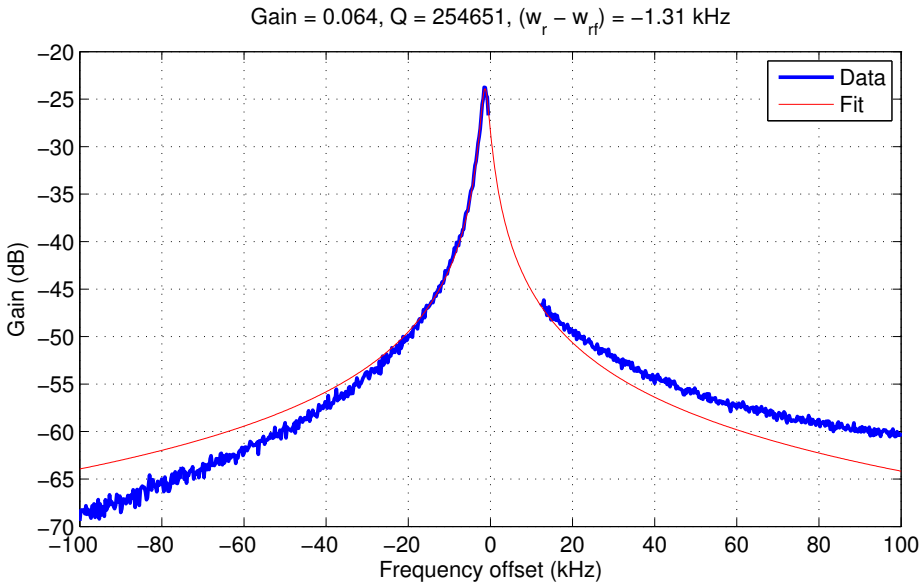

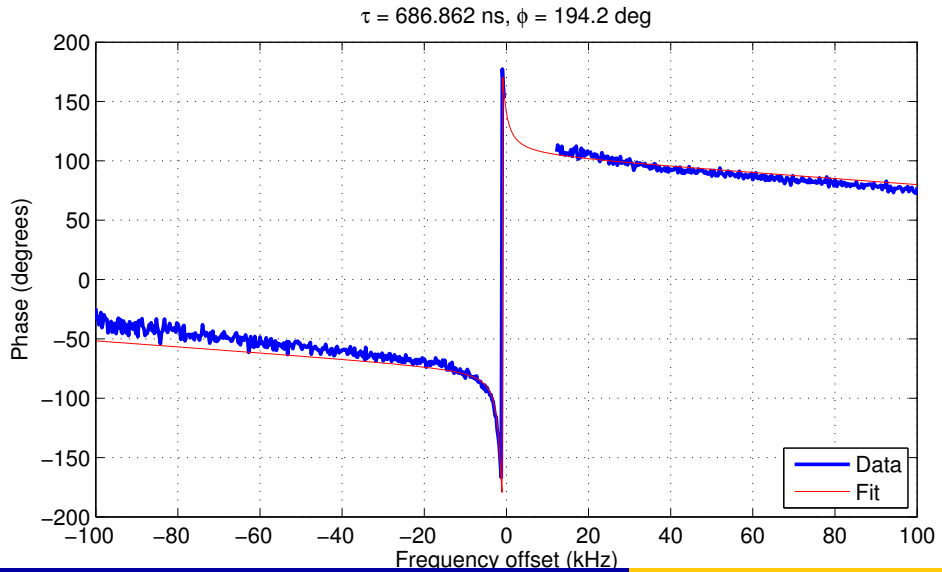

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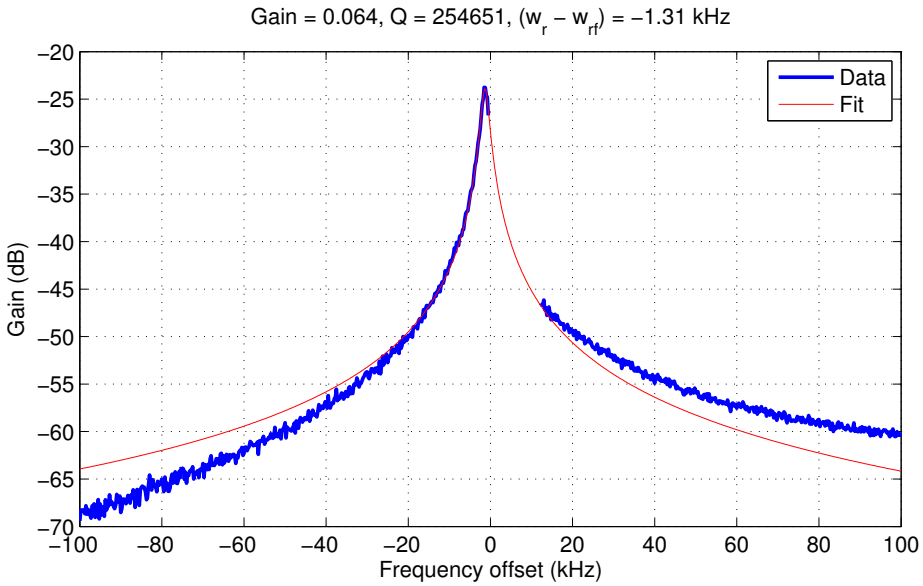

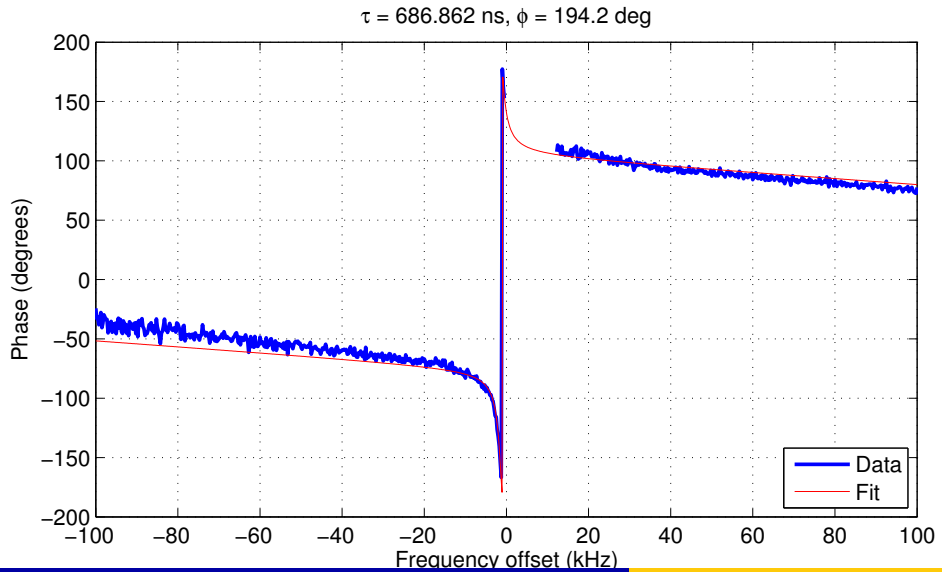

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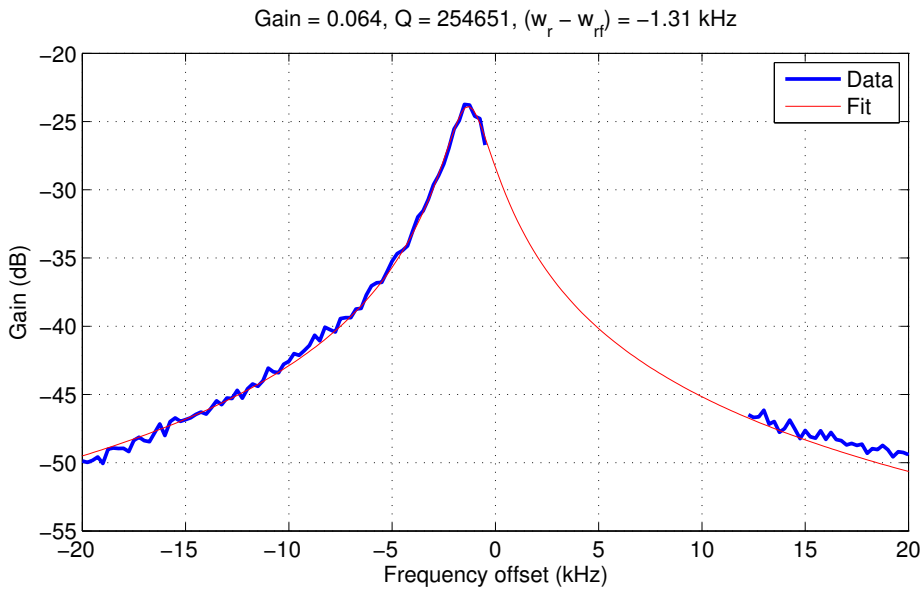

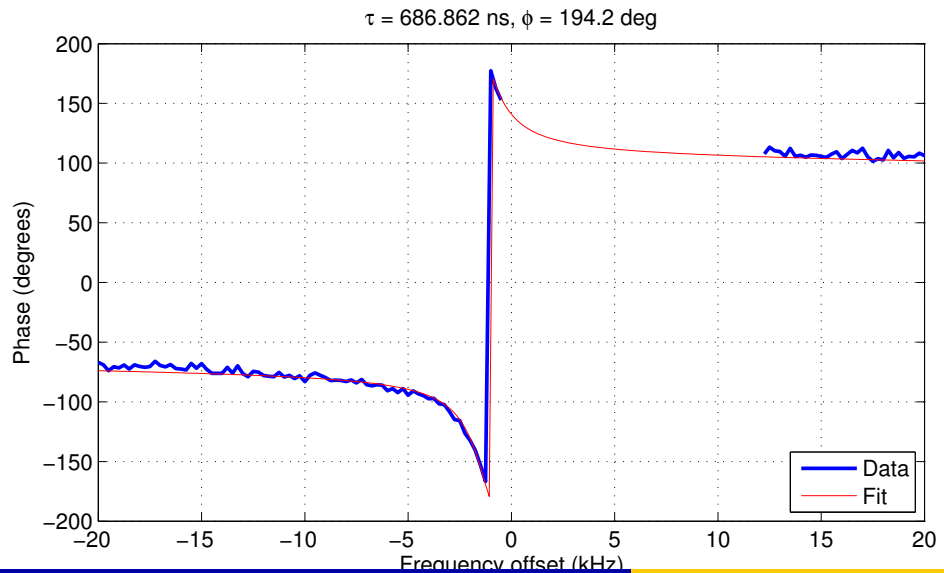

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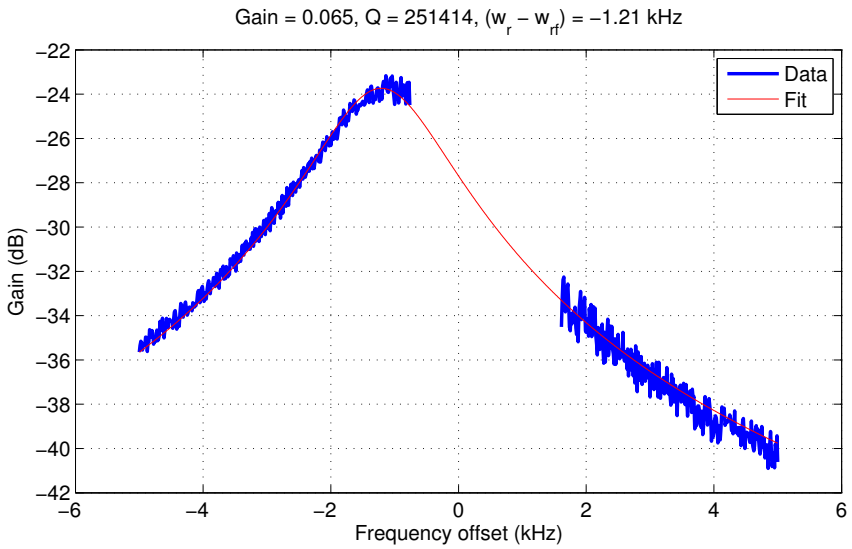
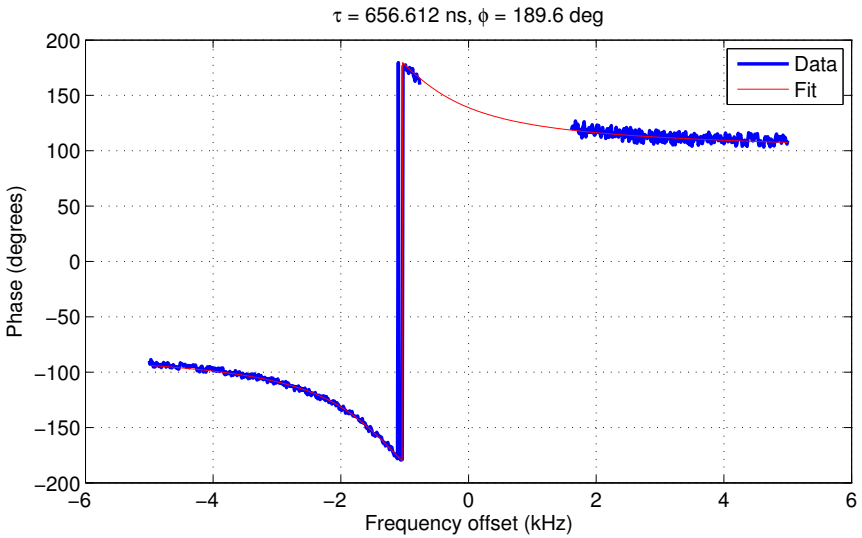
Open Loop Transfer Function, 10 kHz Span





- A good fit (not wideband enough to reliably estimate delay);
- Q_L is 251414, expected 210000;
- Fitted detuning and Q_L give the loading angle $\tan^{-1}(\frac{2\omega_d Q_L}{\omega_r}) = -51°$
- Suspect at nominal settings might be running with $-21°$ loading angle, not $-10°$.

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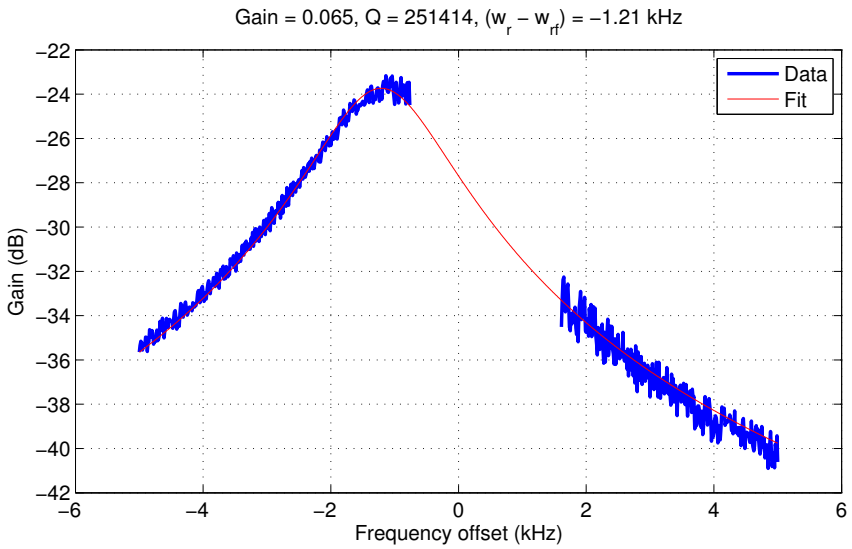

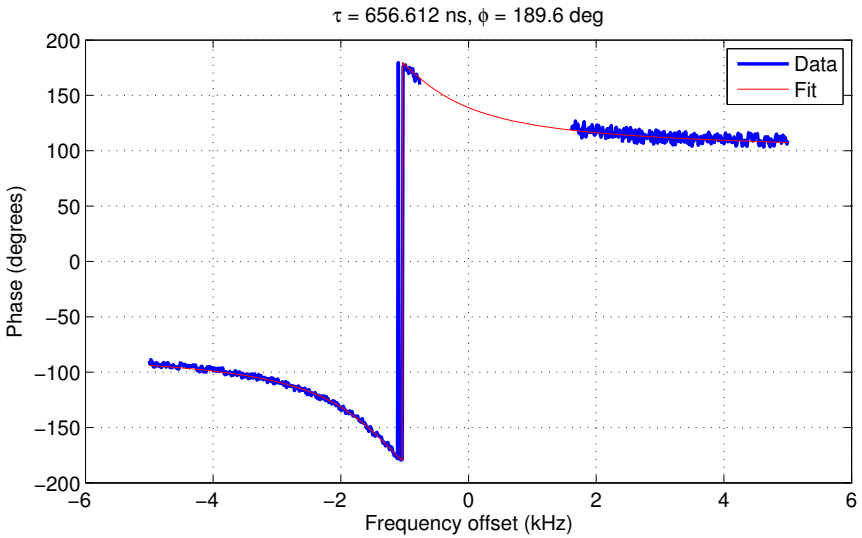

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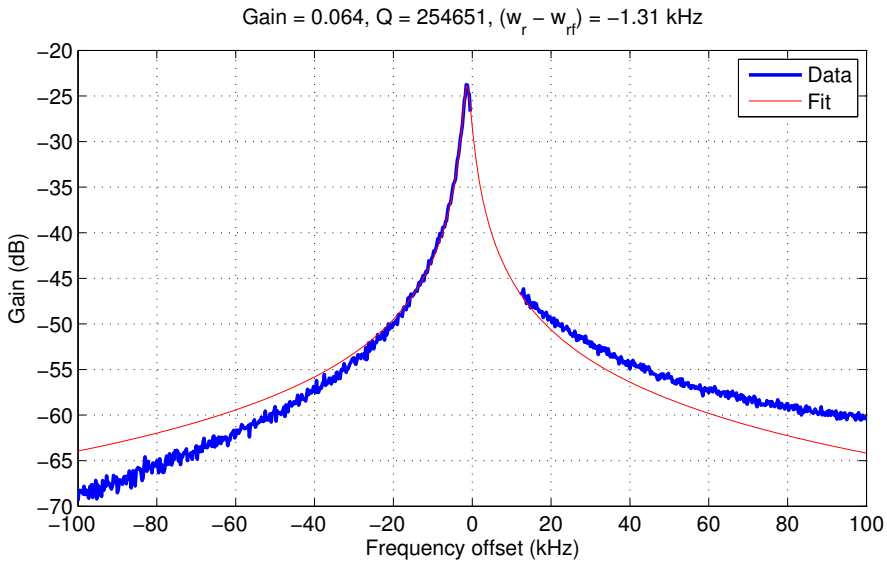
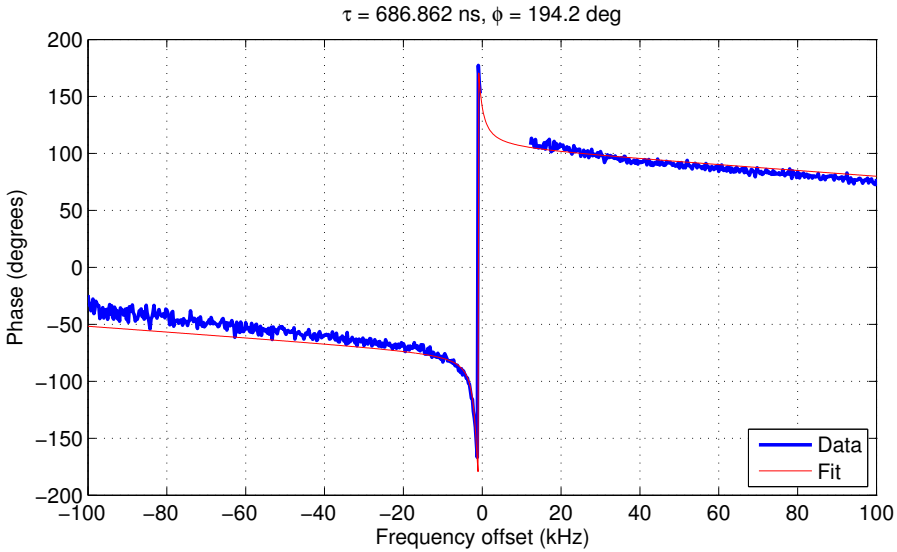
Correcting Systematics





- Magnitude error is most likely due to RF fundamental feedthrough: cavity response rolls off as $1/\Delta f^2$ while NWA IF filter rolls off as $1/\Delta f$, so error increases with offset;
- 180° phase shift across the resonance explains why RF fundamental subtracts below the resonance and adds above;
- Use linear (in dB) correction function;
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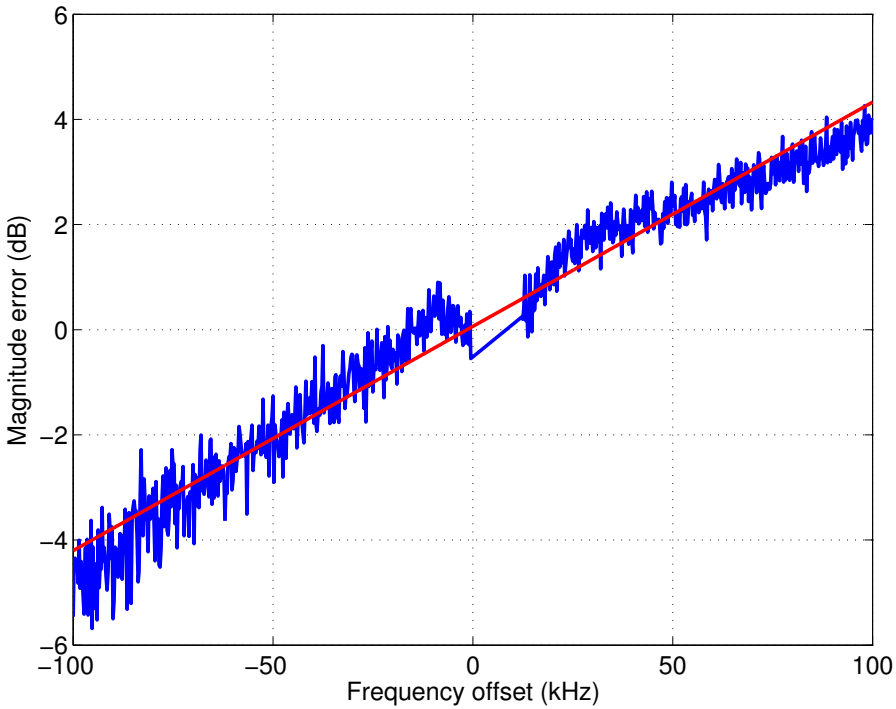

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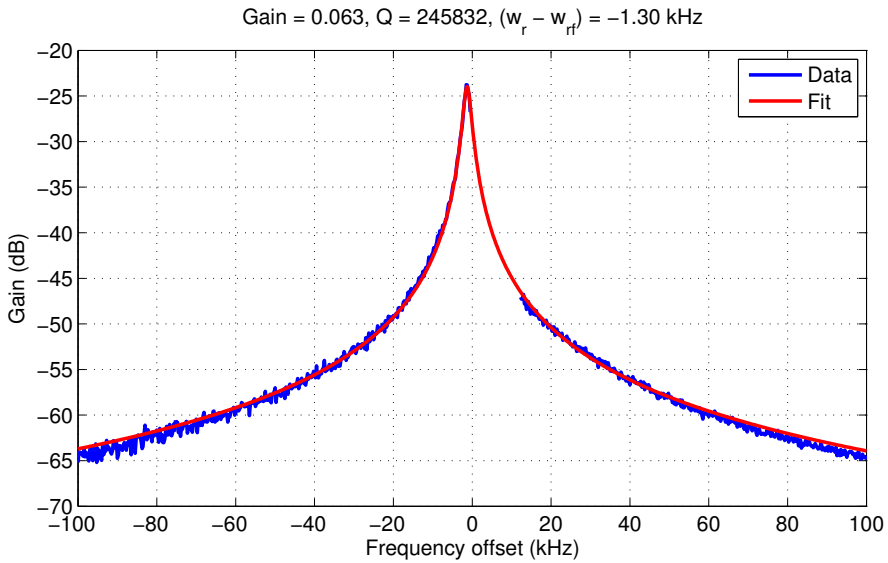

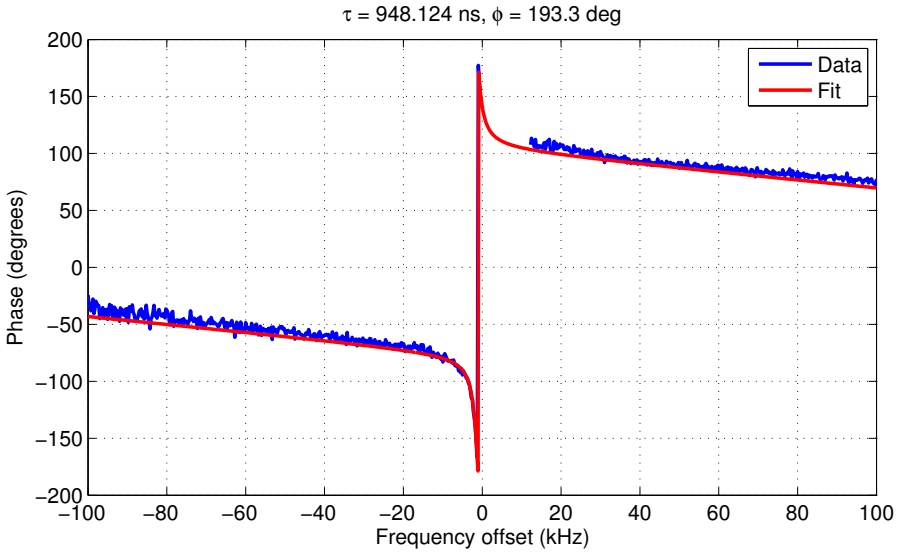

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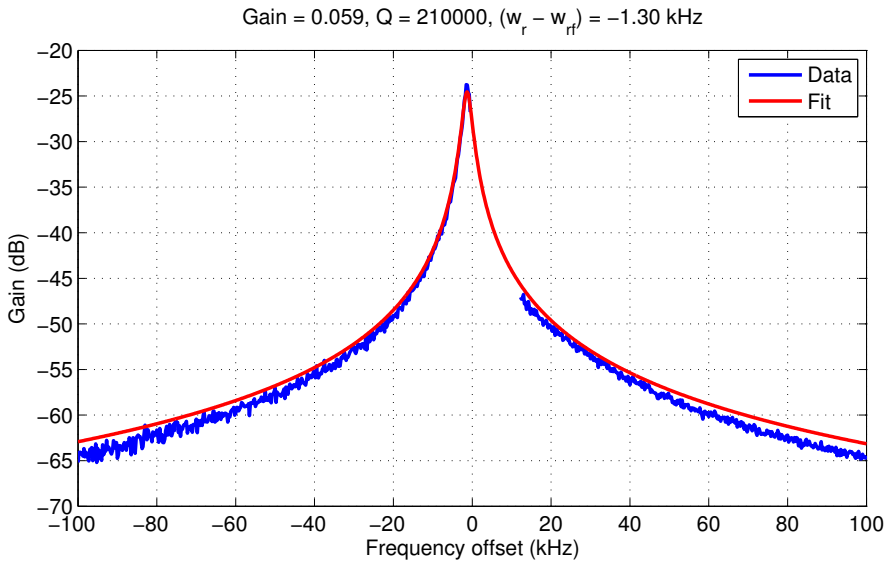
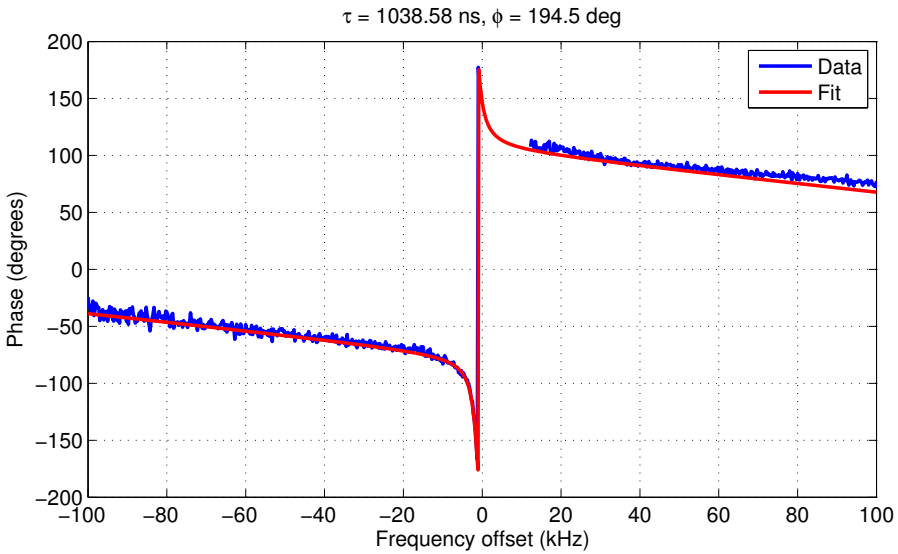
Fitting and Sensitivity to Q





- Forcing $Q_L = 210000$ worsens the fit to compensated data;
- Even if we use $Q_L = 210000$ during initial fitting (used to extract linear compensation), final fit is worse;
- Full 5 parameter fit still comes back to higher Q_L, within 1.6×10^{-5}.

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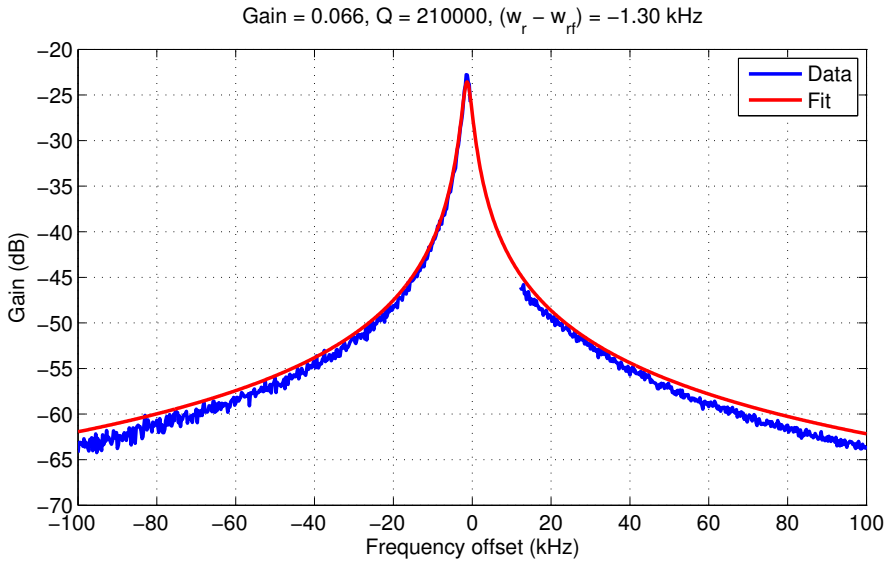

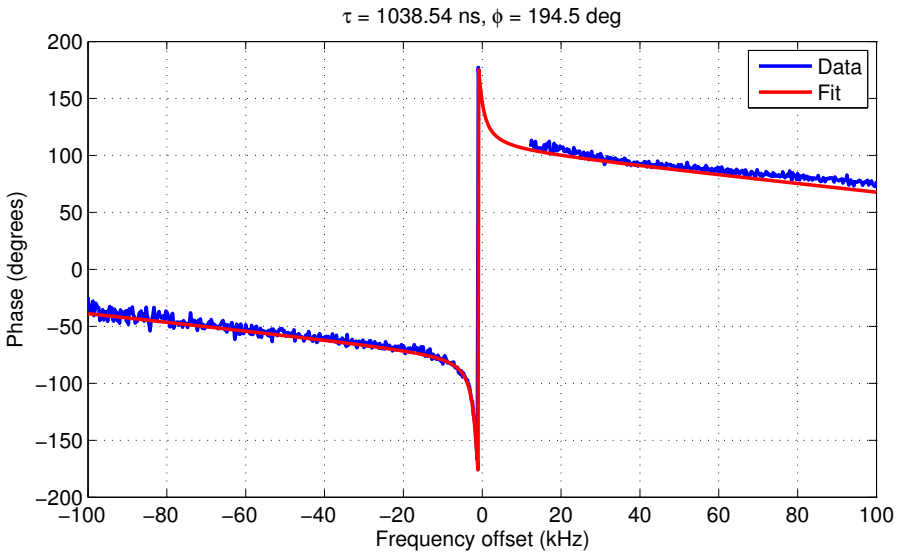

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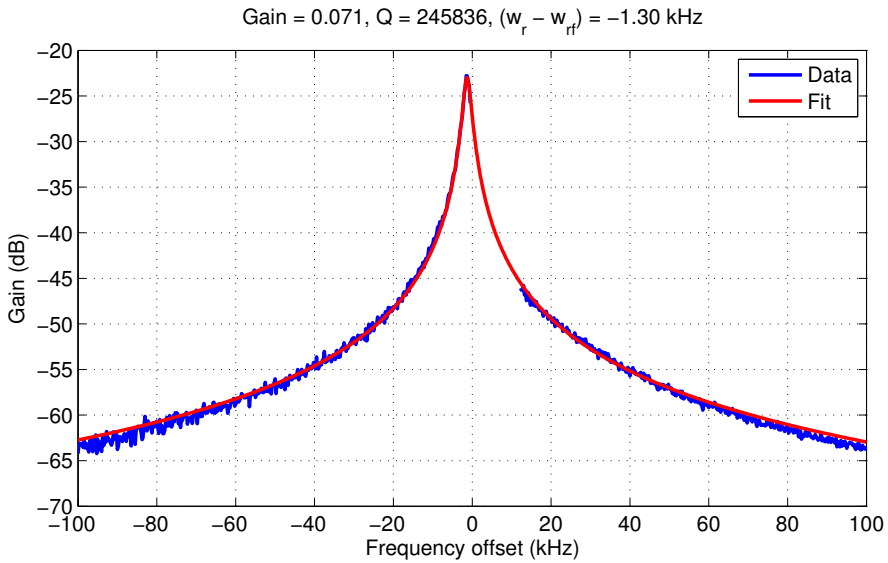

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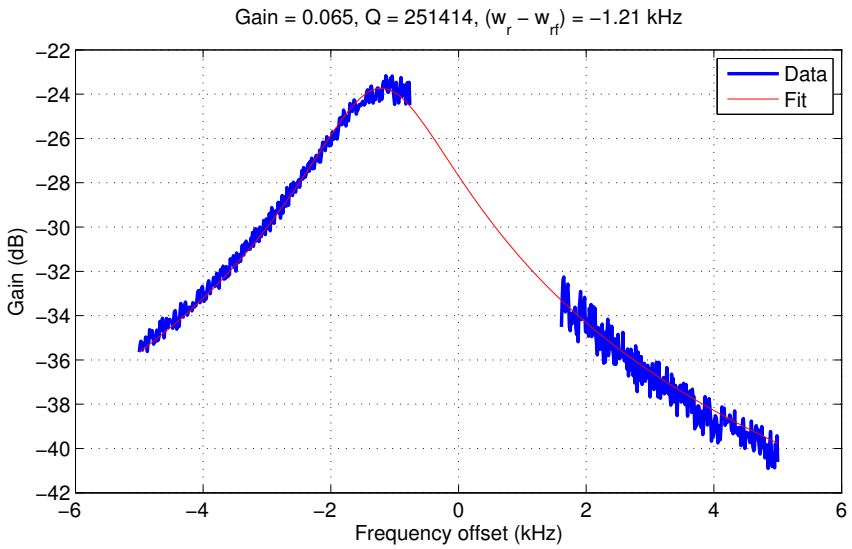

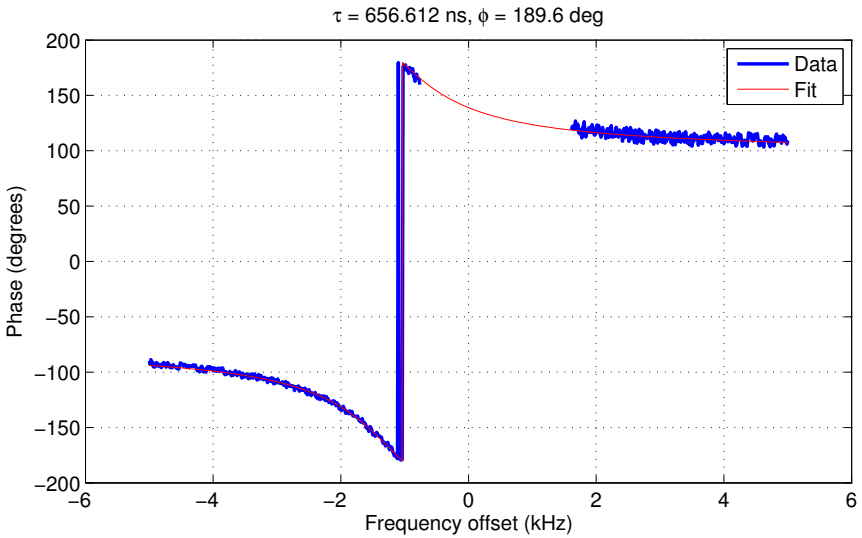

- Open-loop transfer function;
- Closed-loop transfer functions measured at loop gain settings:
  - 4 V;
  - 5 V;
  - 8 V;
  - 10 V.
- Some saturation at higher control voltages;
- Nominal direct loop gain is 0.5 (50% increase in Robinson beam loading limit).

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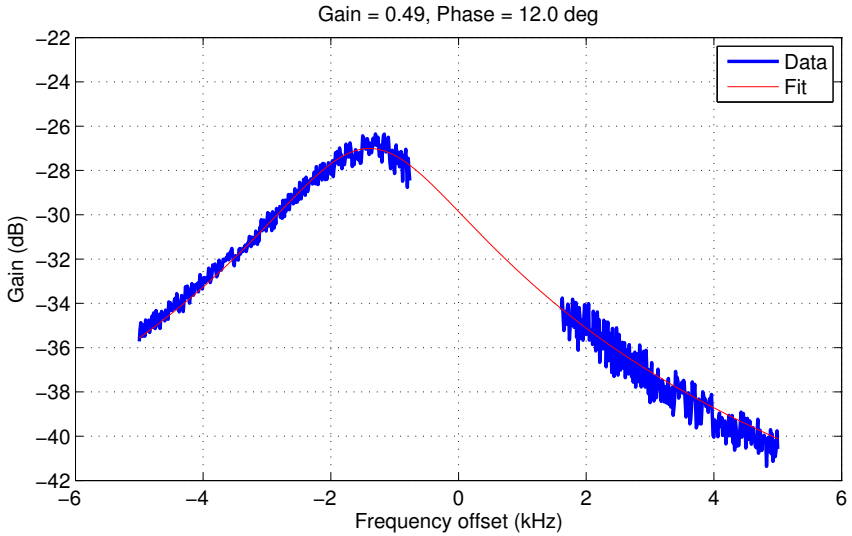

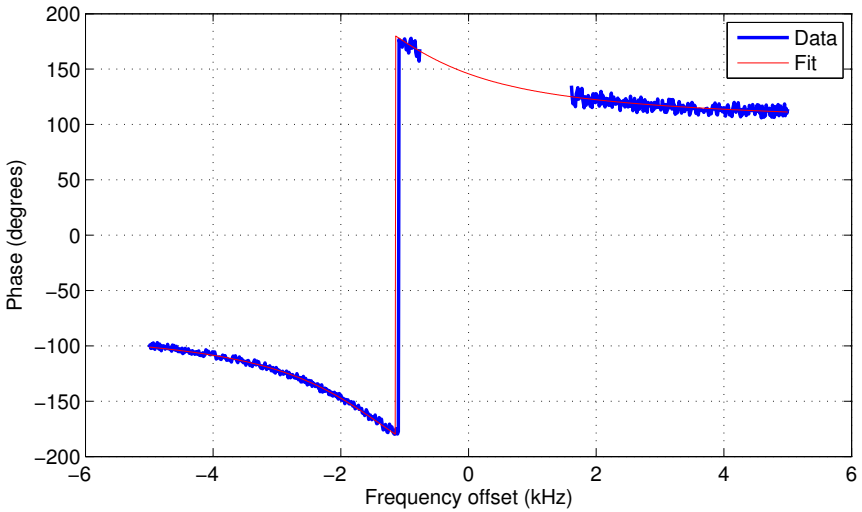

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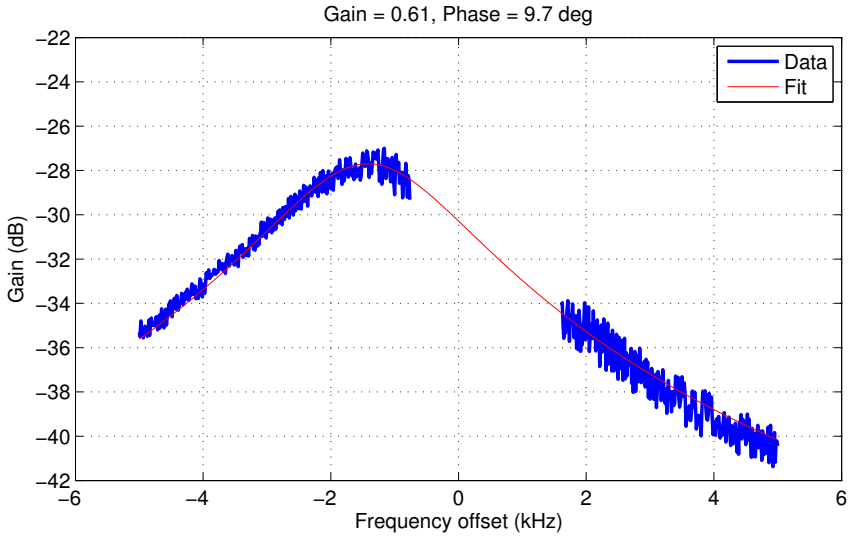

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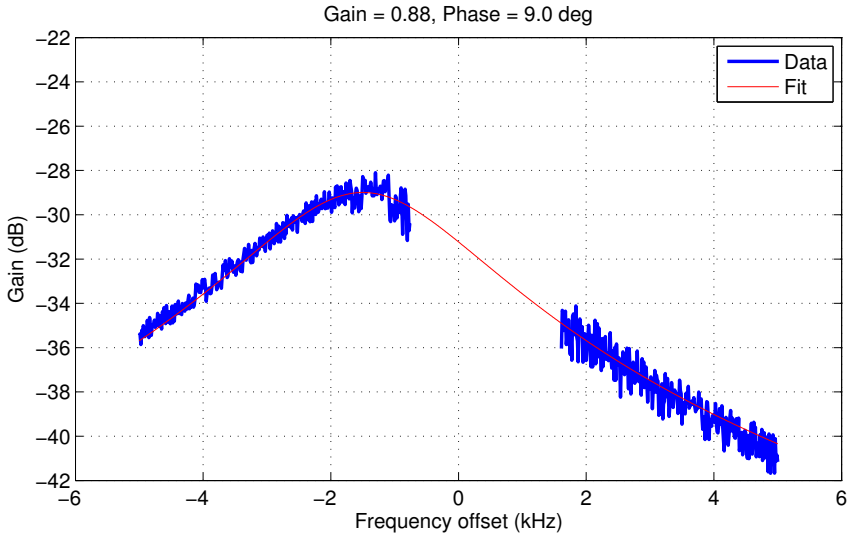

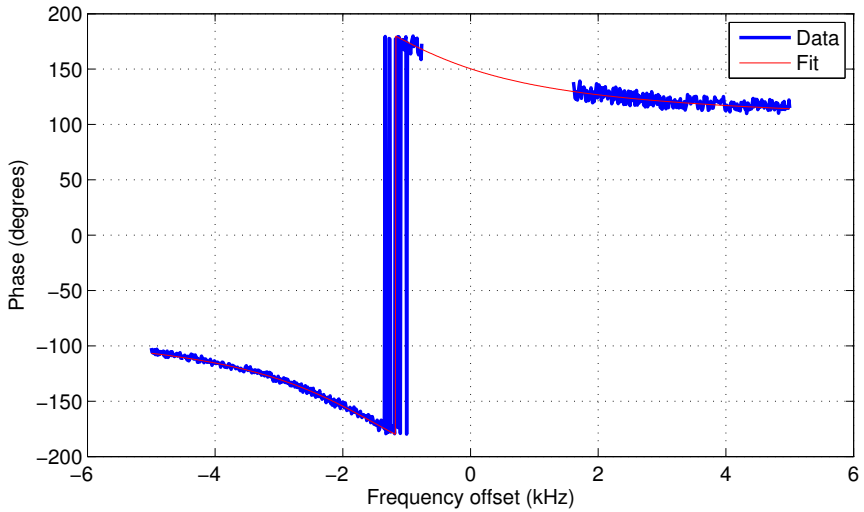

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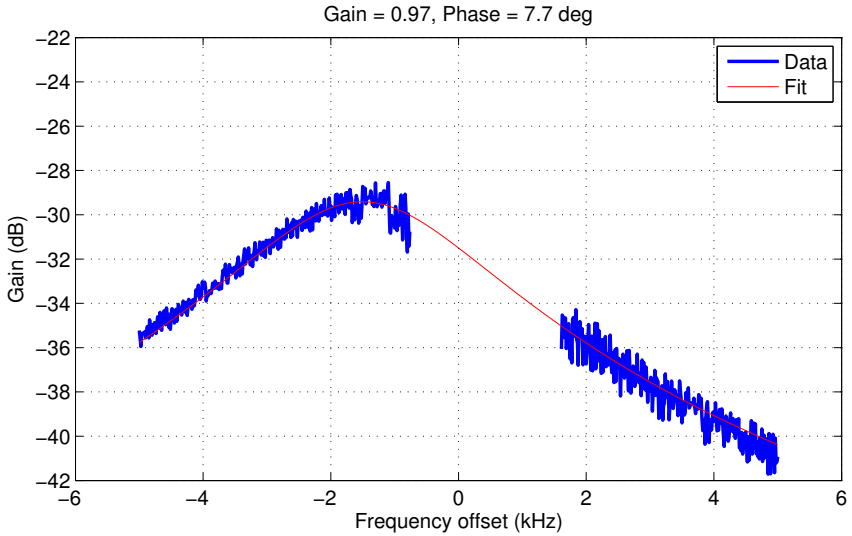

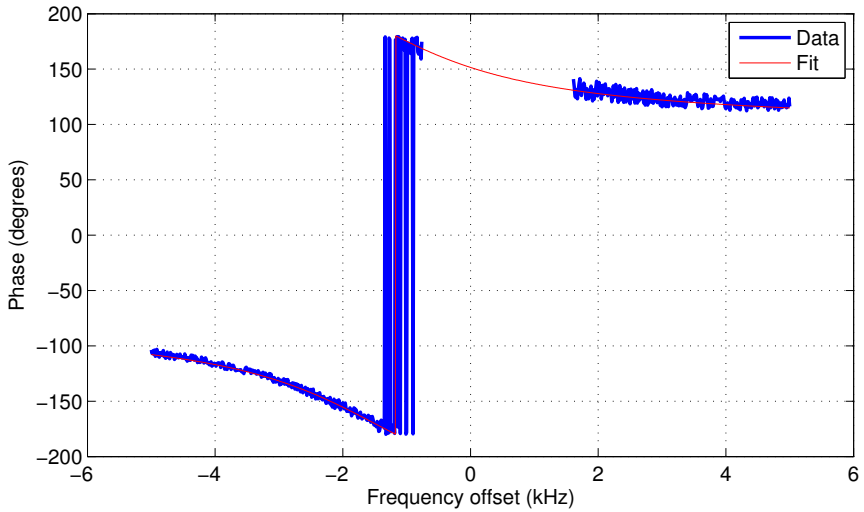

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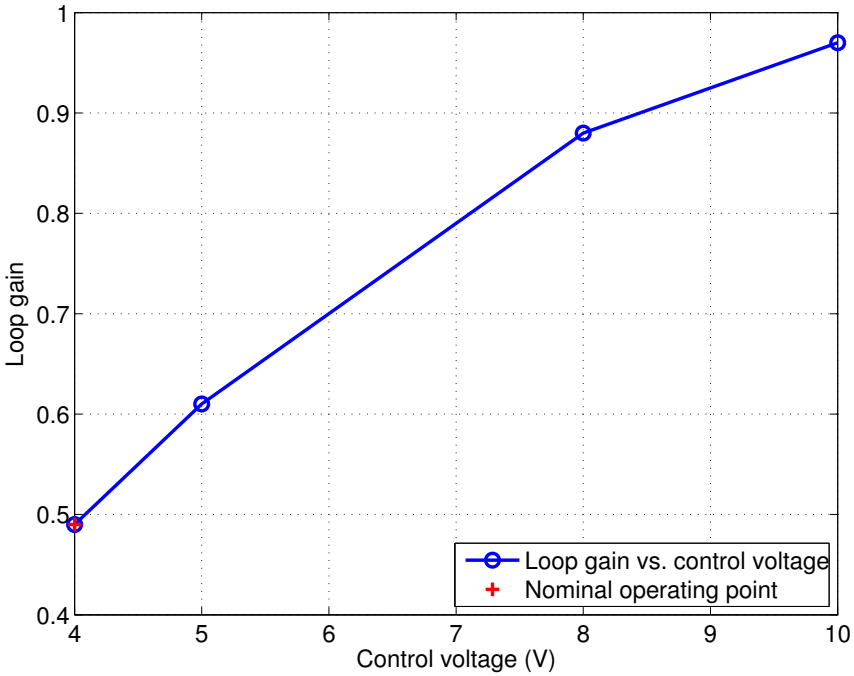

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Experimental Setup

- Attempted to diagnose beam loss events where RF phase activity has been observed;
- Set up iGp12 (demo unit) and iGp8 to generate abort triggers and capture longitudinal bunch-by-bunch data during the abort:
  - iGp8 connected to a front-end channel tuned for amplitude detection of the BPM sum signal;
  - Bunch-by-bunch feedback filters are configured to differentiate bunch currents with 105 turn delay;
  - iGp12 runs longitudinal feedback with a different front-end channel, configured for phase detection;
  - External trigger for iGp12 is generated by iGp8 DAC (105 turn differentiator), trigger threshold adjusted to detect small drop from a single bucket.
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- Set up iGp12 (demo unit) and iGp8 to generate abort triggers and capture longitudinal bunch-by-bunch data during the abort:
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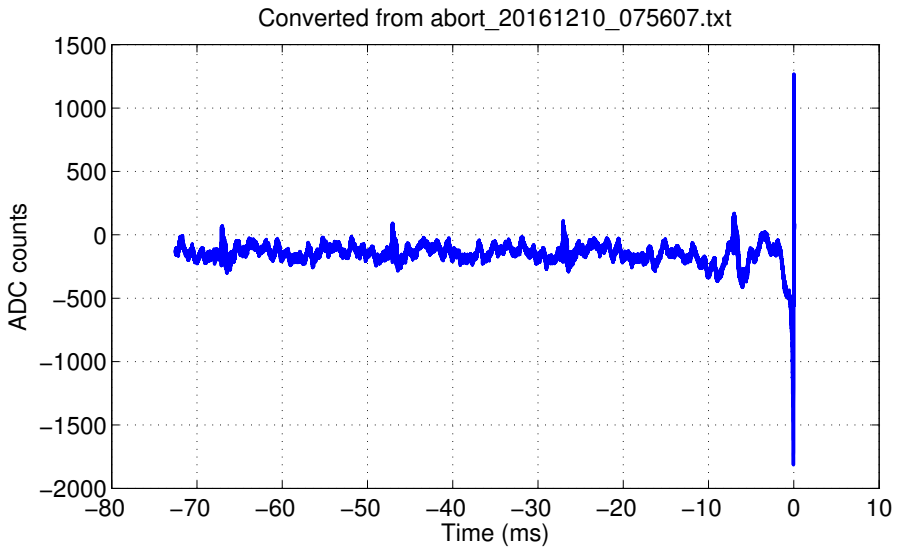

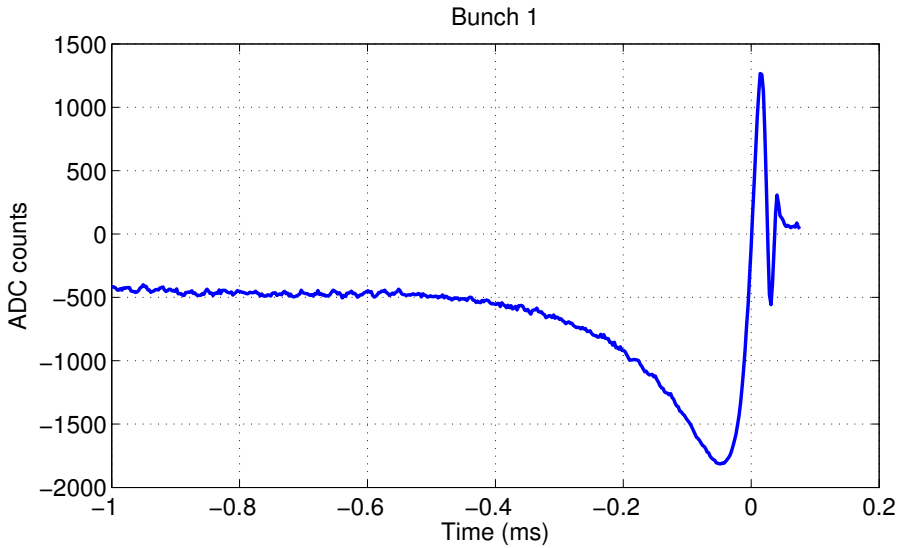

- What looks like oscillation is actually phase wraparound in the 1.5 GHz phase detector;
- Second negative peak is much smaller due to current loss — we are measuring $i_b \times \sin \phi_b$;
- Full 360° oscillation provides all the necessary information to extract the phase signal;
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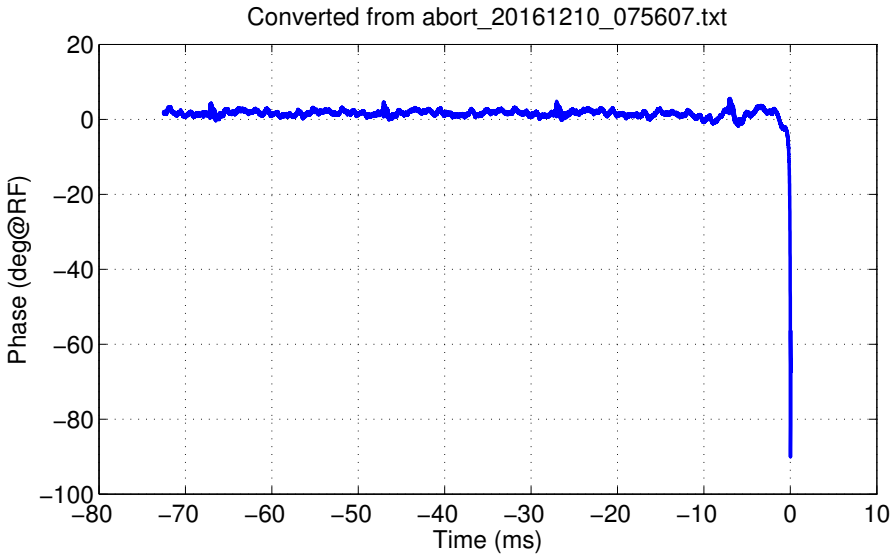

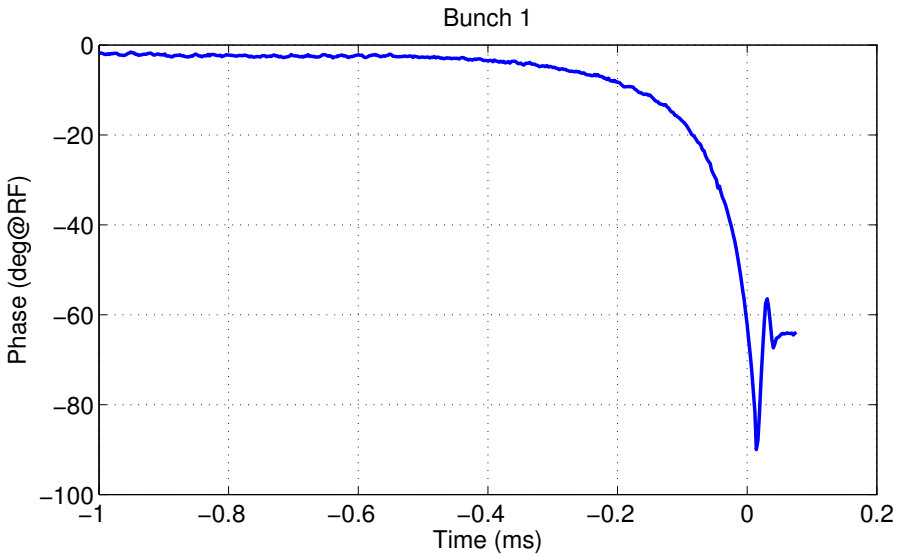

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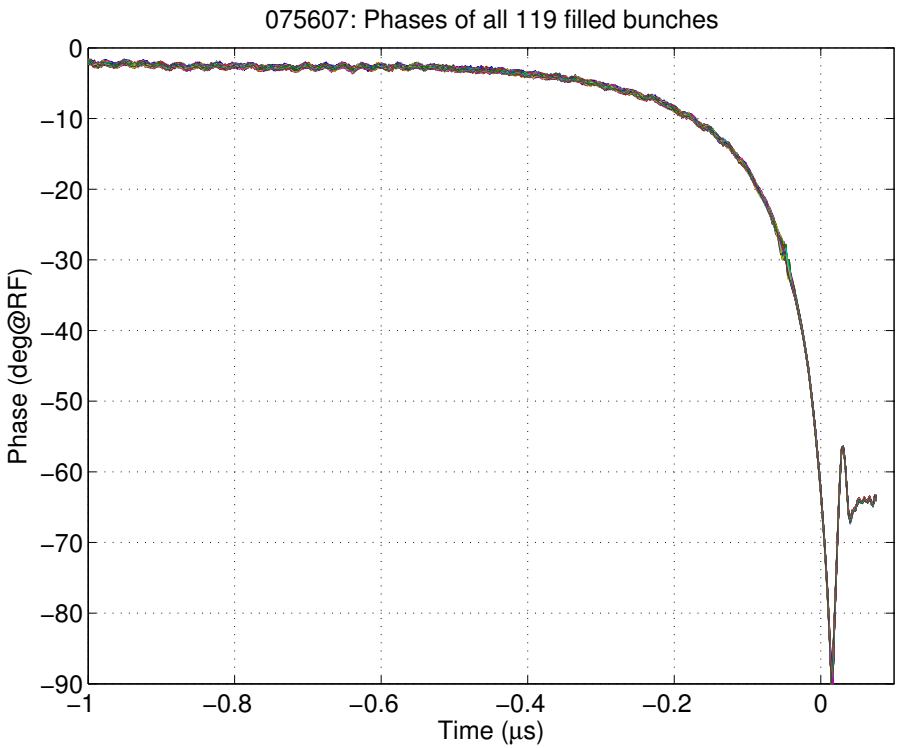

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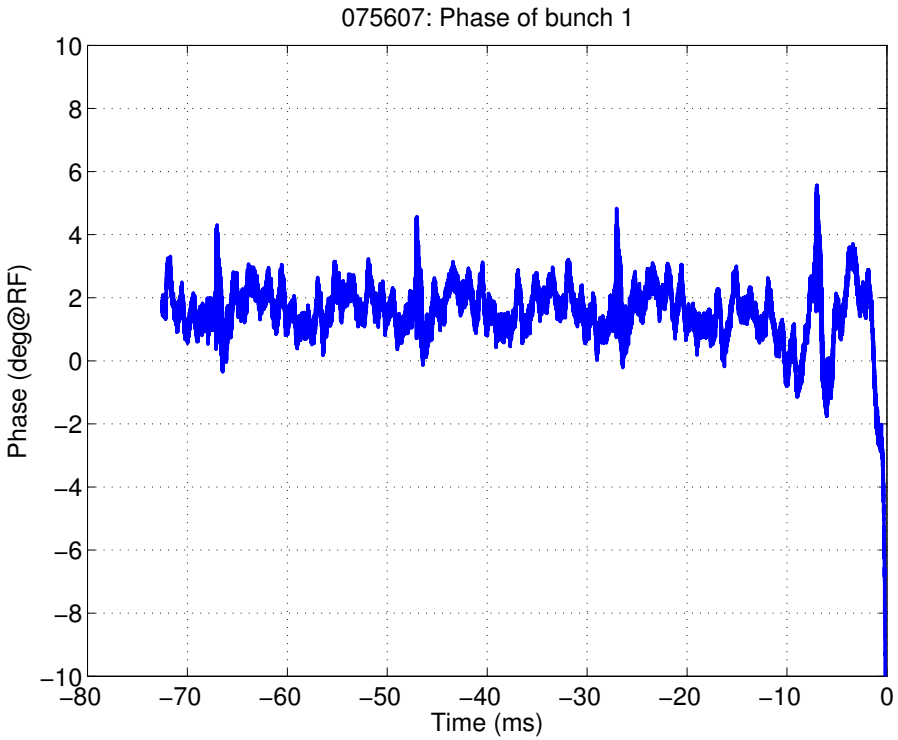

- Excitations every 20 ms;
- Fairly large steady-state excursions (5° peak to peak, 0.6° RMS);
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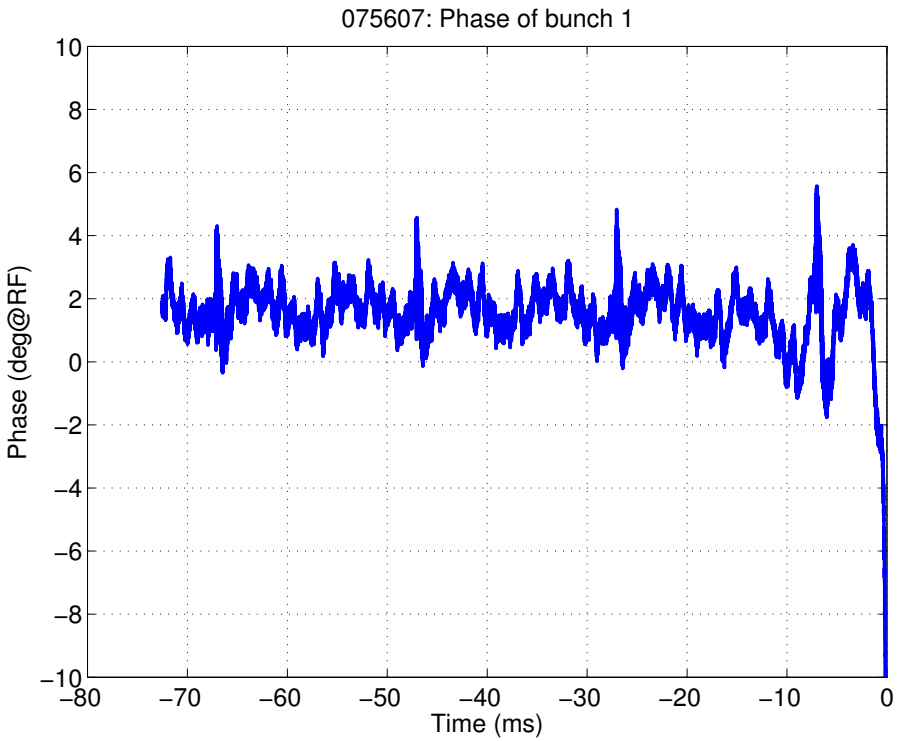

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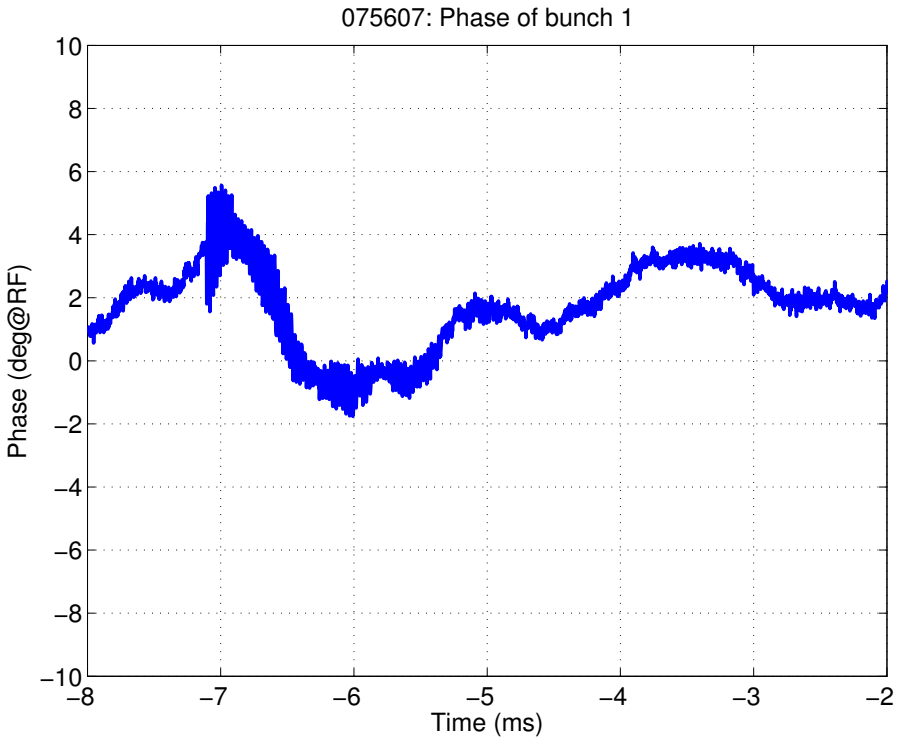

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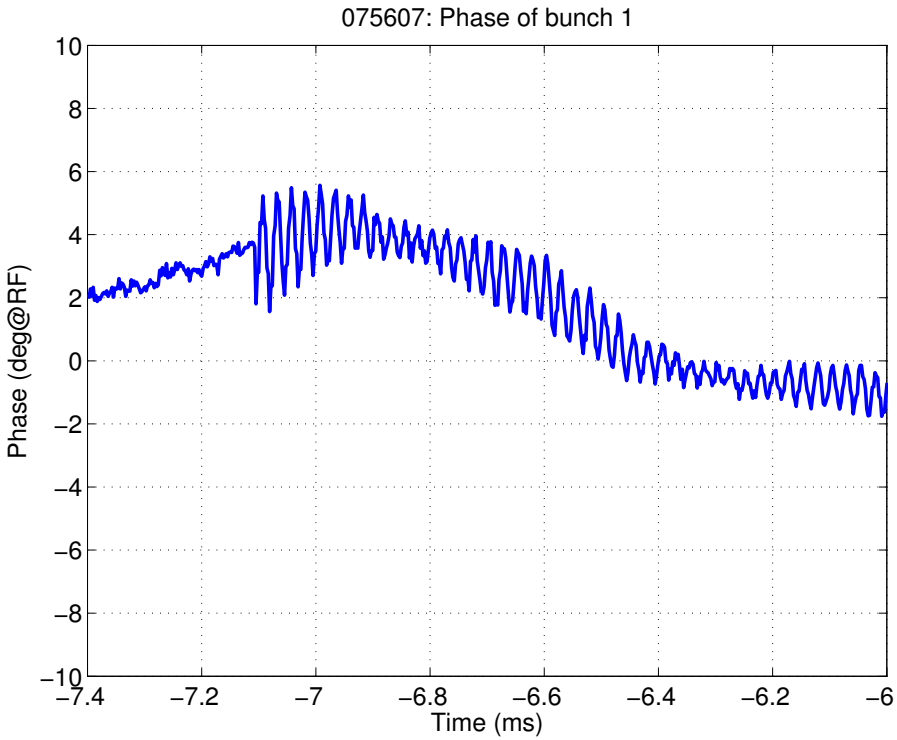

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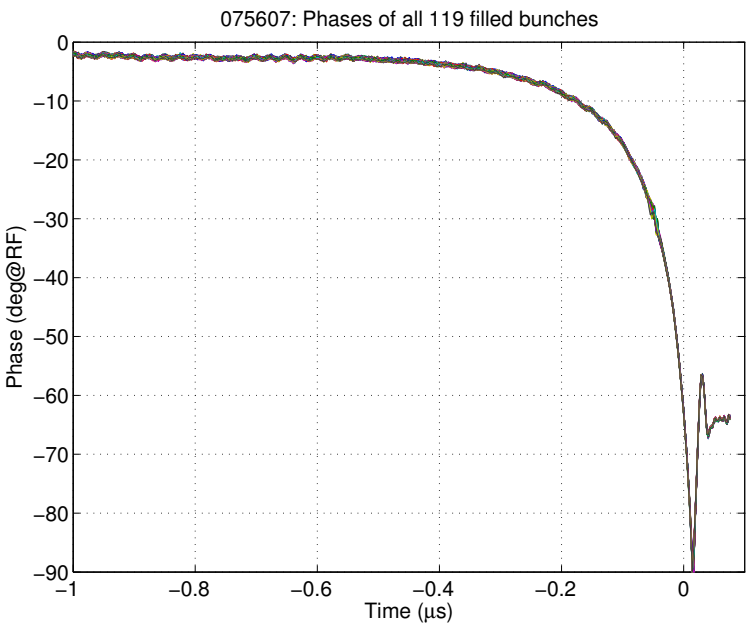

- Exponential beam phase runaway is a typical signature of high beam loading Robinson limit;
- Using cavity parameters estimated earlier, at zero loading angle and without direct feedback the limit is 900 mA (1350 mA with direct feedback);
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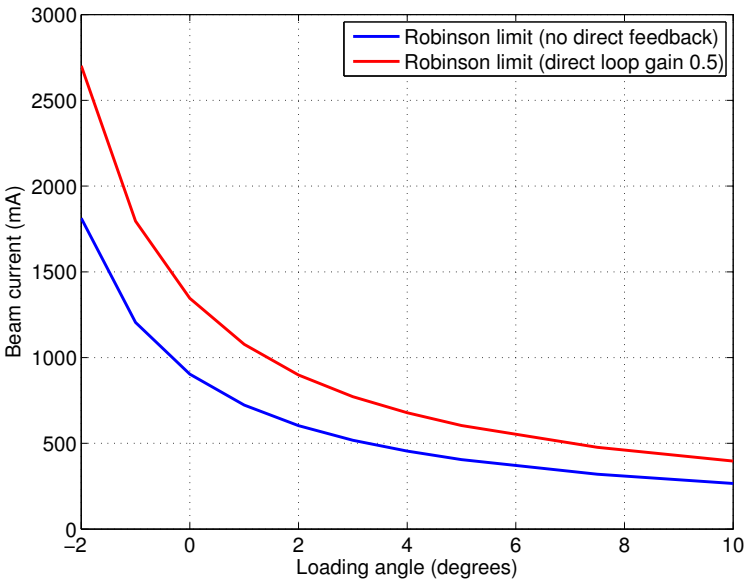

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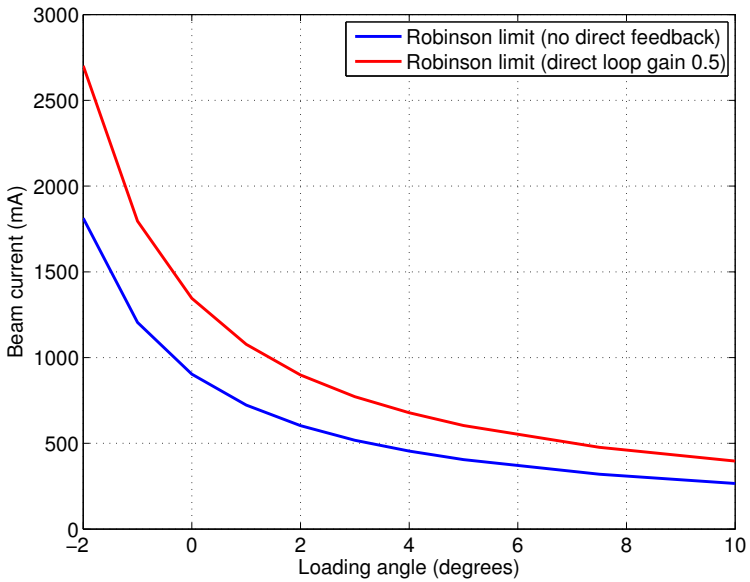

- With loading angle of $-10°$ (or even $-21°$) there should be no beam loading limit;
- Is it possible the loading angle is wandering during operation?
- Small positive angle (3-4 degrees) are consistent with loss events observed;
- Increasing direct loop gain to 0.96 (10 V) should provide a 30% higher margin, a good test of the hypothesis;
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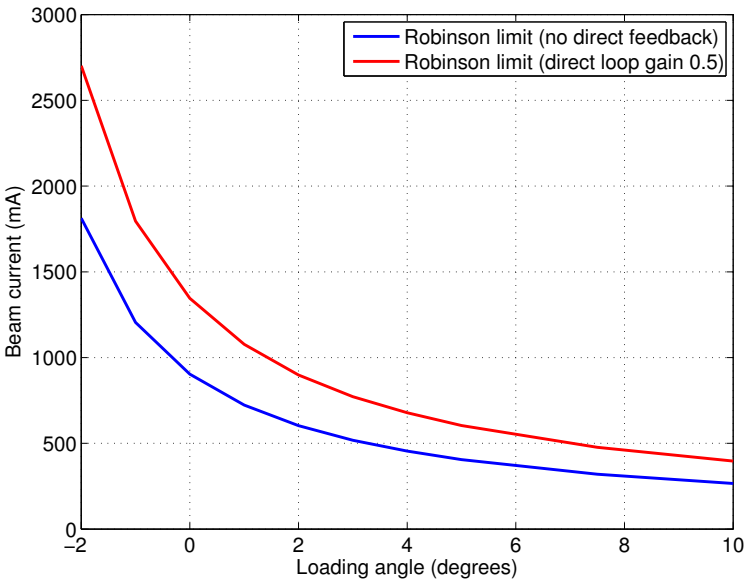

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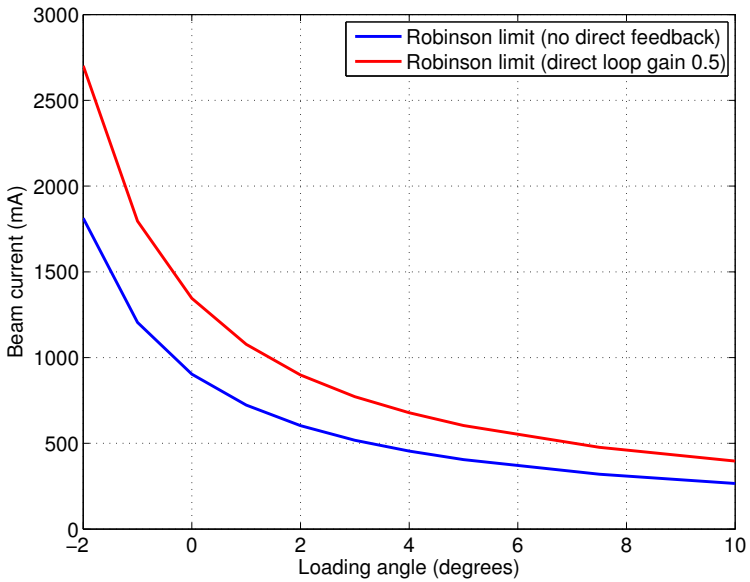

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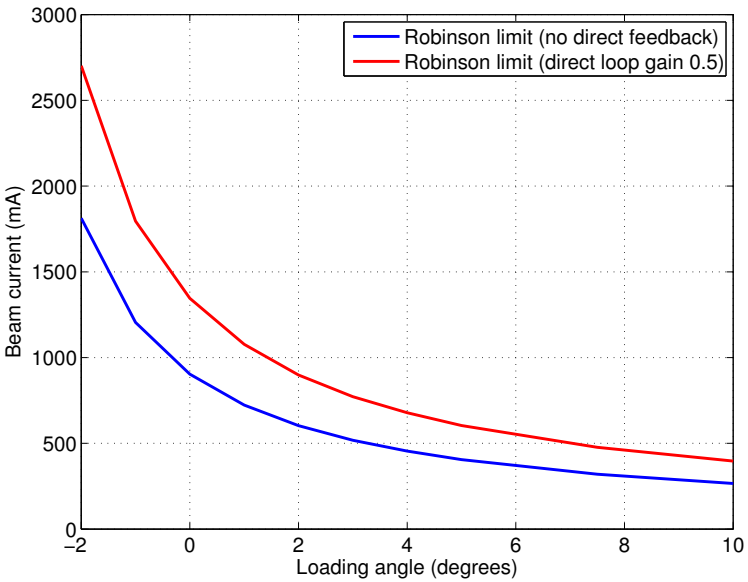

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Introduction

- The goal was to investigate synchronous phase transients and their compensation with fill pattern modulation;
- Turned out to be a very difficult task: due to the machine dynamics peak to peak transients are small, in the 0.5–1.5° range;
- To measure absolute phase to 0.1° all reflections, coupling, HOMs have to be below −71 dB;
- After trying many different measurement approaches as well as different pickups we settled on using iGp12 as a sampling scope;
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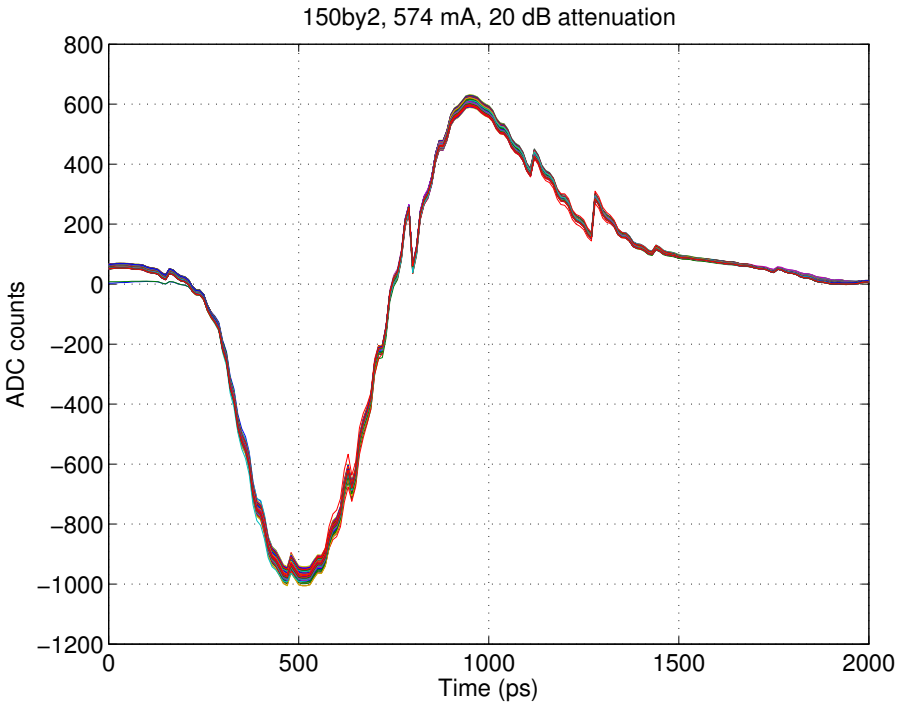

- Uniform fill of 150 bunches, 4 ns spacing;
- Time sweep generated by adjusting digital delay line with 10 ps resolution;
- Jumps in the sweep correspond to binary transitions — delay stages are not perfect 10-20-40-80-160-320-640-1280 ps;
- Modulated pattern doubles bunch current for 24 bunches in the beginning and 24 bunches in the end of the train;
- AM-to-PM conversion.

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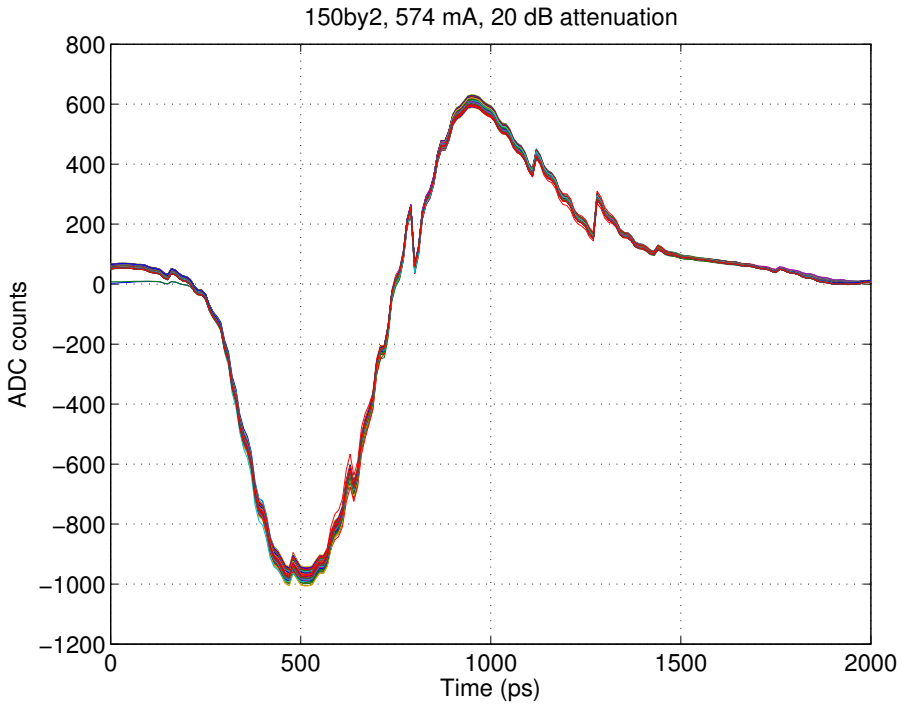

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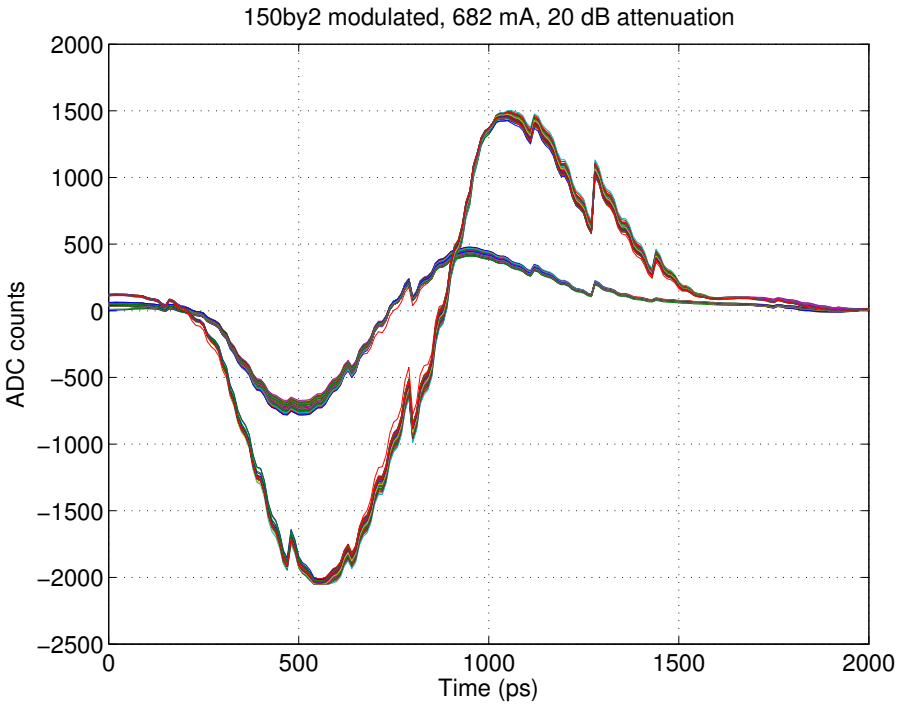

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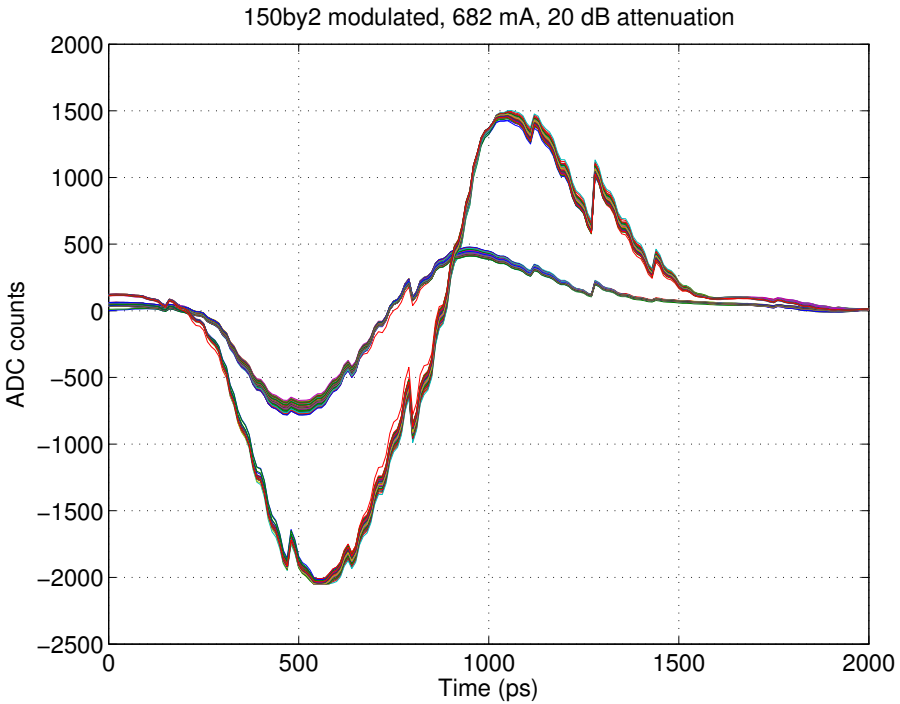

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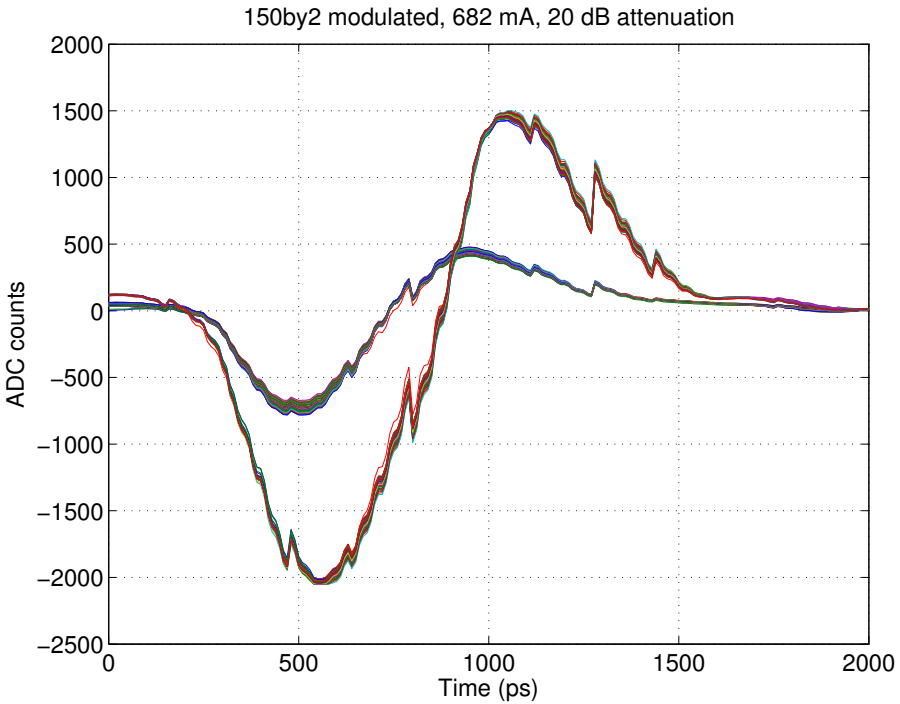

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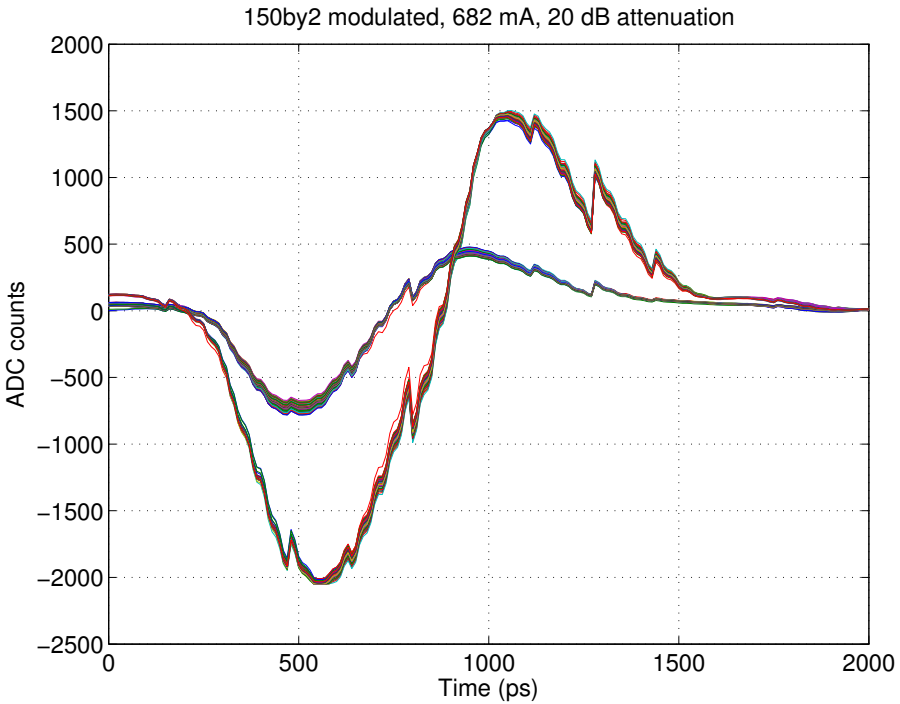

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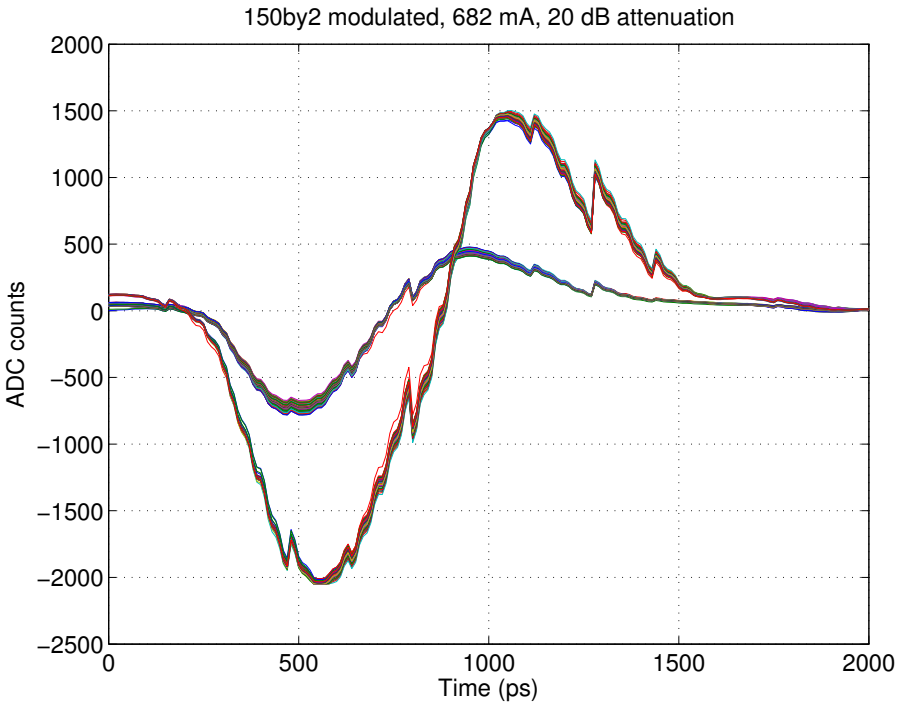

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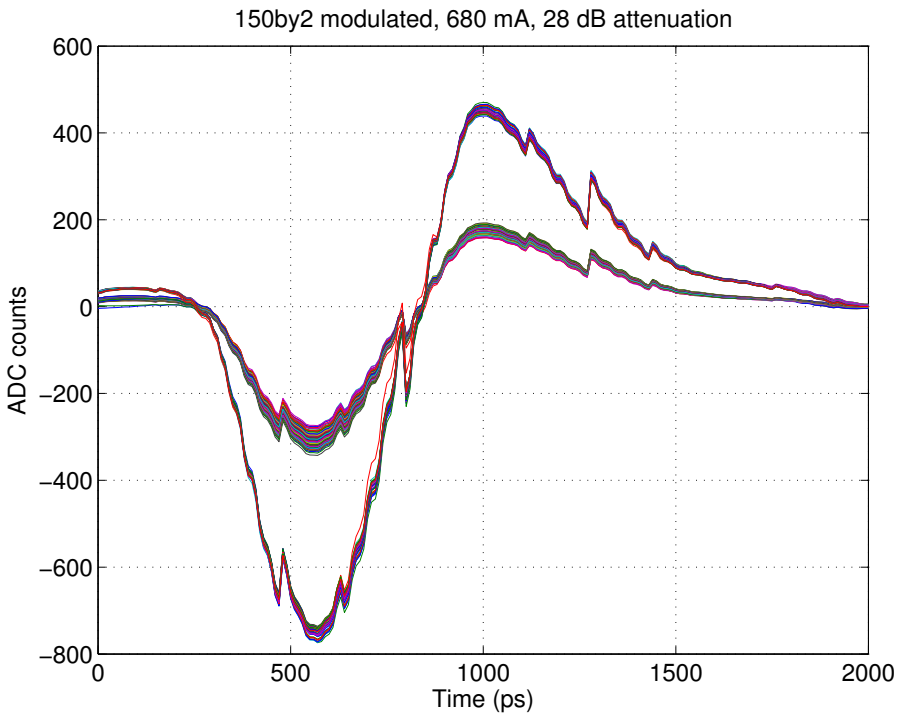

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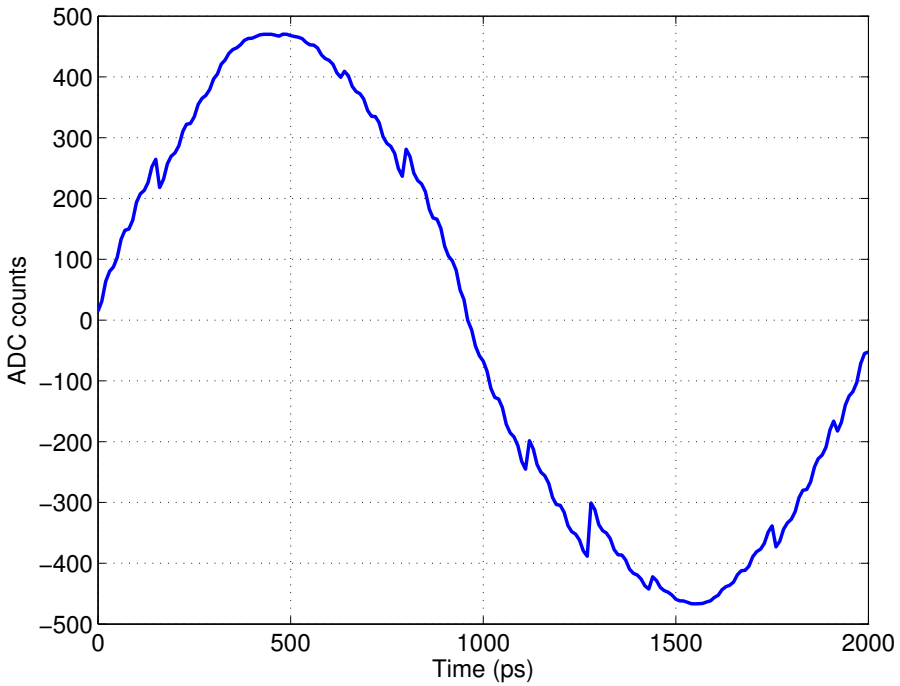

- Calibration based on a measurement of the RF reference signal;
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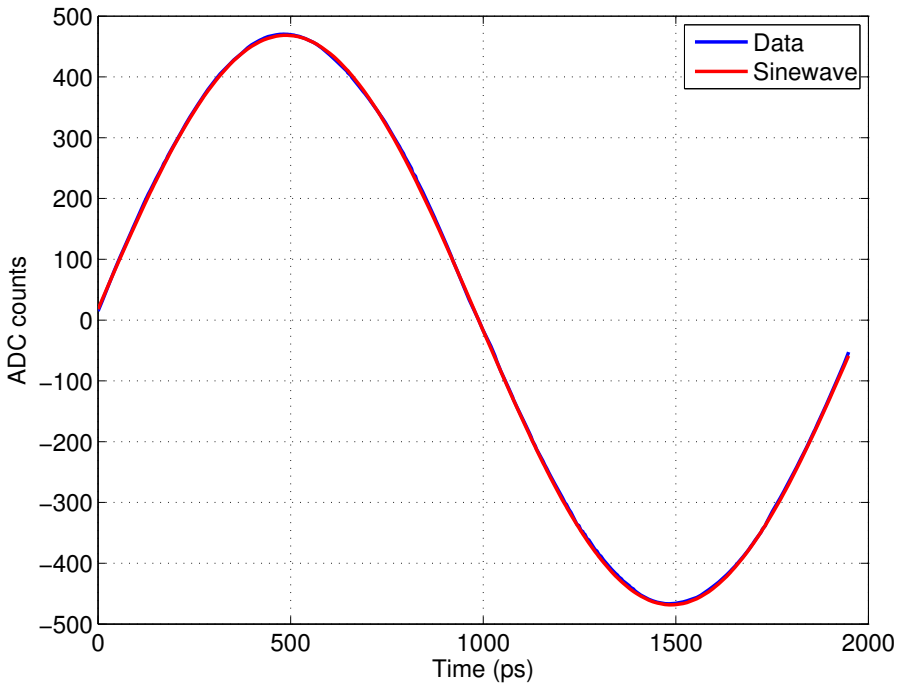

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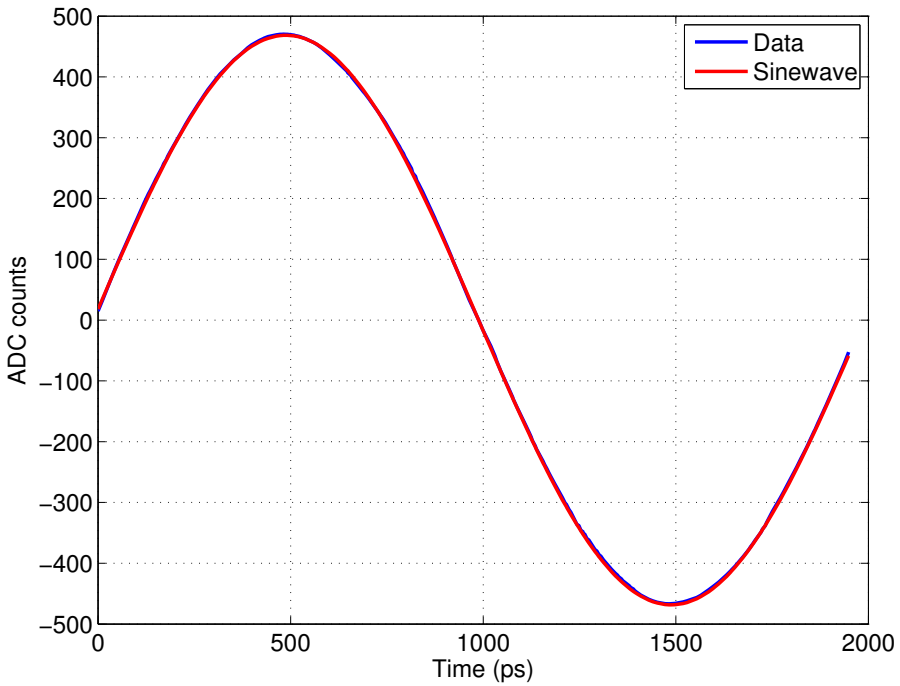

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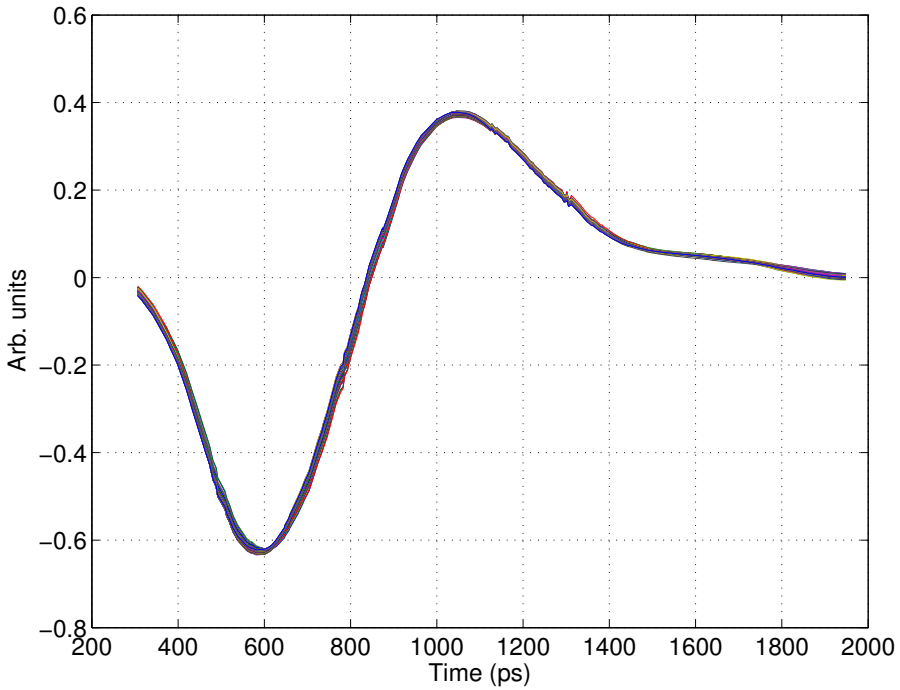

- Start from individual bunch signals normalized by their peak-to-peak amplitude;
- Calculate average shape signal;
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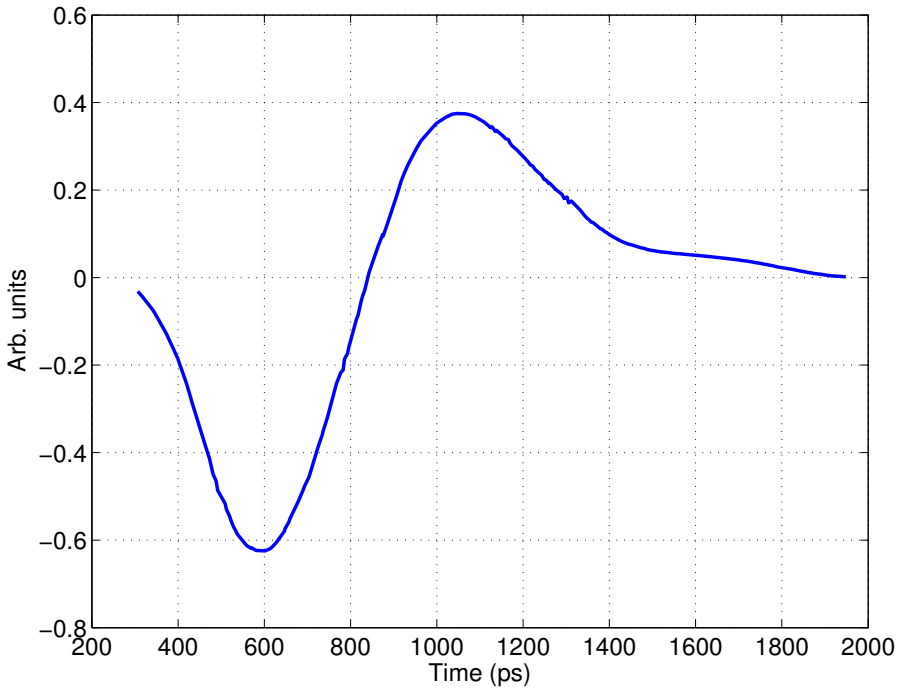

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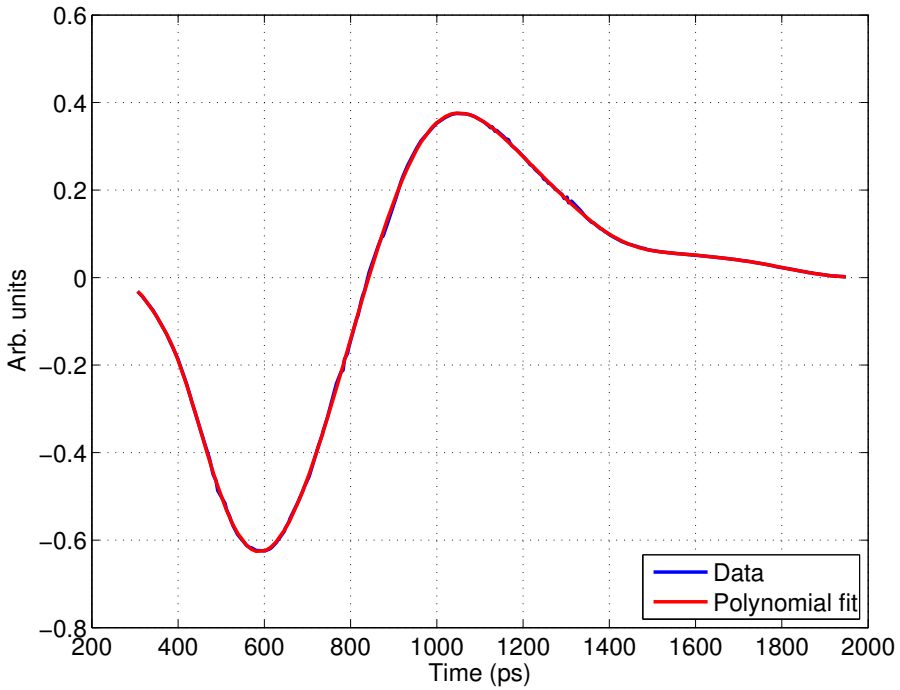

- Start from individual bunch signals normalized by their peak-to-peak amplitude;
- Calculate average shape signal;
- Fit a 21st order polynomial to the average;
- For each bunch perform a two parameter fit: time shift and amplitude scaling;
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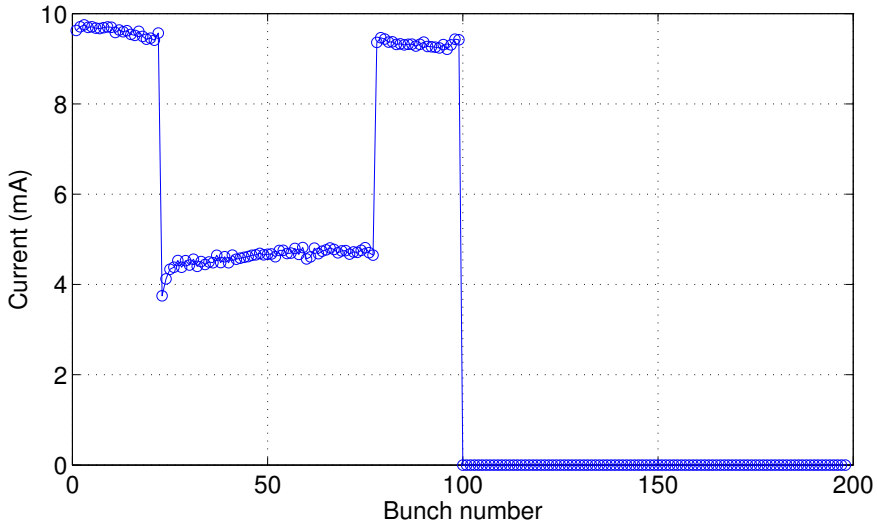

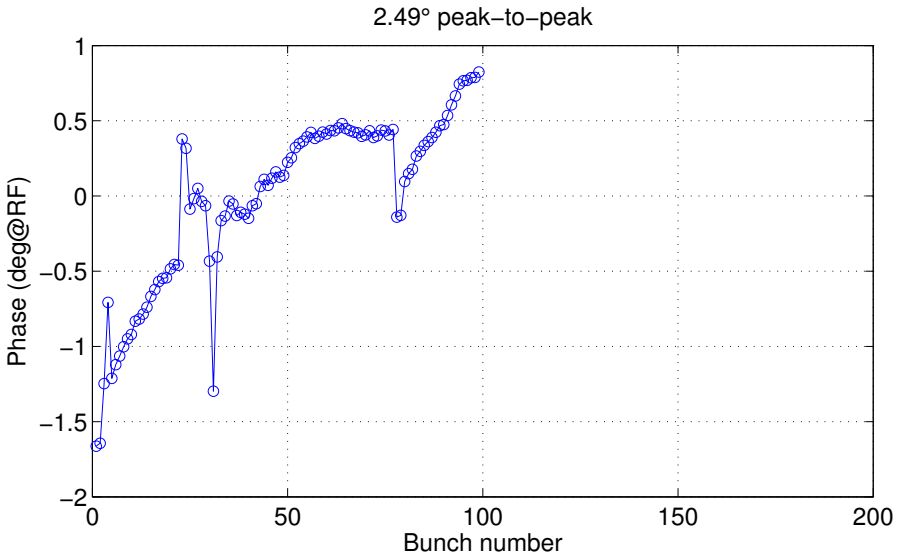

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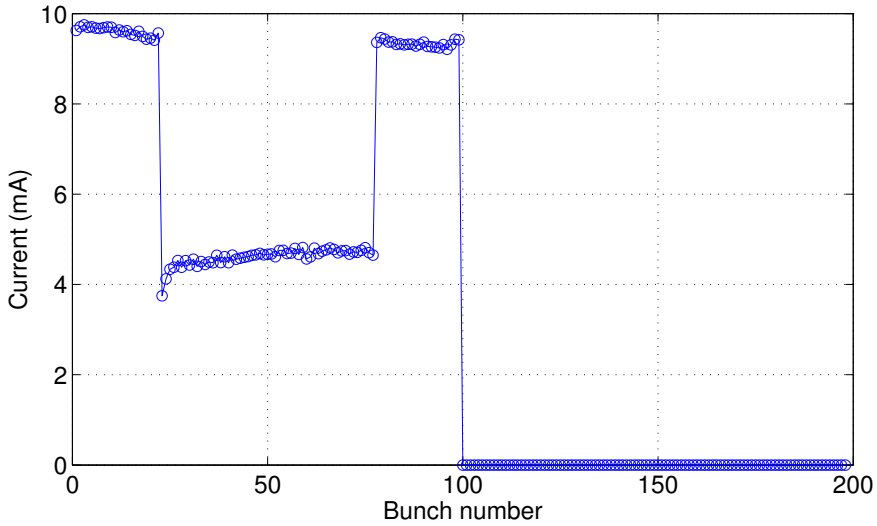

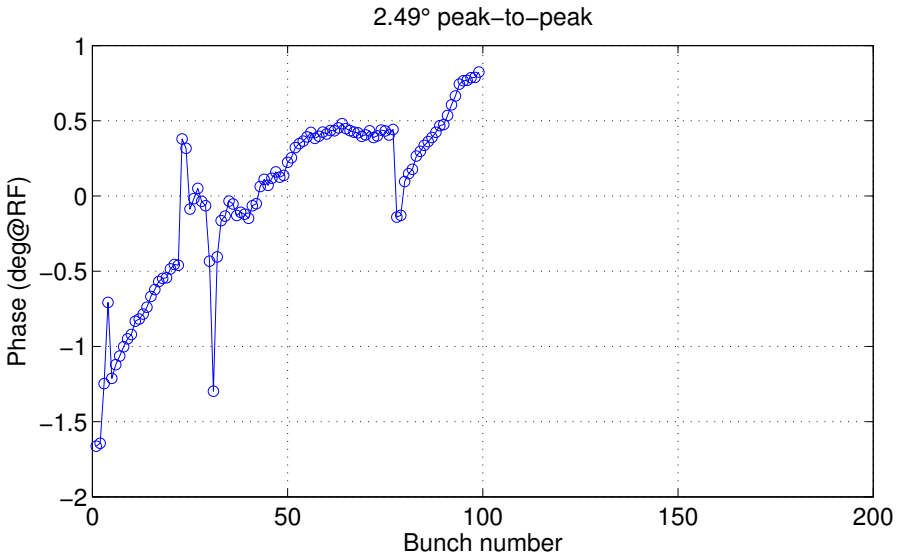

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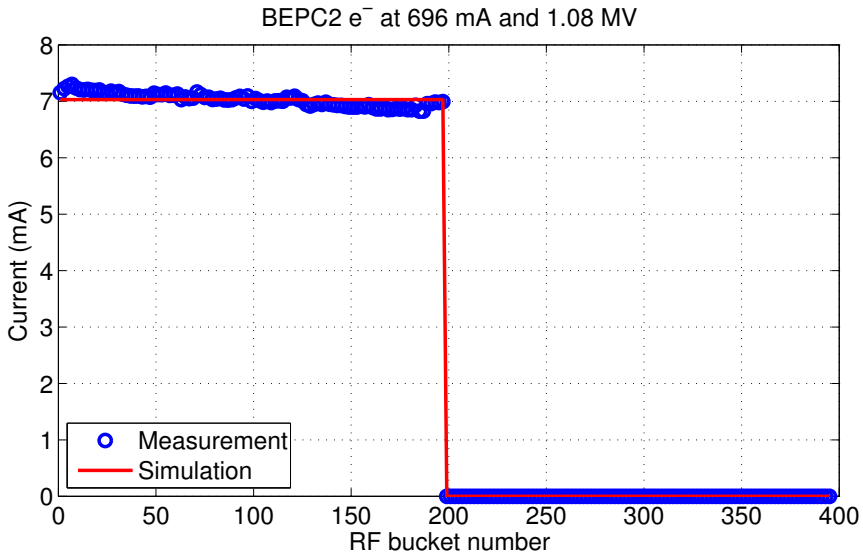
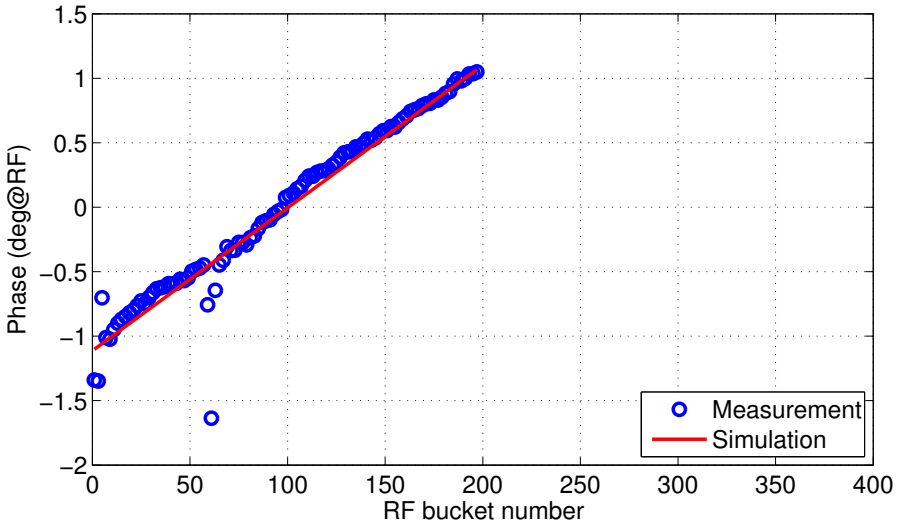
Uniform Train: Measurement and Simulation





- To maximize the transient filled half the ring (99 bunches in 4 ns spacing);
- RF voltage reduced to 1.08 MV;
- Calculated transient using Pedersen's small-signal model;
- Feature around bucket 60 is due to an HOM roughly 18 m downstream.

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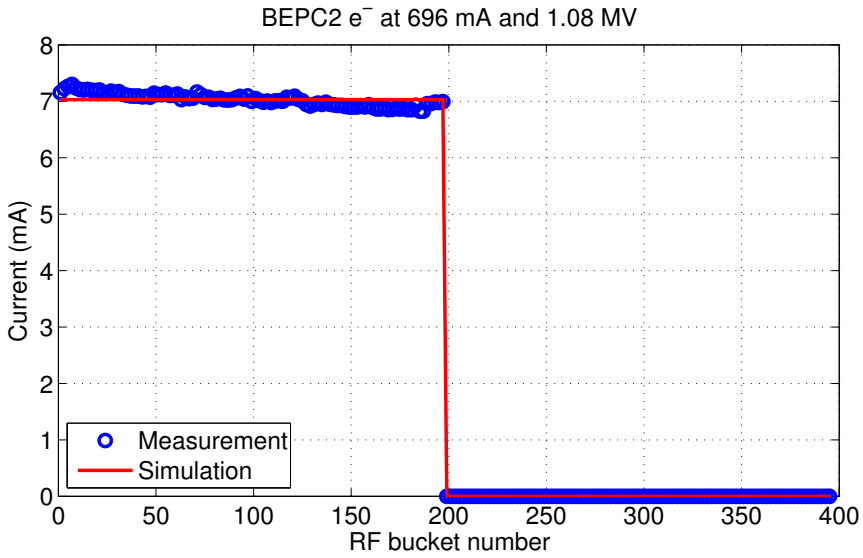

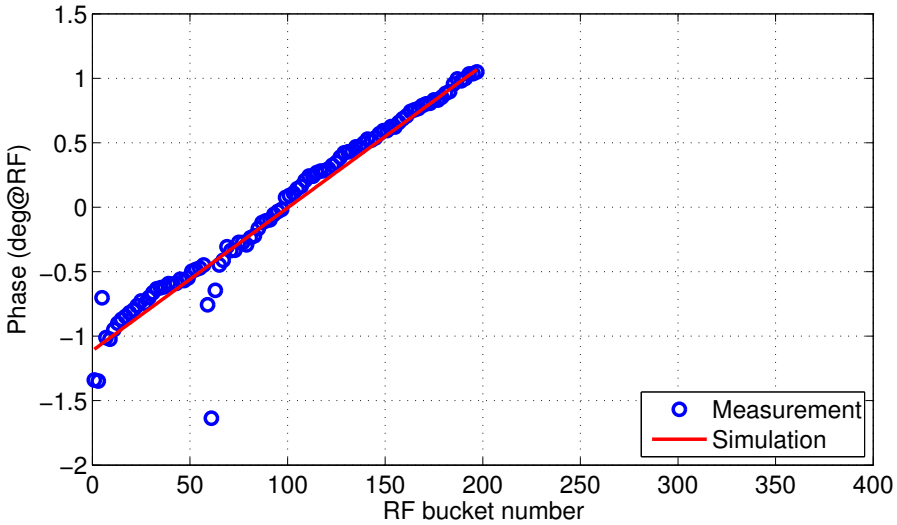

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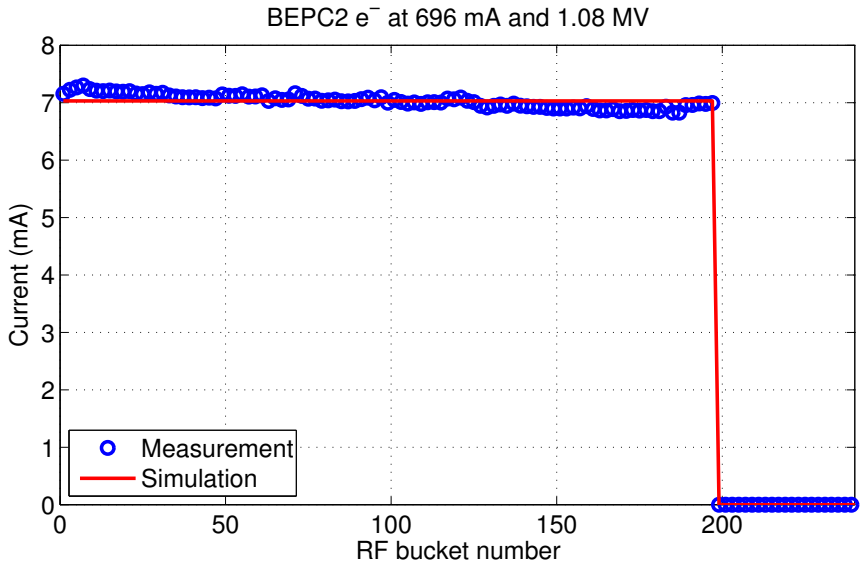

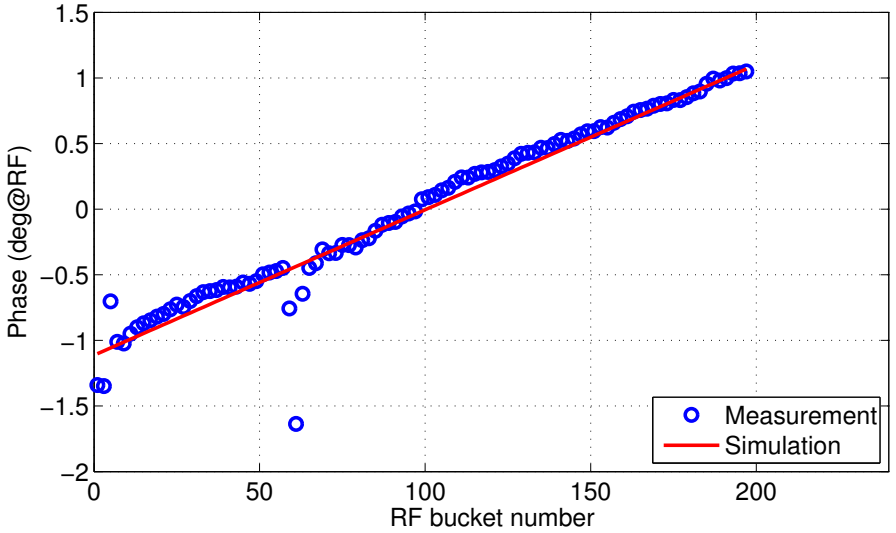

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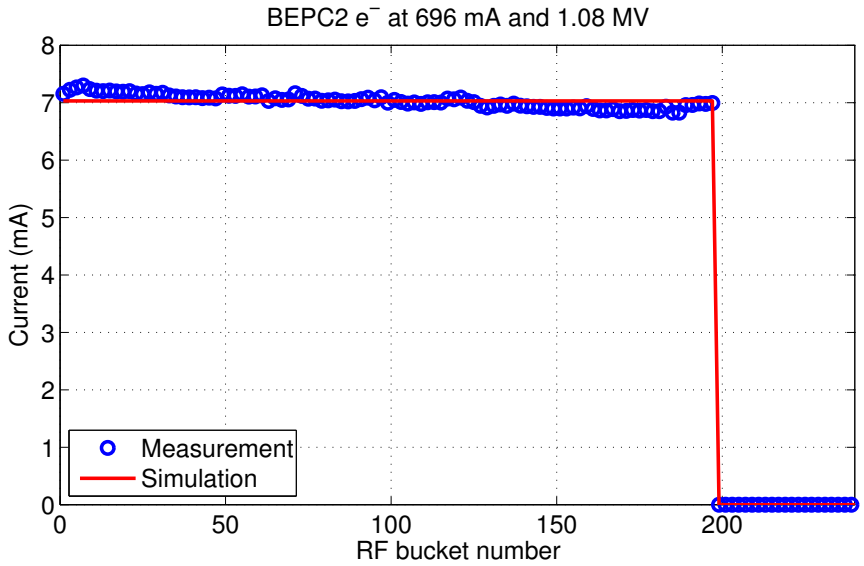

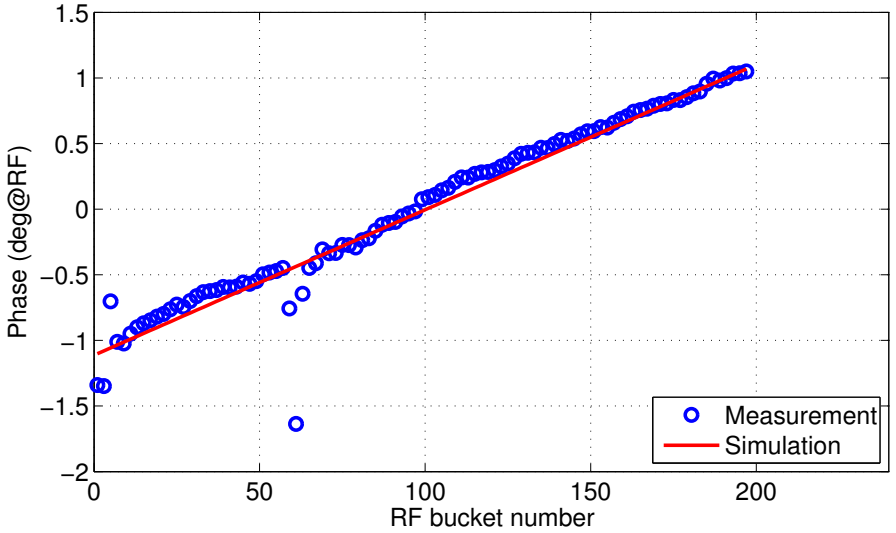

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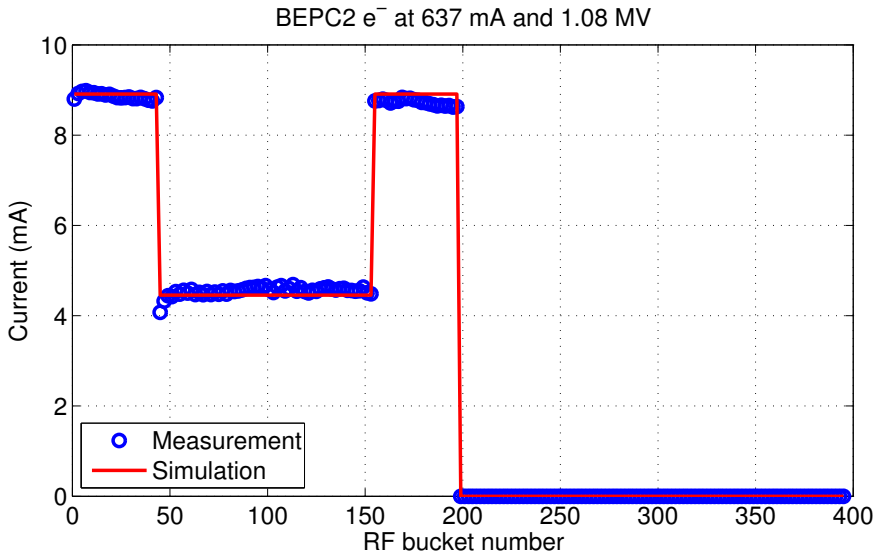

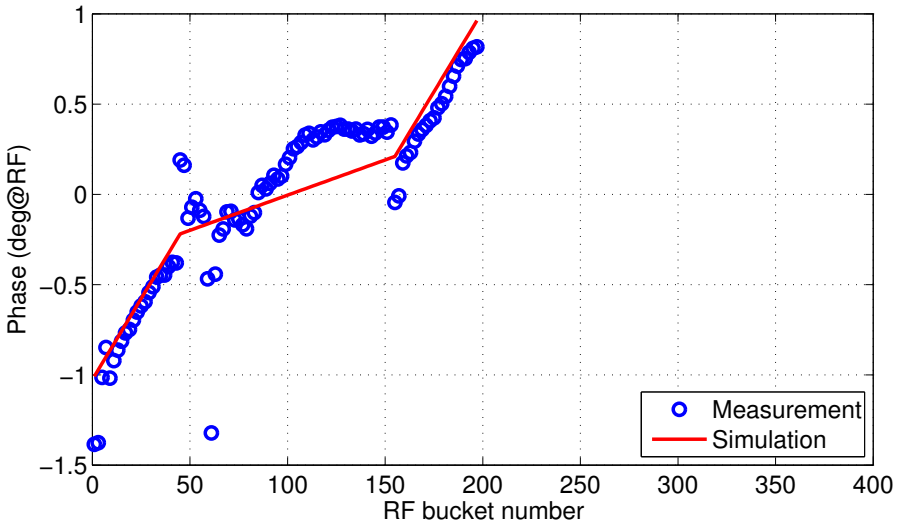

- Modulated fill: 22 bunches at the beginning and the end of the train at twice the current;
- Expect partial transient compensation for 55 bunches in the middle;
- Reasonable agreement between measurements and simulation.

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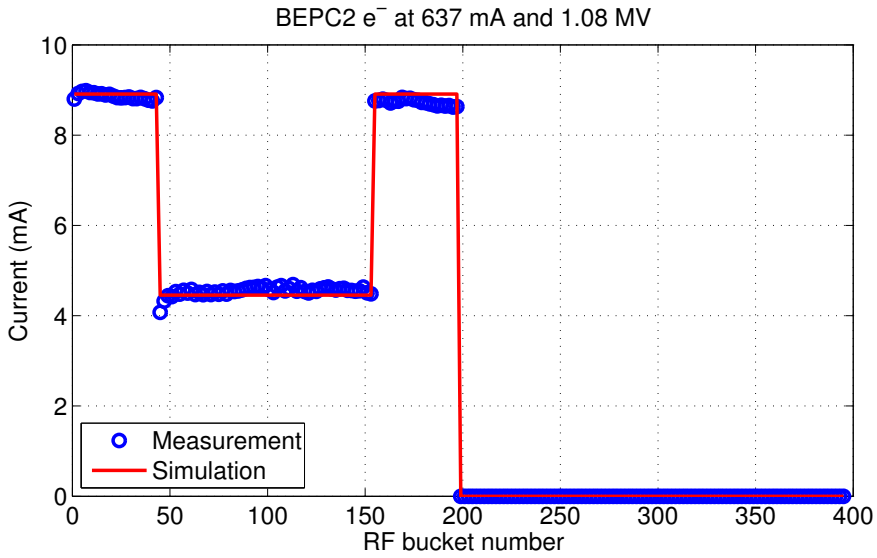

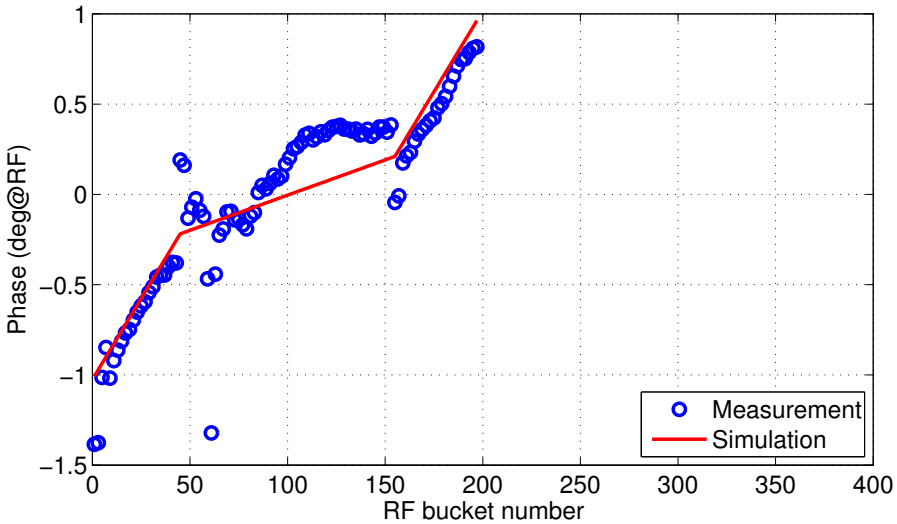

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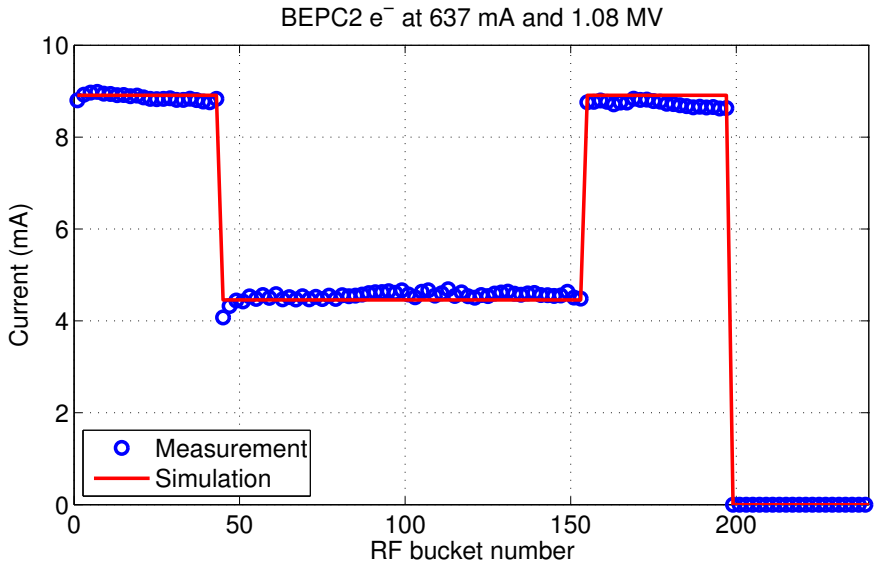

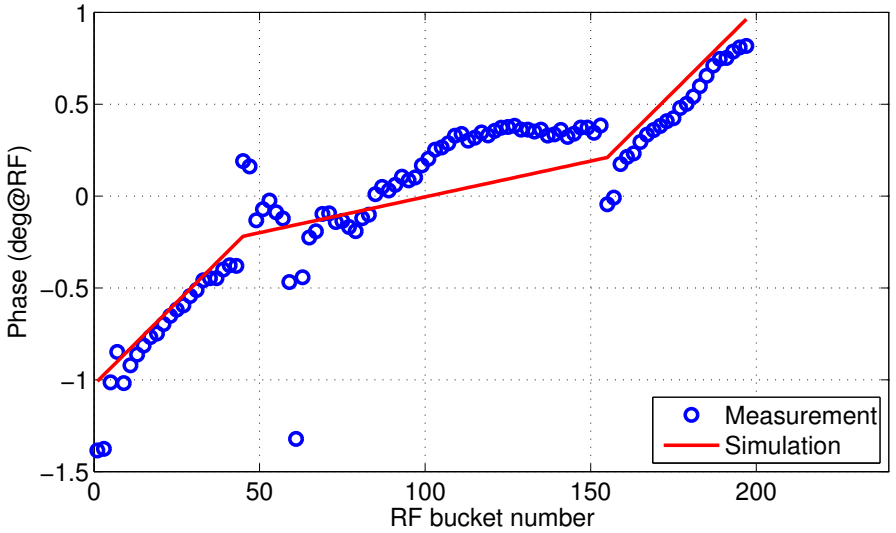

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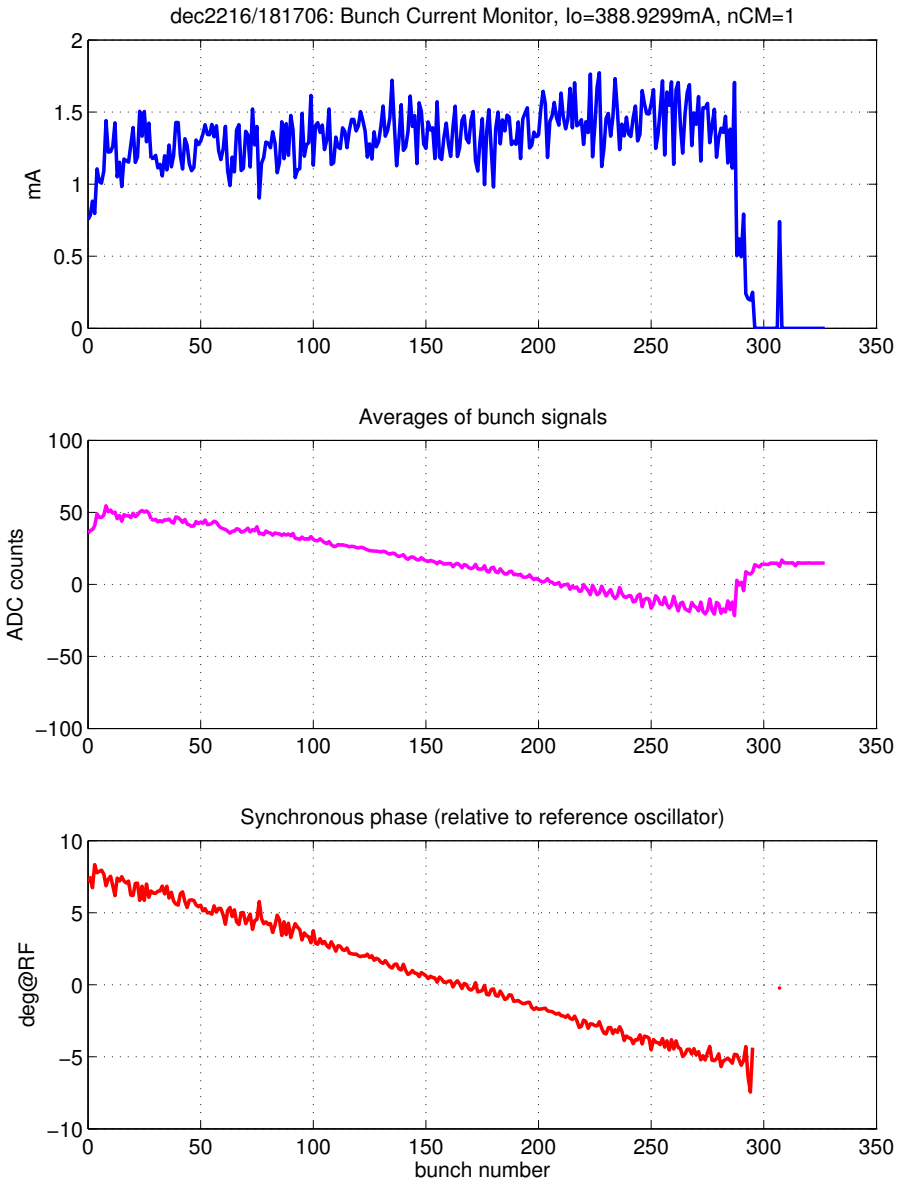

- Nominal fill pattern at the ALS, reduced beam current (388 mA instead of 500 mA);
- Harmonic cavities tuned in;
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- Should detune harmonic cavities to simplify the analysis;
- Can try both current and density (spacing) modulations.

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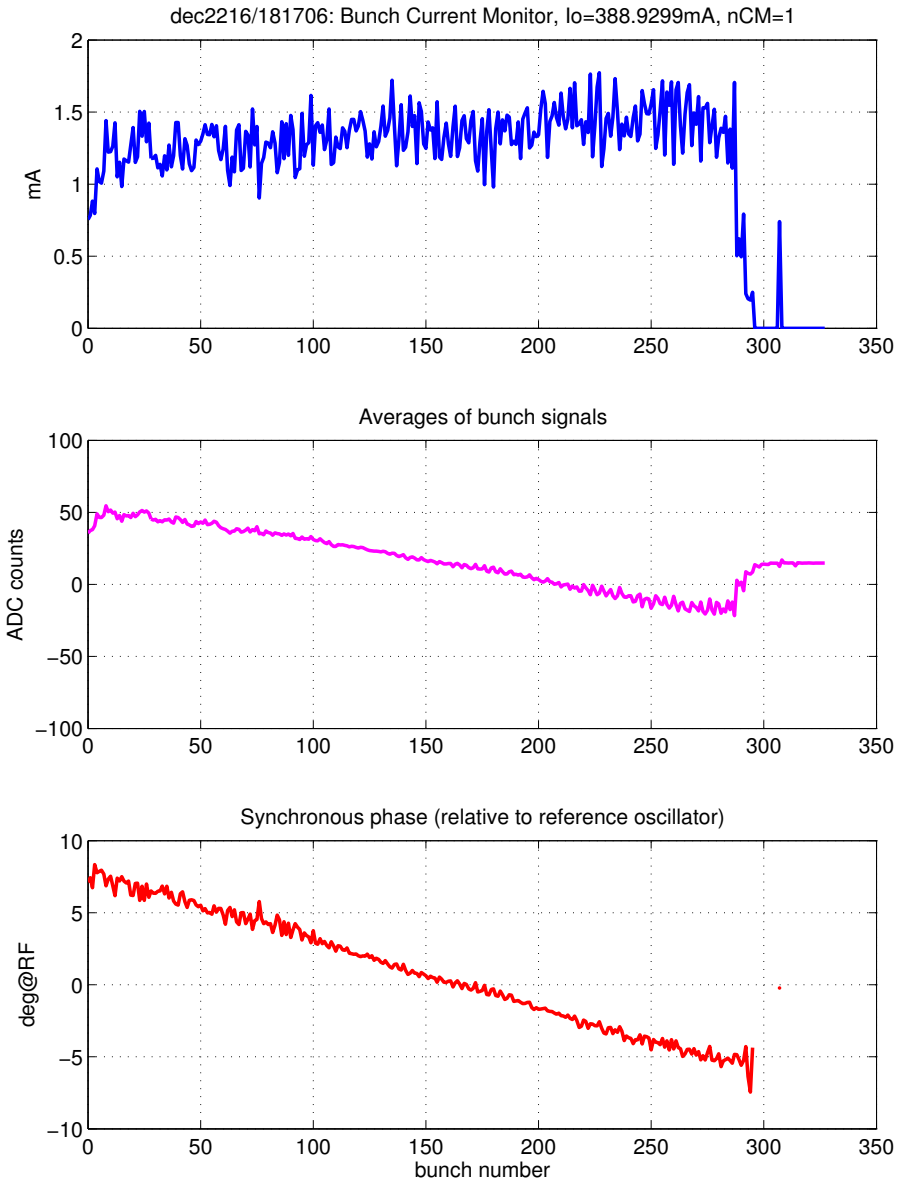

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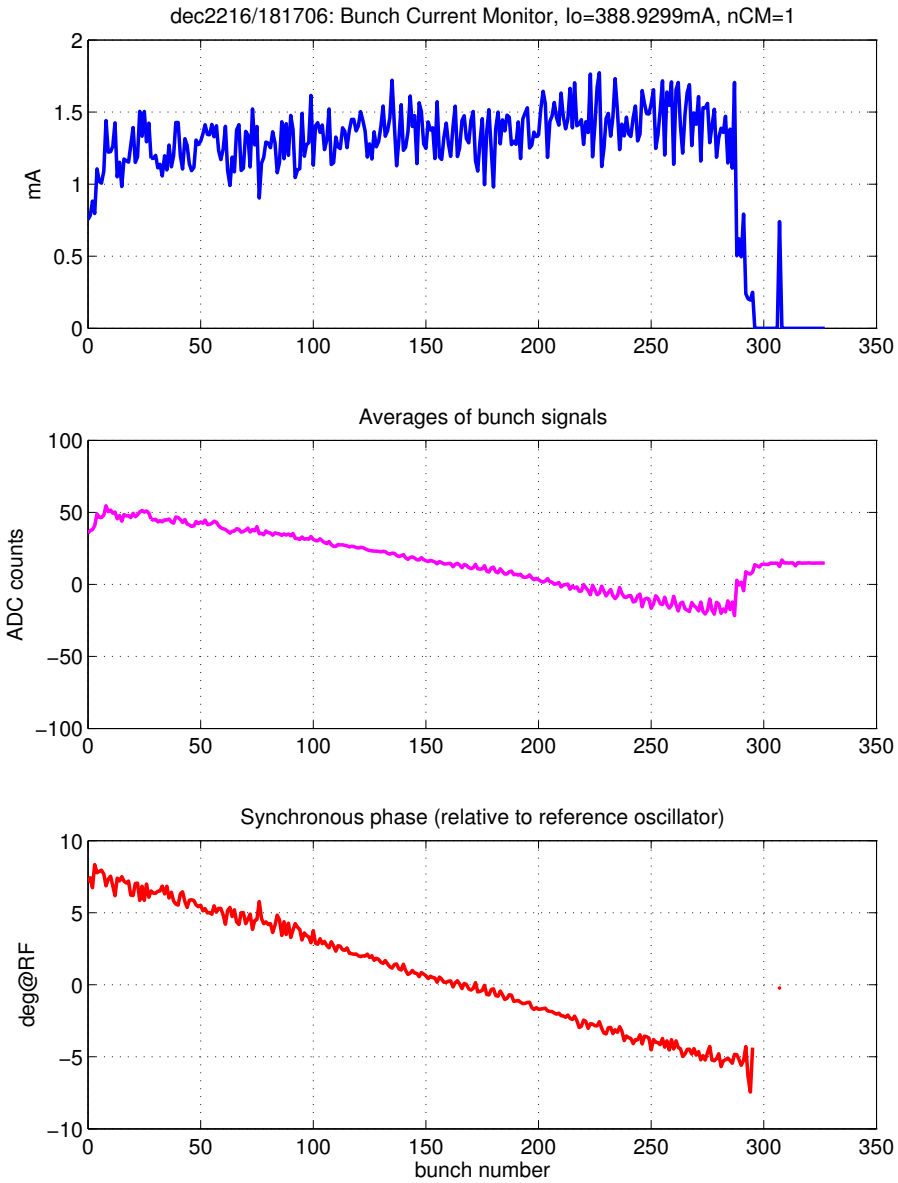

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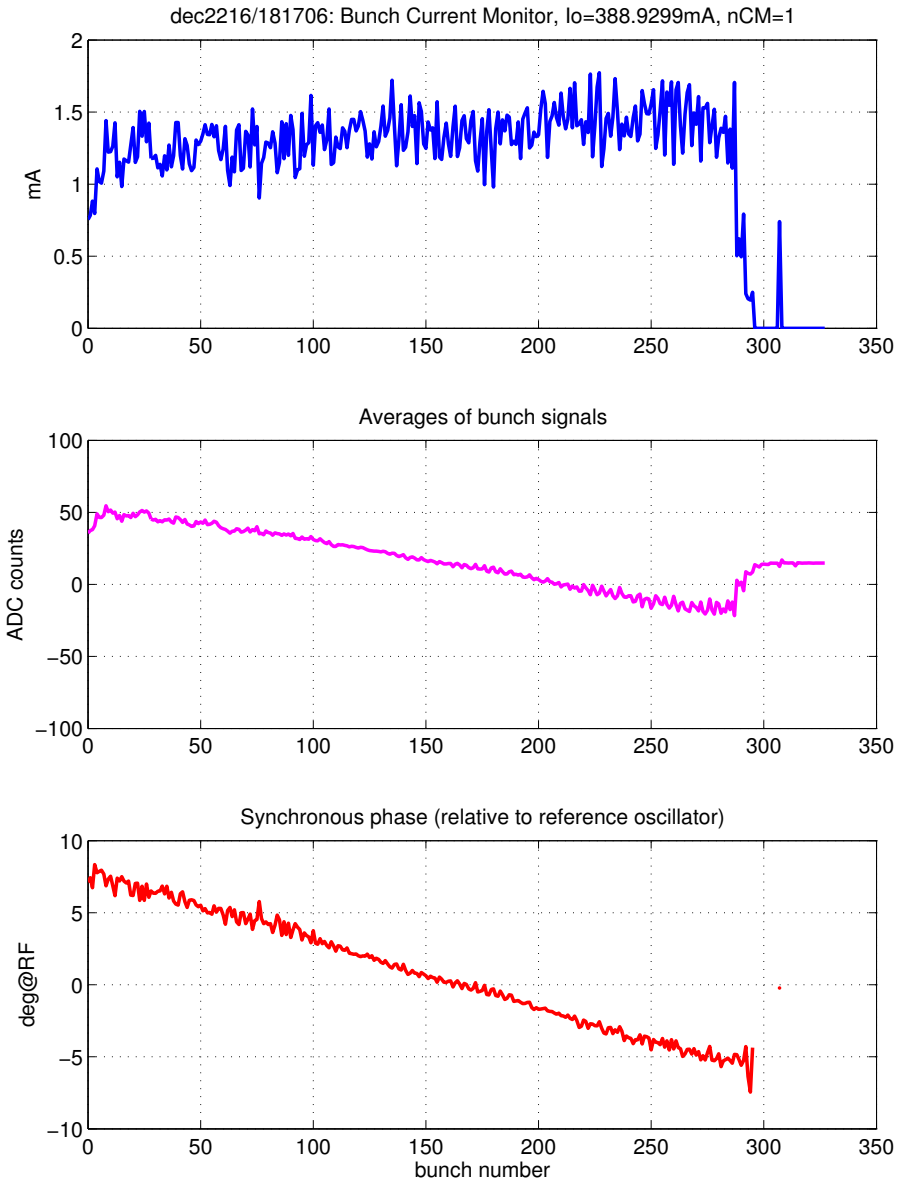

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Summary

- Measurements of RF system transfer functions suggest low direct loop gains and unexpected loaded Q;
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