Transient beam loading

FCC-ee (Z)

D. Teytelman

Dimtel, Inc., San Jose, CA, USA

FCC Week 2017

Outline

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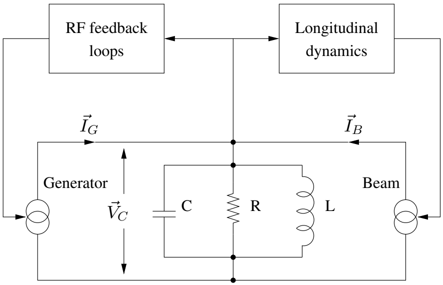
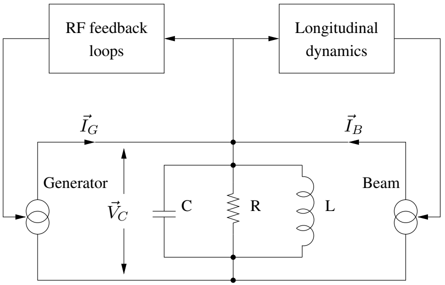
Beam/Cavity Interaction



- RLC model of the accelerating cavity with two input currents: generator and beam;
- Cavity voltage $\vec{V}_C$ is defined by the sum current;
- Low loading ($\vec{I}_B \ll \vec{I}_G$) — cavity voltage is mostly defined by the generator current;
- High loading — cavity voltage is strongly modulated by beam current;
- Like to think of the interaction as a "feedback loop" — beam current source is affected by cavity voltage, while cavity voltage depends on the beam current.

Beam/Cavity Interaction



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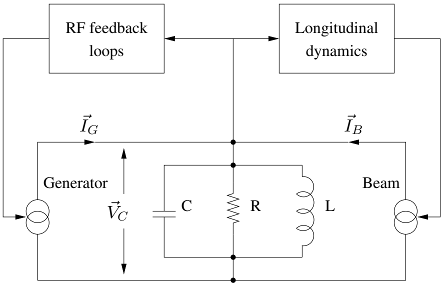

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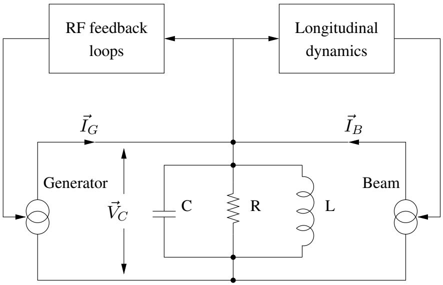

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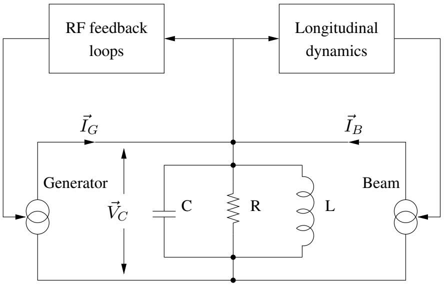

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Why Worry about Beam Loading

- Two main effects of heavy beam loading:
  - Synchronous phase transients;
  - Longitudinal coupled-bunch instabilities driven by the RF cavity fundamental impedance
- Transient effects depend on
  - Total beam loading;
  - Fill pattern.
- Fill patterns can be designed to mitigate transient effects;
- But longitudinal instabilities due to the fundamental impedance remain an issue even with completely uniform fills;
- Reducing beam loading in the RF system design helps both issues.

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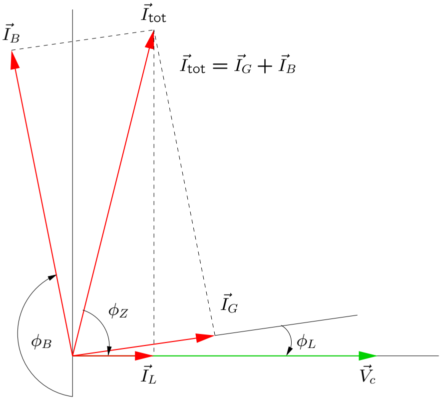
Phasor Diagram



- Phasors at RF frequency, cavity voltage on X axis;
- Synchronous phase ϕ_B is determined by RF voltage, energy loss per turn;
- For minimum generator power keep loading angle $\phi_L = 0$;
- Cavity is detuned to maintain proper phase angle ϕ_Z between the total current and the cavity voltage;
- PEP-II example: $I_B = 6$ A, $I_G = 1.7$ A;
- To compensate fill pattern modulation, when I_B goes to 0 in the gap, I_G would need to match I_T!

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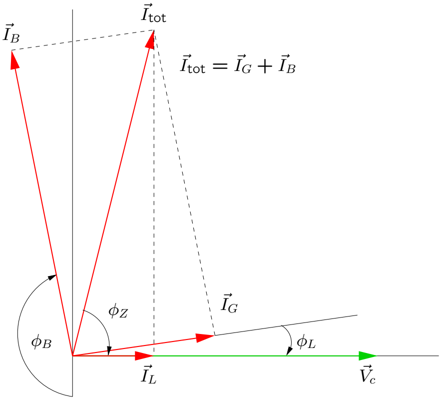

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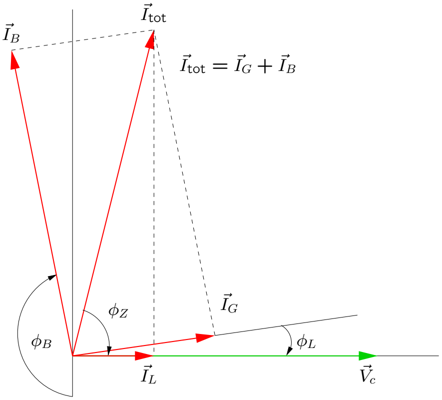

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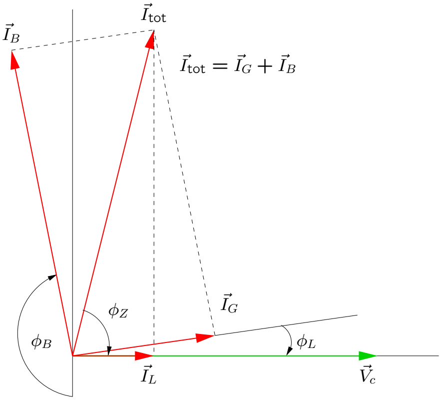

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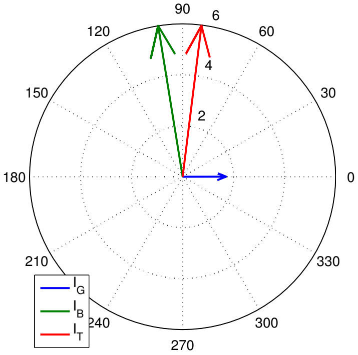
LER; 8/0 powered/parked cavities; V_{gap} = 4.5 MV; I_0 = 3 A; 1722by2 fill



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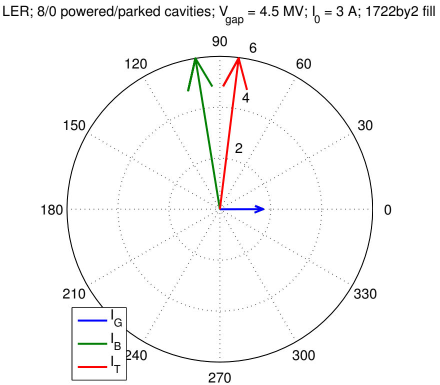

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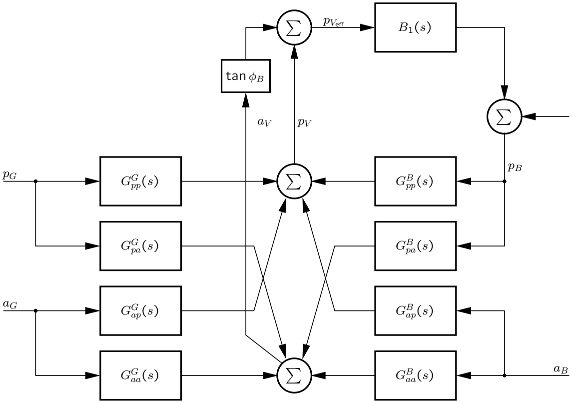
The Model



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- Model extended to include low-frequency coupled-bunch modes;
- Using reduced version that assumes no amplitude or phase modulation from the RF system.

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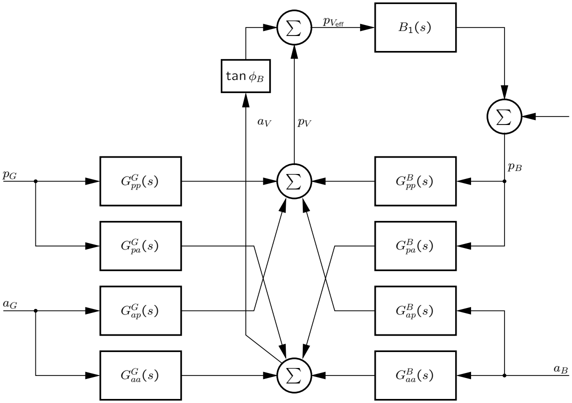

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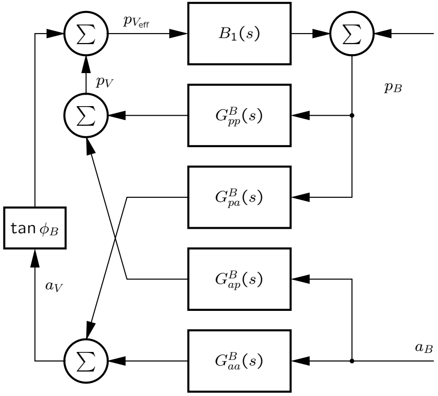

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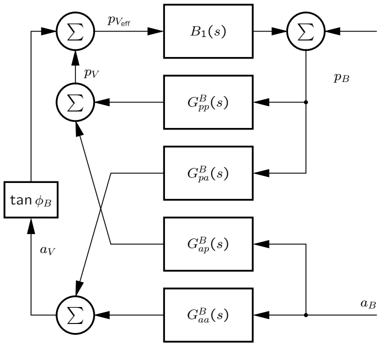
Synchrotron Frequency and Bunch Length



- Start from computing large-signal operating point (cavity detuning, RF power);
- At that operating point, set up the small-signal model;
- Compute a_V and p_V at 130680 points spaced by T_{RF};
- For each bunch calculate
  $\omega_s^k = \sqrt{-\frac{\alpha e \omega_{\text{RF}}}{E T_0} |V_k| \sin \phi_k}$
  $\sigma_z^k = \frac{\alpha_c}{\omega_s^k} \sigma_E$

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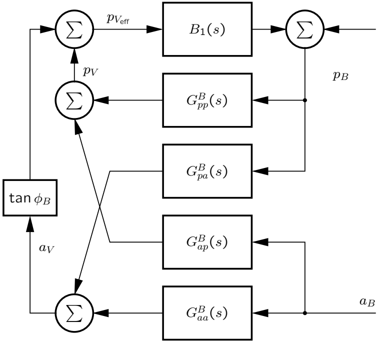

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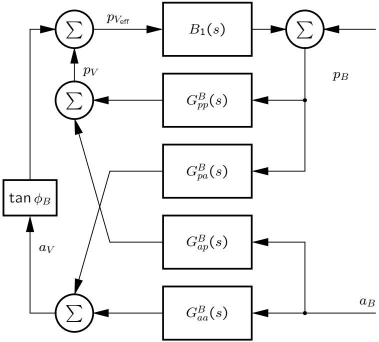

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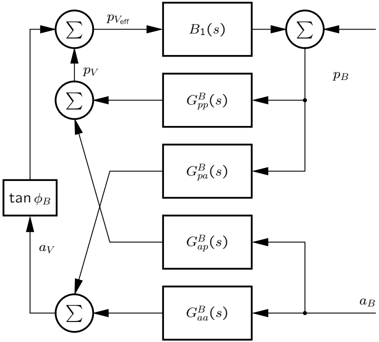

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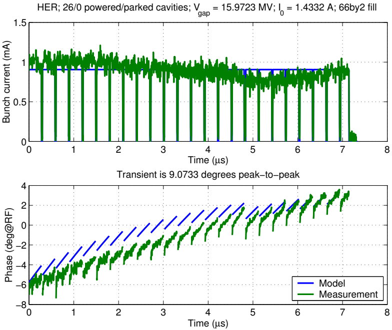
Model Verification



- The model has been developed for ALS and PEP-II;
- PEP-II HER measurement and model output;
- Reasonable overall agreement;
- In the recent history, the model has been used to simulate BEPC-II transient behavior, more on that later.

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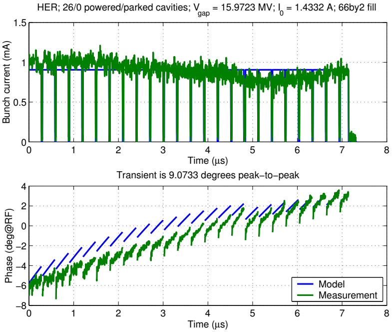

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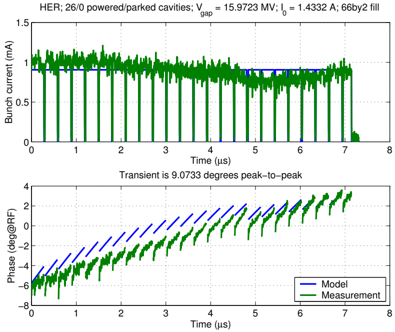

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Parameters

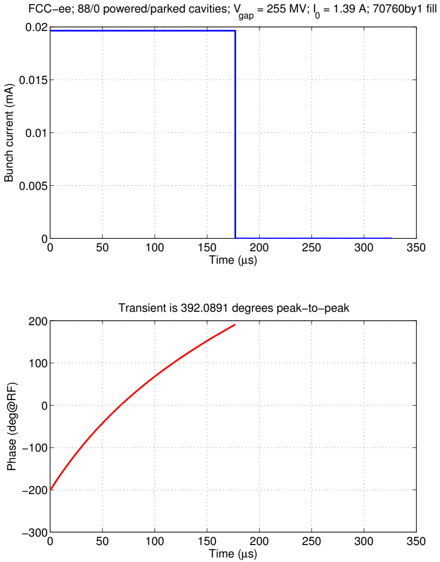
- K. Oide, “FCC-ee Conceptual Machine Design - CDR Plan and Status”,
- A. Butterworth, “Cavity design and beam-cavity interaction challenges”

Parameter	Value
Energy	45 GeV
Energy loss per turn	36 MeV
Momentum compaction	14.79×10^{-6}
Energy spread	3.8×10^{-4}
Radiation damping time	414 ms
Gap voltage	255 MV
Harmonic number	130680
Buckets filled	70760
R/Q	43.5 Ω
Q_0	2×10^9
Coupling factor[1]	11784

[1] Optimized for zero reflected power at 1390 mA

Outline

Single Train



- Single train is unphysical;
- At 300 mA it is slightly more realistic;
- Bunch length is all over the place;
- As is the synchrotron frequency.

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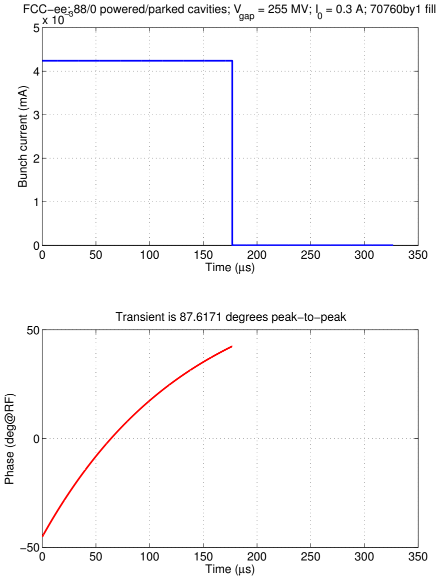

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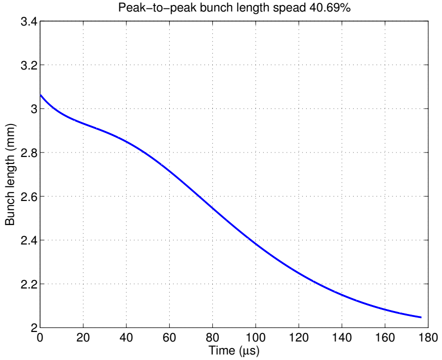

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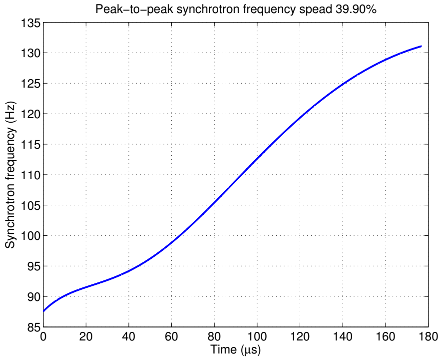

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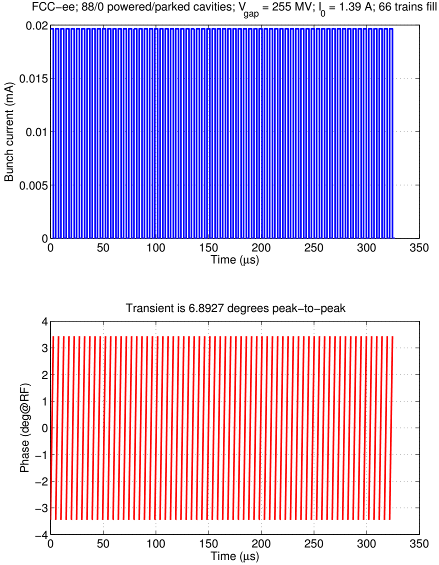
Uniform Trains: 2 μs Abort Gap



- 66 trains of 1072 filled and 908 empty buckets (2.7/2.3 μs);
- 70752 filled buckets;
- Smaller phase transient, within reason — 47.9 ps peak-to-peak;
- 0.2% bunch length variation (peak-to-peak);
- Same range of variation for synchrotron frequency.

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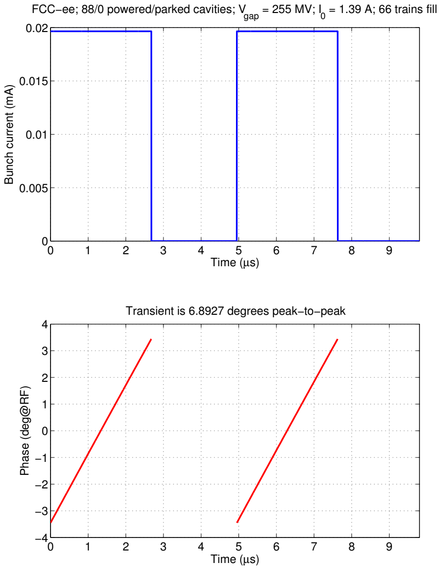

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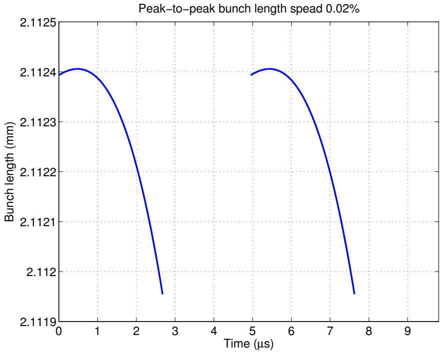

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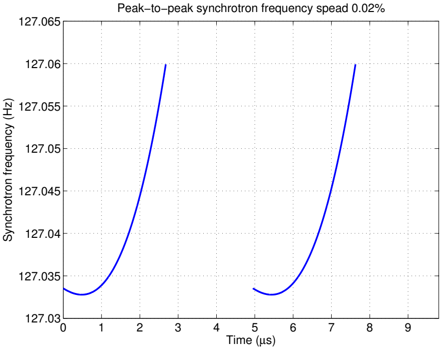

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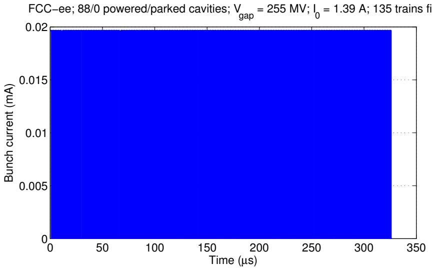

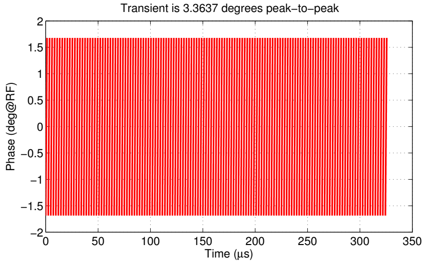

- 135 trains of 524 filled and 444 empty buckets (1.3/1.1 μs);
- 70740 filled buckets;
- If gap transients are matched (two rings with identical fill patterns, RF, total currents), collision point shift is eliminated;
- Such matching is difficult to maintain in practice;
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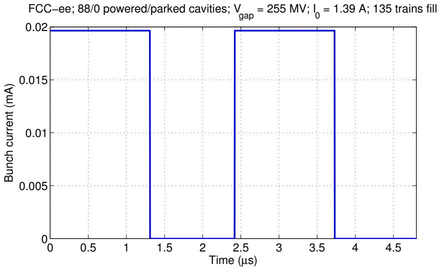

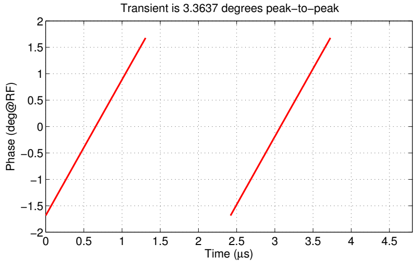

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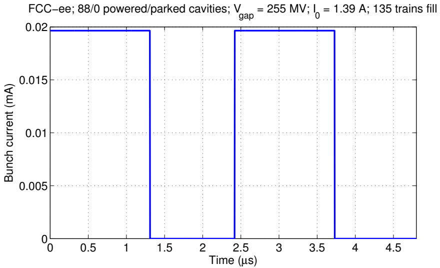

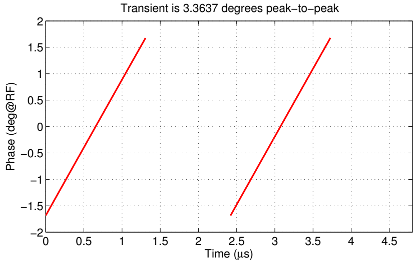

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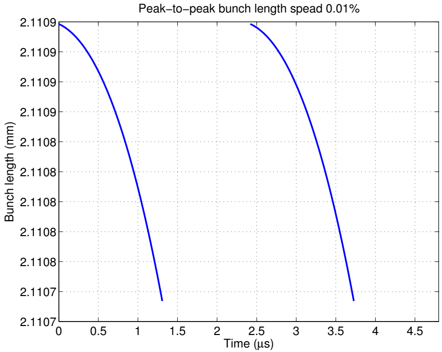

- 135 trains of 524 filled and 444 empty buckets (1.3/1.1 μs);
- 70740 filled buckets;
- If gap transients are matched (two rings with identical fill patterns, RF, total currents), collision point shift is eliminated;
- Such matching is difficult to maintain in practice;
- 0.1% bunch length variation (peak-to-peak);
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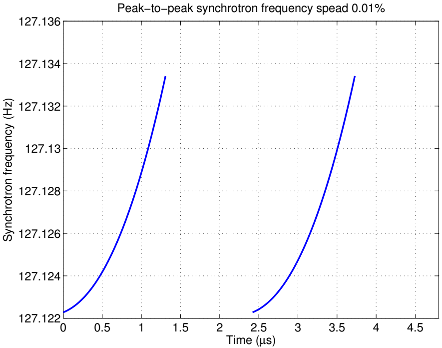

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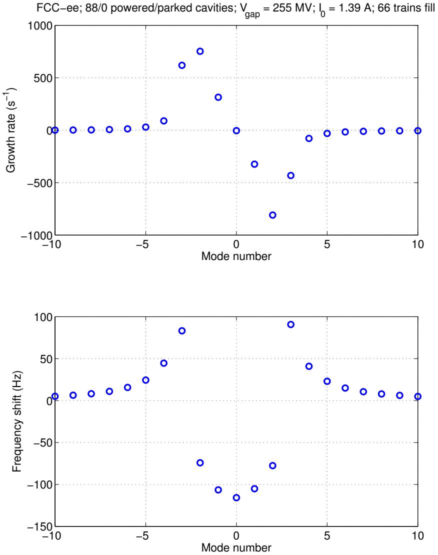
Outline

Introduction
- Beam Loading in Storage Rings
- Model Used

Beam Loading Simulations
- Gap Transients
- Detuning

Optimization
- Cavity Count
- Fill Pattern

Detuning



- At 1.39 A detuning is 8.3 kHz;
- That is 2.7 revolution harmonics;
- Full loaded shunt impedance crosses 2 upper synchrotron sidebands;
- Need aggressive RF feedback to manage longitudinal instabilities;
- Without RF feedback longitudinal growth time is 1.3 ms ($\approx 1/6$ of the synchrotron period);
- Modal tune shifts comparable to the synchrotron frequency.

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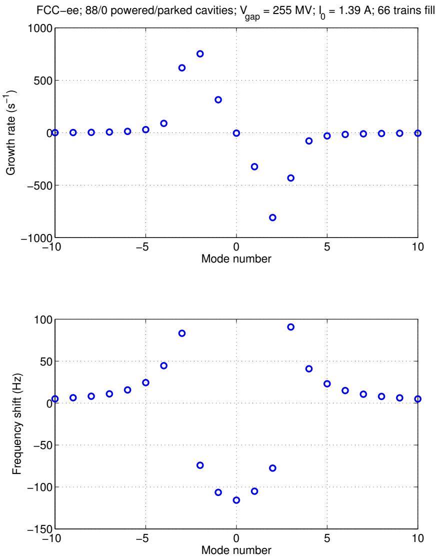

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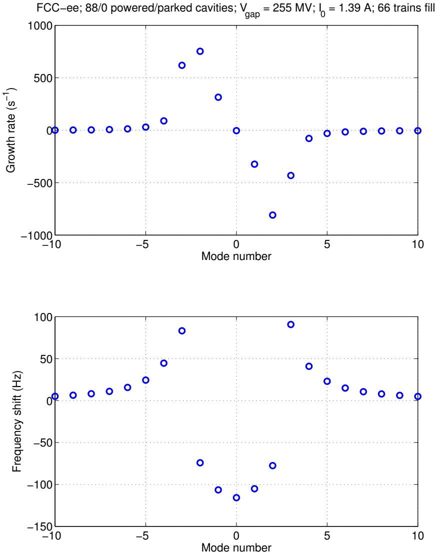

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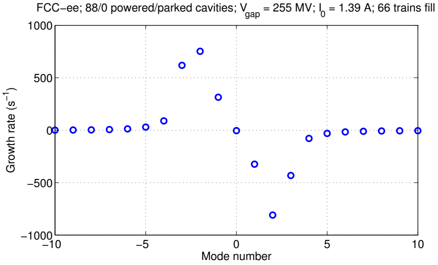

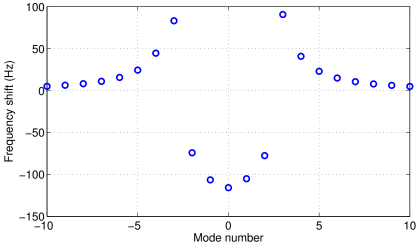

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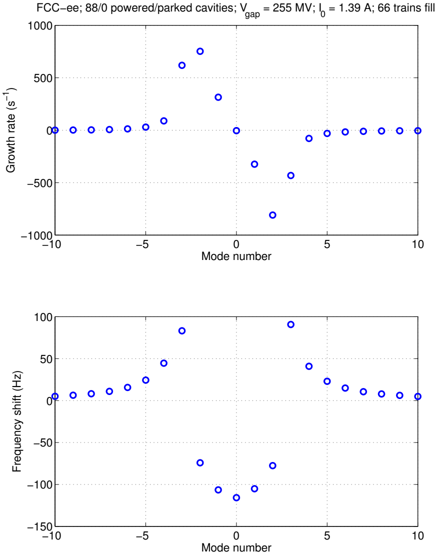

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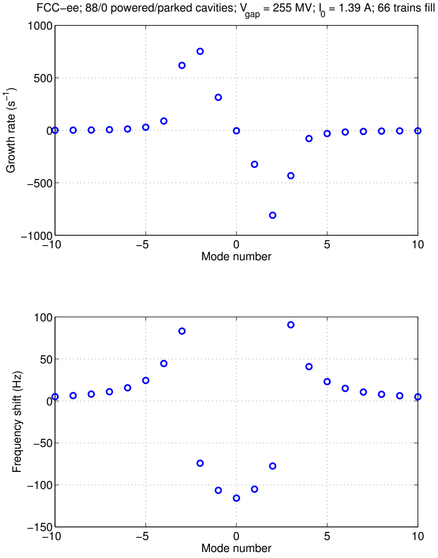

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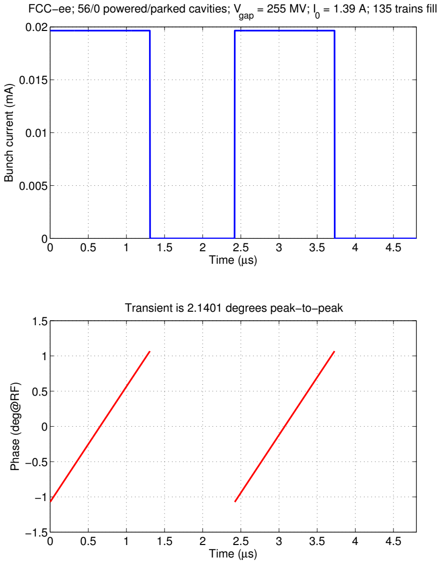
Outline

Optimizing Beam Loading, 400 MHz



- With 88 cavities run 570 kW and 2.9 MV forward power and gap voltage per cavity;
- Push to the limit: 56 cavities, 890 kW and 4.55 MV;
- Transient is reduced;
- Detuning is down to 1.7 revolution harmonics;
- Not a big improvement overall.

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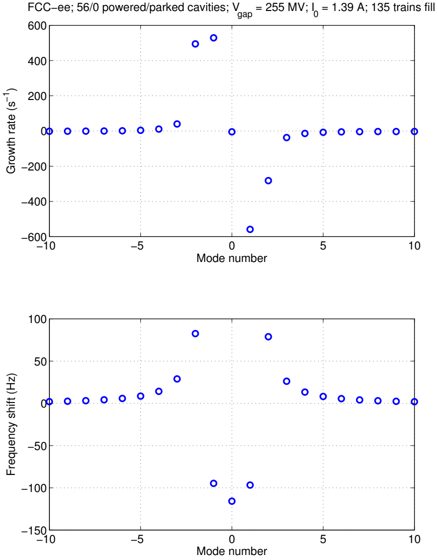

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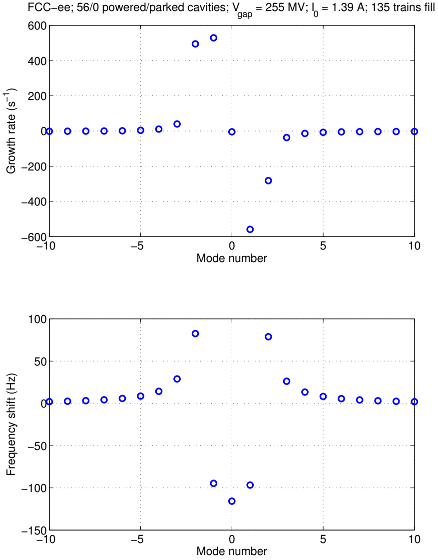

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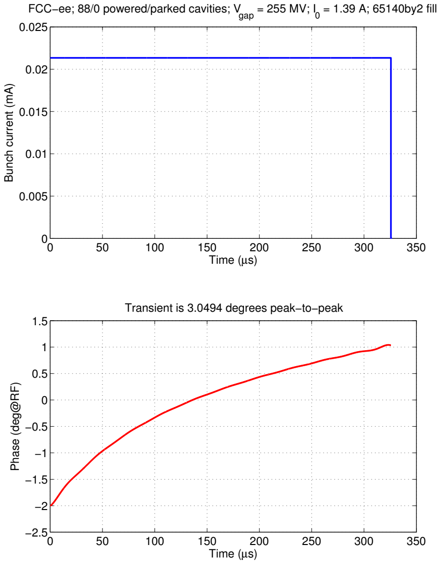
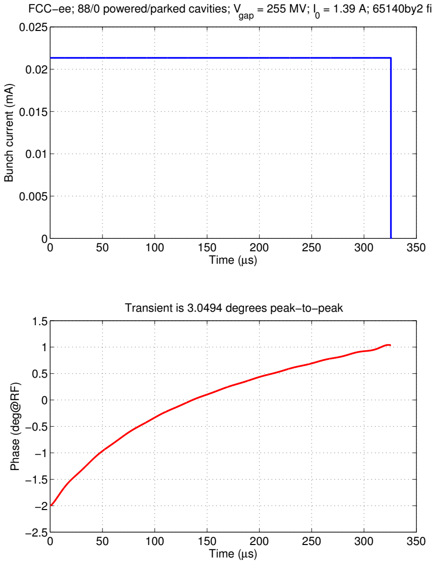
Outline

Single Bunch Train



- 0.3% gap (400 RF buckets, 1 µs);
- Uniform train of 65140 bunches with 5 ns spacing;
- Bunch length moves around by 3.4% (peak-to-peak).

Single Bunch Train



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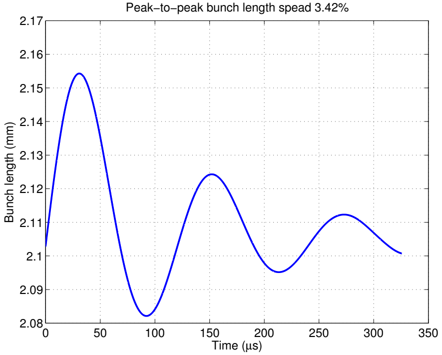

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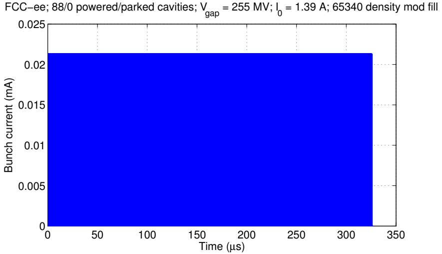
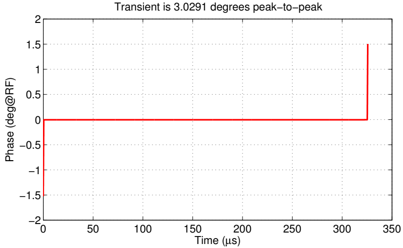
Fill Pattern Density Modulation





- Idea from J. Byrd et al., Phys. Rev. ST Accel. Beams 5, 092001 (2002):
  - Charge removed from the gap is added symmetrically to both ends of the train;
- 200 bunches removed from the gap;
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- Phase transient peak-to-peak amplitude is unchanged.

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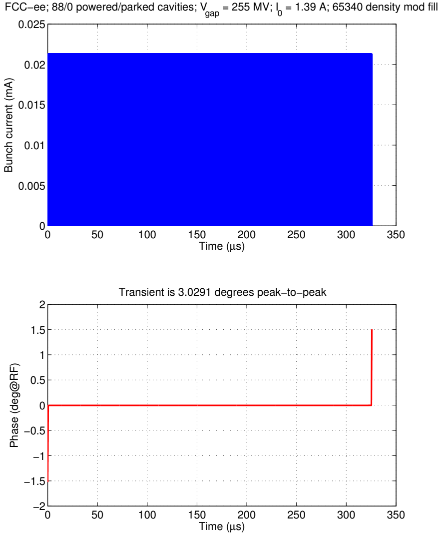

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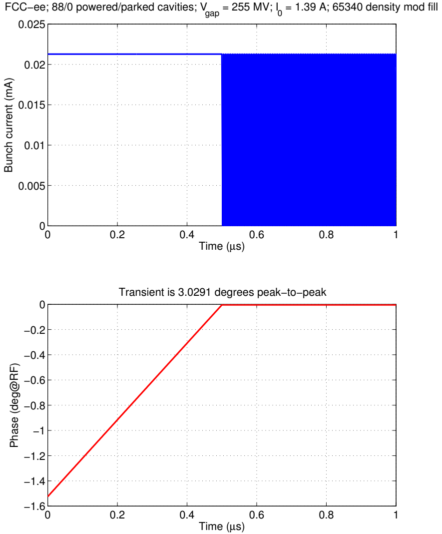

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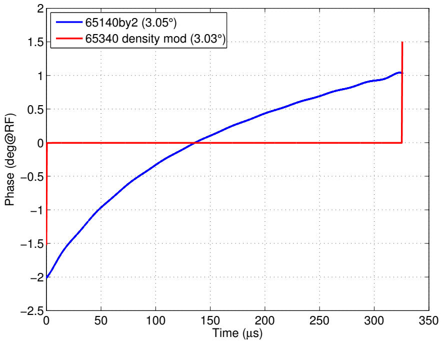

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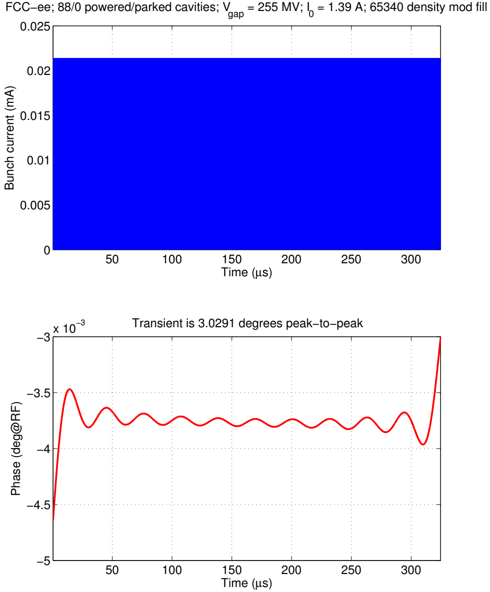

- All transients take place at the ends of the train;
- Mid-train there is very little synchronous phase variation;
- Bunch length varies by 0.01% peak to peak;
- Can uniformly spread additional bunches in the train to match the desired per bunch current (70758 bunch fill shown).

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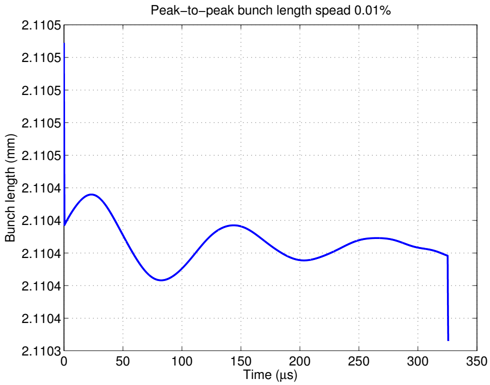

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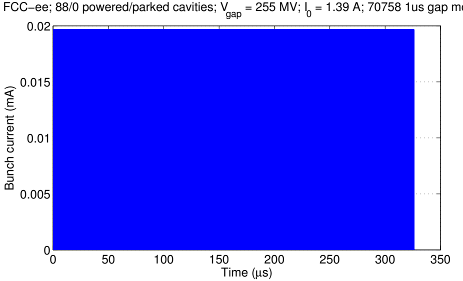

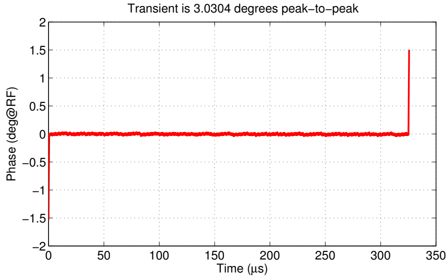

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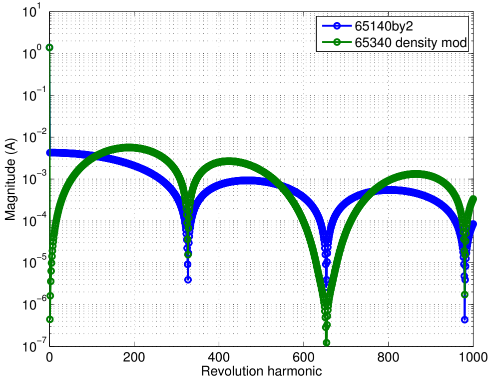

- Two fill patterns used earlier:
  - 65140by2: one long train of 65140 bunches every other RF bucket and 400 bucket gap;
  - 65340 density mod: long train with density modulation.
- Both fill pattern spectra show notches at multiples of $h/400 \approx 327$ revolution harmonics due to identical 400 bucket gaps;
- Density modulation suppresses low-frequency revolution harmonics where cavity impedance is large.

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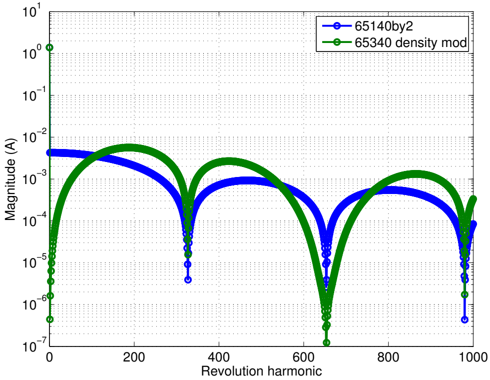

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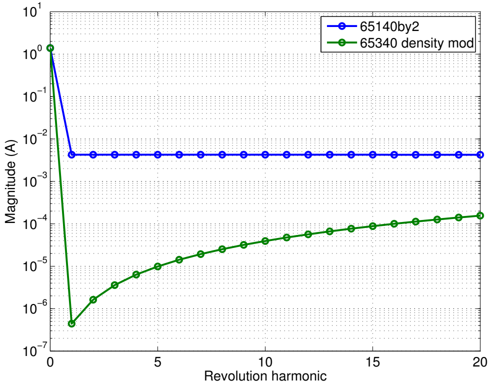

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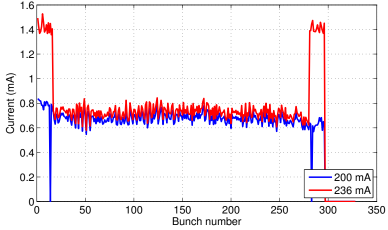

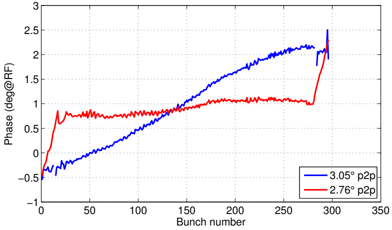

- Measurements from the Advanced Light Source in Berkeley:
  - A train of 296 buckets, 32 bucket gap;
  - Buckets 1–16 and 281–296 filled to twice the charge.
- A bit of first revolution harmonic due to the detuned harmonic cavities;
- Measurements from BEPC-II in Beijing:
  - Half the ring filled (99 bunches, 4 ns spacing);
  - Partial compensation — 22 bunches at the ends filled to twice the charge.

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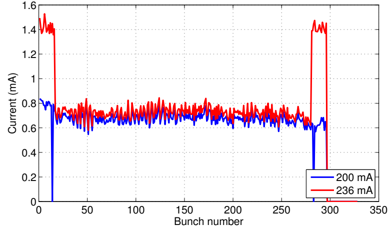

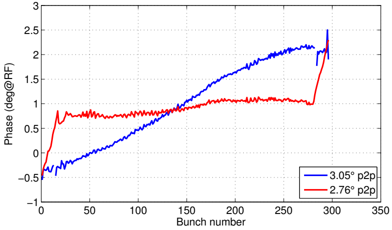

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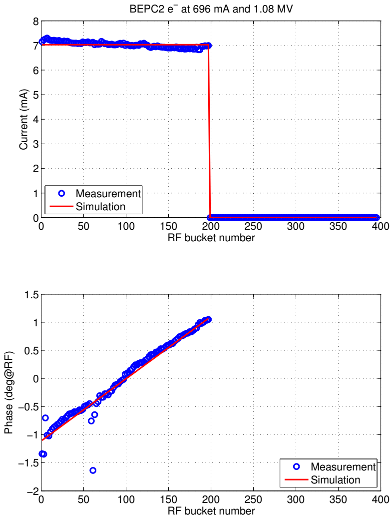

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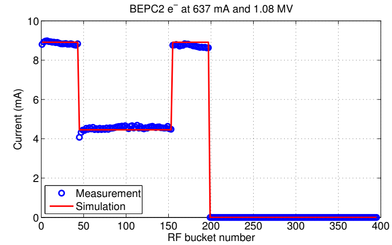

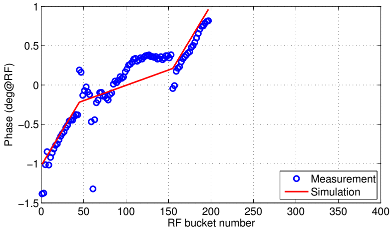

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Summary

- FCC-ee (Z) is heavily beam loaded;
- RF system design should be driven by the beam loading considerations;
- Aggressive RF feedback loops will be needed to bring the longitudinal growth rates within the reach of the bunch-by-bunch feedback systems;
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