Beam loading and coupled-bunch instabilities from a large ring perspective

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CEPC Workshop 2017

Outline

1. Introduction
   - The focus of this talk
2. Instabilities, Beam Loading, Feedback
   - Ring Circumference and Coupled-Bunch Instabilities
   - Beam Loading in Storage Rings
   - Bunch-by-bunch Feedback
3. Beam Loading in CEPC-Z
   - FCC-Z Nominal Parameters
   - Pushing FCC-Z Current

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Coupled-bunch Instabilities and Beam Loading

- This talk will focus on two important effects in storage rings:
  - Coupled-bunch instabilities in transverse and longitudinal planes;
  - Transient beam loading due to non-uniform fill patterns.
- Instabilities:
  - Beam interacts with impedances at betatron or synchrotron sidebands of revolution harmonics
  - Transverse: $M\omega_{\mathrm{RF}} \pm N\omega_{\mathrm{rev}} \pm \omega_{\beta}$
  - Longitudinal: $M\omega_{\mathrm{RF}} \pm N\omega_{\mathrm{rev}} \pm \omega_{s}$
- Transient beam loading:
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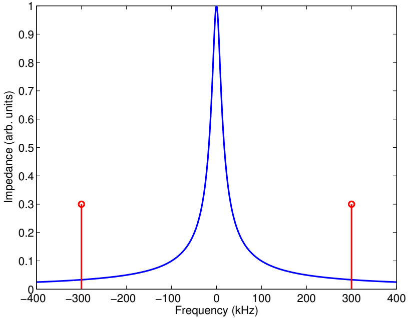
Resonant Modes and Revolution Harmonics



- A 20 kHz resonance ideally "hidden" between two revolution harmonics.
- 1 km ring;
- 1.5 km ring;
- 3 km ring;
- 10 km ring;
- 100 km ring;
- In large rings narrow resonances cannot be "hidden" from the beam.

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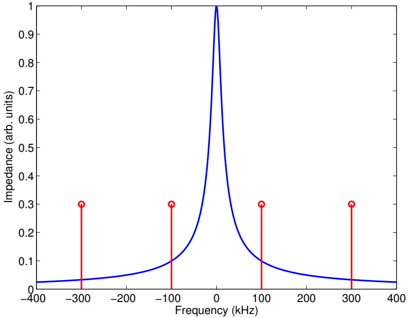

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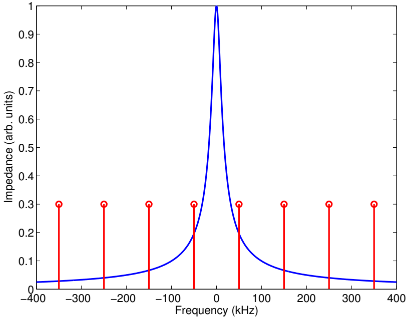

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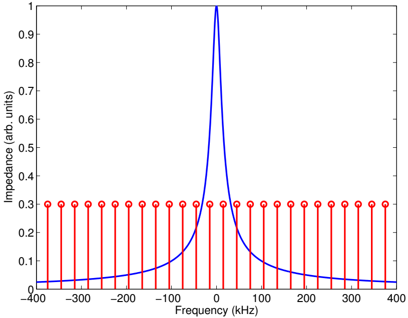

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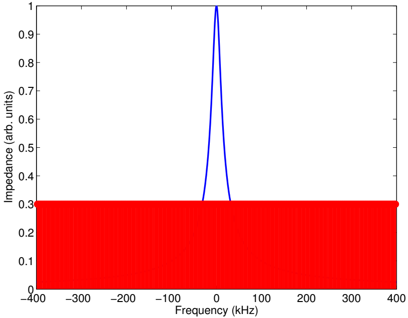

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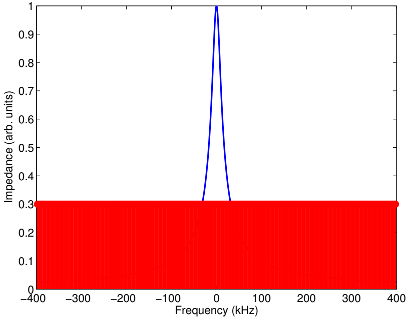

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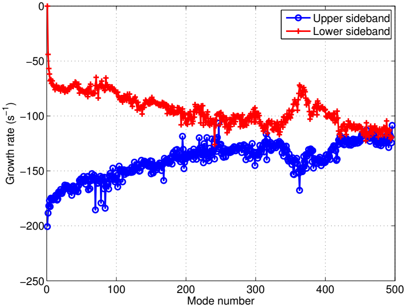
Transverse Planes: Resistive Wall



- Resistive wall impedance scales linearly with circumference;
- Impedance vs. frequency is $\propto 1/\sqrt{\omega}$;
- The most unstable line is the lower betatron sideband of the first revolution harmonic (mode -1);
- Overall impedance scaling $\frac{1}{\omega_{\mathrm{rev}}^{3/2}}$;
- RW growth time (in turns) scales as $\omega_{\mathrm{rev}}^{3/2}$.

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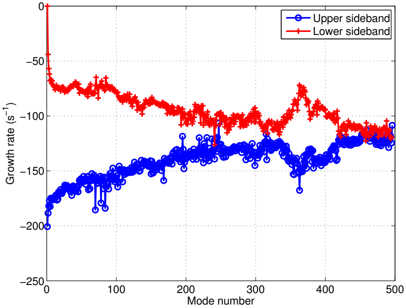

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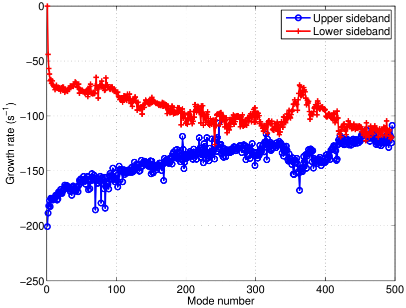

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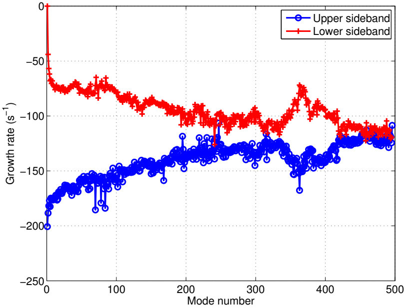

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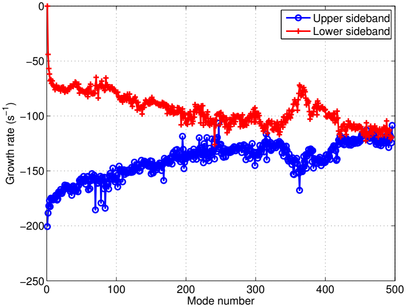

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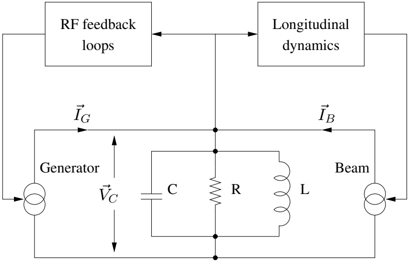
Beam/Cavity Interaction



- 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;
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- "Feedback loop" from cavity voltage to beam current and back to cavity voltage.

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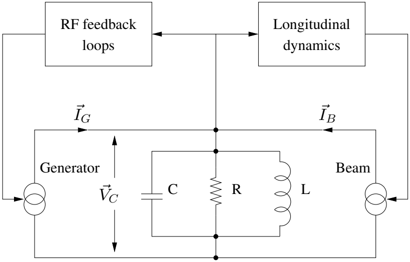

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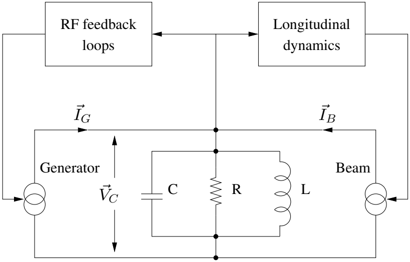

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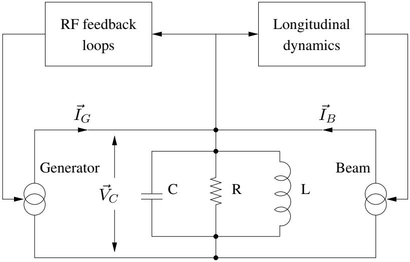

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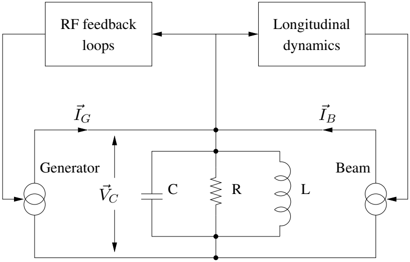

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Why Worry about Beam Loading

- Two main effects of heavy beam loading in large rings:
  - 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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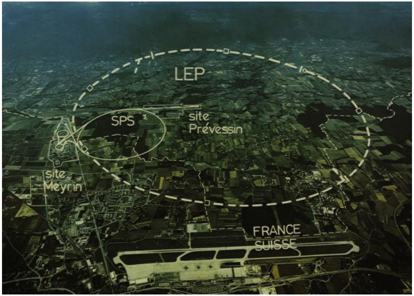
Ring Circumference and Beam Loading



- People don't build multi-kilometer rings just to spend money;
- Large circumference — very high energy;
- Or very high current;
- Or both.
- Large circumference means heavy beam loading of the RF system.

Photo/image credit: CERN, SLAC

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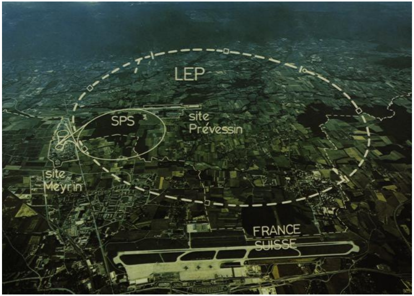

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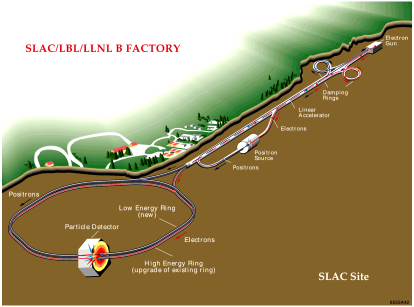

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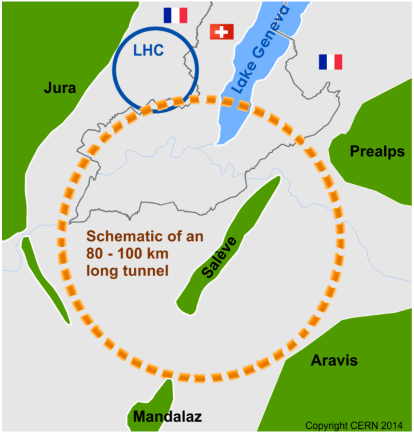

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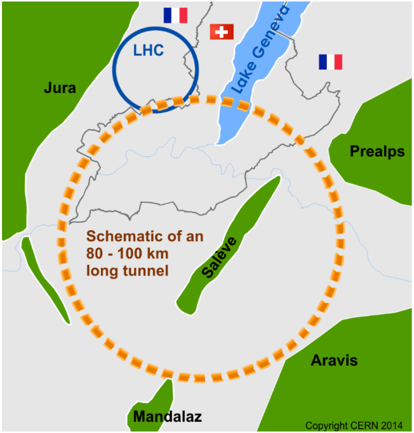

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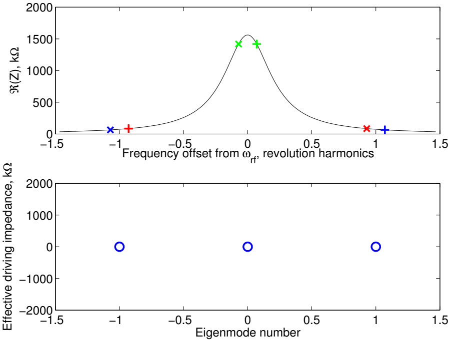
Cavity Detuning and Longitudinal Stability



- Growth rate for mode -1 is $\propto Z(\omega_{\mathrm{rf}} - \omega_{\mathrm{rev}} + \omega_s) - Z(\omega_{\mathrm{rf}} + \omega_{\mathrm{rev}} - \omega_s)$;
- Symmetric on resonance;
- Growth rates peak when fundamental crosses revolution harmonics;
- Need RF feedback to reduce the effective impedance.

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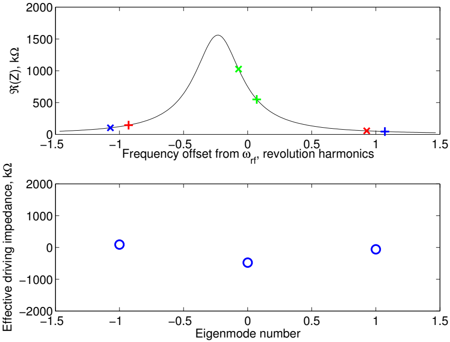

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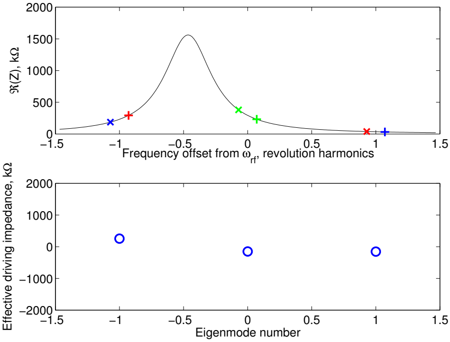

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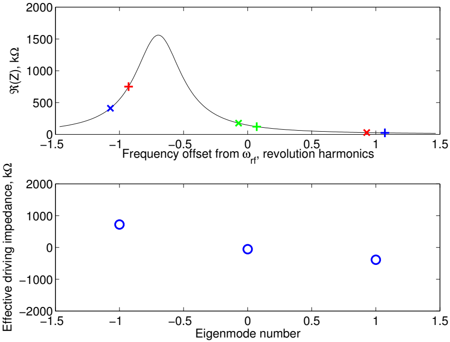

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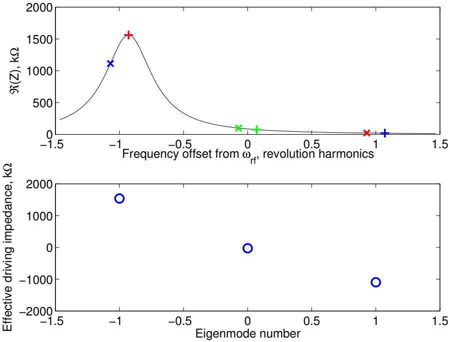

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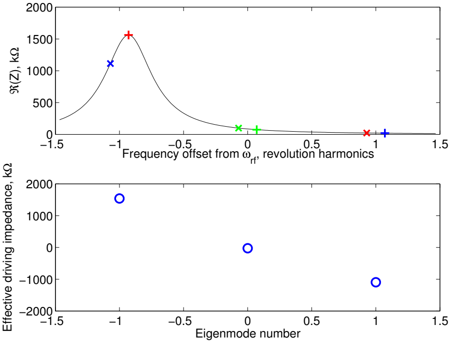

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Mitigating Beam Loading in Design

Cavity detuning

$$\omega_d = \left| \frac{\omega_{\mathrm{rf}} I_0}{V_c} \frac{R}{Q} \cos \phi_b \right|$$

- Minimize the number of cavities:
  - Reduces fundamental impedance interacting with the beam;
  - Limited by the maximum coupler power and/or the maximum cavity voltage.
- Minimize detuning:
  - Cavities with low R/Q;
  - Lower RF frequencies are preferable, especially when coupler limited.

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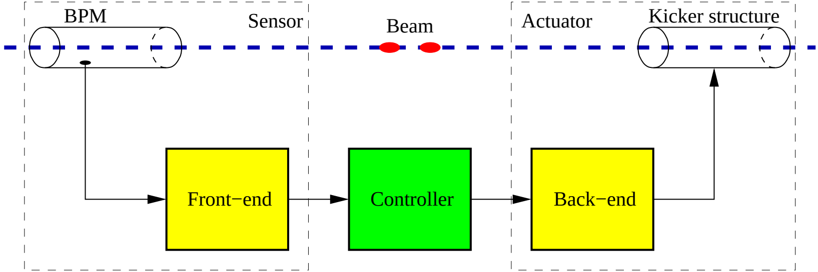
Bunch-by-bunch Feedback

Definition

In bunch-by-bunch feedback approach the actuator signal for a given bunch depends only on the past motion of that bunch.



- Bunches are processed sequentially.
- Correction kicks are applied one turn later.

Feedback Control Limits: Transverse

- For single pickup/single kicker topology the maximum growth rate that can be controlled is limited by the response delay (time from measuring bunch position error to correction kick acting on the same bunch on a later turn).
- Rule of thumb for robust operation: $\lambda_{\mathrm{cl}} \geq -\lambda_{\mathrm{ol}}$.
- Fast damping in time domain corresponds to wide bandwidth in the frequency domain $\rightarrow$ feedback induced noise can be an issue in the vertical plane.
- For fractional tunes in 0.2–0.4 range the limit is around 10 turns growth time (with 10 turns closed-loop damping time);
- Tunes close to integer or half-integer require the feedback with signals from many past turns, slower damping.

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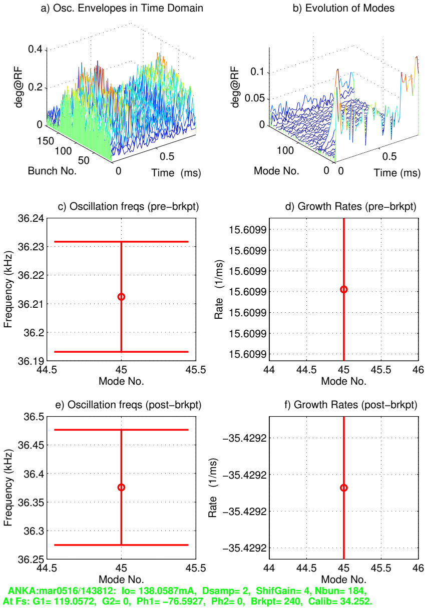

- Measured while cavity tuning walks an HOM onto a synchrotron sideband;
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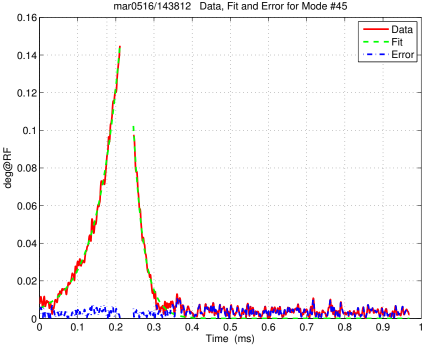

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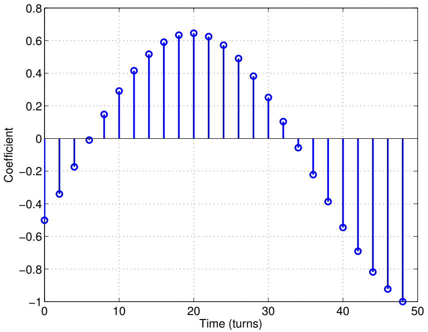

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Parameters

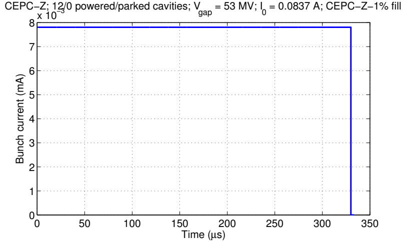
- J. Gao, "CEPC accelerator CDR - status",
- J. Zhai, "CEPC SRF system study"

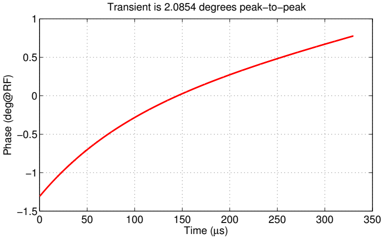
Parameter	Value
Energy	45.5 GeV
Energy loss per turn	35 MeV
Momentum compaction	1.14×10^{-5}
Energy spread	3.7×10^{-4}
Radiation damping time	433 ms
Gap voltage	53 MV
Harmonic number	216664
Buckets filled	10725
R/Q	106.5 Ω
Q_0	10^{10}
Coupling factor[1]	26657

[1] Optimized for zero reflected power at 83.7 mA

Outline

Beam Loading Effects





- Nominal CEPC-Z, no parked cavities, 1 kHz detuning;
- Small gap transient;
- Bunch length modulation is also small;
- Growth rates are moderate (mode -1 at $\approx 3T_s$), but mode 0 is tune shifted nearly to DC, on the verge of high-current Robinson instability;
- With moderate direct loop gain of 10, all modes are stabilized.

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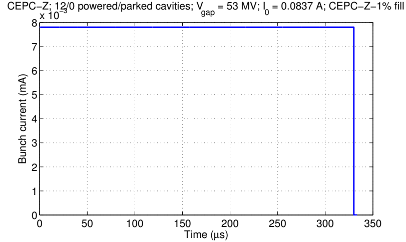

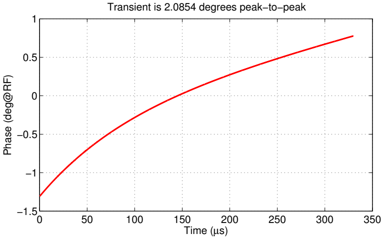

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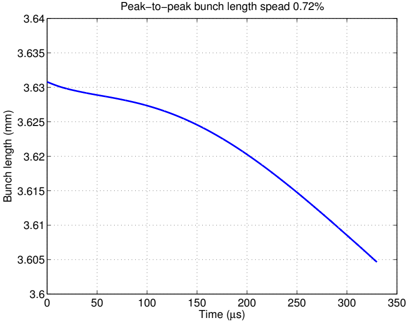

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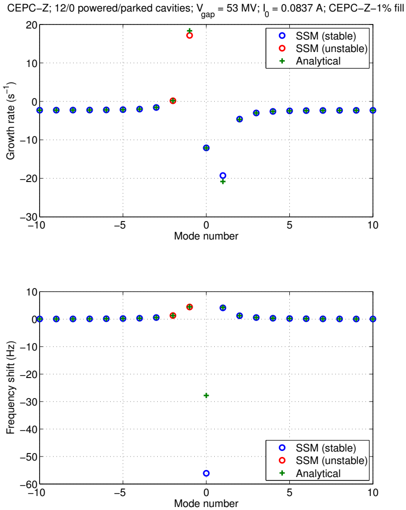

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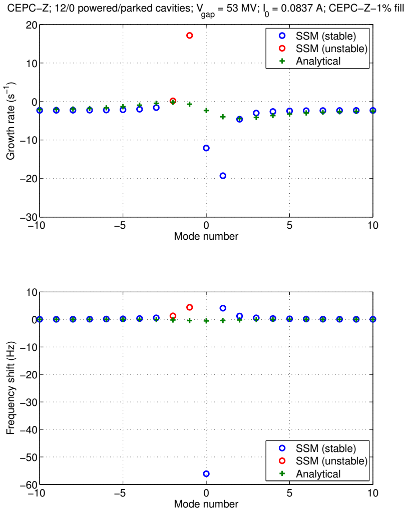

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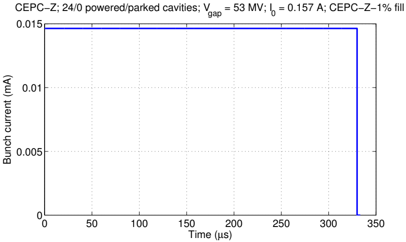
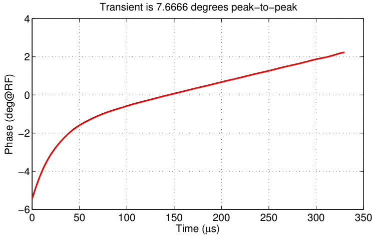
Outline

From 12 to 24 Cavities





- 157 mA, 3.7 kHz detuning;
- Gap transient still acceptable;
- Fastest growth time is 6 ms, a third of synchrotron period;
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- Zoom in to see all modes at radiation damping;
- 6.5 kHz open-loop;
- 446 kHz closed-loop;
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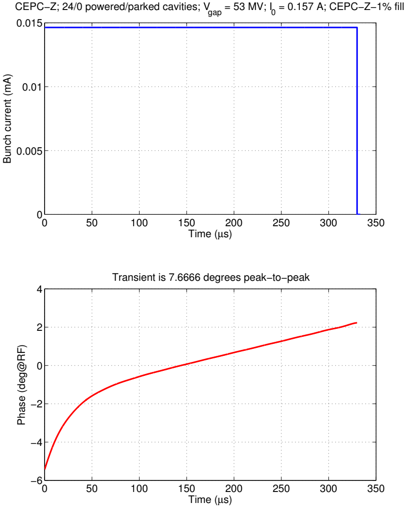

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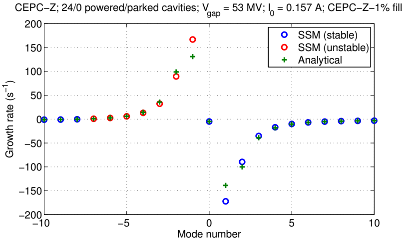

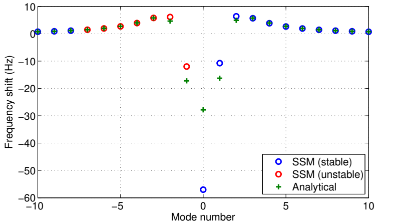

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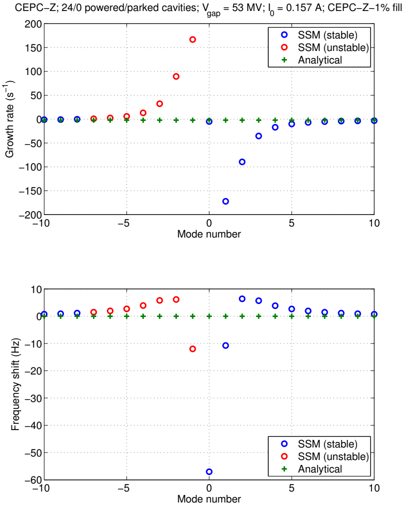

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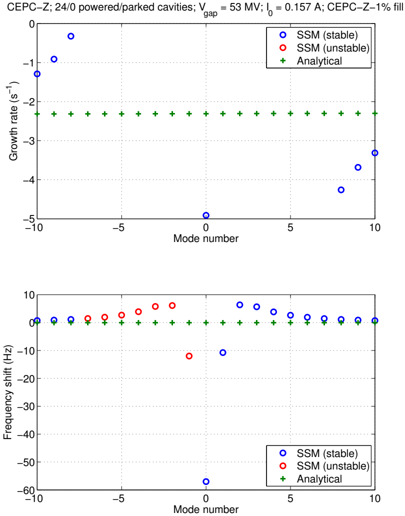

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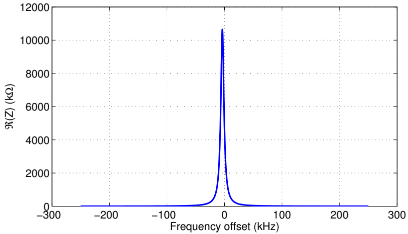

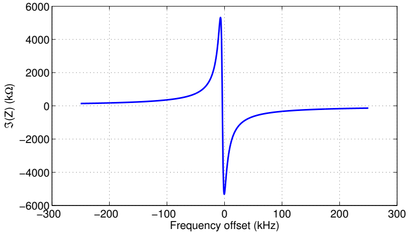

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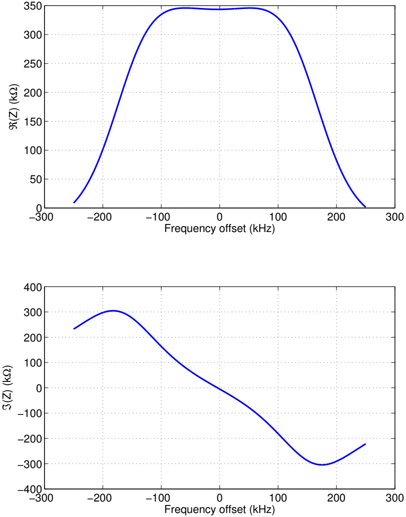

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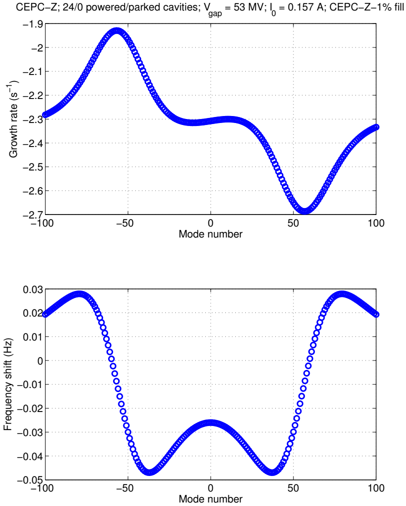

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- Fundamental impedance is large, but very tightly controlled, CBI driving impedance reduction is straightforward;
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