Heavy Beam Loading and Collective Effects

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LLRF Workshop 2019

Outline

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Coupled-bunch Instabilities and Beam Loading

- Looking at heavy beam loading in electron/positron storage rings;
- Two important effects in storage rings:
  - Coupled-bunch instabilities in the longitudinal plane;
  - Transient beam loading due to non-uniform fill patterns.
- In heavily loaded rings both of these will be driven by the fundamental impedance of the RF cavities:
  - Instabilities: beam interacts with the impedances at synchrotron sidebands of revolution harmonics;
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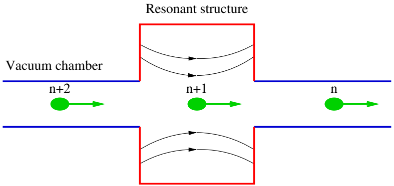
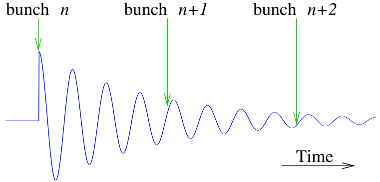
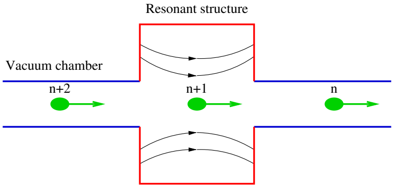
Coupled-bunch Instabilities

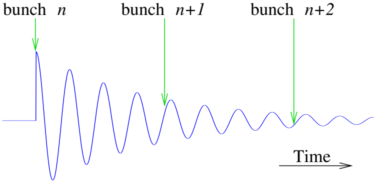




- Bunch passing through a resonant structure excites a wakefield which is sampled by the following bunches — a coupling mechanism;
- In practice the wakefields have much longer damping times than illustrated here;
- Longitudinal bunch oscillation $\rightarrow$ phase modulation of the wakefield $\rightarrow$ slope of the wake voltage sampled by the following bunches determines the coupling.
- For certain combinations of wakefield amplitudes and frequencies the overall system becomes unstable.

Coupled-bunch Instabilities





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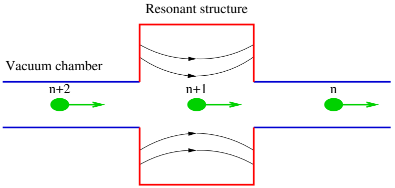

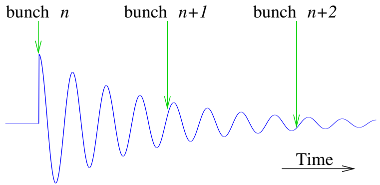

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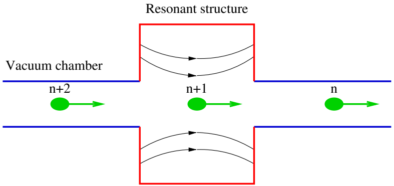

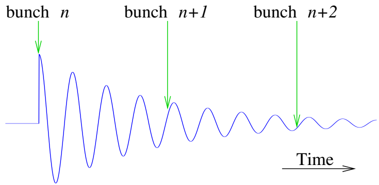

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Coupled-bunch Instabilities: Eigenmodes and Eigenvalues

- A system of N bunches (coupled harmonic oscillators) has N eigenmodes;
- From symmetry considerations we find that the eigenmodes correspond to Fourier vectors;
- Mode number m describes the number of oscillation periods over one turn;
- Motion of bunch k oscillating in mode m is given by: $A_m e^{2\pi km/N} e^{\Lambda_m t}$
  - A_m — modal amplitude;
  - Λ_m — complex modal eigenvalue.
- Wakefields affect the modal eigenvalues in both real (growth rate) and imaginary (oscillation frequency) parts;

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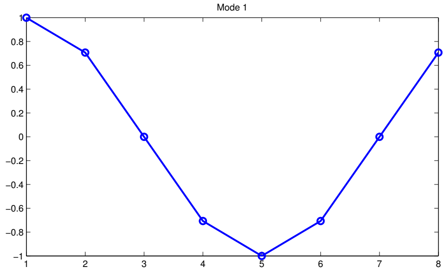
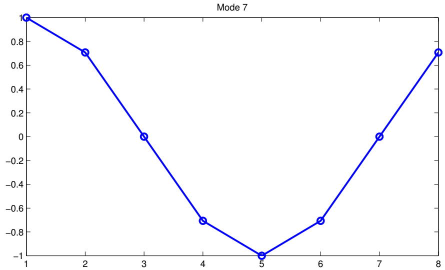
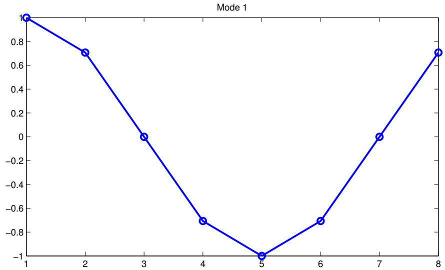
Modal Oscillation Example

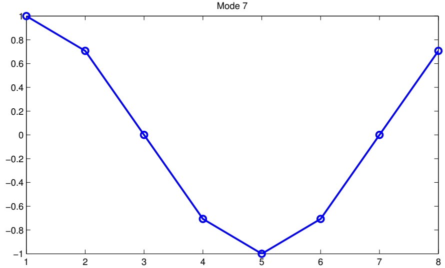




- Harmonic number of 8;
- Top plot — mode 1;
- Bottom — mode 7;
- All bunches oscillate at the same amplitude and frequency, but different phases;
- Cannot distinguish modes m and $N - m$ (or $-m$) from a single turn snapshot.

Modal Oscillation With Damping





- Same modes with damping.

Coupled-bunch Instabilities: Eigenvalues and Impedances

- Beam interacts with wakefields (impedances in frequency domain) at synchrotron sidebands of revolution harmonics;
- Impedance functions are aliased, since they are sampled by the beam;
- $\Lambda_m = (-\lambda^{\|}_{\text{rad}} + i\omega_s) + \frac{\pi\alpha e f_{\text{rf}}^2 I_0}{E_0 h \omega_s} Z^{\|\text{eff}}(m\omega_0 + \omega_s)$;
- Effective impedance: $Z^{\|\text{eff}}(\omega) = \sum_{p=-\infty}^{\infty} \frac{p\omega_{\text{rf}}+\omega}{\omega_{\text{rf}}} Z^{\|}(p\omega_{\text{rf}} + \omega)$
- Normally, instabilities in the longitudinal plane are driven by higher order modes in RF cavities and other resonances;
- In case of heavy beam loading in machines with large circumference, situation is anything, but normal.

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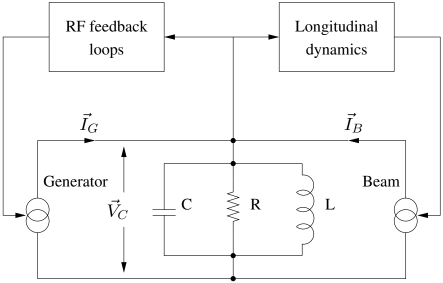
Beam/Cavity Interaction



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

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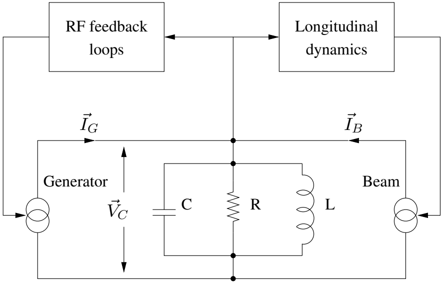

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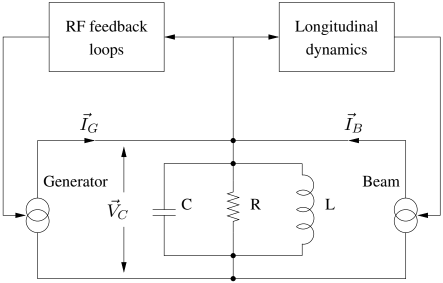

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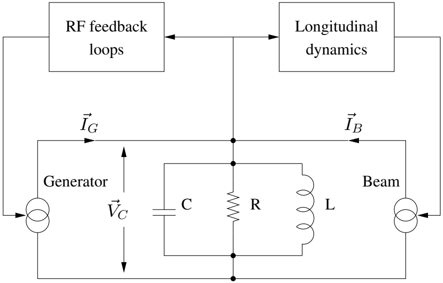

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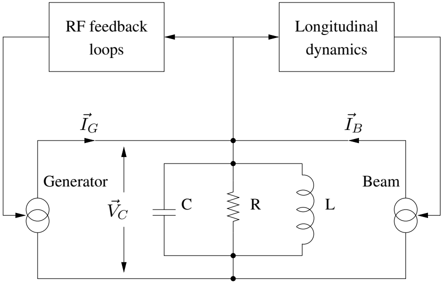

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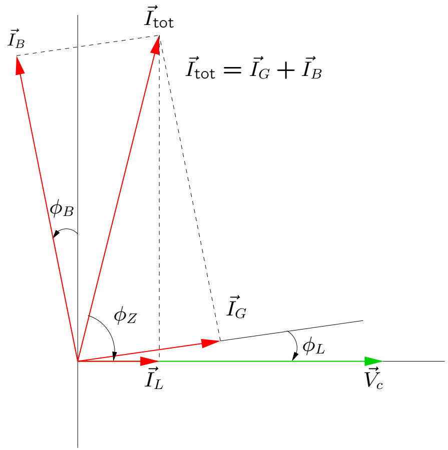
Phasor Diagram



- 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;
- The larger is $\vec{I}_B$, the higher is the detuning.

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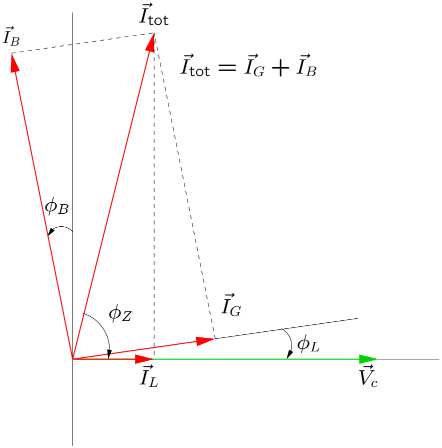

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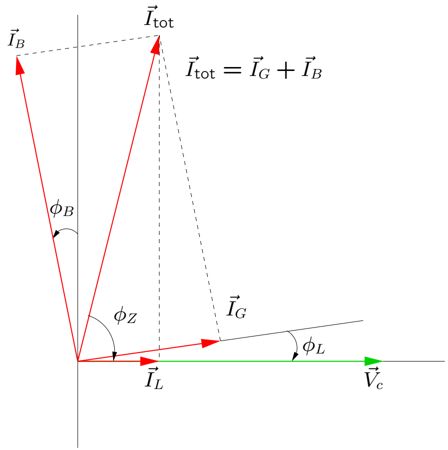

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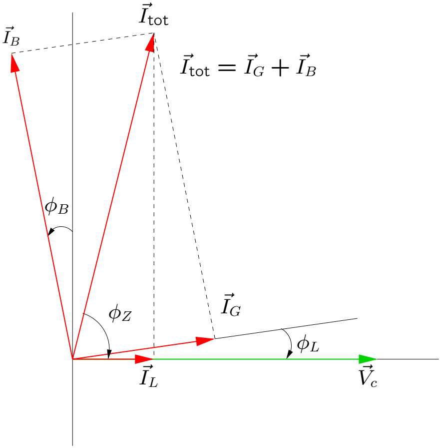

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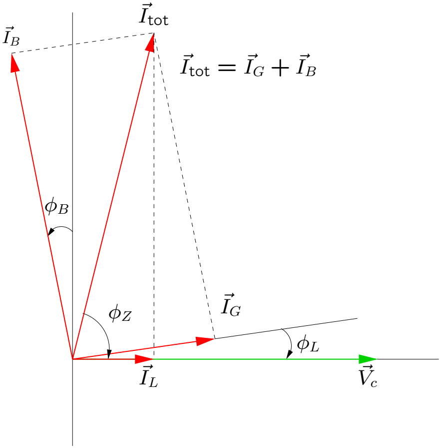

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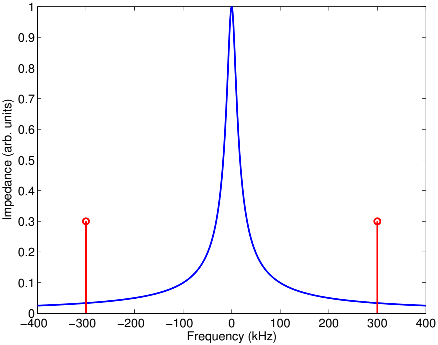
Resonant Modes and Revolution Harmonics



- A 20 kHz resonance ideally "hidden" between two revolution harmonics.
- 500 m ring;
- 1.5 km ring;
- 3 km ring;
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- 100 km ring;
- Narrow resonances cannot be "hidden" from the beam in large rings.

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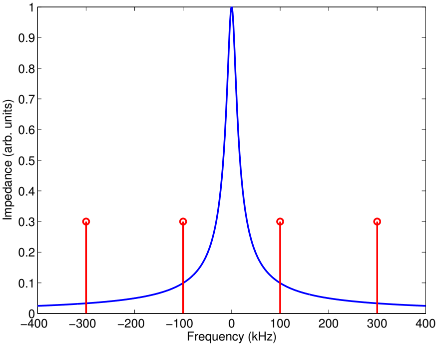

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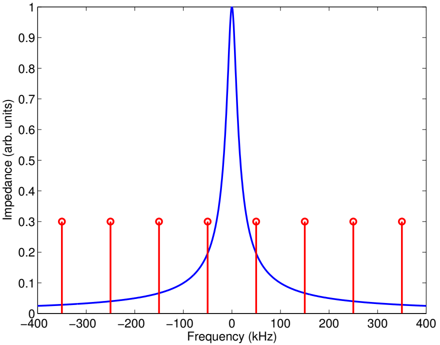

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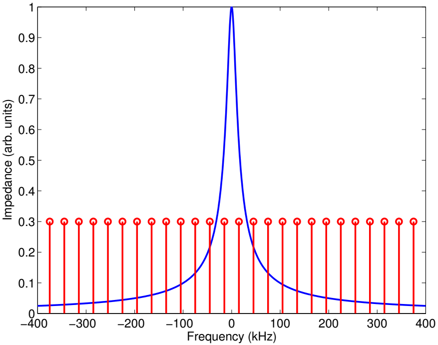

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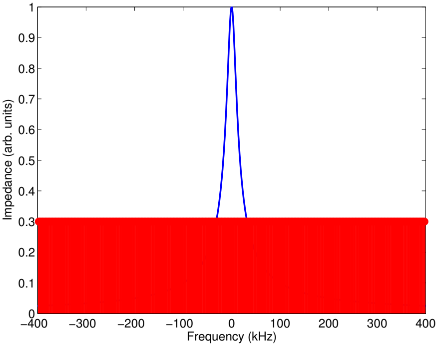

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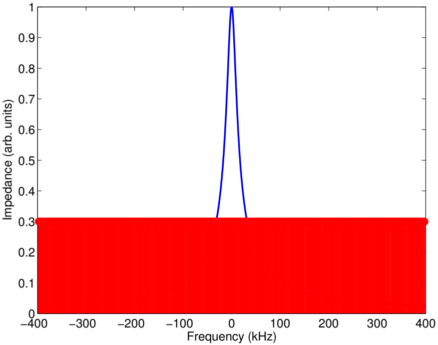

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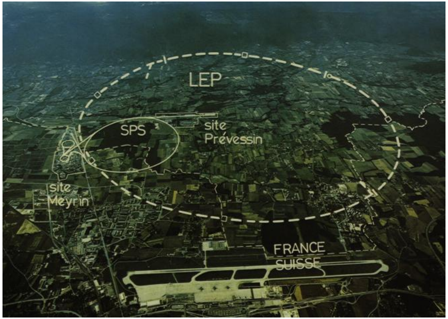
Ring Circumference and Beam Loading



Photo/image credit: CERN, SLAC

- 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.

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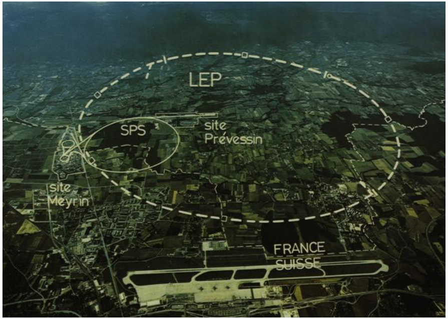

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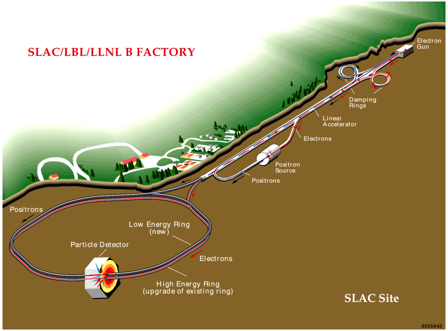

Photo/image credit: CERN, SLAC

- People don't build multi-kilometer rings just to spend money;
- Large circumference — very high energy;
- Or very high current;
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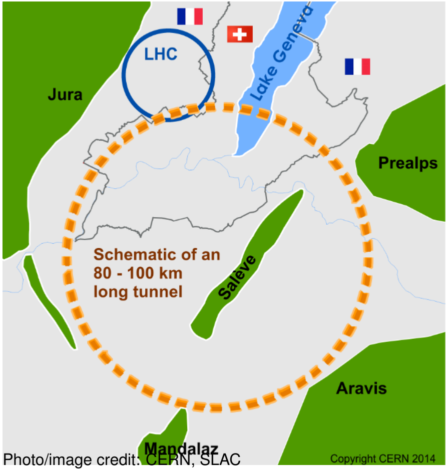

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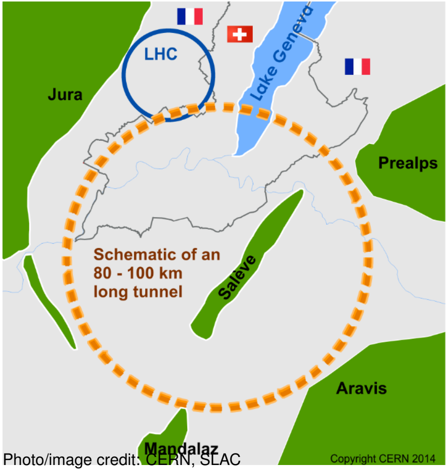

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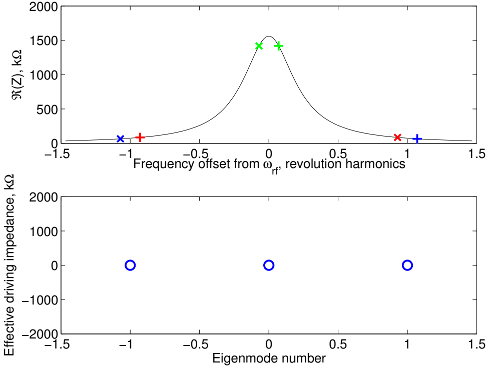
Cavity Detuning and Longitudinal Stability



- 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 upper synchrotron sidebands of revolution harmonics;
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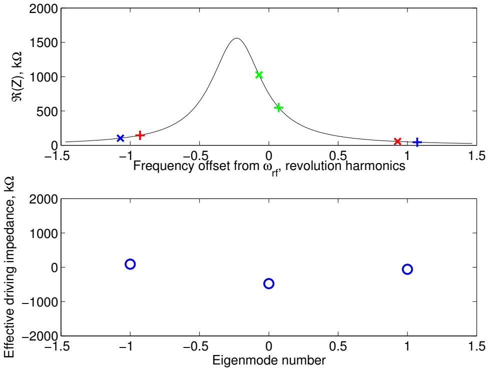

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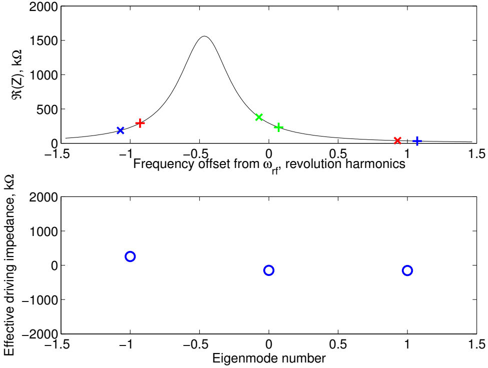

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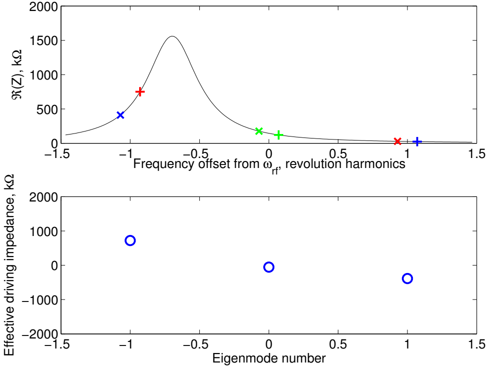

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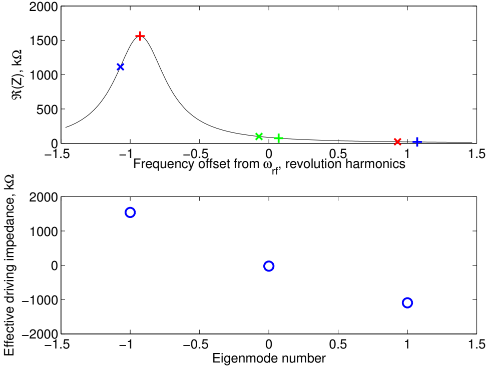

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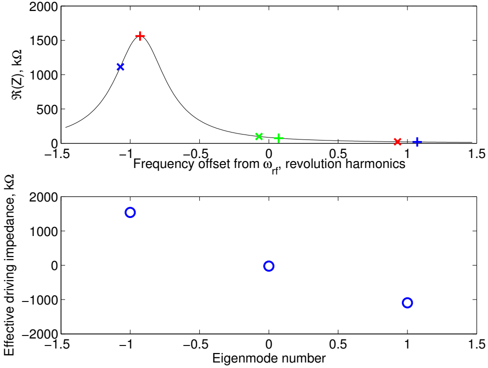

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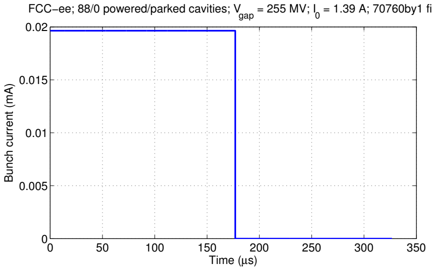
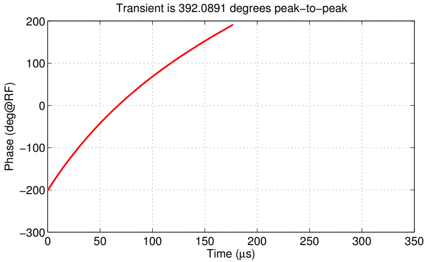
Single Bunch Train in FCC-ee (Z)





- Non-uniform fill pattern puts power at revolution harmonics, modulates cavity field;
- Single train is unphysical;
- At 300 mA it is slightly more realistic;
- Bunch length is all over the place;
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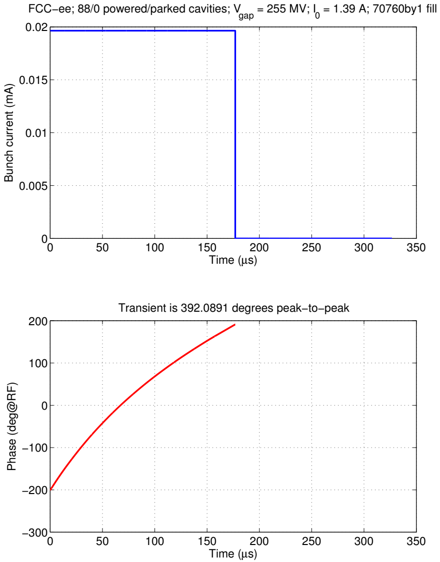

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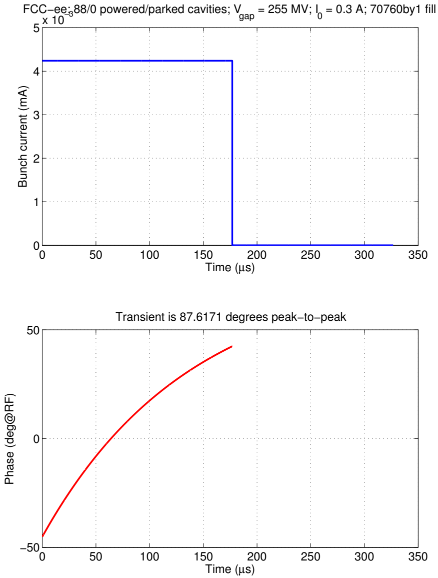

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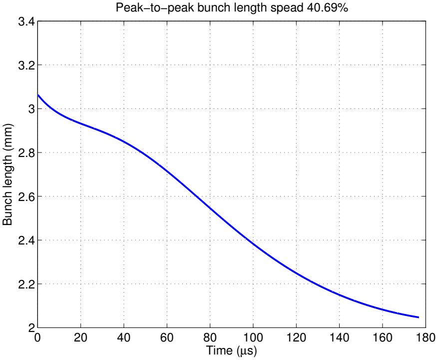

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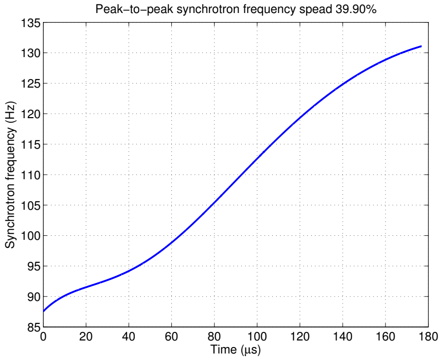

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Dealing With Beam Loading

- Two main effects of heavy beam loading in large rings:
  - Longitudinal coupled-bunch instabilities driven by the RF cavity fundamental impedance;
  - Synchronous phase transients.
- Transient effects depend on
  - Total beam current;
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- Fill patterns can be designed to mitigate transient effects;
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Mitigating Beam Loading in Design Stage

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;
  - Low R/Q favors superconducting cavities.

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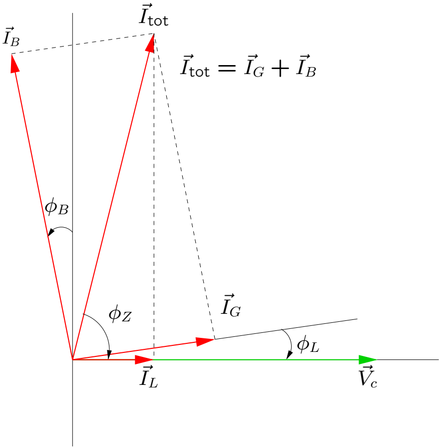
Phasor Argument



- First idea — phase modulate the generator to suppress the transients;
- 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!
- Factor of 10 in peak power.

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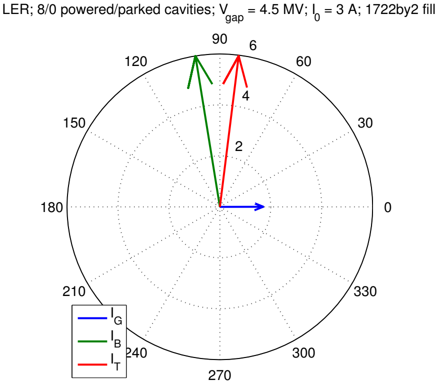

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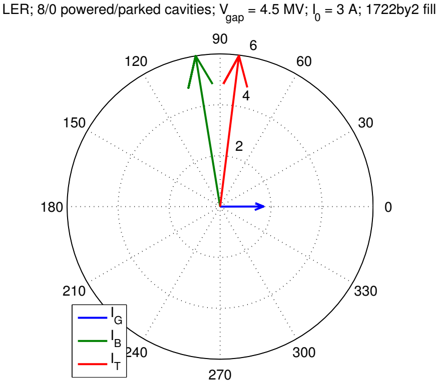

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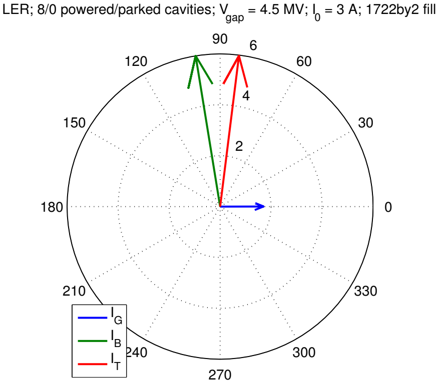

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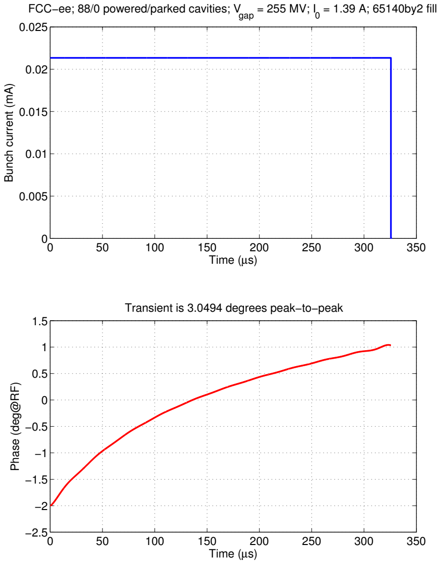

- 0.3% gap (400 RF buckets, 1 µs);
- Uniform train of 65140 bunches with 5 ns spacing;
- Bunch length moves around by 3.4% (peak-to-peak).

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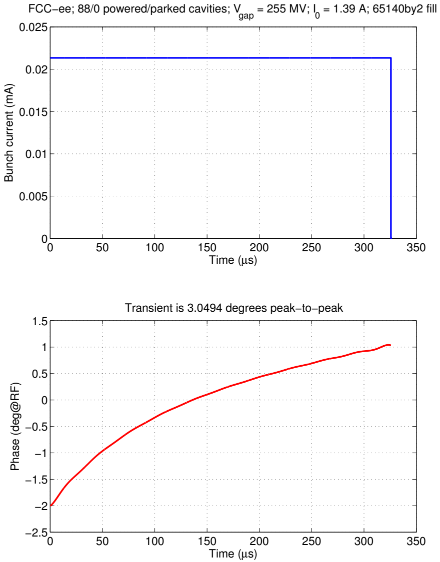

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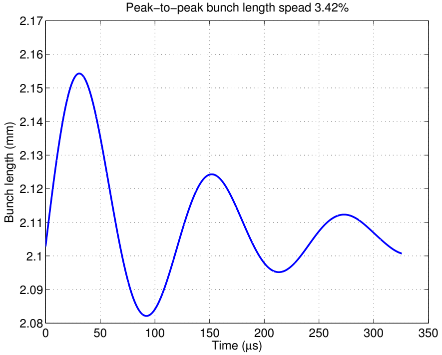

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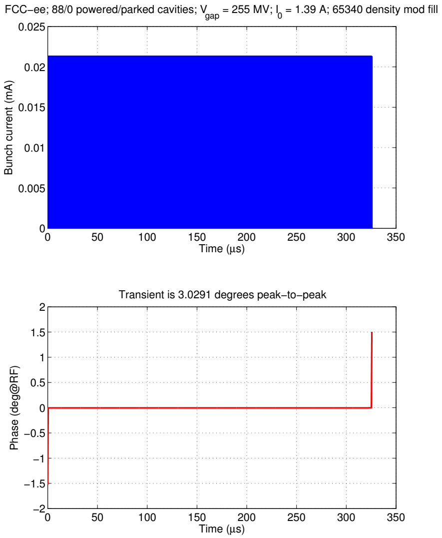

- Idea from J. Byrd et al., Phys. Rev. ST Accel. Beams 5, 092001 (2002):
  - Charge removed from the gap is added symmetrically to both ends of the train;
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- Rather than double the charge, fill 200 buckets at the ends of the train in every bucket (2.5 ns) pattern;
- Phase transient peak-to-peak amplitude is unchanged.

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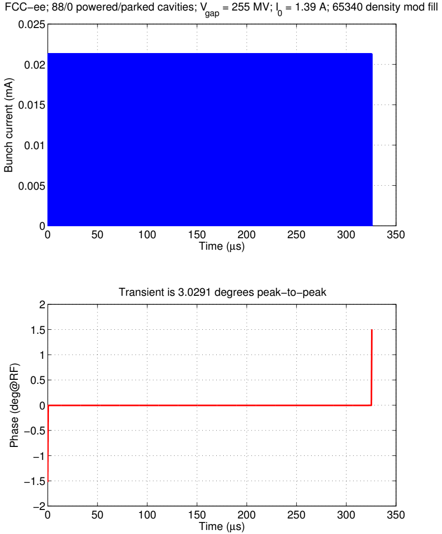

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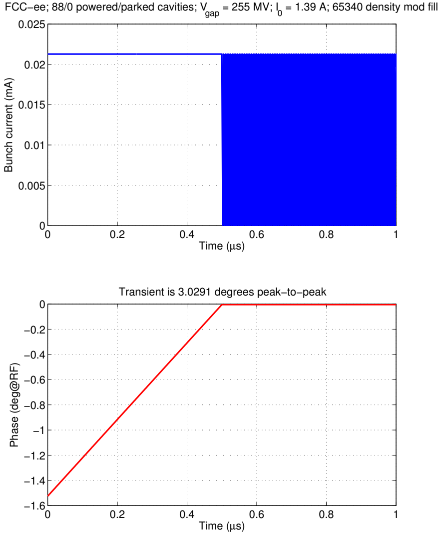

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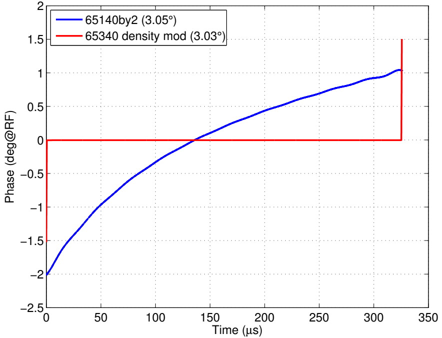

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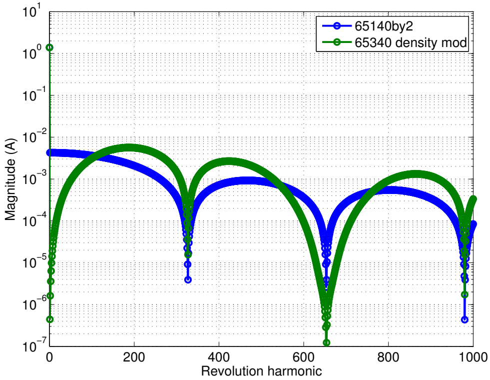

- Two fill patterns used earlier:
  - 65140by2: one long train of 65140 bunches every other RF bucket and 400 bucket gap;
  - 65340 density mod: long train with density modulation.
- Both fill pattern spectra show notches at multiples of $h/400 \approx 327$ revolution harmonics due to identical 400 bucket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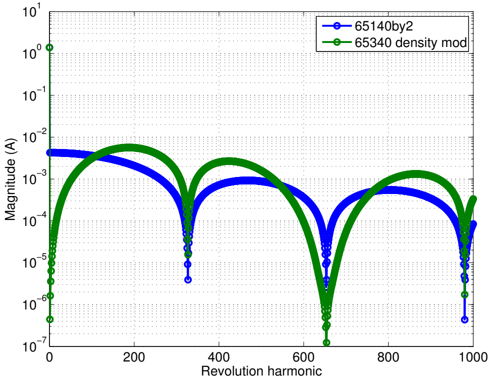

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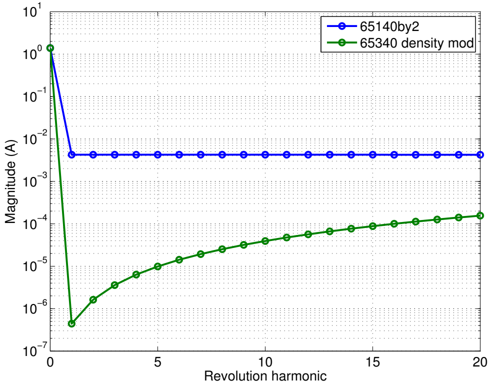

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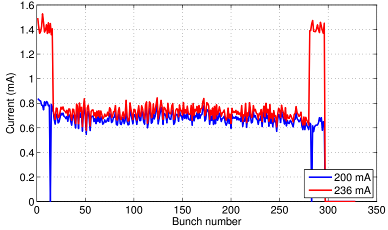

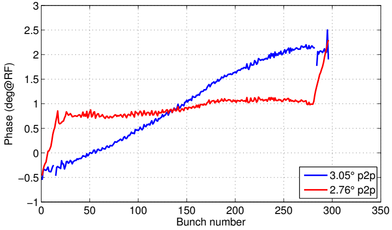

- Measurements from the Advanced Light Source in Berkeley:
  - A train of 296 buckets, 32 bucket gap;
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- A bit of first revolution harmonic due to the detuned harmonic cavities.

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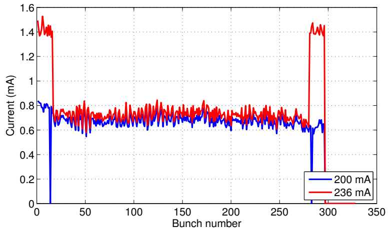

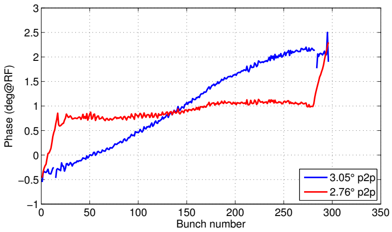

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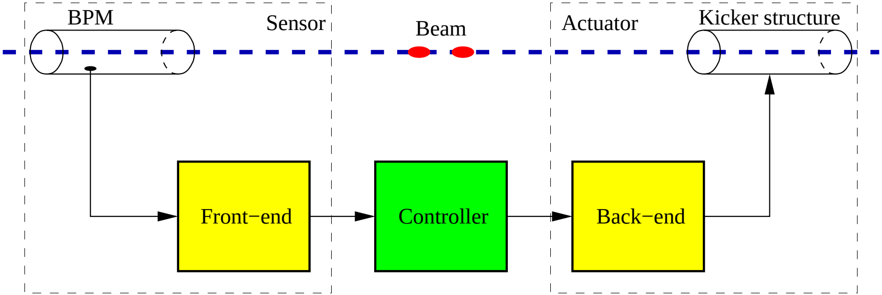
Bunch-by-bunch Feedback

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: Longitudinal

- Measure longitudinal position (time of arrival);
- Correct energy;
- To generate required 90° phase shift the feedback must observe at least half a synchrotron period;
- Fastest controllable growth times on the order of 1–2 synchrotron periods.

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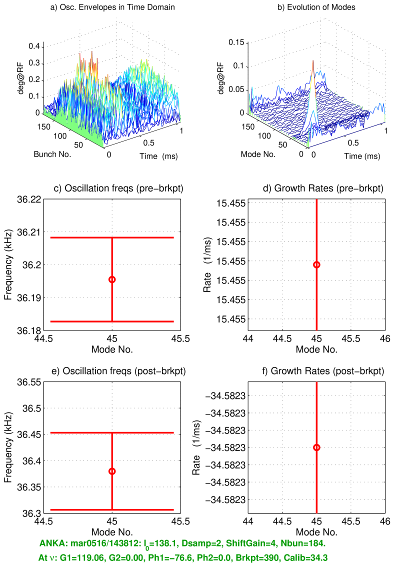

- Measured while cavity tuning walks an HOM onto a synchrotron sideband;
- Growth time is $2.3T_s$, damping time is T_s;
- Actual modal oscillation trajectory;
- Filter is $2/3$ of a synchrotron period.

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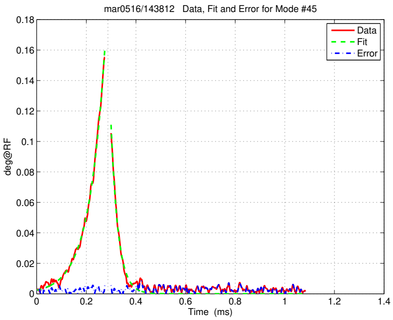

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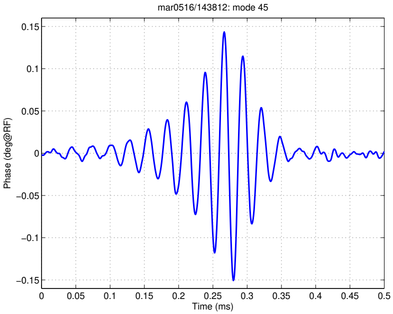

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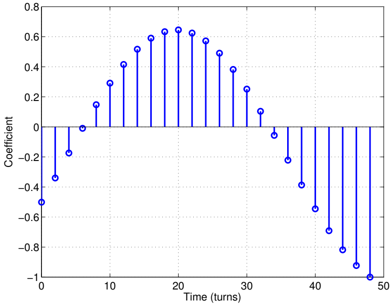
- Filter is $2/3$ of a synchrotron period.

Longitudinal Example from ANKA



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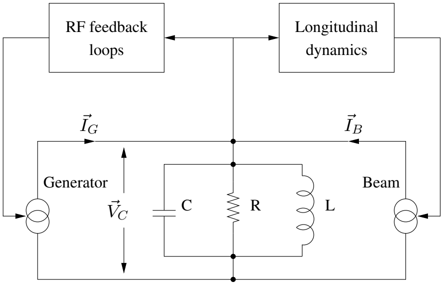
Outline

Low Level RF to the Rescue



- Fundamental impedances at a synchrotron sideband — instability growth times below $T_s/10$;
- Beam feedback cannot control such instabilities;
- RF feedback stabilizes cavity field — low effective impedance as seen by the beam;
- $\frac{dV_C}{dI_B} \approx 0$;
- Use wideband loops to lower the impedance at multiple revolution harmonics around the RF.

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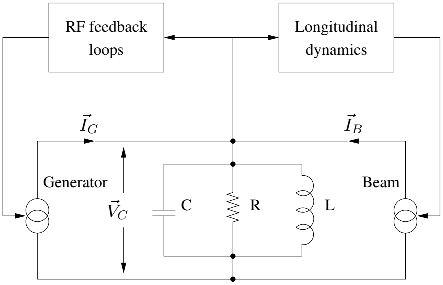

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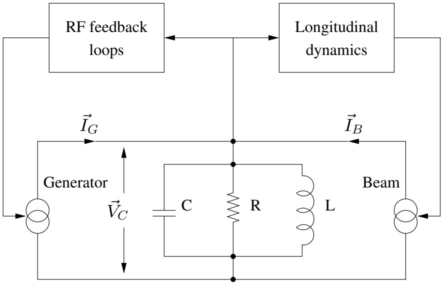

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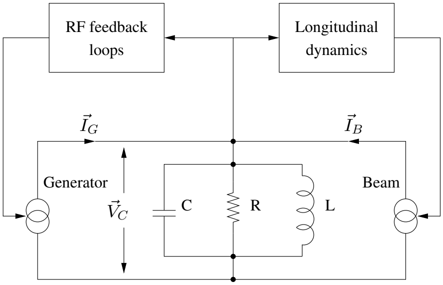

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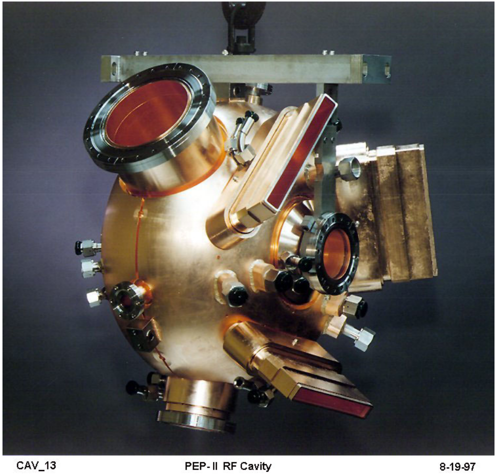
PEP-II Collider



Parameter	HER	LER
Circumference	2.2 km	
Energy	9 GeV	3.1 GeV
Beam current	2.1 A	3.2 A
Cavities	28	8
RF power	11 MW	4 MW

- Copper HOM damped cavity;
- Cavity with the HOM loads;
- Two and four cavity stations, vector sum control, 1 MW klystrons.

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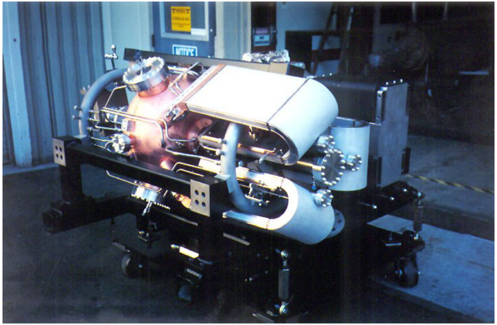

BR_040 RF Cavity 8-19-97

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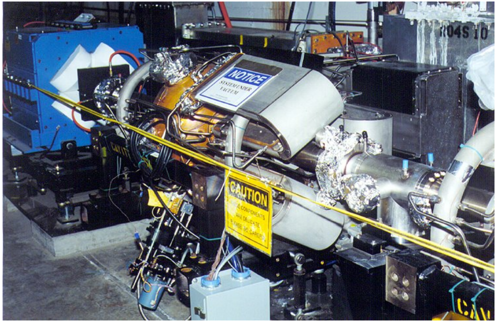

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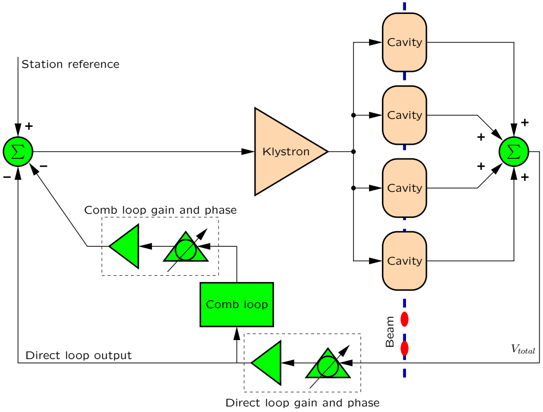
PEP-II Fast Impedance Control



- Two feedback loops: direct and comb;
- Open loop: 33 µs growth time;
- Direct loop only: 333 µs growth time;
- Direct and comb: 3.3 ms growth time.

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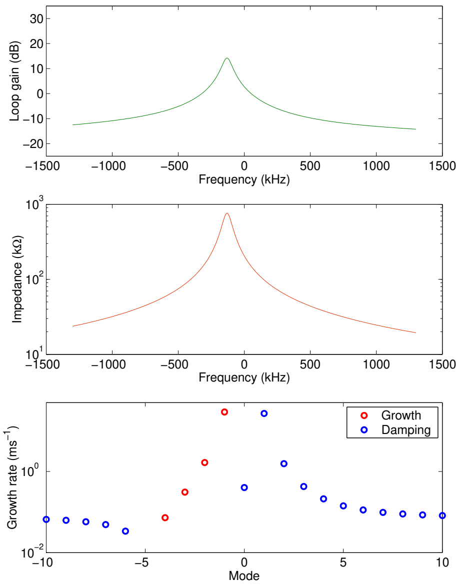

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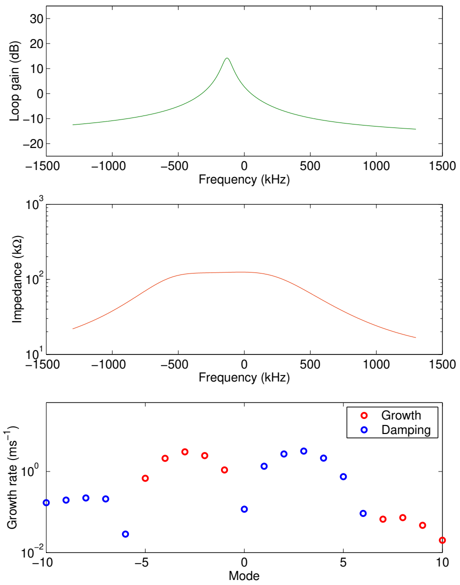

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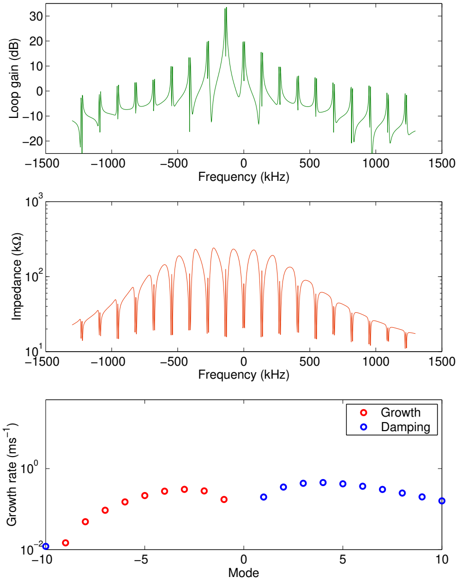

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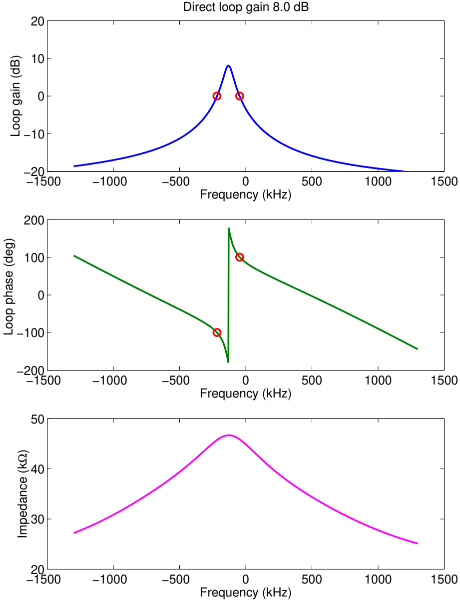

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- OK at 11 dB;
- and 14 dB;
- At 17 dB we are stop impedance reduction;
- Worse at 20 dB.

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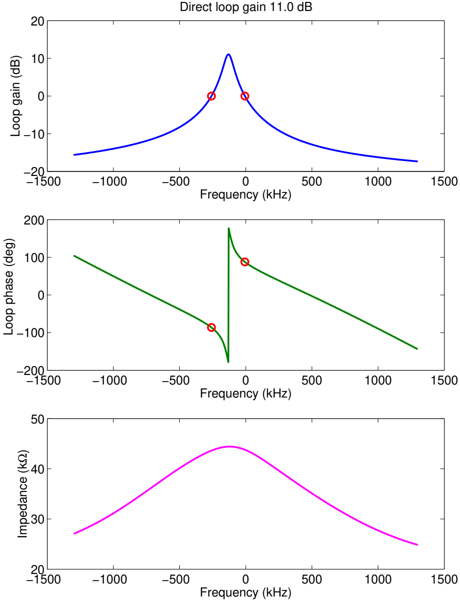

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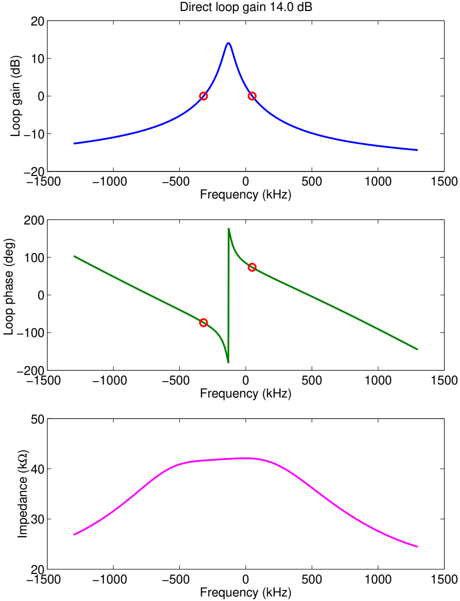

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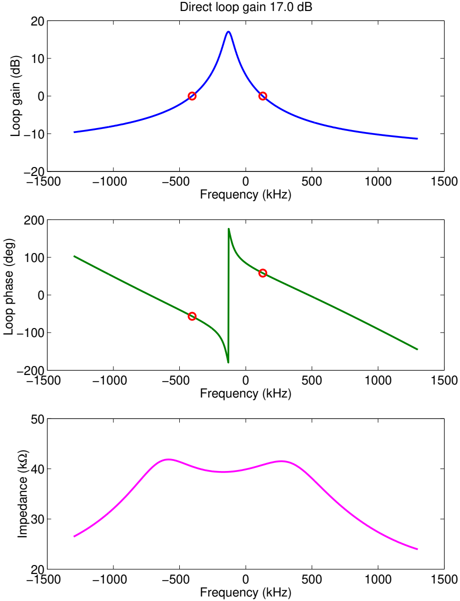

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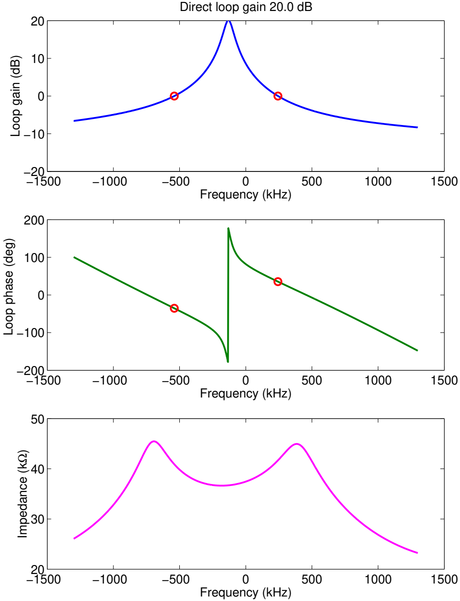

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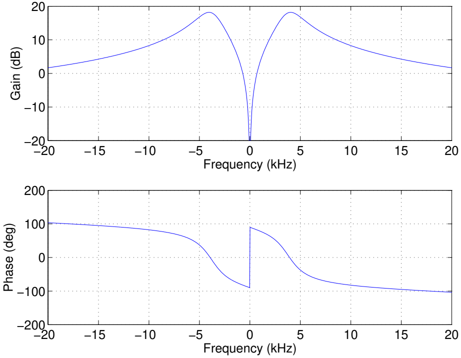
Trade Bandwidth for Gain



- Double peaked comb filter at synchrotron sidebands;
- No response at revolution harmonics;
- Almost 20 dB of gain at synchrotron sidebands.

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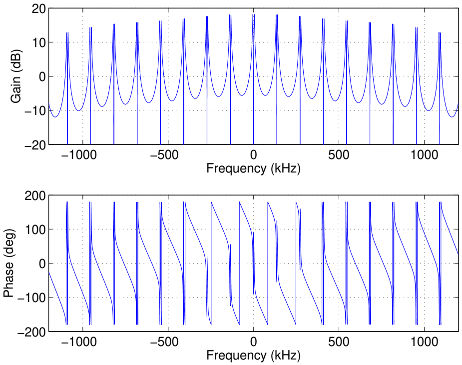

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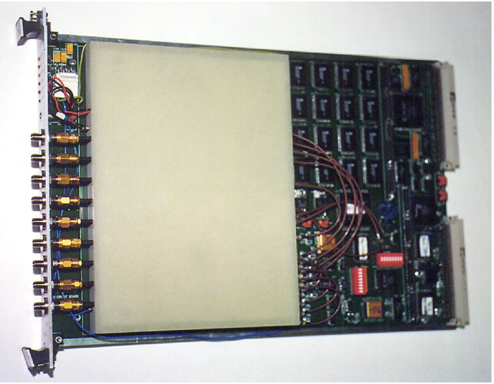
A Word About Technology: RF Processing Module



- Analog direct loop: I/Q demodulation/modulation, op-amp feedback processing;
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- Vector sum, multiple gain/phase blocks, lead/lag compensation, ripple loop DSP.

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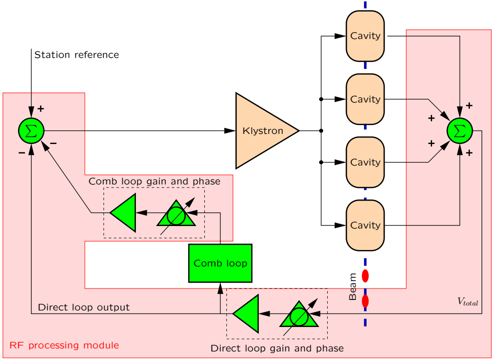

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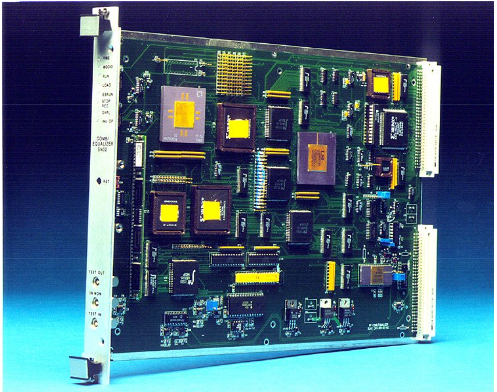

- Baseband digital processor clocked at 9.8 MHz ($72 f_{\mathrm{rev}}$);
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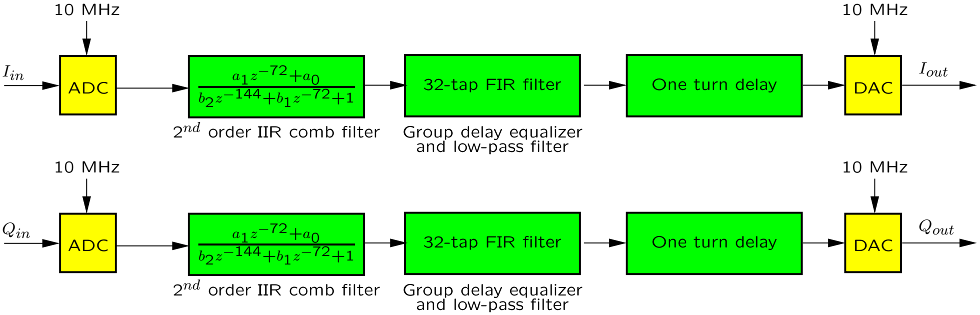

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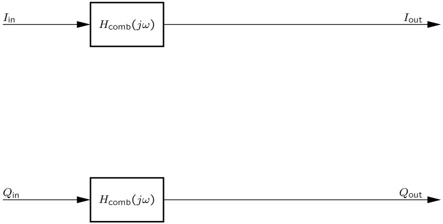

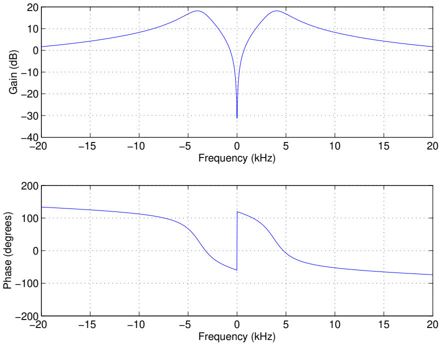

- Upper sideband of comb filter reduces growth rates;
- Lower sideband removes damping impedance;
- Single sideband comb idea;
- Never implemented, only simulated;
- Used comb phase offset to reduce growth rates;
- Trade-off between LLRF and beam stability.

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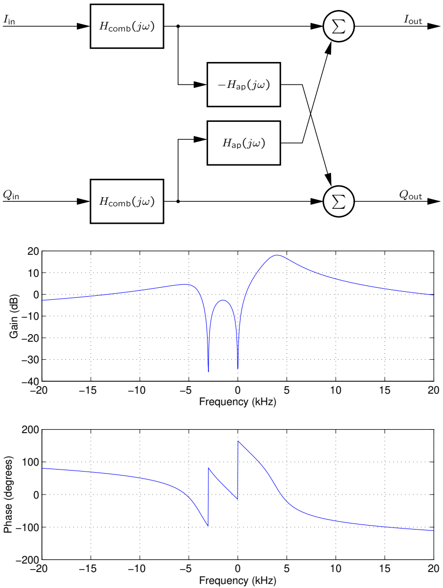

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Summary

- Large ring circumference and high beam currents make for a challenging combination;
- RF system design should be driven by the beam loading and longitudinal stability considerations;
- Fundamental impedance is large, but very tightly controlled, so driving impedance reduction is feasible;
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