Challenges for High-current Beam Interactions with SRF Cavities

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TESLA Technology Collaboration 2023

Outline

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Beam Loading and Stability

- Primarily considering high beam currents in electron/positron storage rings;
- Three important effects:
  - Operating point stability (aka Robinson beam loading limit);
  - Coupled-bunch instabilities in the longitudinal plane;
  - Transient beam loading due to the non-uniform fill patterns.
- Under heavy beam loading both of the latter effects will be driven by the fundamental impedance of the RF cavities:
  - Instabilities: beam interacts with the impedances at synchrotron sidebands of revolution harmonics;
  - Transient beam loading: driven by the impedance at revolution harmonics.

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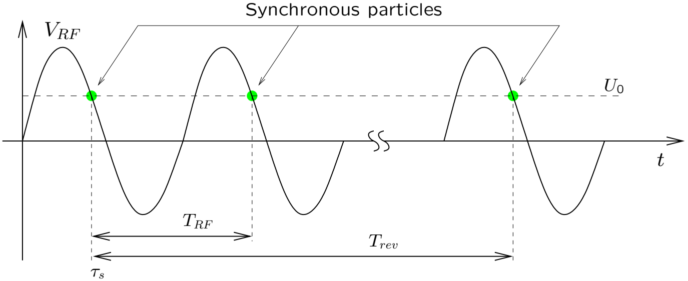
RF and Longitudinal Focusing



- Periodic RF voltage restores the energy lost by particles;
- Synchronous particle gains exactly the energy lost in one turn;
- Particles above nominal energy take a longer path — positive momentum compaction;
- RF voltage slope creates a potential well (longitudinal focusing);
- Integer ratio $T_{\mathrm{rev}}/T_{\mathrm{RF}}$ (harmonic number) is the number of stable RF buckets where bunches of charged particles can be stored.

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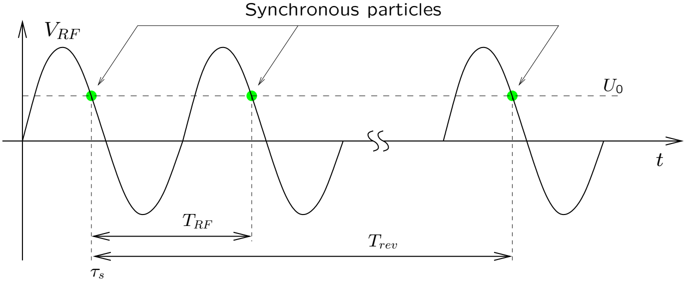

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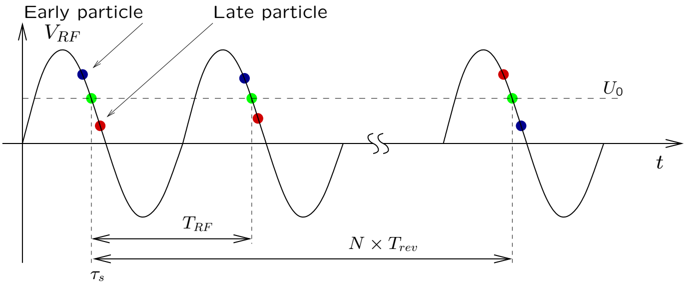

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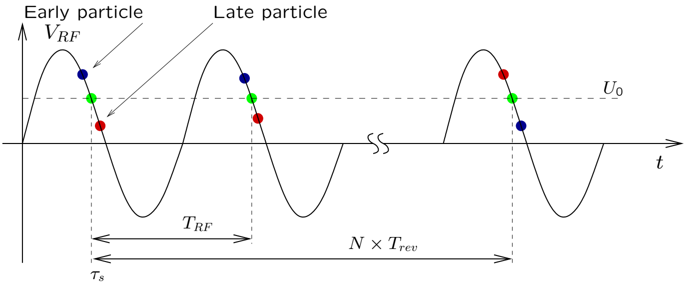

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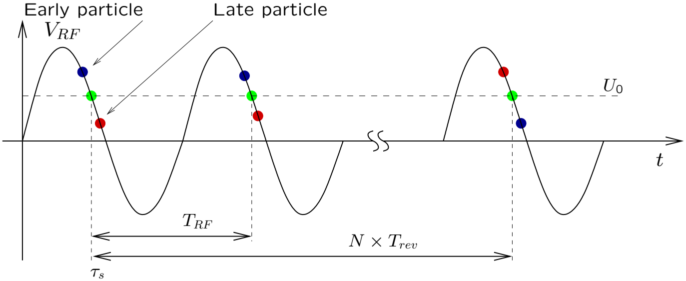

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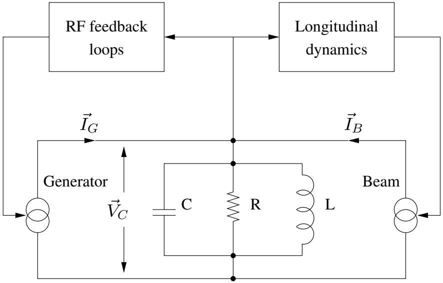
Beam/Cavity Interaction



- 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;
- 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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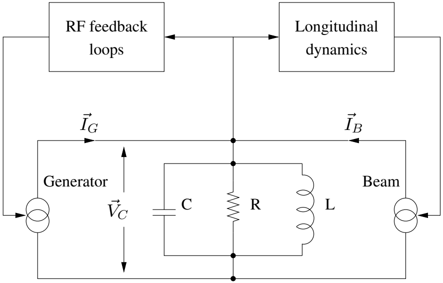

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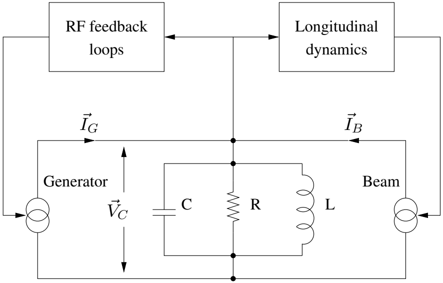

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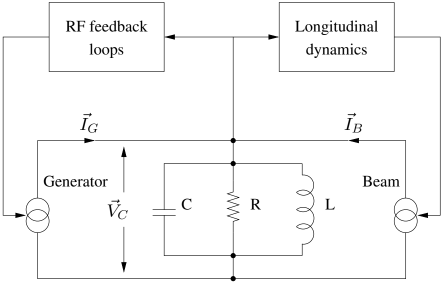

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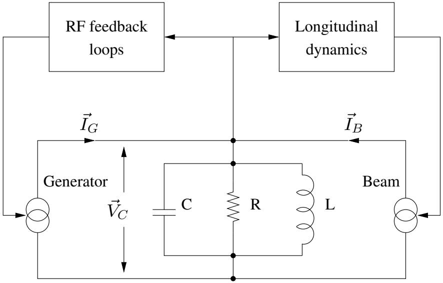

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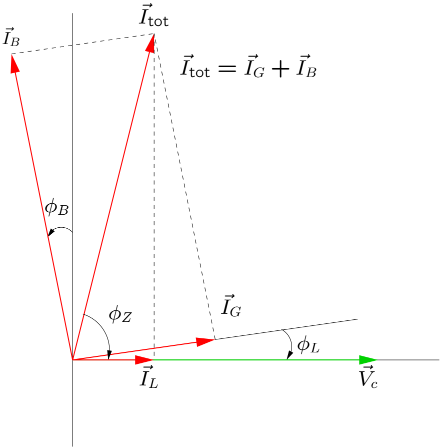

- Phasors at the RF frequency, cavity voltage on X axis;
- Synchronous phase ϕ_B is determined by the RF voltage, energy loss per turn;
- For minimum generator power keep loading angle $\phi_L = 0$;
- Cavity is detuned to maintain proper phase angle ϕ_Z between the total current and the cavity voltage;
- The larger is $\vec{I}_B$, the higher is the detuning.

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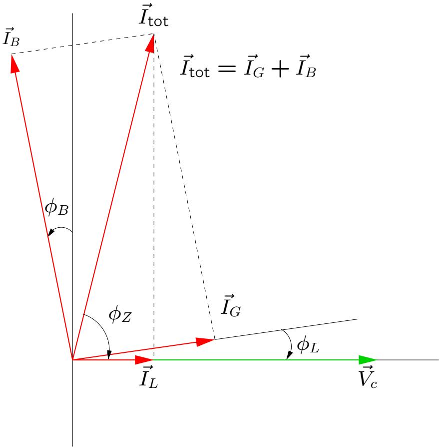

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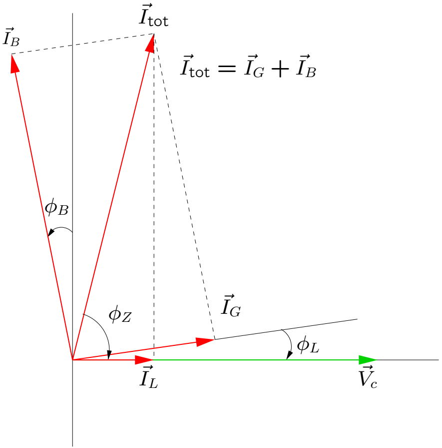

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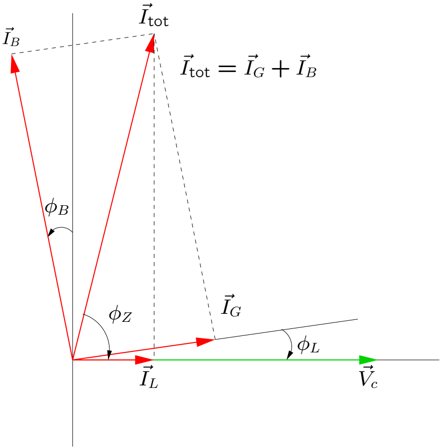

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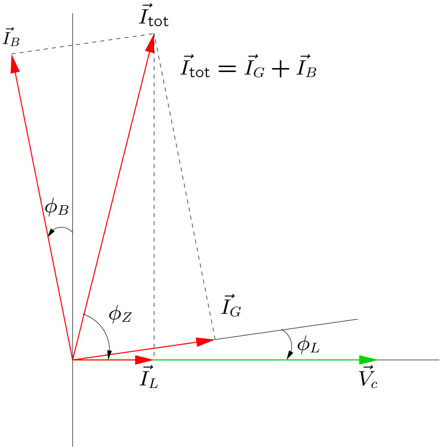

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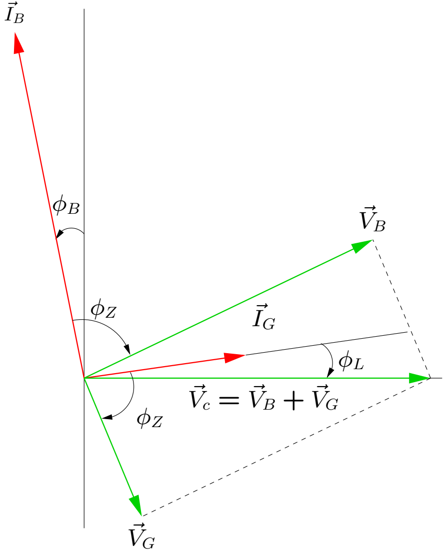
High Beam Loading Robinson Limit



- This elegant graphical derivation of high current limit is from Matt Sands (Beam-Cavity Interaction - I, 1976);
- Cavity voltage $\vec{V}_c$ is a sum of two components: beam and generator voltages;
- Since $\vec{V}_B$ follows the beam in phase, it provides no longitudinal focusing, all focusing is due to $\vec{V}_G$;
- Focusing goes away when beam arrives on the crest of $\vec{V}_G$;
- The limit is when $\vec{V}_G$ is parallel to $\vec{I}_B$;
- $I_{\text{rob}} = \frac{V_c}{2R_L \sin\phi_B}$ when $\phi_L = 0$.

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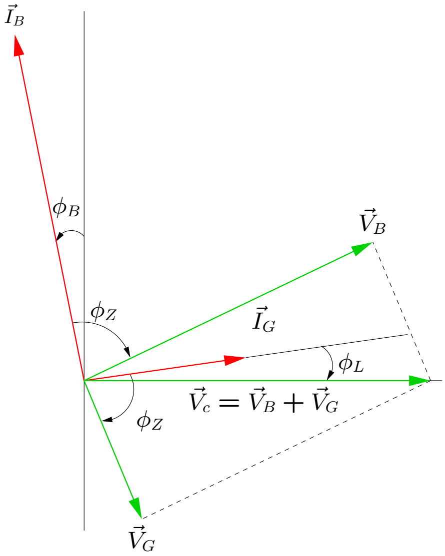

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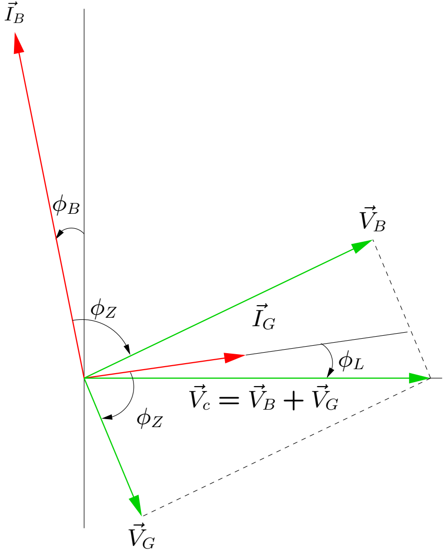

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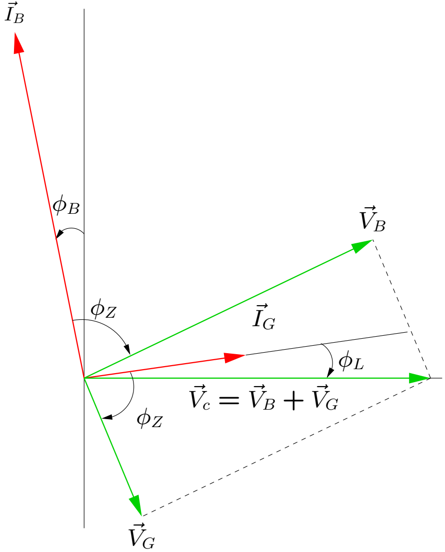

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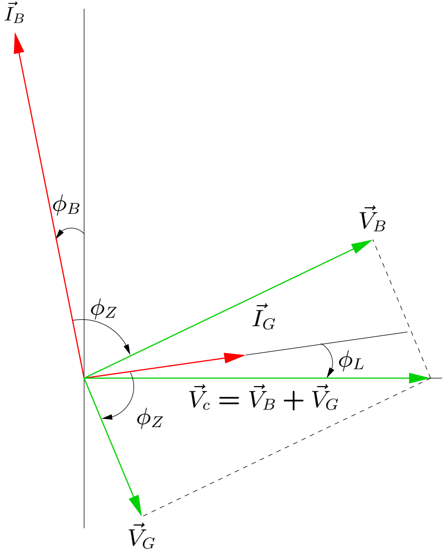

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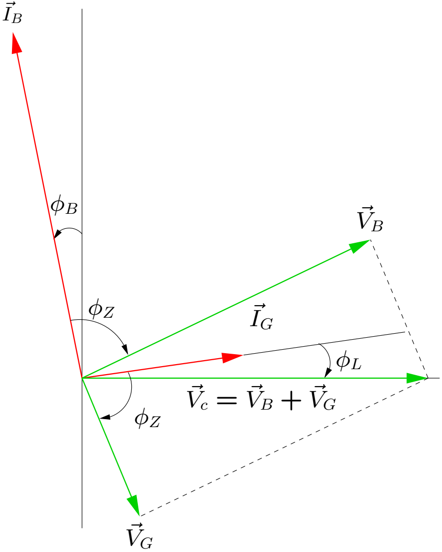

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High Beam Loading Robinson Limit and SRF

- For optimal power utilization:
  - Set the coupling factor for minimum reflected power at the design current;
  - Set loading angle to zero;
- With the normal conducting cavities there is a significant margin between the design point and the Robinson limit;
- Superconducting cavities — the margin is nearly zero ($I_{\mathrm{rob}} \approx I_0 + \frac{V_c^2}{R_s U_0}$);
- A quick example:
  - NC: 30 kW wall dissipation, 1 A design, 1.6 A limit;
  - SC: 30 W wall dissipation, 1 A design, 1.001 A limit;
- Fixes:
  - Increase the coupling factor: 10% in the example above costs 240 W in reflected power vs. 104 kW beam power;
  - Operate with non-zero loading angle, again at the cost of the reflected power;
  - Use wideband proportional feedback around the cavity to stabilize beam-cavity interaction, beam loading limit scales as $1 + H$ where H is the feedback loop gain.

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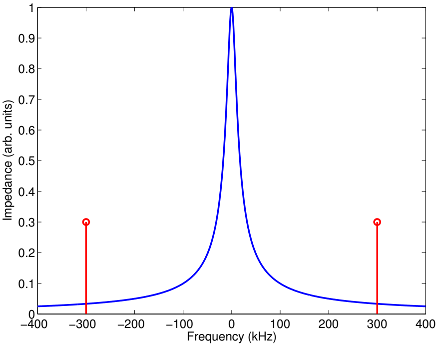
Resonant Modes and Revolution Harmonics



- Storage ring circumference does not affect the Robinson limit;
- Large rings have low revolution frequencies — the beam is more likely to interact with the cavity fundamental impedance;
- A 20 kHz resonance ideally “hidden” between two revolution harmonics.
- 500 m ring;
- 1.5 km ring;
- 3 km ring;
- 10 km ring;
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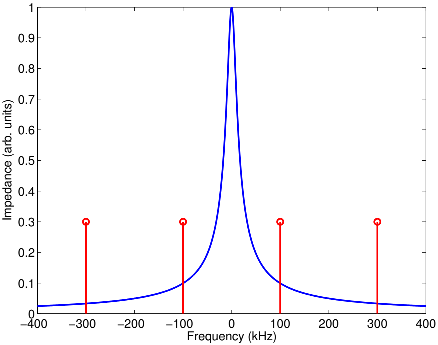

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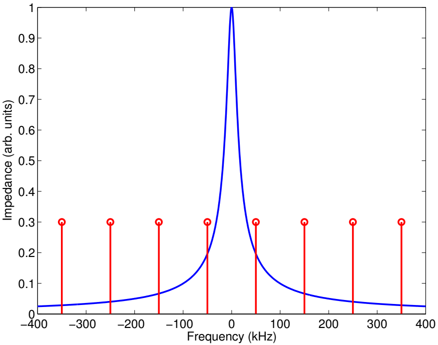

- Storage ring circumference does not affect the Robinson limit;
- Large rings have low revolution frequencies — the beam is more likely to interact with the cavity fundamental impedance;
- A 20 kHz resonance ideally “hidden” between two revolution harmonics.
- 500 m ring;
- 1.5 km ring;
- 3 km ring;
- 10 km ring;
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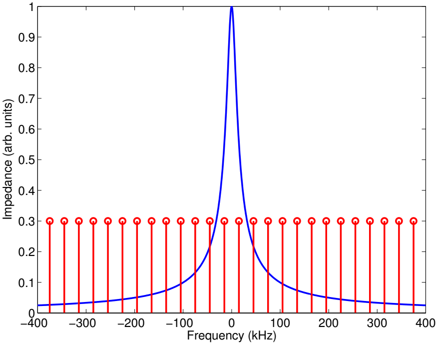

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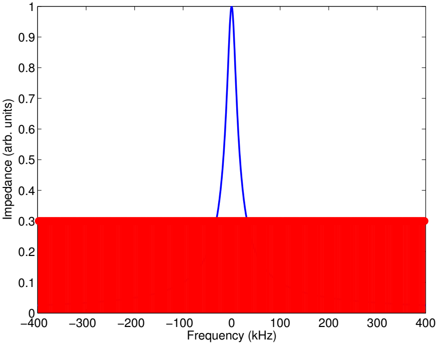

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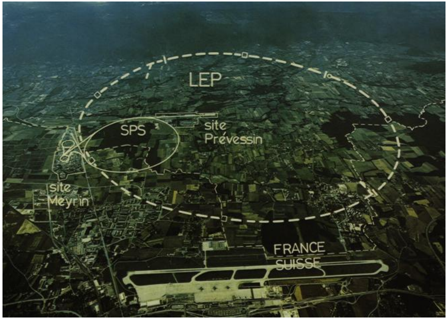
Ring Circumference and Beam Loading



Photo/image credit: CERN, SLAC

- People don't build multi-kilometer rings just to spend money;
- Large circumference typically means high energy;
- Or very high current;
- Or both;
- Large circumference means significant beam loading of the RF system;
- Cavity detuning can easily exceed revolution frequency in such machines.

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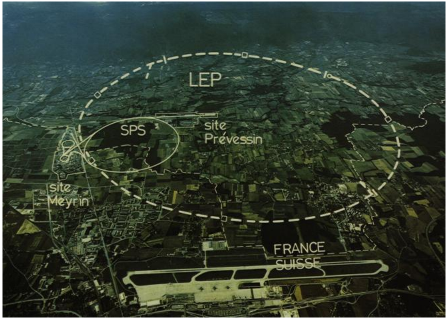

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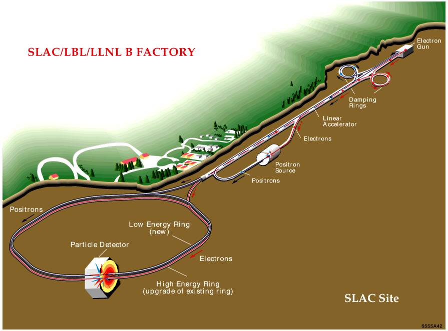

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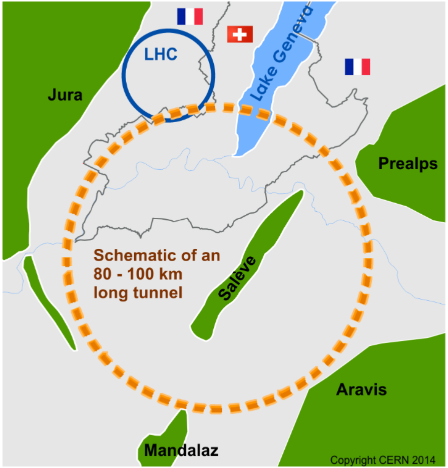

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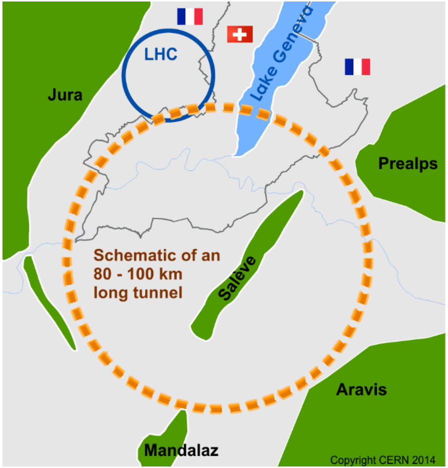

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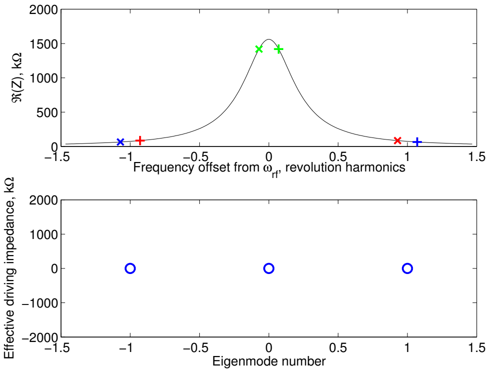
Cavity Detuning and Longitudinal Stability



- Growth rate for mode -1 is $\propto$ $Z(\omega_{\rm rf}-\omega_{\rm rev}+\omega_s)-Z(\omega_{\rm rf}+\omega_{\rm rev}-\omega_s)$;
- Symmetric on resonance;
- Growth rates peak when fundamental crosses upper synchrotron sidebands of revolution harmonics;
- Instability growth times are very small relative to the synchrotron period;
- Such instabilities cannot be cured by the beam feedback systems, need to reduce the effective impedance!

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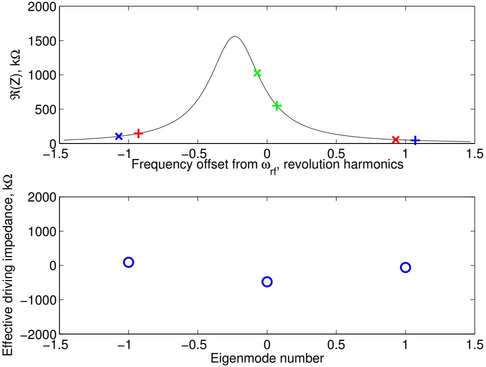

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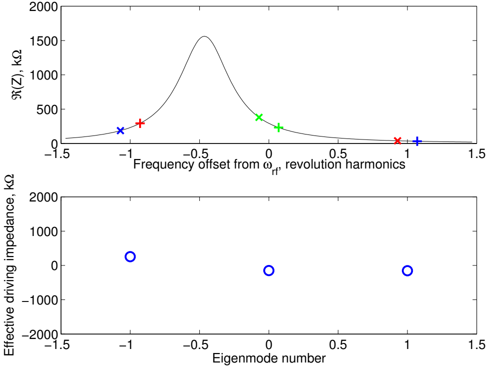

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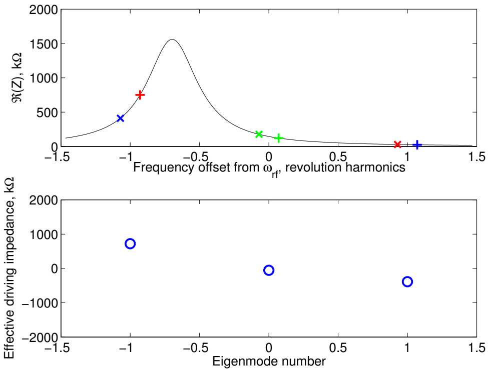

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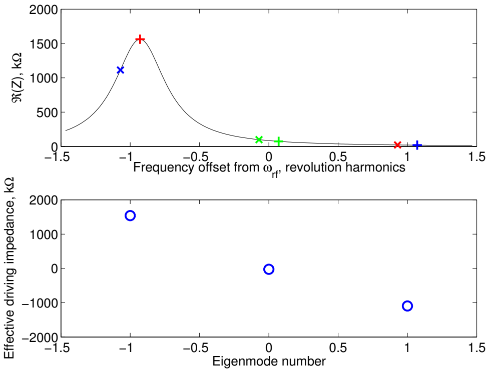

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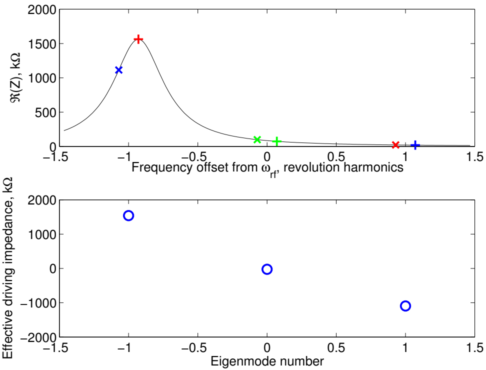

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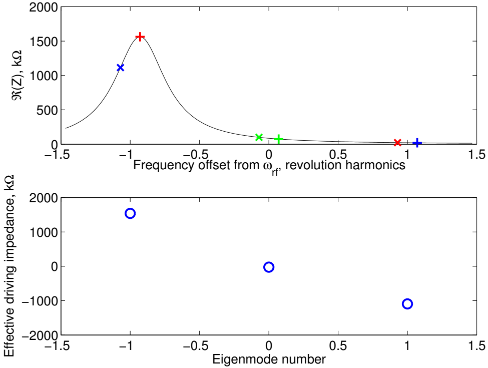

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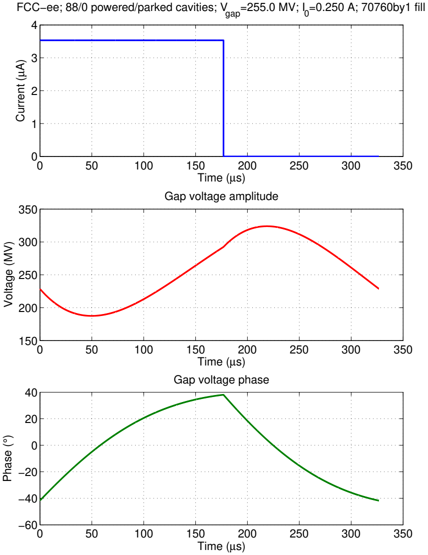
Outline

A Single Bunch Train in FCC-ee (Z)



- Non-uniform fill pattern puts power at the revolution harmonics and modulates the cavity field;
- That leads to the synchronous phase variation along the bunch train;
- Cavity voltage transient leads to bunch length variation;
- As well as the synchrotron frequency.

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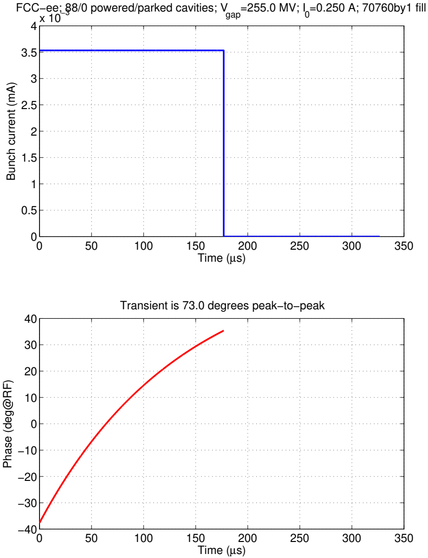

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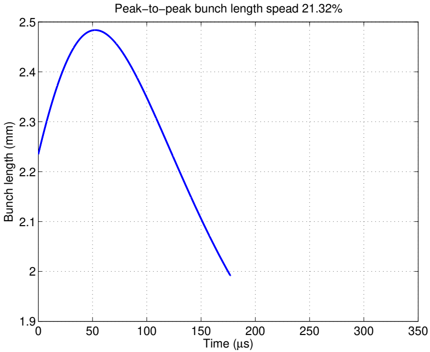

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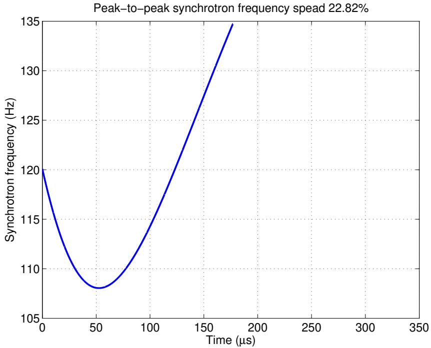

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Dealing With Beam Loading

- 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;
  - 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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Mitigating Beam Loading in the Design Stage

Cavity detuning

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

- 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.
- Counterphasing:
  - Set the number of cavities needed based on the coupler limit;
  - Run a fraction at the defocusing phase, still providing power to the beam;
  - Allows one to maximize per-cavity voltage without overfocusing the beam longitudinally.

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Outline

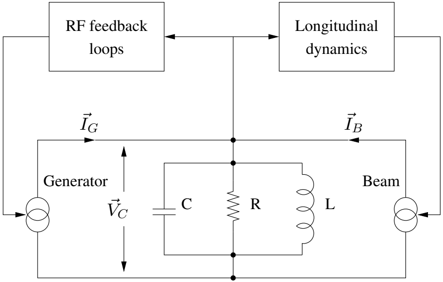
Introduction
- The focus of this talk

High Current Stability Limit
- Basics
- Robinson Limit

Beam Loading Effects
- Ring Circumference and Fundamental Impedance
- Longitudinal Instabilities
- Uneven Fills
- Mitigation
- Impedance Control Loops

Extra Slides

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 the 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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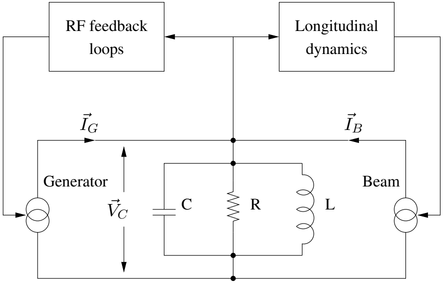

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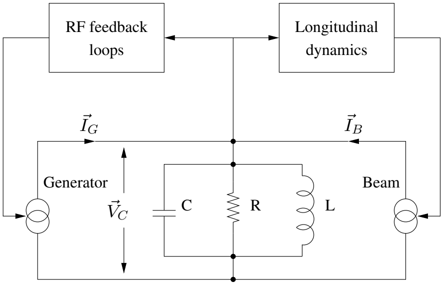

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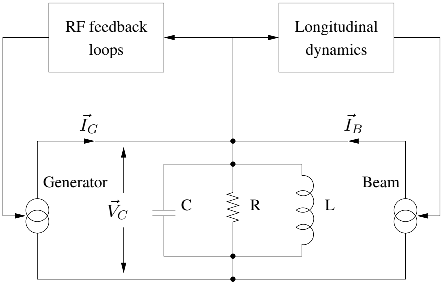

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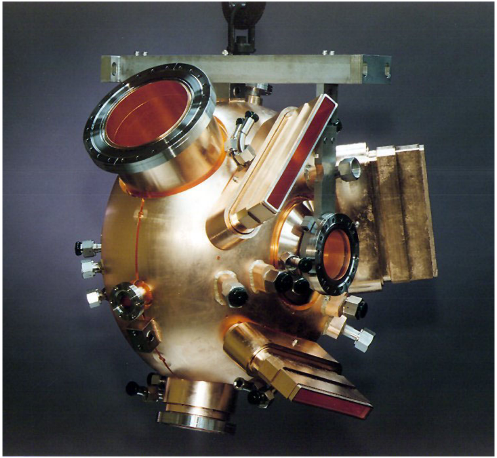

CAV_13 PEP-II RF Cavity 8-19-97

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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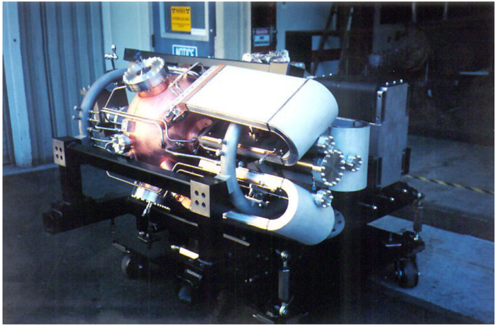

BR_040 RF Cavity 8-19-97

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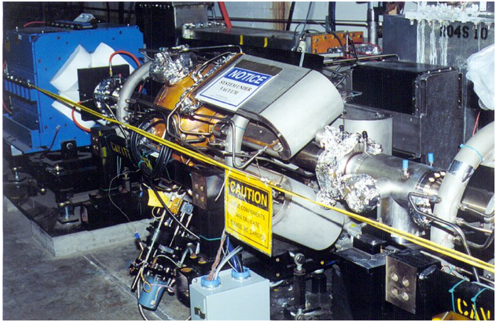

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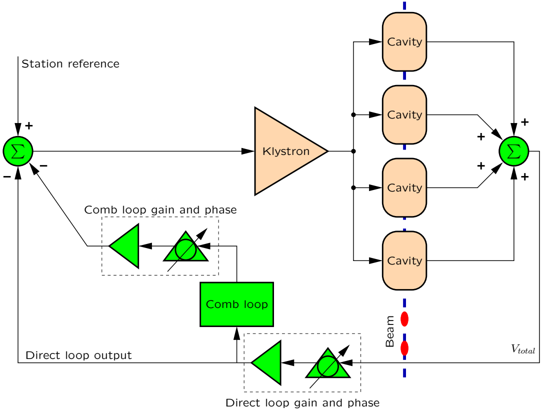

- Two feedback loops: direct and comb;
- Open loop: 33 µs growth time;
- Direct loop only: 333 µs growth time;
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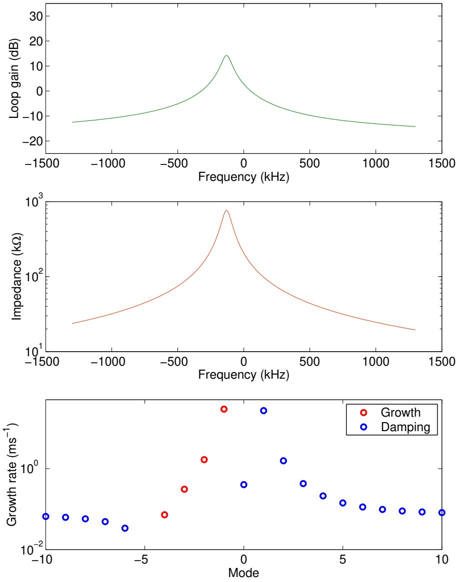

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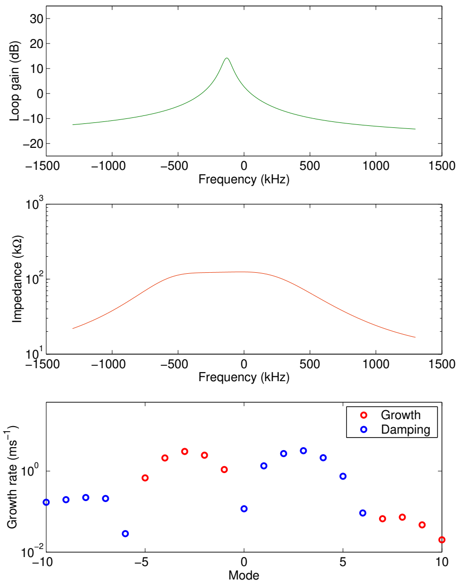

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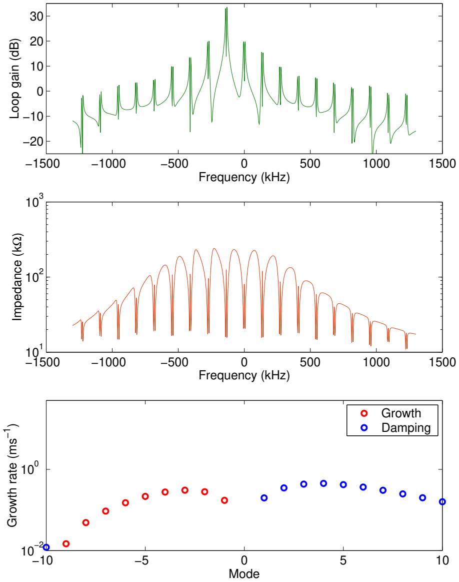

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- Fundamental impedance is large, but very tightly controlled, so driving impedance reduction is feasible;
- Cavity HOMs are relatively unpredictable, need to be damped to levels manageable by the bunch-by-bunch feedback;
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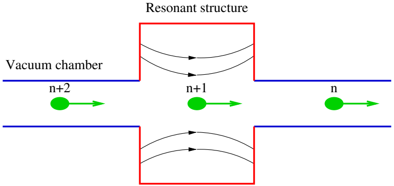
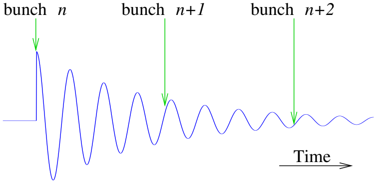
- Fundamental impedance is large, but very tightly controlled, so driving impedance reduction is feasible;
- Cavity HOMs are relatively unpredictable, need to be damped to levels manageable by the bunch-by-bunch feedback;
- Gap transient response cannot be controlled by RF feedback (high peak power), need to manage fill pattern gaps.

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 → phase modulation of the wakefield → 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.

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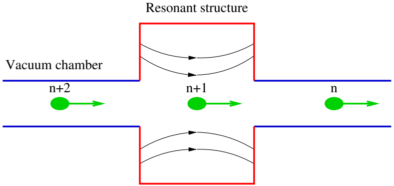

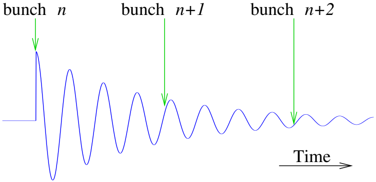

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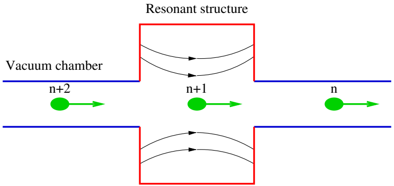

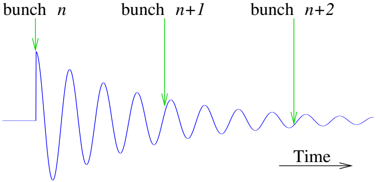

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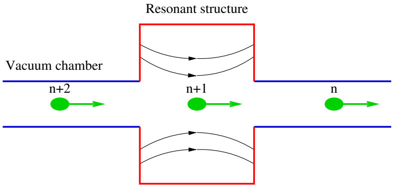

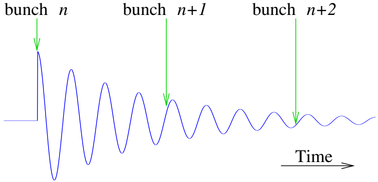

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Coupled-bunch Instabilities: Eigenmodes and Eigenvalues

- 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: $A_m e^{i2\pi km/N} e^{\Lambda_m t}$
  - 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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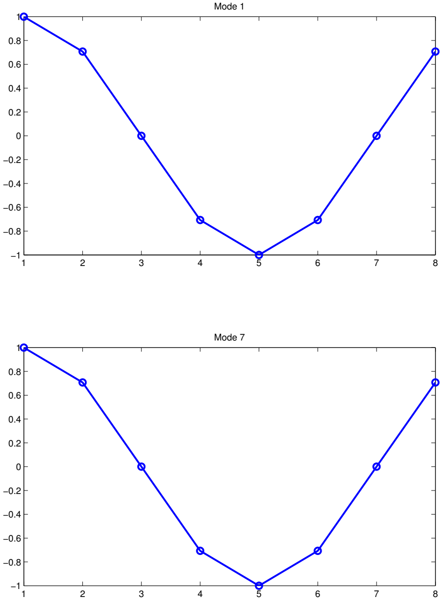
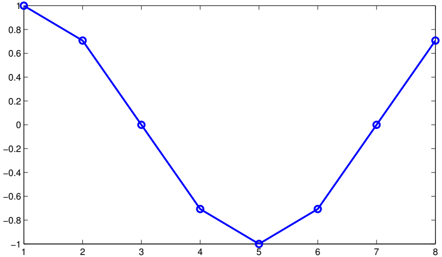
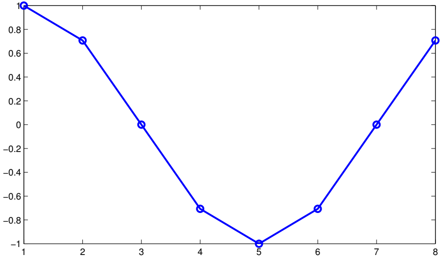
Modal Oscillation Example



- 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


Mode 1


Mode 7

- 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;
- $\Lambda_m = (-\lambda^{\|}_{\mathrm{rad}} + i\omega_s) + \frac{\pi\alpha e f_{\mathrm{rf}}^2 I_0}{E_0 h\omega_s} Z^{\|\mathrm{eff}}(m\omega_0 + \omega_s)$;
- Effective impedance: $Z^{\|\mathrm{eff}}(\omega) = \sum_{p=-\infty}^{\infty} \frac{p\omega_{\mathrm{rf}}+\omega}{\omega_{\mathrm{rf}}} Z^{\|}(p\omega_{\mathrm{rf}} + \omega)$
- 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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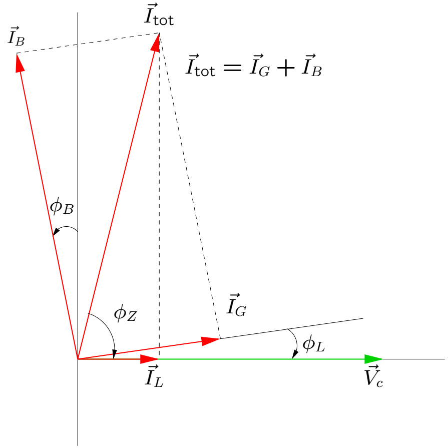

- First idea — phase modulate the generator to suppress the transients;
- PEP-II example: $I_B = 6$ A, $I_G = 1.7$ A;
- To compensate fill pattern modulation, when I_B goes to 0 in the gap, I_G would need to match I_T!
- Factor of 10 in peak power.

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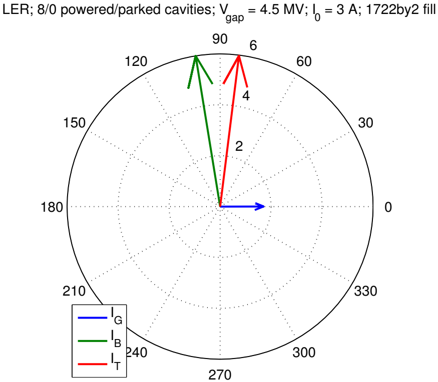

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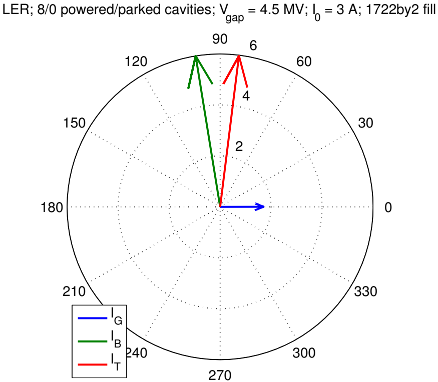

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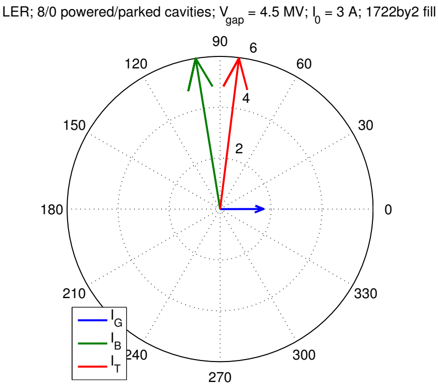

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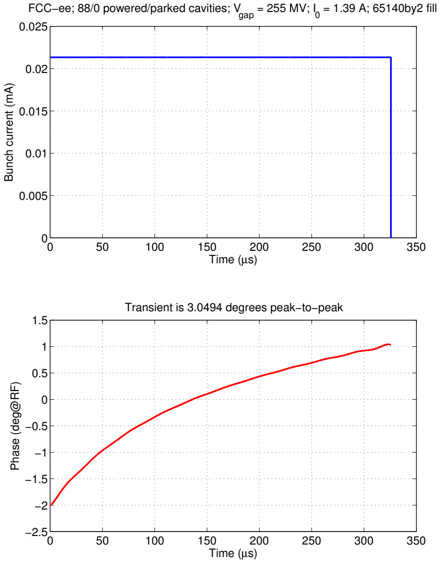
Single Bunch Train



- 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).

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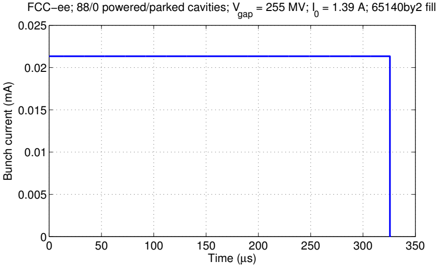
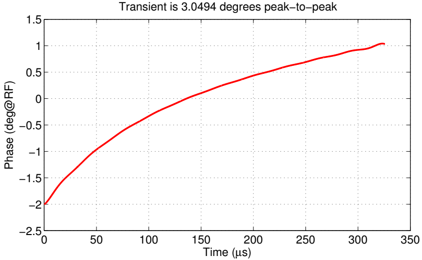

FCC–ee; 88/0 powered/parked cavities; V_{gap} = 255 MV; I_0 = 1.39 A; 65140by2 fill


Transient is 3.0494 degrees peak–to–peak

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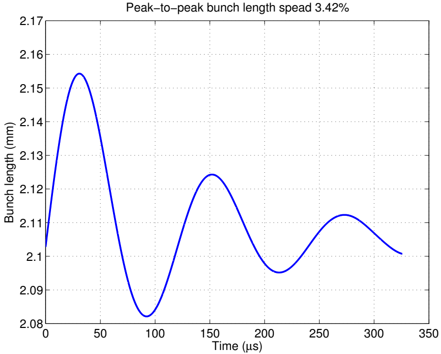

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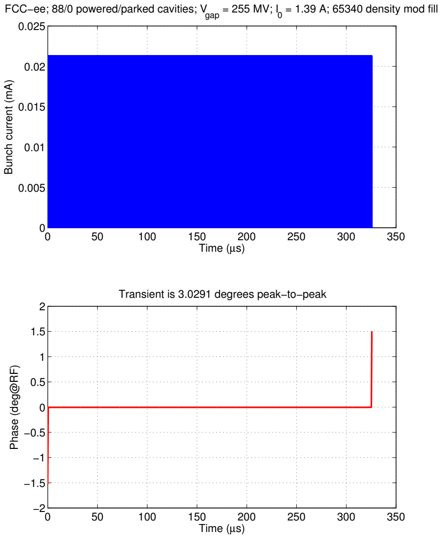
Fill Pattern Density Modulation



- 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;
- Rather than double the charge, fill 200 buckets at the ends of the train in every bucket (2.5 ns) pattern;
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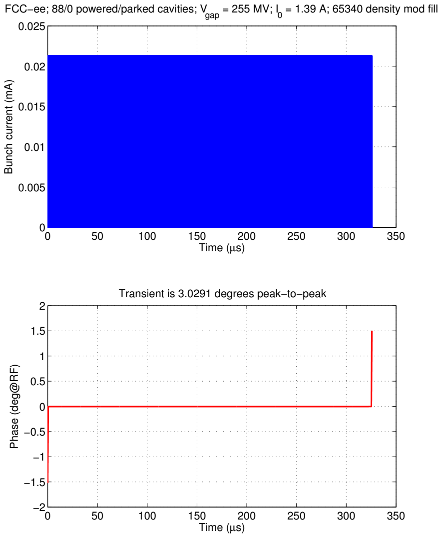

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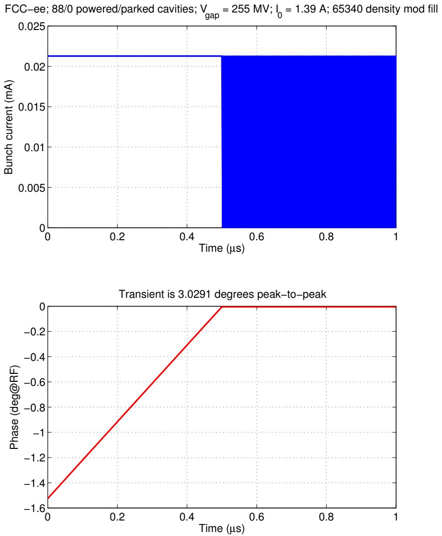

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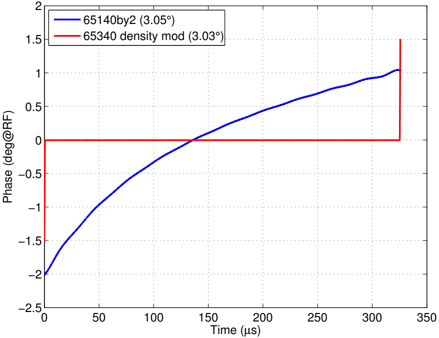

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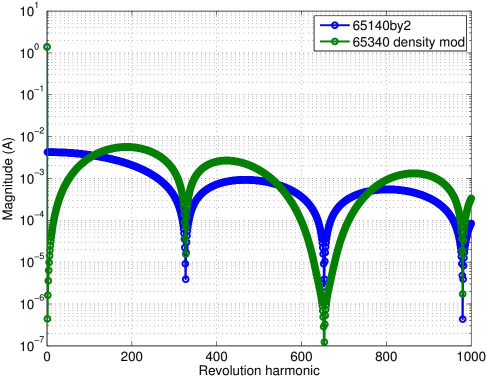

- Two fill patterns used earlier:
  - 65140by2: one long train of 65140 bunches every other RF bucket and 400 bucket gap;
  - 65340 density mod: long train with density modulation.
- Both fill pattern spectra show notches at multiples of $h/400 \approx 327$ revolution harmonics due to identical 400 bucket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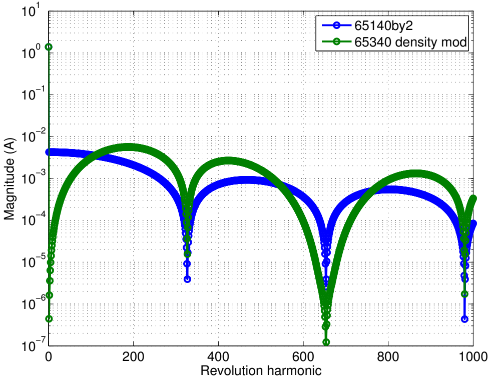

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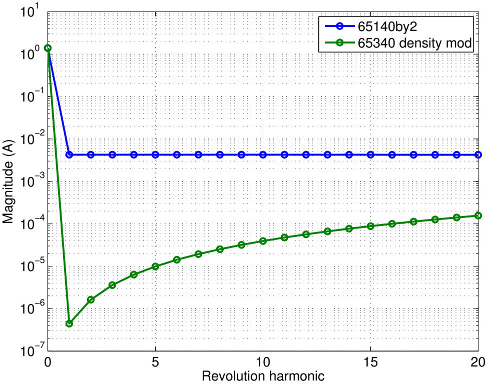

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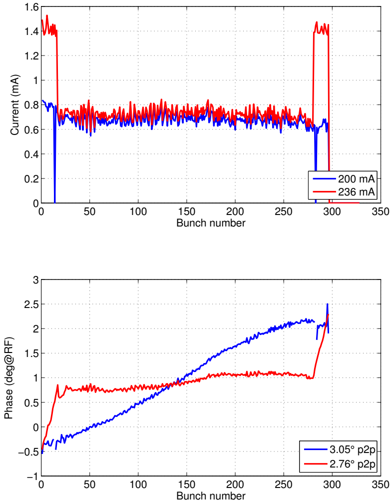

- Measurements from the Advanced Light Source in Berkeley:
  - A train of 296 buckets, 32 bucket gap;
  - Buckets 1–16 and 281–296 filled to twice the charge.
- A bit of first revolution harmonic due to the detuned harmonic cavities.

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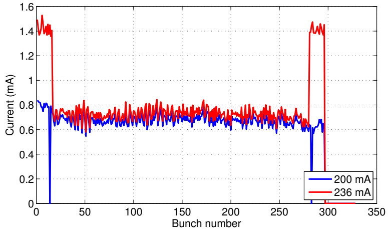

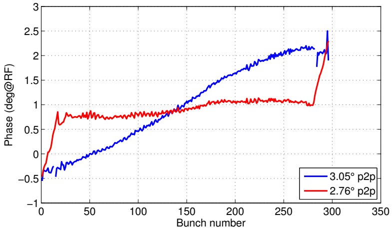

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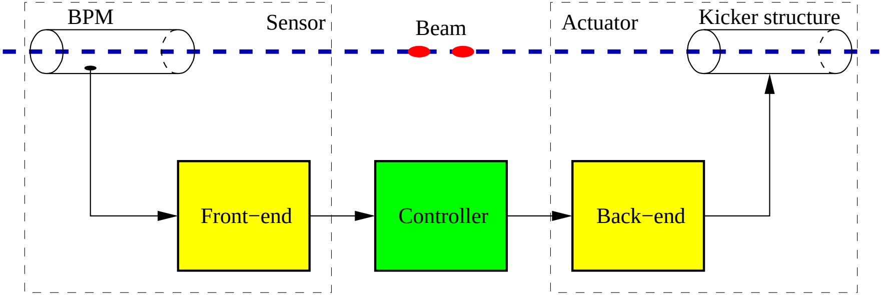
Bunch-by-bunch Feedback

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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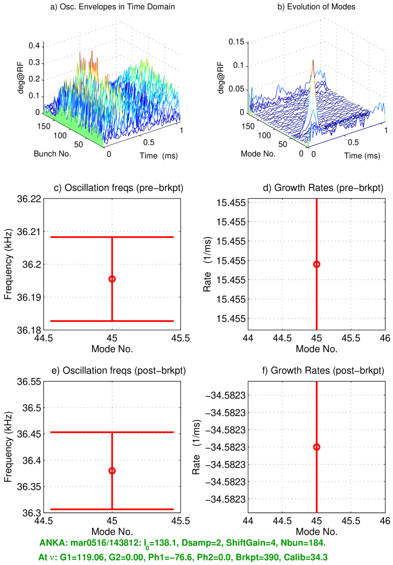

ANKA: mar0516/143812: I_0=138.1, Dsamp=2, ShiftGain=4, Nbun=184.
At ν: G1=119.06, G2=0.00, Ph1=−76.6, Ph2=0.0, Brkpt=390, Calib=34.3

- 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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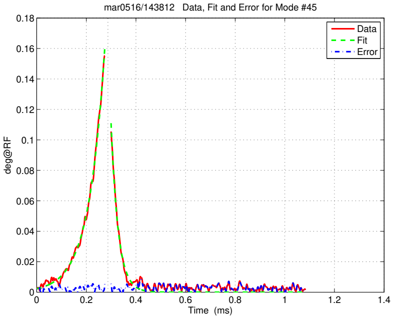

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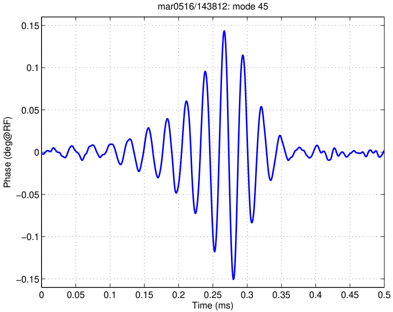

- Measured while cavity tuning walks an HOM onto a synchrotron sideband;
- Growth time is $2.3T_s$, damping time is T_s;
- Actual modal oscillation trajectory;
- Filter is $2/3$ of a synchrotron period.

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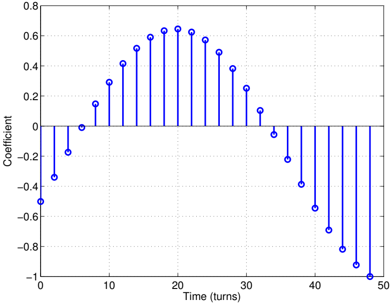

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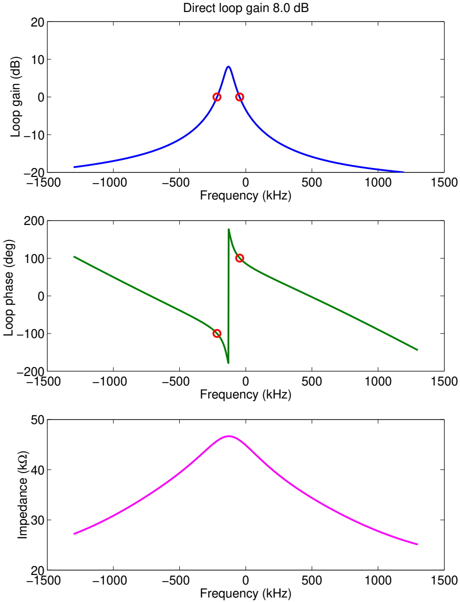
Why Two Loops



- Direct loop gain is limited by delay;
- OK at 11 dB;
- and 14 dB;
- At 17 dB we are stop impedance reduction;
- Worse at 20 dB.

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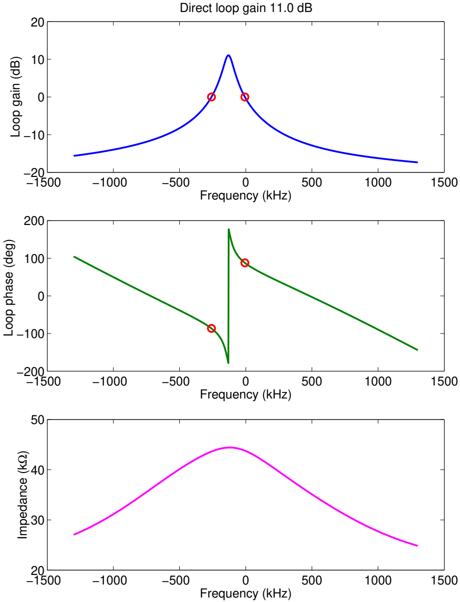

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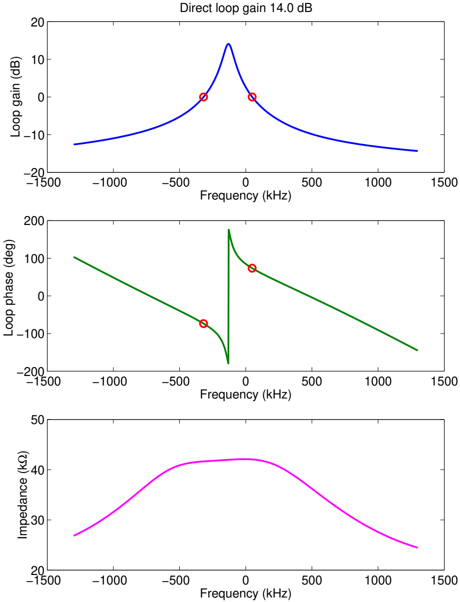

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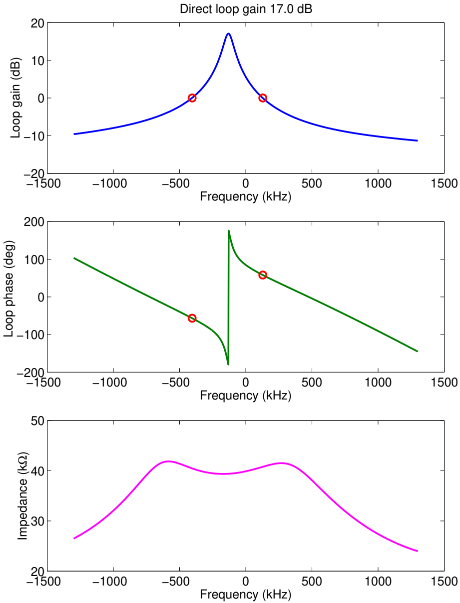

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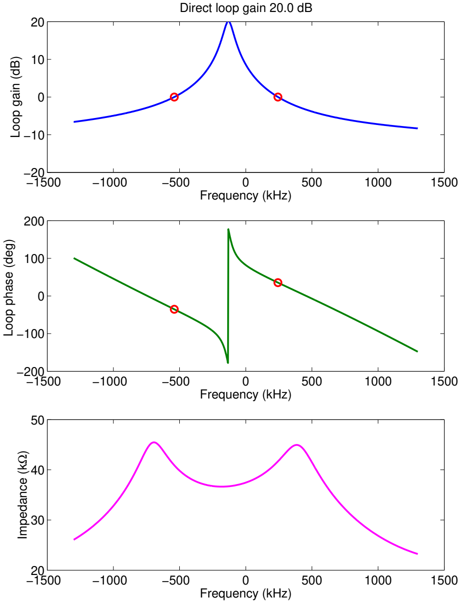

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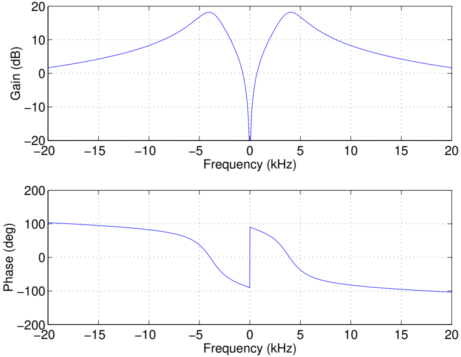
Trade Bandwidth for Gain



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

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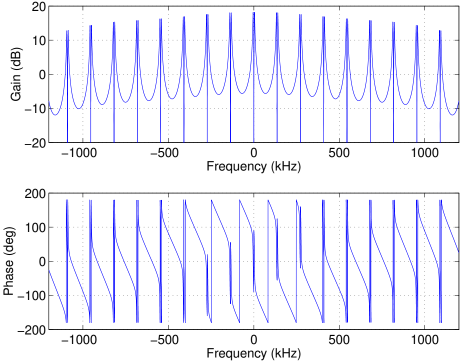

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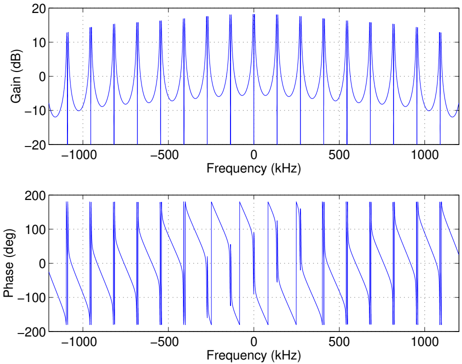

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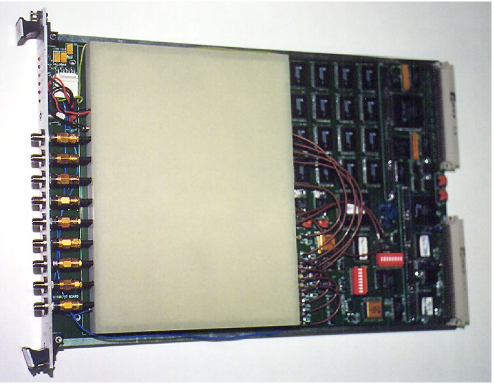
A Word About Technology: RF Processing Module



- Analog direct loop: I/Q demodulation/modulation, op-amp feedback processing;
- 86 ns delay, 3 MHz bandwidth, 450 ns total loop delay;
- Vector sum, multiple gain/phase blocks, lead/lag compensation, ripple loop DSP.

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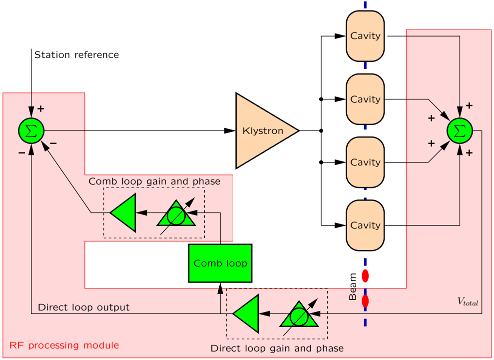

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