Longitudinal stability for the Super-PEP

Super-B Factory Workshop in Hawaii

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Outline

I. The scope of this talk

II. Fundamental impedance of RF cavities and longitudinal instabilities

III. Parameter selection procedure

IV. Evaluation of cavity options

V. Summary

The scope of this talk

Will discuss only the fundamental impedance of the RF cavities and its effect on the longitudinal coupled-bunch stability. Why?

- In the existing B Factories the fundamental impedance drives the fastest growing modes
- While one can work on damping HOM impedances the fundamental impedance cannot be reduced except at the initial machine design stage.
- Very high beam currents in the Super-PEP design mean high beam loading with attendant high detuning → likely high fundamental-driven growth rates

Not discussed:

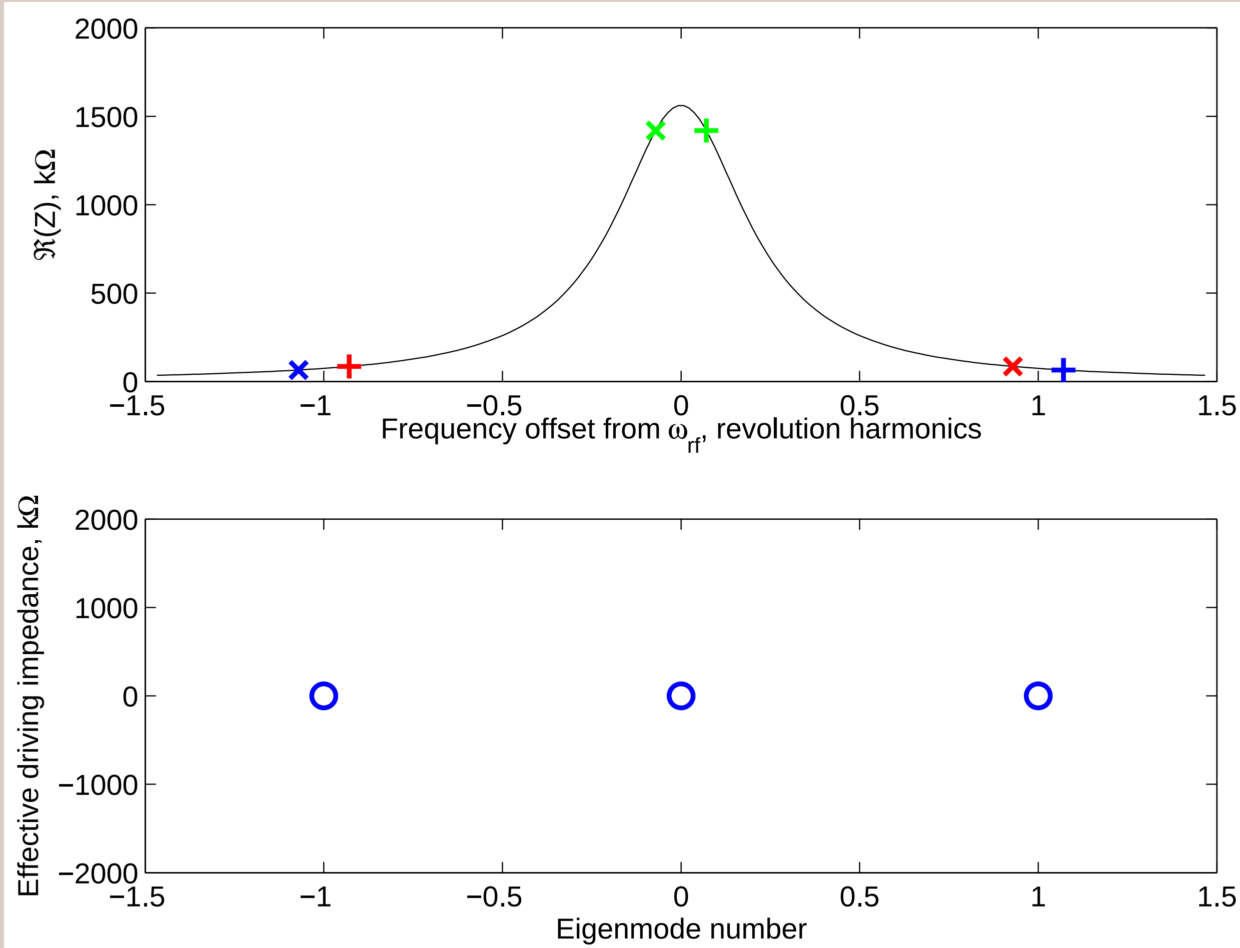
- Longitudinal
- Dipole coupled-bunch instabilities driven by the HOMs
- Higher-order intra- and inter-bunch instabilities
- Transverse
- Dipole coupled-bunch instabilities due to the resistive wall and the HOMs

Fundamental impedance and coupled-bunch instabilities

The growth rate of eigenmode -1 is proportional to the difference between the real parts of the impedance at $\omega_{rf} - \omega_{rev} + \omega_s$ and $\omega_{rf} + \omega_{rev} + \omega_s$

When the cavity is at resonance that difference is very small

However with increasing beam current the cavity center frequency is detuned below the RF frequency causing larger and larger asymmetries



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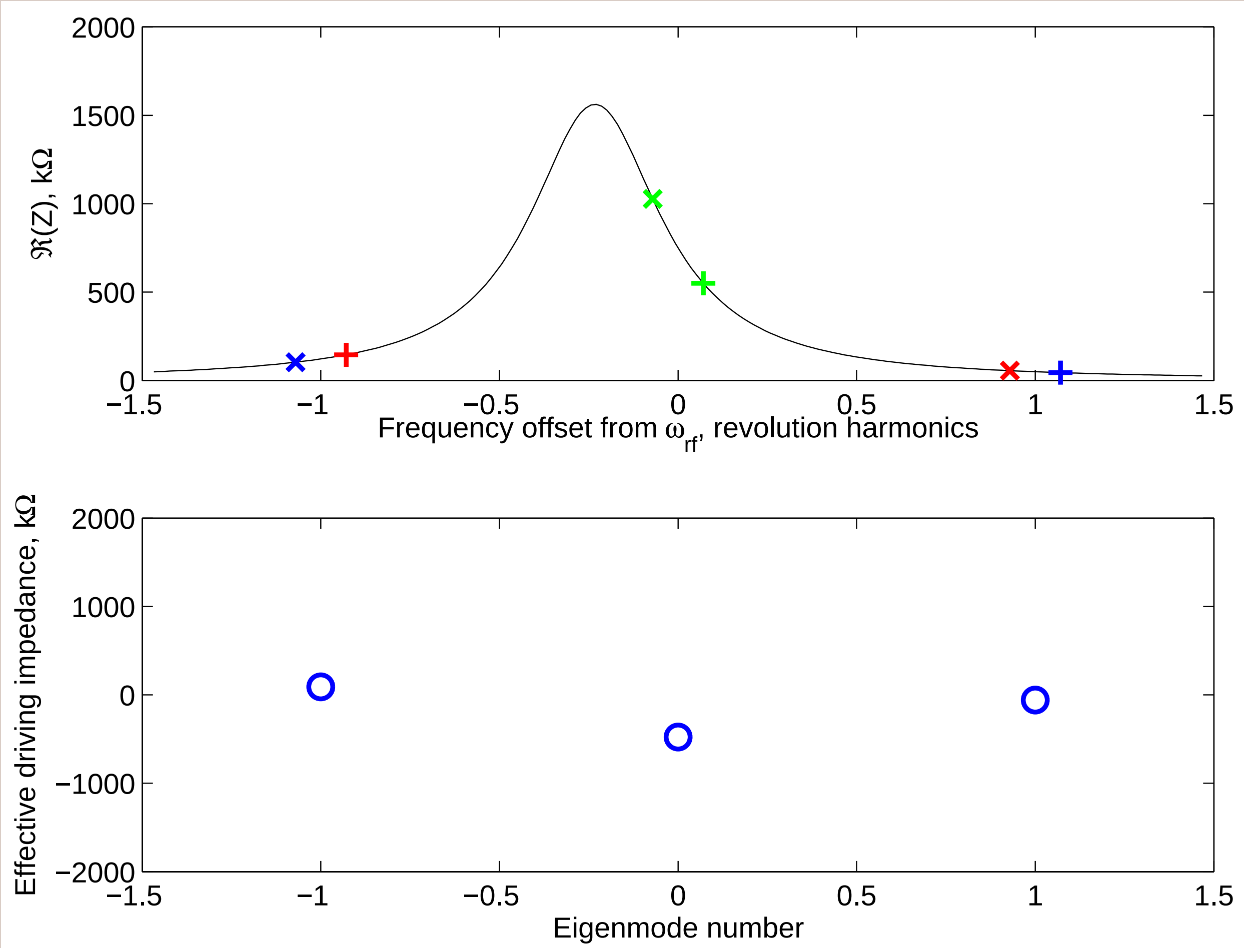

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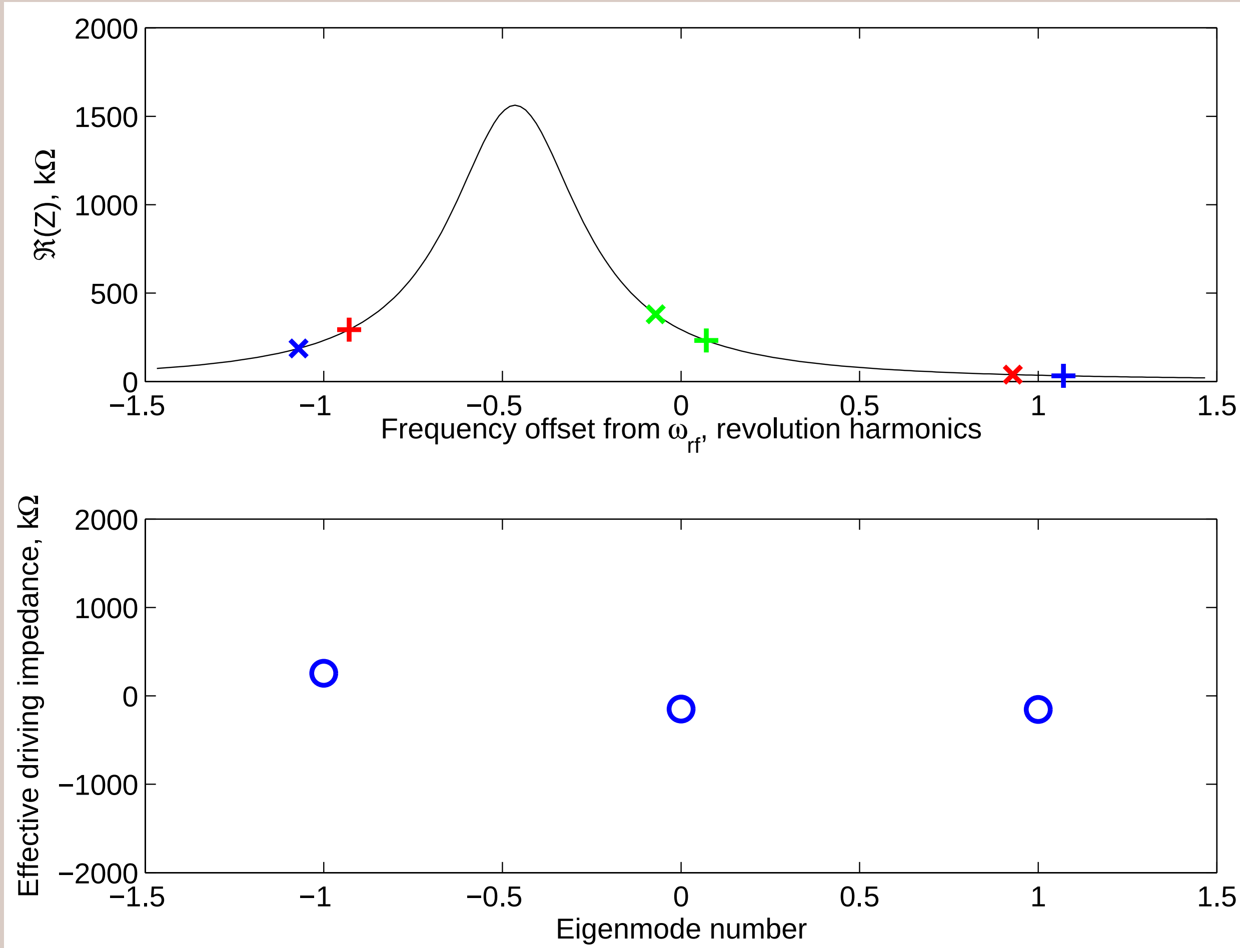

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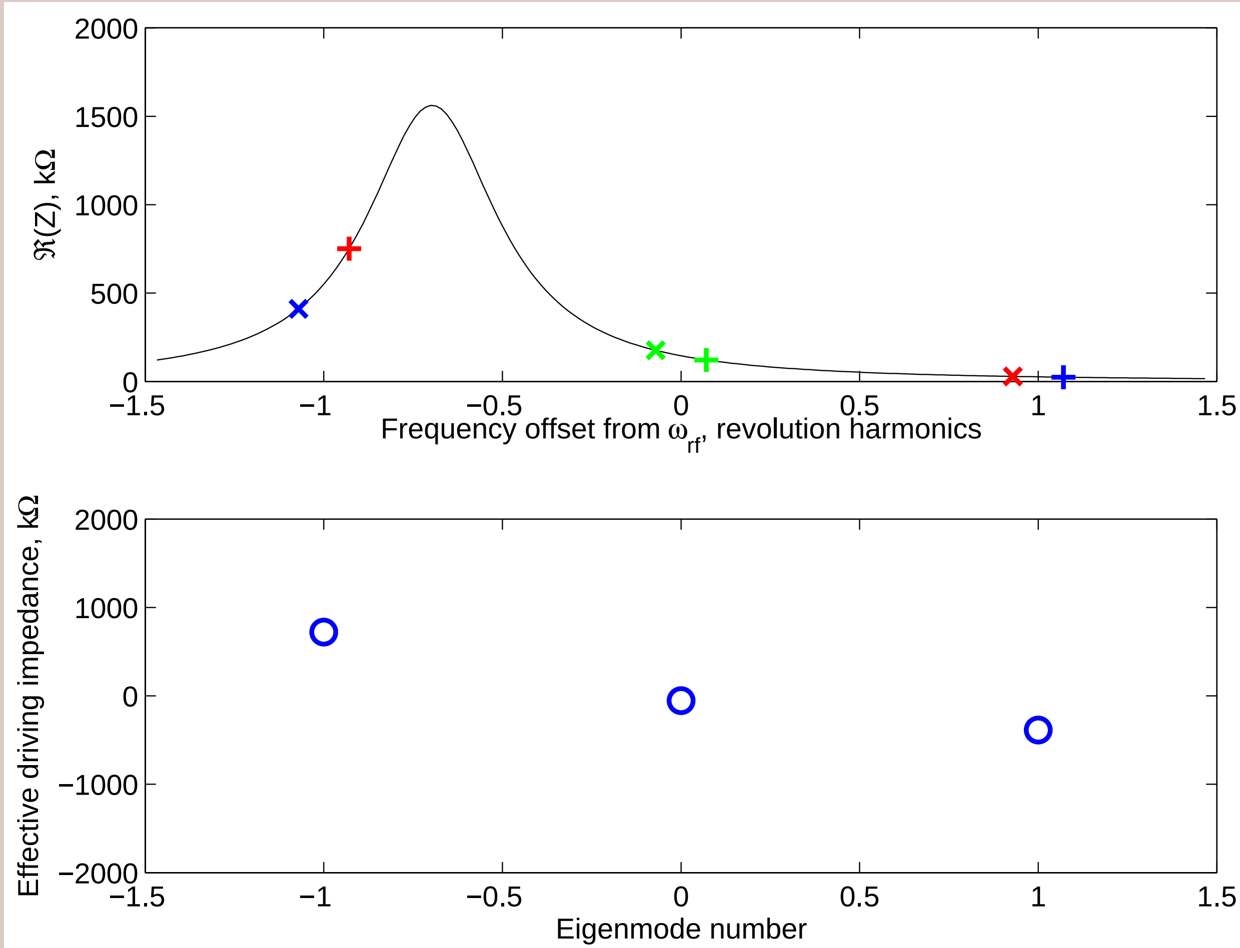

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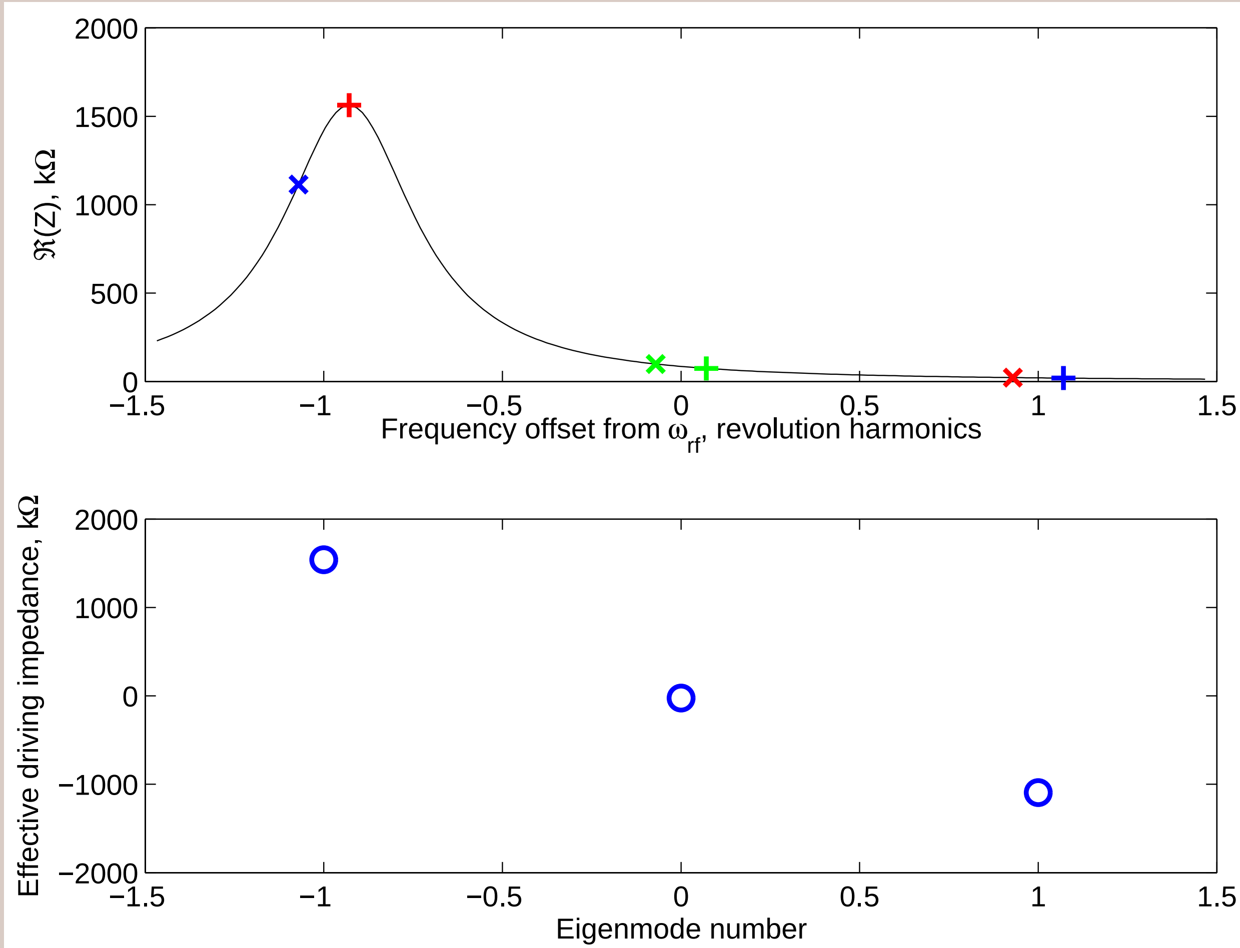

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PEP-II low-level RF feedback: impedances and growth rates

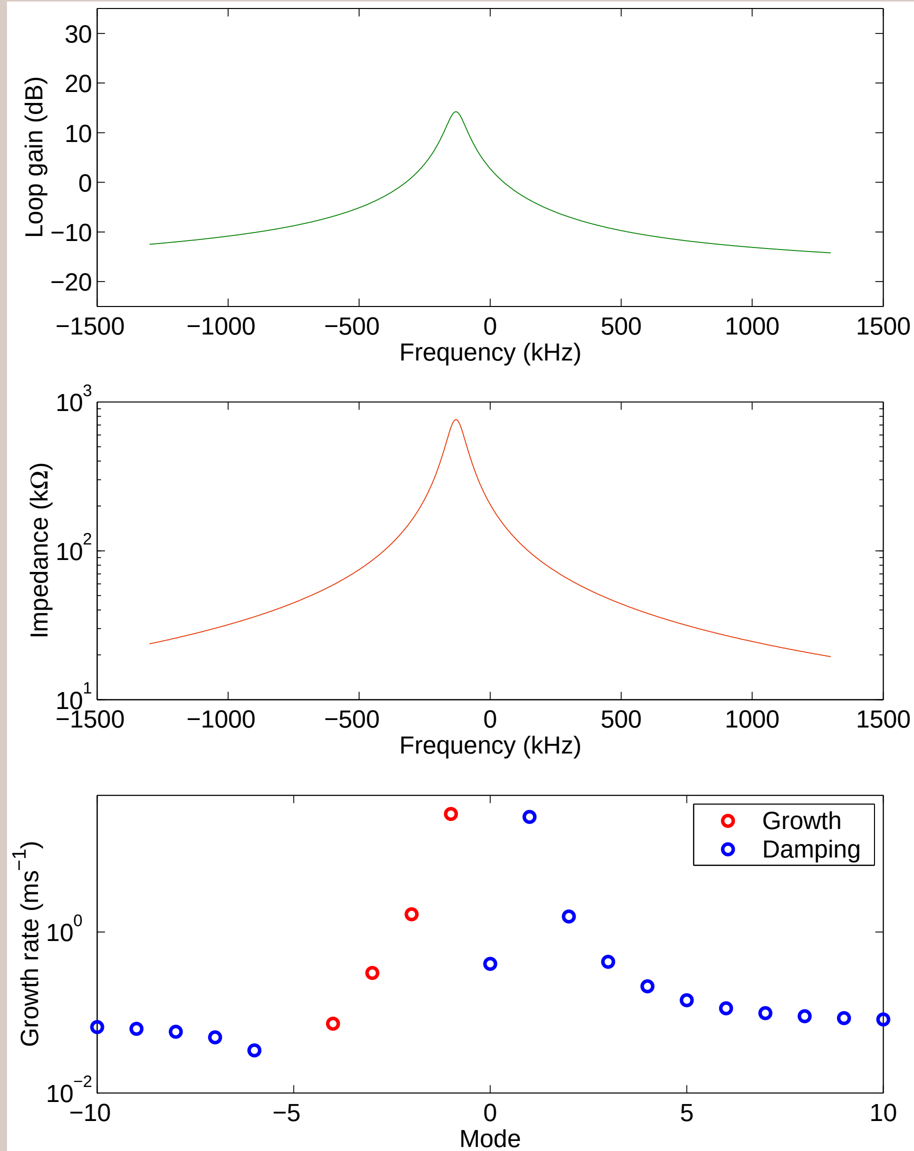
Two feedback loops are used in PEP-II to reduce the fundamental impedance acting on the beam: direct and comb.

Direct loop is a proportional feedback loop around the cavity. Closing the direct feedback loop reduces the effective impedance seen by the beam and lowers the growth rates.

To reduce the growth rates further we add the comb filter with narrow gain peaks at synchrotron sidebands.

Expected growth rates shown here are computed using a linear transfer function model of the RF feedback system.

According to the linear model the growth rate reduction is two orders of magnitude, from 30 to 0.35 ms^{-1}



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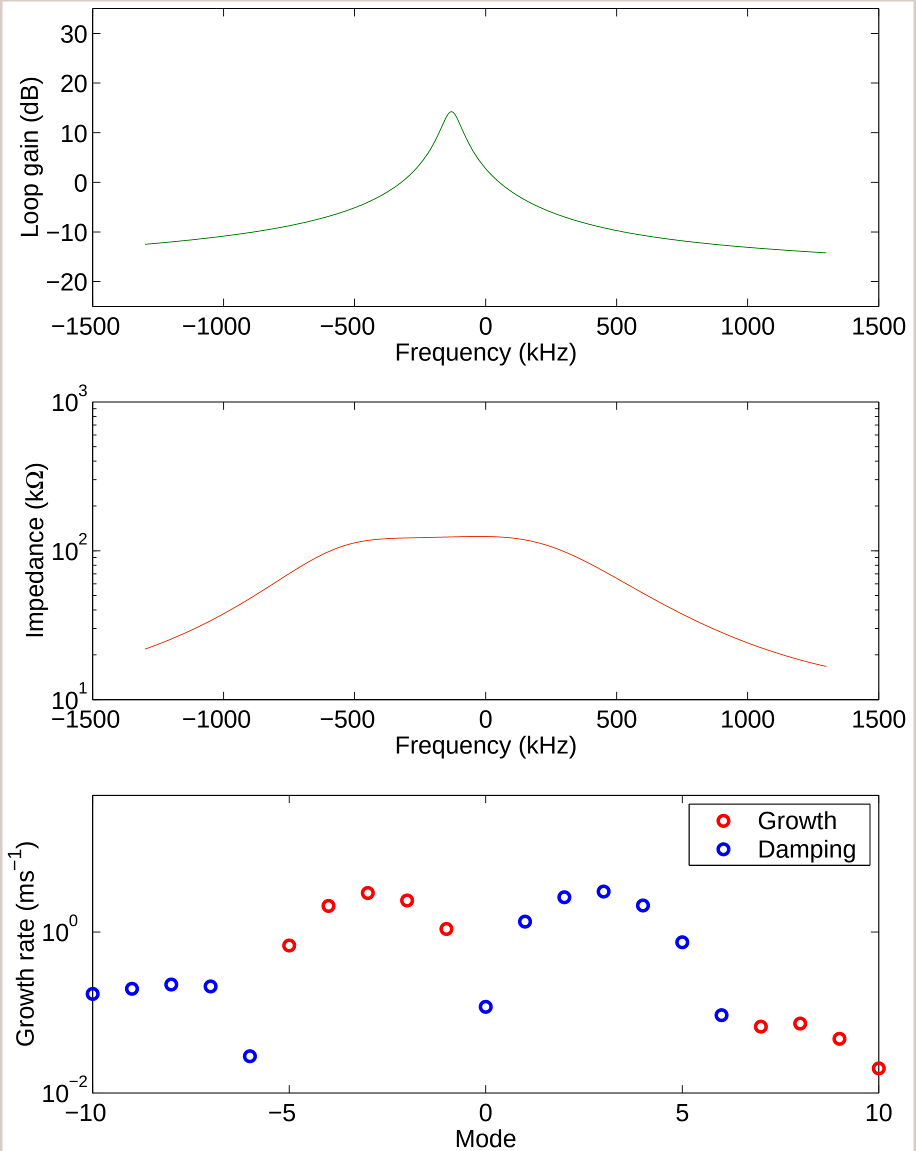

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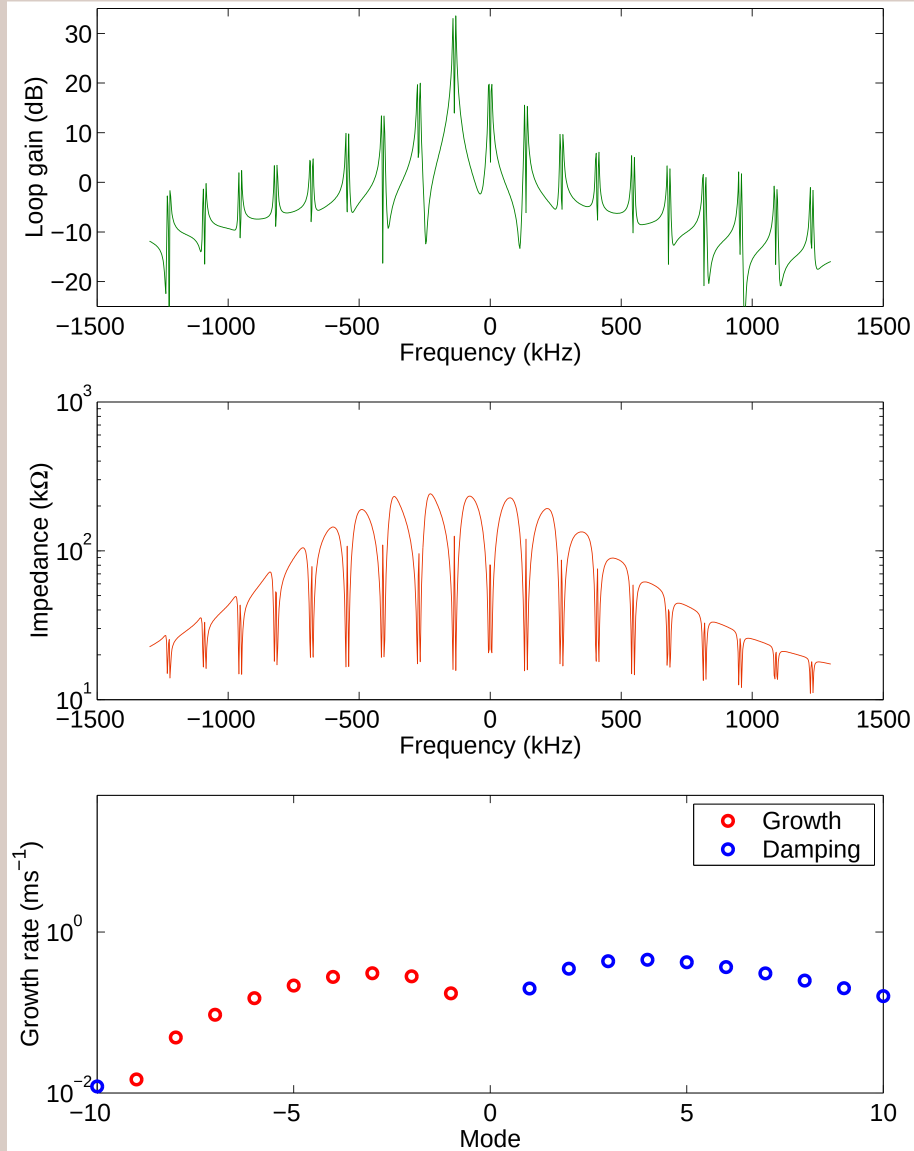

Minimizing the fundamental impedance

Minimize the number of cavities

Keep the detuning low

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

To achieve low detuning

- Need low R/Q
- It is desirable to operate the cavities at as high a voltage as possible

As A. Novokhatski and P. McIntosh showed yesterday low R/Q leads to lower cavity voltage.

Might be useful to minimize the quantity $\frac{1}{V_c} \frac{R}{Q}$

Determining the ring parameters

Start from the achievable cavity parameters:

- Power coupled to each cavity P_{g}
- Maximum cavity voltage V_{c}

Compute the total beam power requirements due to the synchrotron radiation, resistive wall and HOM losses.

Minimum number of cavities N_{c} is determined by the ratio of the beam power to the power delivered to the beam per cavity

Set the total RF voltage to the largest achievable value $N_{\mathrm{c}} V_c$

From $\sigma_z = \dfrac{\alpha \delta_E c}{\omega_{\mathrm{s}}}$ and $\omega_{\mathrm{s}}^2 = \dfrac{\alpha e \omega_{\mathrm{rf}}}{E_0 T_0} V_G$ we get $\alpha = \dfrac{\omega_{\mathrm{rf}} e V_G \sigma_z^2}{E_0 T_0 \delta_E^2 c^2}$

Desired bunch length and gap voltage set the momentum compaction for the ring. For constant bunch length the ratio α / V_G is fixed. If we push the cavity voltage higher the momentum compaction has to increase as well leading to a linear increase in the synchrotron frequency.

Assumptions

Only superconducting cavities are considered

- Conventional normal conducting cavities are unfeasible - very large wall and HOM losses, huge detuning frequencies
- Energy storage cavities have several disadvantages relative to the superconducting cavities
- Wall power loss - at the same generator power one will need more energy storage cavities than superconducting ones
- Relatively low cavity voltage - requires matching low momentum compaction which might be difficult to achieve

Synchronous phase angle is very close to π - quite reasonable for the large overvoltage factors being considered

We can couple 1 MW into each cavity

Maximum cavity voltage is 1.25 MV

- A reasonable assumption for the cavities with R/Q of 5Ω, might be too conservative for higher R/Q.

Parameter decision procedure example

LER at 3.5 GeV and 15.5 A

Synchrotron radiation loss of 15.04 MW

Resistive wall loss of 2.76 MW

HOM loss (excluding RF cavities) of 2.32 MW: total of 20.12 MW

Power delivered to the beam per cavity (loss factor of 0.36 V/pC) is 908 kW

Need 22 cavities

At 1.25 MV per cavity total gap voltage is 27.5 MV

Assuming fractional energy spread $\delta_E = 8 \cdot 10^{-4}$ for $\sigma_z = 1.8$ mm we get

$$\alpha = 3.6 \cdot 10^{-4}$$

$$f_s = 7.65 \text{ kHz}$$

Cavity options under consideration

Cavity	R/Q, Ω	I_0, A	α, 10^{-4}	N_c	Δf, kHz	P_{HOM}, kW	P_b, kW
SC952	30	15.5	3.6	23	353.6	92	908
SC952a	12		3.6	23	141.7	79	921
SC952b	5		3.6	22	60.7	72	928
SC952	30	23	6.9	42	524.7	202	798
SC952a	12		6.7	41	210.2	174	826
SC952b	5		6.6	40	90.1	158	842

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HOM power loss ranges from 7% to 20% of the input power as a function of the loss factor and the beam current.

Growth rates for different cavity designs

Here we consider three RF system configurations

- PEP-II-like LLRF feedback (direct loop + comb filter)
- Same plus klystron linearizer for better impedance reduction
- No RF feedback for cavity SC952b (R/Q of 5)

Cavity	I_0, A	Δf, kHz	R_{tot}, kΩ	Mode	Rate (sat), ms^{-1}	Rate (lin), ms^{-1}
SC952	15.5	353.6	1563	-3	10.58	2.12
SC952a		141.7	584	-3	3.95	0.79
SC952b		60.7	31.7	-1	0.43	
SC952	23	524.7	2986	-2	30	6
SC952a		210.2	1200	-3	12.05	2.41
SC952b		90.1	284	-1	5.7	

From the operational experience in many storage rings we believe that rates under 5 ms^{-1} should be controllable, higher growth rates start eroding the stability margin

Cavity design comparison

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The *R/Q* of 30Ω only works if we have linearized klystrons. Even then it is just marginal at 10^{36}

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For the *R/Q* of 12Ω existing LLRF feedback structure would be sufficient at 15.5 A, but at 23 A we would need to linearize the klystrons.

Currently a preferred choice as a good compromise between fundamental-driven growth rates and the aggressiveness in lowering *R/Q*.

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Since this cavity design was evaluated without feedback there are several unique advantages to that approach

- LLRF feedback system is eliminated.
- Klystrons can be fully saturated leading to better power efficiency.

Growth rate is relatively high at 23 A - marginal control.

- Adding LLRF feedback drops the growth rate to 3.48 ms^{-1} (0.7 ms^{-1})

Summary

Longitudinal coupled-bunch instabilities due to the cavity fundamental impedance to large extent define the RF system design for a highly beam loaded storage ring

Reducing the growth rates of such instabilities to a manageable level will most likely involve a combination of several methods

- Impedance minimization techniques
- Reducing the number of cavities
- Reducing the cavity detuning
- LLRF feedback

Superconducting cavities are the optimal choice for minimizing the instability driving impedance.

For the *R/Q* of 30Ω advanced methods of impedance reduction (currently in development) would be needed for both $7 \cdot 10^{35}$ and 10^{36} approaches.

Both *R/Q* of 12Ω and 5Ω produce acceptable growth rates at both luminosities. The choice between the two is mostly driven by other technical considerations such as HOM loss, wall power loss, presence of the LLRF feedback.