Collective Instabilities

(Strongly biased to storage rings)

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Lecture Summary

- Introduction to Storage Ring Collective Effects
- Wakefields and Impedance
- Longitudinal Multibunch collective effects and cures
  - Longitudinal coupled bunch instabilities
  - Measurements
  - Passive cures
  - The Robinson Instability
  - Harmonic RF systems
  - Feedback systems
- Transverse multibunch collective effects and cures
  - Transverse coupled bunch instabilities
  - Measurements
  - Passive cures
  - Feedback systems
  - Beam-Ion instabilities
  - Electron cloud instabilities

Lecture Summary

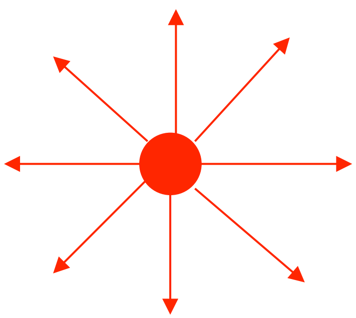
- Longitudinal single bunch collective effects
  - Short-range longitudinal wakefields and broadband impedance
  - Potential well distortion
  - Longitudinal microwave instability
  - Measurements
  - CSR microbunching instability
- Transverse single bunch collective effects
  - Short-range transverse wakefields and broadband impedance
  - Head-tail modes and chromaticity
  - Measurements
  - Damping with feedback
- Not covered here: Touschek and intrabeam scattering

Introduction to storage ring collective effects

- Instabilities can significantly affect a storage ring by increasing the average transverse beam size, energy spread, and reducing the bunch and average beam current of the ring.
- Bad news! Most instabilities effecting storage rings have been understood and cures for most are available.
- Good news! Users want more! We need to push the capabilities of existing and new machines.
- This lecture provide an qualitative overview of the collective effects in storage rings, with a strong bias towards electron storage rings. The emphasis is on
  - minimizing their negative impact wherever possible
  - experimental characterization of the effects.

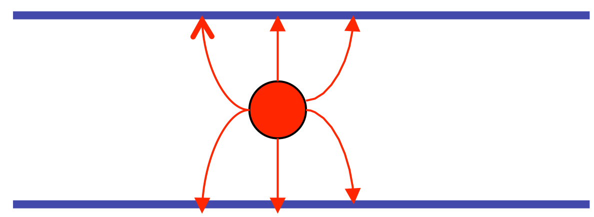
Self fields and wake fields

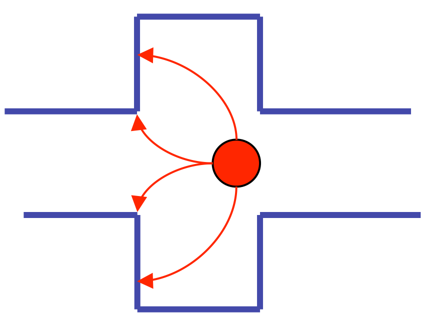
In a real accelerator, there is another important source of e.m. fields to be considered, the beam itself, which circulating inside the pipe, produces additional e.m. fields called "self-fields“:



Direct self fields

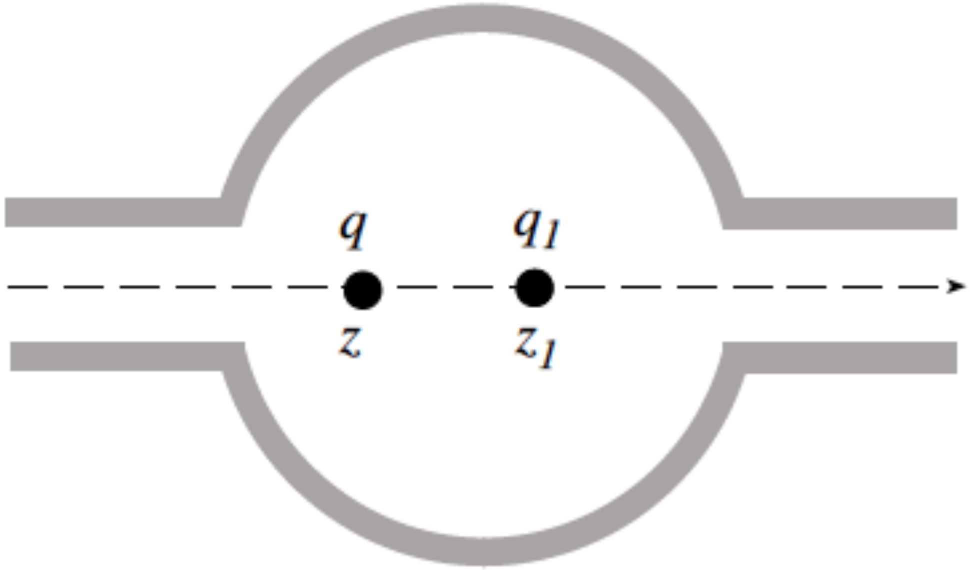
Image self fields





Wake fields

Wake Potentials



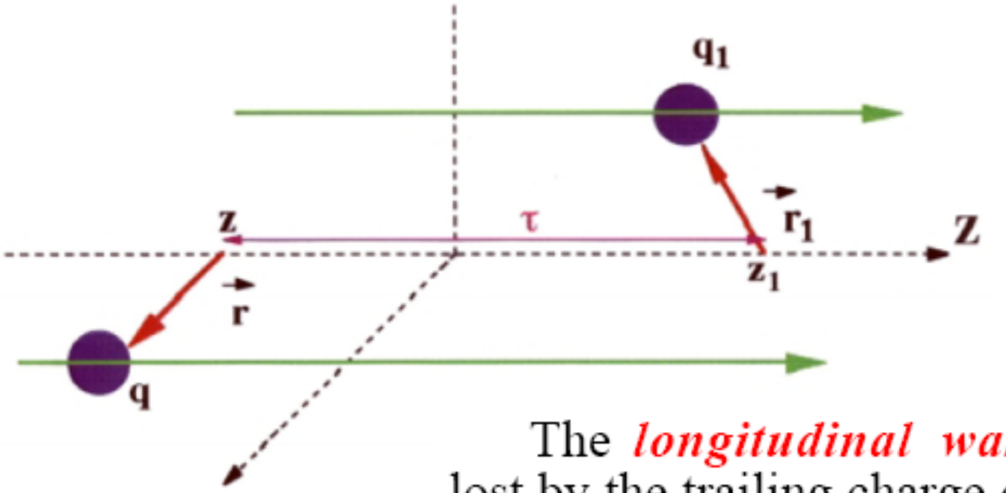
$$\boldsymbol{F} = q\left[E_z\hat{z} + \left(E_x - vB_y\right)\hat{x} + \left(E_y + vB_x\right)\hat{y}\right] \equiv \boldsymbol{F}_{//} + \boldsymbol{F}_{\perp}$$

there can be two effects on the **test charge** :

1) a longitudinal force which changes its energy,

2) a transverse force which deflects its trajectory.

Wakes and Impedances



The *longitudinal wake function* is defined as the energy lost by the trailing charge q per unit of both charges q and q1:

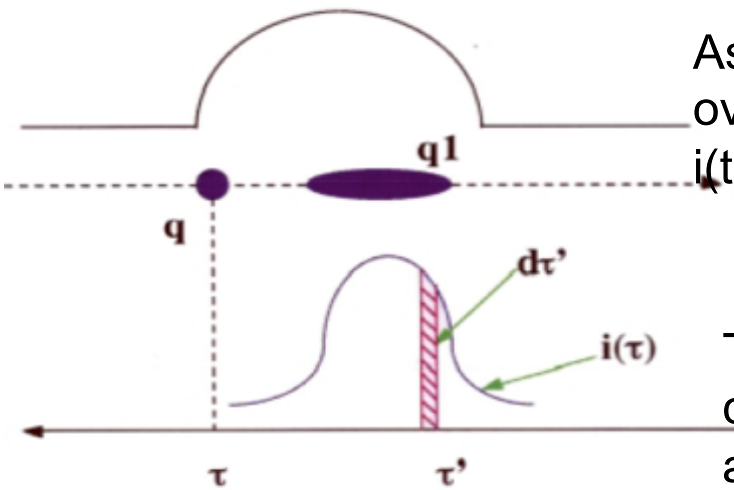
$$w_z(r,r,\tau)=\frac{\Delta U}{qq_1}=-\frac{\int_{-\infty}^{+\infty}E_z(r,z,r_1,z_1;t)dz}{qq_1}; \quad t=\frac{z_1}{v}+\tau \qquad [V/C]$$

where qEz is the longitudinal component of the Lorentz force.

The *coupling impedance* or *beam impedance* is defined as the Fourier transform of the wake function:

$$Z(\omega)=\int w_z(\tau)e^{-j\omega\tau}d\tau$$

Effect of a bunch distribution



Assume that the charge q1 is continuously distributed over z-axis according to the current distribution function i(t) such that:

$$q_1 = \int_{-\infty}^{+\infty} i(\tau) d\tau$$

The wake function $w_z(t)$ being generated by a point charge is a Green function (i.e. impulse response) and allows to compute the *wake potential* of the bunch distribution:

$$W_z(\tau) = \frac{1}{q_1} \int_{-\infty}^{+\infty} i(\tau') w_z(\tau - \tau') d\tau' \quad [V/C]$$

We can use this version of *Ohm's Law* if we know the impedance and the current in the frequency domain.

A convolution in the time domain is a product in the frequency domain.

$$\boxed{q_1 W_z(\omega) \equiv V_z(\omega) = I(\omega) Z(\omega)}$$

Example Wakes: Resonant Cavity

- The longitudinal wake of a resonant cavity is given by

$$V_b(\tau) = \begin{cases} 0, & \text{for } \tau < 0; \\ 2q_1 k e^{\gamma\tau} \left(\cos\omega_1\tau - \frac{\gamma}{\omega_1}\sin\omega_1\tau\right), & \text{for } \tau \geq 0 \end{cases}$$

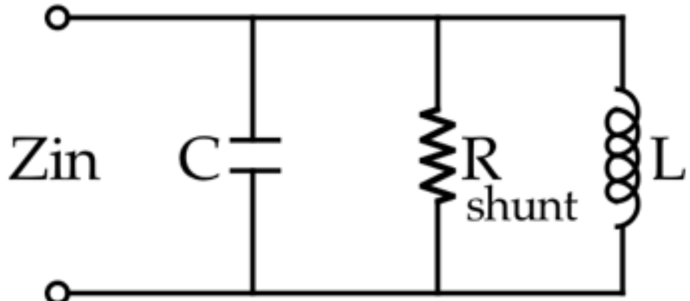
where

$$\gamma = \frac{\omega_r}{2Q},\ \omega_1 = \omega_r\sqrt{1 - \frac{1}{4Q^2}}; \qquad k = \omega_r R_s/2Q.$$

In the frequency domain, the wake becomes an impedance given by

$$Z_{\|}(\omega) = \frac{R_s}{1 + jQ\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)}.$$

Parallel Resonant Circuit Model



parallel resonant circuit

$$Z_{in} = \left(\frac{1}{R} + \frac{1}{j\omega L} + j\omega C\right)^{-1}$$

$$= \frac{R}{1 + jQ\left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right)}$$

$$\approx \frac{R}{1 + jQ2\left(\frac{\delta\omega}{\omega_o}\right)}$$

- Treat impedance of an isolated cavity mode as a parallel LRC circuit
- Voltage gained is given by

$$P_{loss} = \frac{1}{2}\frac{V^2}{R_s}$$

$$\frac{R}{Q} = \sqrt{\frac{L}{C}} = \frac{1}{\omega C} = \omega L$$

$$\omega_o = \frac{1}{\sqrt{LC}}$$

$$Q = \frac{R}{\omega_o L}$$

$$= \omega_o RC$$

Resonant cavity: Quality Factor

Quality Factor Q_0:

$$Q_0 \equiv \frac{\text{Energy stored in cavity}}{\text{Energy dissipated in cavity walls per radian}} = \frac{\omega_0 U}{P_{diss}}$$

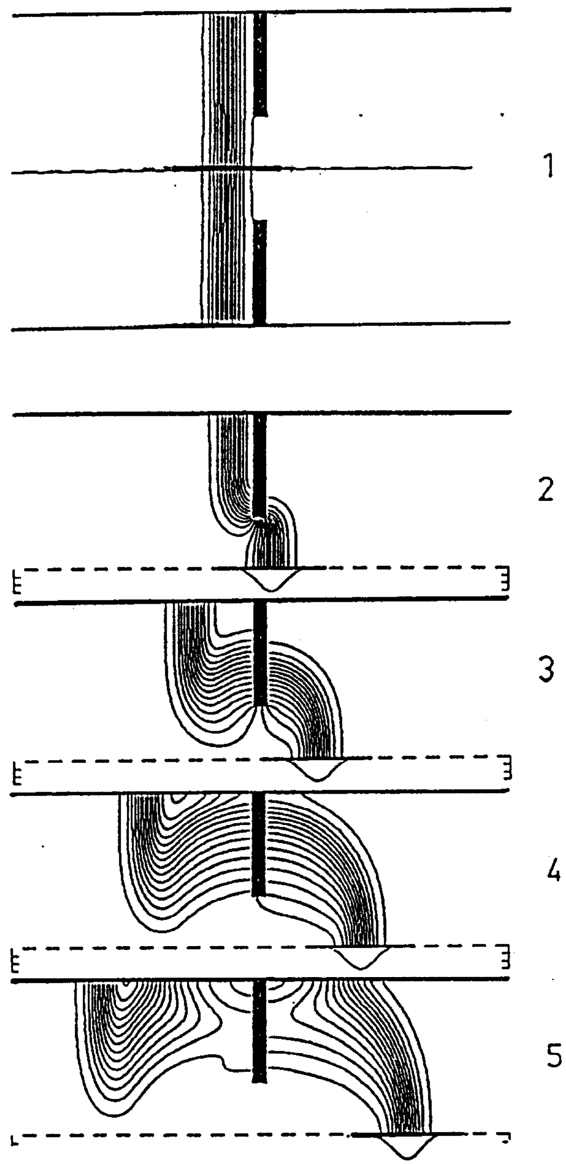
$$= \omega_0 \tau_0 = \frac{\omega_0}{\Delta\omega_0}$$

$$Q_0 = \frac{\omega\mu_0}{R_s} \frac{\int_V dV \, |\mathbf{H}|^2}{\int_A da \, |\mathbf{H}_{||}|^2}$$

Lower surface resistance gives higher Q. For a given R/Q, this gives higher R. Lower external power is required for a given voltage V.

Example Wakes: broadband impedance

- Short-range wakes are usually defined as those where the field damps away before the next RF bucket.
- Many vacuum chamber components contribute to the short-range wakes. In the frequency domain, these are known as the broadband impedance.
- The broadband impedance drives single bunch instabilities.
- Much more on this later.



Impedance properties

- Because the wake function is causal, the impedance has several properties
- The impedance is a complex quantity
  - Real (resistive) and Imaginary (reactive)

$$Z(\omega) = Z_r(\omega) + j\,Z_i(\omega)$$

  - Z_r and Z_i are even and odd functions of omega, respectively

$$Z_r(\omega) = Z_r(-\omega)$$

$$Z_i(\omega) = -Z_i(-\omega)$$

- The real and imaginary parts are related via a Hilbert transform

$$\int_{-\infty}^{\infty} Z_r(\omega)\, cos(\omega\tau) d\omega = \int_{-\infty}^{\infty} Z_i(\omega)\, sin(\omega\tau) d\omega$$

$$Im(Z_{||}(\omega)) = \frac{1}{\pi}\int_{-\infty}^{\infty} d\omega' \frac{Re(Z_{||}(\omega))}{\omega' - \omega}.$$

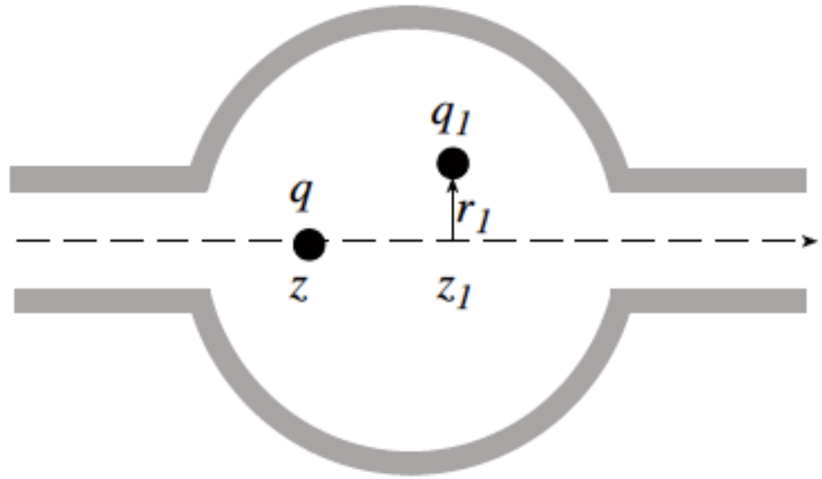
Transverse Wake Potential

- The transverse wake function is the kick experienced by the trailing charge per unit of both charges:

$$w_\perp(\tau) = \frac{\Delta p_\perp}{q q_1} = \frac{q \int\limits_{-\infty}^{+\infty} (E + v \times B)_\perp dz}{q q_1}; \quad t = \frac{z_1}{v} + \tau$$

- The transverse coupling (beam) impedance is found by the Fourier transform of the wake function:

$$Z_\perp(\omega) = j \int\limits_{-\infty}^{+\infty} w_\perp(\tau) e^{-j\omega\tau} d\tau \qquad [\Omega]$$



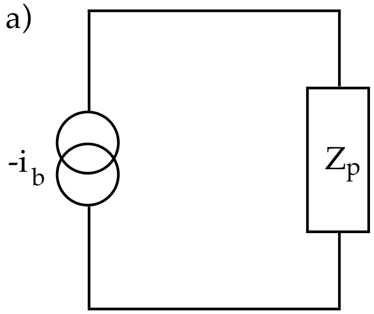
- Since the transverse dynamics is dominated by the dipole transverse wakes, we can define the transverse dipole impedance per unit transverse displacement:

$$Z'_\perp = \frac{Z_\perp(\omega)}{r_1} \qquad [\Omega / m]$$

Beam signals

- The response of the circuit to a current I is the convolution of the current with impulse response of the circuit.
- Strategy: derive the beam signal in time and frequency domain and either convolve or multiply with PU response.

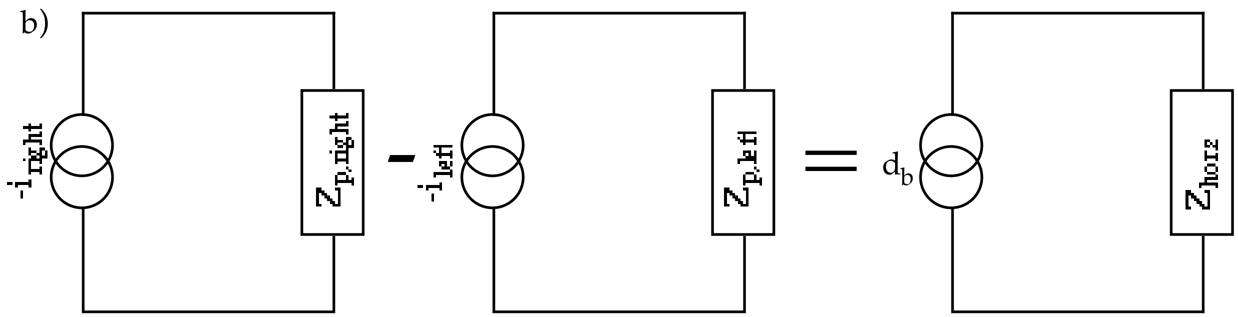
a)



$$V(t) = \int_{-\infty}^{\infty} dt' i(t') W_p(t - t')$$

$$V(\omega) = \tilde{i}(\omega) Z_p(\omega)$$

b)



Single Particle Current

- Consider a point particle going around a storage with revolution period T_0 and rotation frequency $f_0=1/T0$. The current at a fixed point in the ring is given by

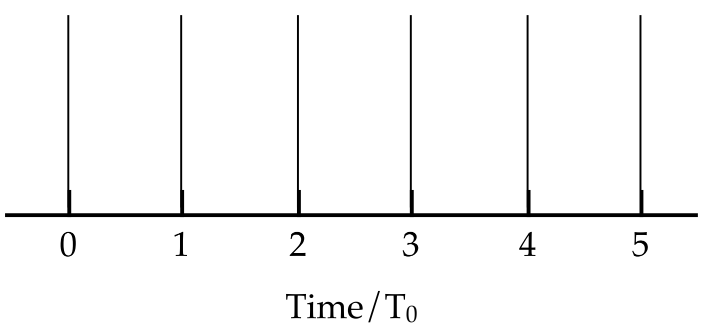
$$i(t) = e\sum_{n=-\infty}^{n=+\infty}\delta(t-nT_0) = e\,\omega_0\sum_{n} e^{jn\omega_0 t}$$

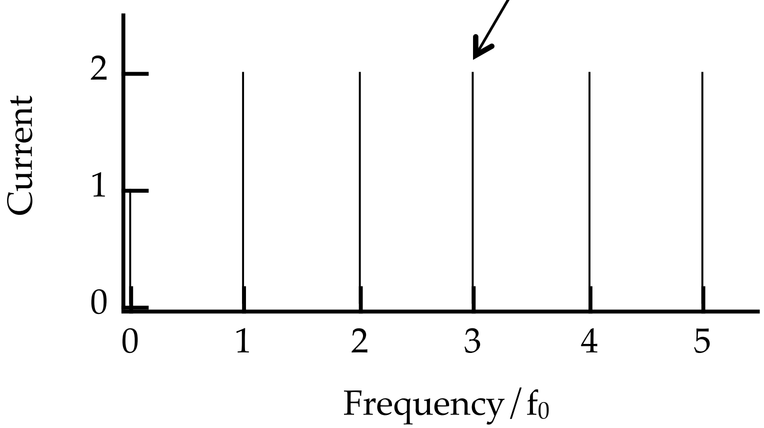
$$= ef_0 + 2ef_0\sum_{n=1}^{\infty}\cos(n\omega_0 t)$$

The FT of this given by

$$I(\omega) = e\,\omega_0\sum_{k}\delta(\omega-k\omega_0)$$

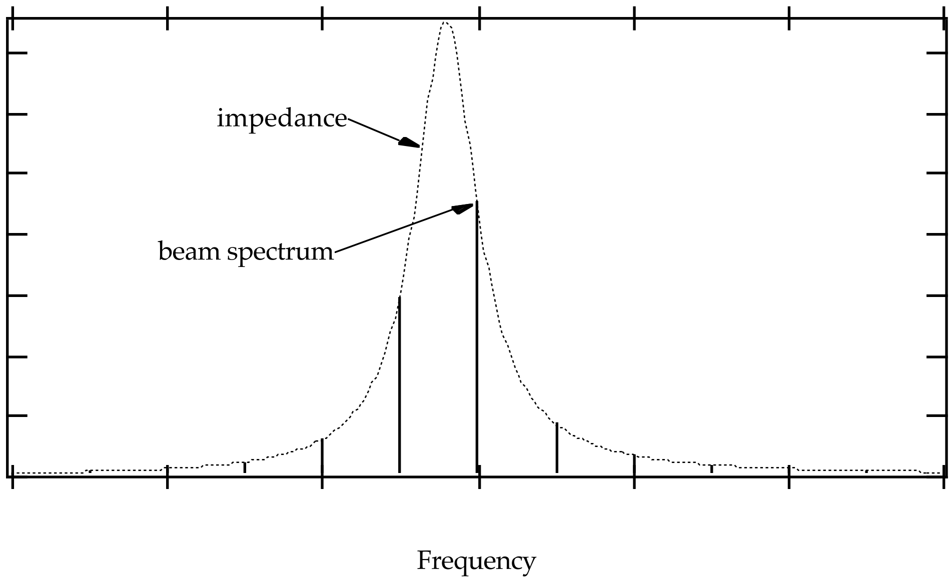
(Negative frequency components can be folded onto positive frequency. AC components are 2X DC component.)





Example: resonant cavity

- Given a particular fill pattern or bunch spectrum, how do we calculate the signal induced in a RF cavity or a pickup? If the cavity or pickup represent a beam impedance Z||(w), (with a corresponding impulse response W(t)), the total signal out is a convolution of the input with the response. In the frequency domain, this is just a multiplication of the beam spectrum with the impedance.



$$V(\omega)=I(\omega)Z_{||}(\omega)$$

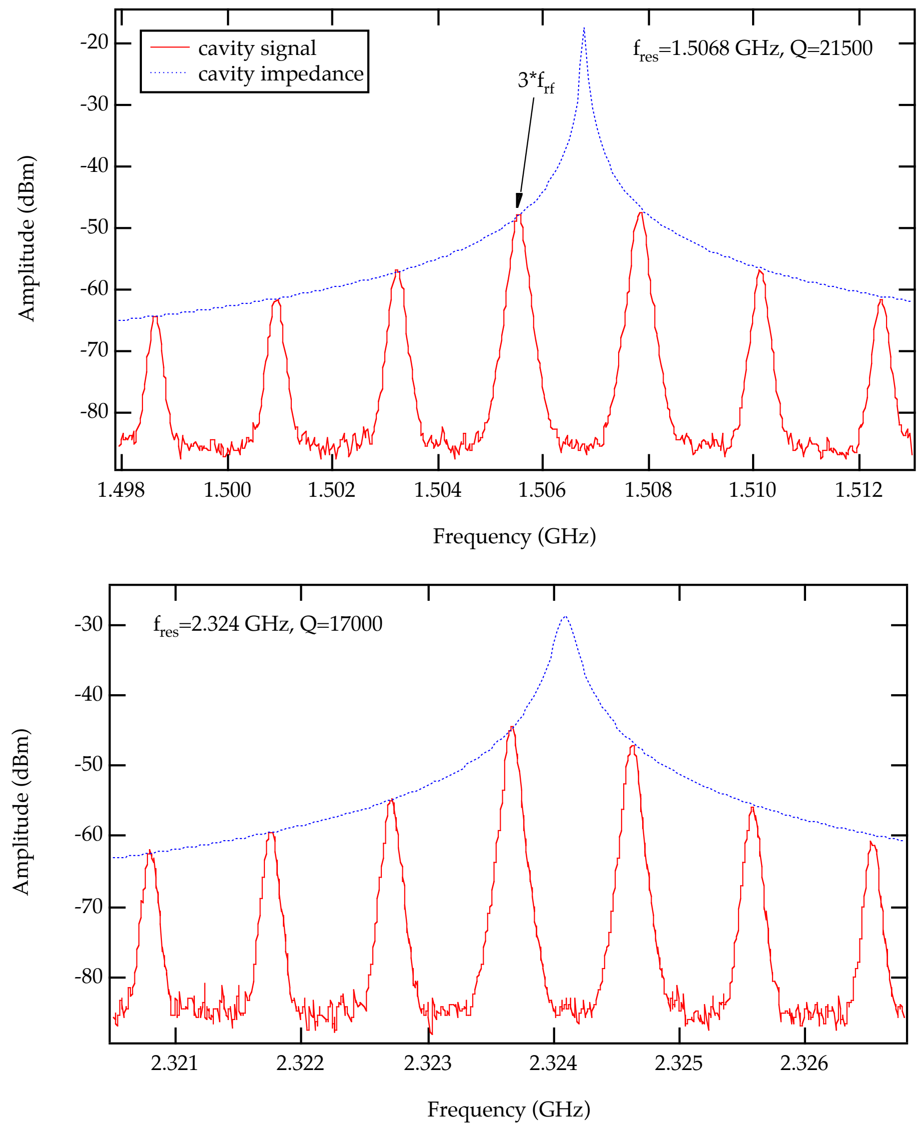
$$P=\left(\frac{1}{2\pi}\right)^2\sum_{n=0}^{\infty}|I(n\omega_0)|^2 Z_{||}(n\omega_0)$$

$$V(t)=\frac{1}{2\pi}\sum_{n=0}^{\infty} I(n\omega_0)Z_{||}(n\omega_0)e^{jn\omega_0 t}$$

Example: ALS Harmonic Cavity

The high-Q cavity modes can be tuned using the single bunch spectrum excited in the cavity probe. The Q and frequency can be found to fairly high accuracy using this method.

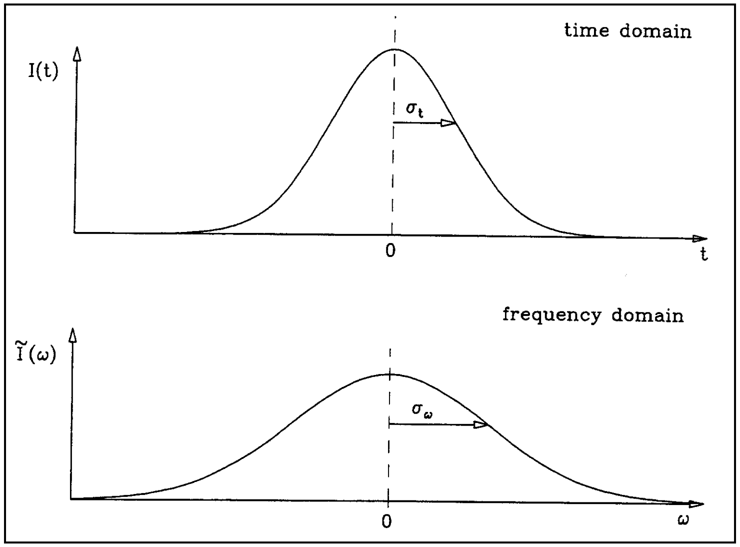
We regularly use this technique to tune the fundamental and TM011 (first monopole HOM).

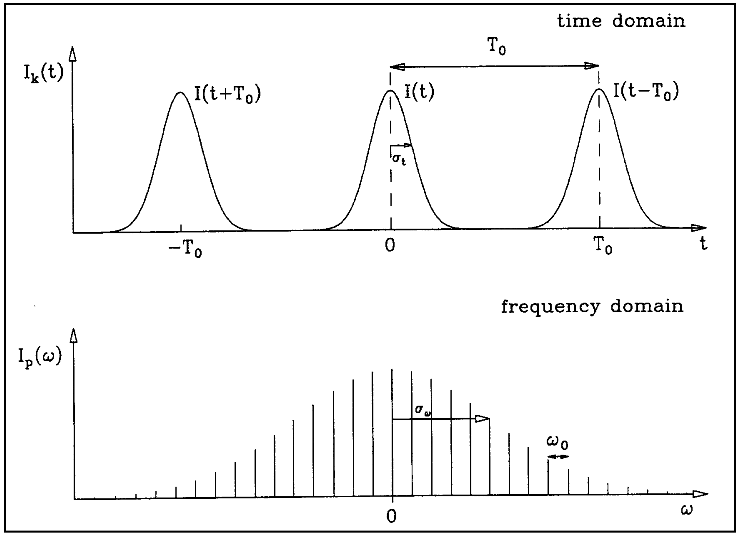


Spectrum of bunch distribution

- The bunch is a distribution of particles
- For a single bunch passage, the spectrum is just the transform of the bunch

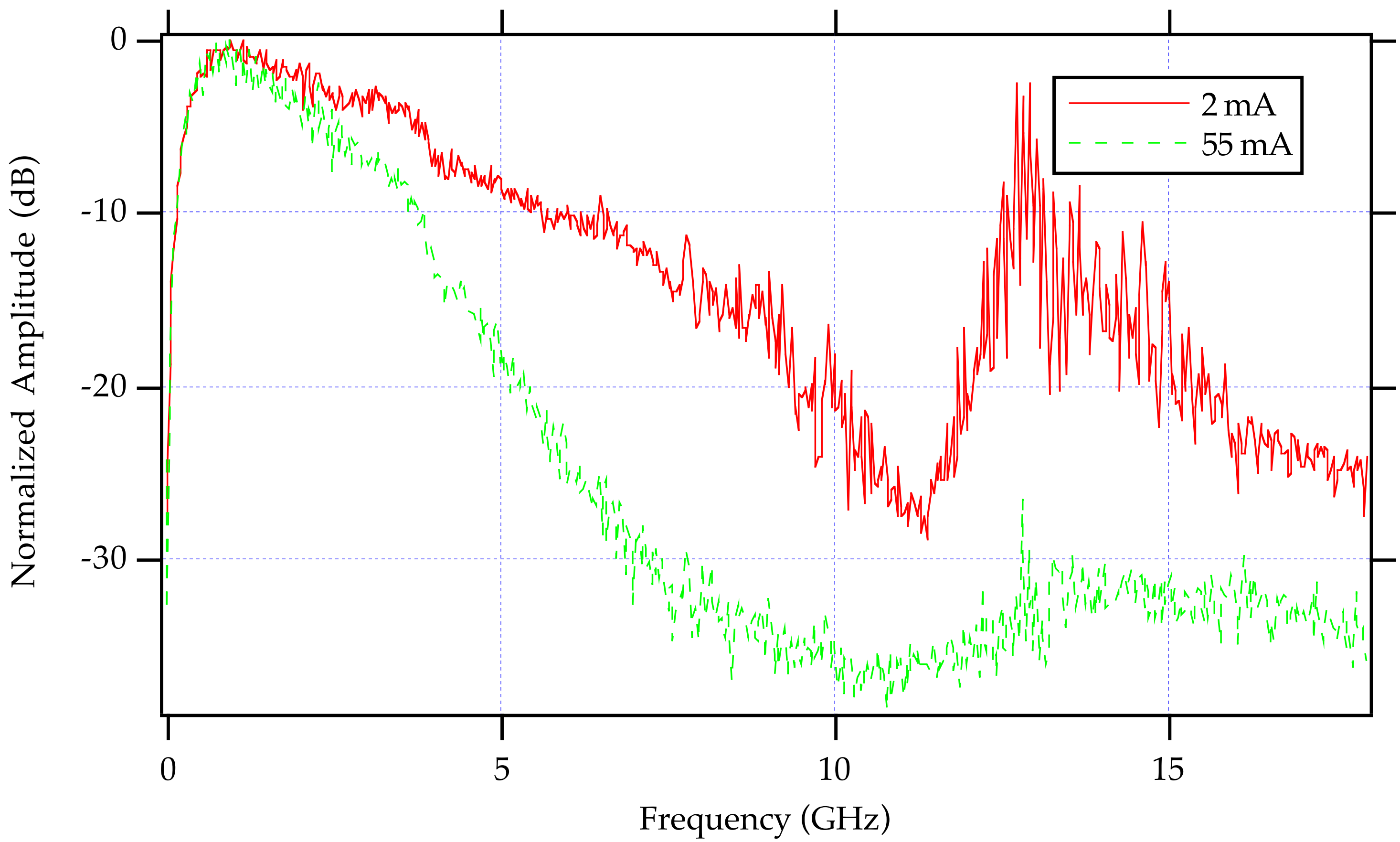
- For a repetitive bunch passage, the spectrum is the series of comb lines with an envelope determined by the single passage spectrum
- Assumes the bunch distribution is stationary. More on this later.





Example: Broadband bunch spectra

- Measured spectrum on a spectrum analyzer is the product of the bunch spectrum and the pickup impedance (button pickup, feedthru, cable)



Single particle signal w/synchrotron oscillations

- Now add synchrotron oscillations with an amplitude tau

$$i(t)=e\sum_n \delta(t-nT_0+\tau_s\cos(\omega_s t))$$

The FT of this given by

$$I(\omega)=e\,\omega_0\sum_n e^{-jn\omega_0(t+\tau_s\cos\omega_s t)}$$

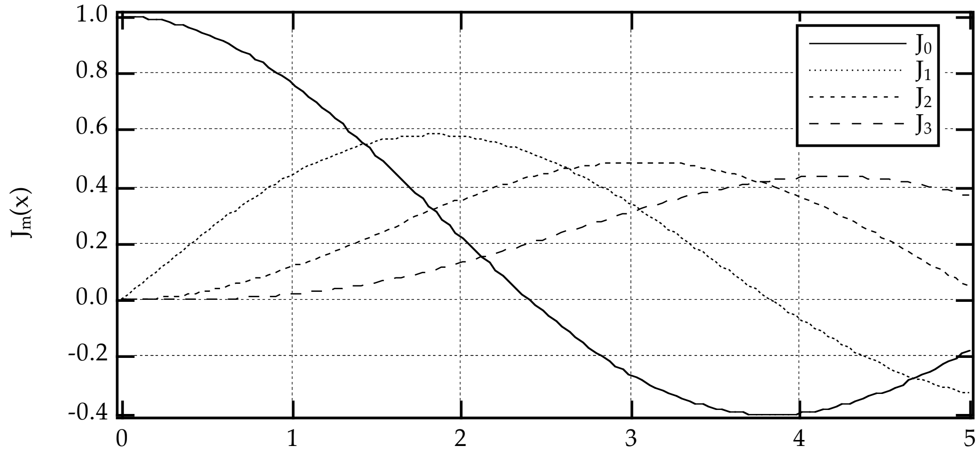
$$=e\,\omega_0\sum_m j^{-m}J_m(\omega\tau_s)\sum_k \delta(\omega+m\omega_s-k\omega_0)$$

$$e^{jx\cos\theta}=\sum_m j^m J_m(x)e^{jm\theta}$$

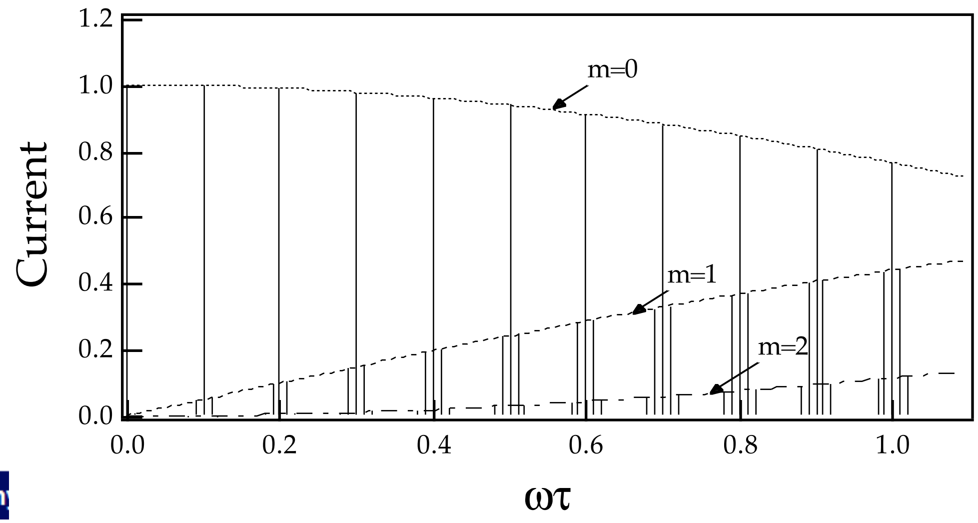
The sideband spectrum is very similar to that of phase (or frequency) modulated signals

Single particle signal w/synchrotron oscillations

- The comb spectrum has added FM sidebands which are contained within Bessel function envelopes.



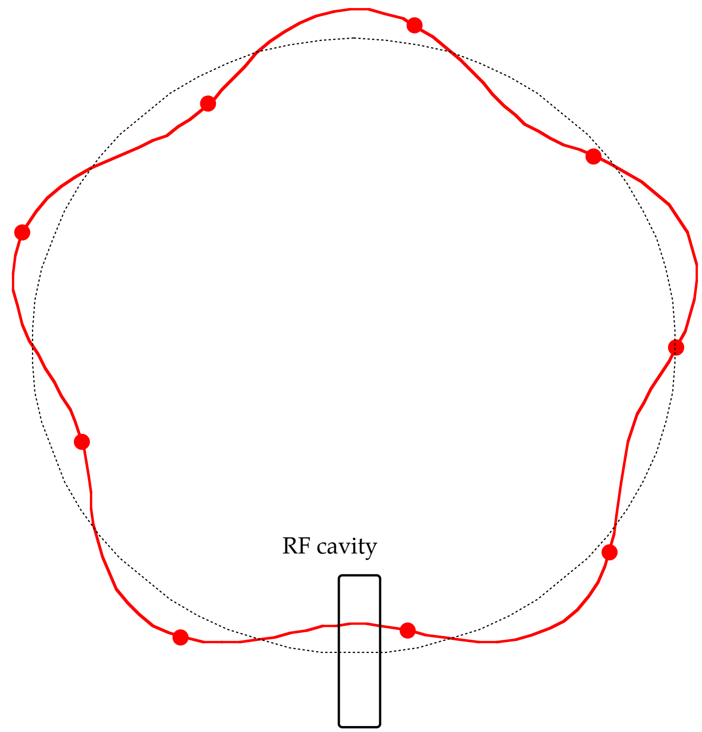
Rotation harmonics follow J_0, first order sidebands follow J_1, etc.



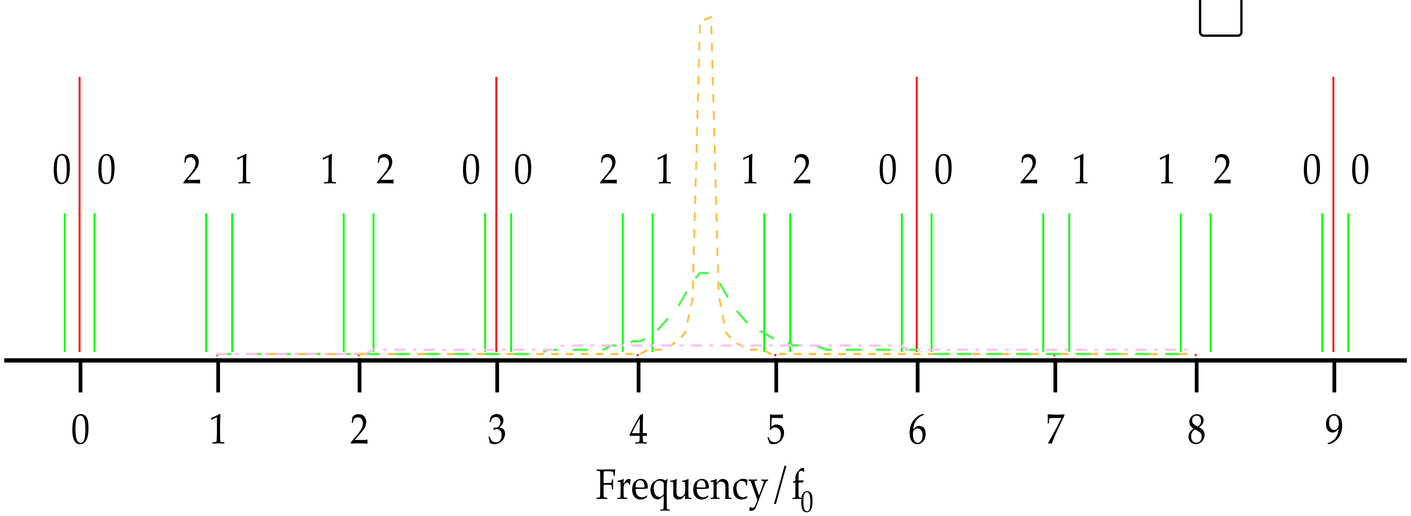
Note that J0~1 and J1~x for x<<1

Introduction to coupled bunch instabilities

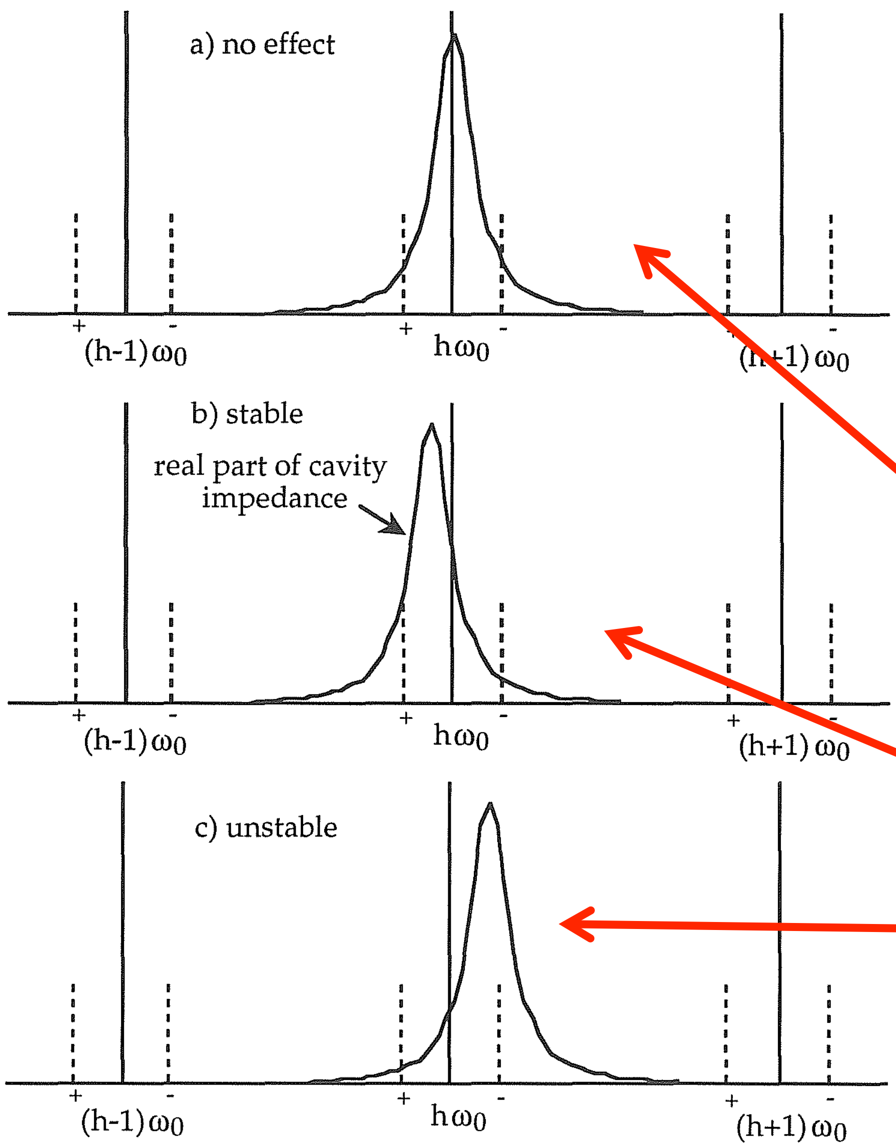
Wake voltages which last long enough to affect a subsequent bunch can couple the synchrotron or betatron oscillations. Under certain circumstances, this results in exponential growth of the oscillations, degrading the beam quality.



In the frequency domain, the normal modes appear as upper and lower sidebands. The stability of a mode depends of the overlap with impedances.

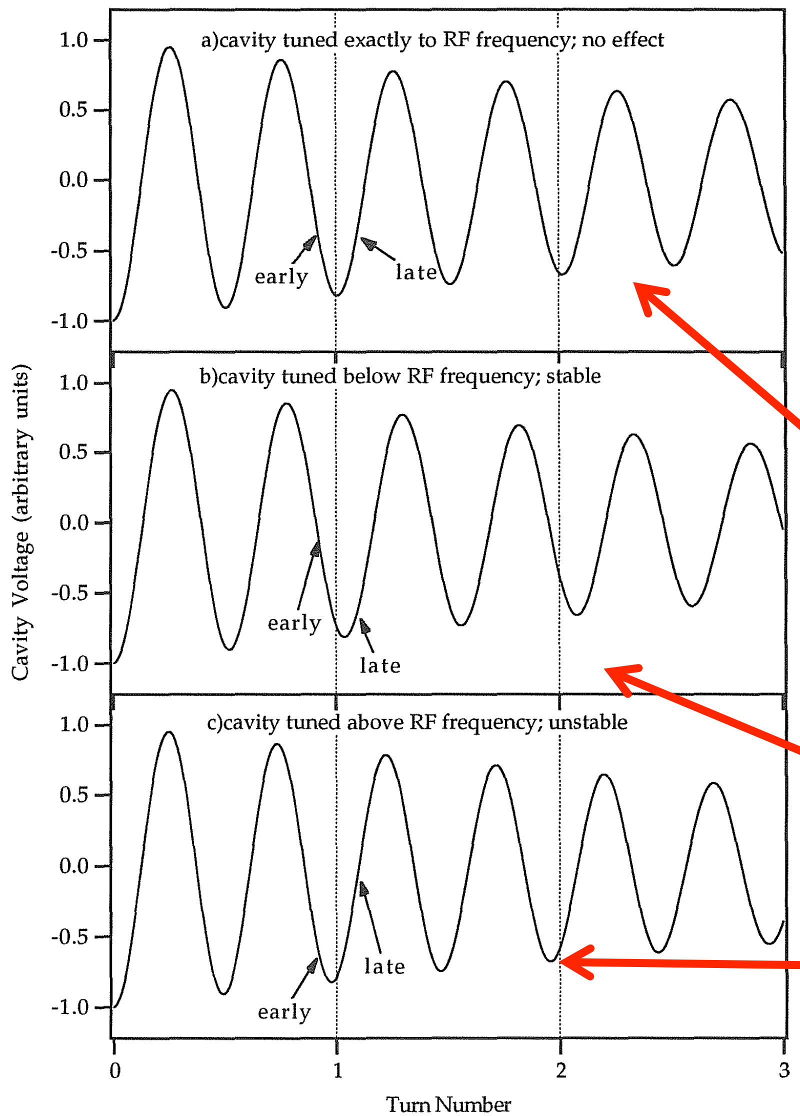


Simple model of a LCBI



- Consider a single bunch with synchrotron oscillations interacting with a high-Q resonator.
- Upper and lower sidebands can be considered a part of the synchrotron oscillation with too little and too much energy, respectively. (For cases above transition)
- Case a) Resonant mode tuned symmetrically. Upper and lower sidebands lose equal energy. No effect.
- Case b) Lower sideband (higher energy) loses more energy to resistive impedance. Oscillation damped.
- Case c) Upper sideband (lower energy) loses more energy. Oscillation anti-damped.

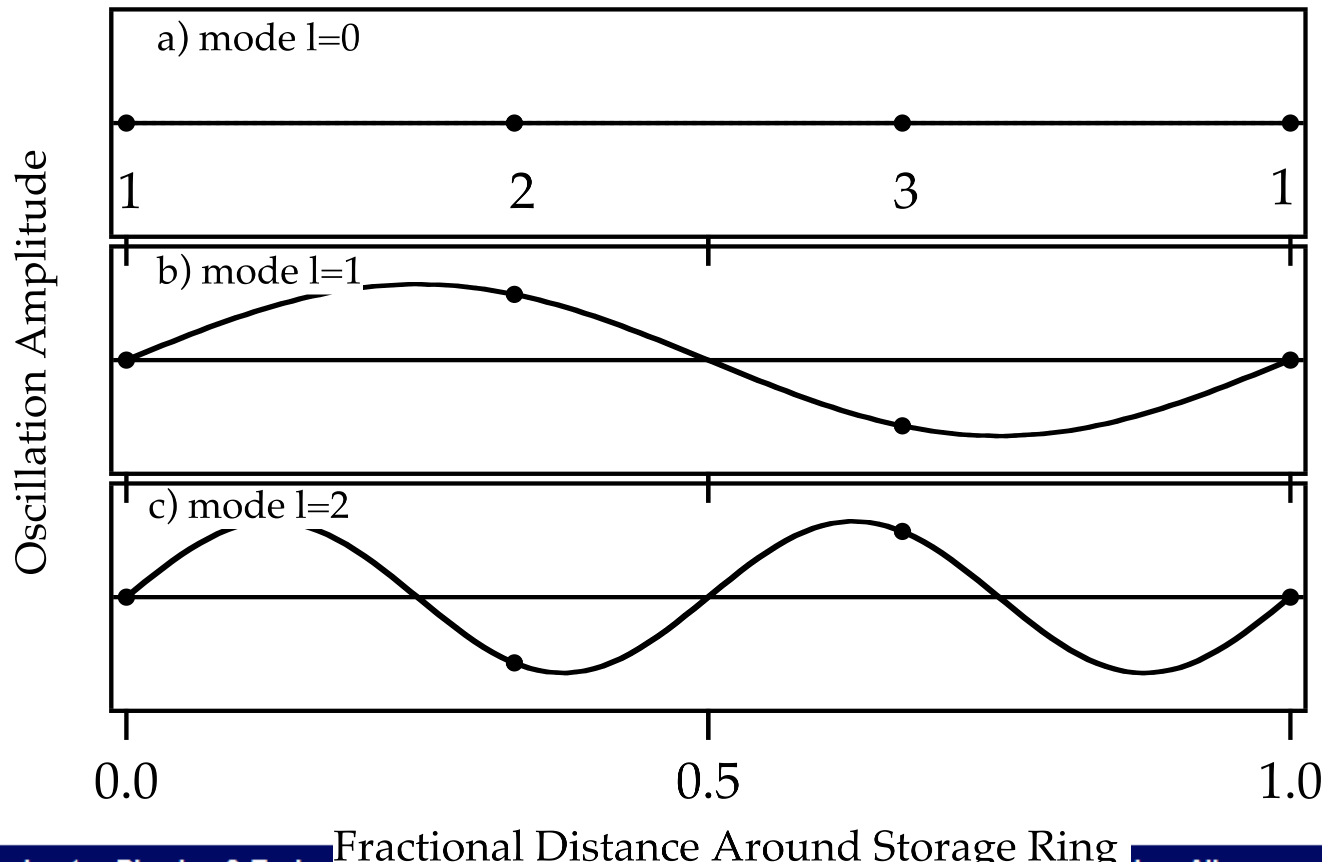
Simple model of a LCBI: time domain



- Consider a single bunch with synchrotron oscillations interacting with a high-Q resonator.
- Early and late arrival of the synchrotron oscillation correspond to too little and too much energy, respectively. (For cases above transition)
- Case a) Resonant mode tuned symmetrically. Early and late arrival lose equal energy. No effect.
- Case b) Late arrival loses more energy than early arrival. Oscillation damped.
- Case c) Early arrival loses more energy than late arrival. Oscillation anti-damped.

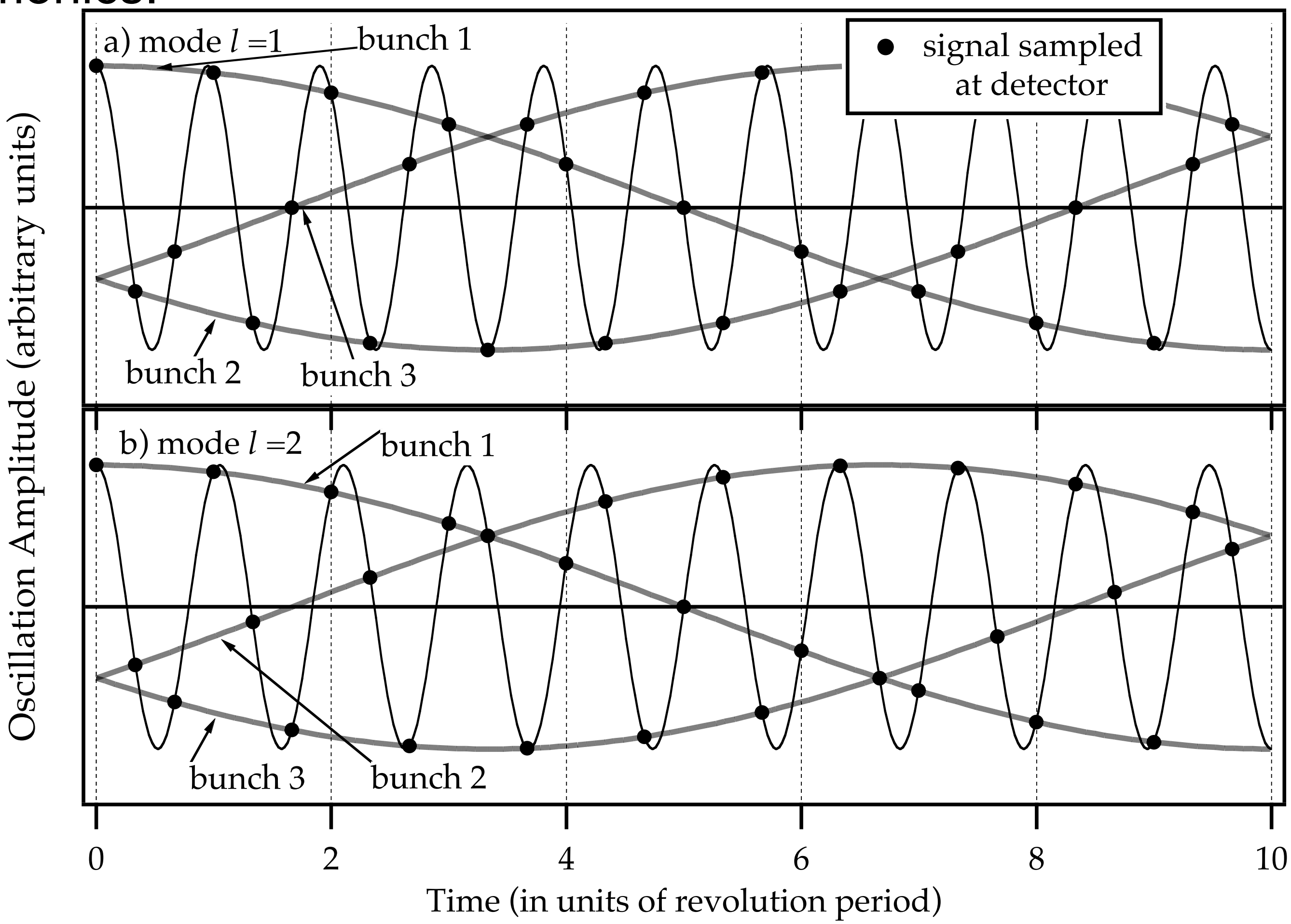
Multibunch modes

- The long-range wakes couple the motion of successive bunches. We can describe the motion of N coupled bunches and N normal modes. Each mode, l, has a relative oscillation phase of $\Delta\phi = \frac{2\pi}{N} l$ For the case of 3 bunches, a snapshot of the ring for the 3 modes is shown below.



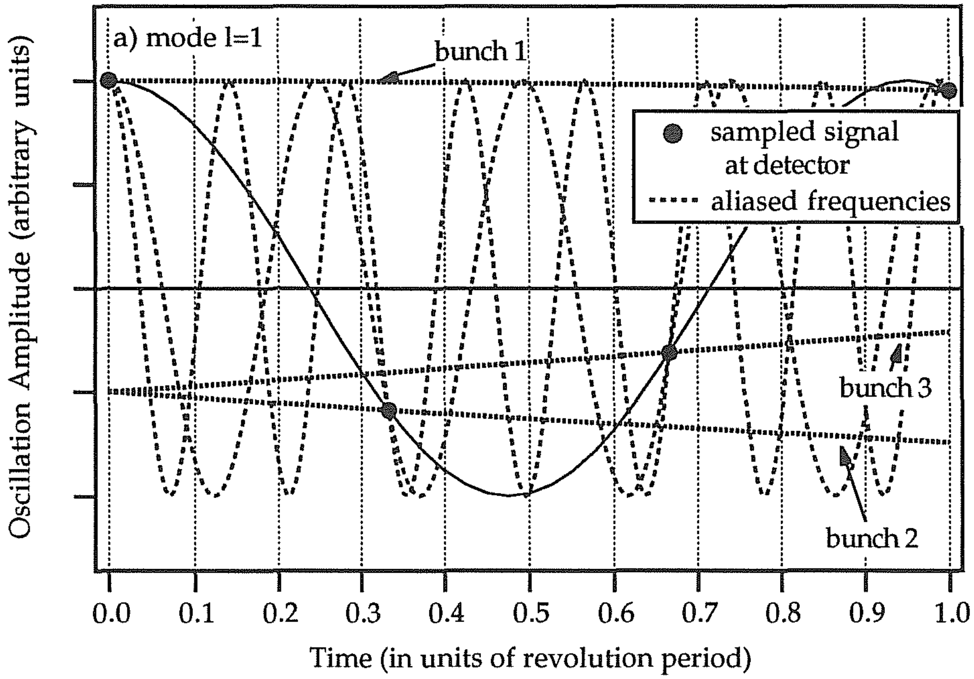
Multibunch spectrum

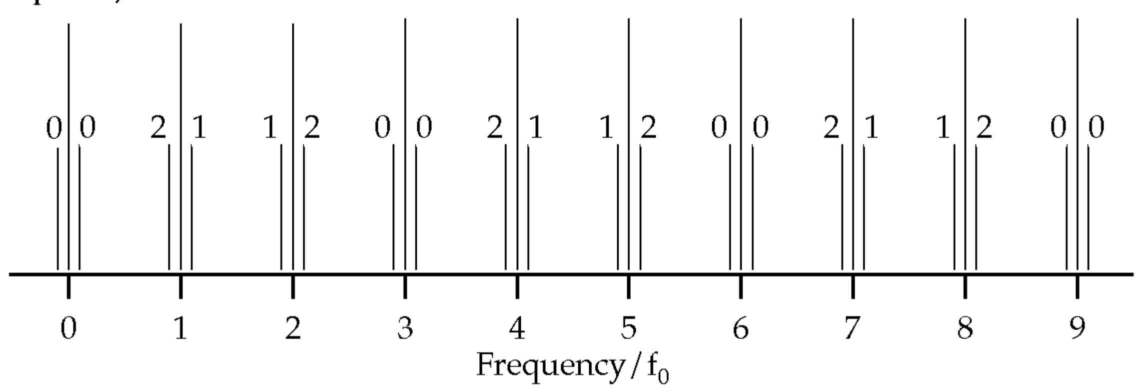
- Even though each bunch is oscillating at its natural frequency, the multibunch modes show up as upper and lower sidebands of the rotation harmonics.



Multibunch beam signal

- Each multibunch mode can appear at a number of frequencies.





Longitudinal growth rates

Longitudinal growth rate

$$\frac{1}{\tau}=\frac{1}{2}\frac{1}{E}\frac{\partial V}{\partial \varepsilon}=\frac{1}{2}\frac{h\alpha}{EQ_s}\frac{\partial V}{\partial \phi}$$

$$V = I_0\phi Z_\parallel = I_0\phi_0(f_r/f_{rf})Z_\parallel$$

This gives

$$\phi=\omega\tau=\frac{\omega_r}{\omega_{rf}}\omega_{rf}\tau=\frac{f_r}{f_{rf}}\phi_0$$

$$\frac{1}{\tau}=\frac{1}{2}\frac{I_0\alpha}{(E/e)Q_s}\left[Z_{||}\right]_{\mathrm{eff}}$$

Effective impedance

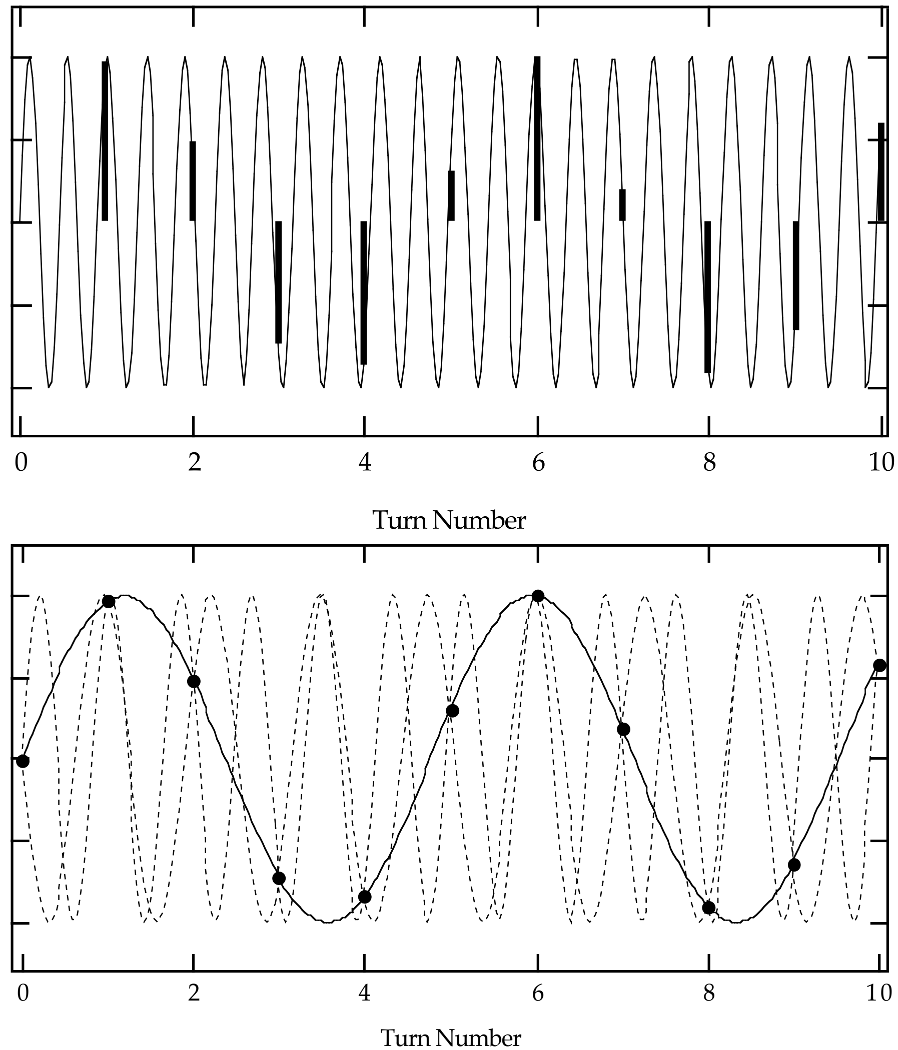
$$\left[Z_{||}\right]_{\mathrm{eff}}^{1}=\sum_{p=-\infty}^{p=+\infty}\frac{\omega_p}{\omega_{rf}}e^{-(\omega_p\sigma_\tau)^2}Z_{||}(\omega_p)$$

note frequency dependence of impedance

- General growth can be found from the fractional energy change for a small energy offset.
- Sum over all impedances
- Note that phase modulation for a given time modulation is larger at higher frequencies: higher frequencies have larger effective impedance.

Multibunch aliasing

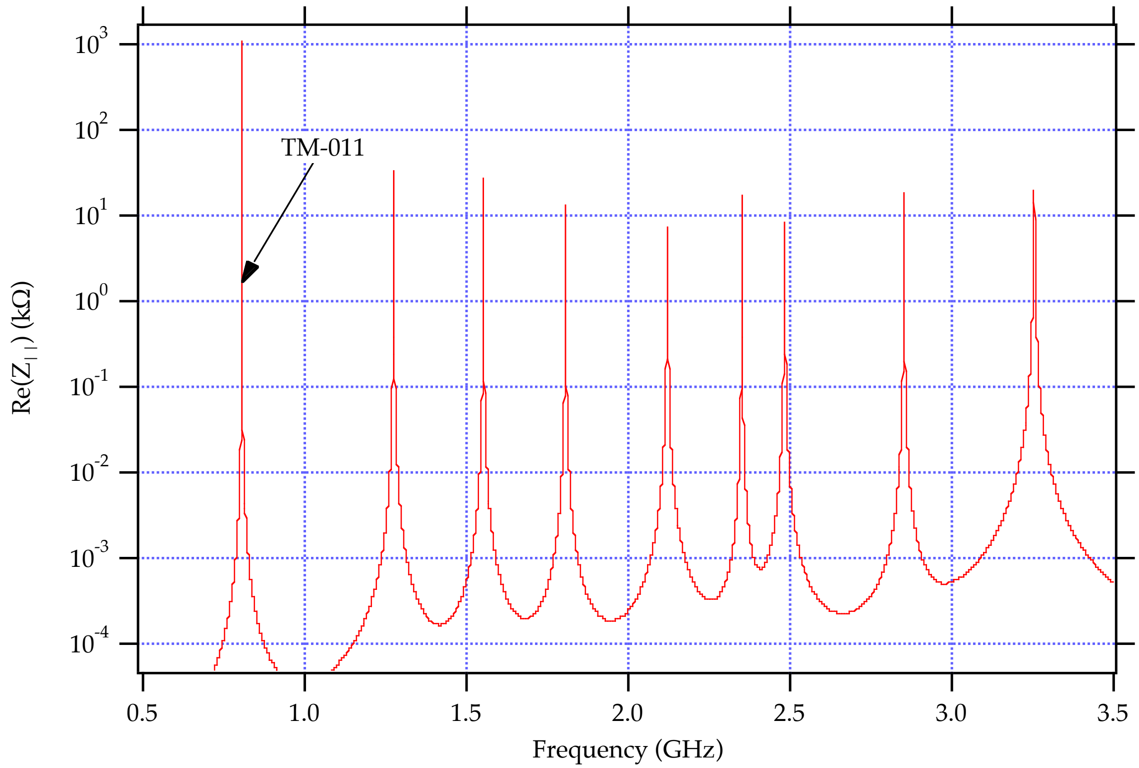
- Because of the periodic nature of the beam pulses, the long-range wakes are aliased into the sampling bandwidth of the beam.
- For example, a beam rate of 500 MHz (2 nsec bunch spacing), all wakes are aliased into a 250 MHz bandwidth.



Example:ALS RF Cavity HOMs

#	Freq(MHz)	Q	Rs(kOhm)
1	808.44	21000	1050
2	1275.1	3000	33
3	1553.55	3400	26.52
4	2853	4000	18.8
5	2353	5100	16.8
6	1807.68	2900	13.34
7	3260	1500	6
8	3260	1500	1.535
9	2124.61	1800	7.56
10	2419.3	7000	5.53
11	1309.34	810	5.508
12	3183	1500	1.86
13	1007.96	840	1.764
14	2817.4	1000	1.6
15	3149	1500	1.125
16	1846.72	2200	0.88
17	3252	1500	0.81
18	2266.6	2200	0.55
19	2625.9	1500	0.141
20	2769.1	1500	0.135
21	2968	1500	0.075
22	2979	1500	0.075
23	3243	1500	0.03
1	1500	21000	1700
2	2324	17000	625.6

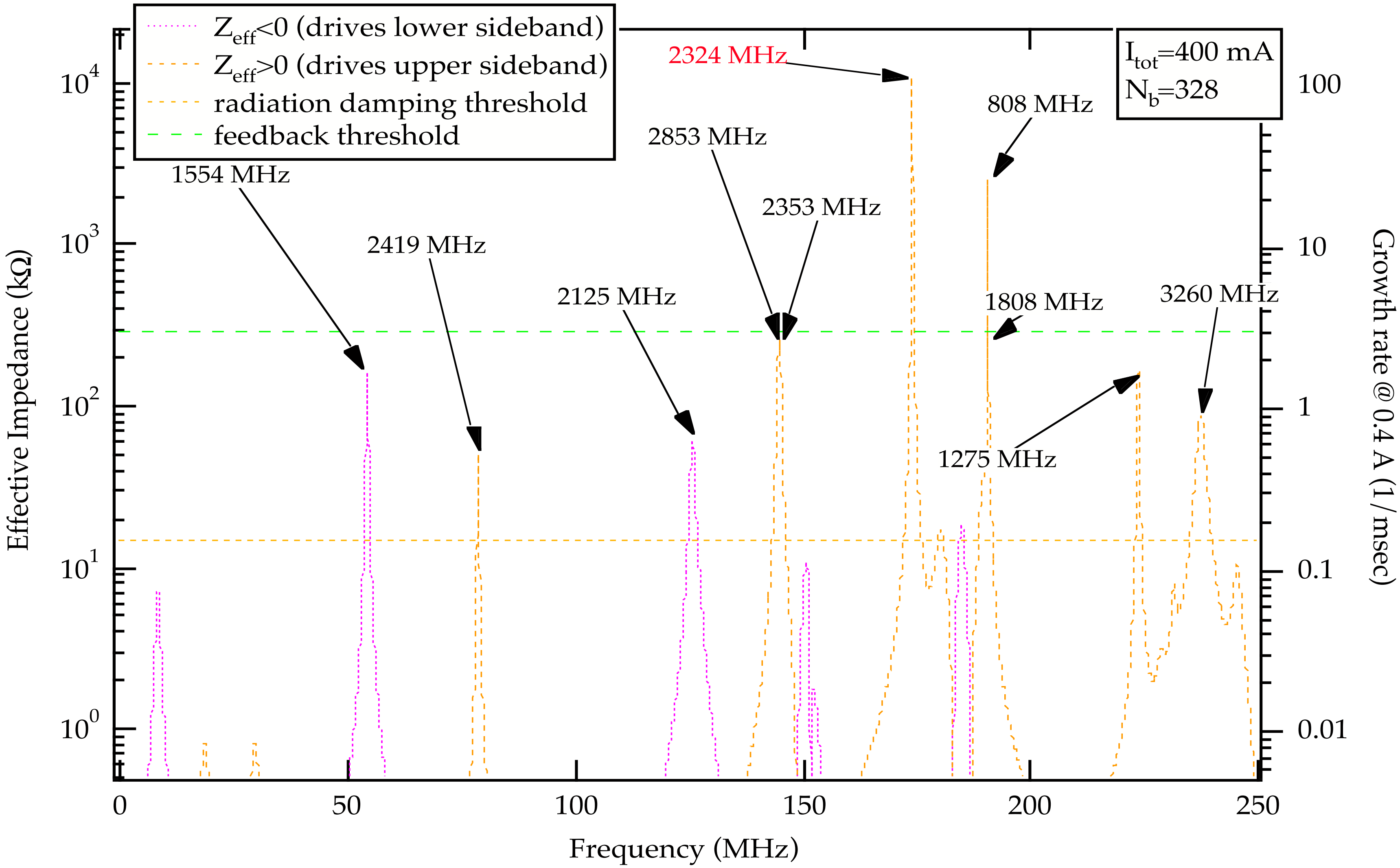
Measured values



Narrowband impedances for ALS main RF cavity up to beam pipe cutoff

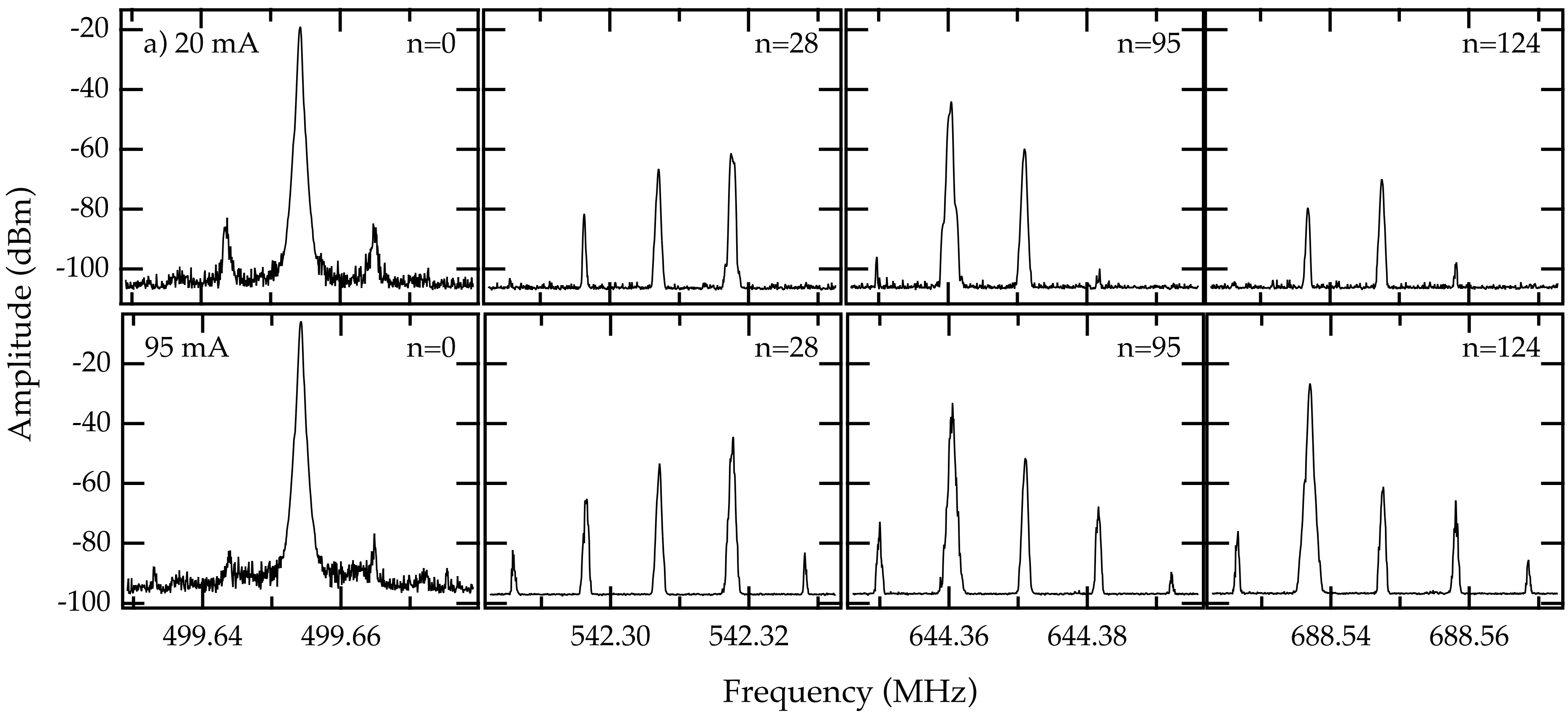
Aliased Longitudinal Impedance

- Aliased longitudinal impedance with thresholds for radiation damping and feedback (at maximum damping of 3/msec.)



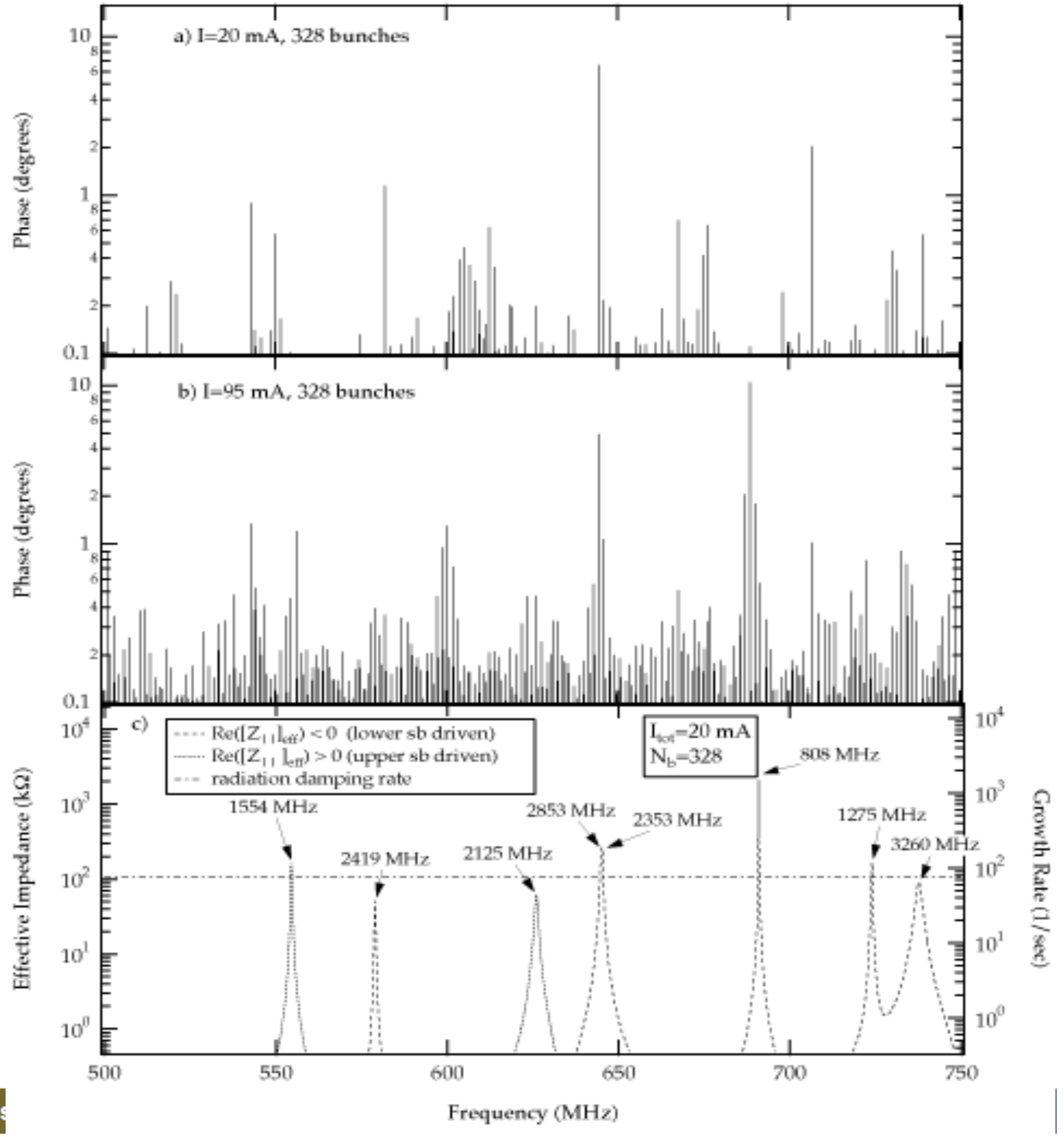
ALS Longitudinal Multibunch Spectrum

Measured spectrum of first-order synchrotron sidebands at ALS with beam longitudinal unstable (LFB off)



ALS Longitudinal Multibunch Spectrum

Spectrum of first-order synchrotron sidebands at ALS with beam longitudinally unstable (LFB off). Compare with the calculated Z_{eff} from the measured cavity modes.



This can be used to identify the driving HOMs.

Coherent Frequency Shift

- In general, the interaction with the impedance, creates a complex coherent frequency shift.
  – Resistive (real) impedance gives damping or anti-damping of beam oscillations
  – Reactive (imaginary) impedance shifts the frequency of the beam oscillations.
  – Assuming the growth rate and frequency shifts are small compared to the oscillation frequency, we can write the complex frequency shift as

$$j\,\Delta\Omega = \frac{\alpha\, I_0}{4\pi\, E/e\, \nu_s}\, Z_{eff}\left(n\,\omega_0 + \omega_s\right)$$

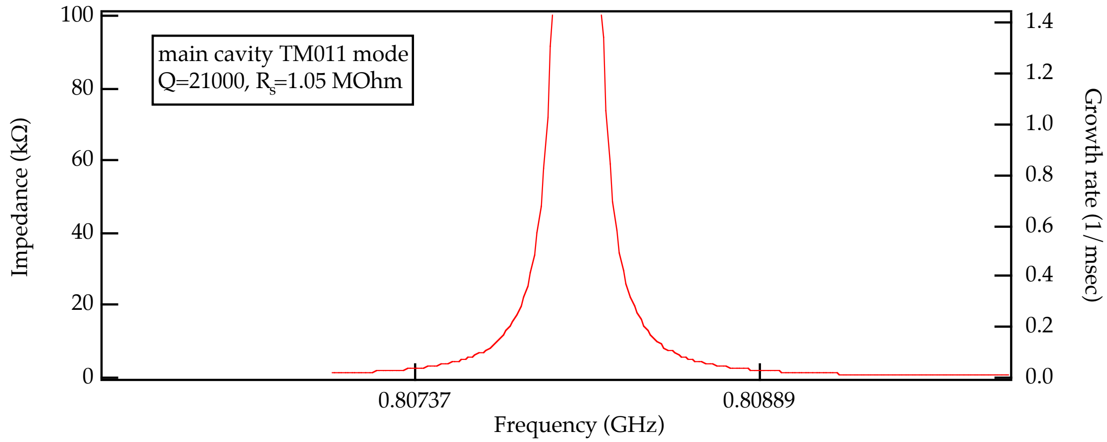
$$1/\tau = \Re e\left[\,j\,\Delta\Omega\right]$$

Controlling narrowband impedances

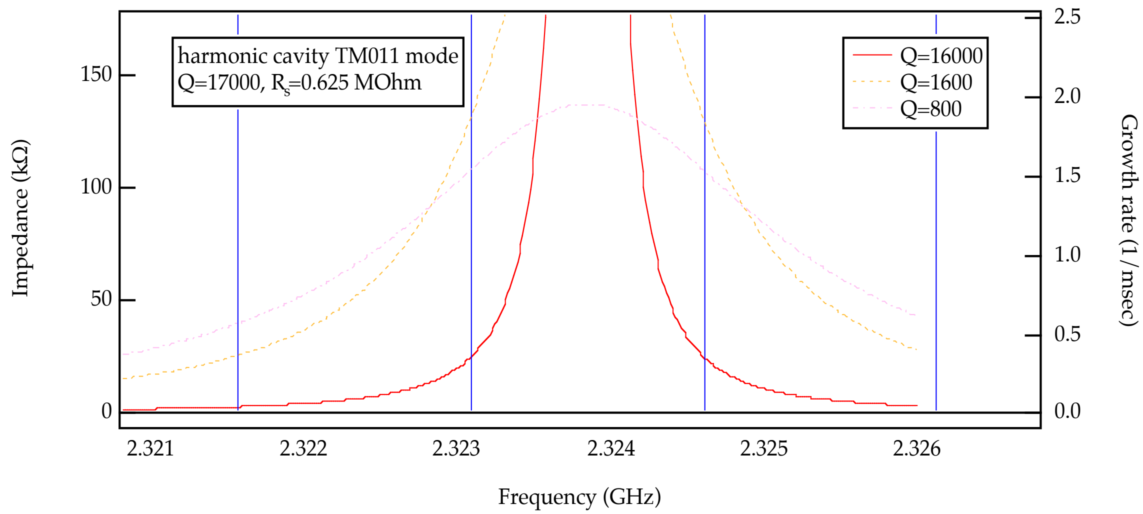
- **Damping of cavity High Order Modes (HOMs)**
  – heavy damping required to decrease growth rates
  – decreases sensitivity to tuners, temperature
  – most desirable approach if possible
- HOM tuning
  – done using plunger tuners or with cavity water temperature
  – requires HOM bandwidth less than revolution frequency
  – difficult for many HOMs
- Vacuum chamber aperture (transverse only)
  – strongly affects transverse resistive wall impedance ($Z \sim 1/b^3$)
  – trends in insertion device design are going to small vertical aperture (<5 mm)

HOM Tuning

The ALS uses a combination of LFB and tuning of HOMs to control instabilities. Tuning of HOMs in the main cavities is done mainly with cavity water temperature. Tuning is done using 2 tuners in HCs.



This tuning scheme requires that the modes are high Q. If insufficiently damped, the growth rates could actually increase.

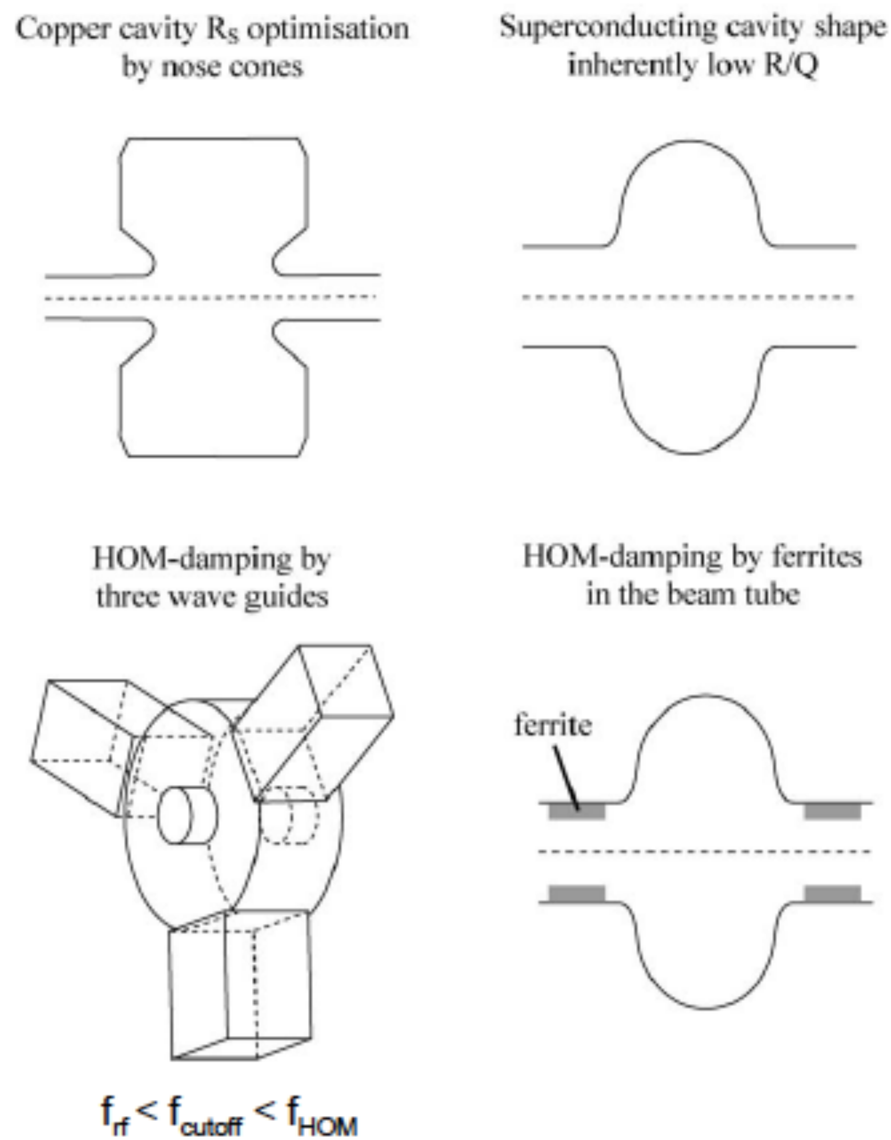


Concepts for HOM-damped cavities

- Instability Threshold

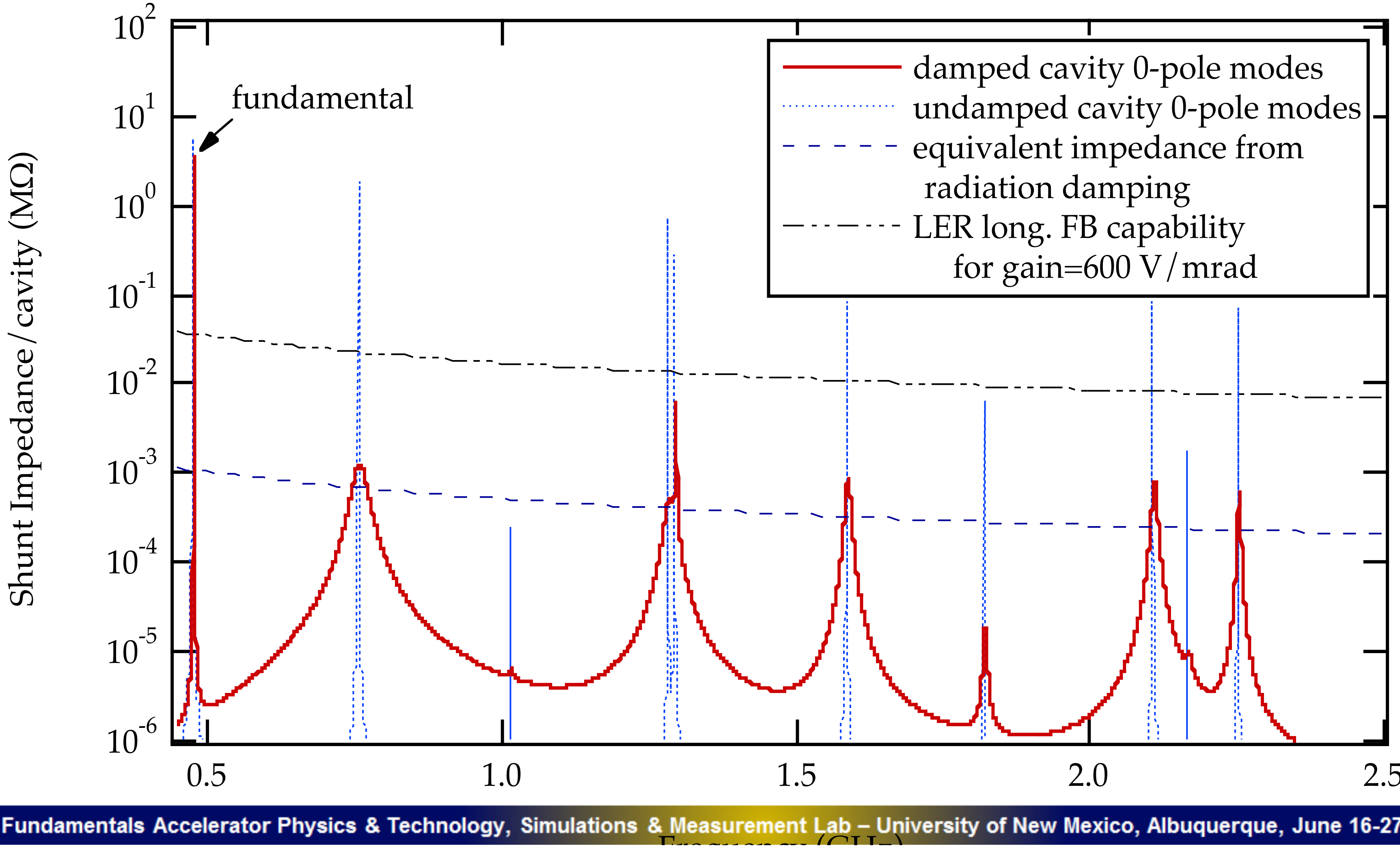
$$1/I_{threshold} \propto Z_{tot} = N_c \left(\frac{R}{Q_0} \right)_{HOM} Q_{ext}$$

- Reduce impedance by
- Minimize total number of cells
  - Large R/Q for fundamental
  - Large voltage/cell
- Minimize R/Q for HOMs
  - Cavity shape design
- Minimize Q for HOMs
  - HOM-damping



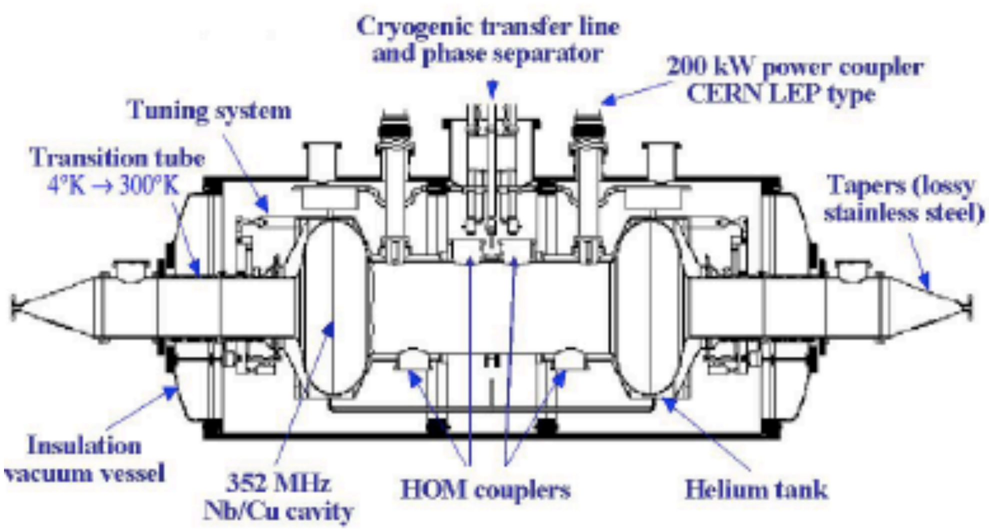
HOM Damping

Modern damped normal-conducting cavity designs use waveguides coupled to the cavity body, dissipating HOM power in loads without significantly affecting the fundamental.



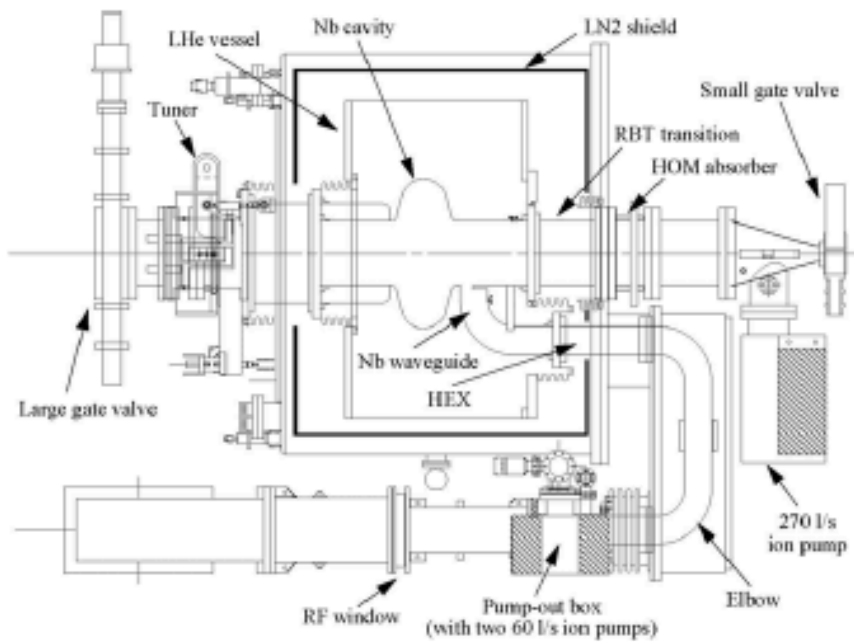
HOM-damped SC cavities

SOLEIL Cavity



- Nb sputtered on Cu
- 4 coaxial loop type HOM couplers
- 2 coaxial input couplers 200 kW each
- cooling capacity: 100 W at 4.5 K, 20 l/h LHe

CESR-B Cavity

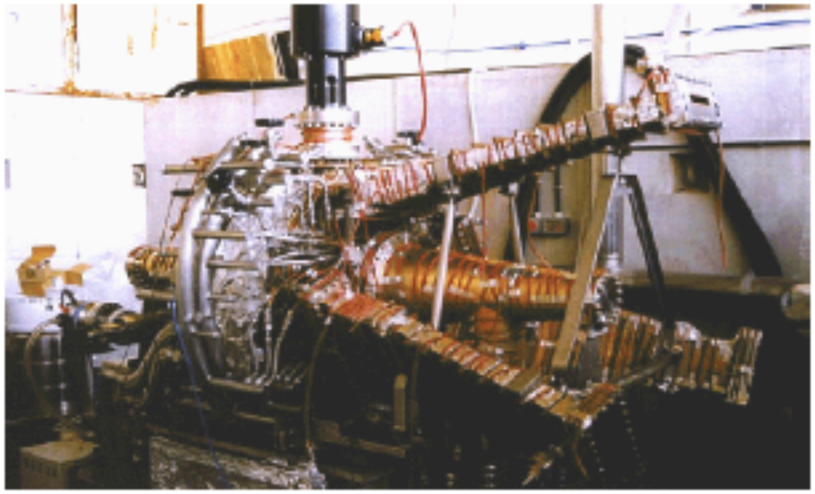


- Nb sheet material
- 2 cylindrical HOM loads
- rectangular waveguide input coupler, 500 kW
- cooling capapcity: 100 W at 4.2 K

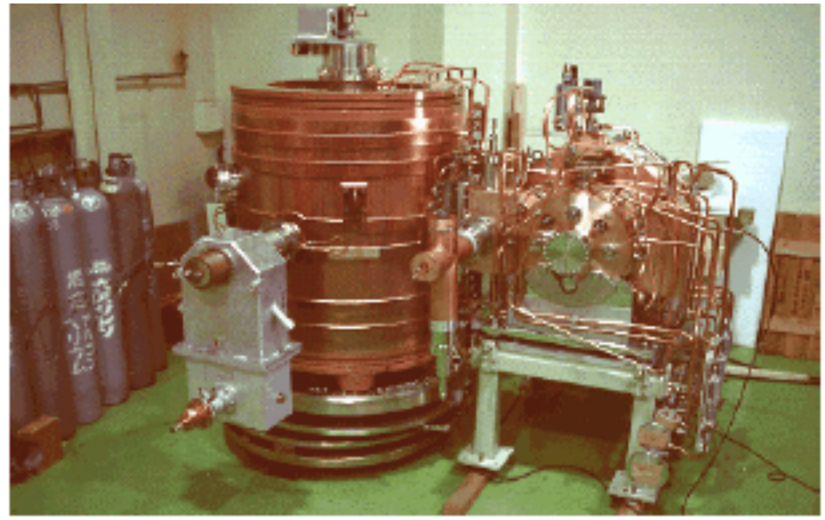
Cavity used at

CLS/Canada
NSRRC/Taiwan
SLS/China
DIAMOND/England

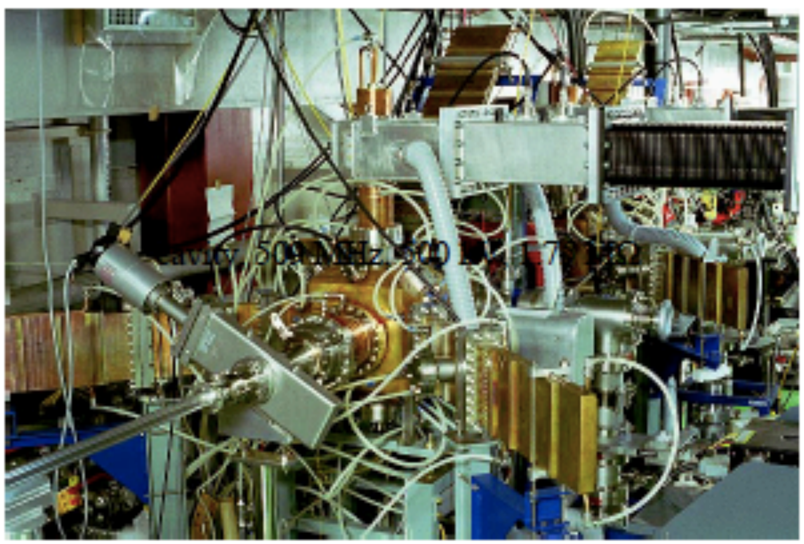
NC HOM-damped cavities



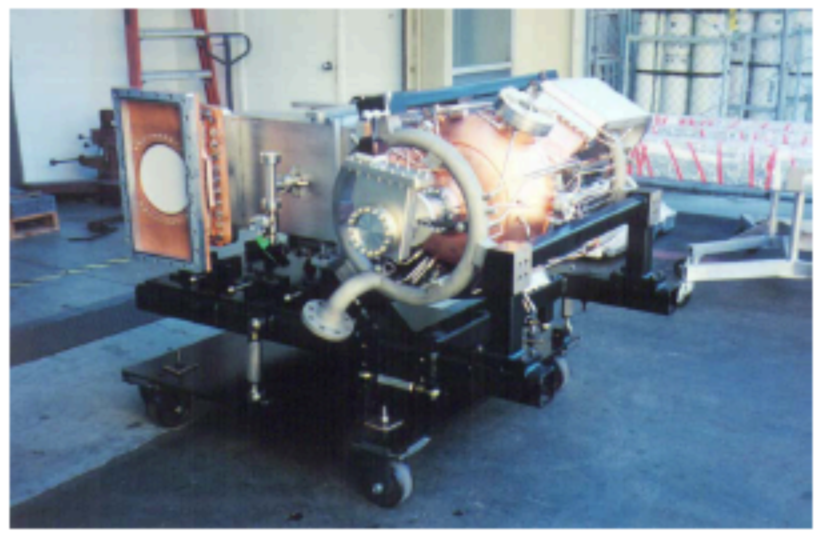
Daphne cavity, 368.26 MHz, 250 kV, 2 MΩ



KEK ARES cavity, 509 MHz, 500 kV, 1.7 MΩ



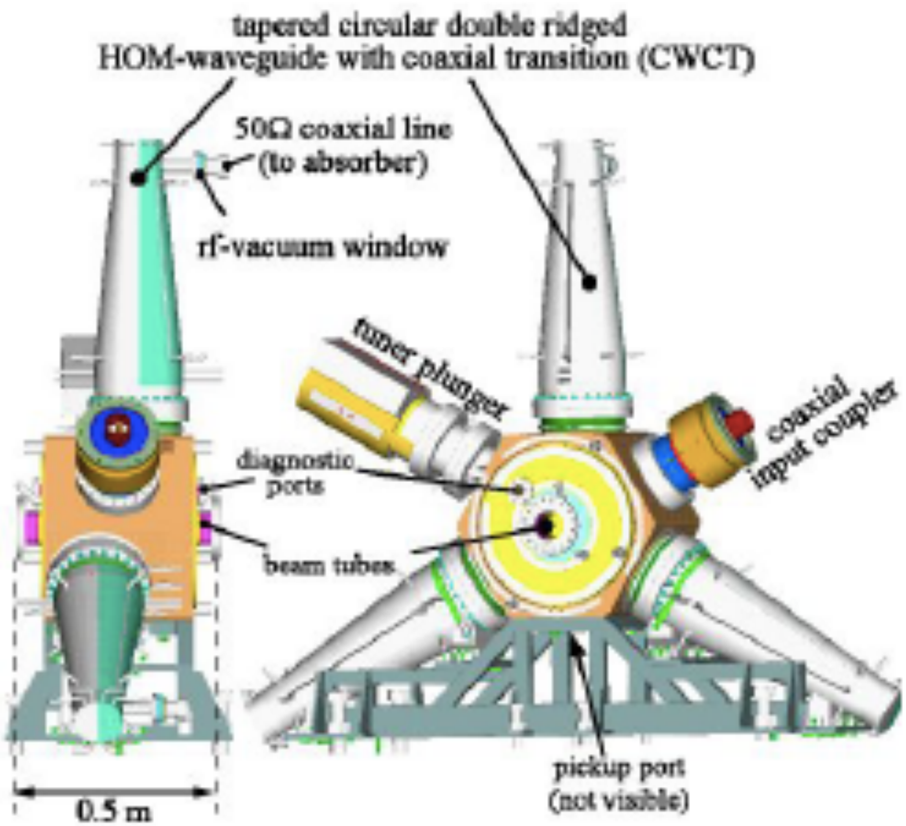
ATF cavity, 714 MHz, 250 kV, 1.8 MΩ



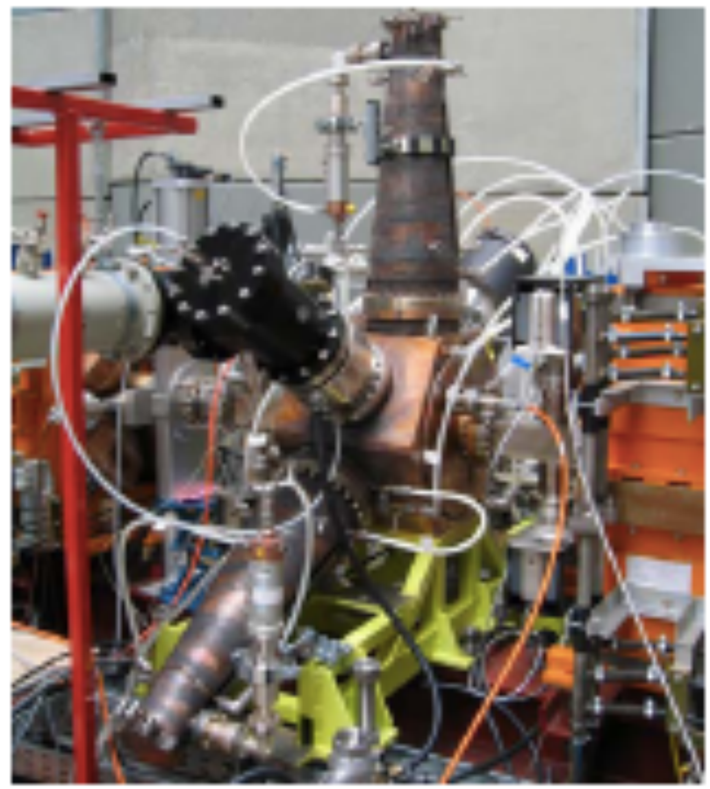
PEP-II cavity, 476 MHz, 850 kV, 3.7 MΩ

Bessy HOM-damped design

- Developed to be a commercially available NC HOM-damped cavity design
- Used at ALBA



Prototype cavity installed in the DELTA ring



Passive techniques

- Damp instabilities by increasing synchrotron frequency spread within a bunch (Landau damping)
- Decoupling the synchrotron oscillations by varying the synchrotron frequency along a bunch train
- Modulate synchrotron motion at multiples of synchrotron frequency
- Difficult to predict effects in advance.

Longitudinal Feedback Systems

Design Issues:

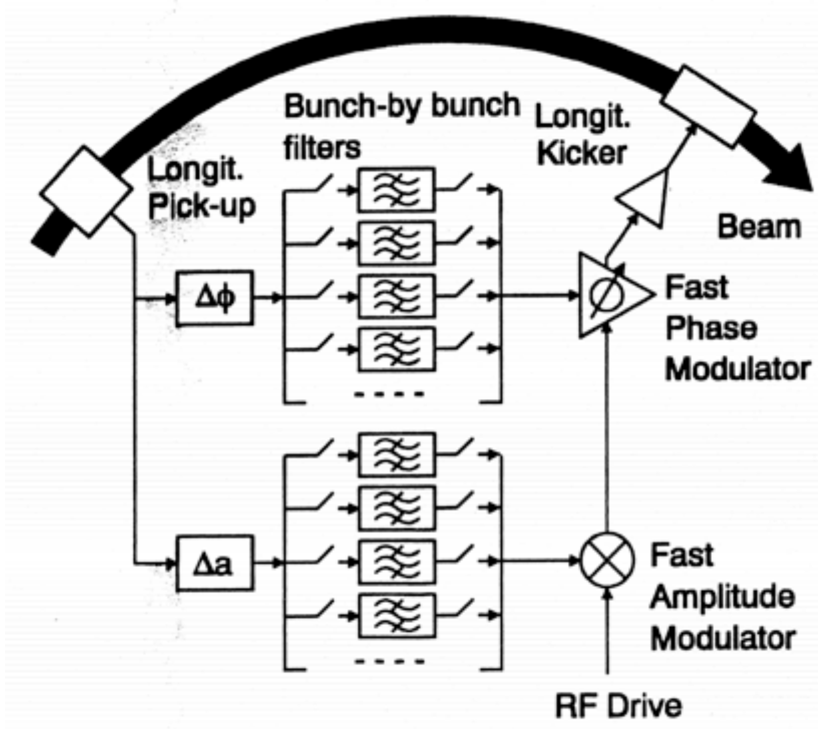
•Bandwidth>1/2 bunch frequency (M*revolution freq) to handle all possible unstable modes

•PUs: phase or radial(energy)

- •radial:
  - •PUs in dispersive region
  - •no phase shift required and much less signal processing.
  - •sensitive to DC orbit and betatron oscillations
  - •insensitive to beam phase shifts
- •phase:
  - •usually more sensitive and less noisy than radial PU
  - •requires 90 degree phase shift (1/4 synchrotron period delay)

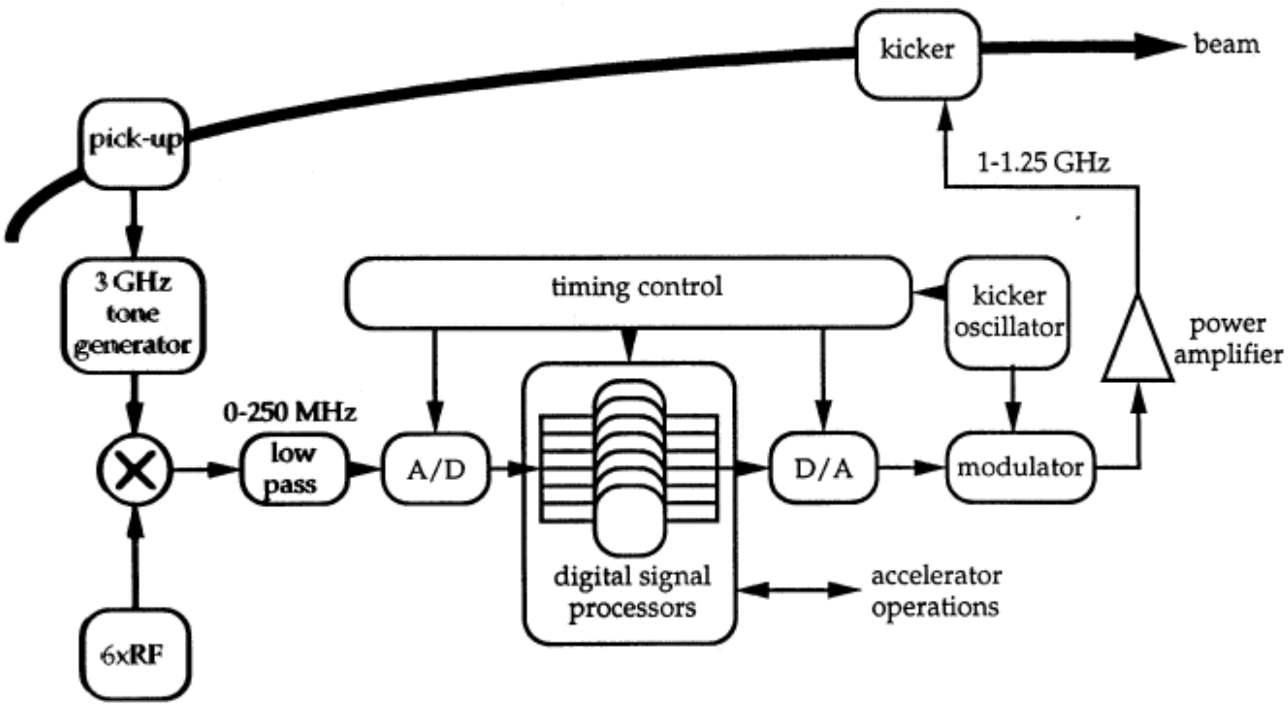
•AC coupling of each bunch signal

•Sufficient system gain to damp fastest growth rate



ALS LFB system

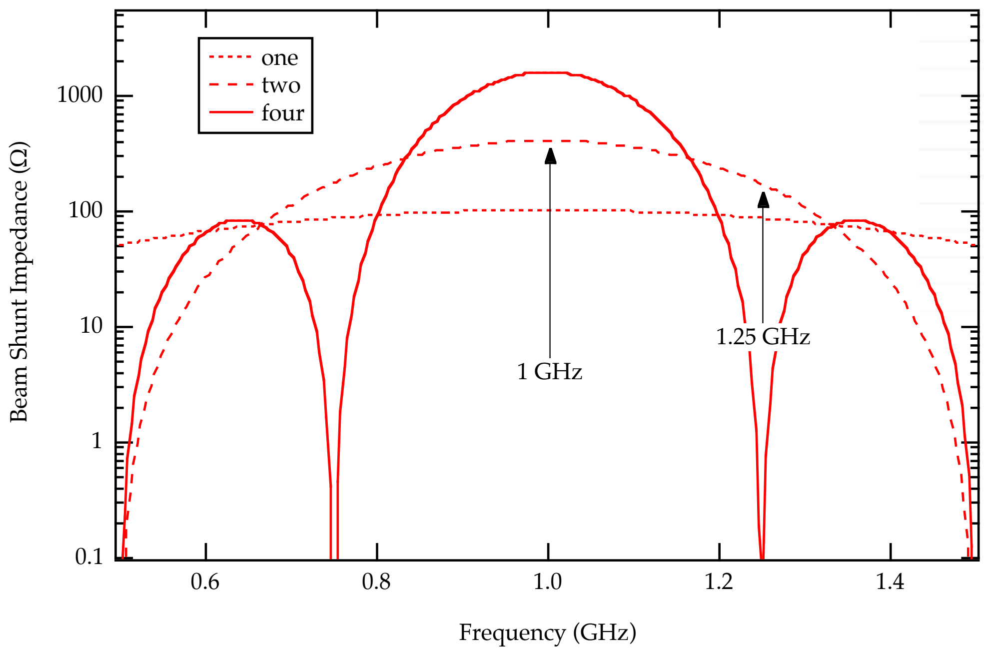
- PUs operate at 3 GHz (6*Frf); phase detection following comb filter
- synchrotron oscillations downsampled by factor 20
- QPSK modulation scheme from baseband to 1 GHz (2*Frf)
- TWT 200 W amplifier drives 4 2-element drift tubes kickers.



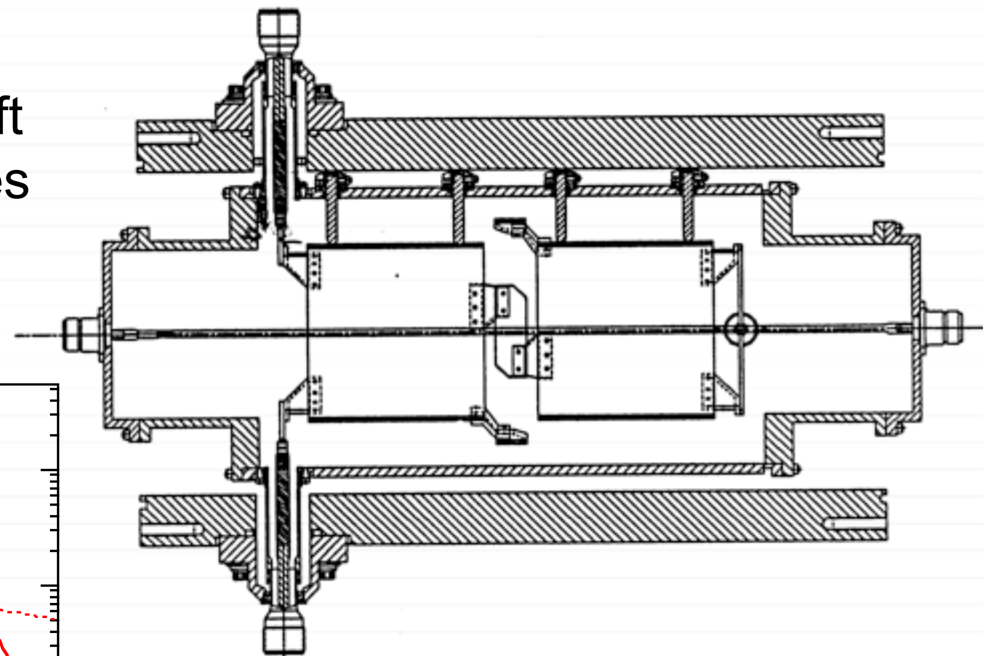
LFB Issues:
- drifting phase of beam wrt. master oscillator
- variation of synchronous phase/ synch. frequency along bunch train.
- strong growth rates (>1/msec)
- excitation of Robinson mode

ALS LFB Kicker

The ALS uses a series drift-tube structure as an LFB kicker. Thje drift tubes are connected with delay lines such that the kick is in phase.



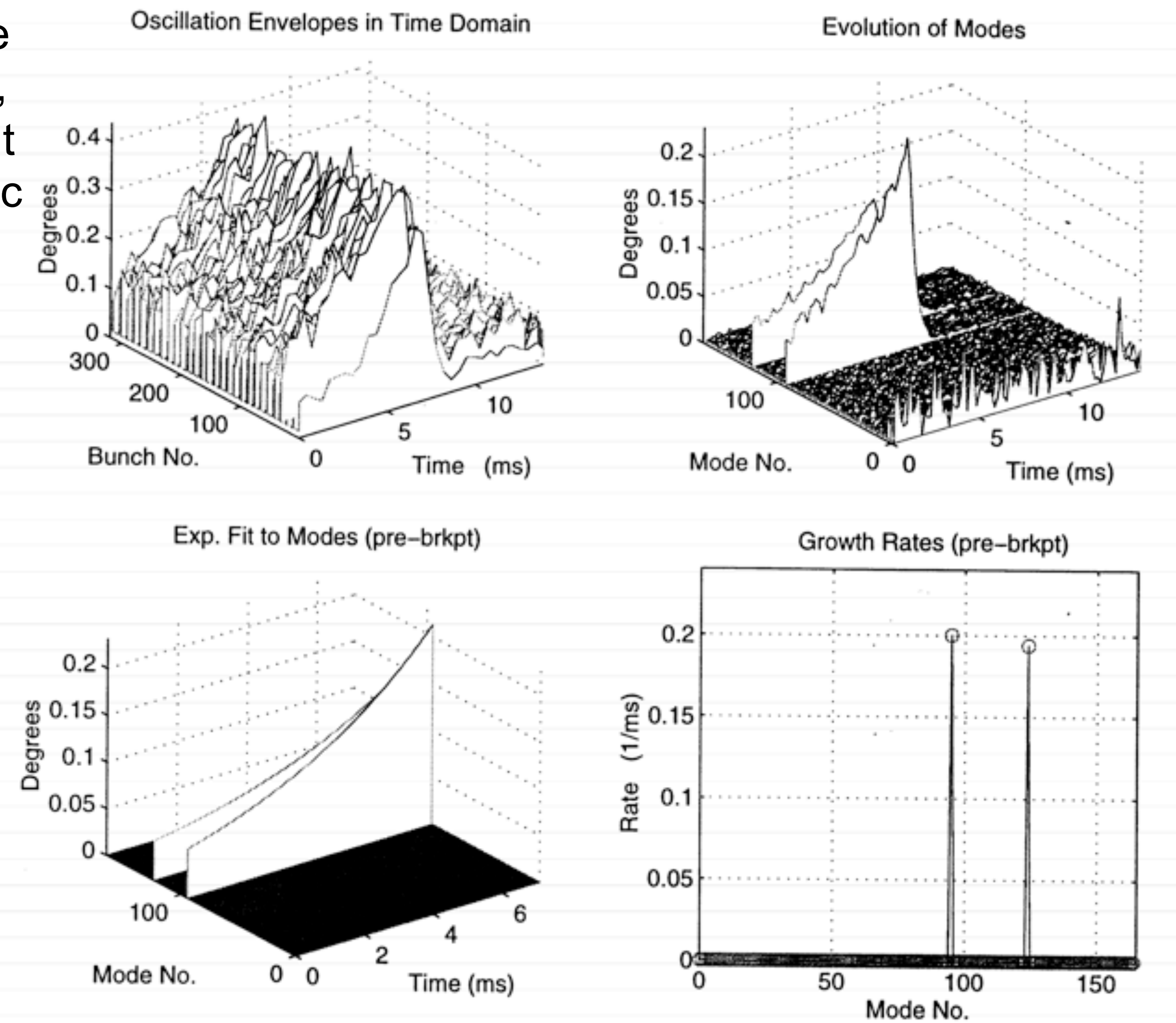
Beam impedance for 1,2, and 4 series drift-tubes.



Other rings have designed a heavily loaded cavity as a kicker. (DAFNE,BESSY-II)

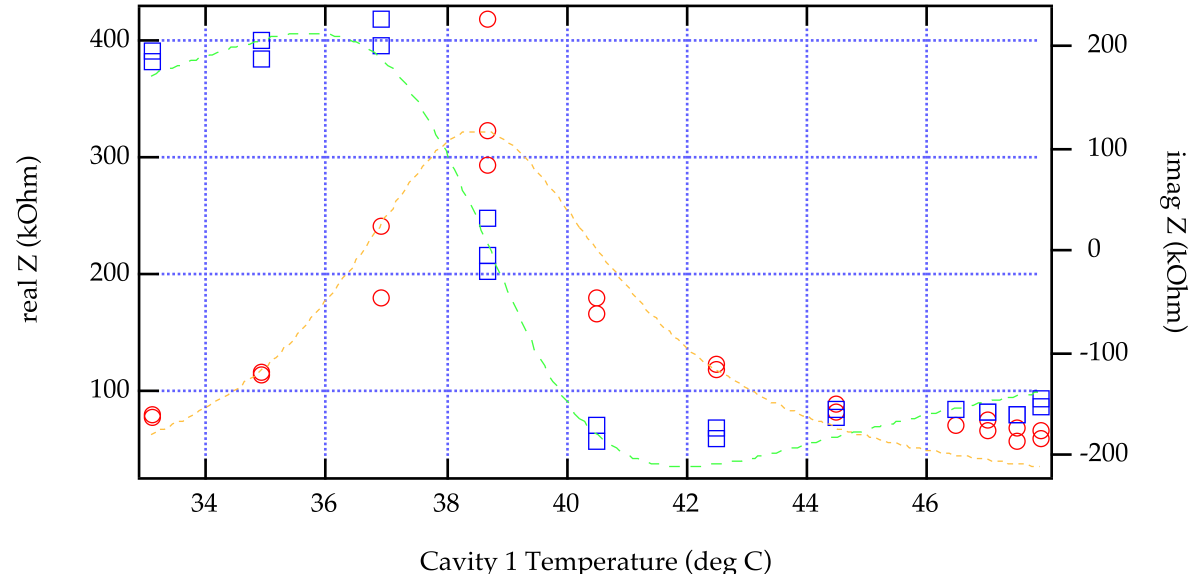
LFB Diagnostics

The digital LFB system in use at ALS, PEP-II, DAFNE, PLS, Bessy-II, and many other light sources has built-in diagnostic features for recording beam transients. This is useful for measuring growth rates.

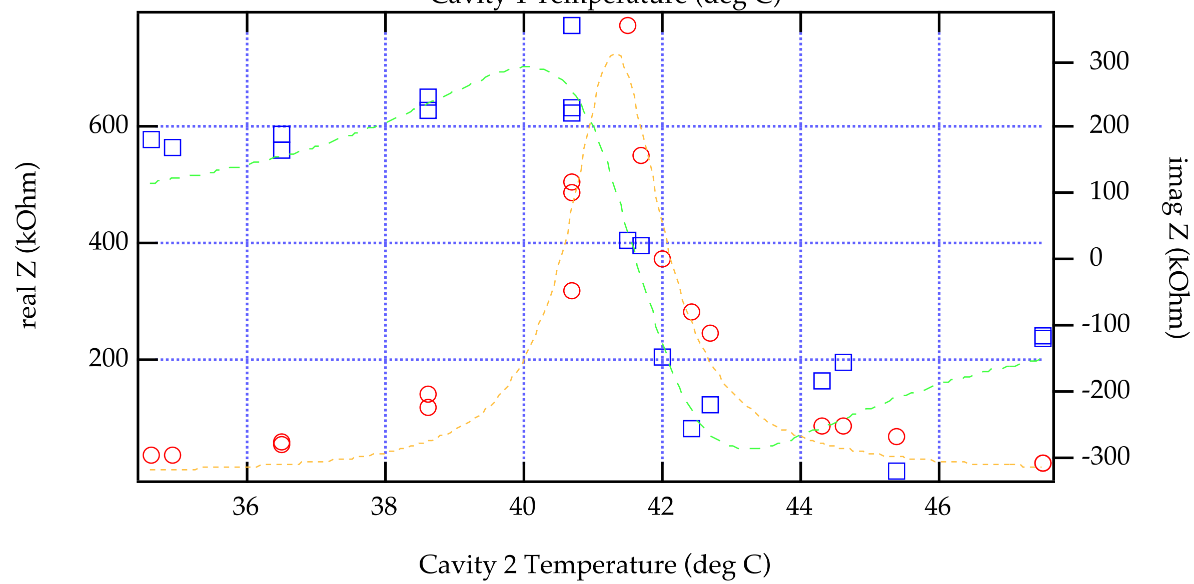


LFB diagnostics (cont.)

The impedance of a driving mode can be determined by measuring the growth rate and frequency shift of the beam



Example: Measurements to characterize a cavity mode showed significantly higher impedance than was expected. The mode was tuned by varying the cavity water temperature. By measuring the frequency sensitivity to temperature, the Q can be found.

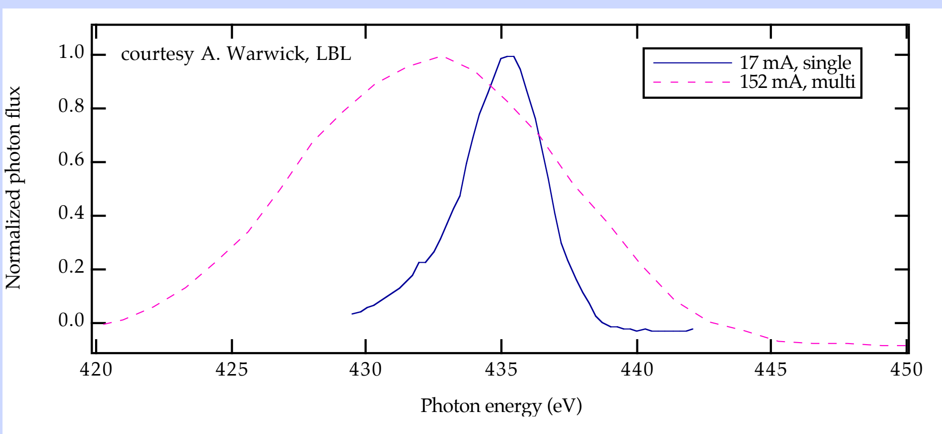


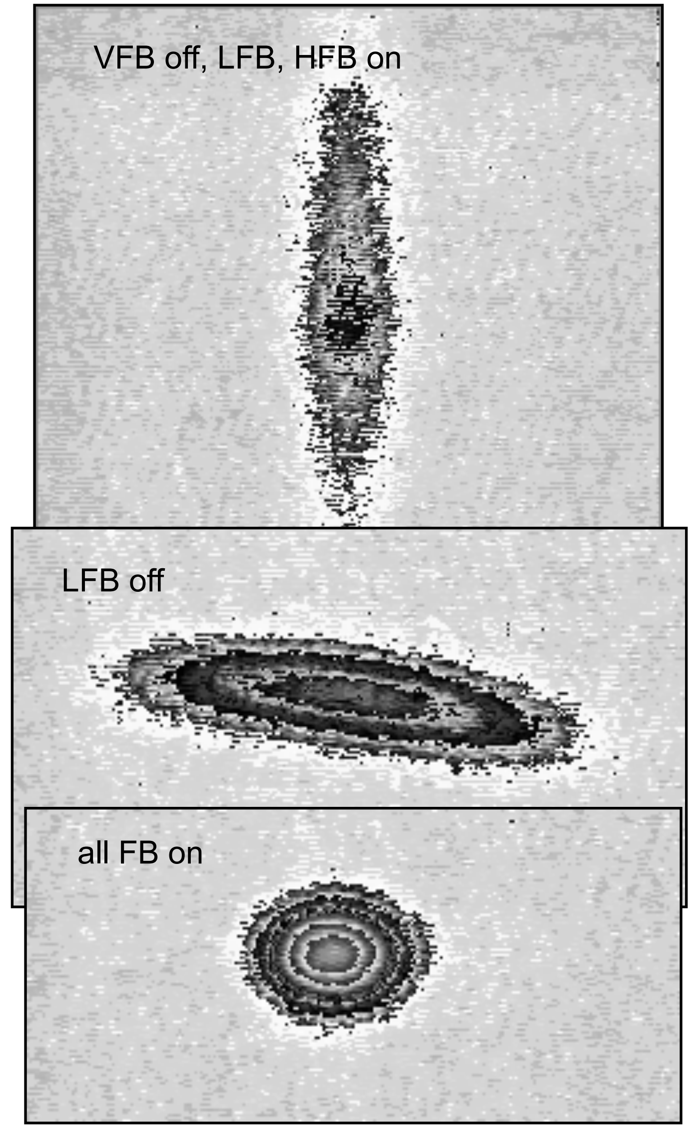
Effect of FB on beam quality

The effect of the feedback systems can be easily seen on a synchrotron light monitor (at a dispersive section)

Energy oscillations affect undulator harmonics

$$\left(\frac{d\omega}{\omega}\right)^2 = \left(\frac{1}{nN}\right)^2 + 2\left(\frac{d\gamma}{\gamma}\right)^2$$





Beam loading and Robinson Instabilities

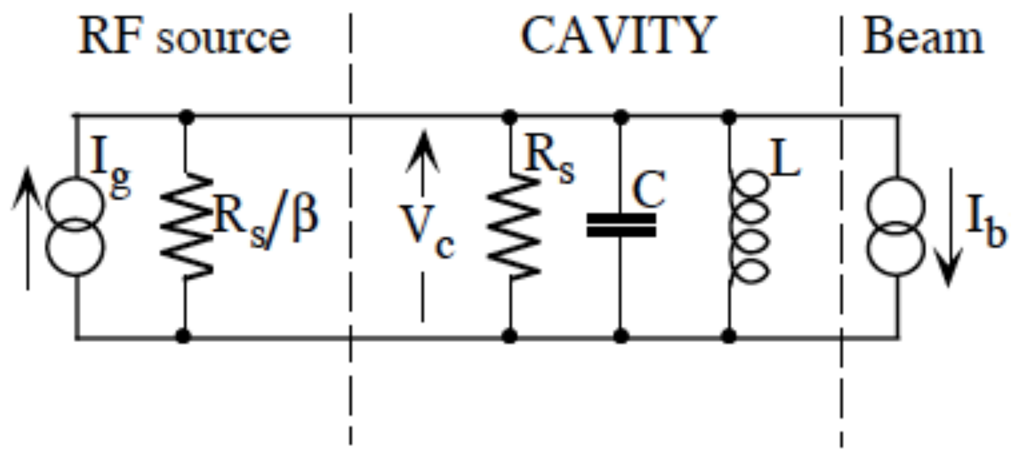
- Basics of beam loading
- Examples of beam loading for ALS
- Robinson's analysis of beam cavity interaction
- Pedersen model of BCI

Beam Cavity Interaction: Equivalent Circuit

From the point of view of a rigid beam current source, beam loading can be represented by excitation of of a parallel RLC circuit. This approximation is valid for a generator coupled to the cavity via a circulator.

The coupling to the cavity is set to make the beam-cavity load appear to be a resistive load to the external generator and matched at some beam current.

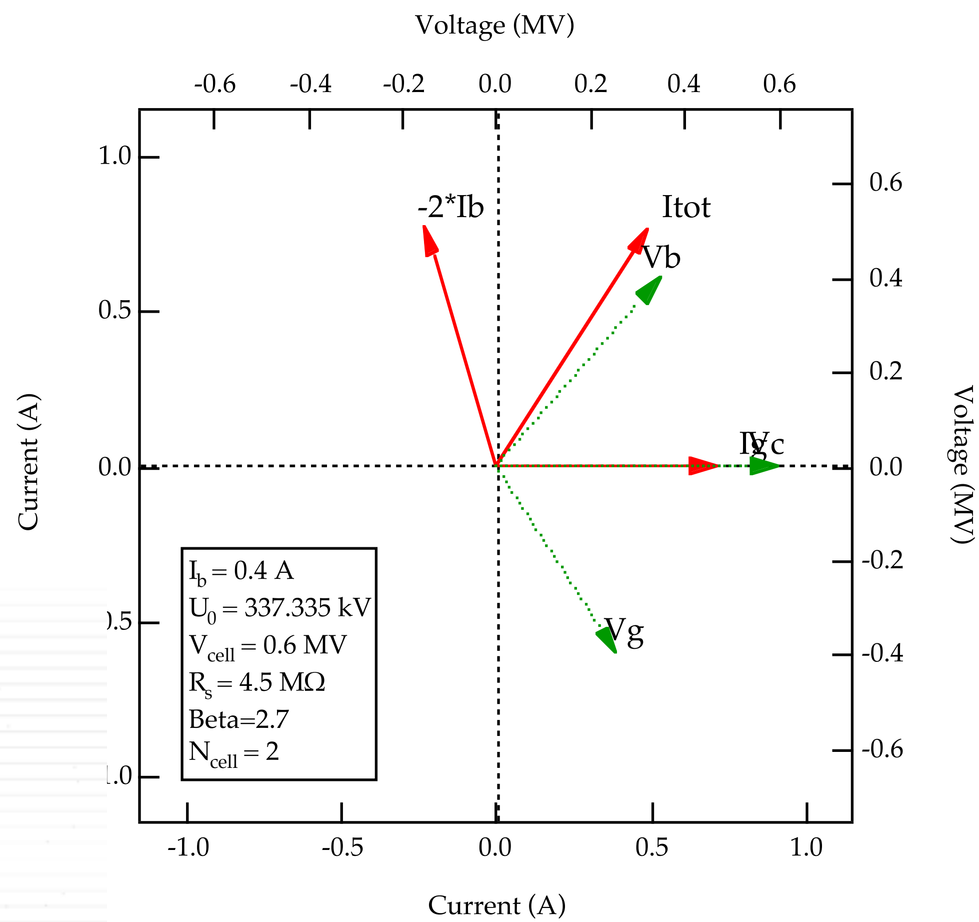
For zero beam, the optimal coupling (beta) is 1. To match at nonzero beam, the optimal beta is $1+P_{beam}/P_{cavity}$.



The beam loading appears to the generator as an additional resistive and inductive load. We can adjust the cavity coupling (beta) and the detune the cavity to make it appear to be a perfect match.

Phasor representation

The beam and generator voltages can represented as phasors. Common usage has either the cavity voltage or beam current as the reference phase.



Conditions for detuning to get minimum generator power.

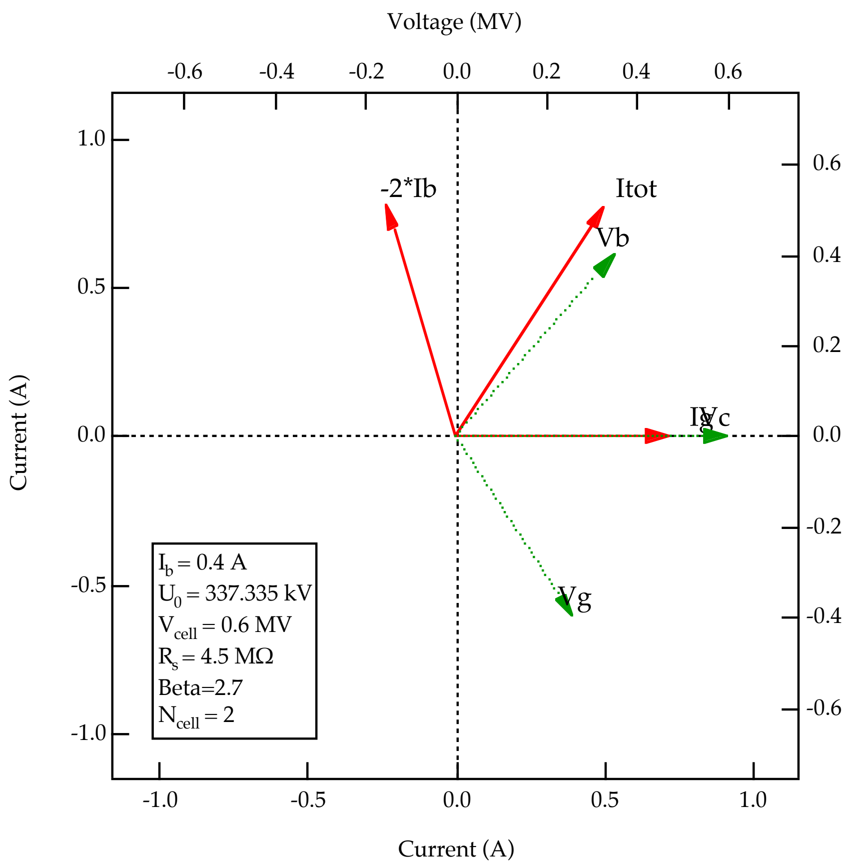
$$I_G = \frac{I_0 + I_B \sin\phi_B}{\cos\phi_L} = \frac{I_0(1 + Y\sin\phi_B)}{\cos\phi_L} = 2\frac{P_0 + P_B}{V\cos\phi_L}$$

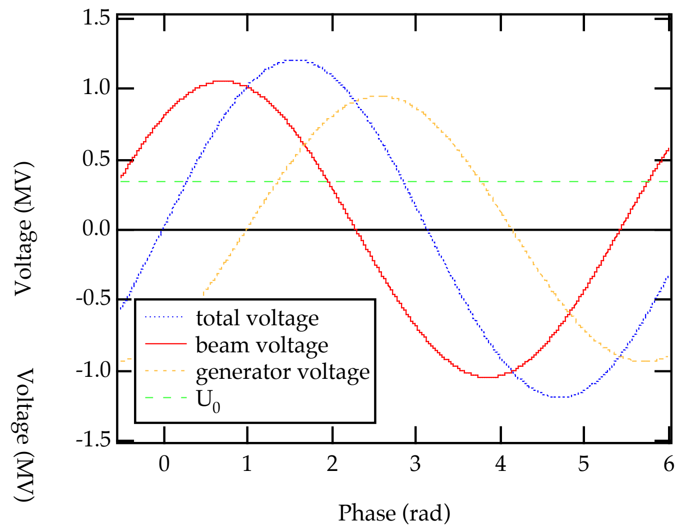
$$\tan\phi_L = \frac{I_0\tan\phi_Z - I_B\cos\phi_B}{I_0 + I_B\sin\phi_B} = \frac{\tan\phi_Z - Y\cos\phi_B}{1 + Y\sin\phi_B}$$

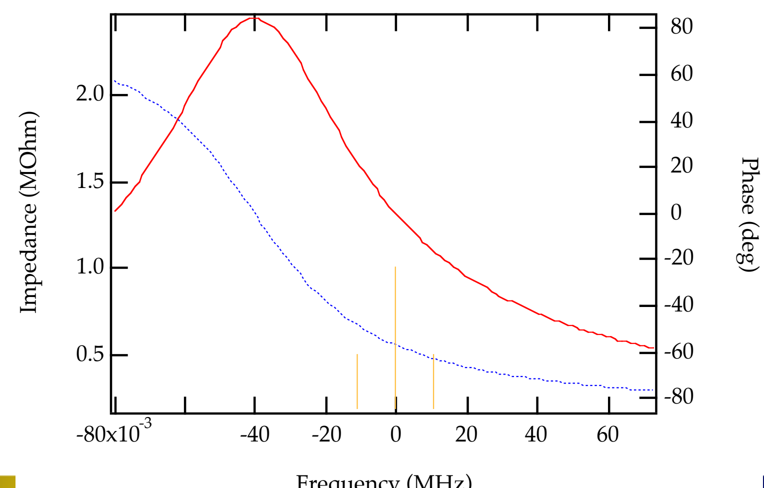
Minimum generator current by *detuning cavity* to obtain $\phi_L = 0$:

$$\tan\phi_Z = (I_B / I_0)\cos\phi_B$$

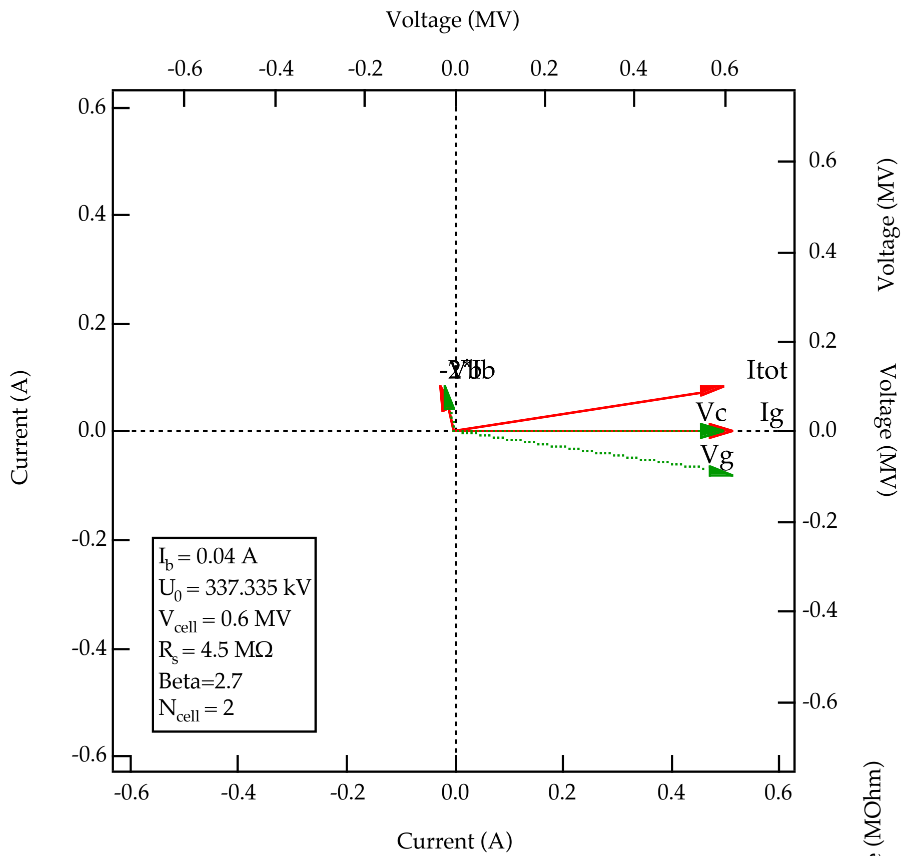
Phasor diagram

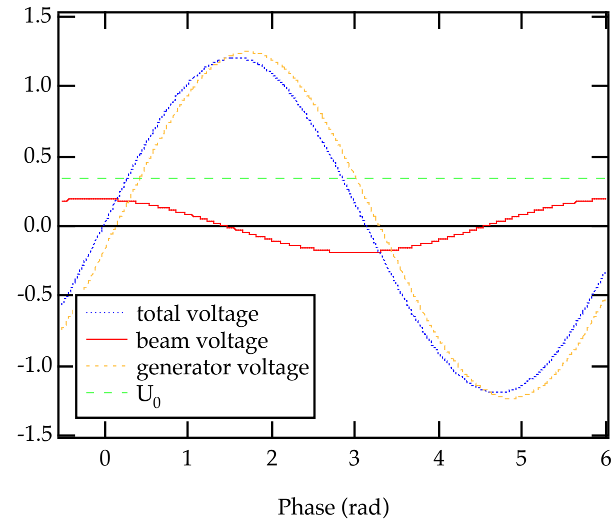


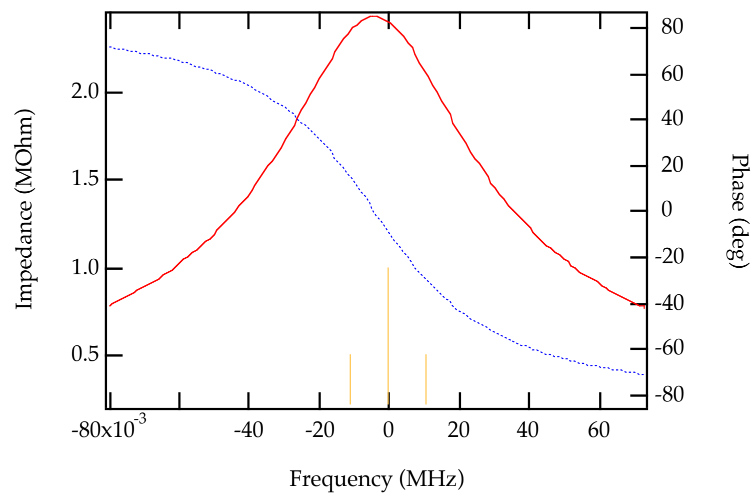




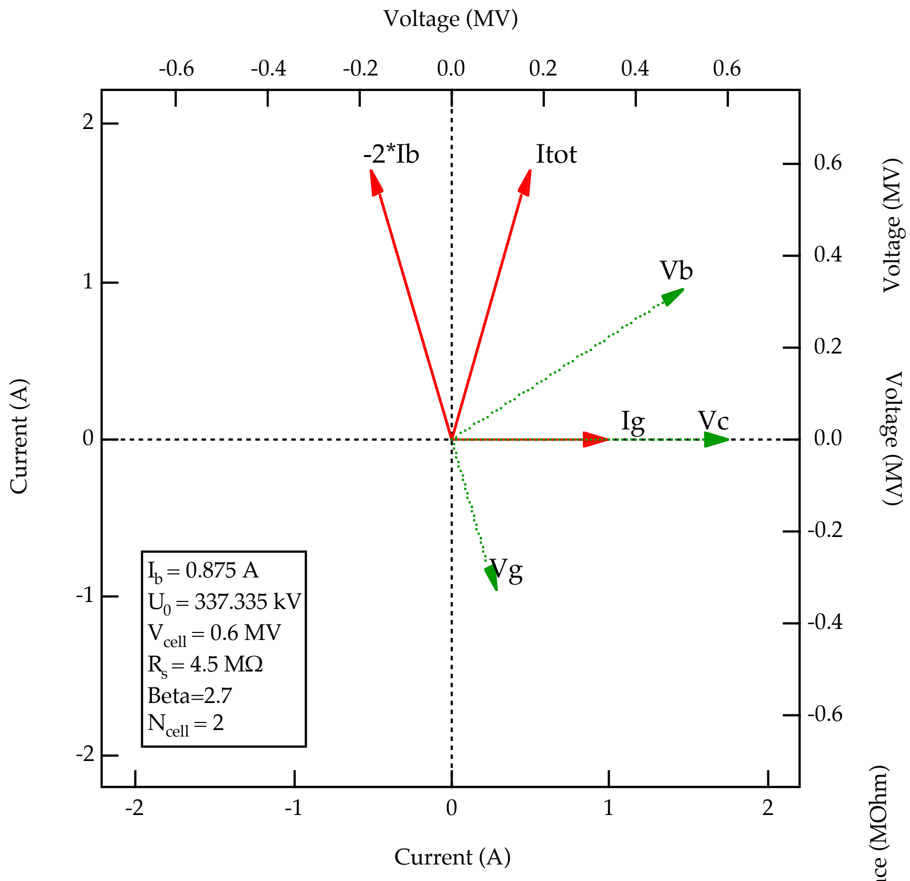
Low current

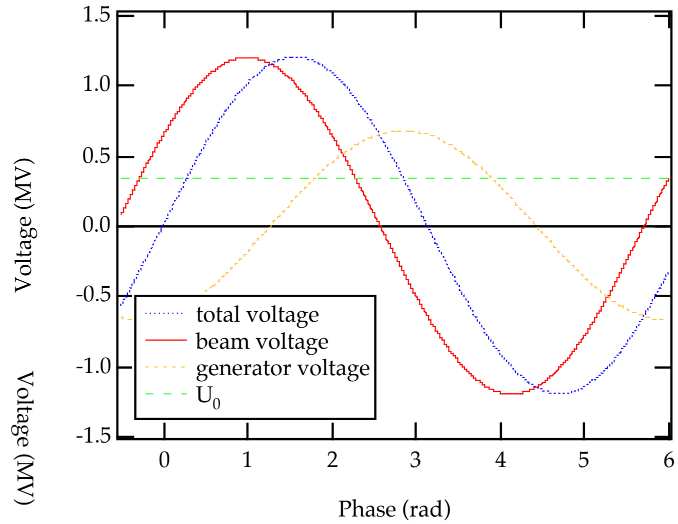

Voltage (MV)
Current (A)
Itot
Ig
Vc
Vg
-2Vbb
Ib
I_b = 0.04 A
U_0 = 337.335 kV
V_{cell} = 0.6 MV
R_s = 4.5 MΩ
Beta=2.7
N_{cell} = 2

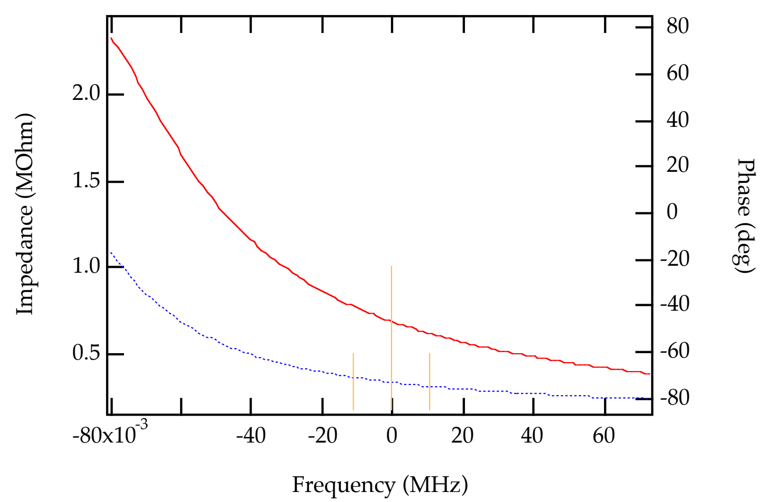

Voltage (MV)
Phase (rad)
total voltage
beam voltage
generator voltage
U_0


Impedance (MOhm)
Phase (deg)
Frequency (MHz)
-80x10^{-3}

High current limit

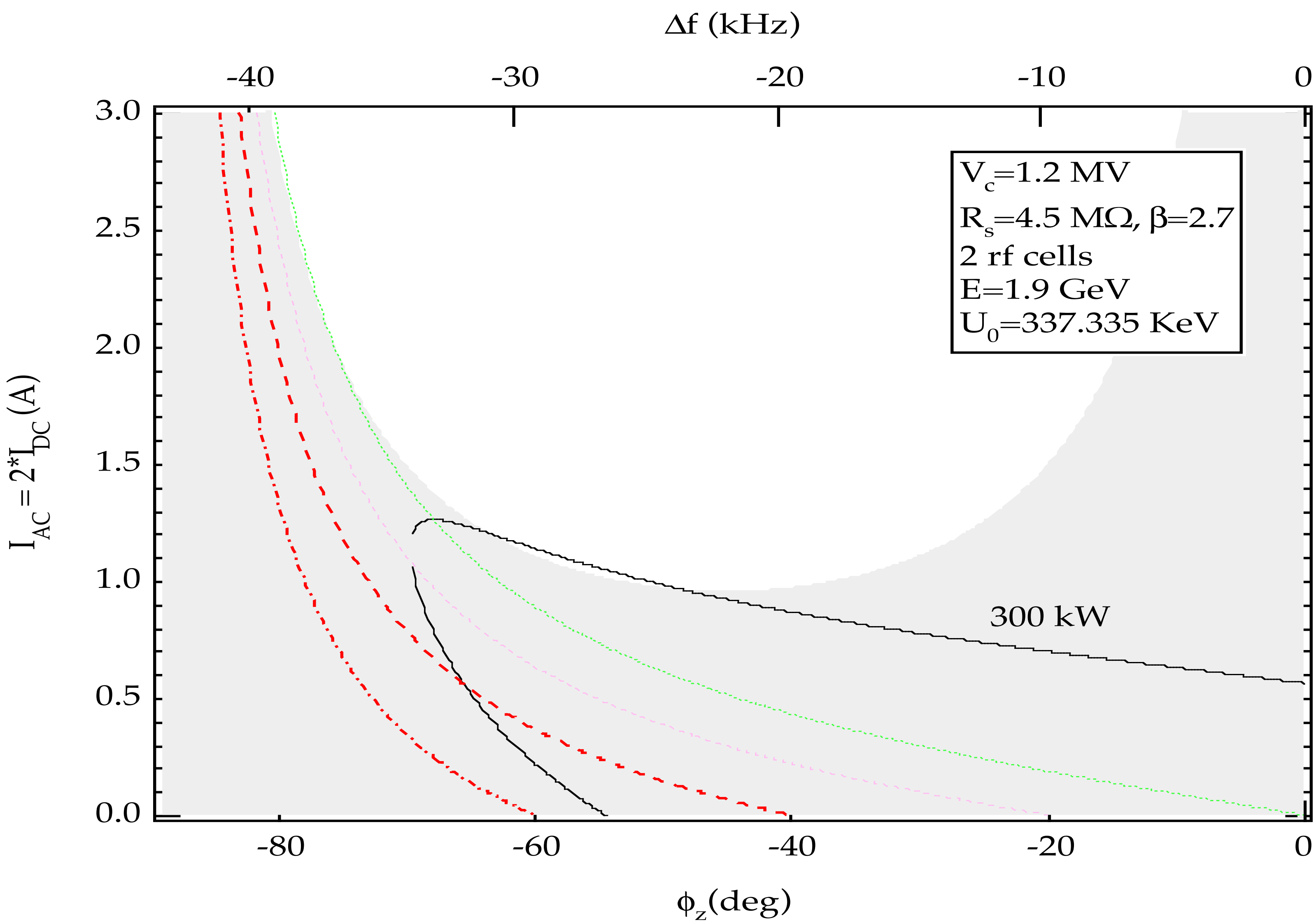






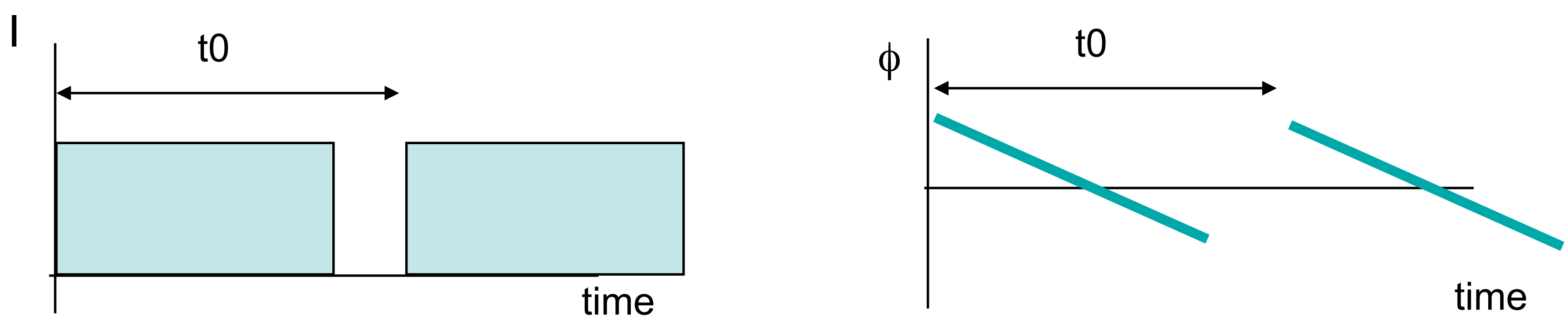
Robinson high current limit occurs when the phase focussing from the generator voltage is lost. This corresponds to the Robinson mode freq.->0.

High current limit (cont.)



Transients beam loading effects

The unequal filling of the ring (i.e. gaps) create a transient loading of the main RF systems, causing bunches to be at different RF phases (i.e. different arrival times.)



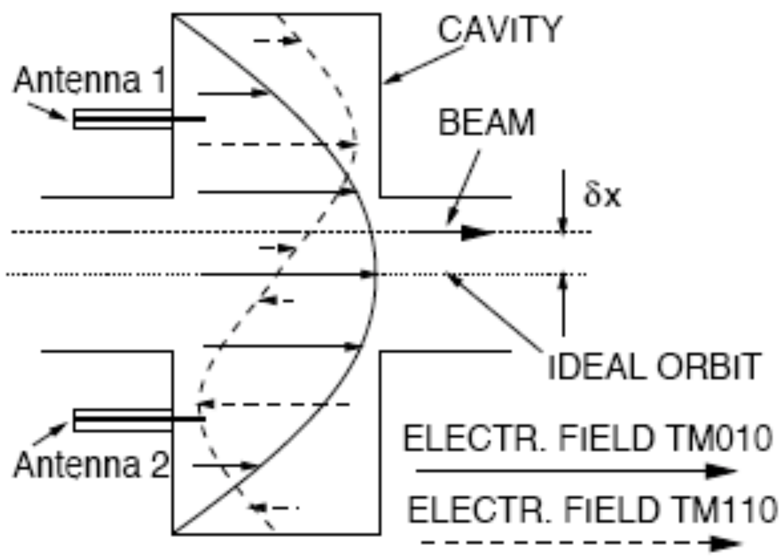
For the main RF only, this effect is small (few degrees).

Lecture Summary 2

- Transverse multibunch collective effects and cures
  - Transverse coupled bunch instabilities
  - Measurements
  - Passive cures
  - Feedback systems
  - Beam-Ion instabilities
  - Electron cloud instabilities

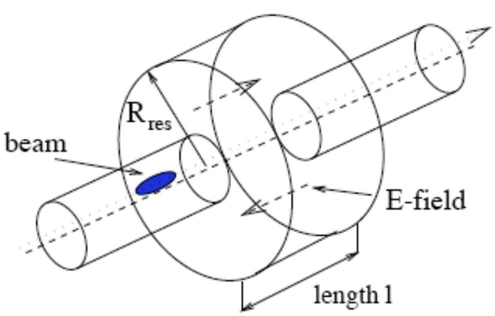
Dipole and monopole modes

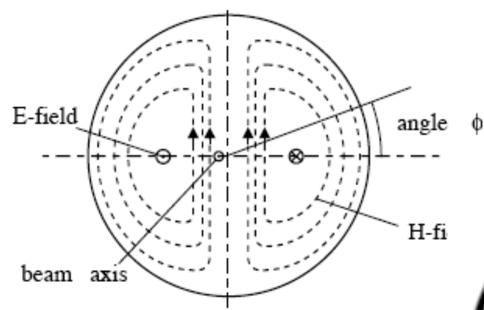
- Monopole mode (m=0, TM_{01x}) have
  - uniform azimuthal symmetry
  - Negligible dependence of longitudinal field on transverse position
- Dipole modes (m=1, TM_{11x}) have
  - Lateral symmetry with two polarizations
  - Linear dependence of long. field on transverse position.

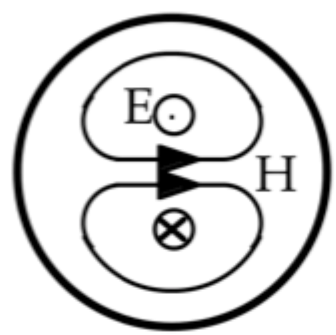


Dipole modes

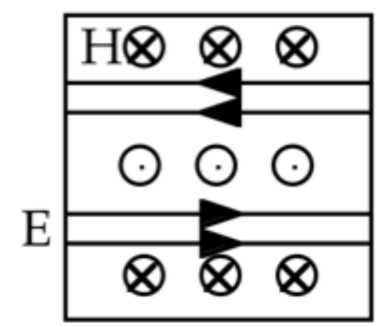
- Characterized by one full period of variation around the azimuth (m=1)
- For TM modes this means there is no longitudinal field on axis and that the field strength grows linearly with radius close to the center, with opposite sign either side of the axis.
- This transverse gradient to the longitudinal field gives rise to a transverse voltage kick which is proportional to the beam current and the beam offset.
- Therefore, no transverse kick to the beam without a longitudinal field gradient (Panofsky-Wenzel Theorem)







TM_{110}

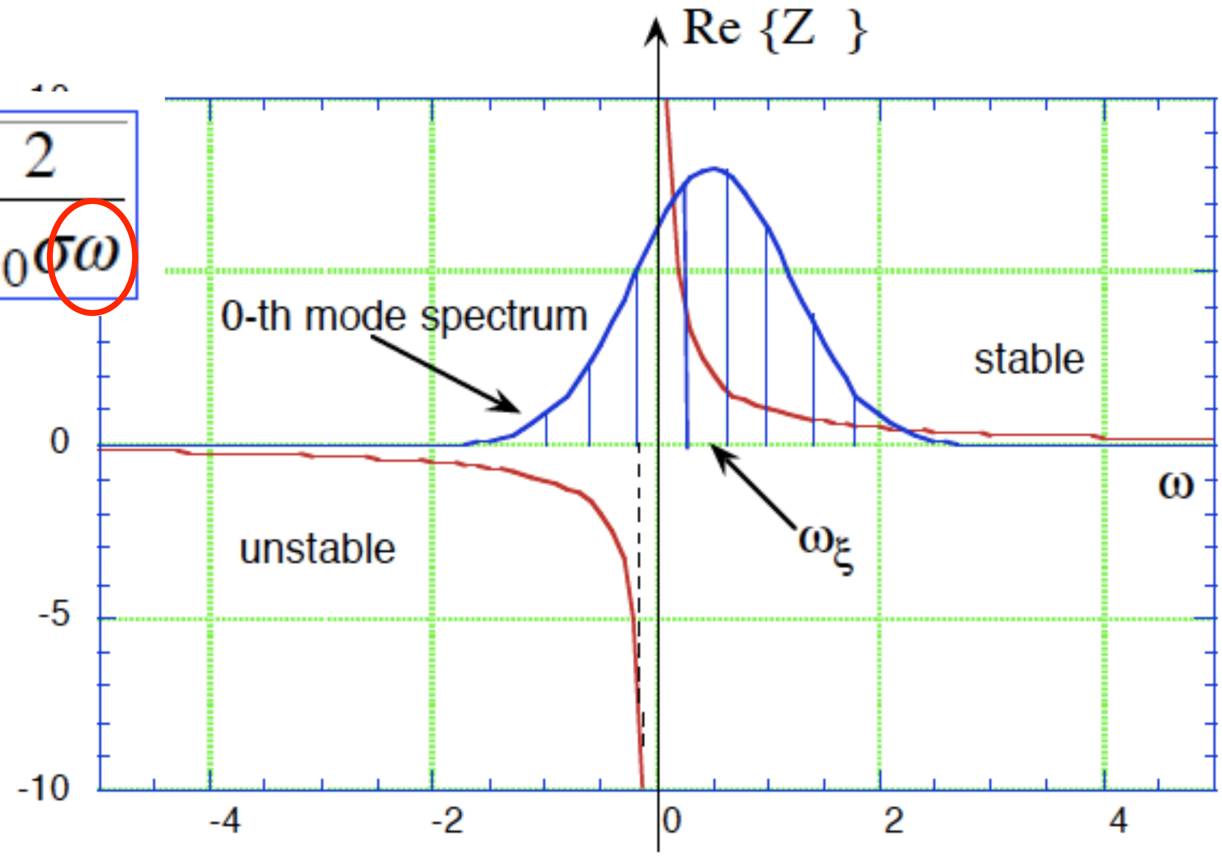


Resistive Wall Impedance

- As the beam passes through the vacuum chamber, it takes time for the beam fields to penetrate the skin depth of the metallic surface.
  - Negligible effect on long-range longitudinal wake
  - Large effect on long-range transverse wake; small gaps critical; low modes affected

$$Z_{\perp}(\omega) = (1+j)\frac{RZ_0}{b^3}\sqrt{\frac{2}{\mu_0 \sigma \omega}}$$

Z_0=120*pi Ohms
R=average ring radius
B=pipe radius
Sigma=conductivity

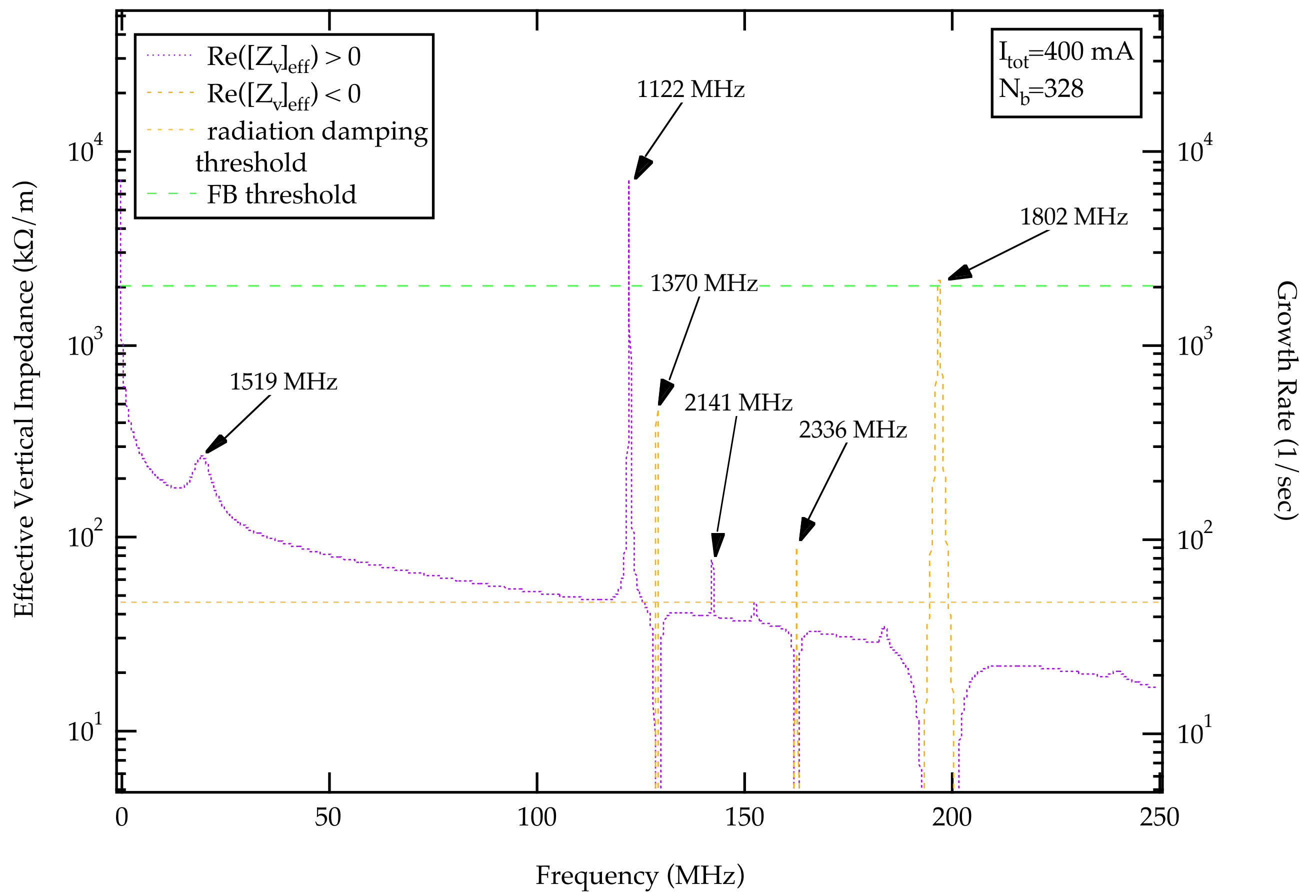


Transverse growth rates

Transverse growth rate

$$\tau^{-1} = \frac{1}{2} f_0 \frac{I_0}{(E/e)} \beta_\perp \sum_{p=-\infty}^{p=+\infty} \mathrm{Re}\big(Z_\perp(\omega_p)\big)$$

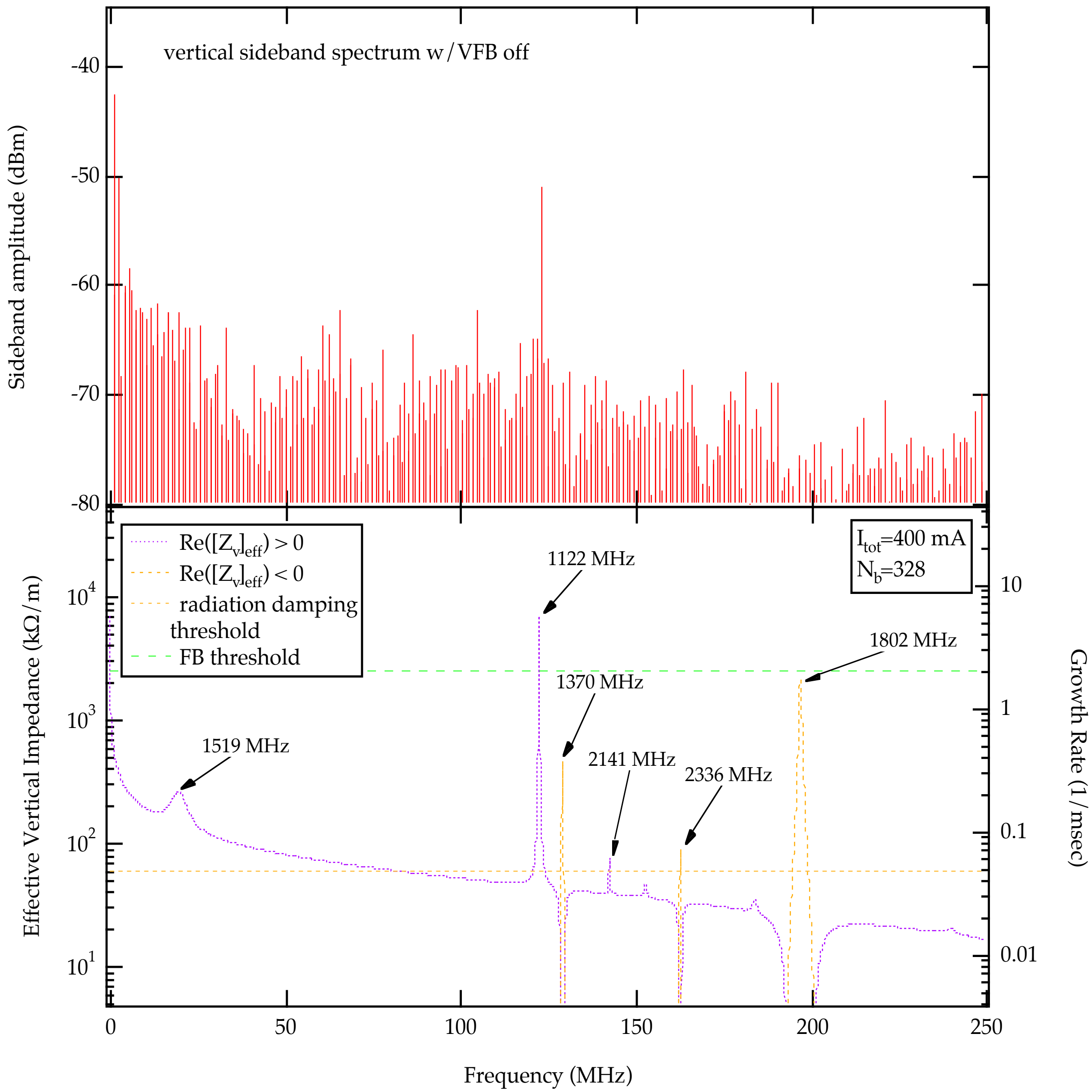
The resistive wall impedance cannot be avoided by tuning.



Aliased vertical impedance for the ALS.

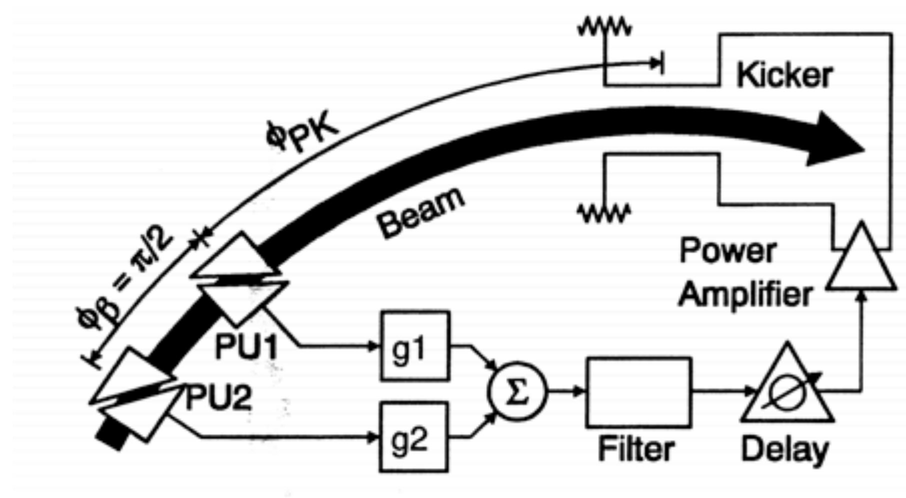
Transverse beam spectrum

The unstable spectrum of betatron sidebands can be used to identify the driving beam modes.



Transverse feedback systems

Design issues:
•Bandwidth>1/2 bunch frequency (M*revolution freq) to handle all possible unstable modes
•Phase shift from PU to pi/2
    options:
    •properly locate PU and kicker- sensitive to lattice configuration
    •use quadrature PUs/kickers
    •use multiturn delay
•Suppress DC orbit offset (wastes expensive broadband power)
    options
    •zero orbit at PUs
    •electronically suppress orbit offset
    •notch filters



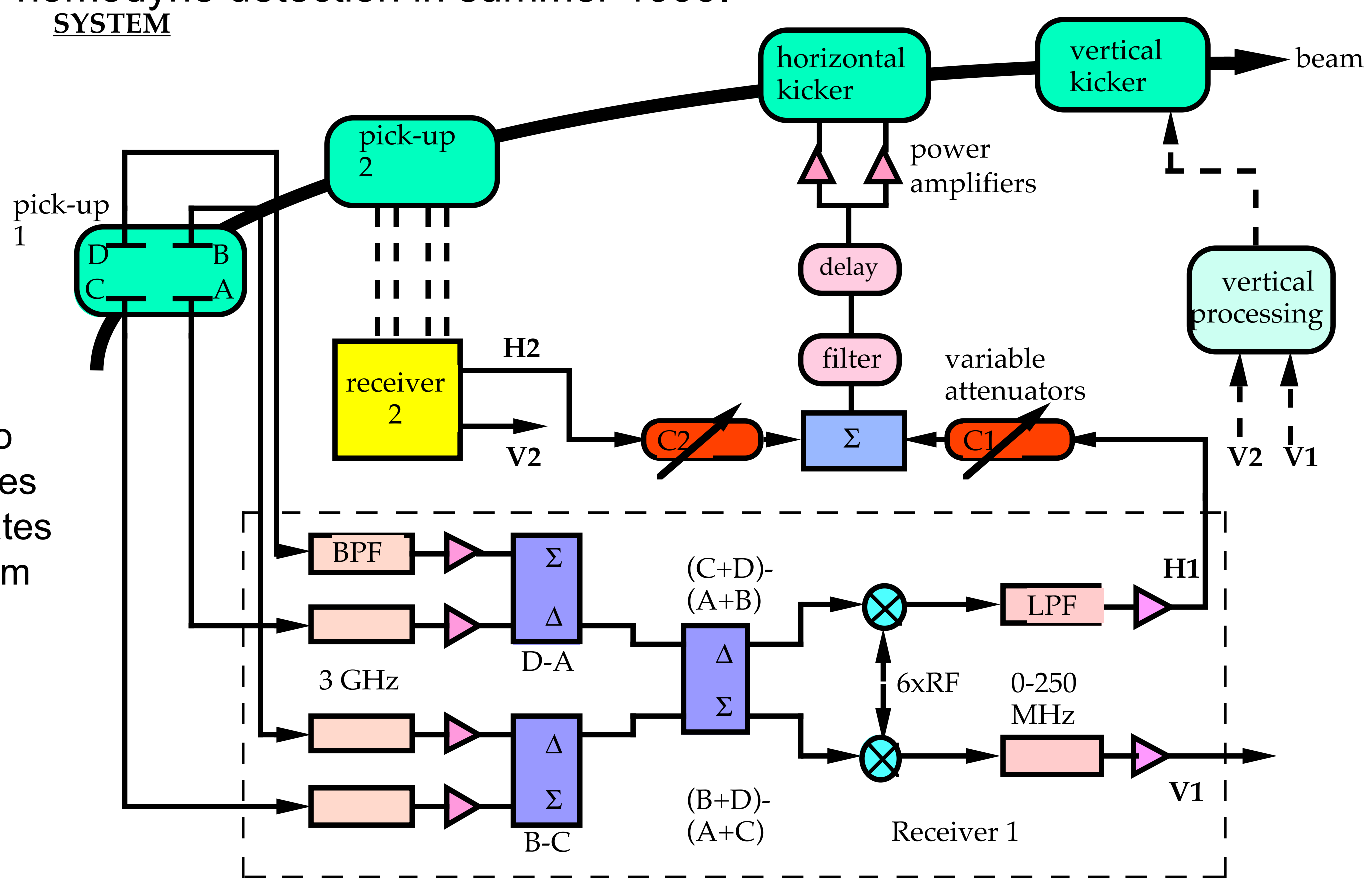
Typical transverse damping system

•Total system gain must provide damping rate faster than fastest growth rate (minus radiation and Landau damping)
•Noise
    •total system noise must drive oscillations at small fraction of beam size
    •important at high gain settings
•Amplifier power scaled to damp largest mode

ALS TFB system

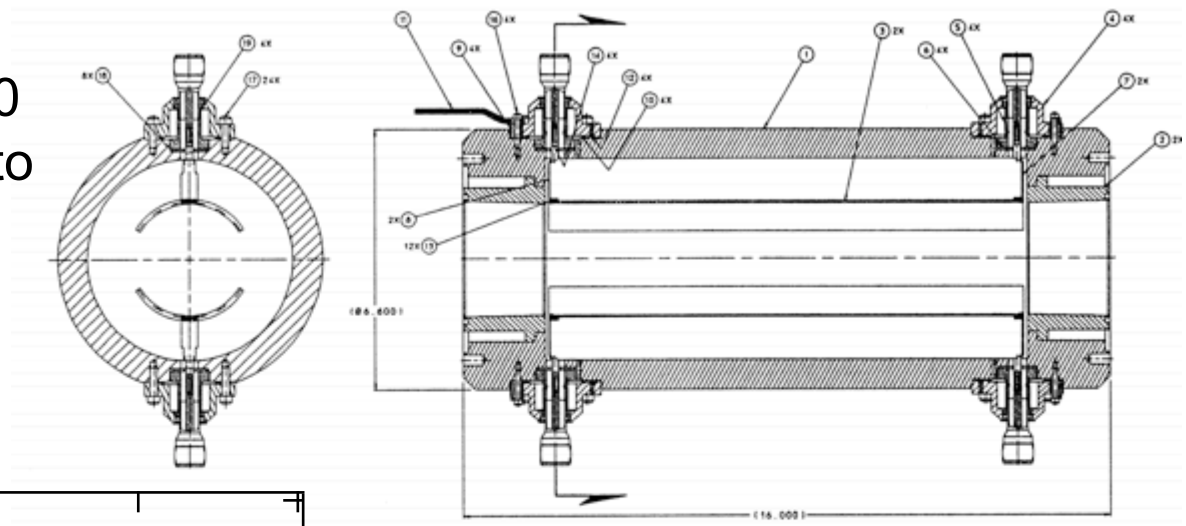
•high gain/low noise receivers (3 GHz heterodyne detection), current dependent gain
•2 PUs w/quadrature processing
•150 W amplifiers driving stripline kickers (single plate only), maximum kick of ~1 kV
•2-tap analog notch filter for removing DC orbit offsets
•system upgraded to homodyne detection in summer 1999.

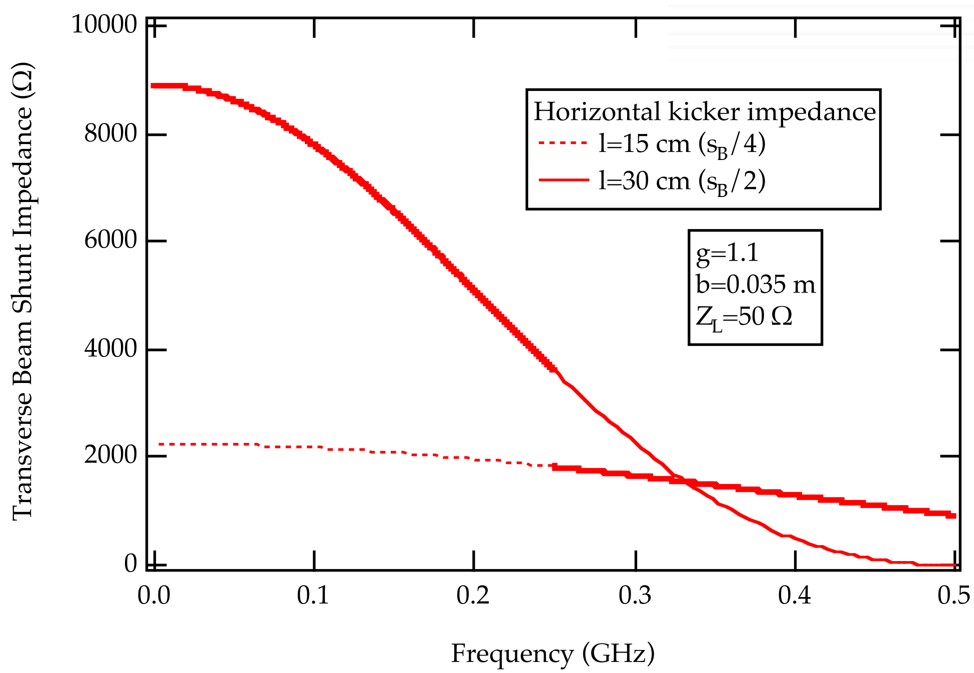
TFB Issues:
•increased gain req'd to damp a few dipole modes
•analog notch filter creates dispersion across system bandwidth.



ALS TFB Kicker

Stripline kickers at with L=30 cm are driven at baseband to gain the advantage at low frequency against the RW.

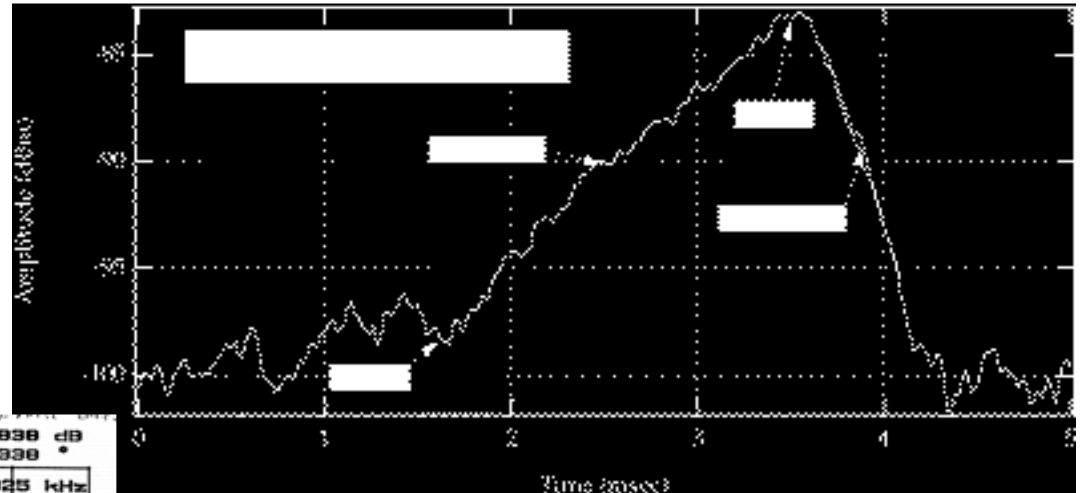


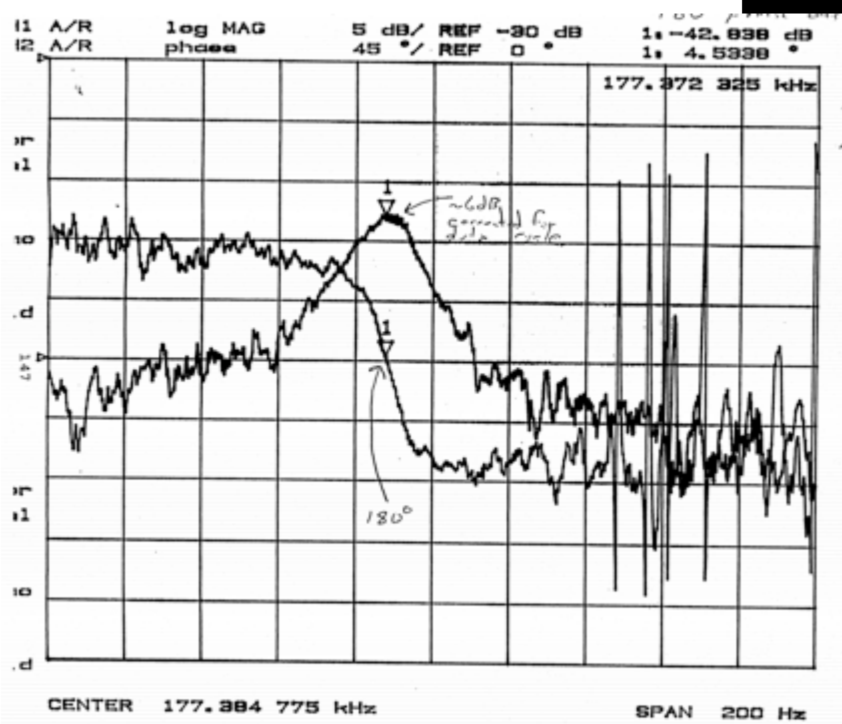


Baseband operation requires an amplifier which extends to lower frequency of lowest betatron frequency. More amplifiers are available in the higher operational bands.

TFB diagnostics

Time domain growth rates can be measured by modulating the FB on/off. Betatron mode is measured with SPA in zero-span mode.

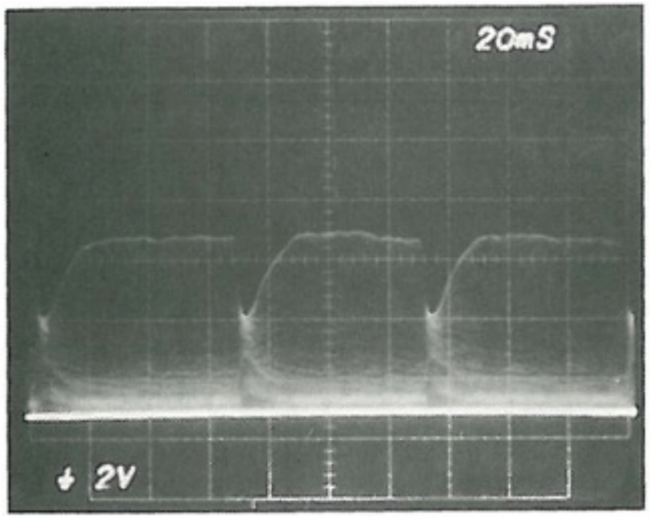




The TFB system can be adjusted be measuring beam transfer functions on a network analyzer. Shown is an open-loop measurement of x channel.

Ion instabilities

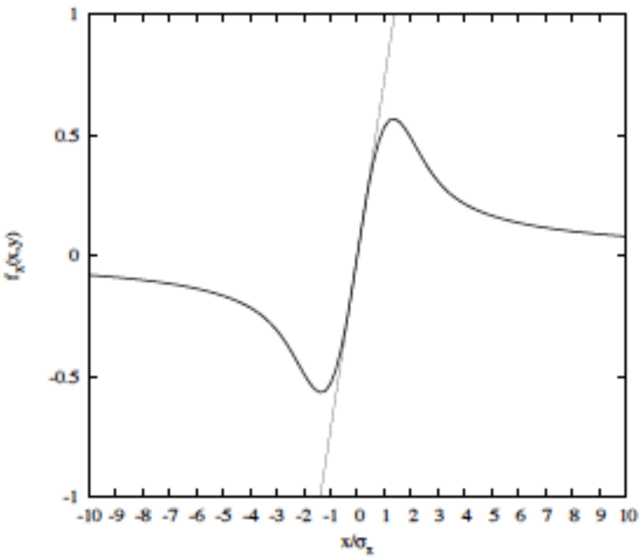
- Even in ultra-vacuum, circulating electrons collide with the residual gas and ions created.
- Ions may be trapped in the electrostatic potential of the electrons.
- Trapped positively charged ions perturb electron motions.
- Effects of ions on the electron beam:
  - Beam size blow-up
  - Limitation in stored beam current
  - Reduction in lifetime due to additional collisions
  - Tune shifts
  - Two-beam instability
- These undesirable effects were observed in many early light sources (DCI, ACO, SRS, KEK-PF, UVSOR, NSLS, Aladdin, …)

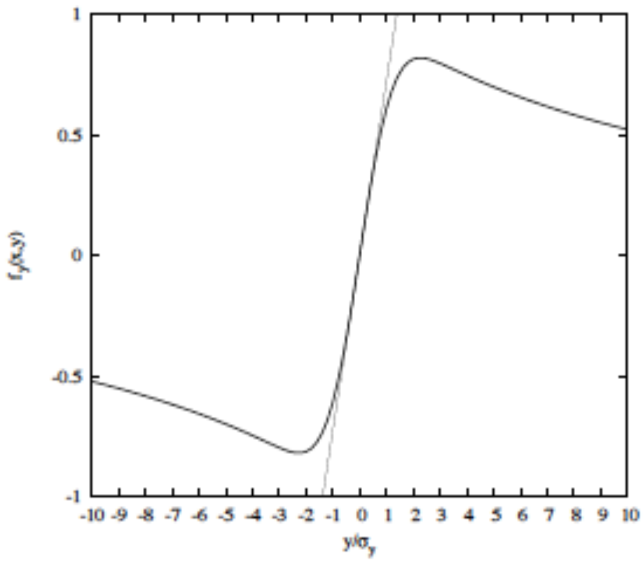


Two-beam instability observed at KEK-PF (from S. Sakanaka, OHO Lecture note 1986)

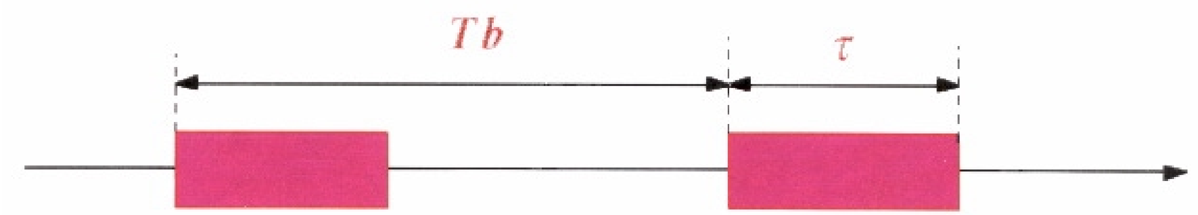
Ion (and Dust!) Trapping

- Ions are focussed in the linear part of the beam potential





  - The stability of the motion can be broken by introducing gaps in the beam filling pattern, allowing ions to drift to the walls. Lighter ions are more unstable.

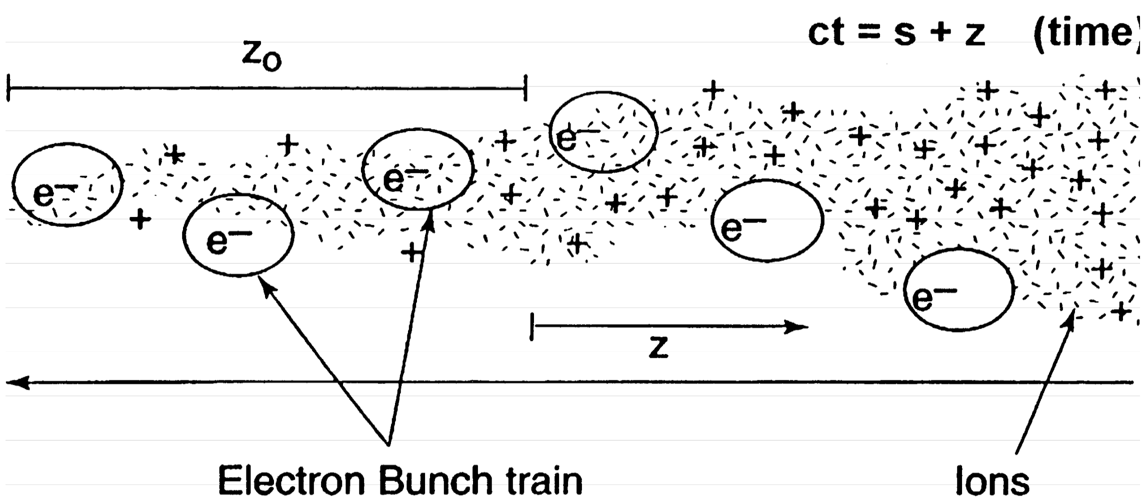


Ion instability cures

- Introduction of beam gaps
  - Destabilize ion motion. Effective for lighter ions
- Use of clearing electrodes
  - Electric move ions to wall
- Electron beam shaking
  - Indirectly resonantly drive ions via electron beam. Shake at ion frequency.
- Shift of chromaticity to positive/Use of octupoles
- Use of positron beams. In particular, positron beams were used in a number of light sources (DCI, ACO, KEK-PF, APS, …)
  - Although the problems of ions are cleared with positrons, high current positron operation can suffer from electron cloud instability. ;

Introduction to the FBII

"classic" ion trapping occurs when the motion of ions is stable in the beam's potential well over many beam passages. The ion motion becomes unstable for large enough gap in the filling pattern (i.e. clearing gap). This is the typical "passive" solution for curing ion problems.
For high currents and low emittances, transient interactions between the beam and ions can cause significant beam oscillations.

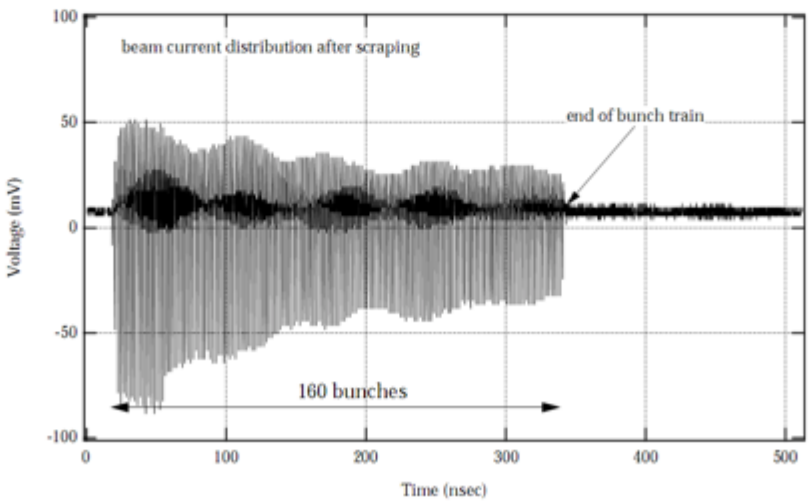


References:
T. Raubenheimer and F. Zimmermann, Phys. Rev. E, 52 5487 (1995)
G. Stupakov, T. Raubenheimer and F. Zimmermann, Phys. Rev. E, 52, 5499 (1995)

Experimental Studies of FBII in Some 3rd GLSs

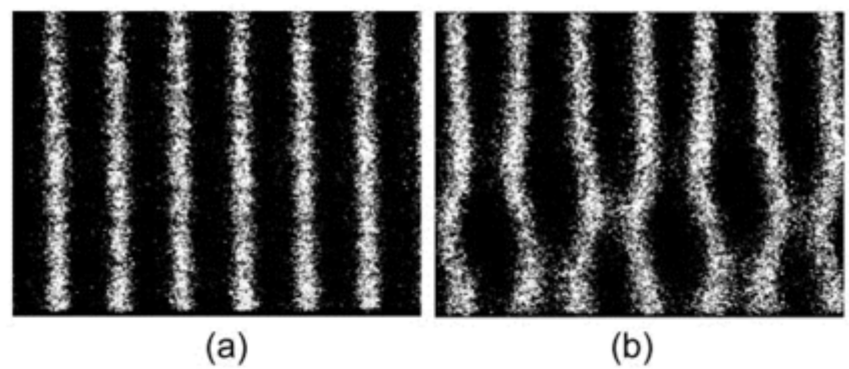
The vacuum pressure was deliberately increased (pump off/He-gas injection) and the existence of FBII as well as its characteristics were compared with theory in ALS, PLS, ESRF, …

➔ Observed results were in qualitative agreement with theory



Beam current after moving a vertical scraper towards the beam

*(J. Byrd et al., PRL, **79** (1997) 79)*



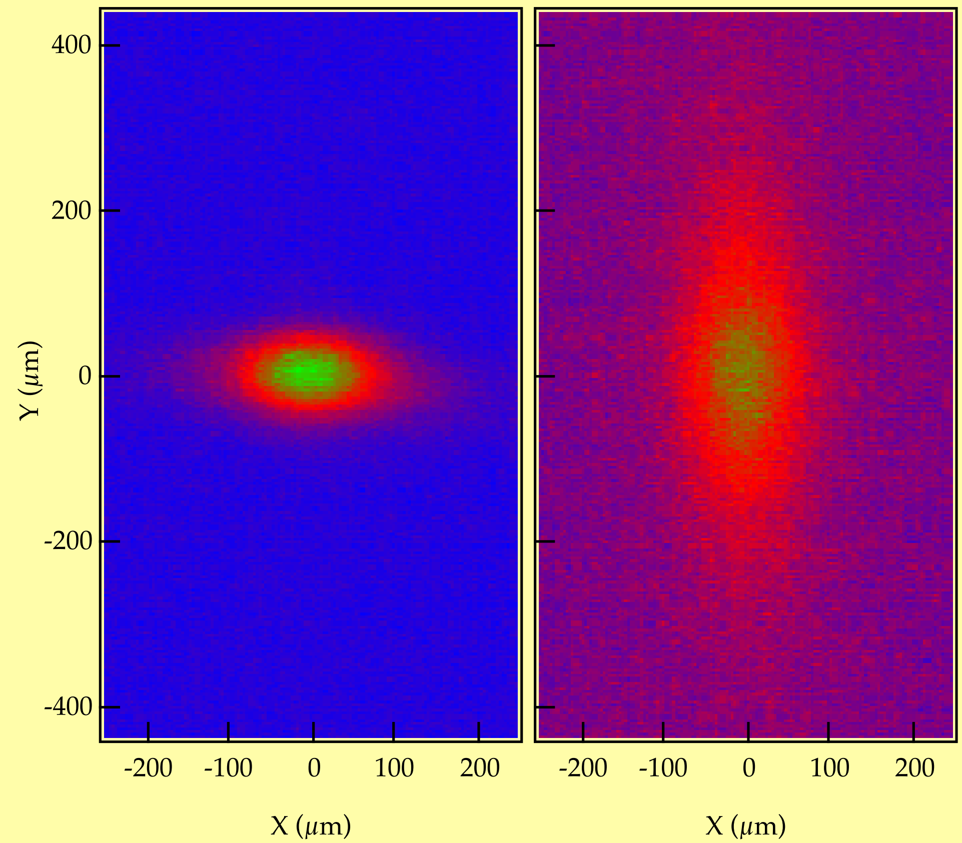
Dual sweep streak camera image of a bunch train

*(M. Kwon et al., Phys. Rev. **E57** (1998) 6016)*

Dedicated FBII Expt

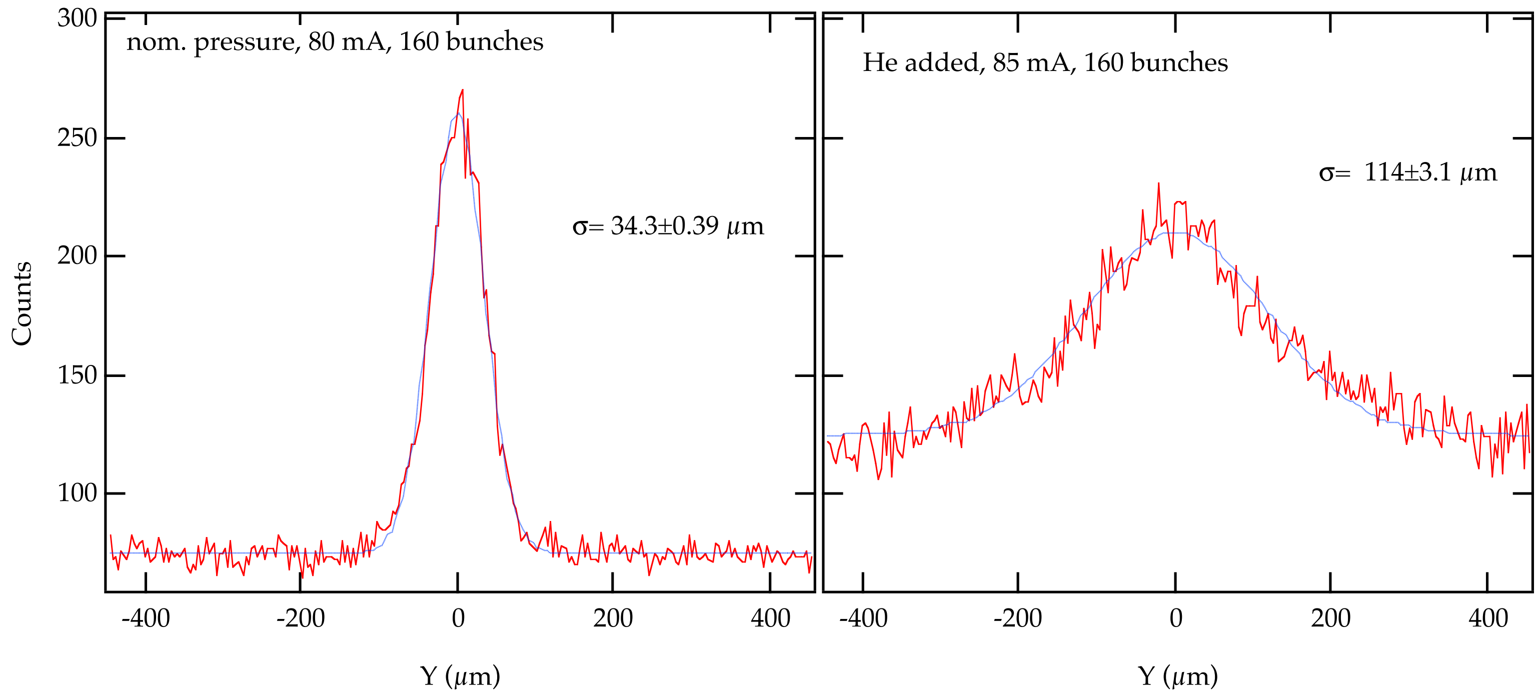
Setup conditions where the FBII is expected with growth rates at least an order of magnitude above growth rates from cavity HOMs and resistive wall impedance

- Use He gas because it is not pumped well by passive NEG pumps
- He at 80 ntorr gives growth rates <1/msec
- Use bunch patterns where ion trapping of helium not expected (typically 1/2 ring filled with 2 nsec spacing.)



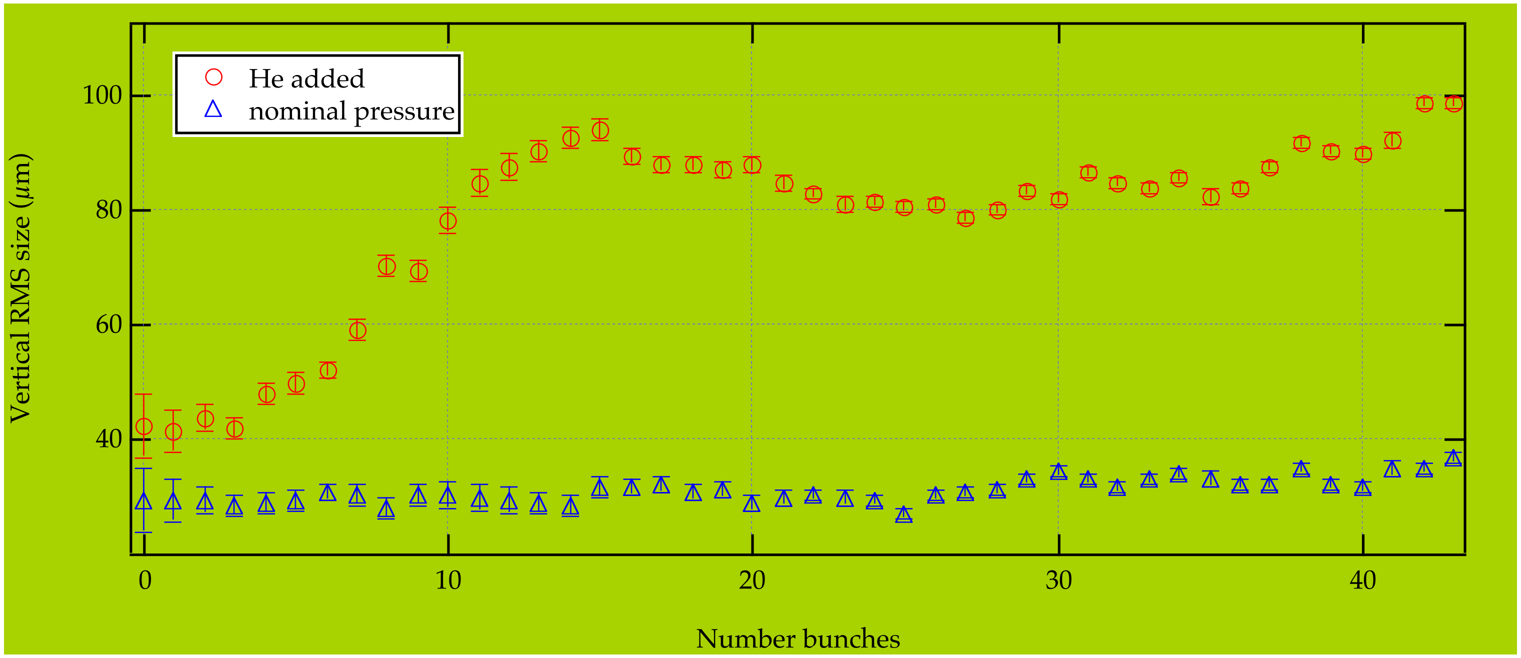
Synch light monitor image at nominal and high pressure. Vertical blowup evident but much smaller than typically vertically blowup due to HOM-driven instability.

Vertical beam size increase



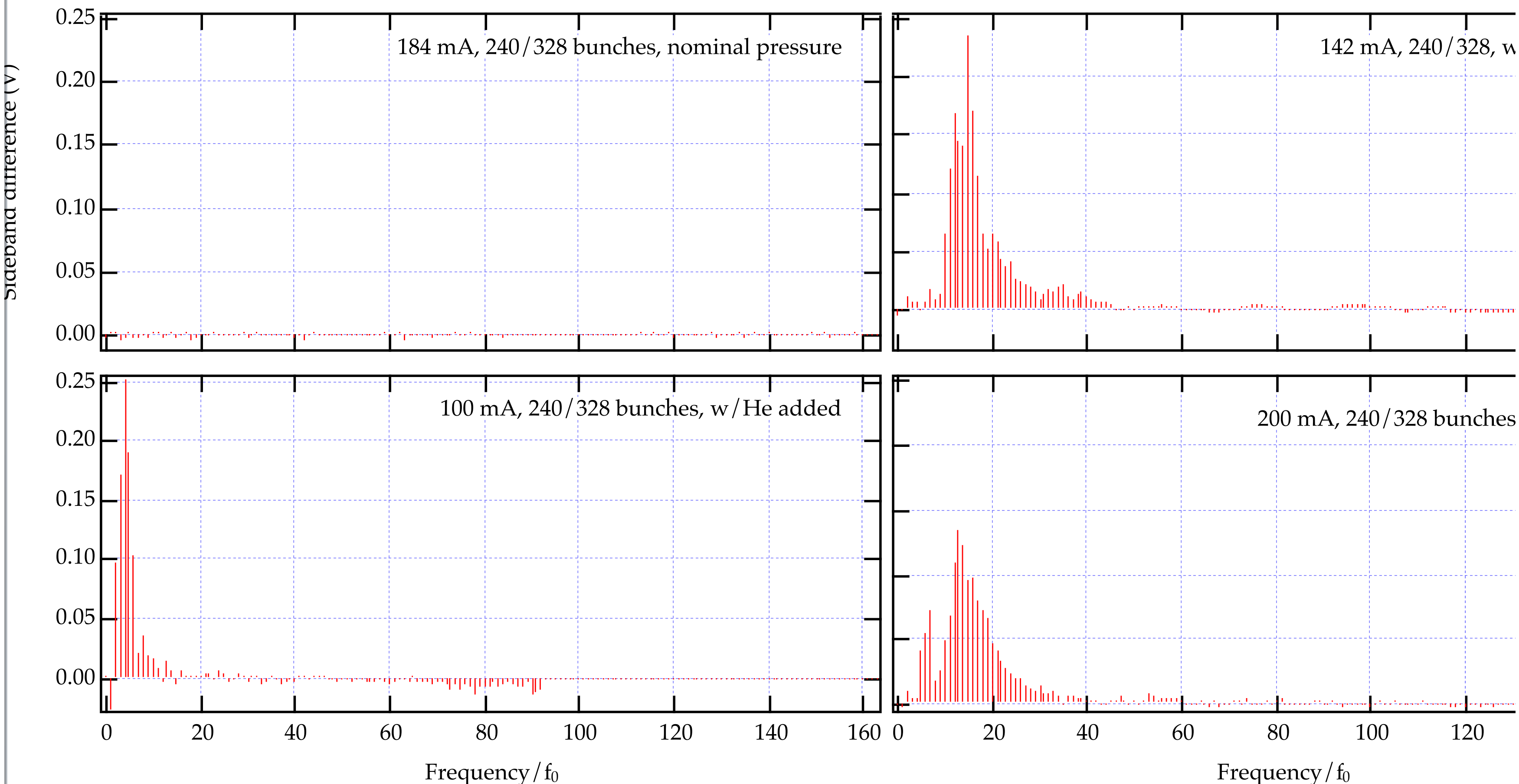
- We see between a factor 2-3 increase in average vertical beam size. Horizontal size is unaffected.
- Single bunch images show no increase with higher gas pressure.
- Simulations show a similar saturation effect.
- variation of vertical FB gain has no effect on beam size or sidebands

Indirect Growth Rate Measurement



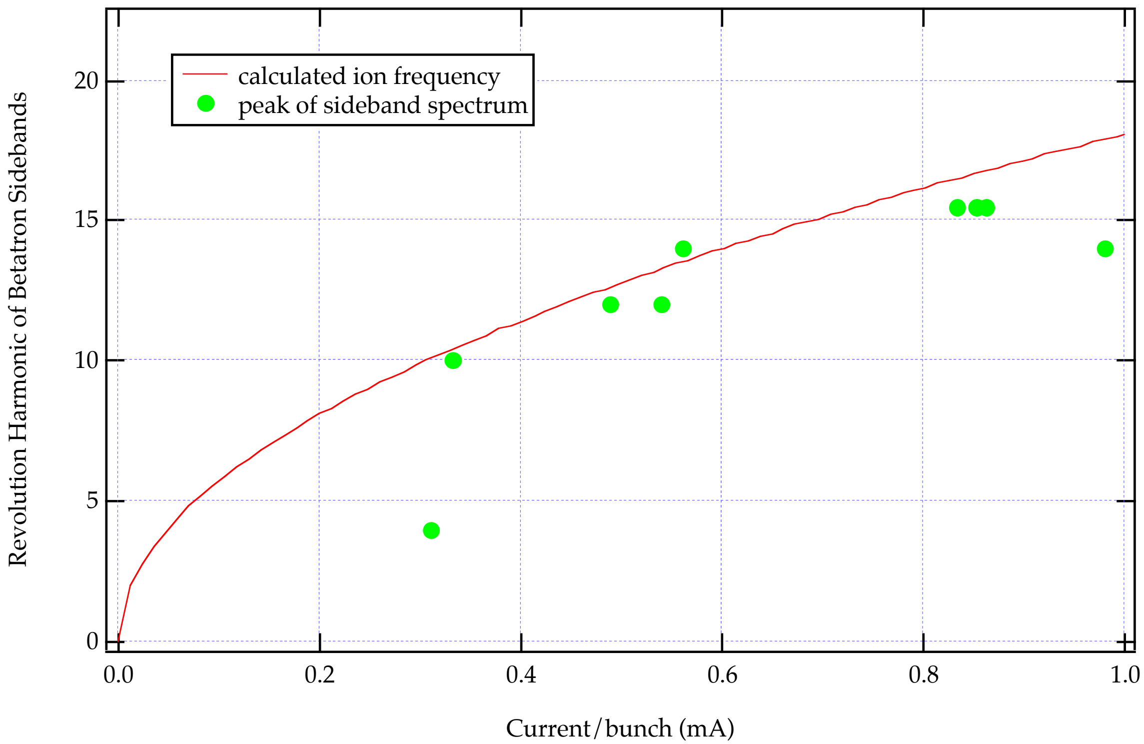
•at a given pressure, we can vary the instability growth rate by varying the length of the bunch train (using a fixed current/bunch)
•for the experimental conditions, the theory predicts a growth rate of ~1/msec at about 8 bunches. Our FB damping rate for 0.5 mA/bunch is ~1.2 msec.

Vertical sideband spectrum



- record the amplitudes of all vert betatron sidebands over 250 MHz range
- plot the linear difference of lower-upper sideband amplitude
- peak frequency of sideband pattern agrees with calculated coherent ion frequency
- coherent oscillations not always observed (decoherence? 4-pole mode?)

Frequency of sideband spectrum



- Peak frequency of the sideband spectrum shows fair agreement with the calculated ion frequency
- Detailed agreement requires precise knowledge of the vertical beam size which is difficult to determine when the beam is unstable.
- Coherent signal is not always visible on the spectrum analyzer, even though the beam is clearly vertically unstable.

Ion instability summary

- Ion trapping was a serious issue in early light sources and many studies (theory and experiment) made to overcome it.
- Improved vacuum engineering and the use of beam gap manages to avoid ion trapping in most 3rd GLSs and no serious problems of ion trapping reported.
- No serious effect of FBII encountered in light sources
- However, FBII could become a serious issue for future light sources operating at high current with low emittance, and further studies required.

Lecture Summary 3

- Landau Damping
- Longitudinal single bunch collective effects
  - Short-range longitudinal wakefields and broadband impedance
  - Potential well distortion
  - Longitudinal microwave instability
  - Measurements
  - CSR microbunching instability
- Transverse single bunch collective effects
  - Short-range transverse wakefields and broadband impedance
  - Head-tail modes and chromaticity
  - Measurements
  - Feedback

Effects of single bunch instabilities

- The brightness of a 3GLS is proportional to the total current:
  - I=Number of bunches x current/bunch
- The strategy for 3GLS is to minimize single bunch collective effects by using many bunches.
- Exception 1: some users want to have timing gaps between bunches of ~200 nsec
  - Number of bunches reduced
  - Maximize current/bunch while maintaining stable beam.
- Exception 2: some users want short bunches (<10 psec)
  - Larger peak bunch current drives more collective effects
  - Bunches less than ~3 psec have large effects from radiation impedance.

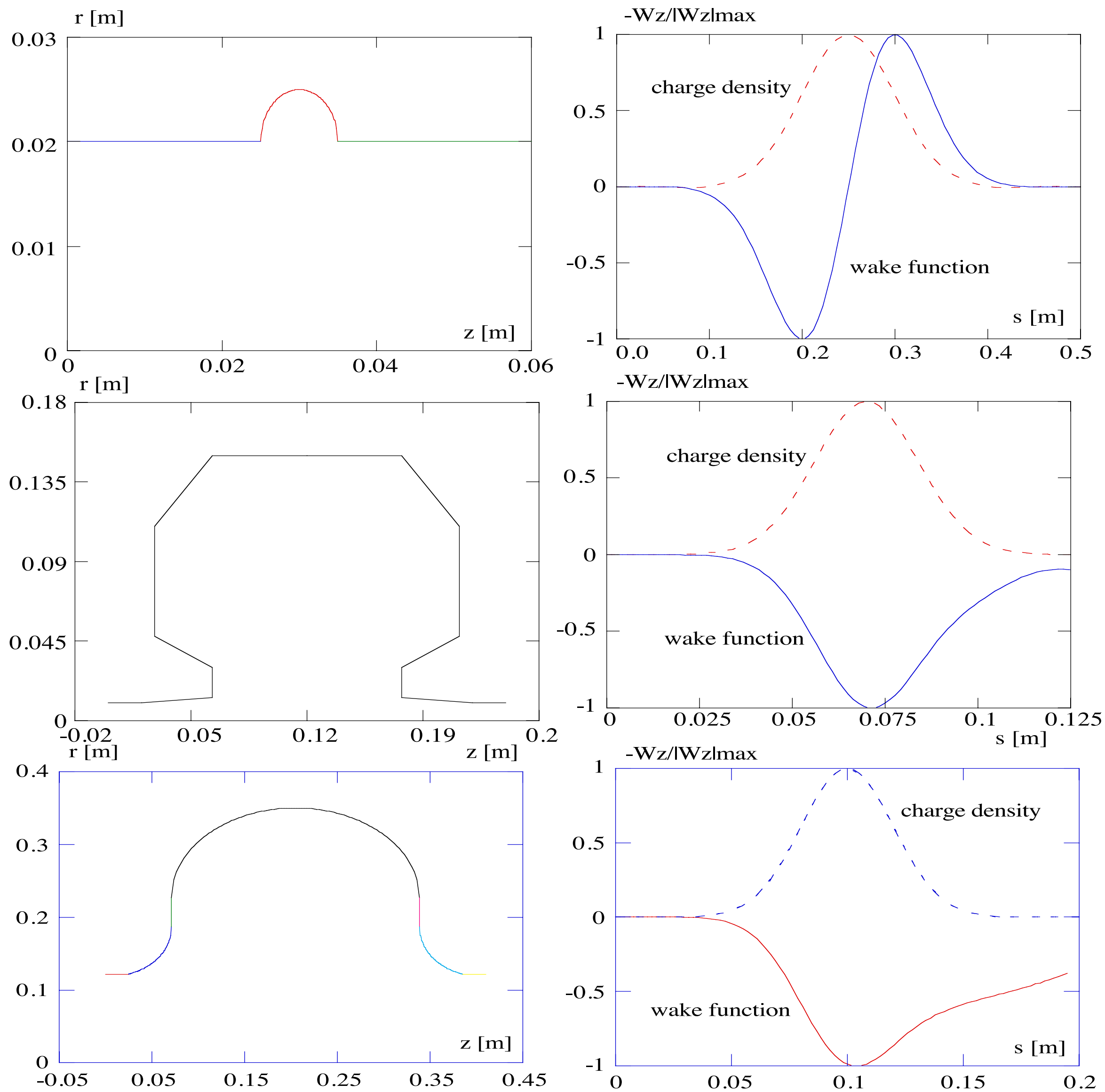
Single Bunch Collective Effects

- Driven by short-range wake fields (broadband impedance)
- Longitudinal effects
  - Potential well distortion
    - Bunch length increase
  - Microwave instability
    - Bunch length and energy spread increase
- Transverse
  - Head-tail damping
    - Uses chromaticity to provide additional transverse damping. Very good for stabilizing coupled bunch instabilities
  - Transverse mode-coupling instability
    - Hard limit to total bunch current. In 3GLS, driven by tapers and small gap ID vacuum chambers.

Short-range wakes and broadband impedance

- Short-range wakes are those that last over the length of the bunch.
- Generated by the many discontinuities in the vacuum chamber: RF cavities, kickers, pumps, tapers, resistive wall, etc.
- The wake (and impedance) of all of these components can be calculated with modern EM codes.
- The total wake is summed together and assumed to act at a single point in the ring. Valid for slow synchrotron motion.

Example Wakes



- Small cavity
- V~dI/dt
- Inductive

- Large cavity, small beam pipe
- V~I
- Resistive

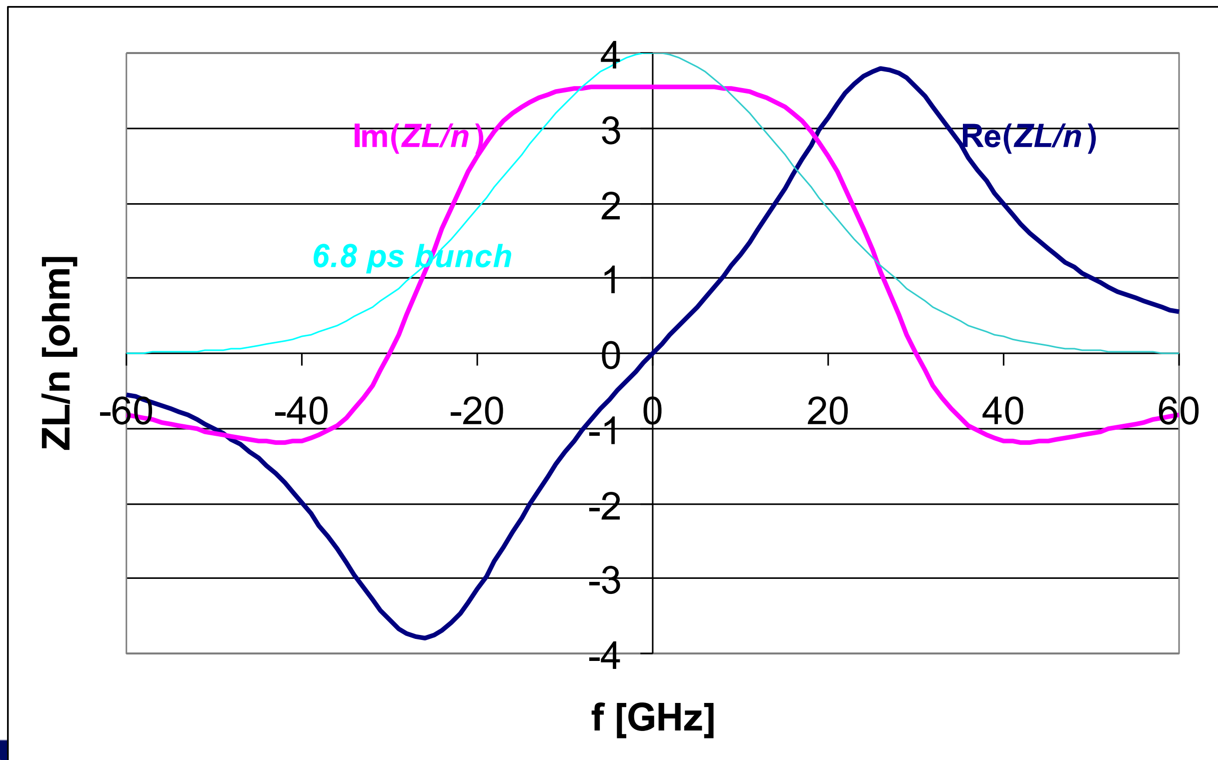
- Large cavity, big beam pipe
- V~∫I
- Capacitive

Broadband Impedance Model

- In order to characterize the total short range wakes in the machine for use in estimating instability thresholds, several broadband impedance models have been developed. I mention two below.

Broadband resonator model

- Model the broadband impedance as a ~Q=1 resonator
  - Low frequency component is inductive characterized by the inductance Z~wL
  - $Z/n \sim w_0 L$ where $n = w/w_0$
- – Note that this is only an approximate model which is convenient for calculations



Heifets-Bane-Zotter Model

- Characterize the broadband impedance as a expansion in orders of sqrt(w). This account for various types of impedance (inductive, capacitive, etc.)

$$Z(\omega) = j\omega L + R + \left(1 + j\,sign(\omega)\right)\sqrt{|\omega|}B + \frac{1 - j\,sign(\omega)}{\sqrt{|\omega|}}\tilde{Z}_c + \ldots$$

Inductance

resistance

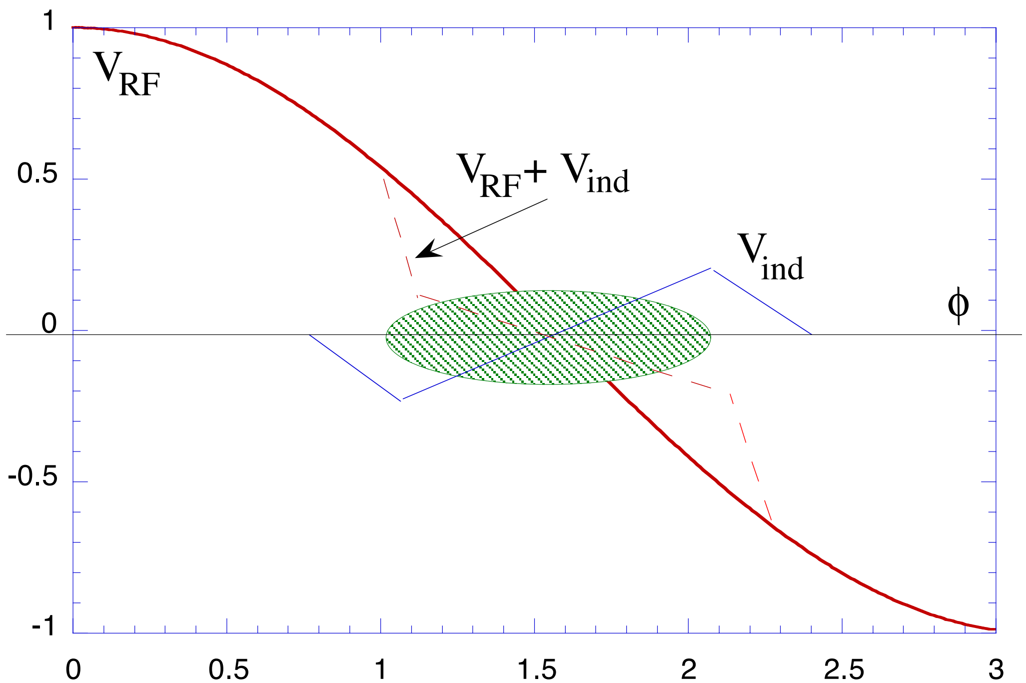
Resistive wall

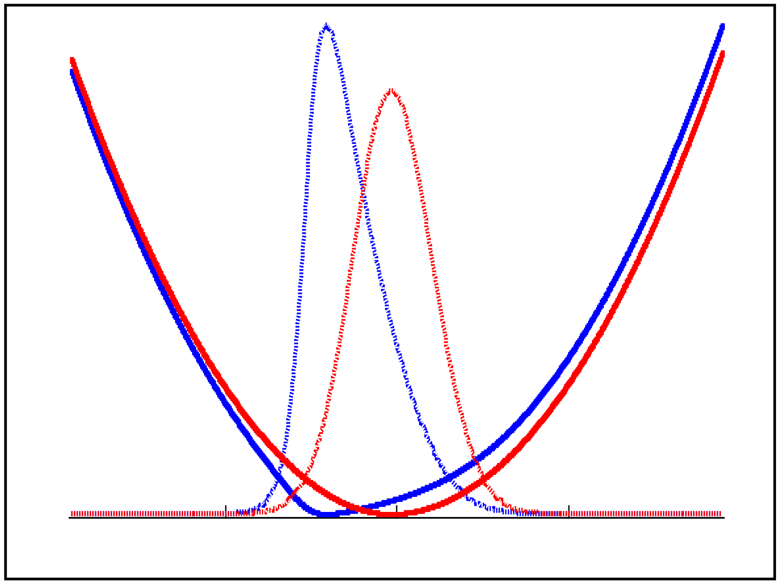
High frequency cavities

The values for individual terms can be found from fitting to the computed wakes

Potential Well Distortion

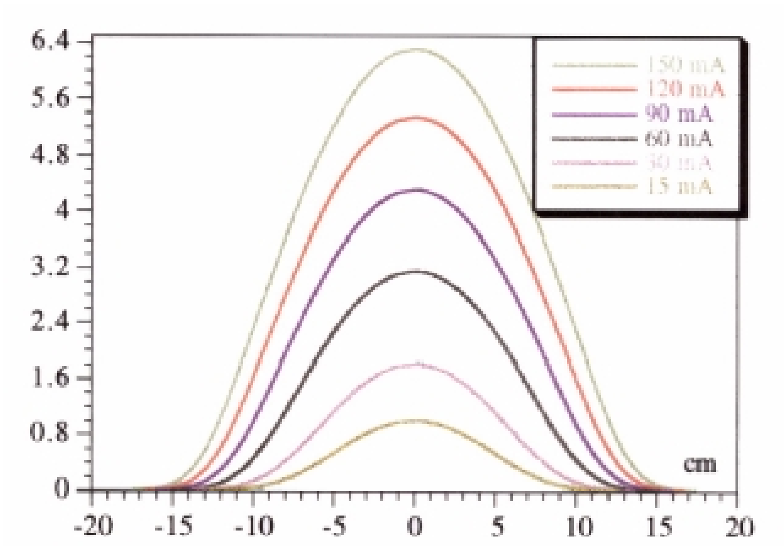
- The nominal bunch shape and length is determined by the linear (almost!) restoring force of the main RF voltage. If we add the short-range wake potential, the bunch shape can change. This is known as PWD.
- The stable phase position also changes. This accounts for resistive losses into the broadband impedance.

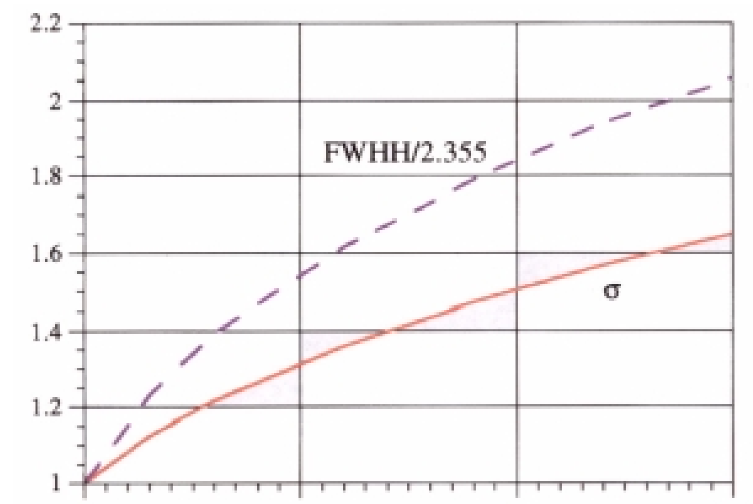


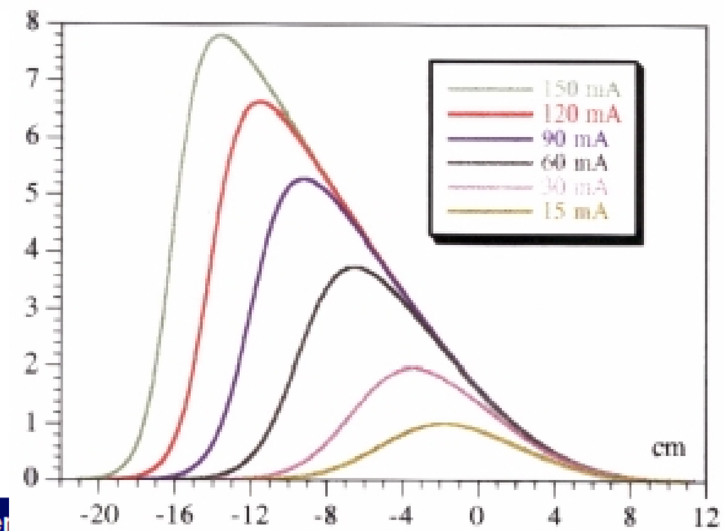


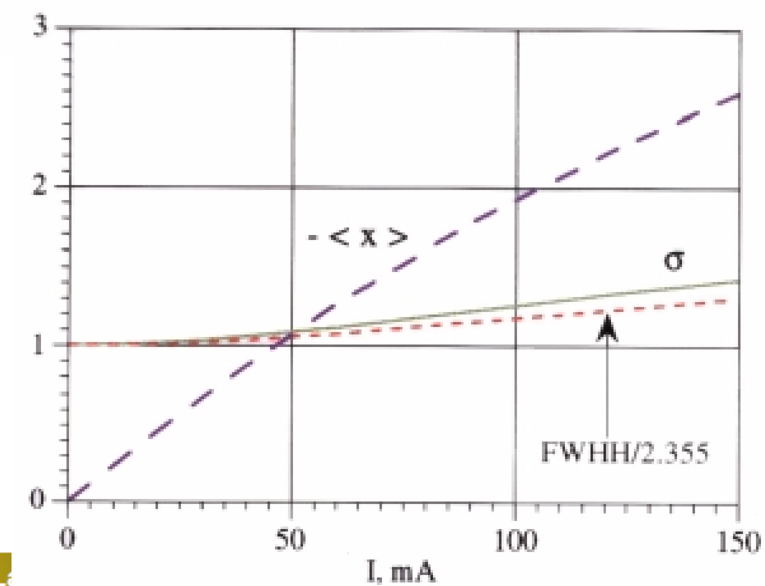
Potential well distortion

- Example calculation for a purely inductive Z=wL and resistive Z=R impedance









Microwave Instability

- PWD is a static deformation of the bunch shape
- Above a threshold, instabilities develop within the bunch, increasing the energy spread and bunch length and thus decreasing the peak current.
- The instabilities have characteristic lengths less than a few tens of cm. Therefore they are known as **microwave instabilities**.
- The details of such an instability depends on the details on the short-range wake, and the detailed bunch parameters (energy spread, synchrotron tune, momentum compaction.)
- There is a general characterization of the microwave threshold known as the **Boussard criterion**. Turbulence starts when the slope of the total voltage (RF plus wake-fields) becomes zero at some point within the bunch. It can be shown that for a Gaussian bunch and a purely inductive impedance both criteria are equivalent.

Boussard Criterion

- The microwave instability can be approximated by the Boussard criterion.

$$\frac{eI_p\,|Z(n)/n|}{2\pi\alpha E_o\sigma_E^2} = 1$$

Peak bunch current
~I_{bunch}/bunch length

Momentum
compaction

Effective impedance

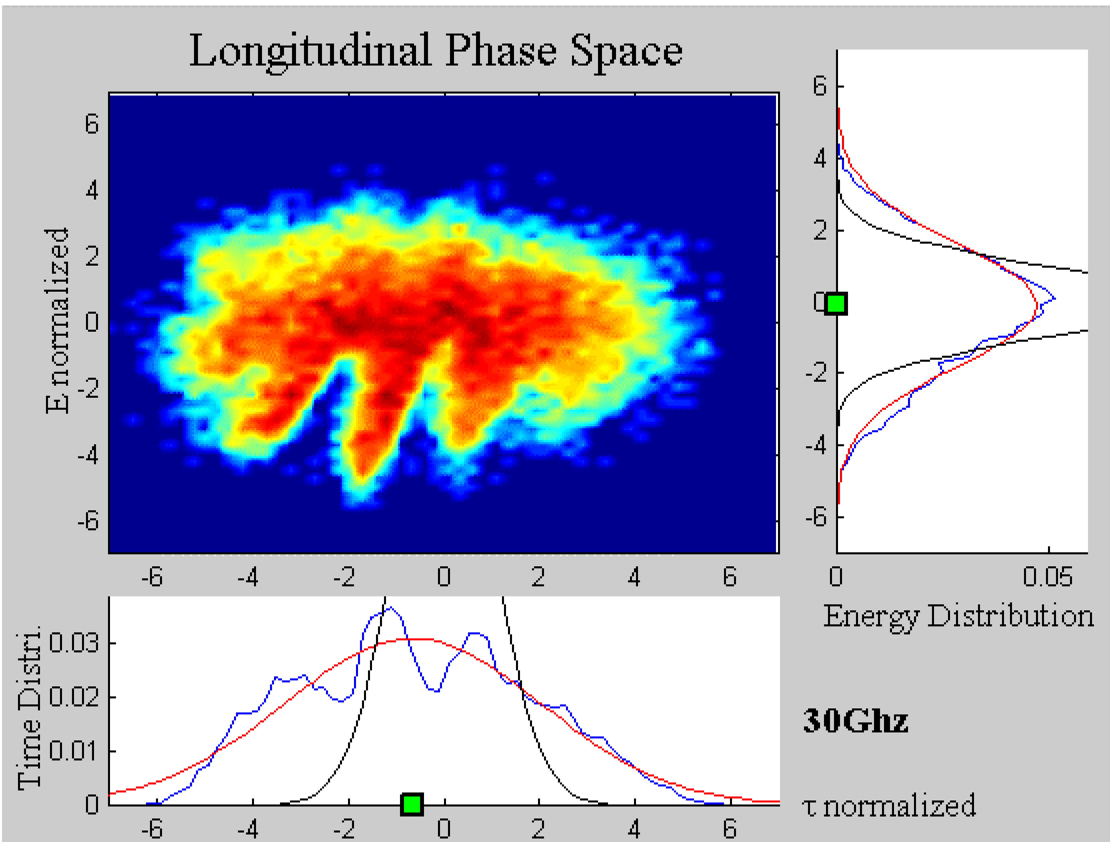
Energy spread

- Above threshold, as the bunch current, the energy spread increases to satisfy the Boussard criterion.

$$\sigma_\tau \quad follows \quad \left(\frac{\left|\frac{Z}{n}\right|_{eff} I}{\omega_{rf} V_{rf}}\right)^{1/3}$$

Examples (simulations)

- One can visualize the dynamics of a microwave instability via particle tracking including the wake potentials.

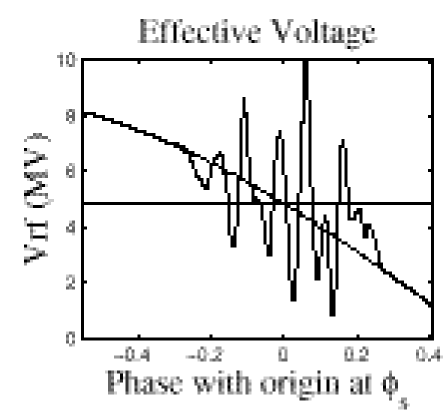


Cecile Limborg

f_r = 30 GHz

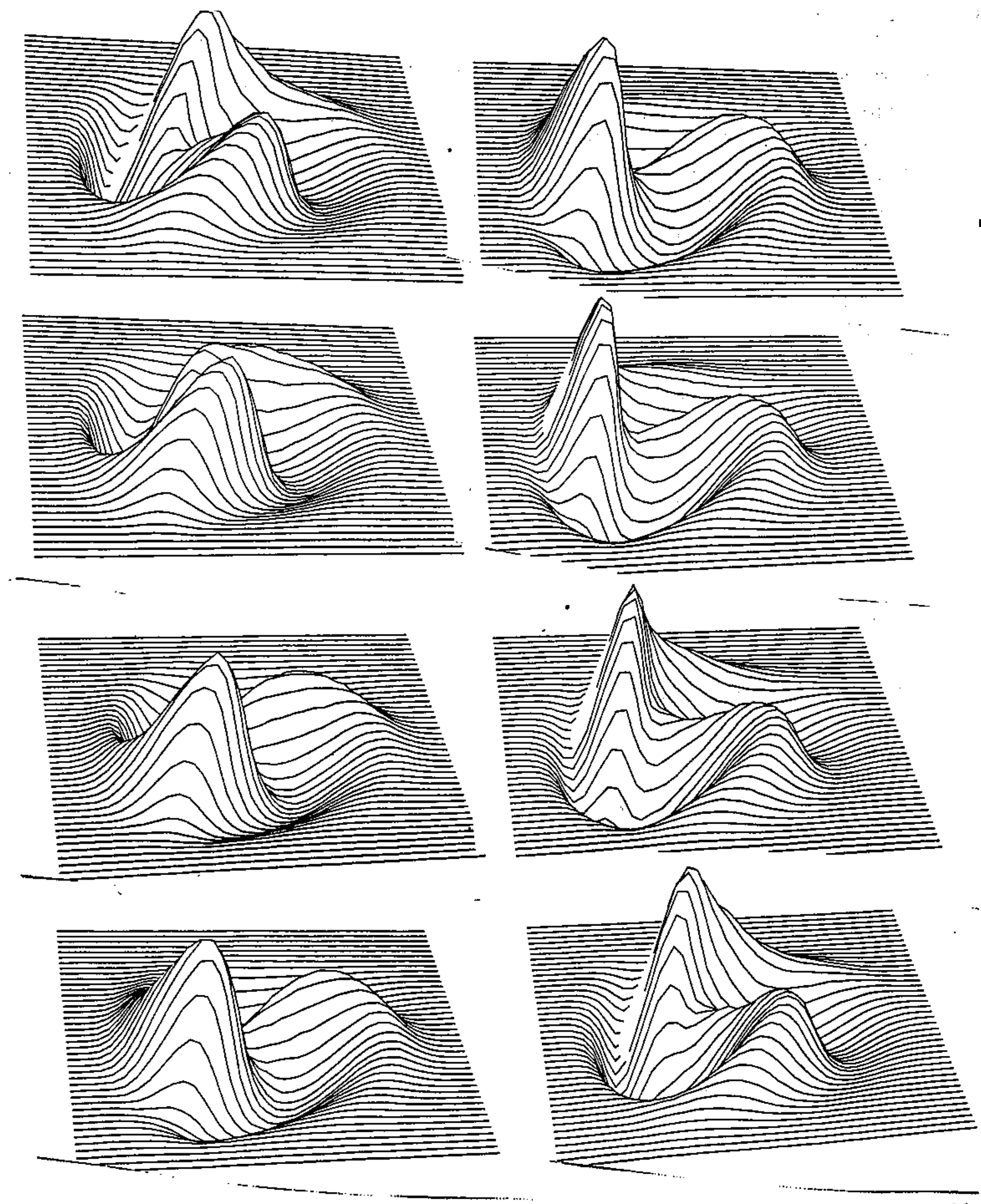
R_s = 42 kΩ

Q = 1



Examples (simulations)

- The motion often appears as a particular modal oscillation of the bunch



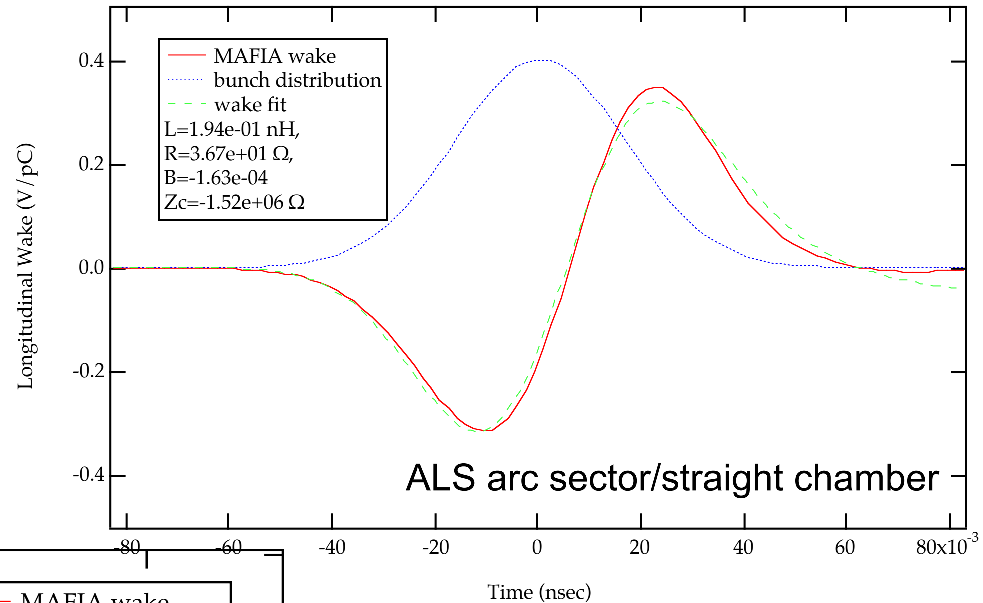
Karl Bane

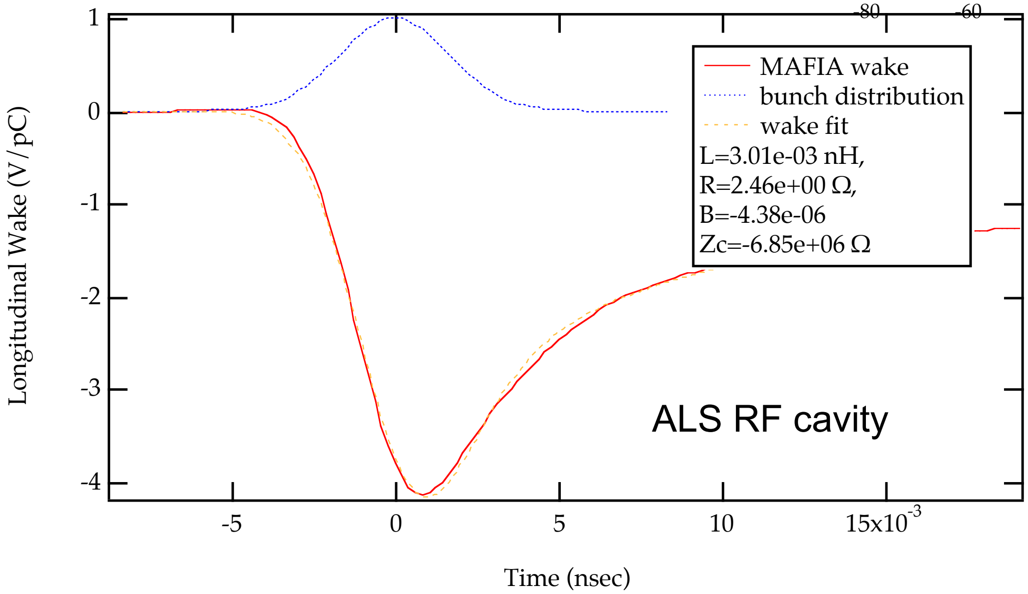
Example: ALS Vacuum Chamber

- 200 m circumference
- 12 sectors: 1 straight for injection, 1 for RF/FB kickers, 1 for pinger/ harmonic cavs
- vacuum chamber w/antechamber design
- 2 main RF cavities (500 MHz), 5 harmonic cavities (1.5 GHz)
- 48 bellows with flexbend shields
- 4 LFB "Lambertson" style kickers, 2 transverse stripline kickers
- 1 DCCT
- 96 arc sector BPMs, 24 insertion device BPMs
- 4 small gap insertion device chambers (8-10 mm full height) w/ tapers to 42 mm arc sector chamber.

ALS Wakes

Use calculated MAFIA wakes and fit with Zotter/ Bane/Heifets impedance



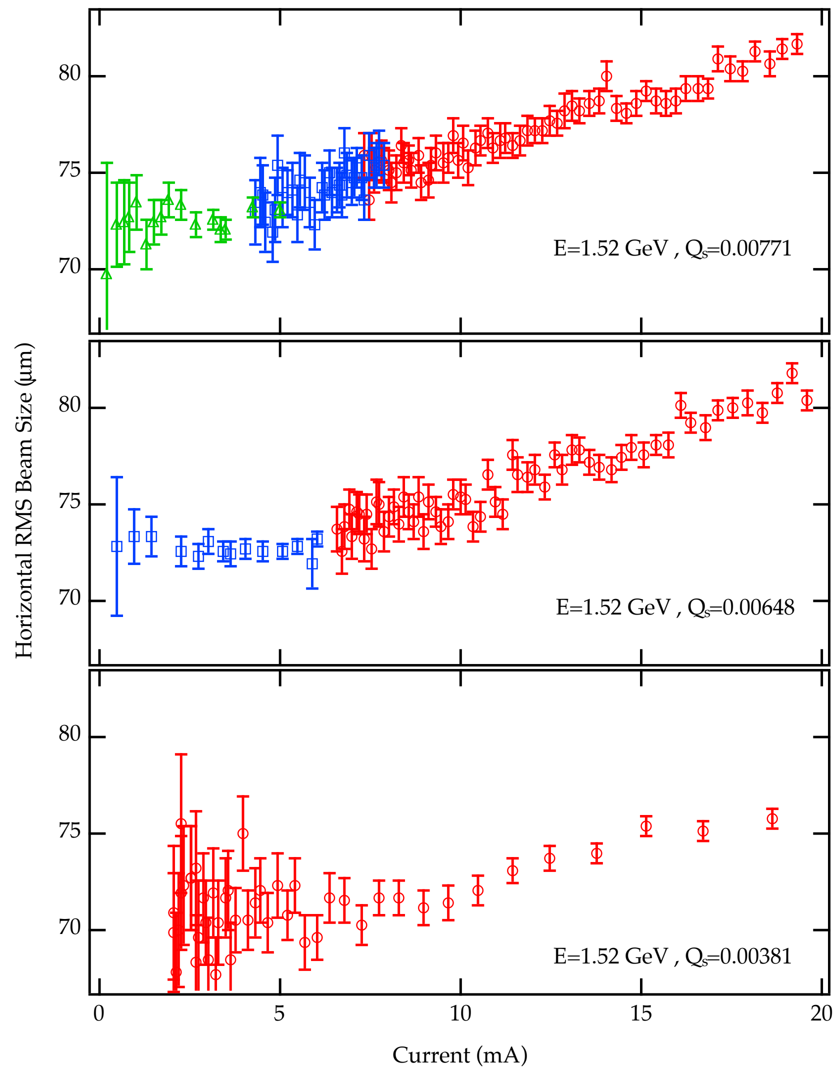


Energy Spread

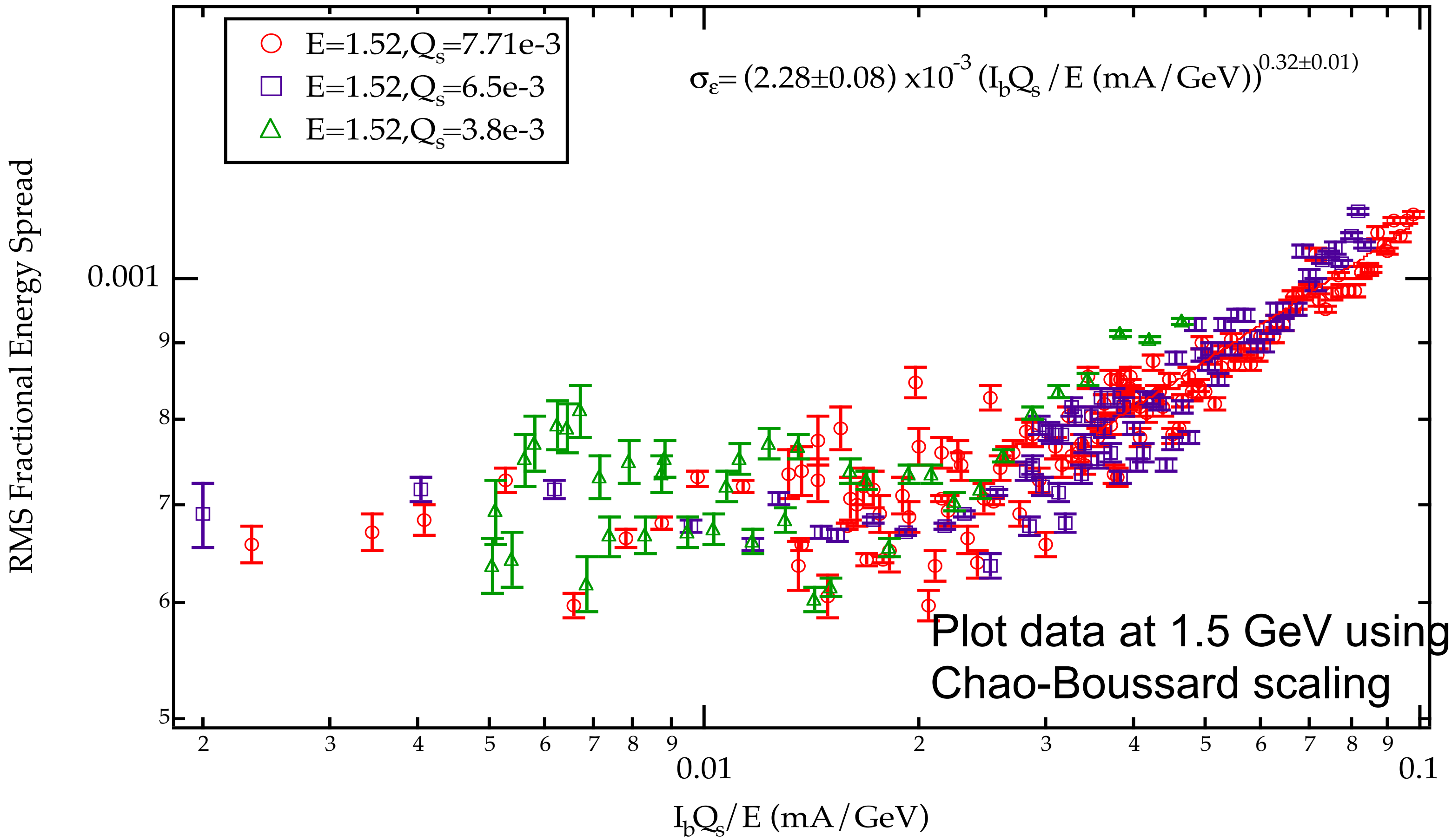
Technique: measure transverse beam size at a point of dispersion. Zero current beam size assumed to be due to nominal emittance and energy spread.

$$\sigma_{\varepsilon}^{2}=\frac{1}{\eta_{x}^{2}}\left(\sigma_{x}^{2}-\sigma_{x0}^{2}+(\eta_{x}\sigma_{\varepsilon 0})^{2}\right)$$

Measured at 1.5 GeV at 3 nominal RMS bunch lengths: 4.3, 5.1, 8.7 mm

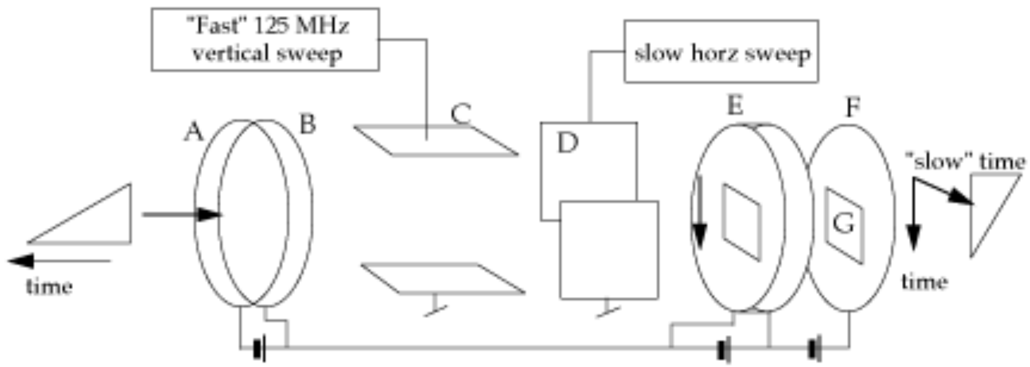


Energy spread summary



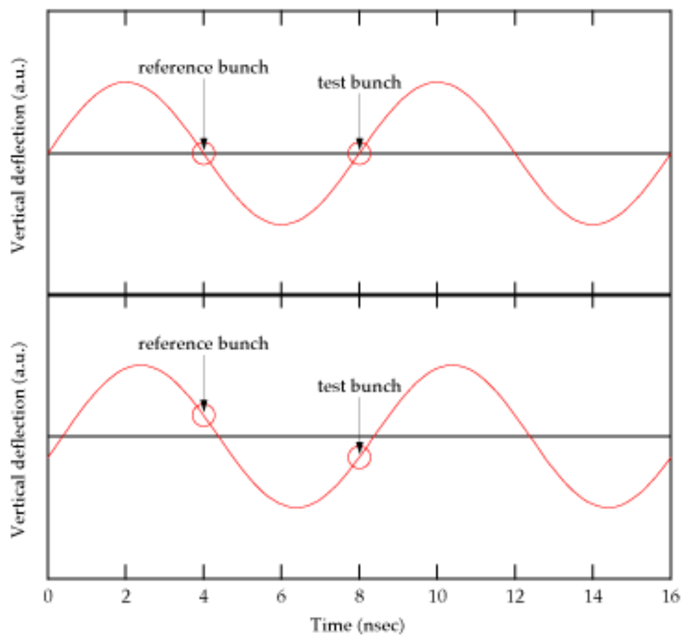
$$\sigma_\varepsilon^3 = \frac{1}{\sqrt{2\pi}\alpha^2}\left(\frac{I_b Q_s}{(E/e)}\right)\left[\left|\frac{Z_{//}}{n}\right| + \mathrm{Im}\frac{Z_{//}}{n}\right] \Longrightarrow Z/n = 0.08\ \Omega$$

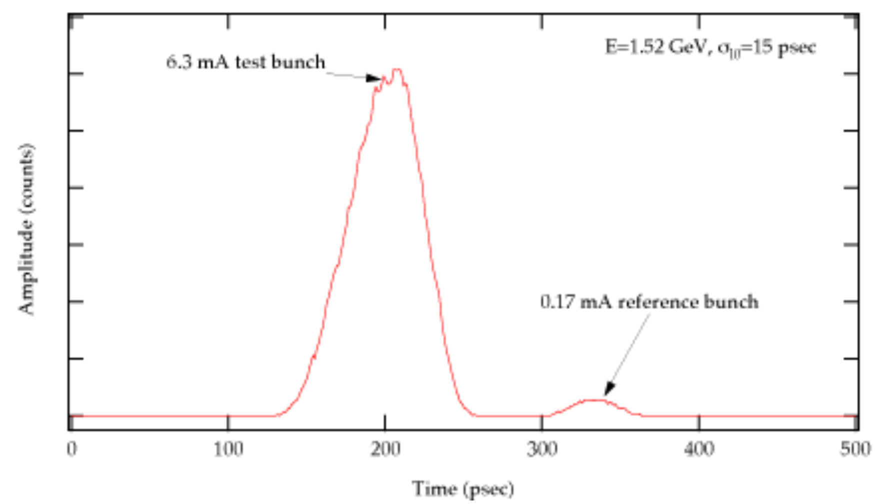
Dual-Scan Streak Camera



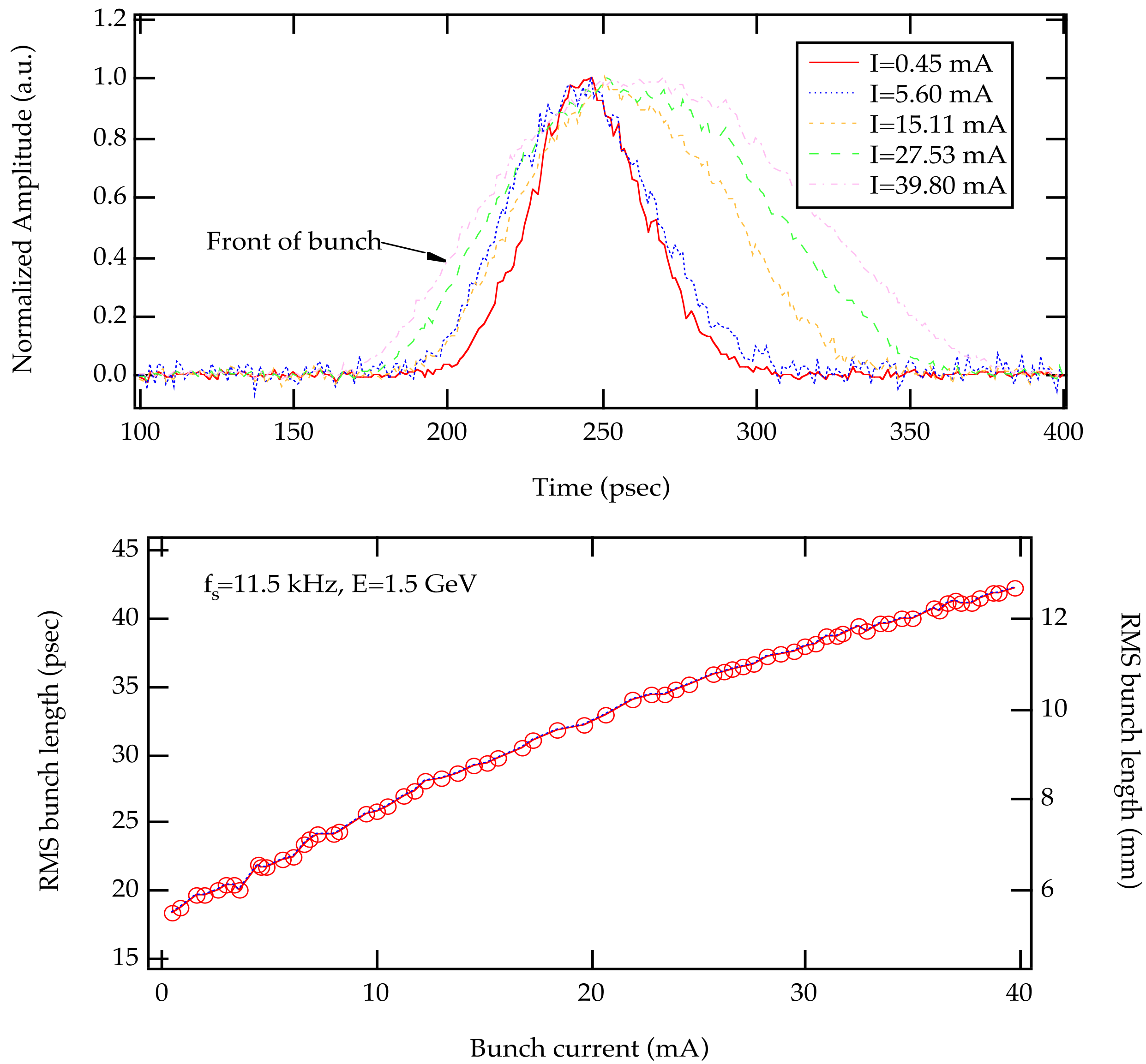
All bunch length measurements done using Hamamatsu C5680 Streak camera w/dual synchroscan

Phase shift measurements done using small test bunch





Bunch length vs. current



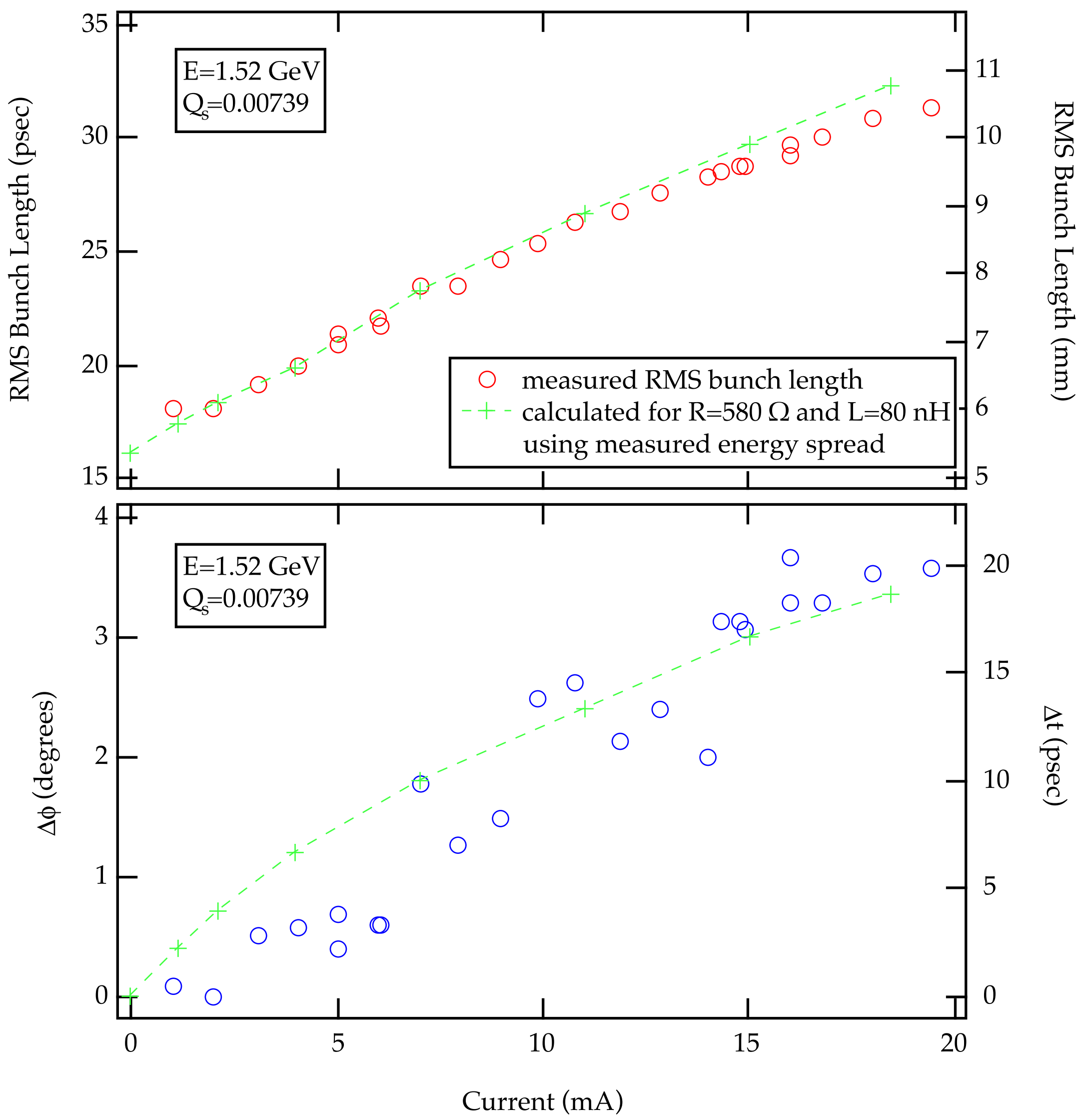
Bunch length and synchronous phase shift

Measured results fit with Haissinski equation using simple RL model.

Measured energy spread used in sooution to the Haissinski equation.

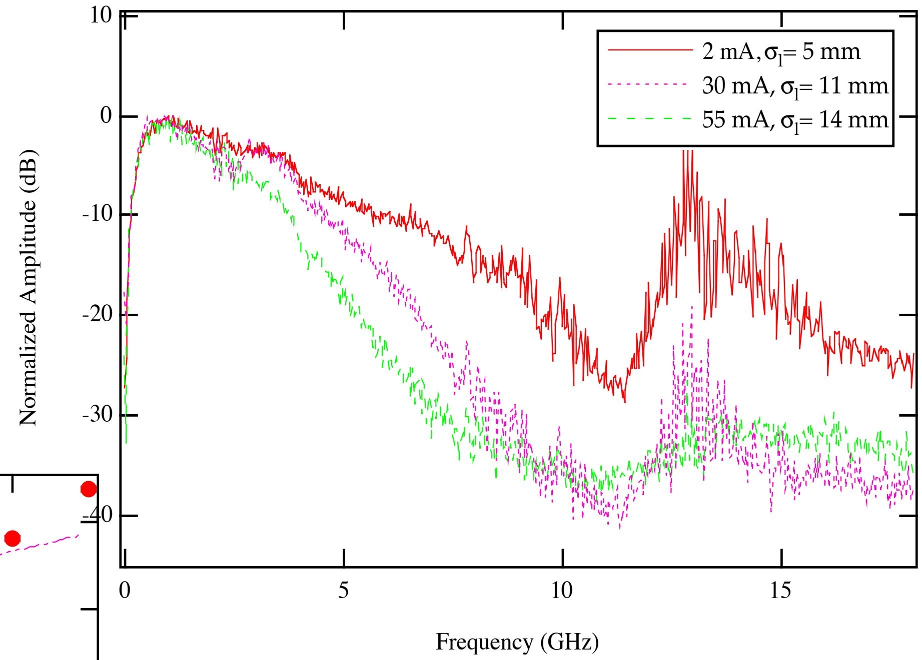
Results consistent with R=580 Ω, L=80 nH.

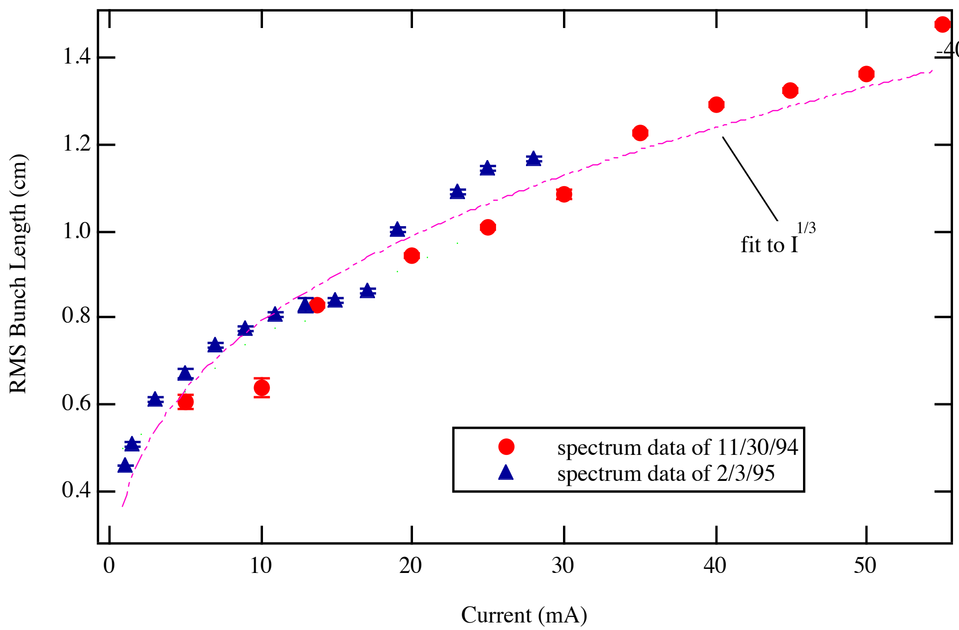
Data made at longer bunch shows worse agreement, probably due to coherent quadrupole instability at higher currents.



Broadband BPM spectra

Prior to buying a streak camera, we used a broadband BPM signal to measure bunch length.

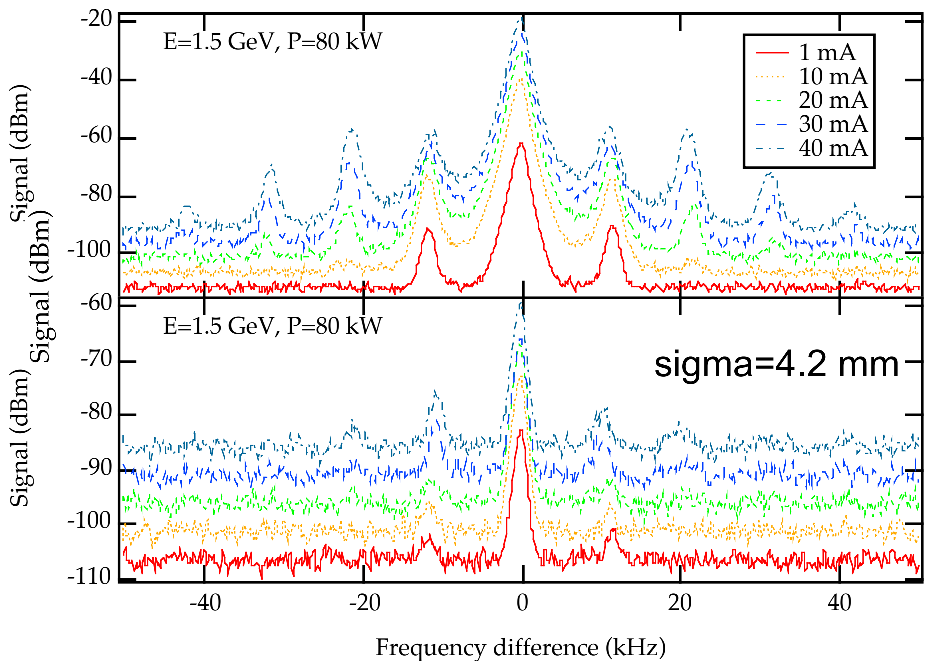


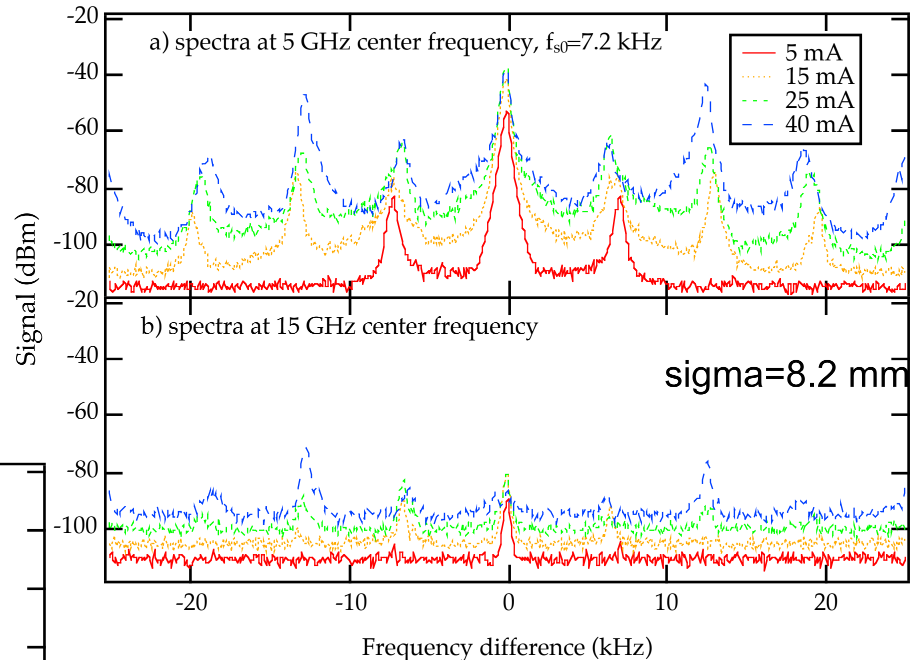


bunch length follows $I^{1/3}$ scaling up to bunch currents of 60 mA

Sideband spectra

We also measured synchrotron sideband amplitudes at various frequencies. The dipole motion at low current is driven by RF phase noise.





The spectra at longer bunch length shows a clear coherent quadrupole motion. This is also evident on streak camera data. The short bunch data does not show any clear modes.

Transverse Single Bunch Effects

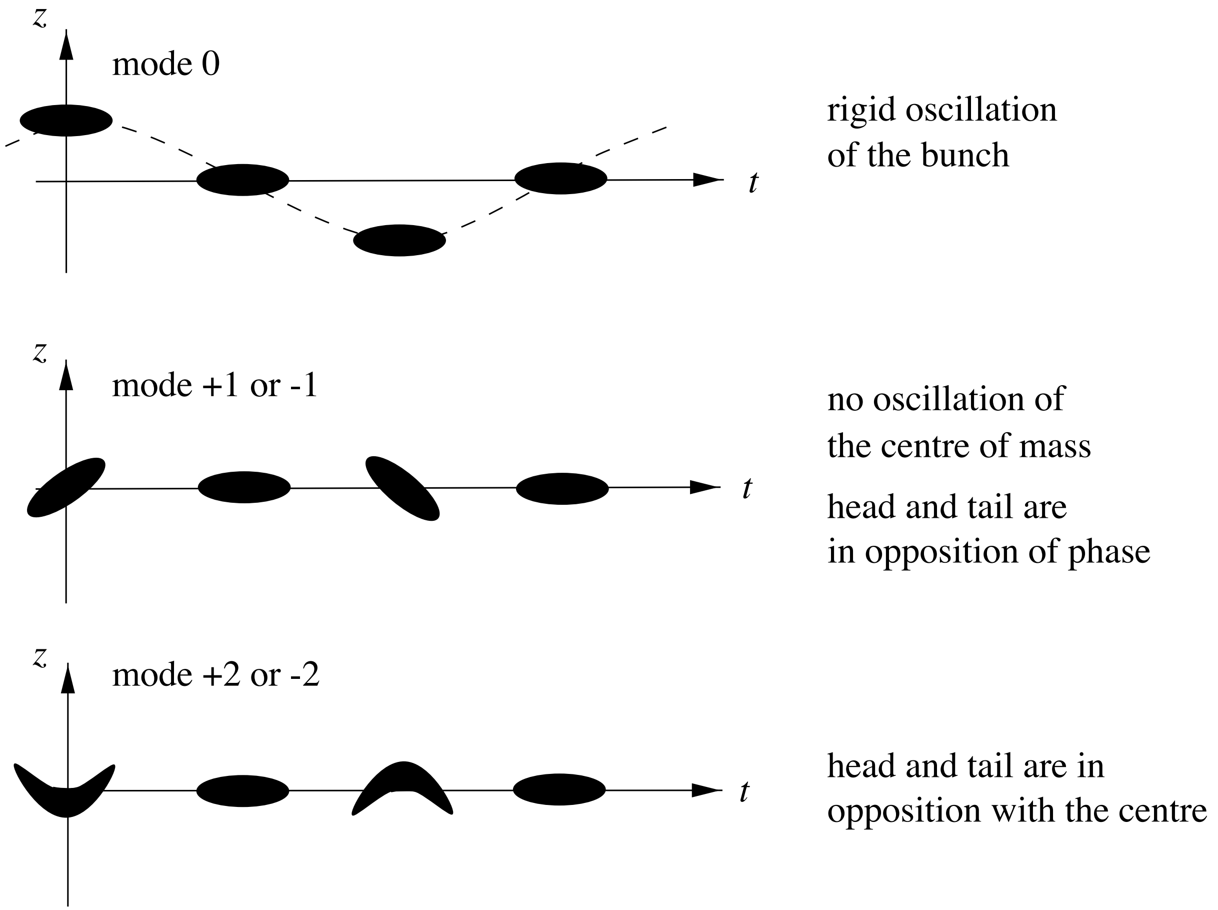
- Transverse effects are driven by the transverse short-range wake or the transverse broad-band impedance.
- There is a very approximate relation between the longitudinal and transverse from the Panofsky-Wenzel theorem given by

$$Z_1^{\perp}(\omega) = \frac{2c}{b^2\omega} Z_0^{\parallel}(\omega).$$

- What beam pipe size to use?
  - 3GLSs transverse broadband impedance dominated by ID chambers: tapers and small gaps
- **The bunch current is limited by the transverse mode coupling instability (TMCI) in the vertical direction**
  - Instability threshold can be raised with chromaticity. However, this has adverse effect on the lifetime.

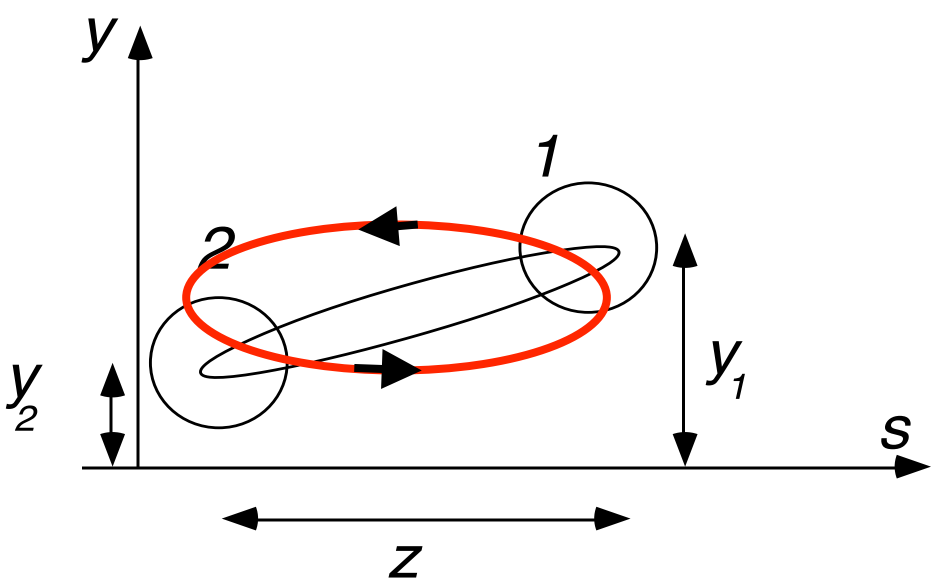
Transverse modes

- The transverse motion of the bunch is composed of a set of normal modes



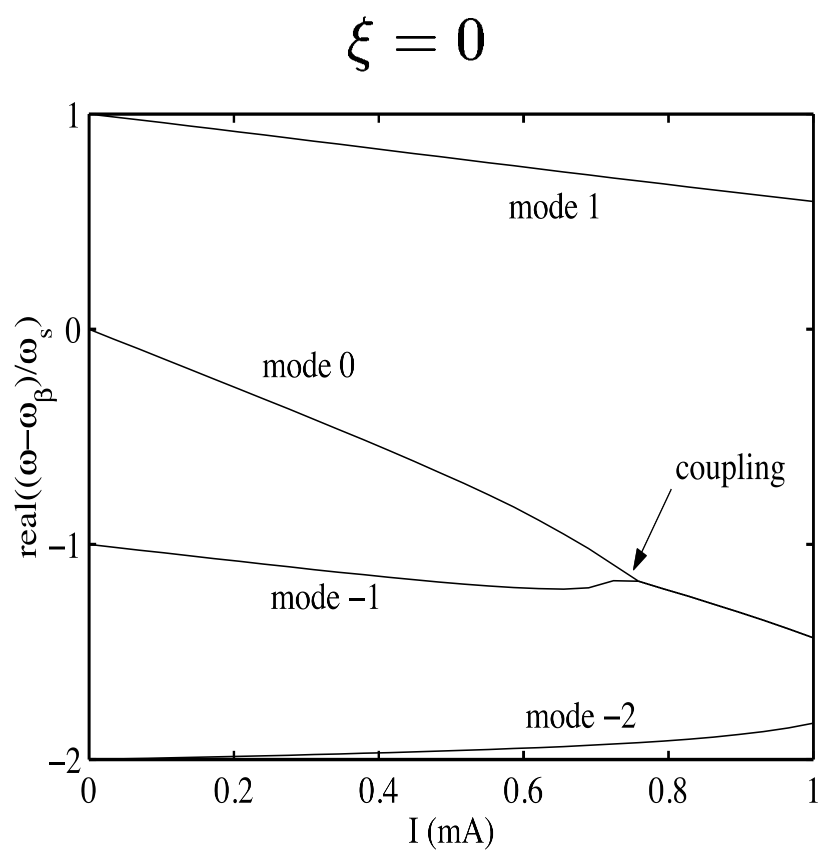
Head-tail instability

- Consider a simple model where the bunch has two macroparticles
- Each macroparticle has an equal amplitude of synchrotron oscillation. There is an exchange of the head and tail of the bunch every half synchrotron period.
- If we add a transverse wake field, the each macroparticle drives the other when it is at the head of the bunch.
- The wake couples the motion of the macroparticles and can lead to a variety of collective effects.



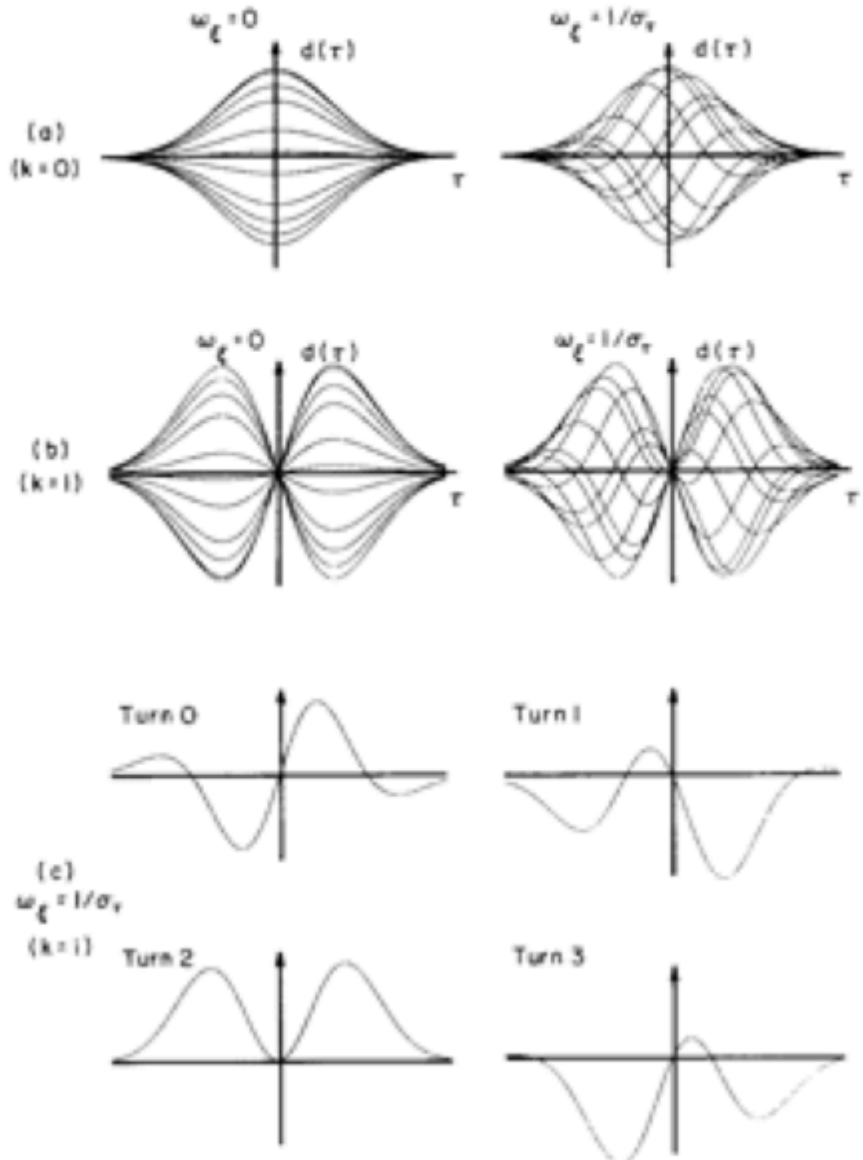
Head-tail mode coupling

- The coupling of the wake field causes frequency shifts of the modes.
- When the modes merge, there is a growth of the motion: instability.
- The physical interpretation of this effect is that instability occurs when the growth rate of the tail (driven by the head) is faster than the synchrotron period.



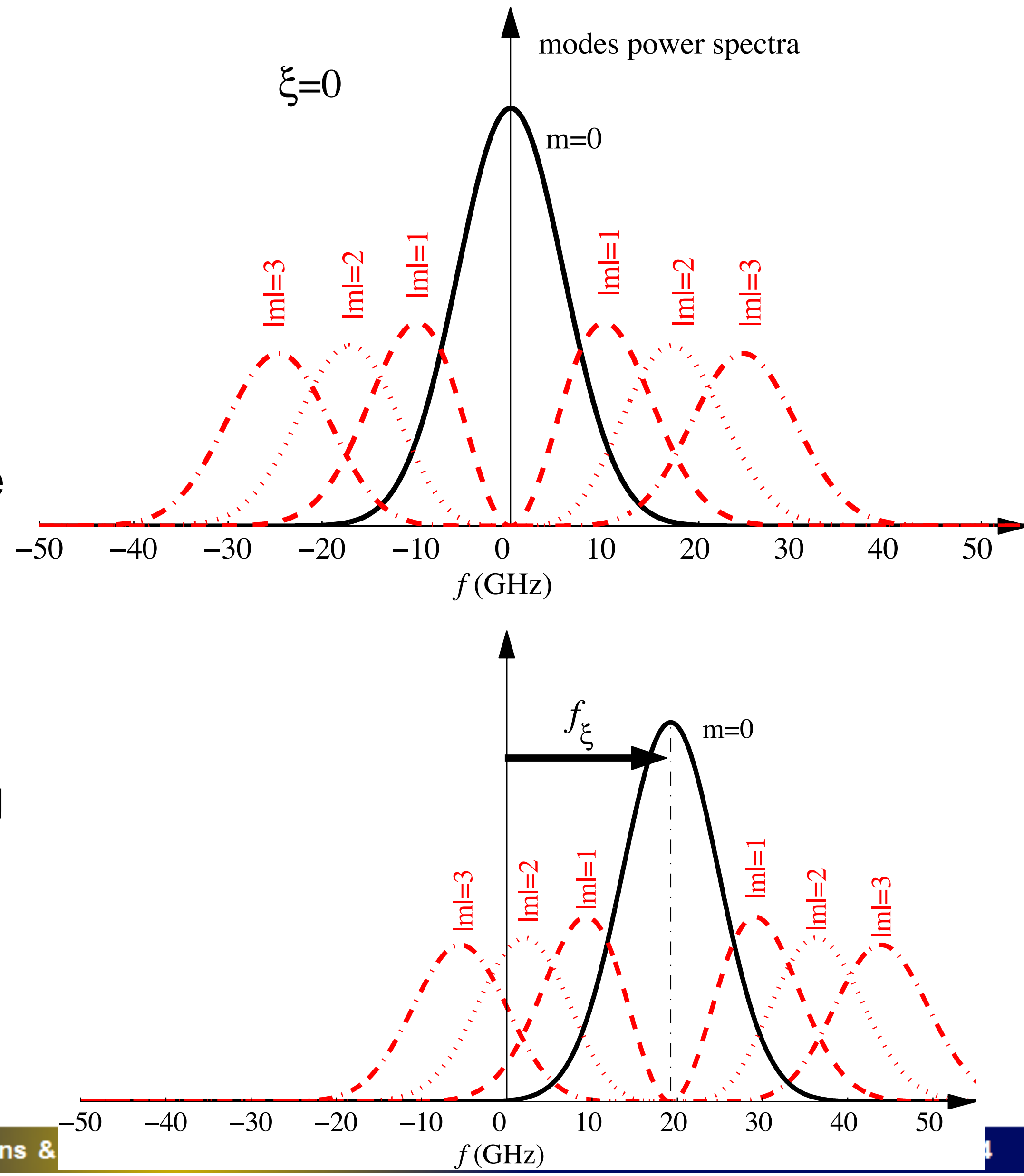
Head-tail motion with chromaticity

- If there is a nonzero chromaticity, this adds an additional effect to the head-tail motion.
- The chromaticity adds a phase shift between the head and tail of the bunch, modifying the effect of the wake.
- For example, some modes can be damped, and some modes are antidamped.
- Note that increase of the chromaticity lowers the dynamic acceptance of the storage ring with an adverse effect on the lifetime.

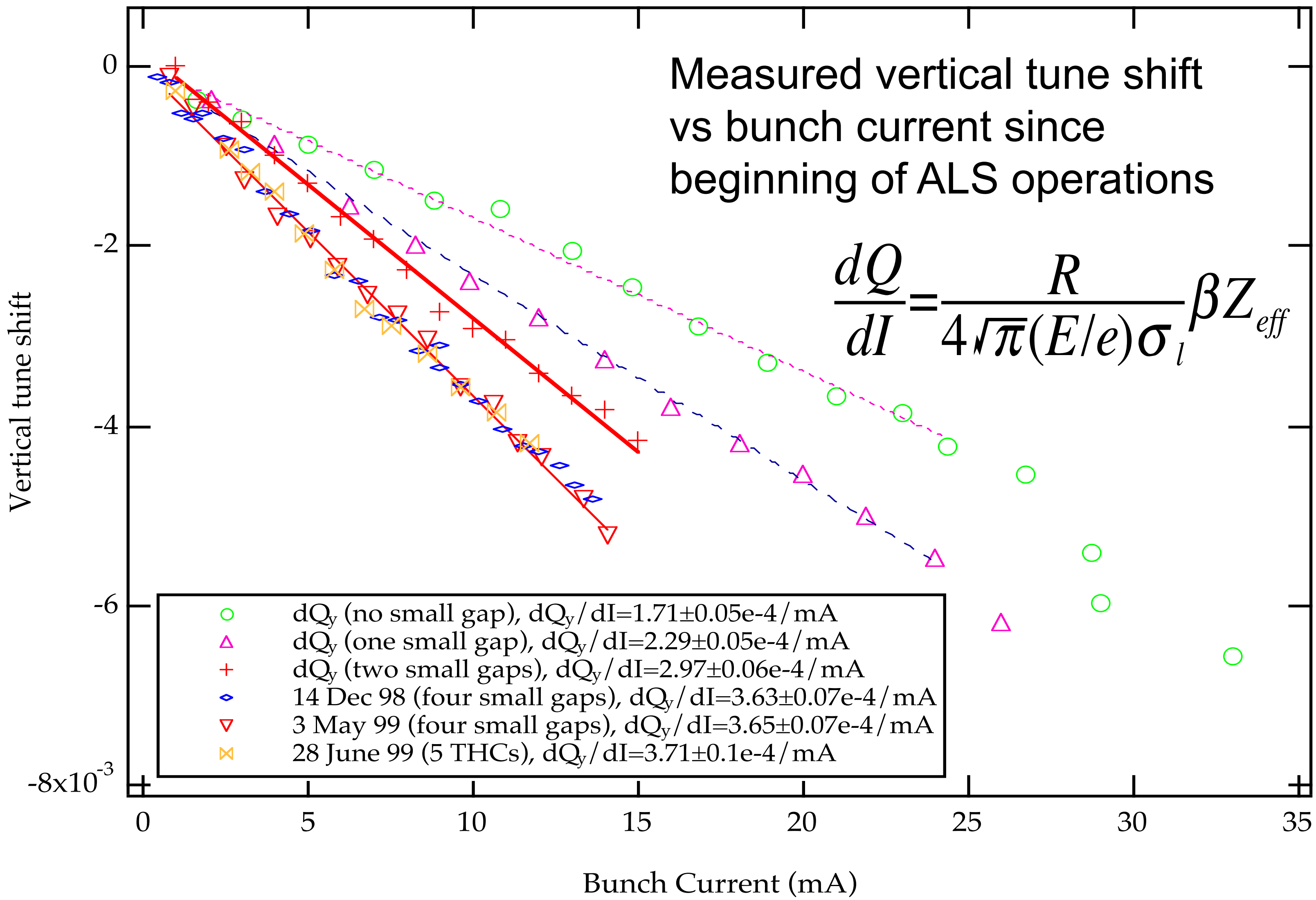


Head-tail modes in frequency domain

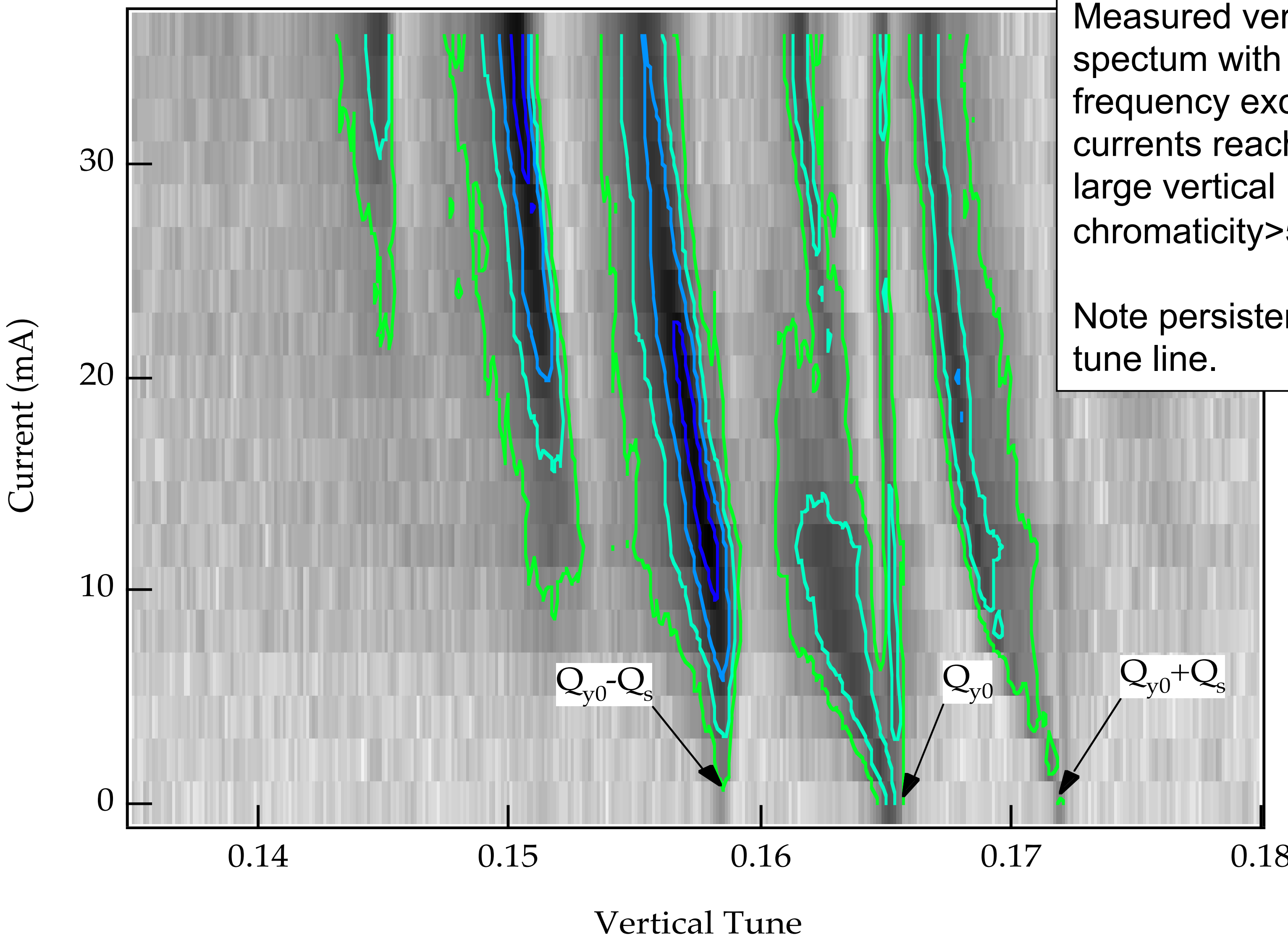
- The spectra of head-tail modes is analogous to those for the longtidinal modes.
- The addition of chromaticity shifts the mode spectrum in frequency.
- The total wake function is the overlap of the mode spectrum with the transverse broadband impedance.
- The main effect of increasing the chromaticity is a damping of the m=0 mode.
- This is known as head-tail damping and can be used to damp transverse coupled bunch instabilities.



Vertical tune shift vs. bunch current



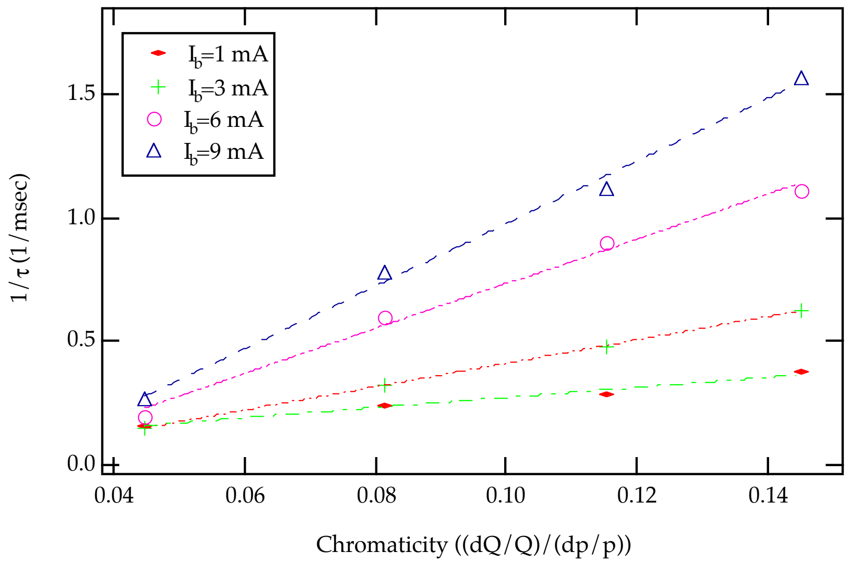
Tune shift vs. bunch current



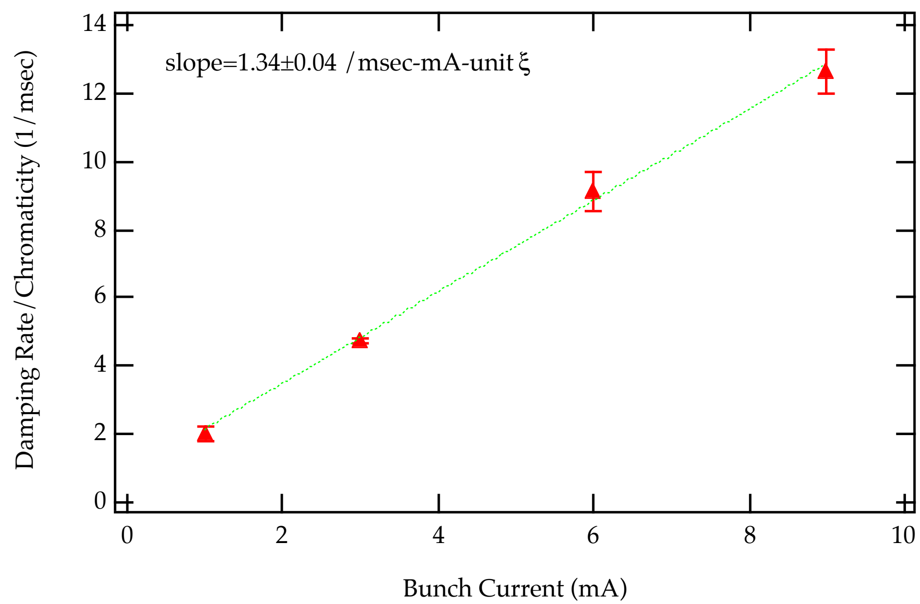
Measured vertical tune spectum with swept frequency excitation. Large currents reached using large vertical chromaticity>5.

Note persistence of original tune line.

Head-tail damping rate vs. I



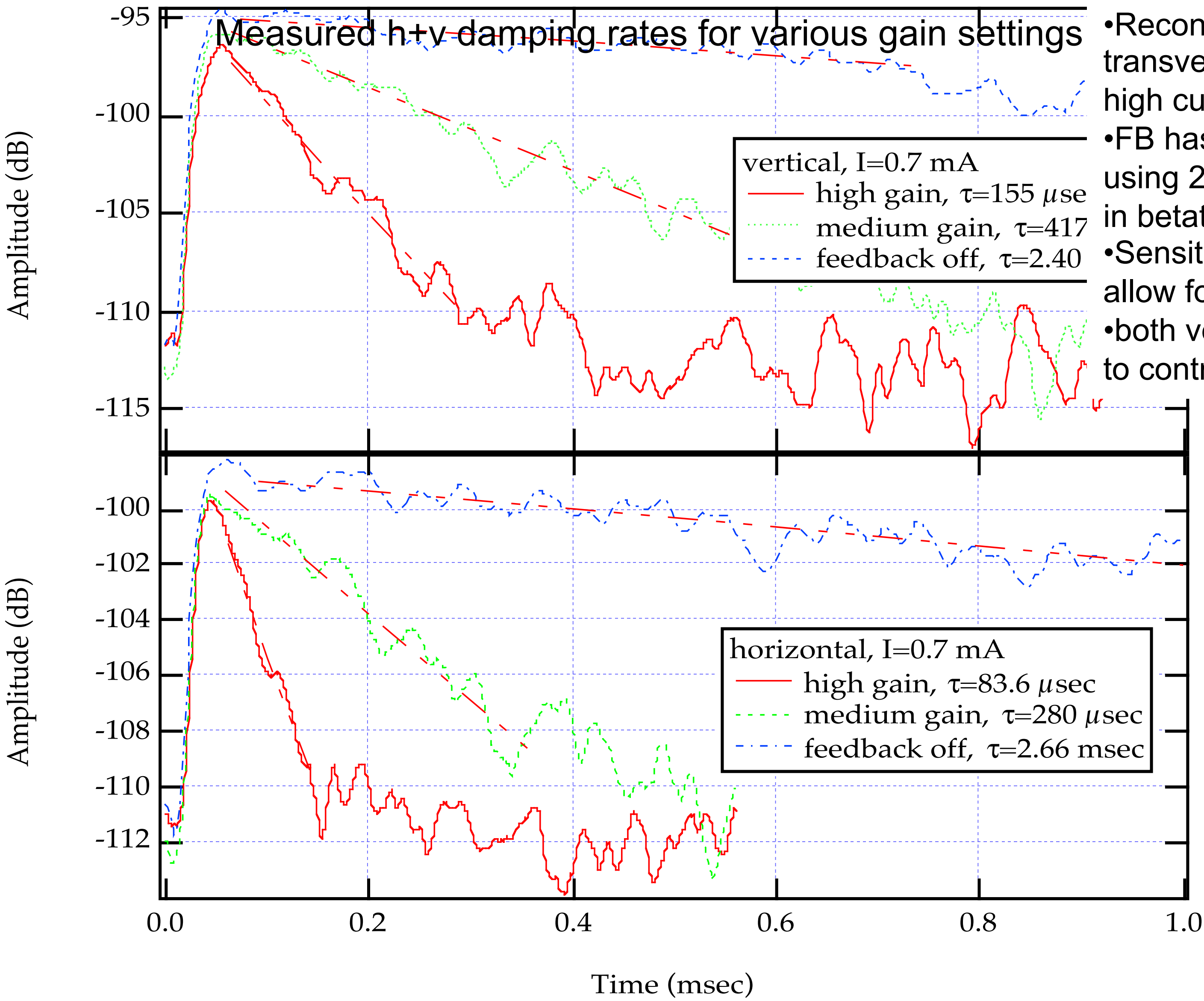
Measure vertical and horizontal damping rates vs. X and I.



Mode-coupling threshold

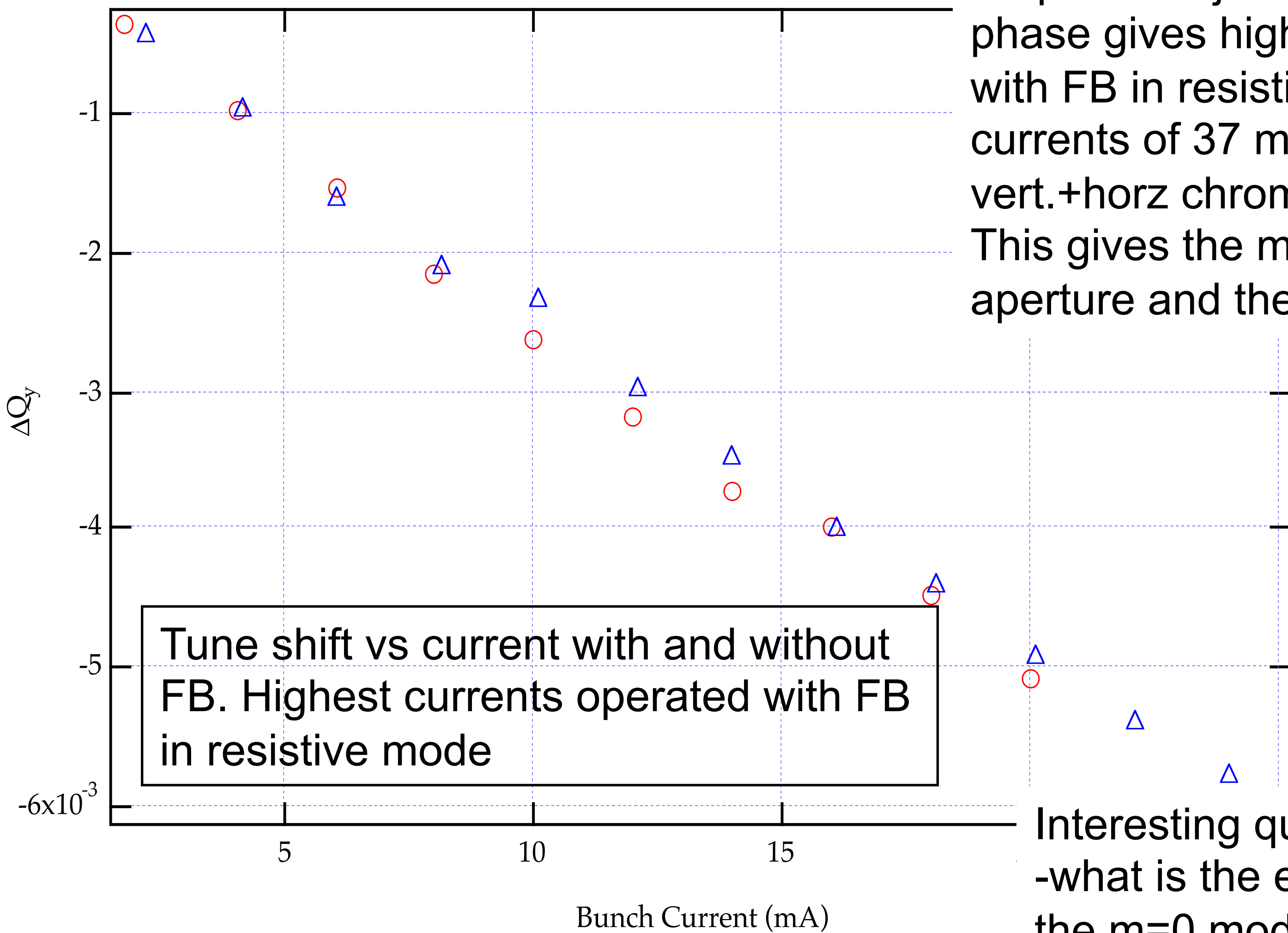
- Vertical mode-coupling threshold has dropped by a factor of 2 with installation of 5 small gap vacuum chambers
- Main current-limiting mechanism due to small vertical physical aperture.
- Unclear whether generated by resistive wall impedance or tapers.
- Threshold depends on vertical orbit through small gap chamber
- Threshold *decreases* with vertical X up to around 5 when it vanishes. Maximum current injection limited to around 35-40 mA with very short lifetime.
- Horizontal threshold appears to be around 25 mA.
- Displays hysteretic behavior.

Feedback control of TMCI



- Reconfigured existing multibunch transverse FB system to work for high current single bunch.
- FB has arbitrary phase adjustment using 2 PUs about 60 degrees apart in betatron phase.
- Sensitive buttons and electronics allow for high gain.
- both vertical and horizontal FB used to control TMCI.

FB control of TMCI (cont.)



Tune shift vs current with and without FB. Highest currents operated with FB in resistive mode

Empirical adjustment of the FB phase gives highest bunch currents with FB in resistive mode. Bunch currents of 37 mA achieved with vert.+horz chromaticities of ~0.5. This gives the maximum dynamic aperture and the longest lifetime.

Interesting questions:

-what is the effect of damping of the m=0 mode on the coupling?

-How much of a perturbation is req'd to start the growth?