Collective Instabilities (Part 2)

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Lecture Summary Part 2

- 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

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.

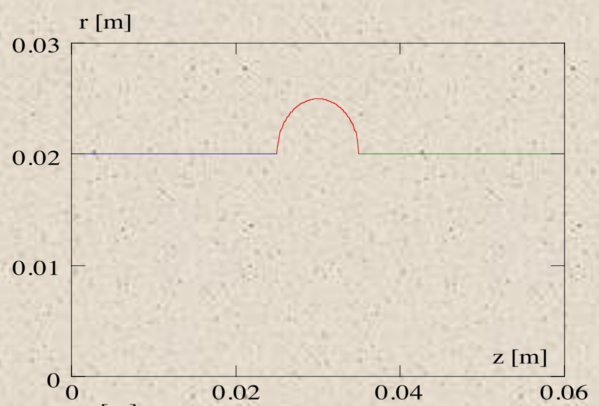
Single Bunch Collective Effects

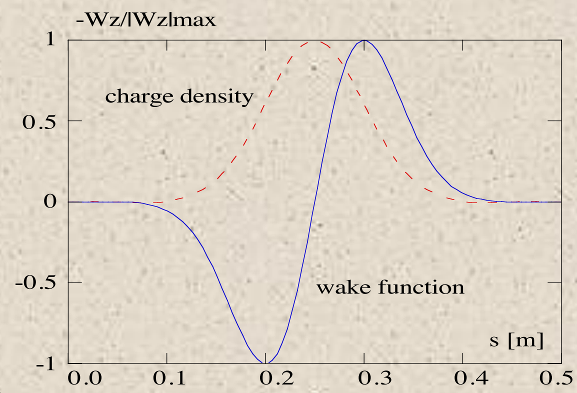
- Driven by short-range wake fields (broadband impedance)
- Longitudinal effects
  - Potential well distortion
    - Bunch length increase
  - Microwave instability
    - Bunch length and energy spread increase
- Transverse
  - Head-tail damping
    - Uses chromaticity to provide additional transverse 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

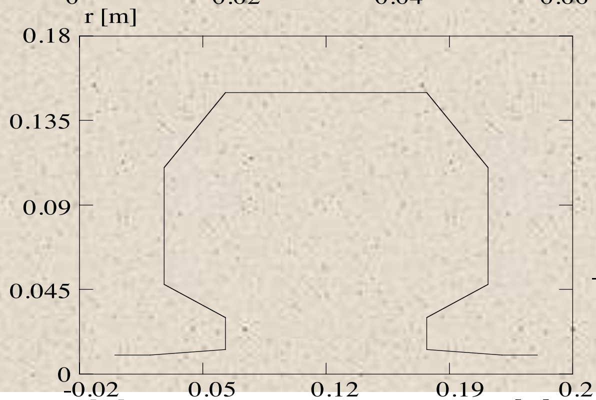
- Short-range wakes are those that last over the length of the bunch.
- Generated by the many discontinuities in the vacuum chamber: RF cavities, kickers, pumps, tapers, resistive wall, etc.
- The wake (and impedance) of all of these components can be calculated with modern EM codes.
- The total wake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

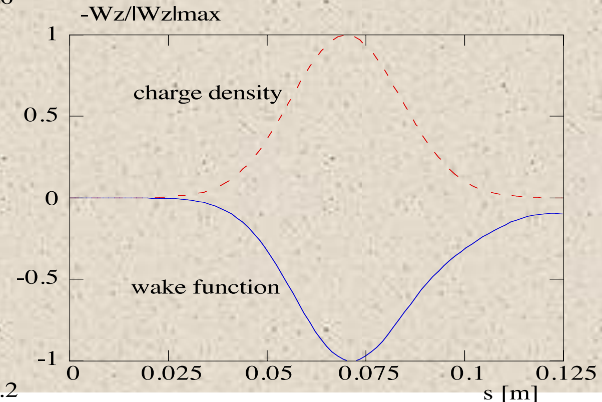
Example Wakes



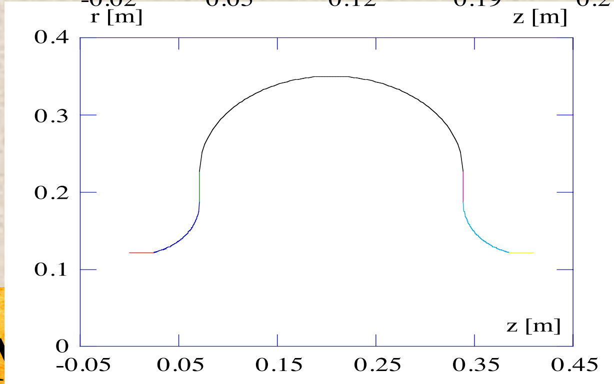


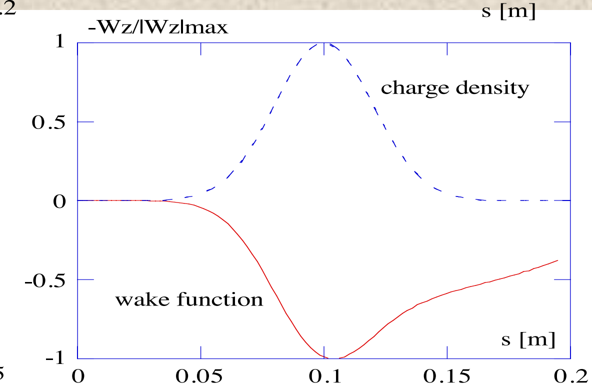
- Small cavity
- V~dI/dt
- Inductive





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





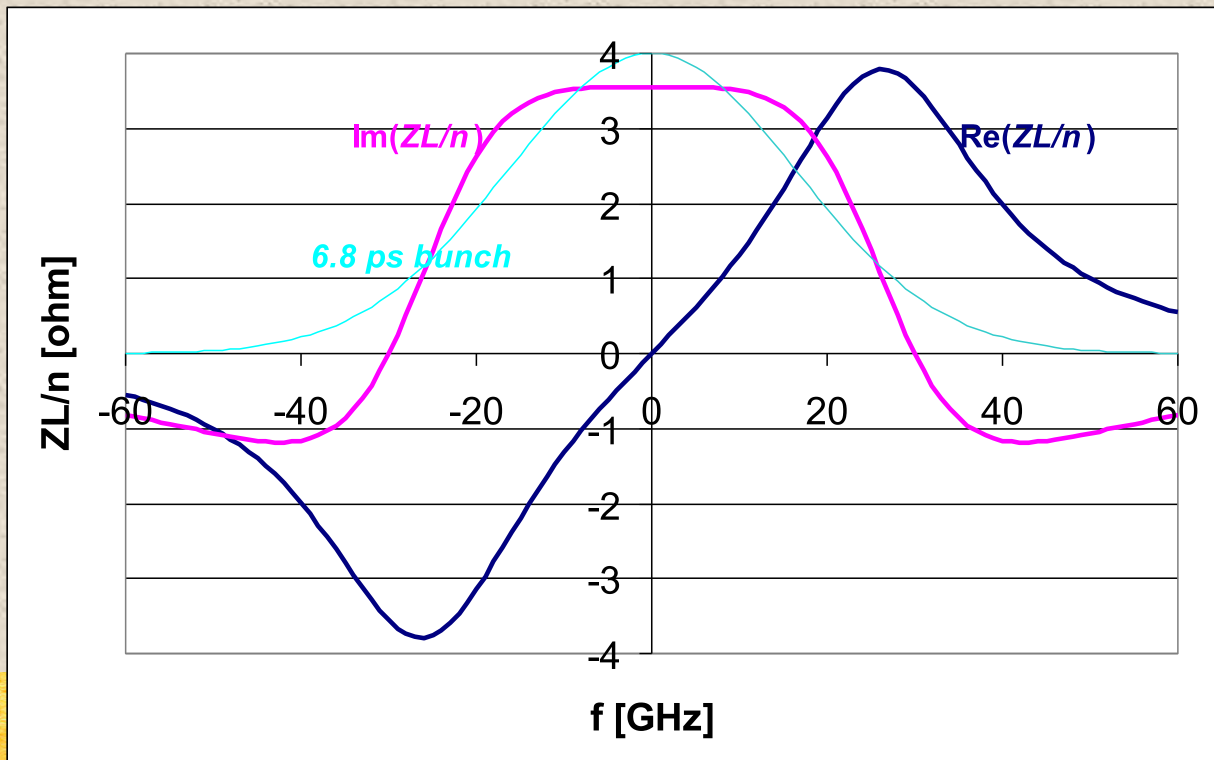
- Large cavity, big beam pipe
- V~∫I
- Capacitive

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~w_0L 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

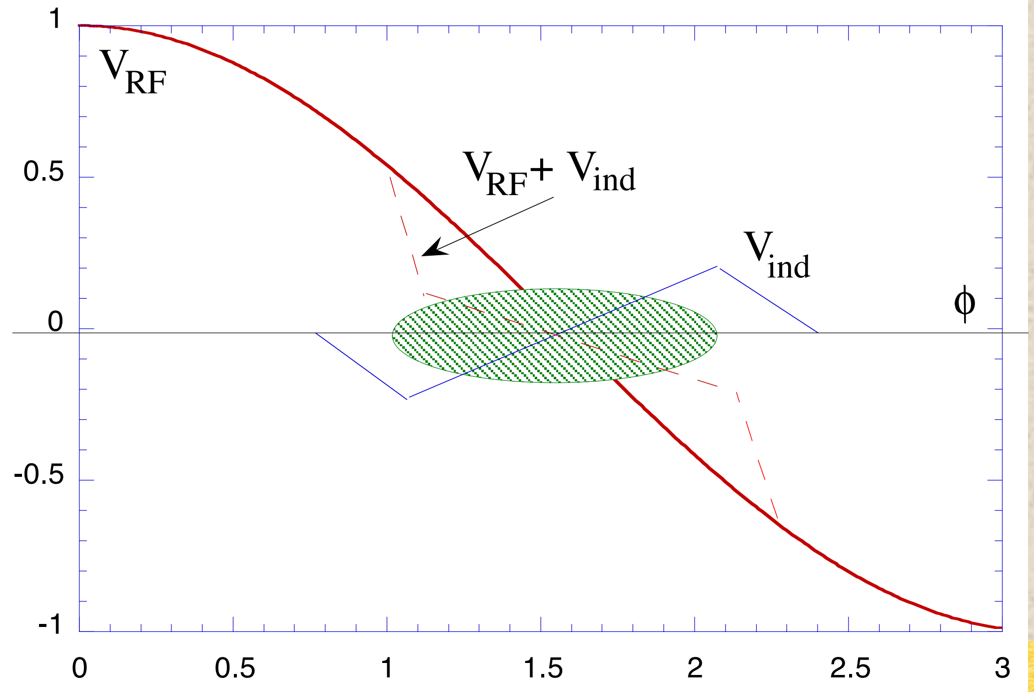
Resistive wall

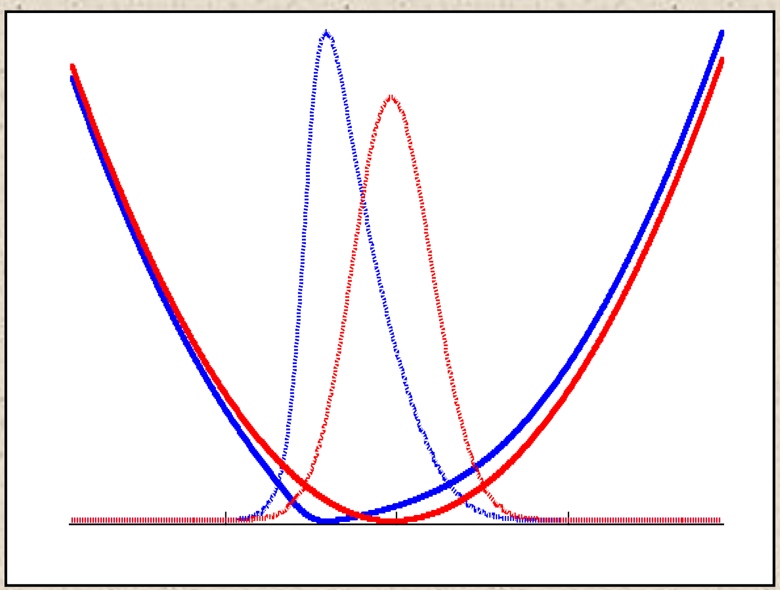
High frequency cavities

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

Potential Well Distortion

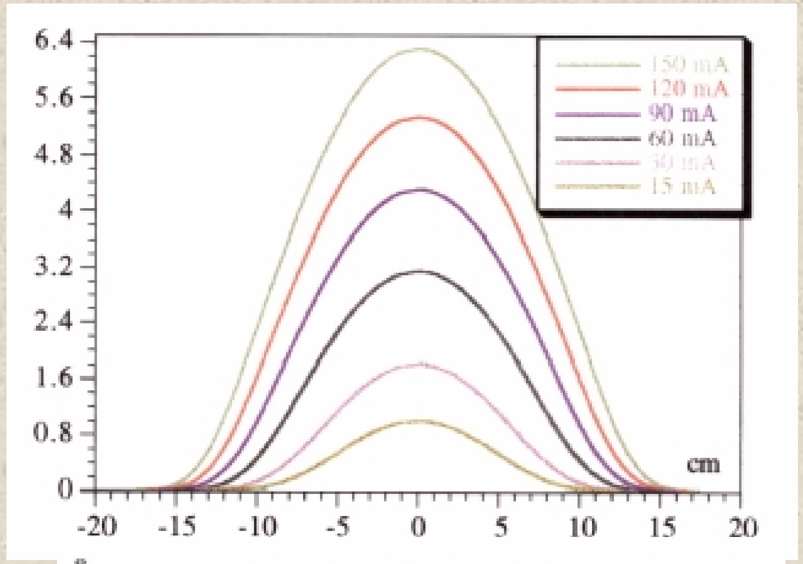
- The nominal bunch shape and length is determined by the linear (almost!) restoring force of the main RF voltage. If we add the short-range wake potential, the bunch shape can change. This is known as PWD.
- The stable phase position also changes. This accounts for resistive losses into the broadband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

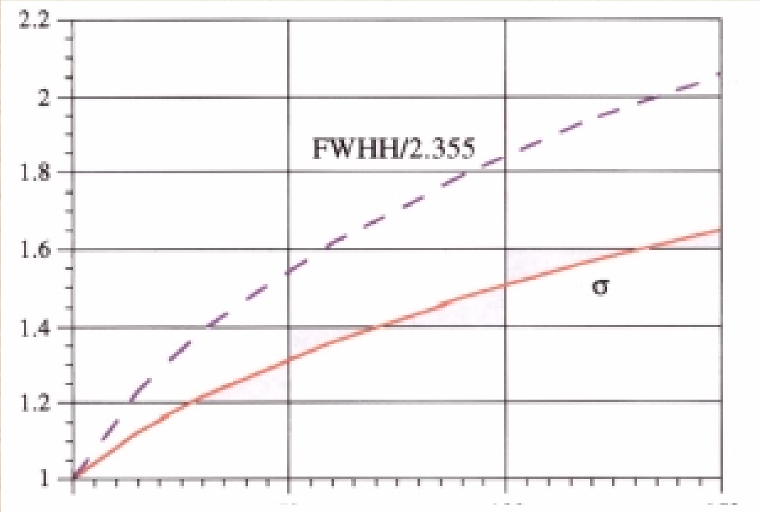


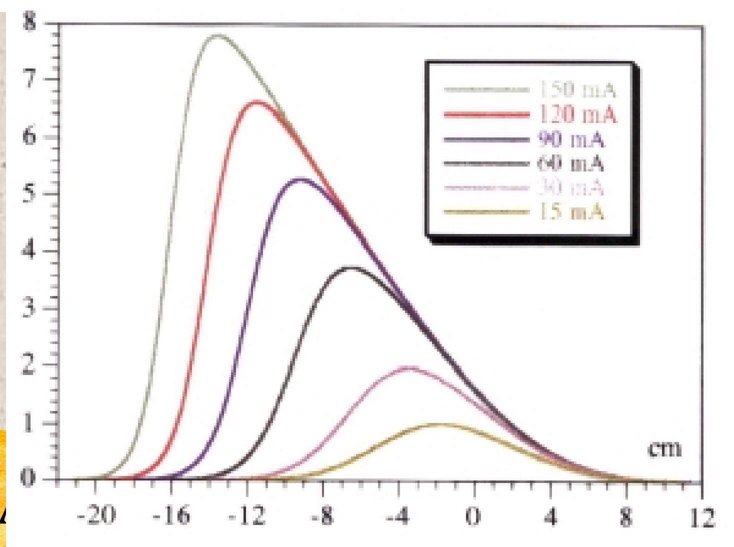


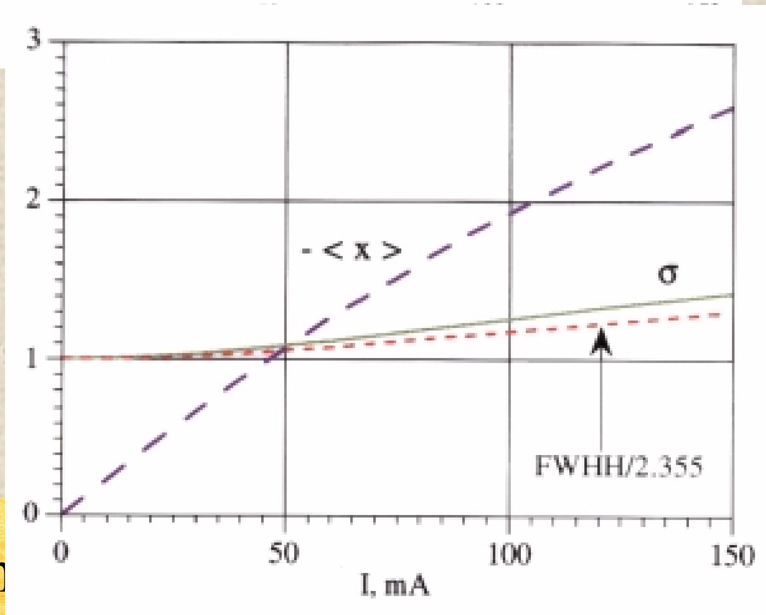
Potential well distortion

- 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

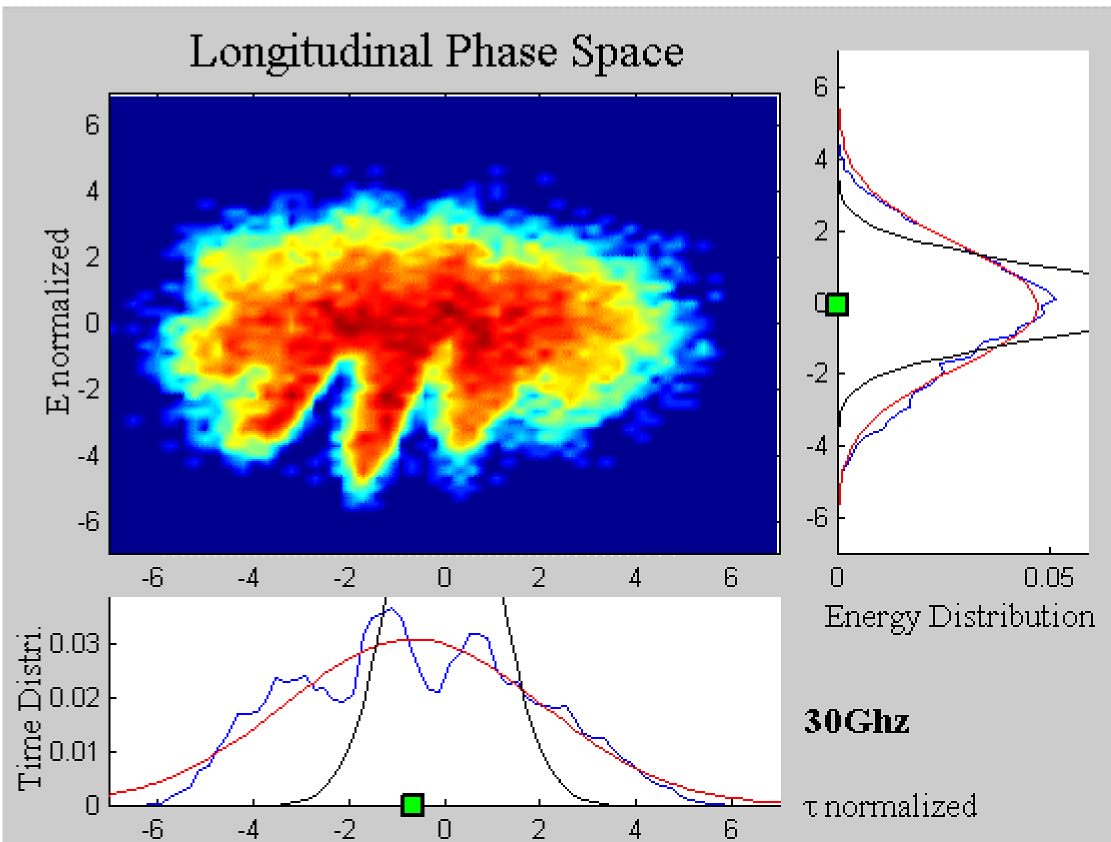
Energy spread

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

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

Examples (simulations)

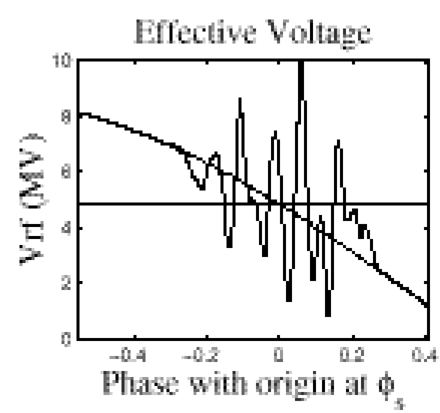
- One can visualize the dynamics of a microwave instability via particle tracking including the wake potentials.



$f_r = 30$ GHz

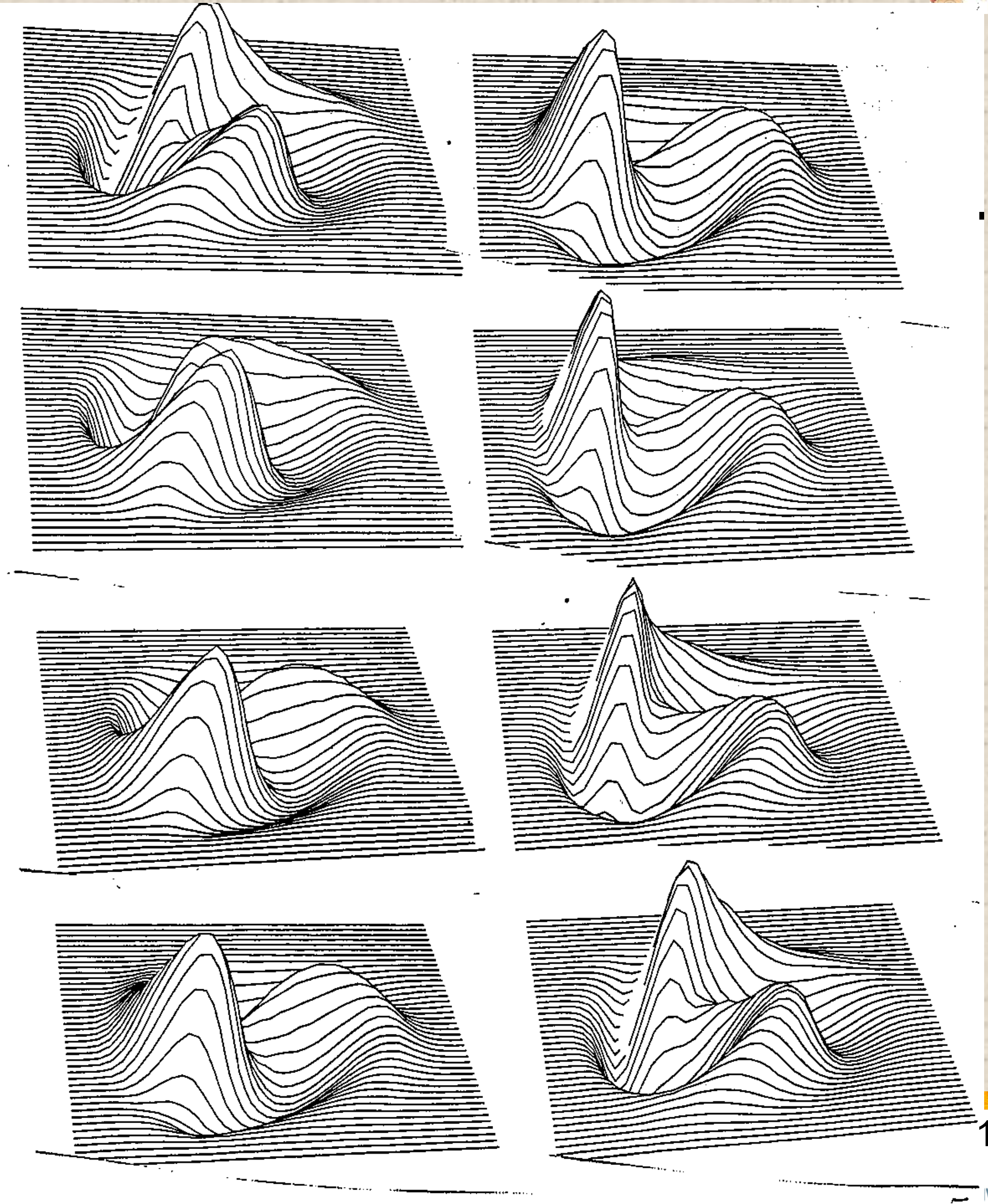
$R_s = 42$ kΩ

$Q = 1$



Examples (simulations)

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

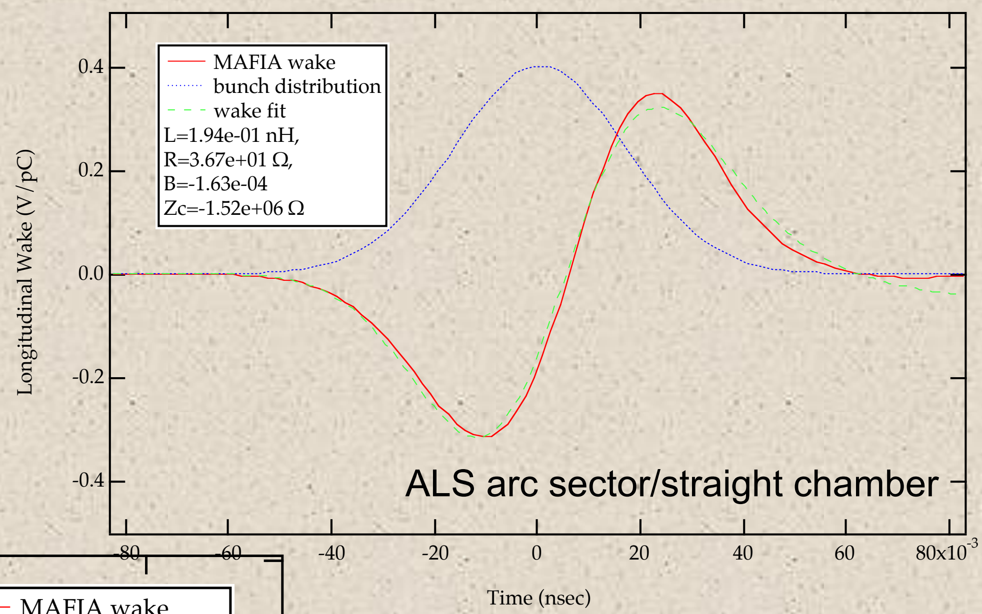


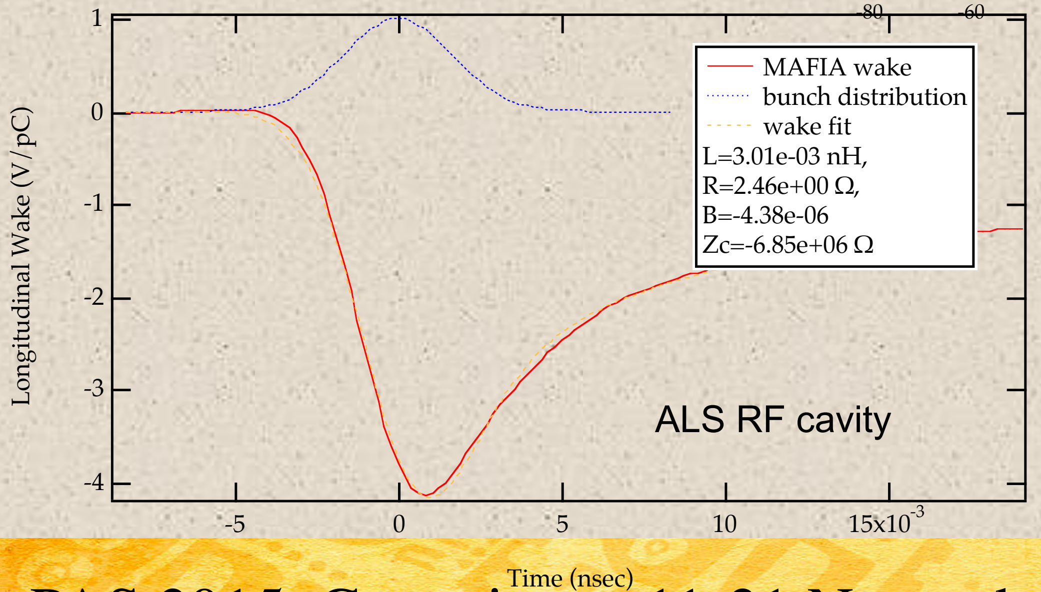
Example: ALS Vacuum Chamber

- 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



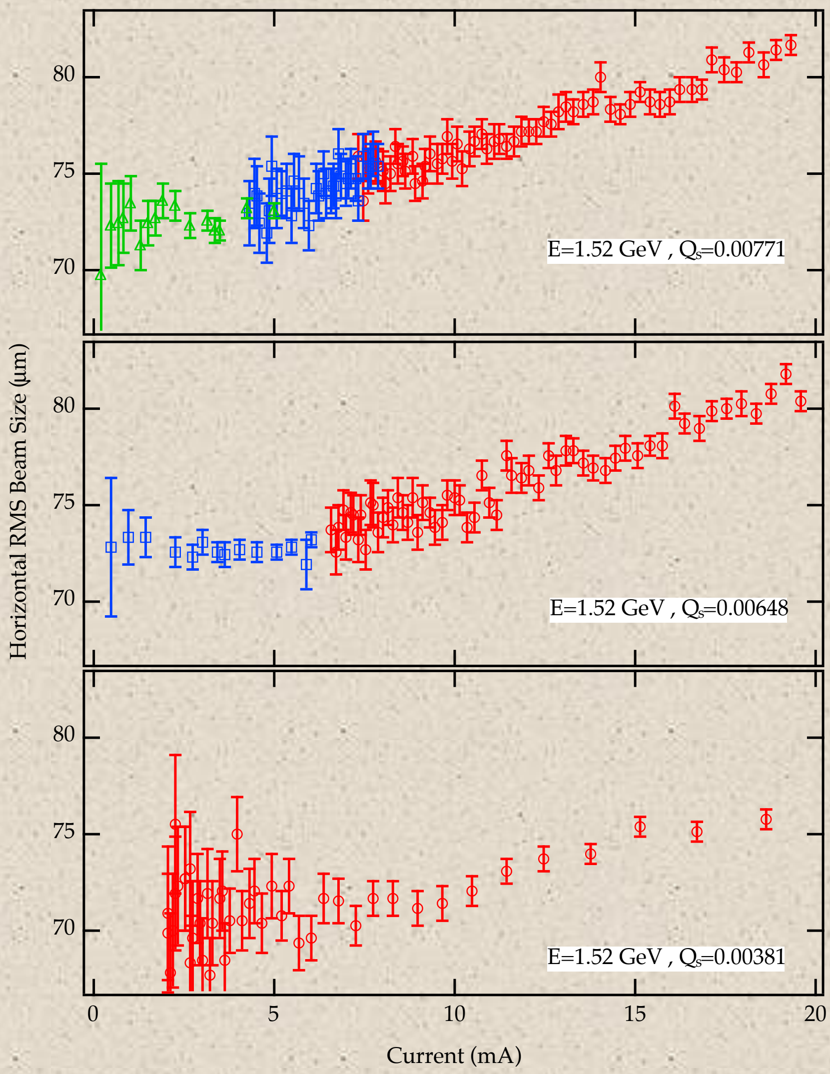


Energy Spread

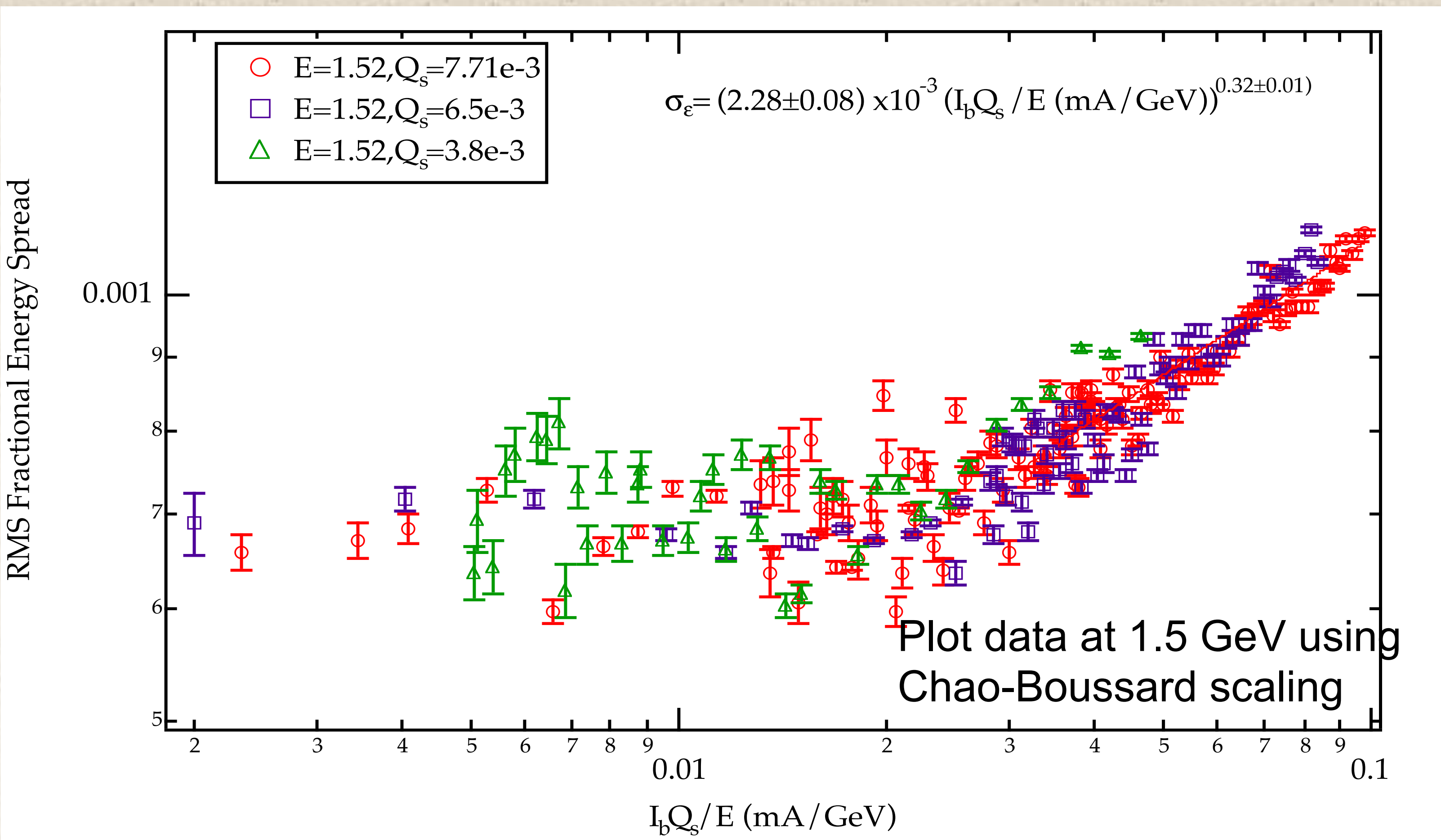
Technique: measure transverse beam size at a point of dispersion. Zero current beam size assumed to be due to nominal emittance and energy spread.

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

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



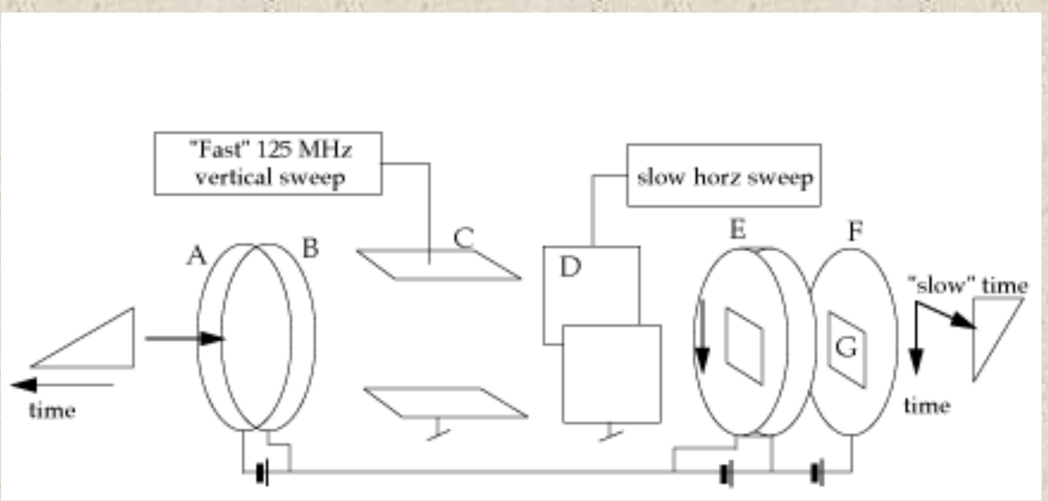
Energy spread summary



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

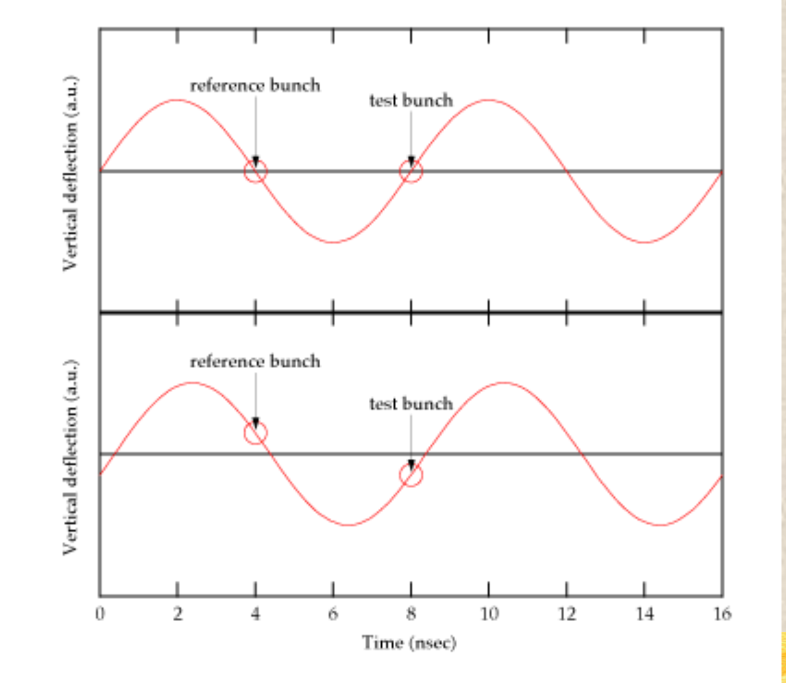
⟹ Z/n=0.08 Ω

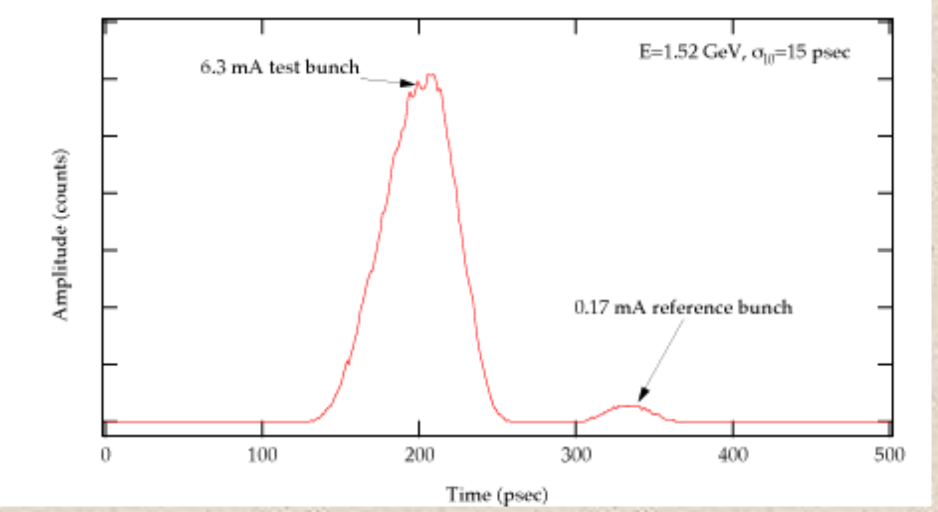
Dual-Scan Streak Camera



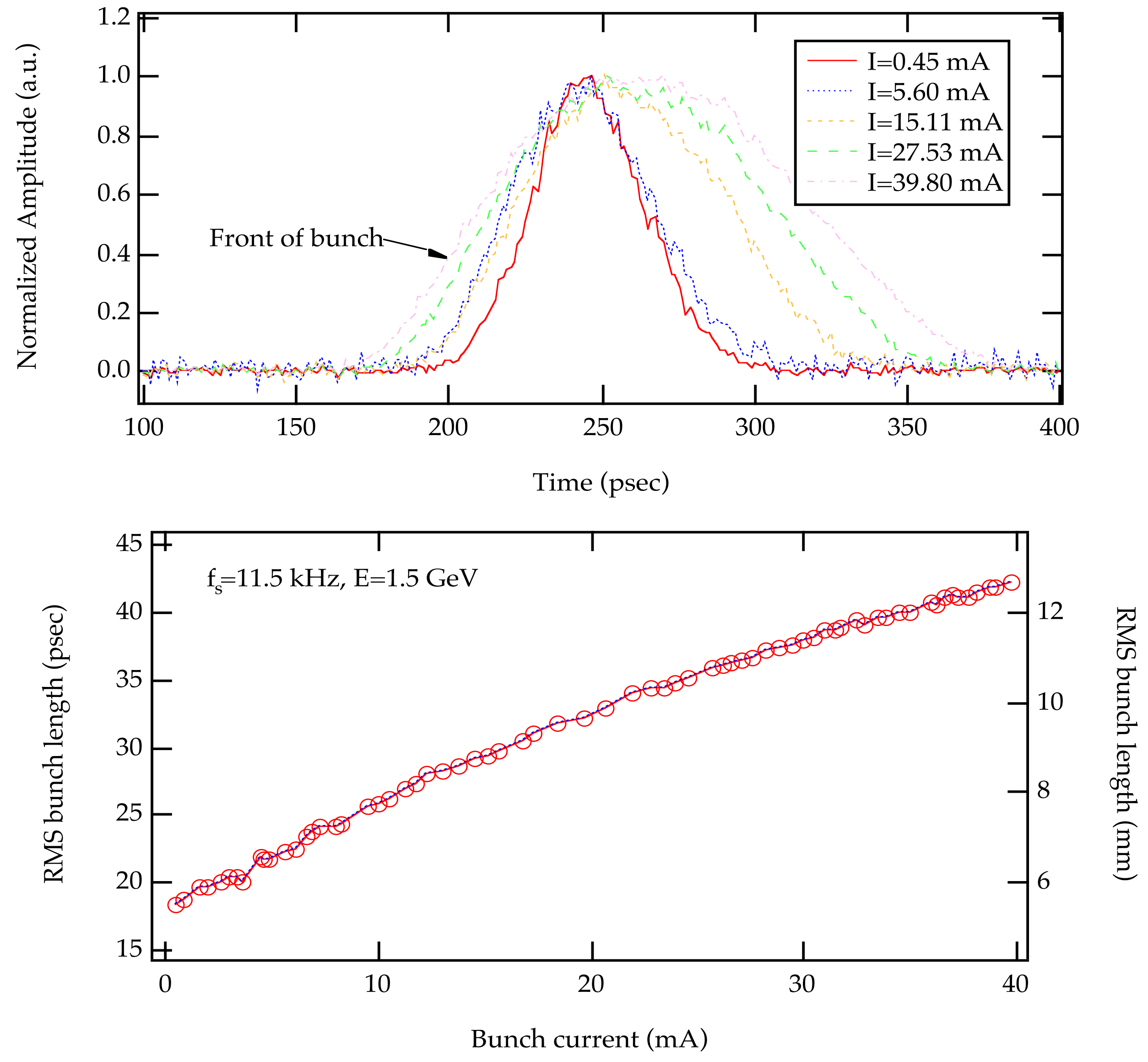
All bunch length measurements done using Hamamatsu C5680 Streak camera w/dual synchroscan

Phase shift measurements done using small test bunch





Bunch length vs. current



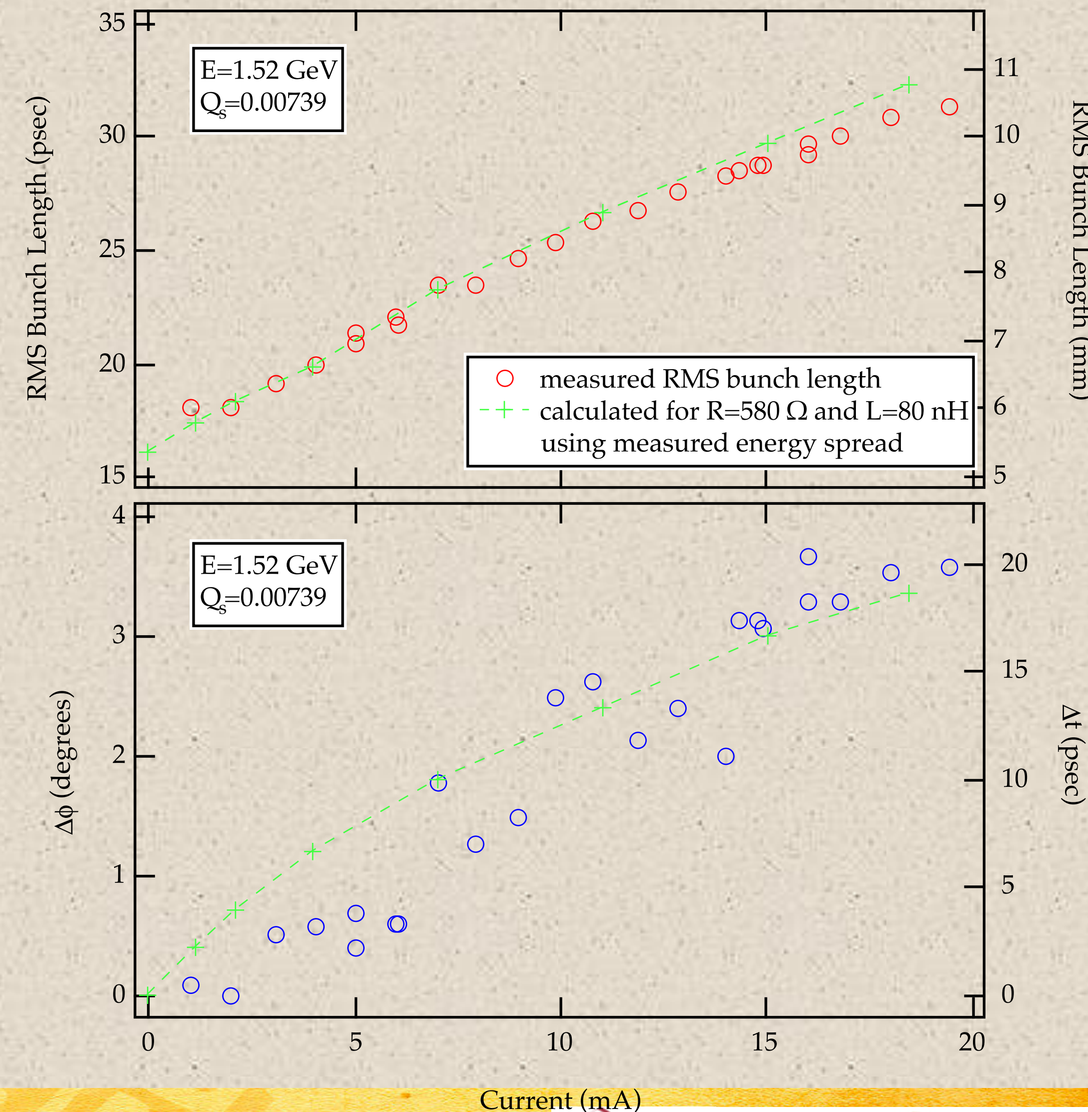
Bunch length and synchronous phase shift

Measured results fit with Haissinski equation using simple RL model.

Measured energy spread used in sooution to the Haissinski equation.

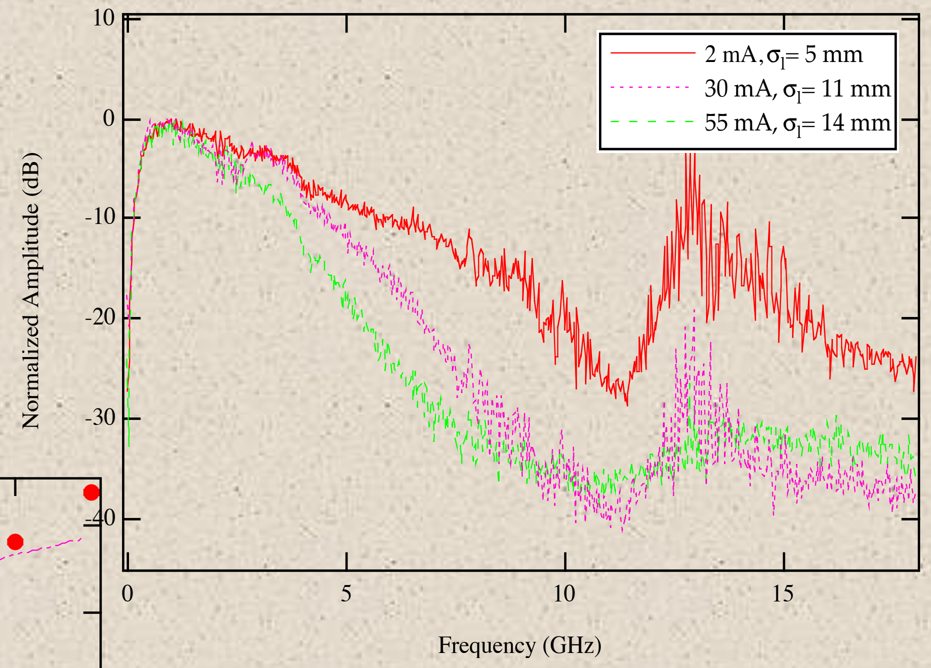
Results consistent with R=580 Ω, L=80 nH.

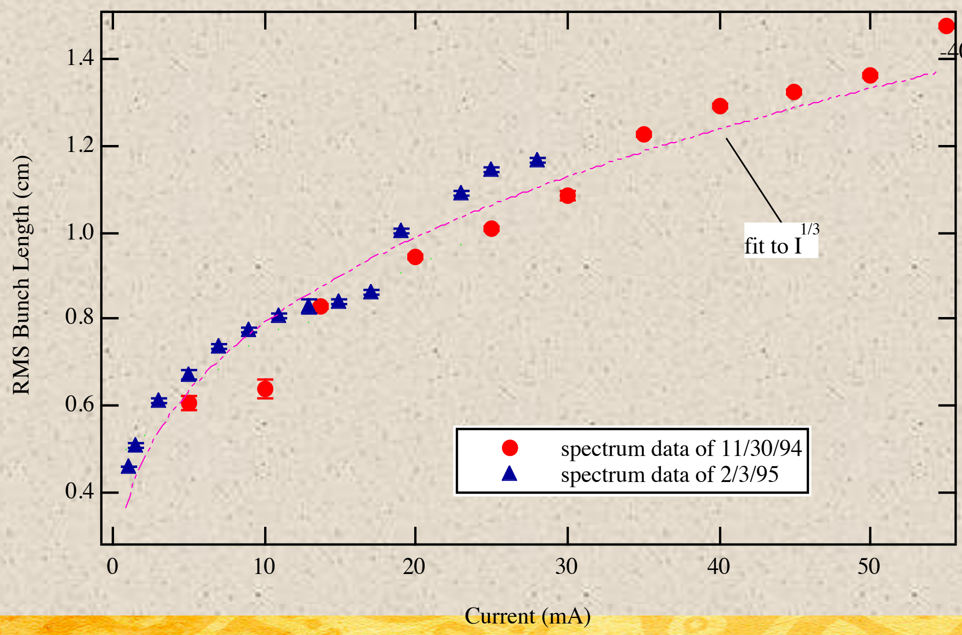
Data made at longer bunch shows worse agreement, probably due to coherent quadrupole instability at higher currents.



Broadband BPM spectra

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

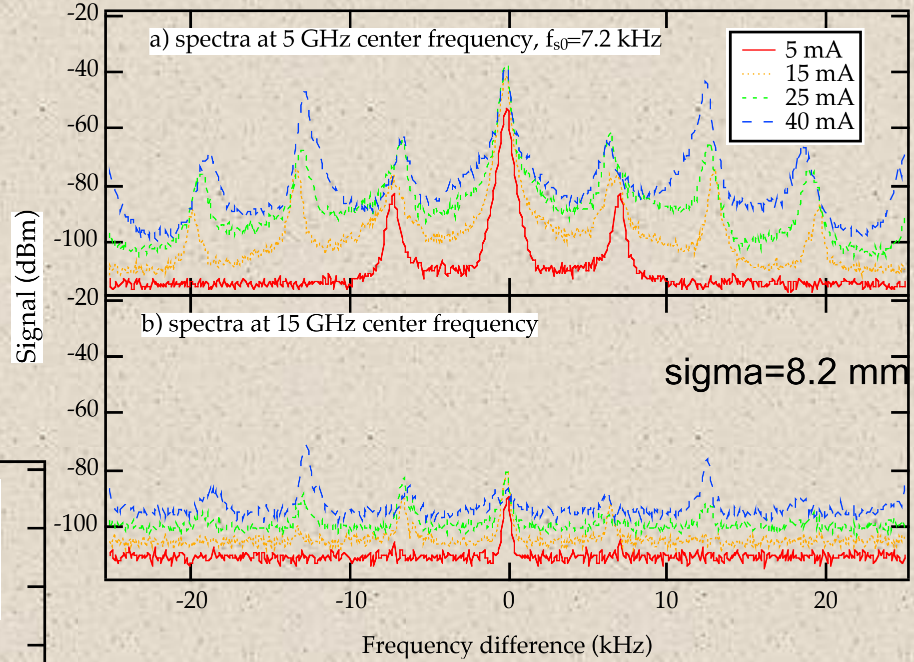


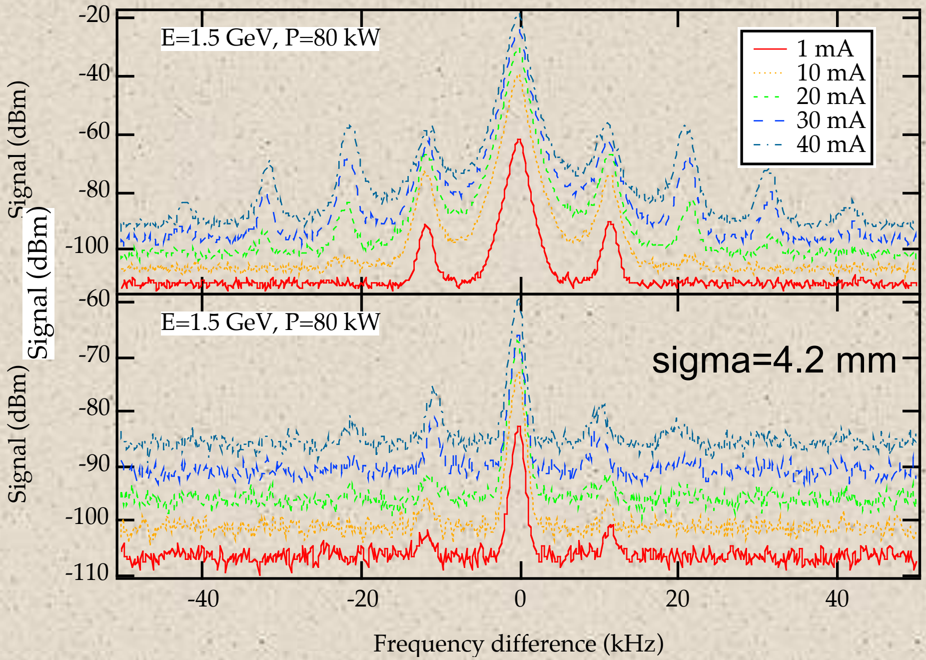


bunch length follows $I^{1/3}$ scaling up to bunch currents of 60 mA

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

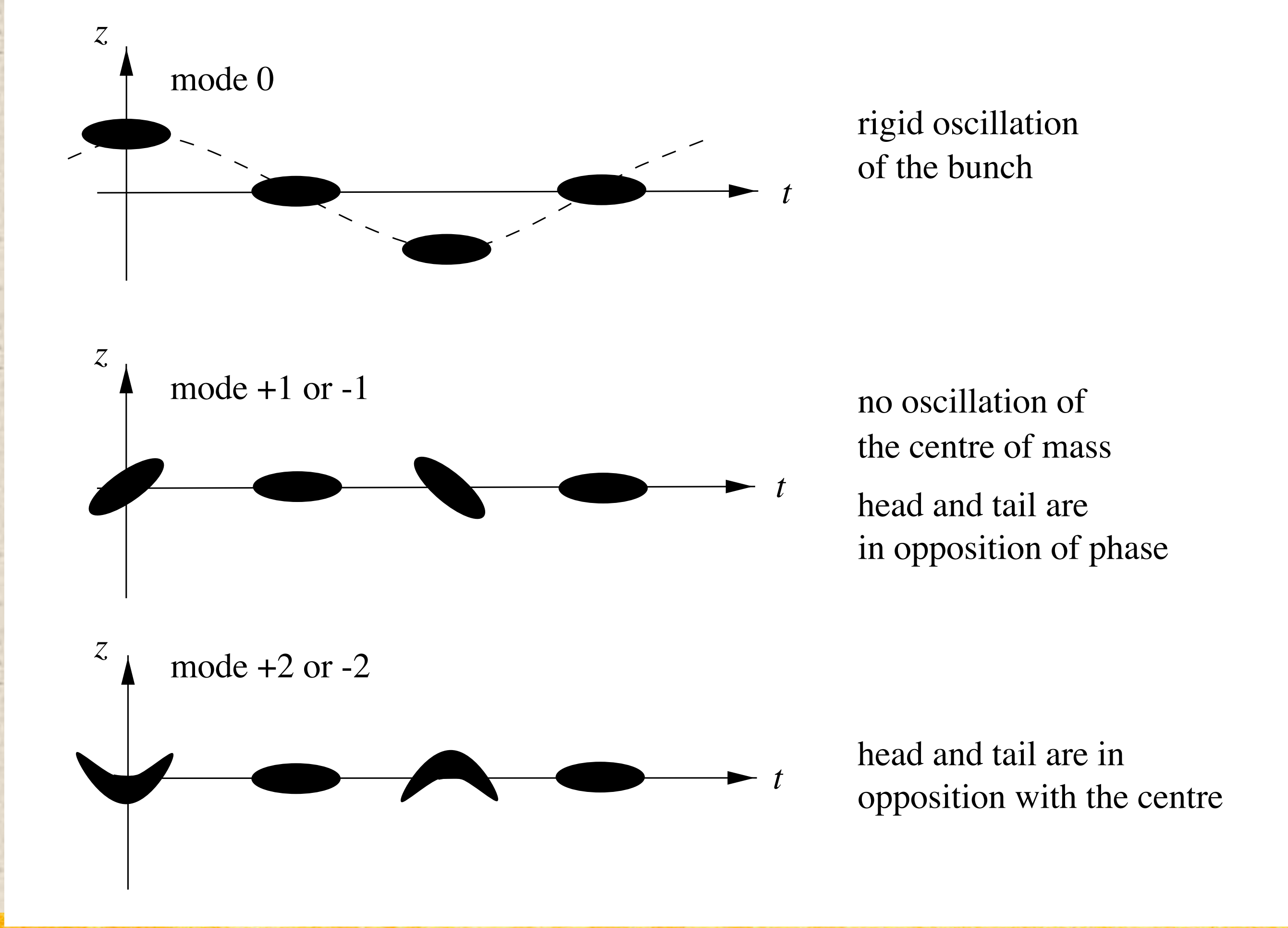
- Transverse effects are driven by the transverse short-range wake or the transverse broad-band impedance.
- There is a very approximate relation between the longitudinal and transverse from the Panofsky-Wenzel theorem given by

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

- 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.

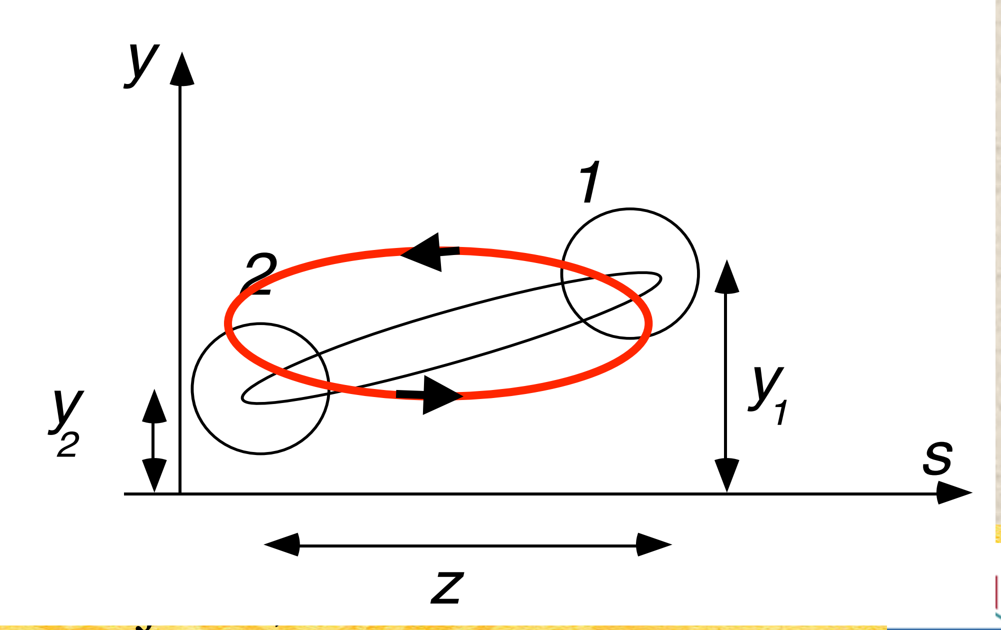
Transverse modes

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



Head-tail instability

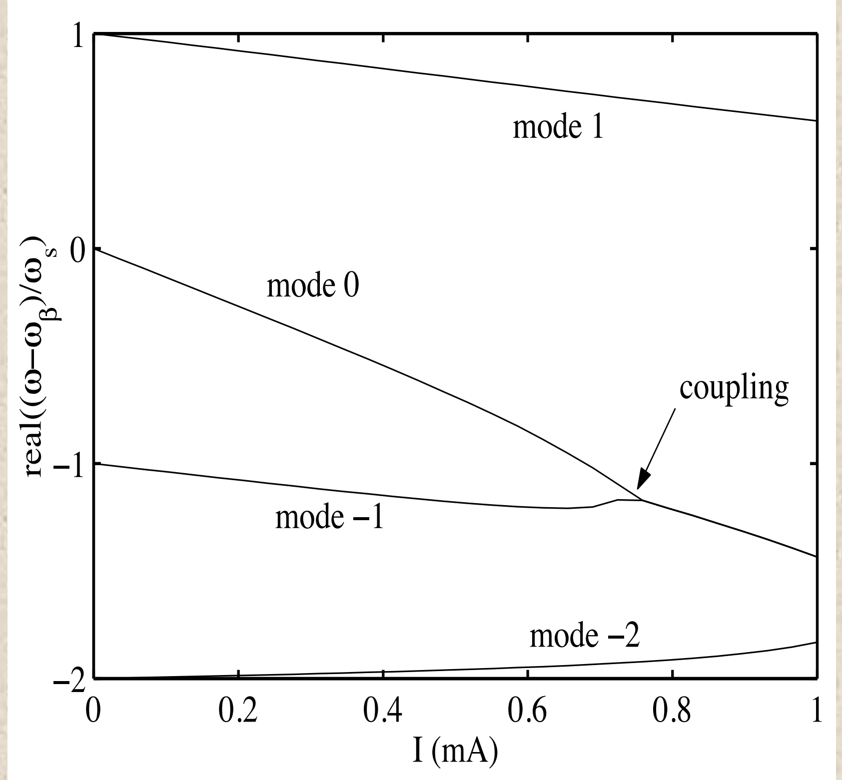
- Consider a simple model where the bunch has two macroparticles
- Each macroparticle has an equal amplitude of synchrotron oscillation. There is an exchange of the head and tail of the bunch every half synchrotron period.
- If we add a transverse wake field, the each macroparticle drives the other when 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

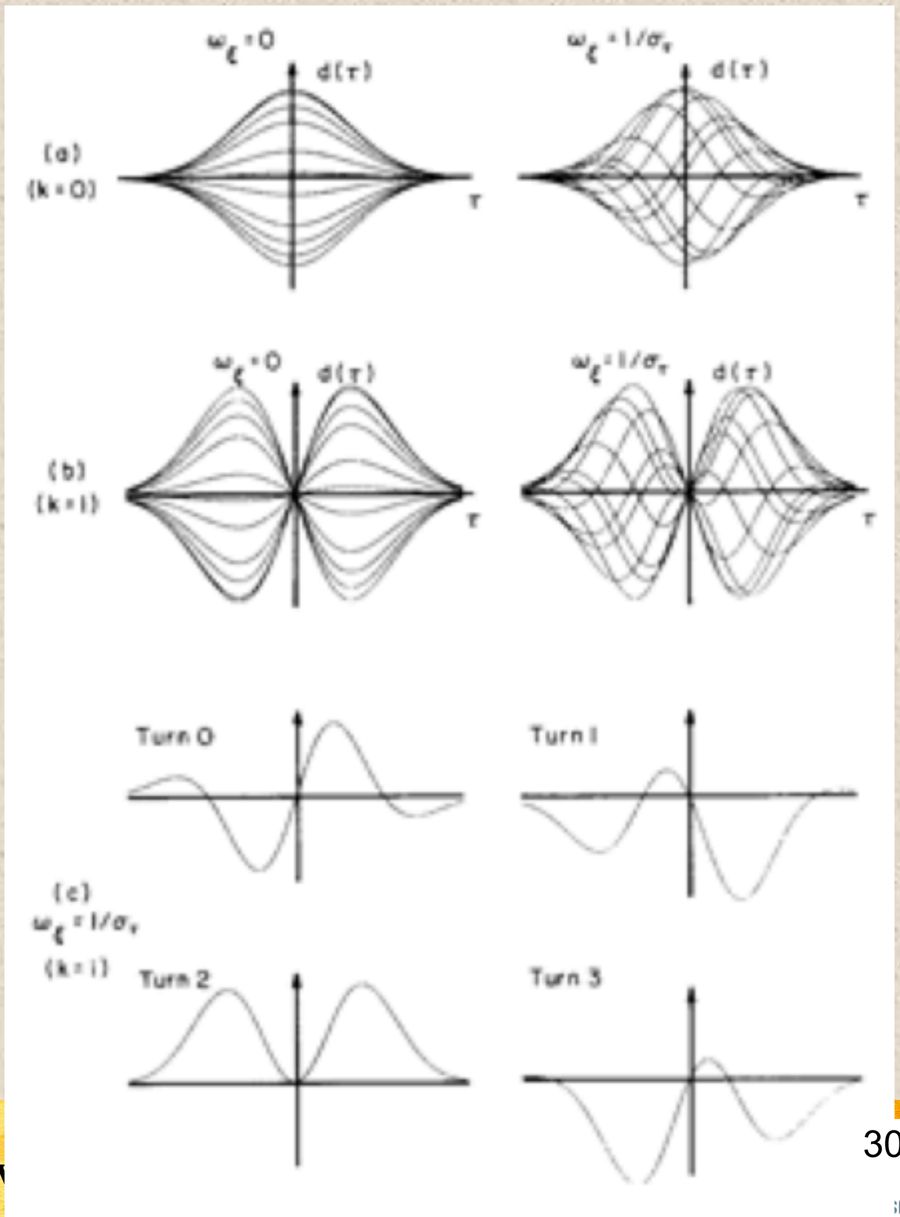
- The coupling of the wake field causes frequency shifts of the modes.
- When the modes merge, there is a growth of the motion: instability.
- The physical interpretation of this effect is that instability occurs when the growth rate of the tail (driven by the head) is faster than the synchrotron period.

$$\xi = 0$$



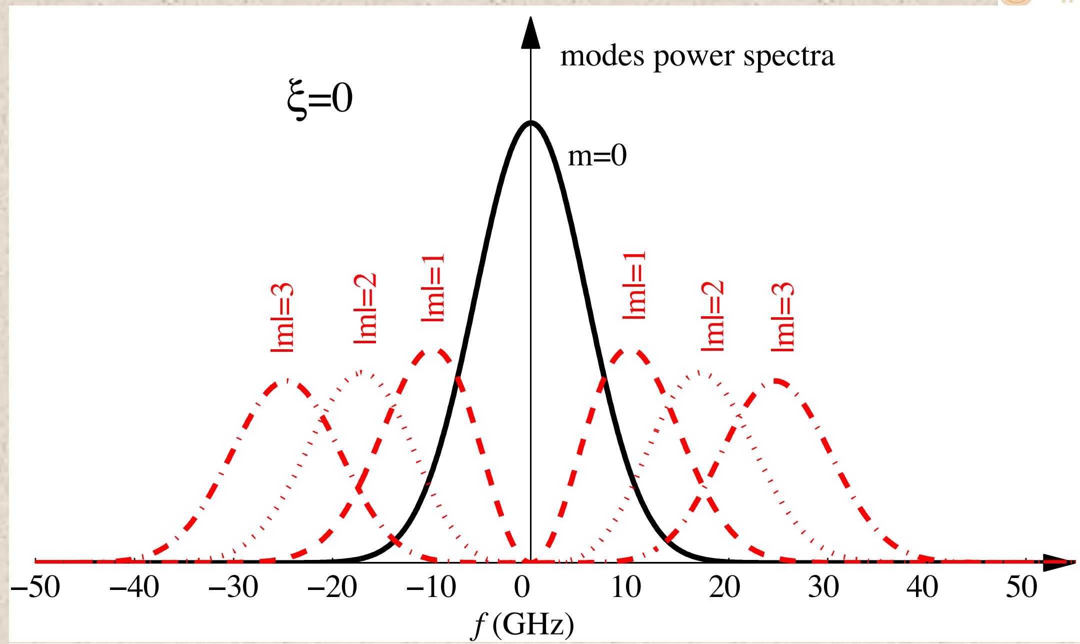
Head-tail motion with chromaticity

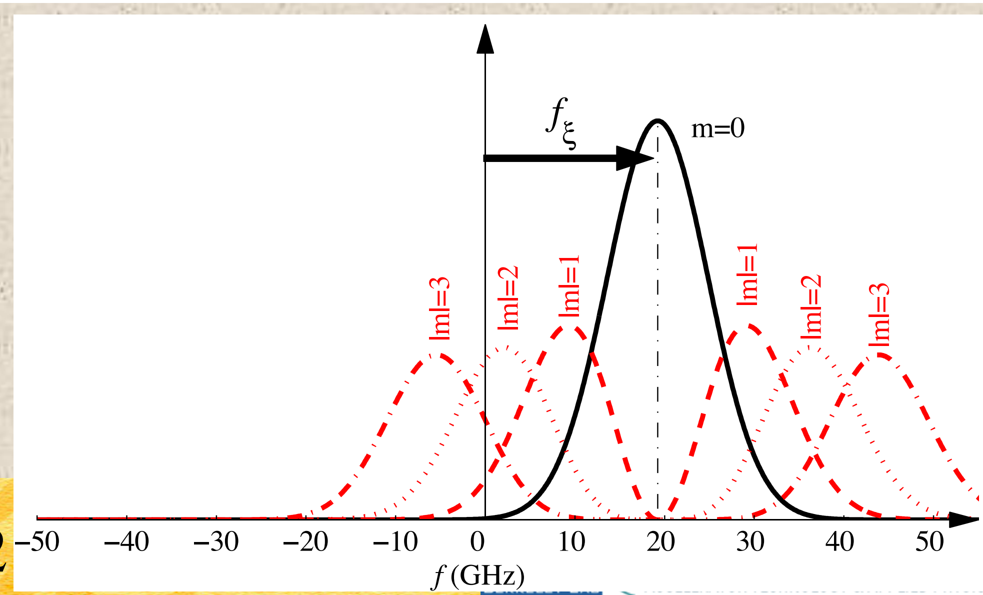
- If there is a nonzero chromaticity, this adds an additional effect to the head-tail motion.
- The chromaticity adds a phase shift between the head and tail of the bunch, modifying the effect of the wake.
- For example, some modes can be damped, and some modes are antidamped.
- Note that increase of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



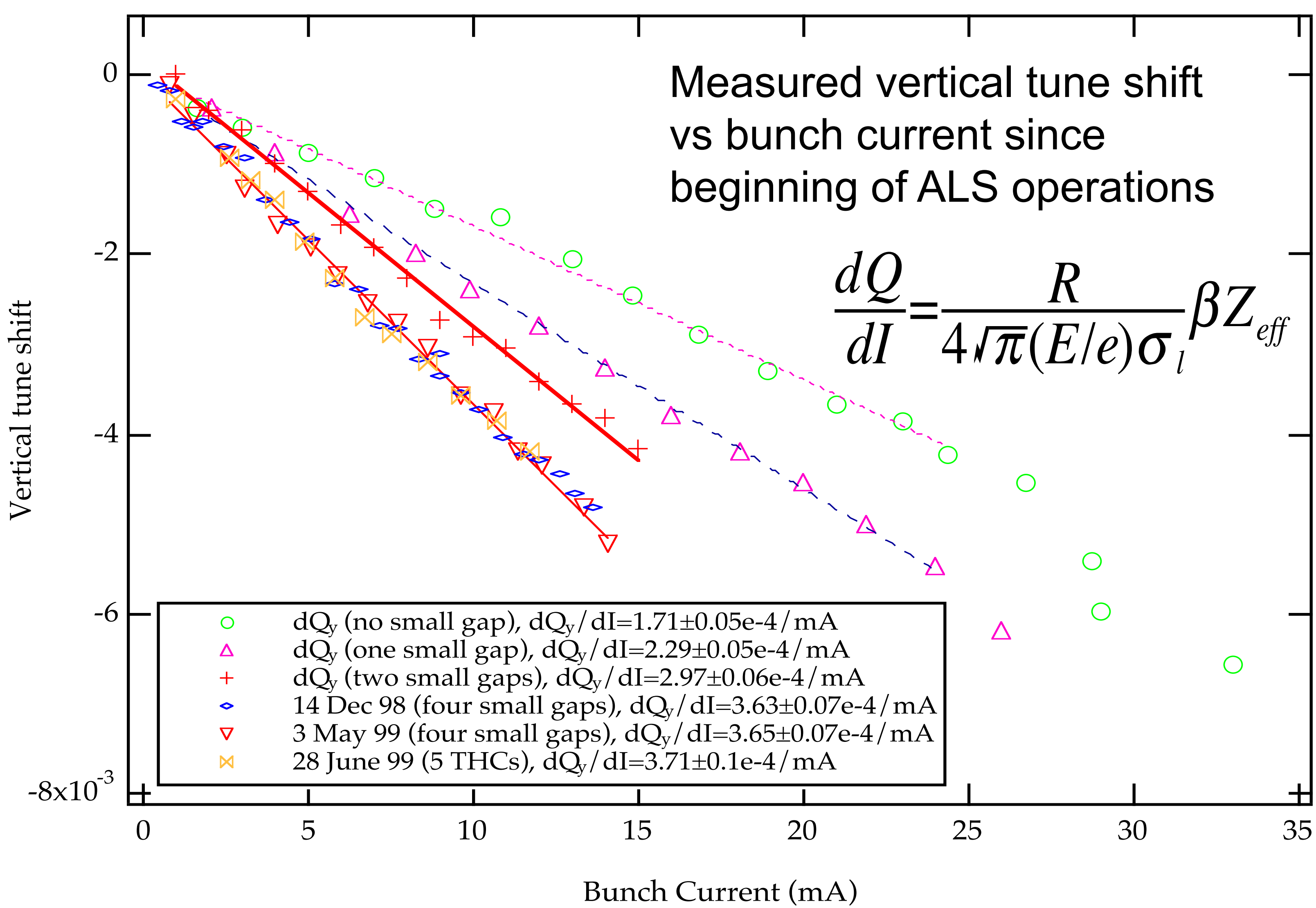
Head-tail modes in frequency domain

- 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

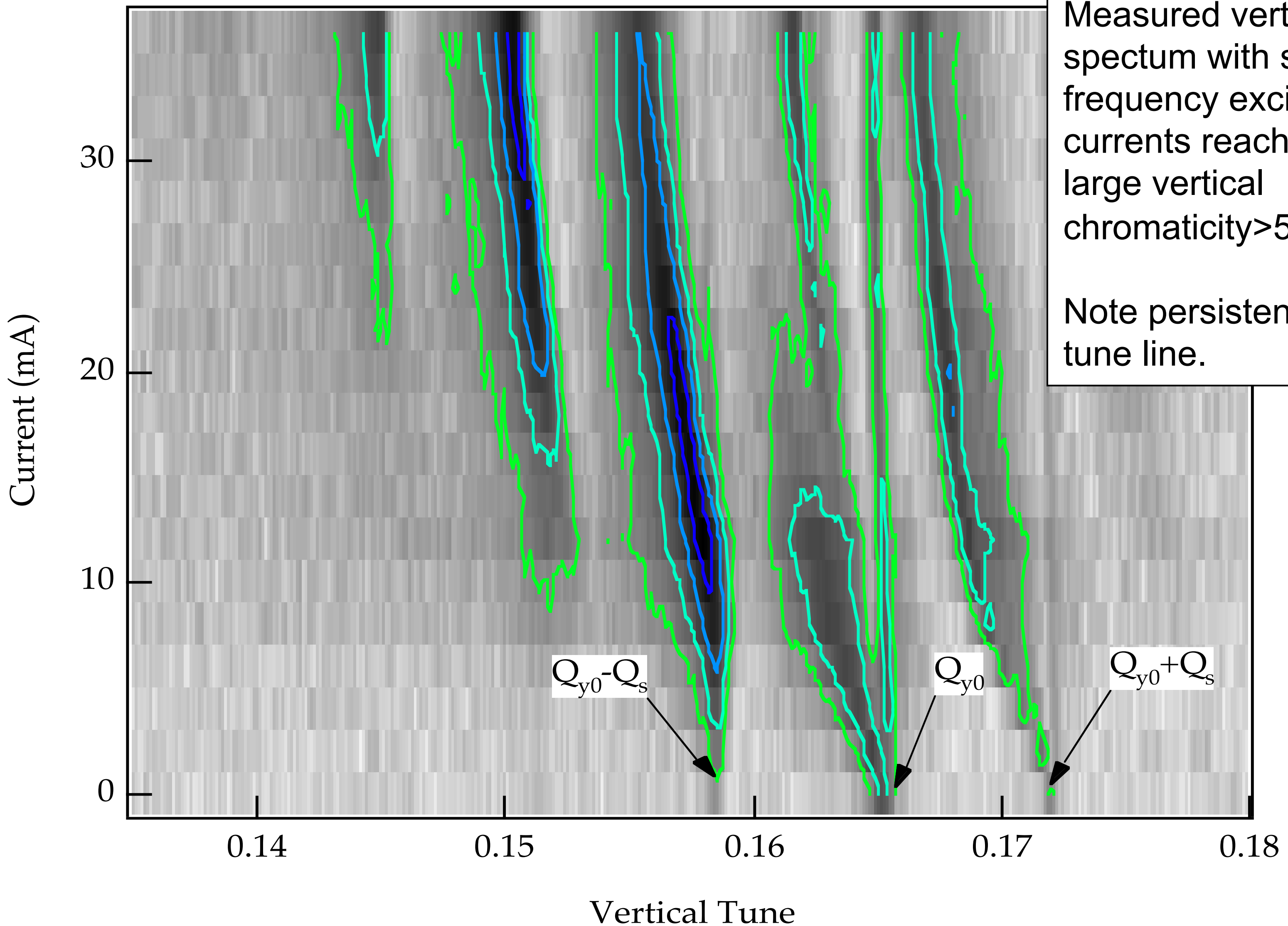




Vertical tune shift vs. bunch current



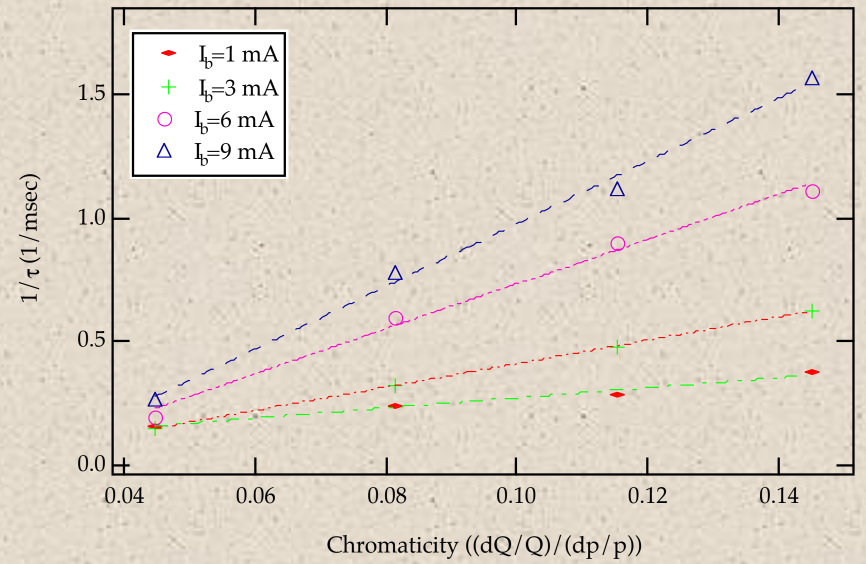
Tune shift vs. bunch current



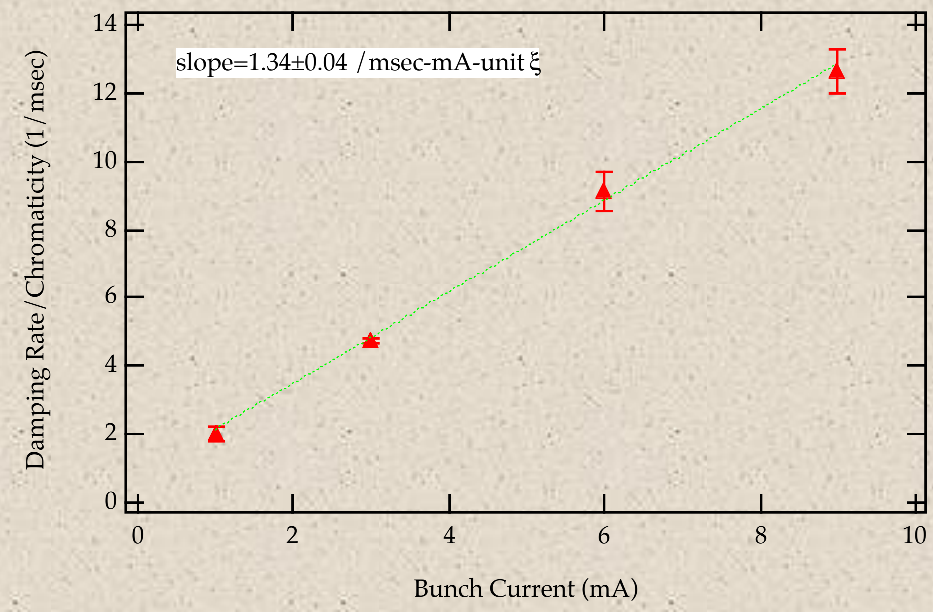
Measured vertical tune spectum with swept frequency excitation. Large currents reached using large vertical chromaticity>5.

Note persistence of original tune line.

Head-tail damping rate vs. I



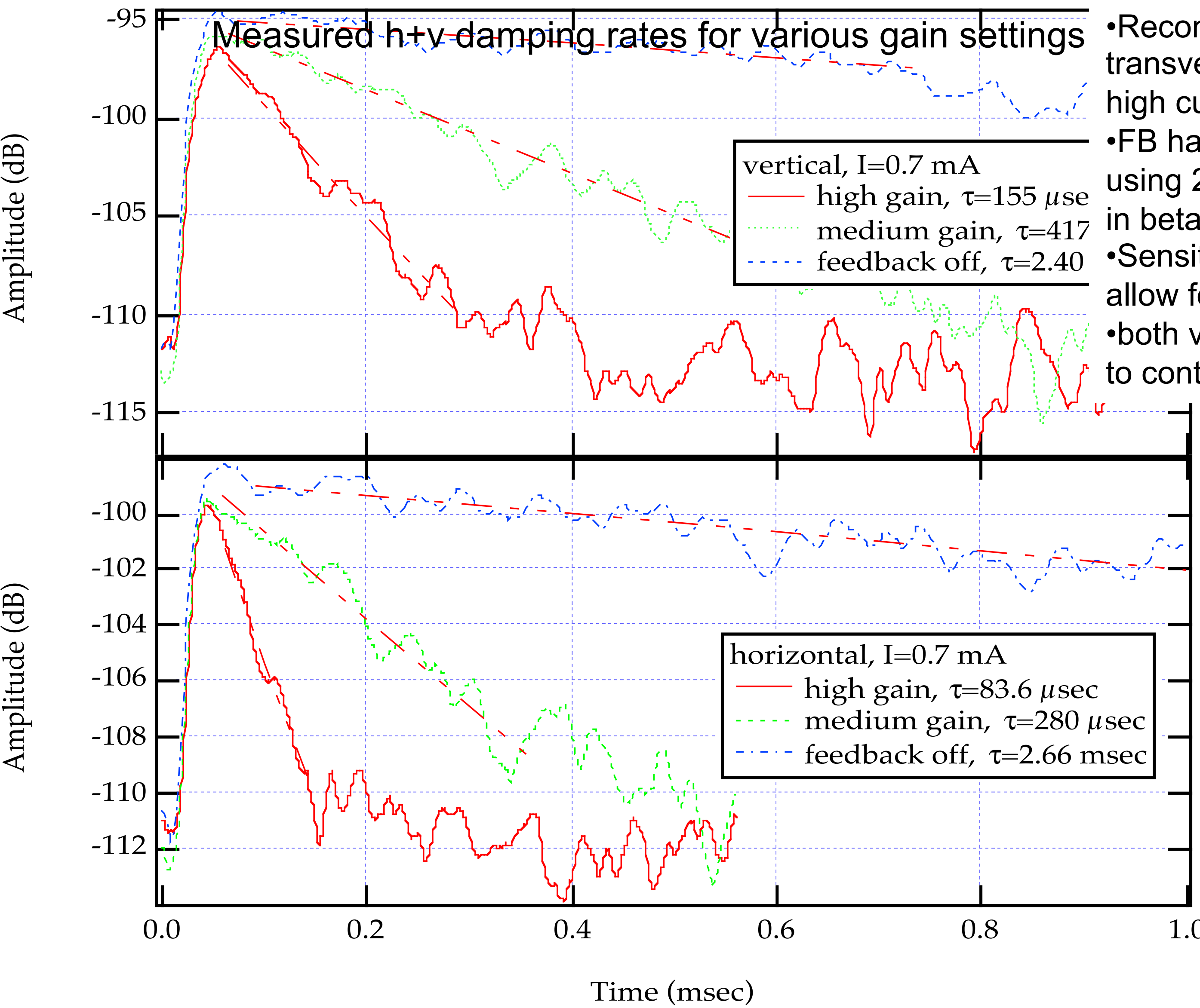
Measure vertical and horizontal damping rates vs. X and I.



Mode-coupling threshold

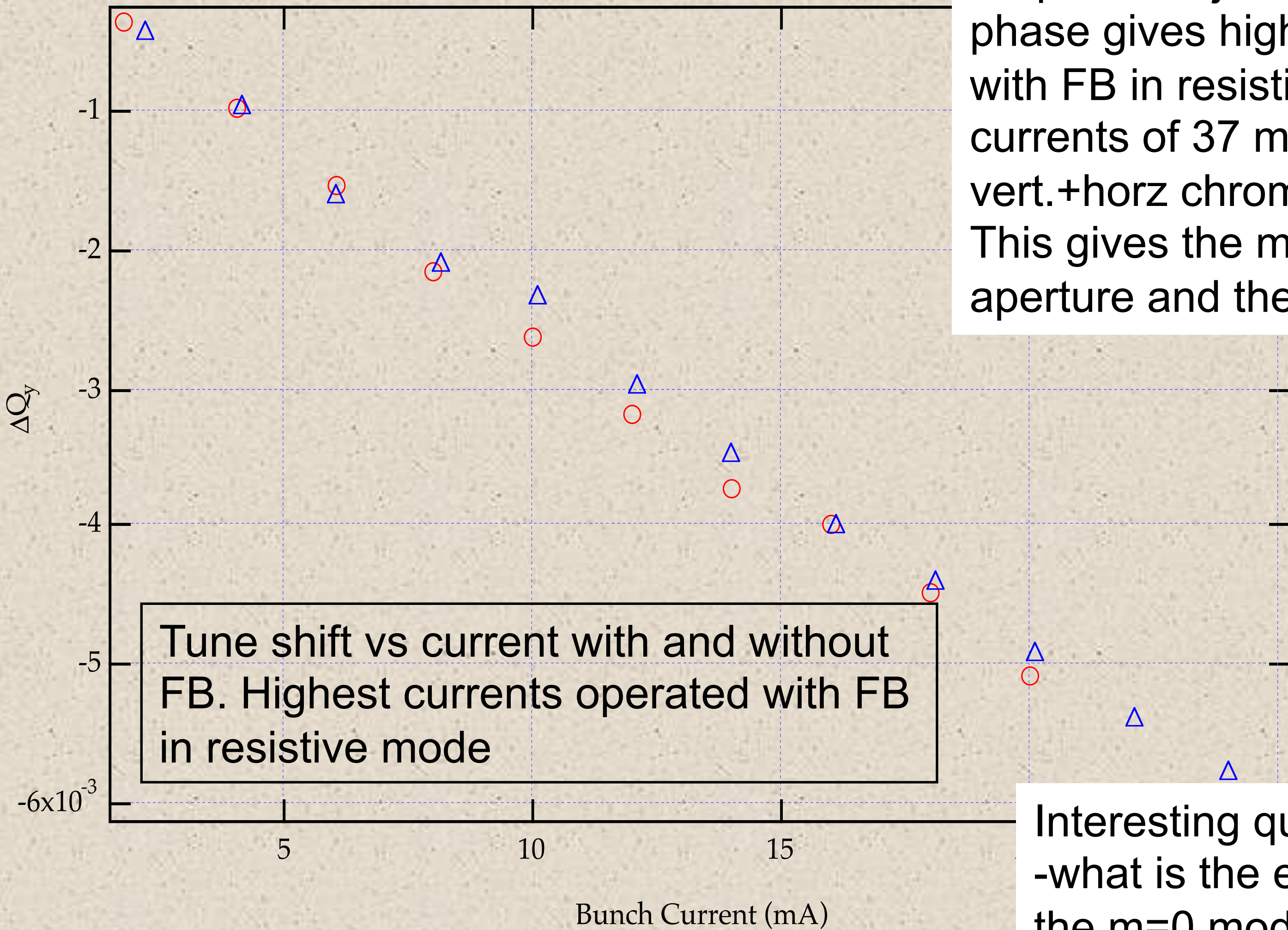
•Vertical mode-coupling threshold has dropped by a factor of 2 with installation of 5 small gap vacuum chambers
•Main current-limiting mechanism due to small vertical physical aperture.
•Unclear whether generated by resistive wall impedance or tapers.
• Threshold depends on vertical orbit through small 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?