# Storage ring measurements, the basics

○ **Beam Diagnostics**

- DCCT
- BPMs
- Synchrotron light monitors
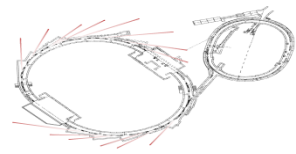- Scrapers
- Loss monitors
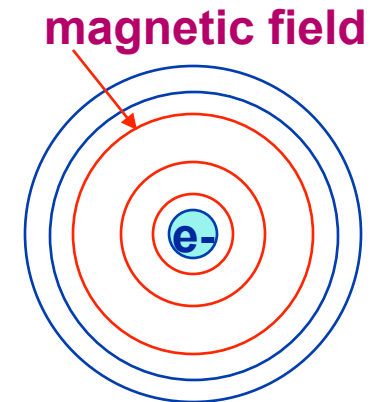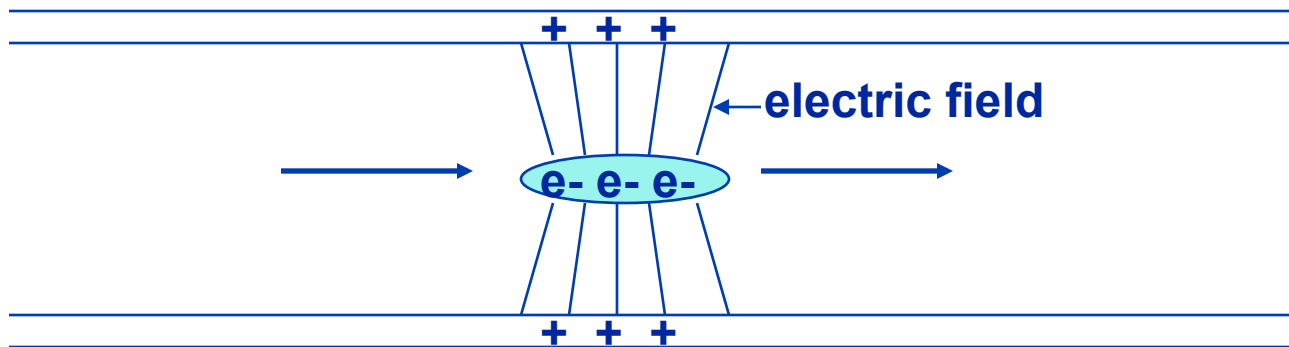
○ **Measuring lifetime, tunes, $\beta$, $\eta$, chromaticity, $\alpha$**
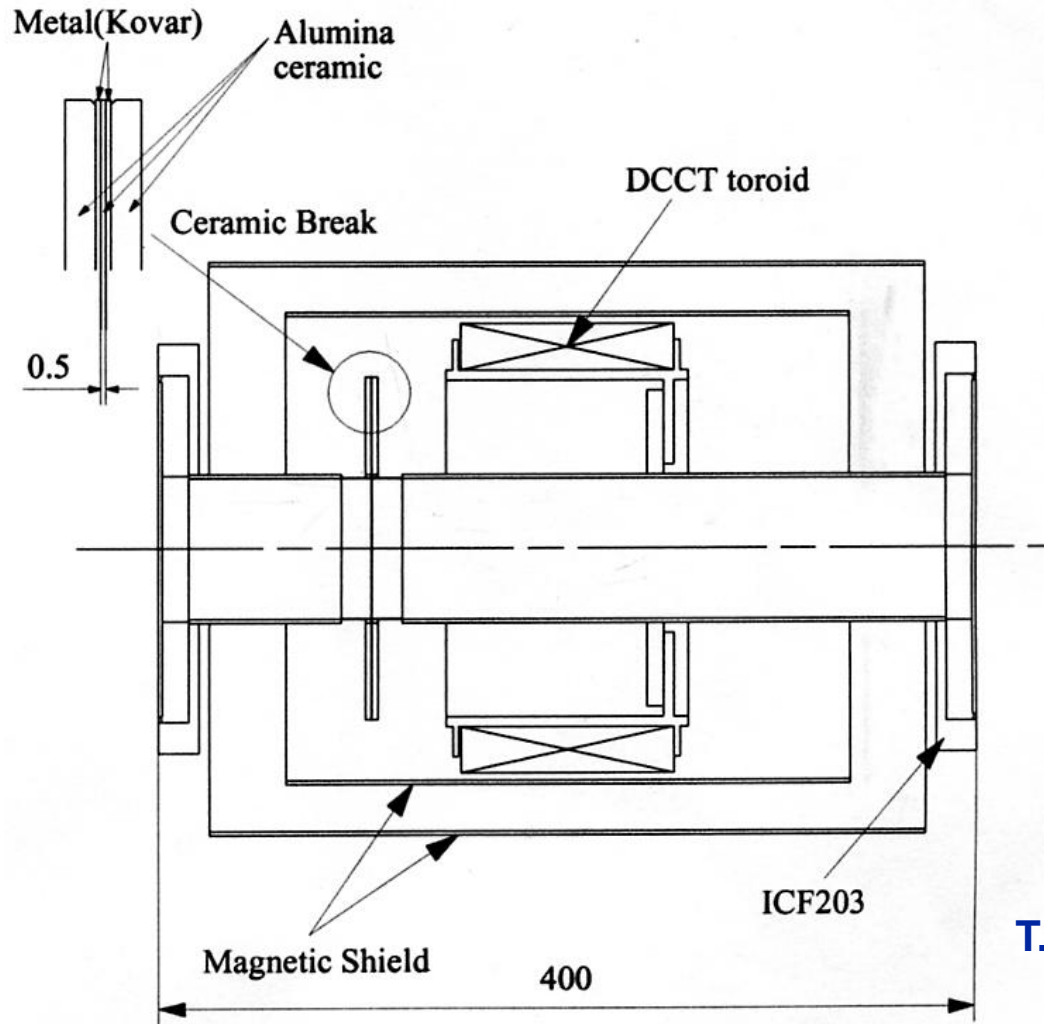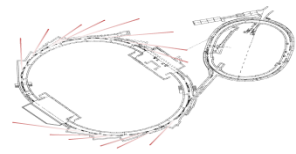
# Beam diagnostics: Intensity/current

○ **To measure the intensity of a beam one can apply many methods (capacitive pickups, wall current monitor, toroids, synchrotron radiation based methods …)**

○ **Most commonly used to measure current in a calibrated way are toroidal monitors (ferrite toroid around beam, coil to pick up induced voltage signal).**

↳ **Complication is always stray fields, shielding of beam field due to vacuum chamber (image currents), …**

○ **If the beam current is DC or nearly DC, methods becomes more complicated – DCCTs are used (also in DC power supplies, …)**
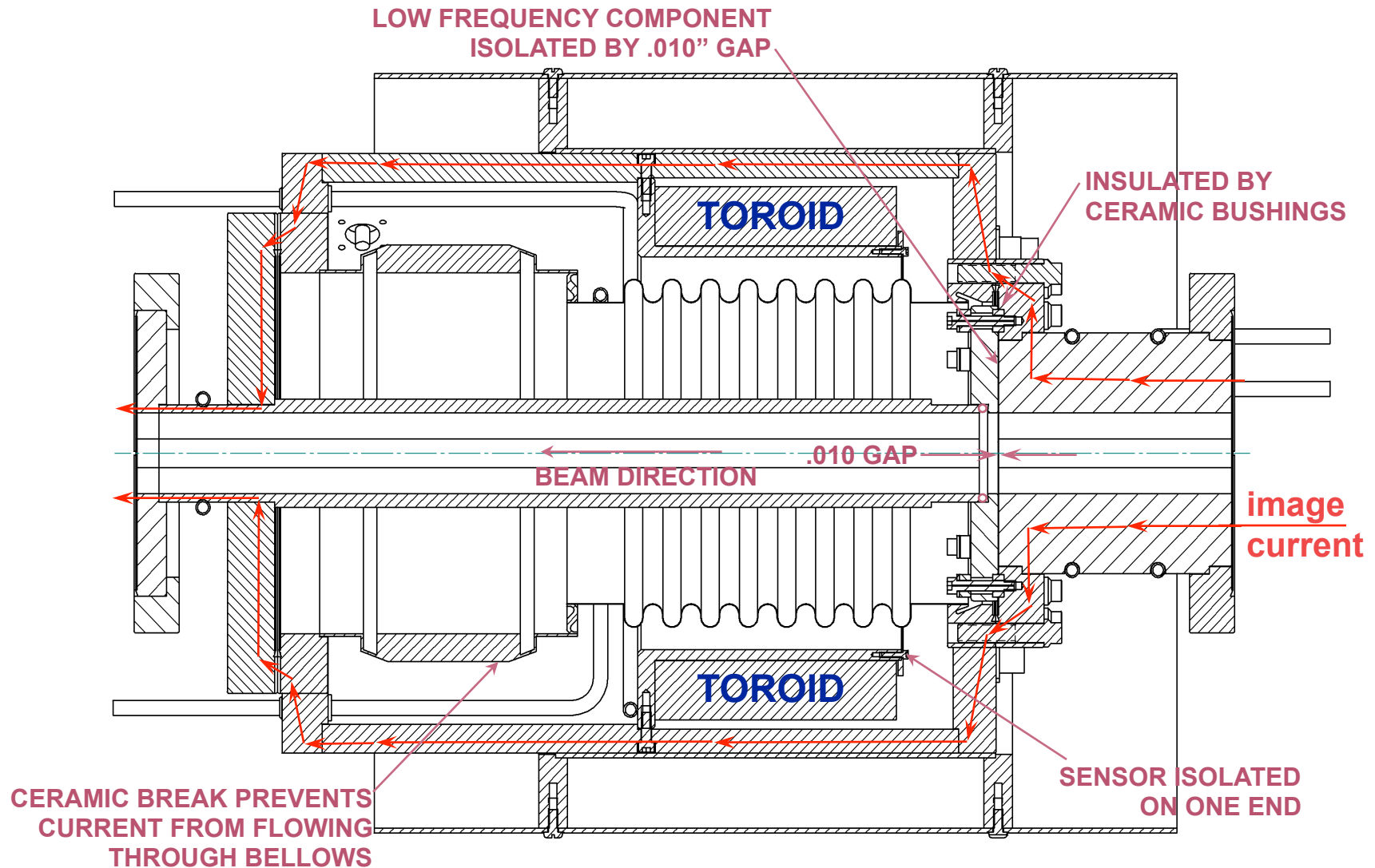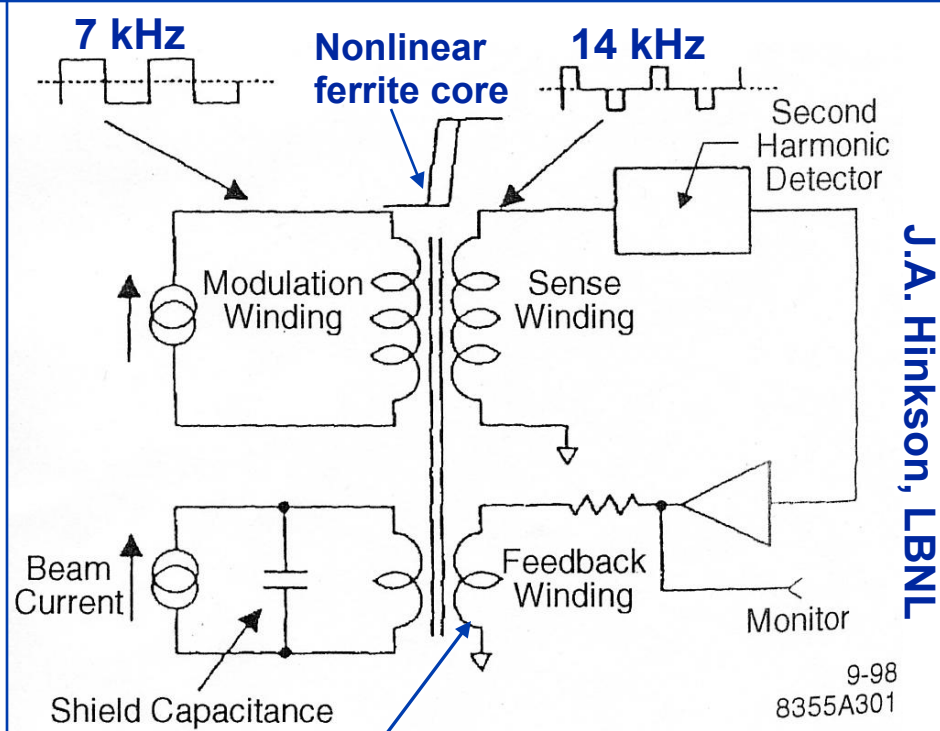
magnetic field

electric field

+ + +

e- e- e-

+ + +

e-

# Photon factory DCCT

Metal(Kovar)
Alumina ceramic
Ceramic Break
DCCT toroid
0.5
Magnetic Shield
ICF203
400

T. Honda et al., EPAC98

# SPEAR3 DCCT



LOW FREQUENCY COMPONENT
ISOLATED BY .010" GAP

TOROID

INSULATED BY
CERAMIC BUSHINGS

.010 GAP

BEAM DIRECTION

image
current

TOROID

CERAMIC BREAK PREVENTS
CURRENT FROM FLOWING
THROUGH BELLOWS

SENSOR ISOLATED
ON ONE END

# DCCT (or PCT) circuit

**7 kHz**

**Nonlinear ferrite core**

**14 kHz**

**Bergoz PCT**

Second Harmonic Detector

Modulation Winding

Sense Winding

Beam Current

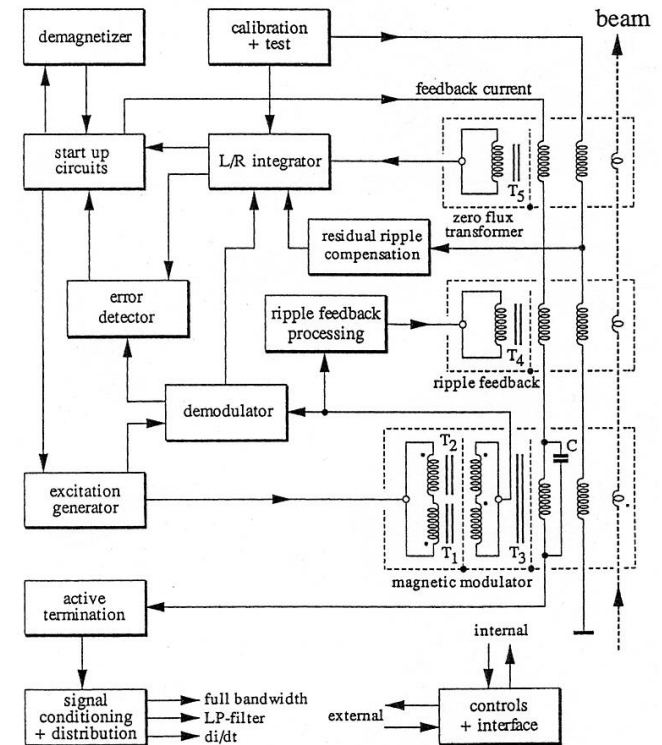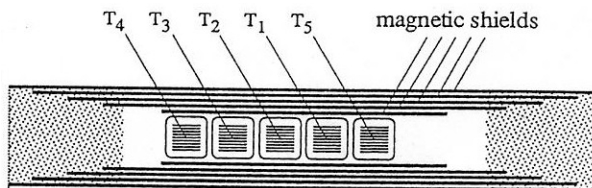Feedback Winding

Monitor

Shield Capacitance

9-98
8355A301

J.A. Hinkson, LBNL

**The DC bias current is adjusted to remove the 2nd harmonic (14 kHz) response of toroid. The beam current is proportional to the DC bias current.**
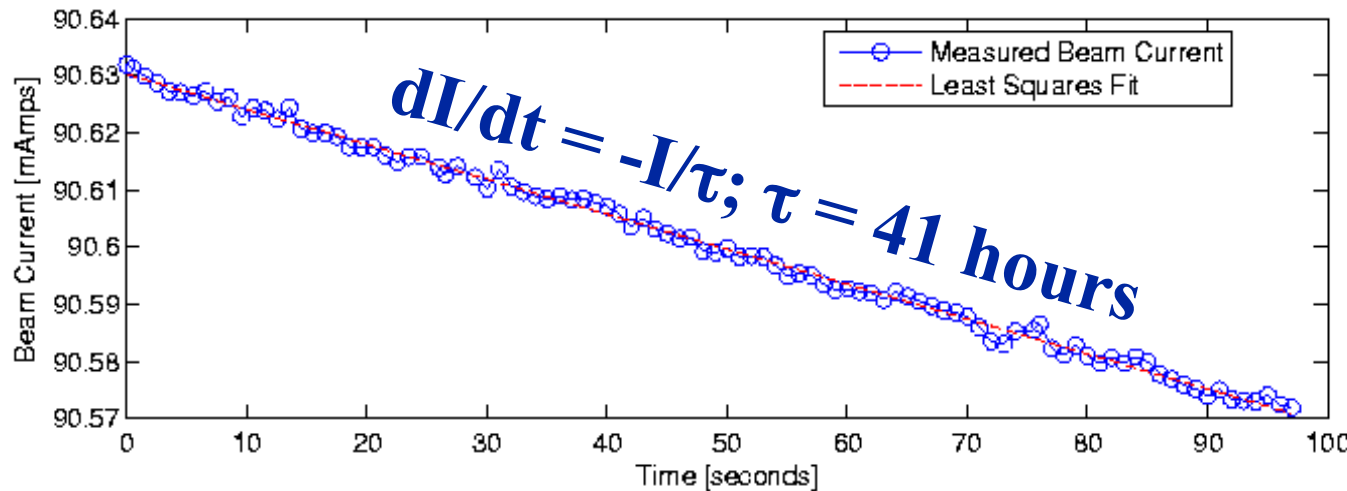
**Ferrite core Xsection**

$T_4$  $T_3$  $T_2$  $T_1$  $T_5$   magnetic shields

demagnetizer

calibration + test

feedback current

start up circuits

L/R integrator

zero flux transformer

residual ripple compensation

$T_5$

beam

error detector

ripple feedback processing

$T_4$

ripple feedback

demodulator

excitation generator

$T_2$

$T_1$   $T_3$

magnetic modulator

C

active termination

internal

signal conditioning + distribution

full bandwidth
LP-filter
di/dt

external

controls + interface

**Simplified circuit, K. Unser, 1992**

# SPEAR3 lifetime measurement w/ DCCT

$dI/dt = -I/\tau; \ \tau = 41 \text{ hours}$

**DCCT resolution:**

**1 $\mu$A in 1 second**
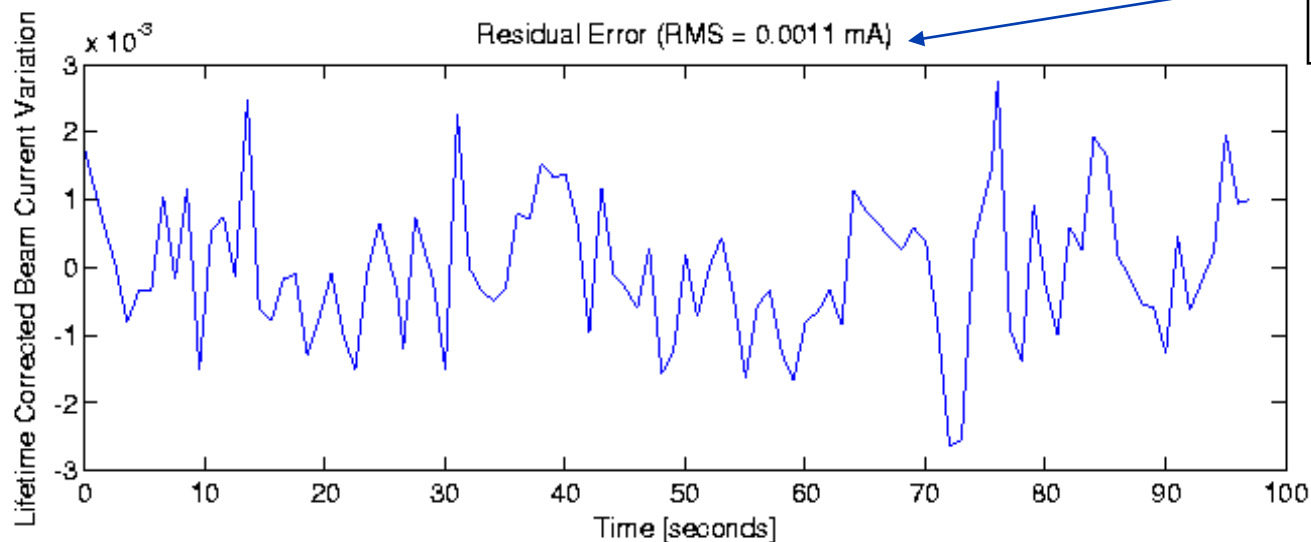
11-Feb-2005

# Lifetime vs. tunes
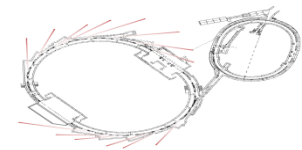
○ **Resonant line:**

  ↳ $\nu_x - \nu_y = 9$

○ **$*$ = operating tunes (14.19, 5.23)**

○ **Data gathered automatically on owl shift.**



1/(τ*I) versus tune (raw data)
R:/Controls/matlab/Shifts/safranek/2004-02-14/scantunedata-00-23-36.mat
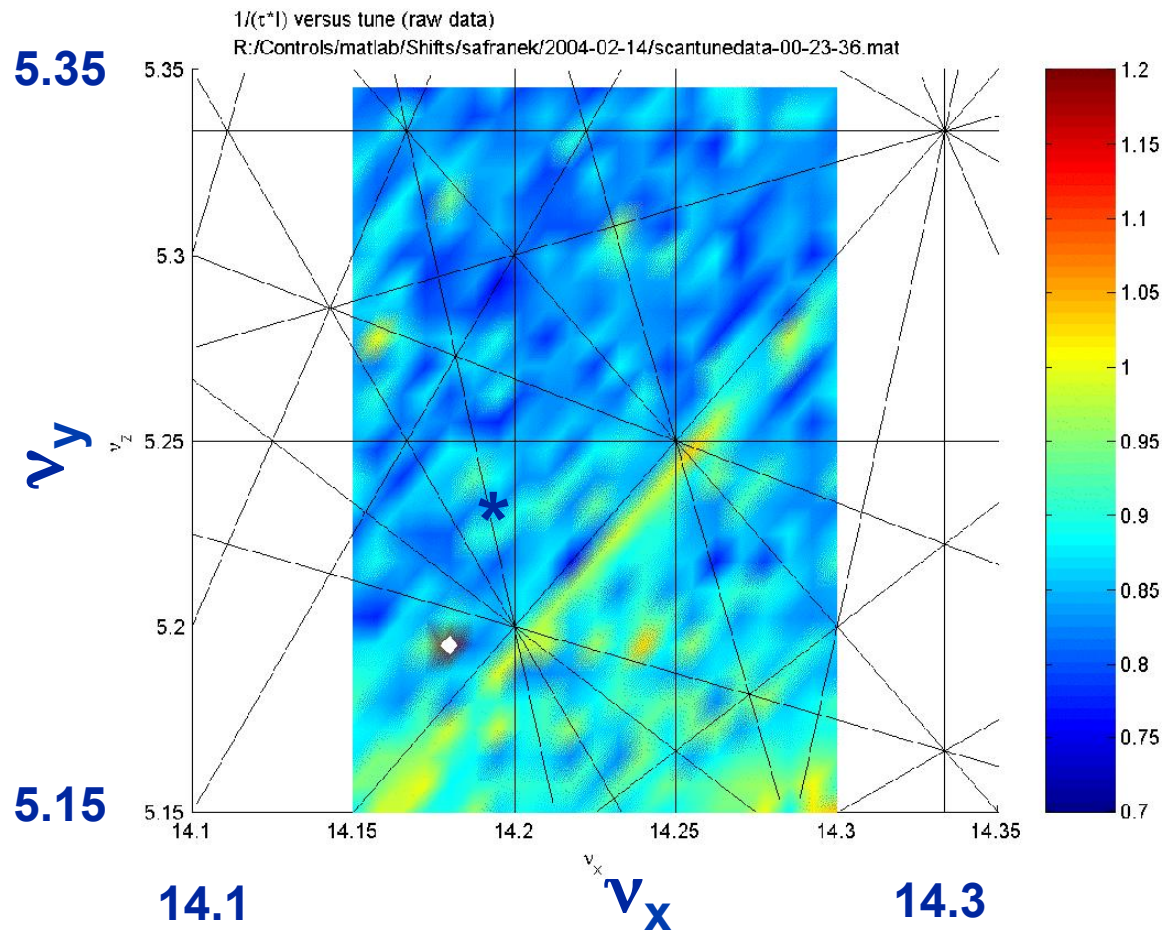
# Dynamic aperture vs. tune

○ **Resonant lines:**

↪ $\nu_x - \nu_y = 9$

↪ $3\nu_x + \nu_y = 48$

↪ $4\nu_x + \nu_y = 62$

○ **Resonances offset from tune shift with amplitude.**

○ **\* = operating tunes (14.19, 5.23)**

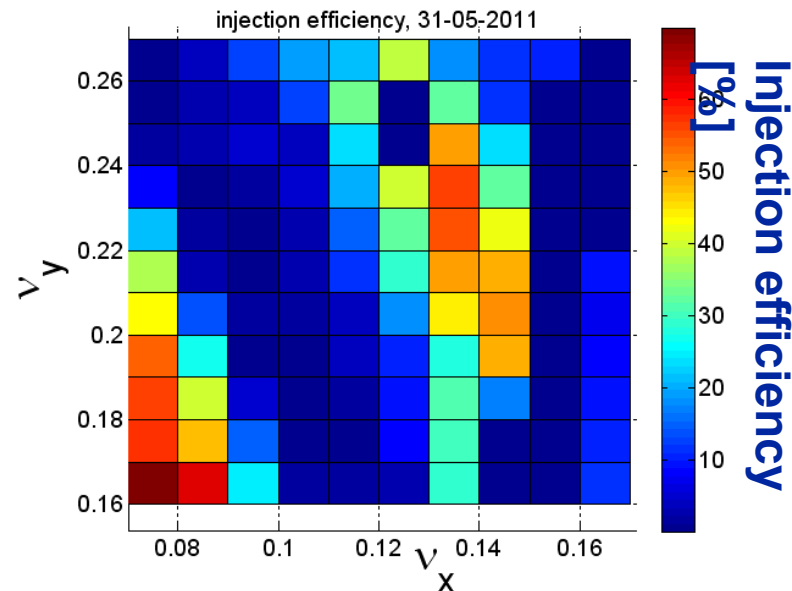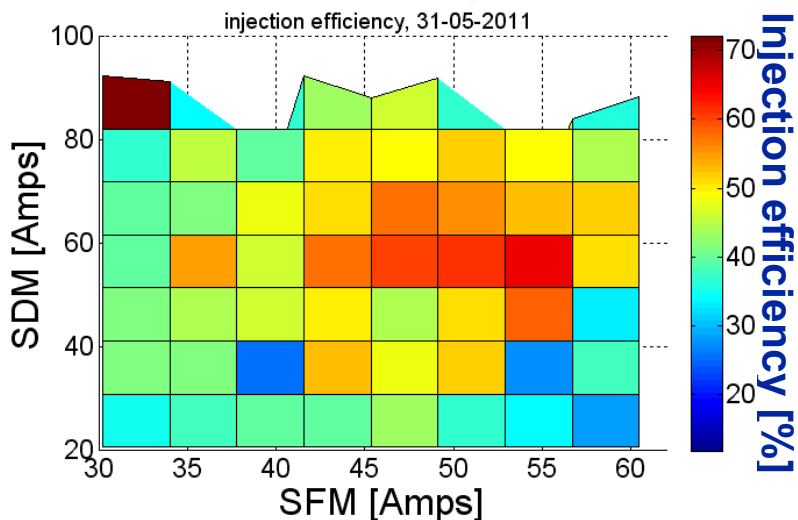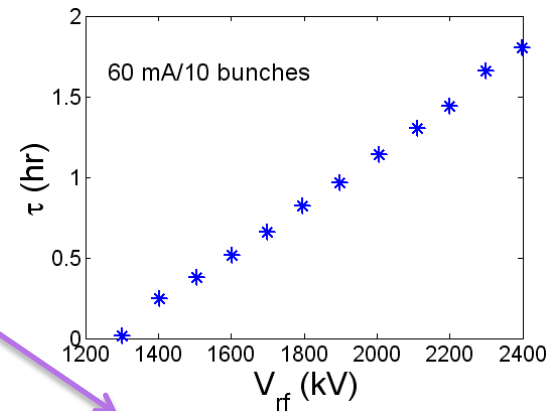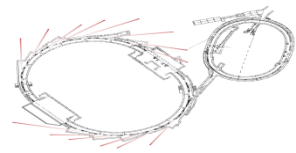○ **Data gathered automatically on owl shift.**



Maximum K3 amplitude [kV] versus tune (raw data)
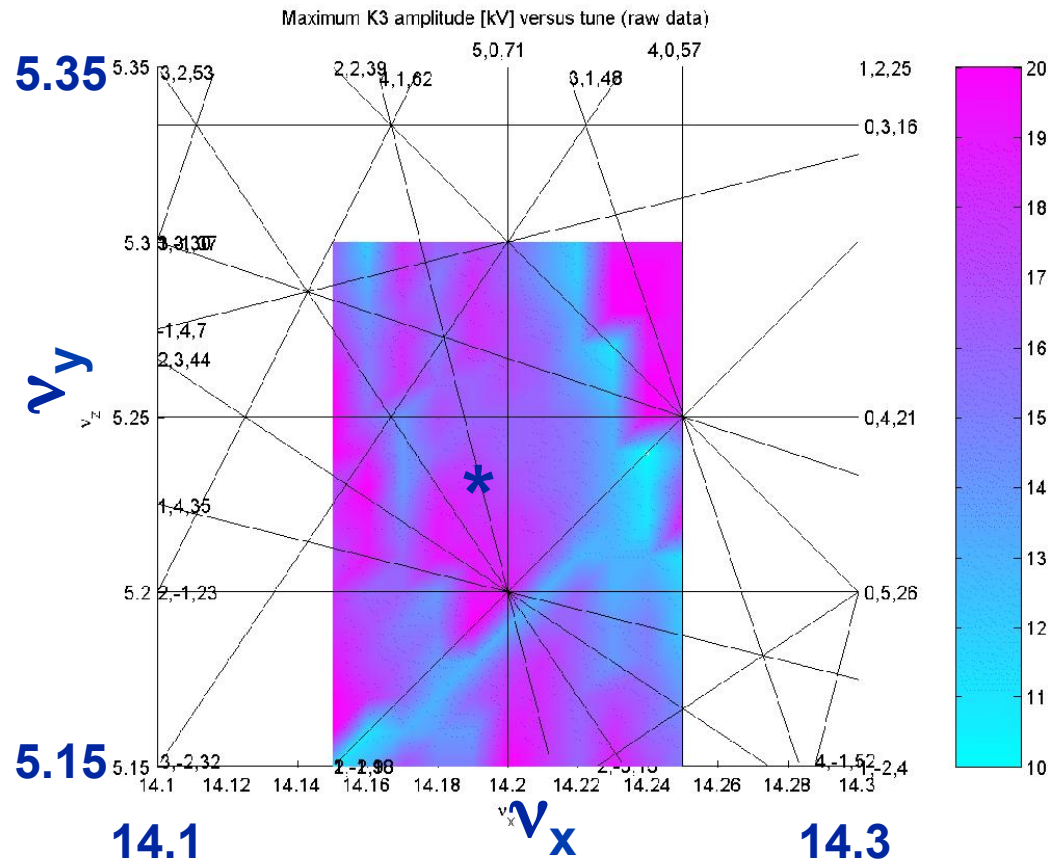
# More DCCT-based measurements

○ **Energy acceptance**

○ **Injection rate vs. tune scan**

○ **Injection rate vs. sextupole scan**

**Scrapers measure beam halo**

**W.J. Corbett**

**Peter Stefan et al., NIMA, 1998**

**halo, Coulomb scattering**

**core, $\sigma_y$=20$\mu$m**

**core, $\sigma_y$=7$\mu$m**
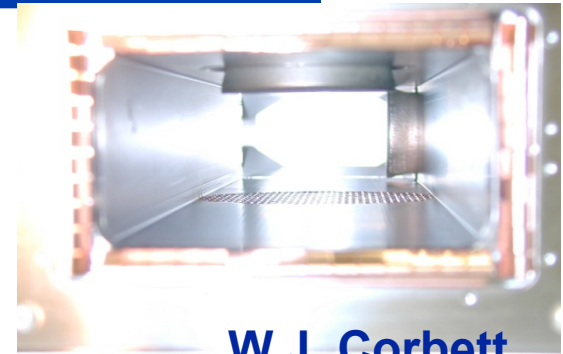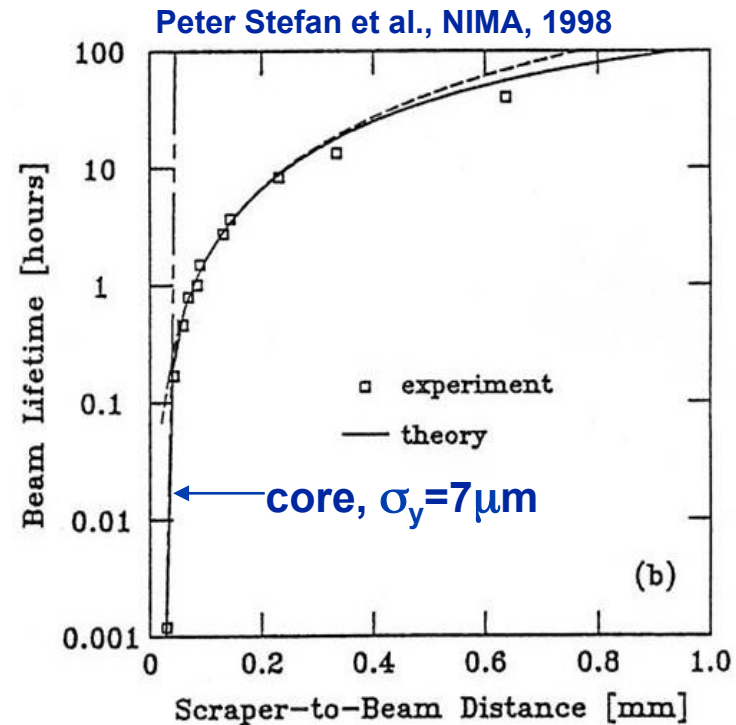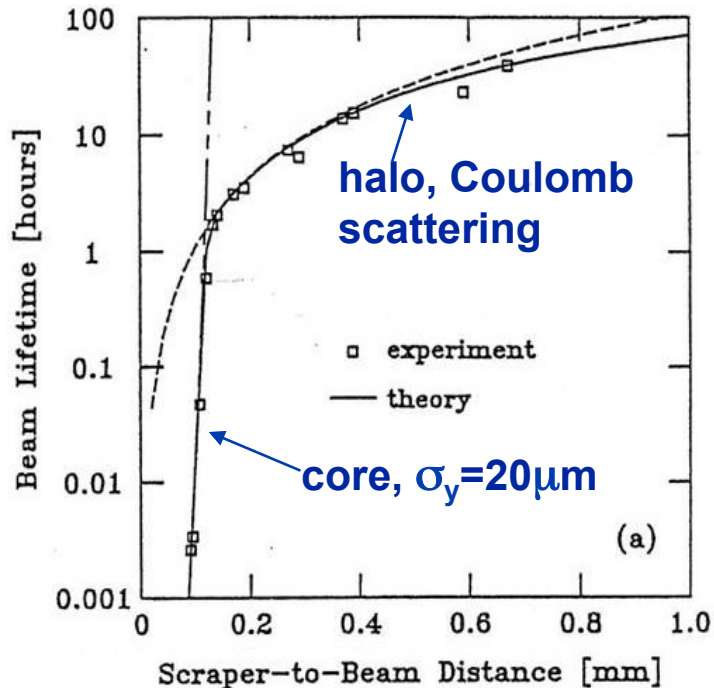
# SPEAR3 scraper measurements

**Three contributions to lifetime:**

• **Elastic gas scattering (Coulomb)**

• **Brehmsstrahlung**

• **Intrabeam scattering (Touschek)**

$$\frac{1}{\tau} = \frac{1}{\tau_C} + \frac{1}{\tau_B} + \frac{1}{\tau_T}$$

Five fit parameters:
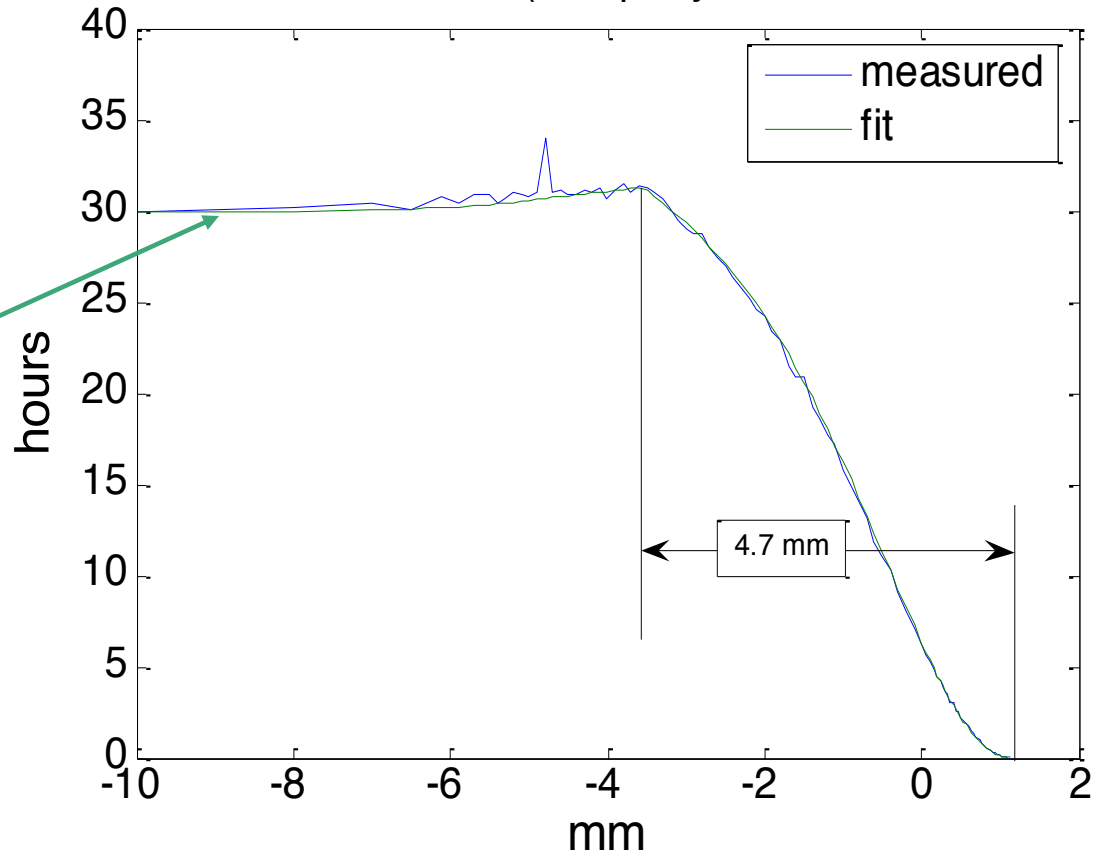
$$\tau_{C0}, \tau_{B0}, \tau_{T0},$$

$$y_{beam}, y_{ring}$$

$$\tau_C \propto \text{pressure} * y_{\text{aperture}}^2 \approx I_{tot} * y^2$$

$$\tau_B \propto \text{pressure} * f(E_{\text{aperture}}) \approx I_{tot}$$

$$\tau_T \propto \frac{I_{tot}}{N_{bunch}} * f(E_{\text{aperture}}) \approx I_b$$

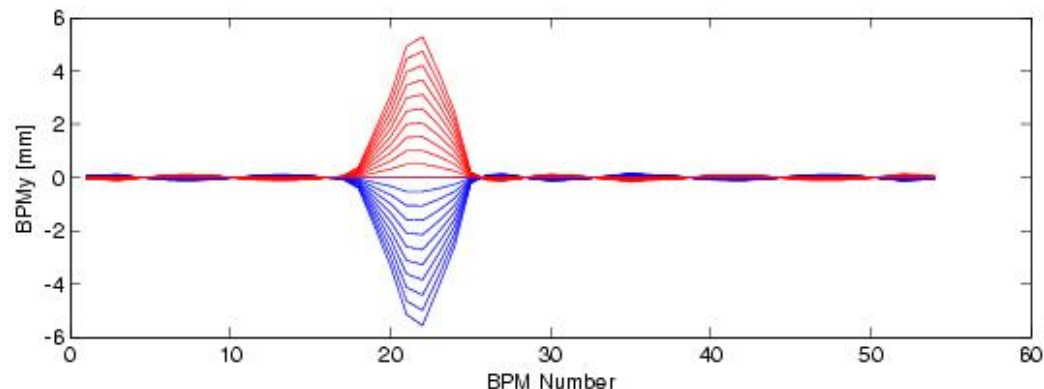~100 mA, 280 bunches (Scraper y 2005-02-02 00-43-19)

# Physical aperture probe
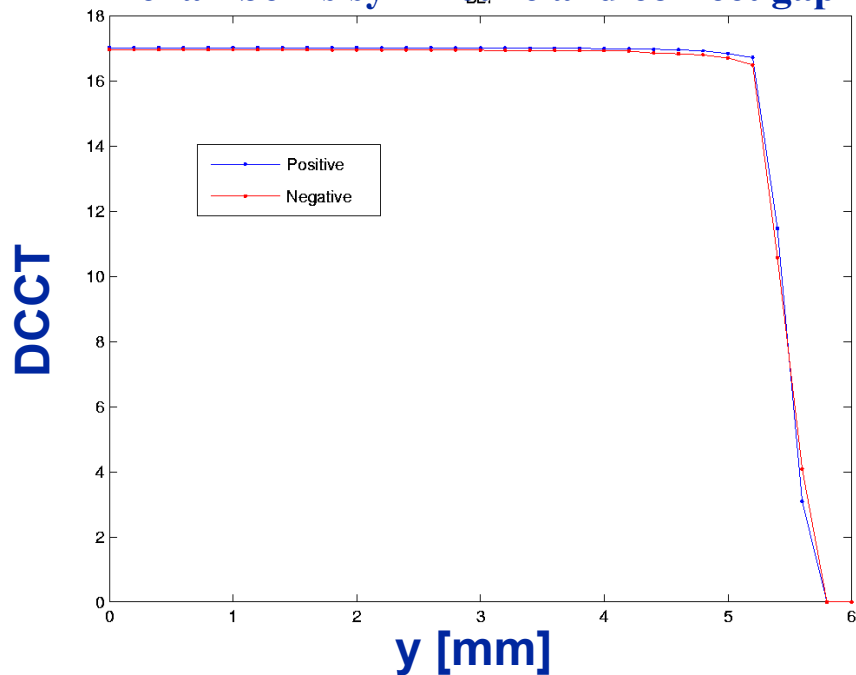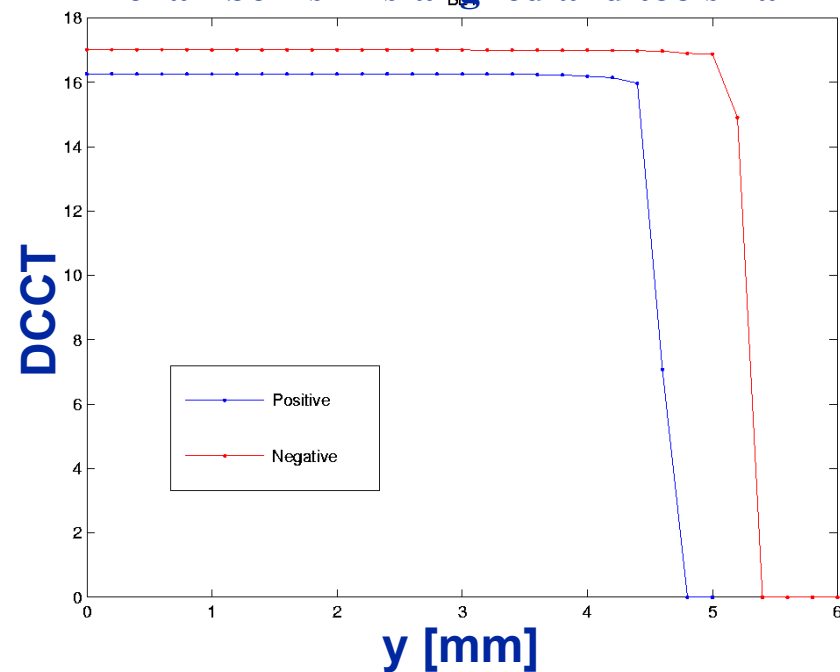
## Vertical beam bump in ID chamber

y-bump in ID chamber:

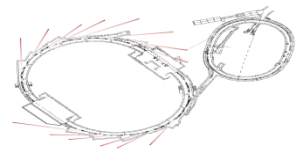- Bump beam up until lost

- Refill

- Bump beam down until lost



### ID7 chamber is symmetric and correct gap



### ID4 chamber is mis-aligned and too small

# Beam loss monitors

**Electrons hit vacuum chamber and generate e+/e- shower which can be detected with beam loss monitors.  Advantages over DCCT:**
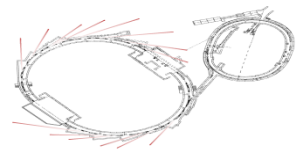
- **Large dynamic range – can measure small losses**

- **Can localize losses for injected and stored beam**

  - **Losses at small vertical gaps (insertion devices) from Coulomb scattering.**

  - **Losses at high dispersion locations (Touschek scattering).**

**Bergoz PIN diodes generate pulses when from ionizing particles.**
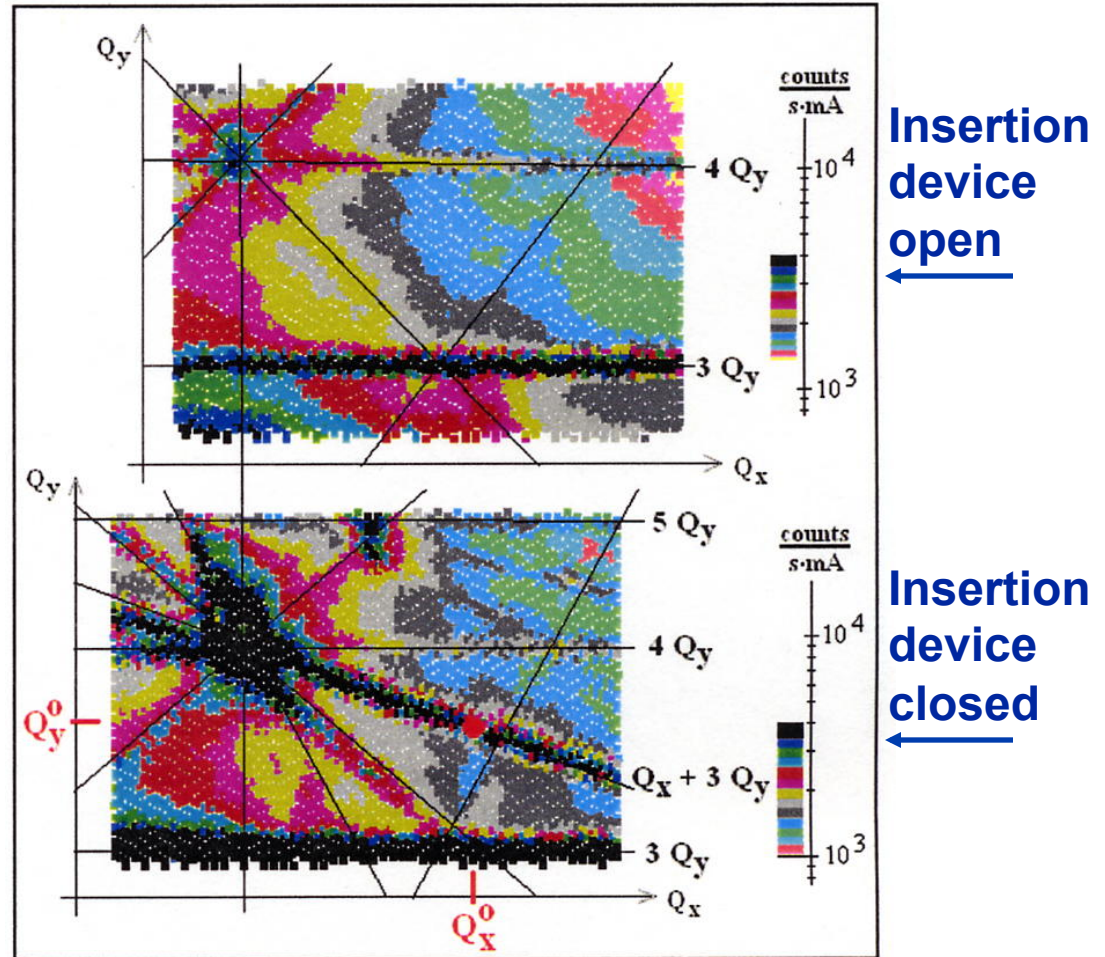


Operating principle
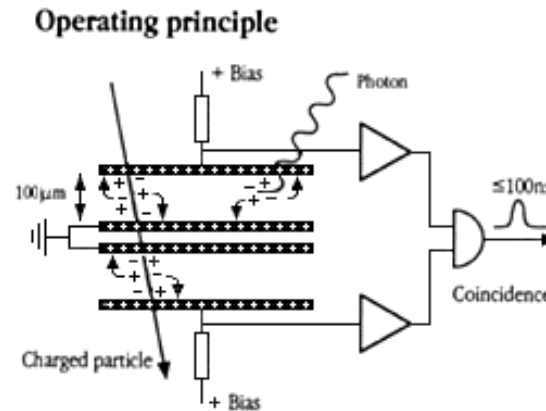
**A scintillator with a photomultiplier is another commonly used BLM.**
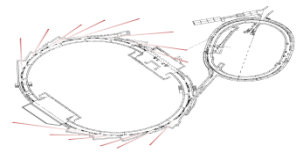
# Beam loss monitor measurement

At BESSY, the beam loss was measured as a function of tunes.  The additional losses associated with an insertion device showed a problem with nonlinear fields.  (More on Thursday).

**Insertion device open**

**Insertion device closed**

**Kuske et al., PAC01.**

# Beam Diagnostics: Position/Closed Orbit

○ **BPMs are very important, and very challenging (electronics).**

○ **There are many reasons why good orbit stability is necessary:**

○ **Particle Physics:**

 ↬ **Changes in orbit cause changes in gradient distribution (e.g. horizontal offset in sextupoles) or coupling (vertical offset in sextupoles)**

 ↬ **The dipole errors that cause the orbit changes directly create spurious dispersion (can lead to emittance increase, synchro-betatron coupling, deleterious effects from beam-beam interactions, …) or change the beam energy.**

 ↬ **Photon beams can be mis-steered, resulting in damage.**

 ↬ **Beam-beam overlap at interaction point.**

○ **Synchrotron Light Users:**

 ↬ **Stability of photon source point (flux through apertures, photon energy after monochromator, motion of beam spot on inhomogenous sample, …)**
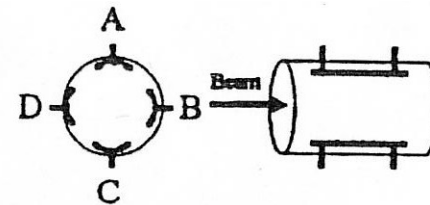
 ↬ **Stability of interaction point in colliders.**

# Beam position monitors

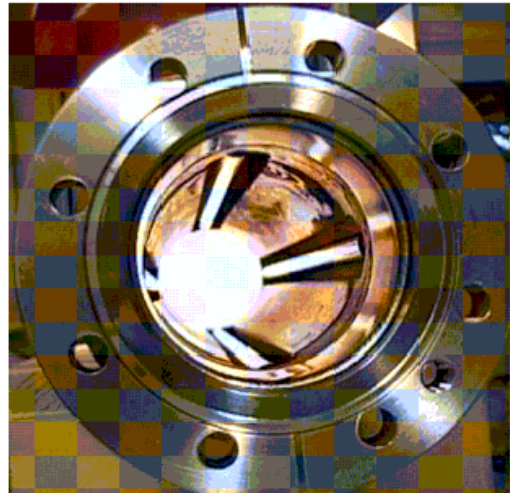$$x = \frac{r}{\sqrt{2}} \frac{(V_A + V_D - V_B - V_C)}{(V_A + V_B + V_C + V_D)}$$
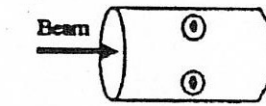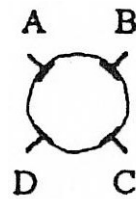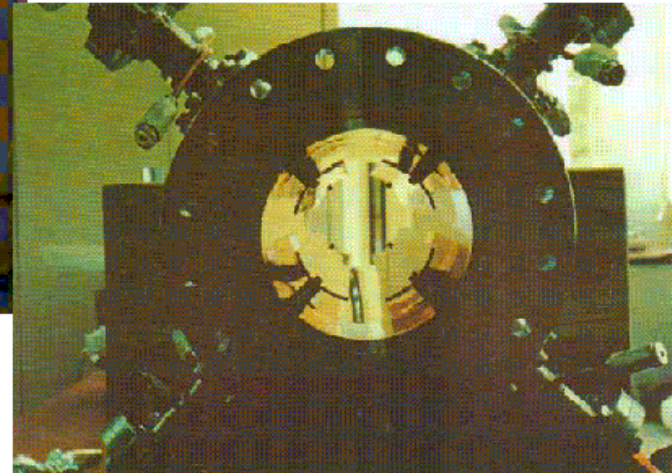


Buttons        Striplines

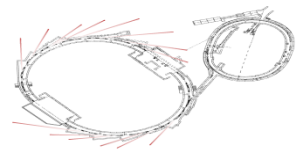**Electron** **BPM buttons sample electric fields; striplines couple to electric and magnetic fields.**

**Striplines**



M. Wendt, DESY

M. Tobiyama, KEK
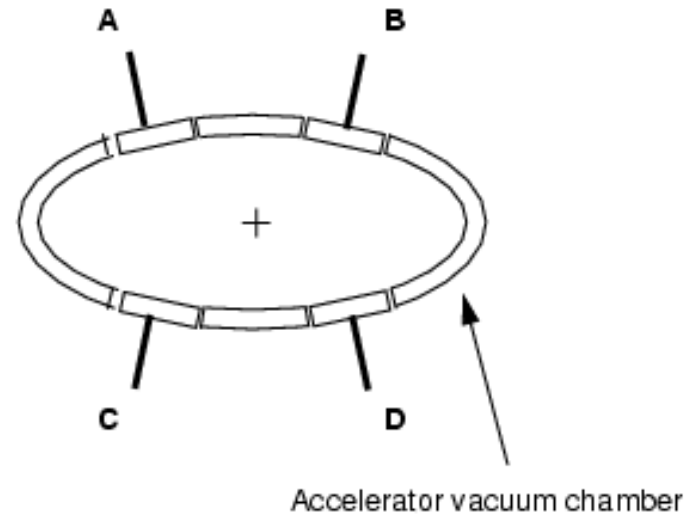
# Capacitive Pickups, Button BPMs

## Charged Particle Beam Pickup Electrodes

**Capacitive buttons**

- Broadband, up to > 10 GHz

- Most effective when button diameter is comparable
  to the bunch length

- Minimal wakefield interaction with beam

$$X = K_x \frac{A-B+C-D}{A+B+C+D}$$

$$Y = K_y \frac{A+B-C-D}{A+B+C+D}$$

A     B

+

C     D

Accelerator vacuum chamber

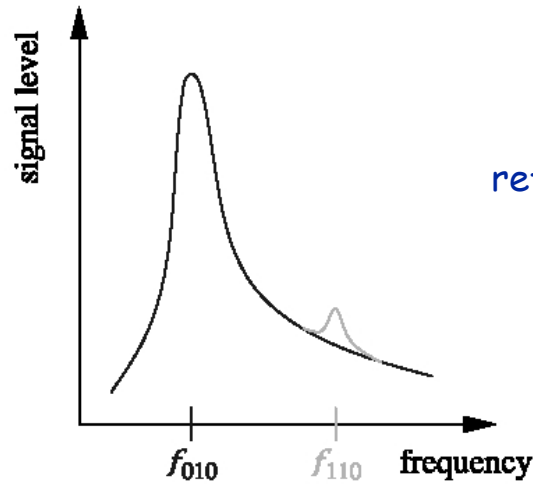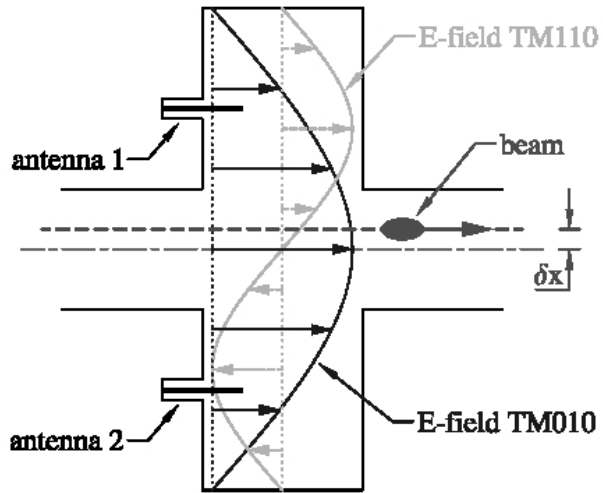e.g. for round buttons of radius a in round pipe of radius r

$$Z_t(\omega) = V_p / I_b = \frac{a^2 \omega}{2 r \beta c} \frac{R}{(1 + j\omega RC)}$$

where $\beta = v/c$,
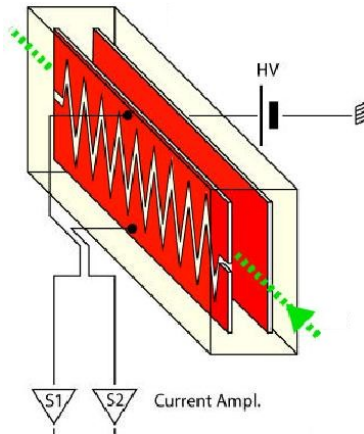R = Transmission line impedance,
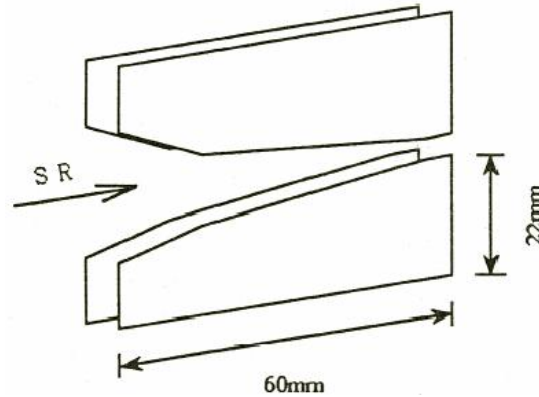C = Button capacitance

# CAVITY BPMs:

E-field TM110

antenna 1

beam

δx

antenna 2

E-field TM010

signal level

frequency

$f_{010}$   $f_{110}$

reference:
    "Cavity BPMs", R. Lorentz
    (BIW, Stanford, 1998)

# PHOTON BPMs:
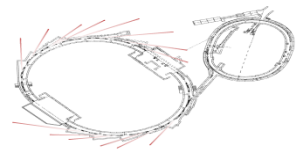
**Copper fluorescence bpm:**

**Split ion chamber:**

HV

S1   S2   Current Ampl.

**Tungsten blade monitor:**

S R

22mm

60mm

DETECTORS

SLITS

MASK
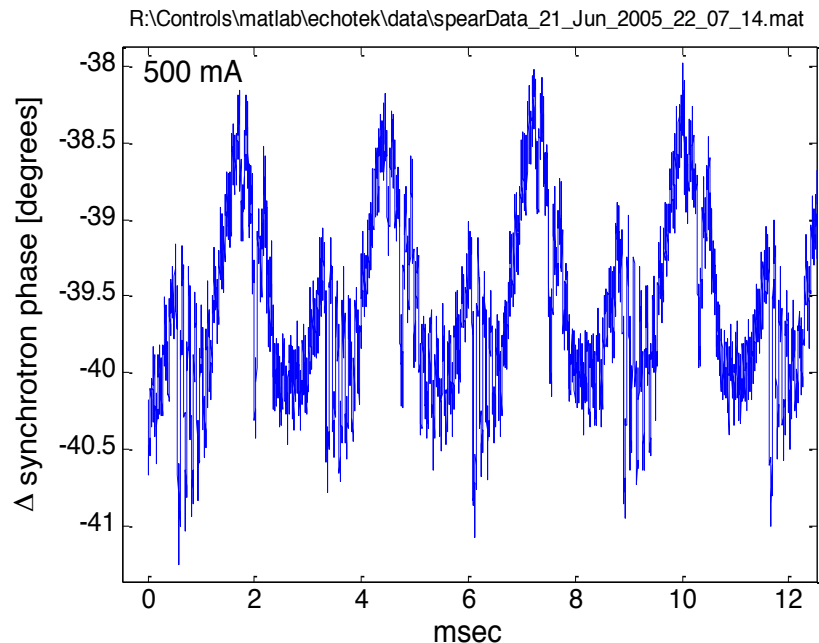
Be WINDOW

BEAM
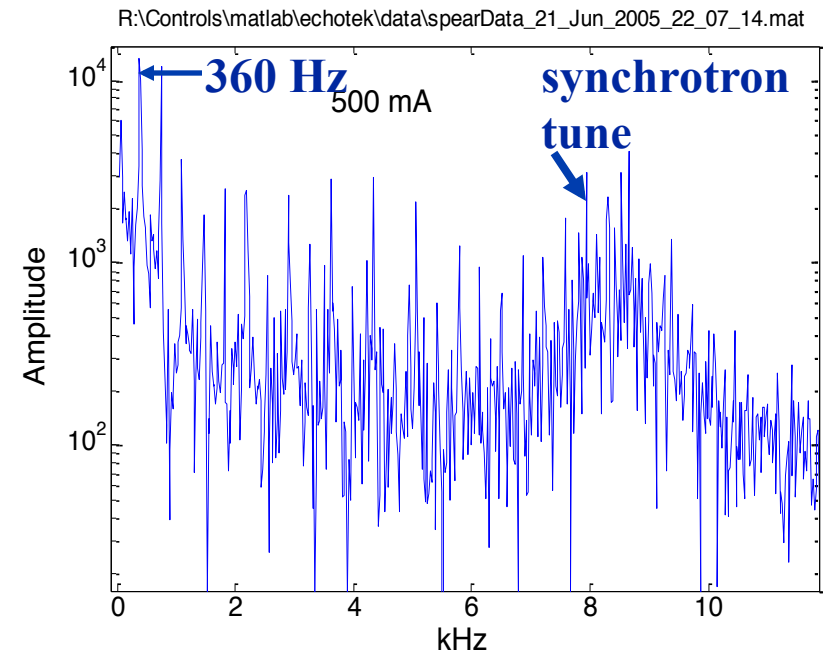
TARGET
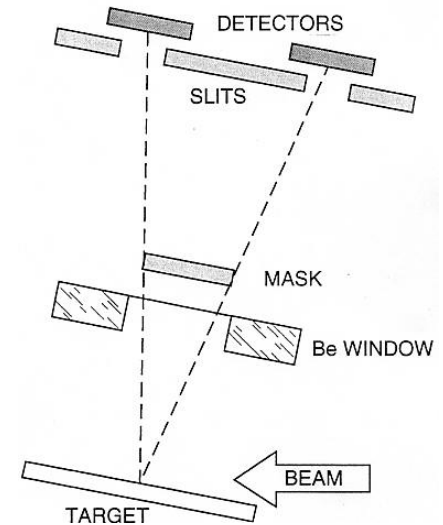
# Longitudinal oscillations, BPMs

**SPEAR3 digital receiver BPMs measure not only the amplitude from each button, but also the phase with respect to the RF, giving the variation in time of arrival of the bunches.**
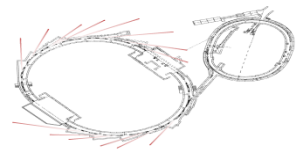
## Synchrotron phase vs. time

R:\Controls\matlab\echotek\data\spearData_21_Jun_2005_22_07_14.mat



## FFT of synchrotron motion

R:\Controls\matlab\echotek\data\spearData_21_Jun_2005_22_07_14.mat

# Beam frequencies

**Using a spectrum analyzer with a BPM can yield a wealth of information on beam optics and stability. A single bunch with charge q in a storage ring with a revolution time $T_{rev}$ gives the following signal on an oscilloscope**
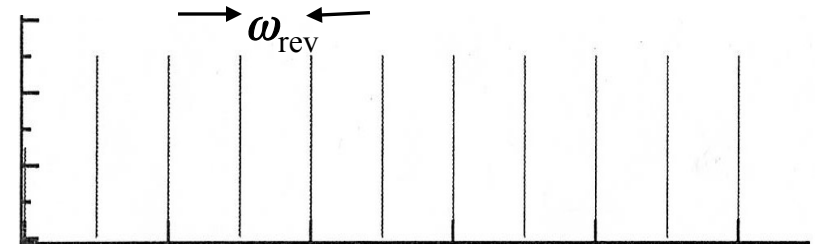
$$I(t) = \sum_{n=-\infty}^{\infty} q\delta(t - nT_{rev}),$$

**where I'm assuming a zero-length bunch. A spectrum analyzer would see the Fourier transform of this,**

$$I(\omega) = \sum_{n=-\infty}^{\infty} q\omega_{rev}\delta(\omega - n\omega_{rev})$$
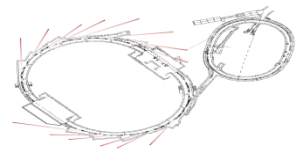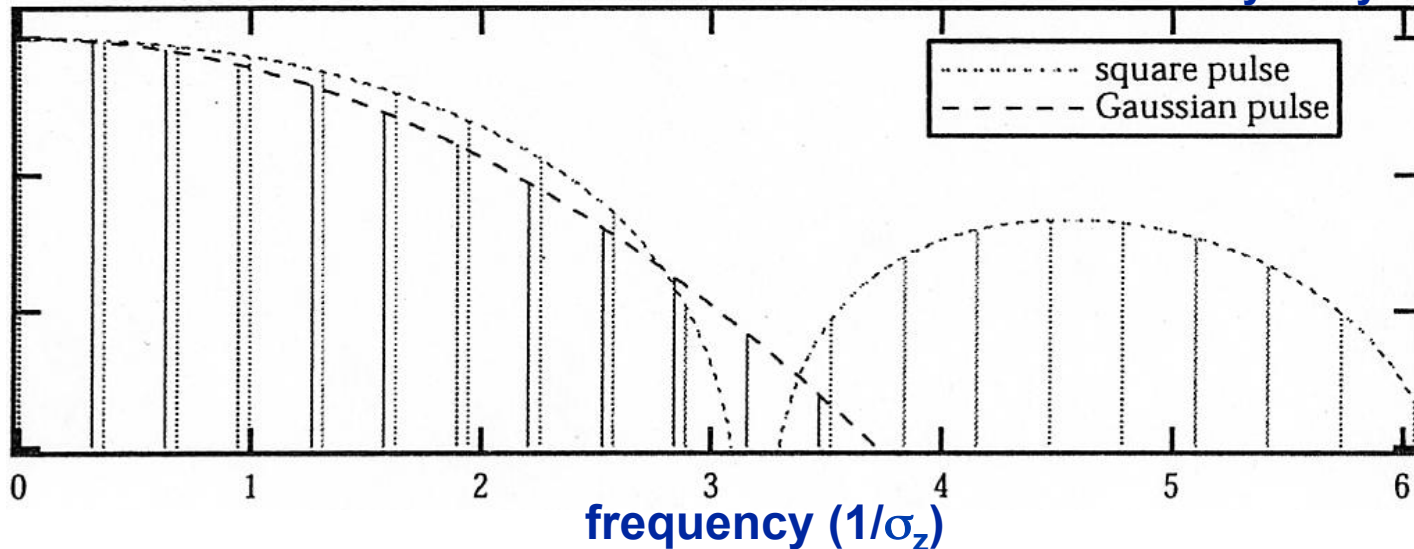
$T_{rev}$

$\omega_{rev}$
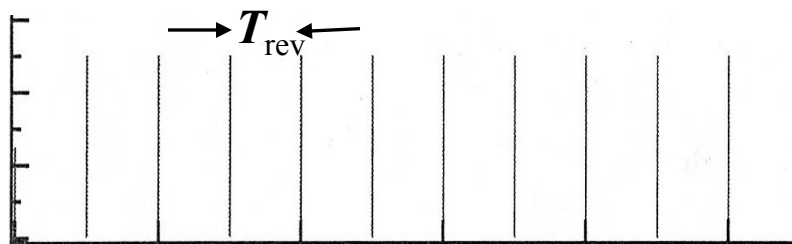
**Time**

**Frequency**

# Spectrum for finite bunch length

**For finite bunch length, the single bunch spectrum rolls off as the Fourier transform of the longitudinal bunch profile (Gaussian for e-rings).**

**Courtesy J. Byrd**



Legend:
·········· square pulse
– – – – – Gaussian pulse

x-axis: **frequency ($1/\sigma_z$)**

**For SPEAR3 $\sigma_z$ = 4.5 mm, so $c/\sigma_z$ = 67 GHz.**
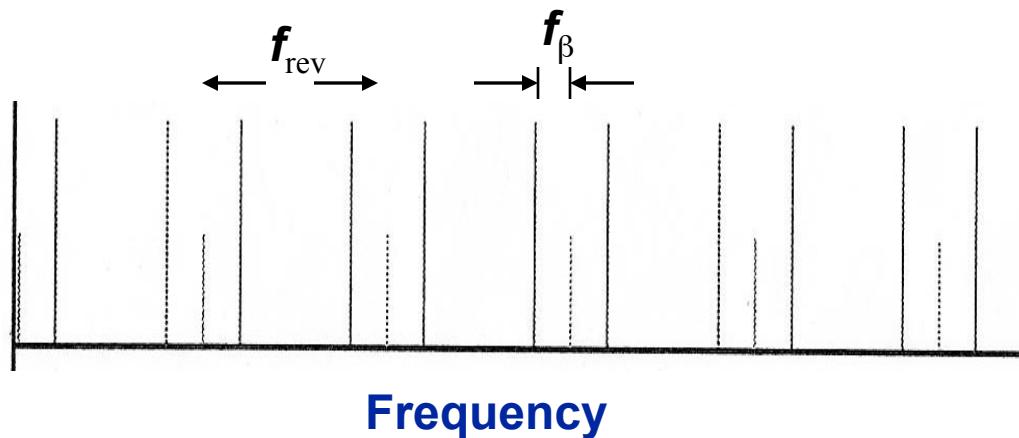
# Betatron tune

**Combining BPM signals, $V_A$-$V_B$-$V_C$+$V_D$, gives a dipole signal that scales as the product of beam current and position. For a closed orbit $x_{c.o.}$ and a betatron oscillation $x_\beta$, the signal is**

$$d(t) = (x_{c.o.} + x_\beta \cos(2\pi\nu t)) \sum_{n=-\infty}^{\infty} q\,\delta(t - nT_{\text{rev}})$$

**The Fourier transform is**

$$d(\omega) = q\omega_{\text{rev}}x_{c.o.} \sum_n \delta(\omega - n\omega_{\text{rev}}) + q\omega_{\text{rev}}x_\beta \sum_n \delta(\omega - (\omega_\beta + n\omega_{\text{rev}}))$$
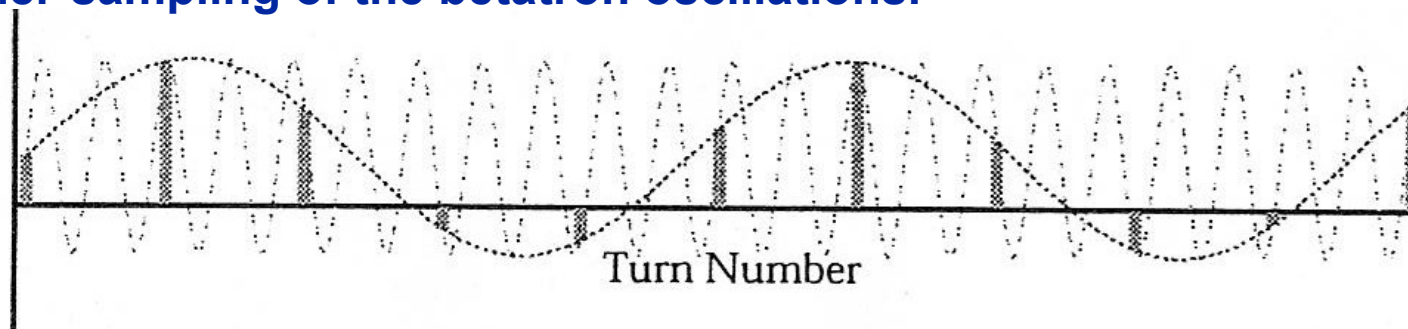


Frequency

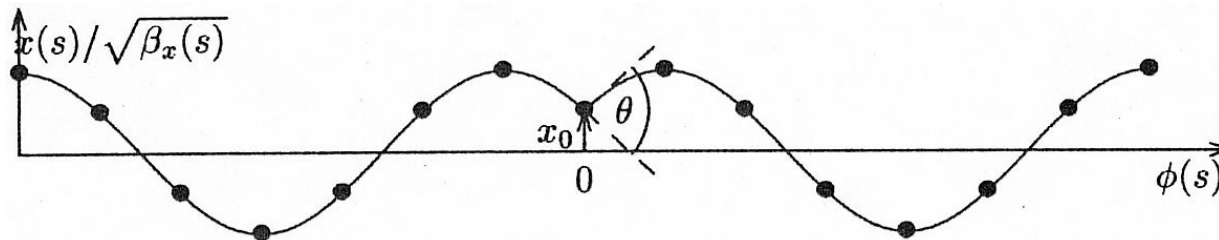**The tune is given by $\nu = f_\beta / f_{\text{rev}}$ (with integer/half-integer ambiguity).**

# Betatron tune, 2

**The integer/half-integer ambiguity in tune measurement arises from under-sampling of the betatron oscillations.**
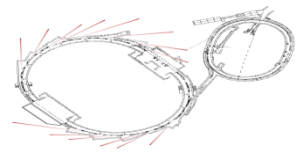


Turn Number

**It can be resolved by measuring the shift in closed orbit from a single steering magnet.**

$$\frac{\Delta x_i}{\Delta \theta_j} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin(\pi \nu)} \cos(|\phi_i - \phi_j| - \pi \nu)$$
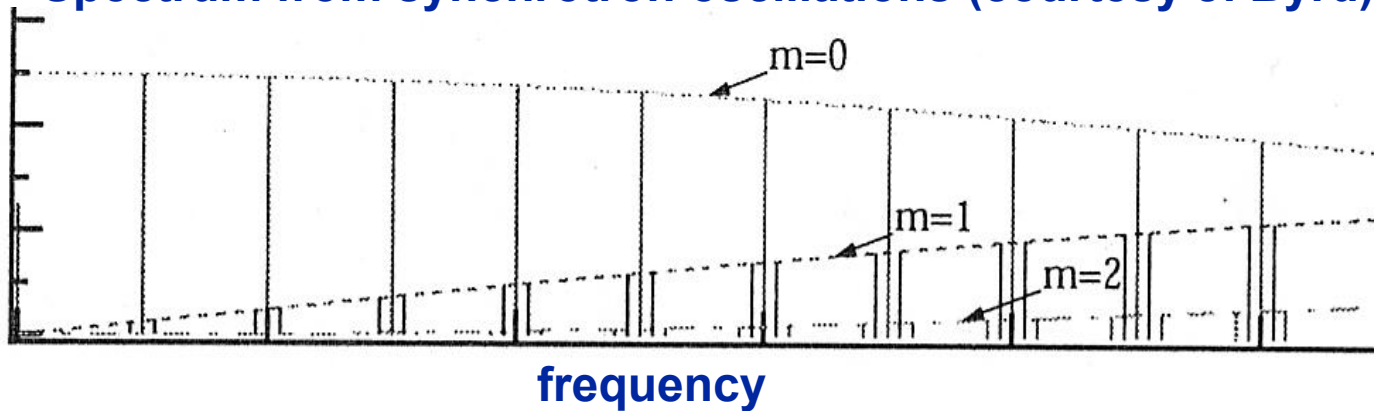
# Synchrotron tune

**Synchrotron oscillations cause modulation of the arrival time of the beam by the synchrotron tune.  This also shows up as sidebands around the revolution harmonics.**
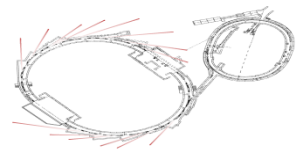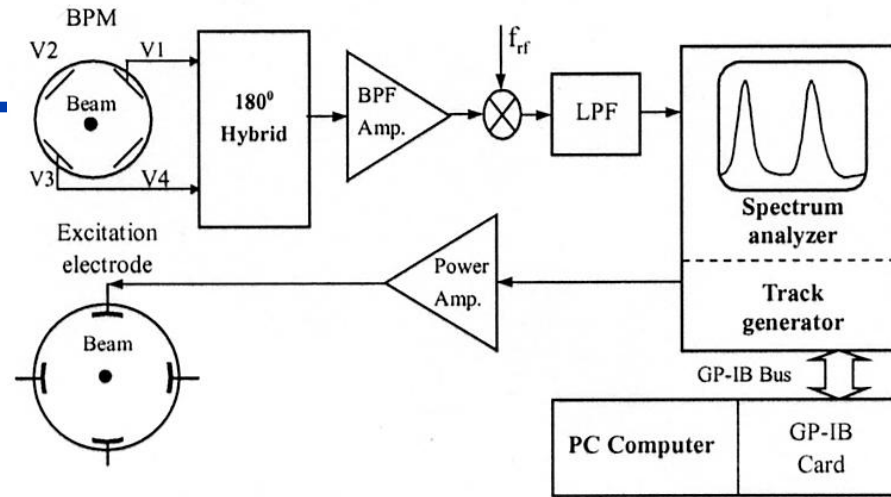
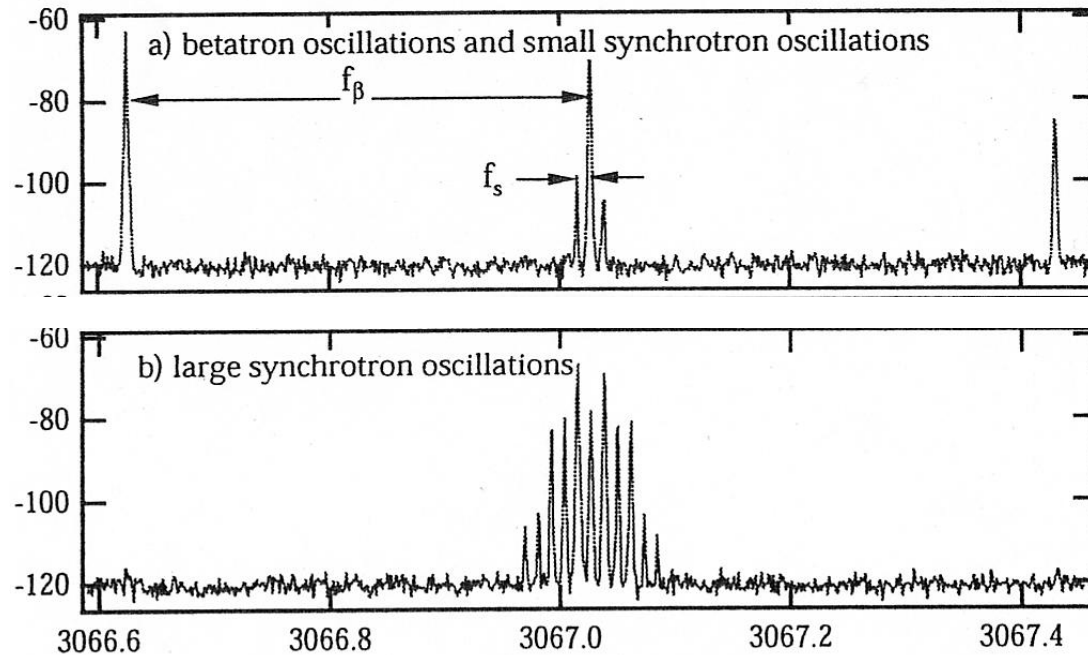**Spectrum from synchrotron oscillations (courtesy J. Byrd)**



frequency

# Measured spectra

**Typical tune measurement**

**Typical measured spectra**

**HLS tune meas., Sun et al. PAC01**



a) betatron oscillations and small synchrotron oscillations

$f_\beta$

$f_s$

b) large synchrotron oscillations
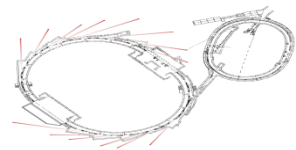
# More on spectrum

**Tune measurements play an important role in many storage ring measurements.**

• **Turn by turn measurements, FFT, NAFF**

• **Betatron phase measurement (Wednesday)**

• **Nonlinear dynamics (tune vs. amplitude; tune maps; tune vs. closed orbit; Friday)**

• **Impedance measurements**

• **Beta function measurements**

• **Chromaticity**

# Beta function measurement

**Beta functions can be measured by measuring the change in tune with quadrupole strength:**
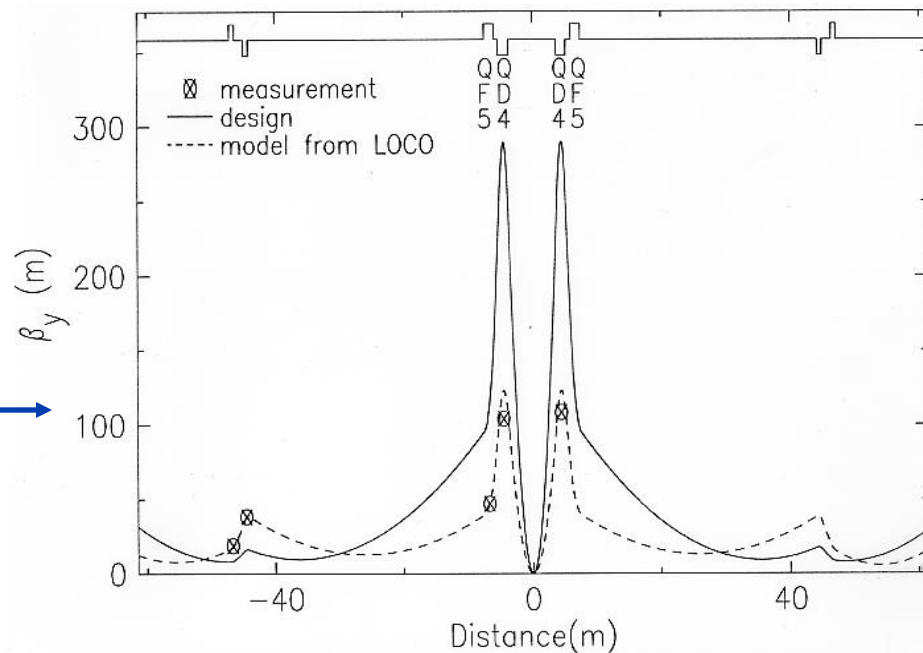
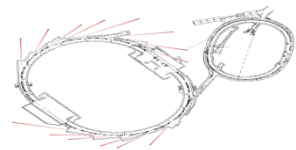$$\Delta\nu = \beta\,\frac{\Delta(KL)}{4\pi}$$

**Measurement issues**
- **Keep orbit constant**
- **Hysteresis**
- **Saturation**
- **Sometimes cannot vary individual quadrupoles**

**β measurement in PEPII HER IR indicates optics problem.**

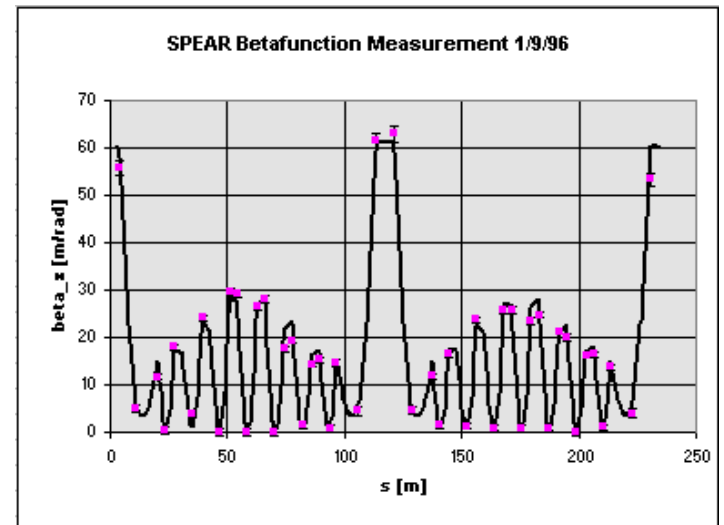**(Methods to be described Tuesday were used to find source of problem and correct it.)**
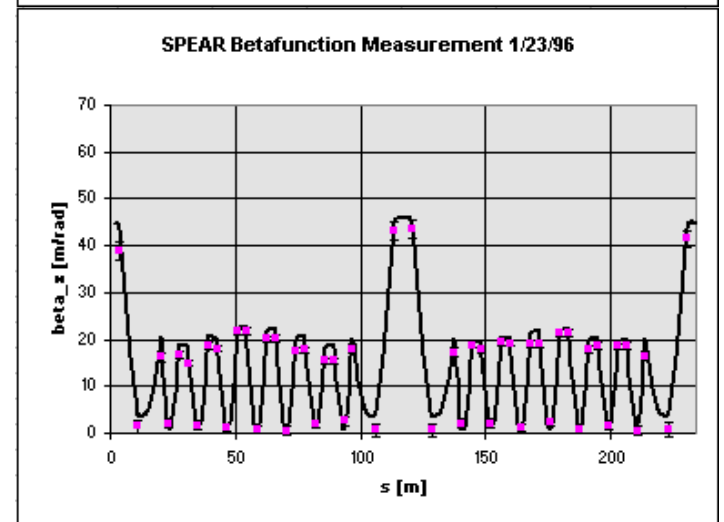
# SPEAR β-function correction

1. β functions measured at quads.

2. MAD model fit to measurements.

3. MAD quadrupoles adjusted to fix β's.

4. Quadrupole changes applied to ring.

5. β functions re-measured at quads.

6. Iterate.



**Courtesy Heinz-Dieter Nuhn**

# Other β measurements

1. **Fit β and φ to measured orbit response matrix (Y. Chung et al., PAC'93)**

$$M_{ij} = \frac{\Delta x_i}{\Delta \theta_j} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin(\pi \nu)} \cos(|\phi_i - \phi_j| - \pi \nu)$$
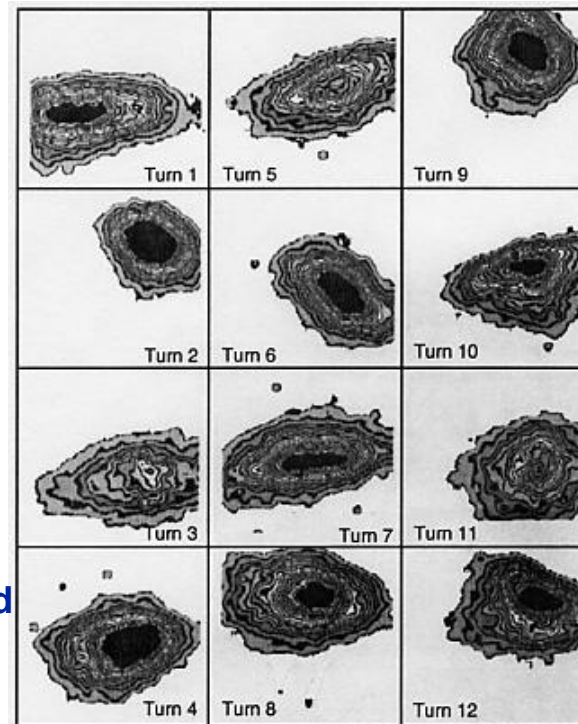
$N_{BPM}*N_{steerer}$ **data**

$2*N_{BPM}+2*N_{steerer}+1$ **unknowns**

2. **Fit quadrupole gradients, K, to measured orbit response matrix. From K get β (Tuesday lecture).**

3. **Derive from betatron phase measurements (Wednesday lecture).**
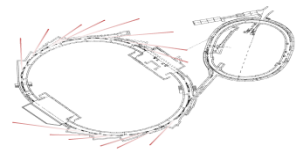
4. **Beam size measurement**

$$\sigma = \sqrt{\varepsilon \beta}$$

**Measuring β mismatch; injected beam; SLC damping rings.**



**Minty and Spence, PAC'95**

# Dispersion

**Dispersion is the change in closed orbit with a change in electron energy.**

$$\eta \equiv \Delta x \bigg/ \frac{\Delta p}{p}$$

**The energy can be changed by shifting the rf frequency.**

$$\alpha \equiv \frac{\Delta L}{L} \bigg/ \frac{\Delta p}{p} \qquad \Rightarrow \qquad \frac{\Delta p}{p} = -\frac{1}{\alpha} \frac{\Delta f_{rf}}{f_{rf}} \qquad (\alpha = \text{momentum compaction})$$

**So the dispersion can be measured by measuring the change in closed orbit with rf frequency.**

$$\eta = -\alpha f_{rf} \frac{\Delta x}{\Delta f_{rf}}$$
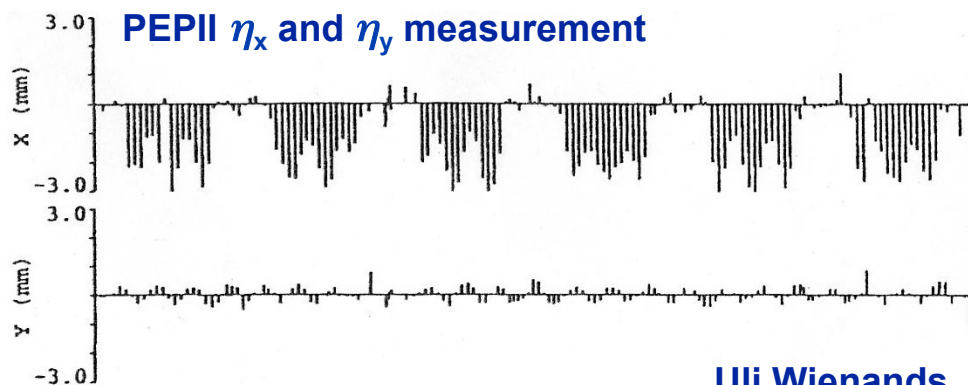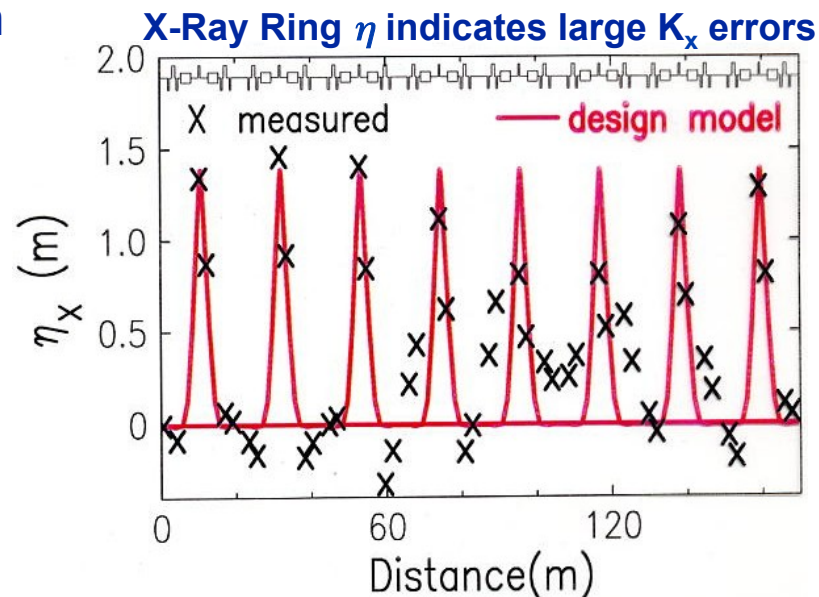
# Dispersion measurement

**Dispersion distortion can come from quadrupole or dipole errors.**

$$\eta_x'' + K_x \eta_x = \frac{1}{\rho_x}$$

**Vertical dispersion gives a measure of vertical bending errors or skew gradient errors in a storage ring.**

**X-Ray Ring $\eta$ indicates large $K_x$ errors**



$$\eta_y'' + K_y \eta_y = \frac{1}{\rho_y} + K^{\text{skew}} \eta_x$$

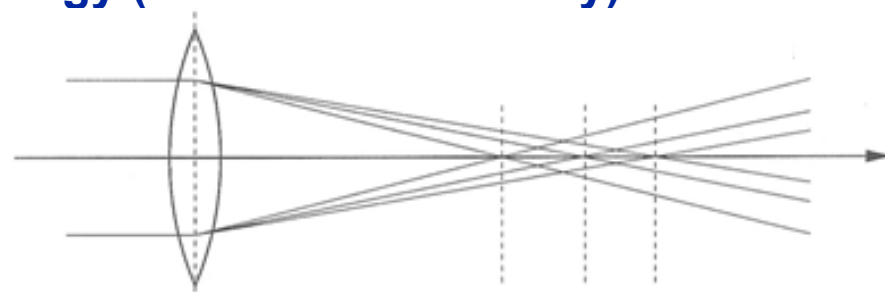**PEPII $\eta_x$ and $\eta_y$ measurement**
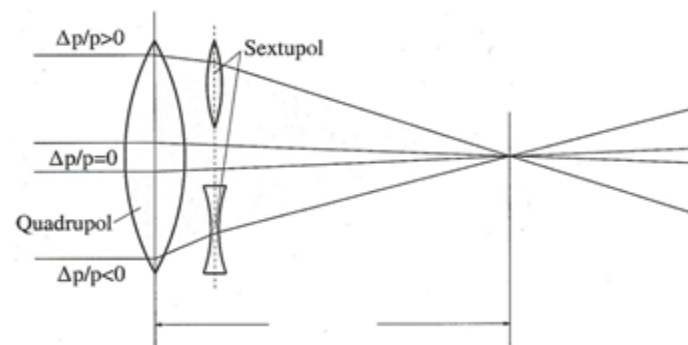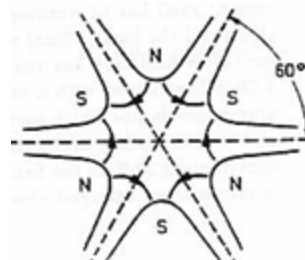


**Uli Wienands**

# Chromaticity

**Quadrupoles focus high energy particles less than low energy particles. This leads to a decrease in tune with energy (natural chromaticity):**

$$\xi_N = \Delta \nu \left/ \frac{\Delta p}{p} \right.$$

**Decrease in tune with energy is corrected with sextupoles (position dependent focusing),**

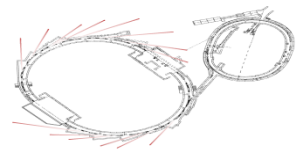$$K = mx = m\eta \, \Delta p / p$$

$K$ **is the gradient,** $m$ **is the sextupole strength.**

**The chromaticity with sextupoles is called the corrected chromaticity,**

$$\xi$$

# Chromaticity measurement

**To measure the chromaticity, the beam energy can be changed in one of two ways:**

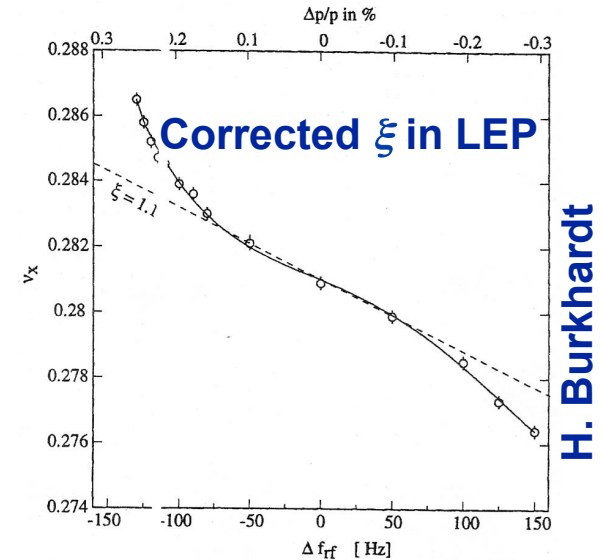1. **Change the rf frequency. This shifts the orbit in sextupoles, giving the corrected chromaticity.**

$$\xi = -\alpha f_{rf} \frac{\Delta \nu}{\Delta f_{rf}}$$

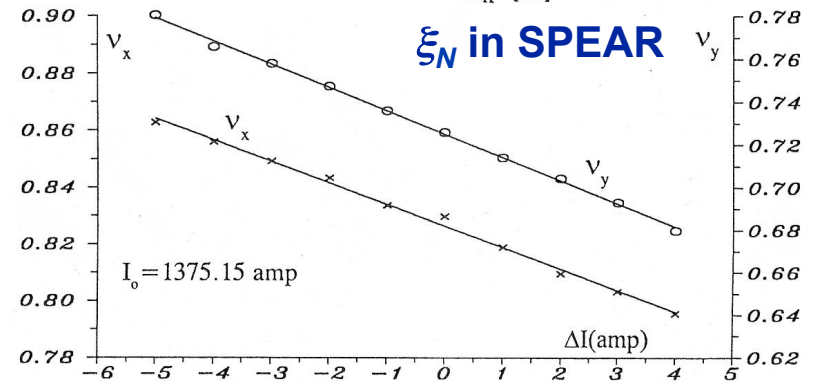**Used to diagnose sextupole mis-wiring in PEPII-HER.**

2. **Change the dipole field. This keeps orbit constant, measuring the natural chromaticity.**
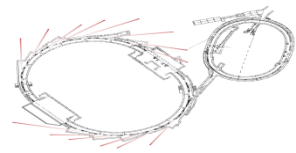
$$\xi_N = \frac{\Delta \nu}{\Delta B / B}$$

**Corrected $\xi$ in LEP**

**H. Burkhardt**

**$\xi_N$ in SPEAR**

$I_o = 1375.15$ amp

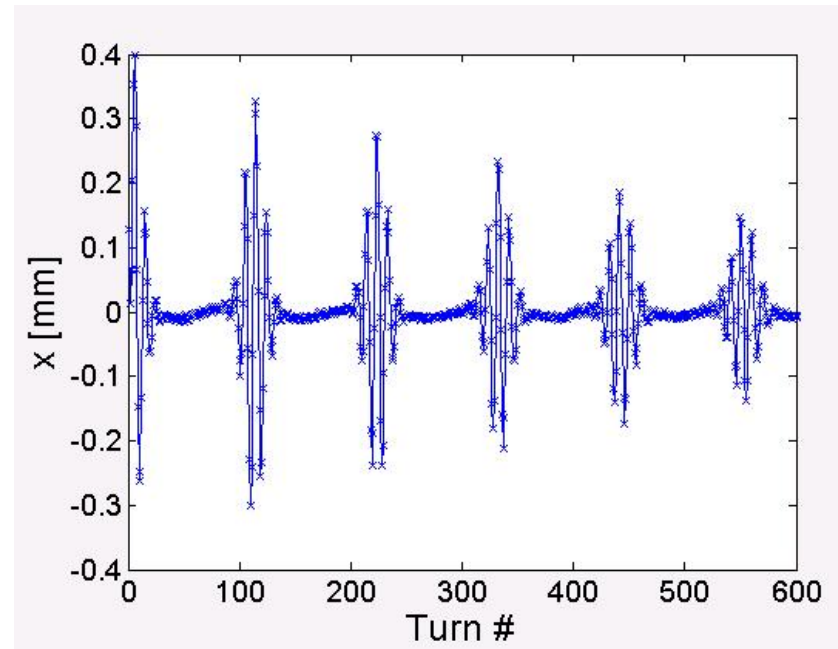**$\xi_N$ can also be measured from n vs. frf with sextupoles turned off.**

# Natural chromaticity measurement

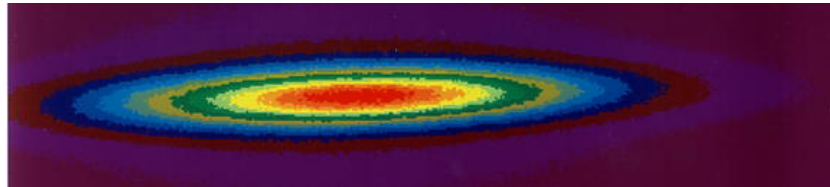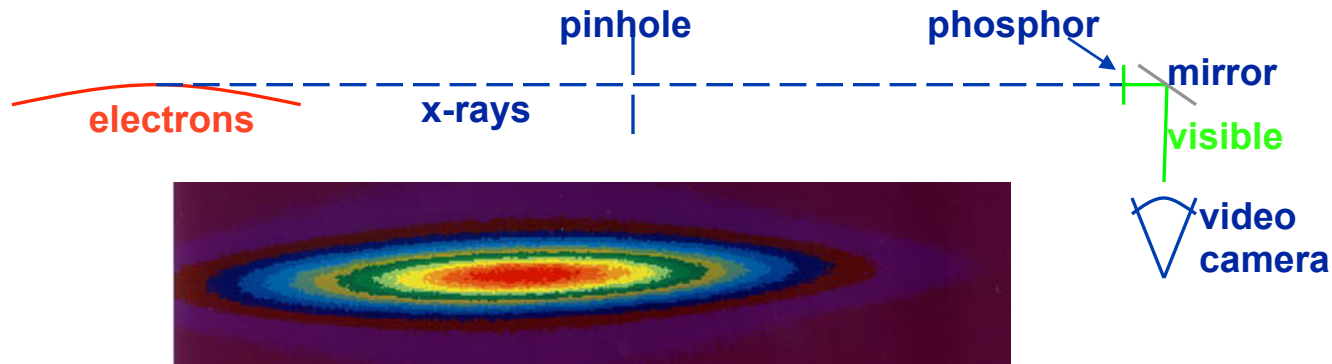○ **Turn-by-turn BPM readings during natural chromaticity measurement (sextupoles off)**

○ **Beam was kicked with injection kicker to measure $\nu_x$**

○ **Why do oscillations disappear and reappear?**

# Beam size measurements

## X-Ray pinhole camera

pinhole        phosphor

mirror

electrons      x-rays

visible

video camera

## Pinhole camera array
### (Kuske et al., Bessy)

Phosphor screen

Al filter

Pinhole array

$\phi d$

Source

$\Delta$

Intensity

$R_2$        $R_1$

400

300

Pixel number

200

100

0

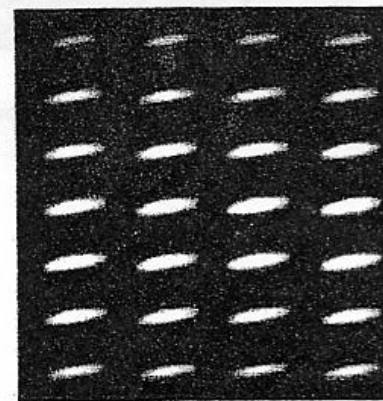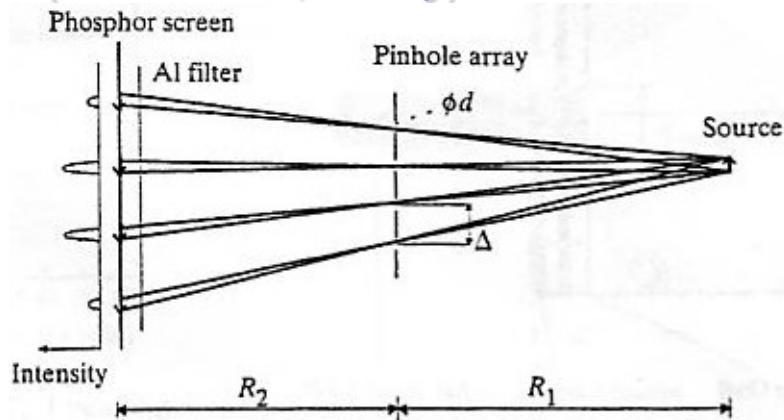0 10 20 30 40 50 60 70 80
Intensity (grey levels)
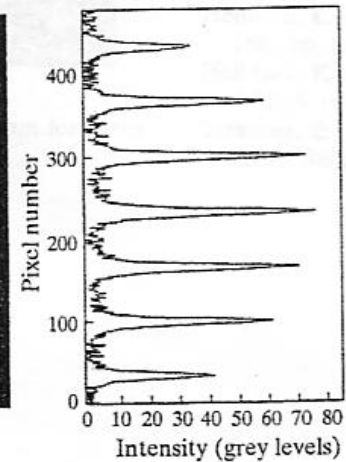
Figure 2
Left: image of a portion of the phosphor observed on a BESSY I bending magnet. Right: integrated intensities of one column of images on the phosphor.

**See beam size lecture for more details**
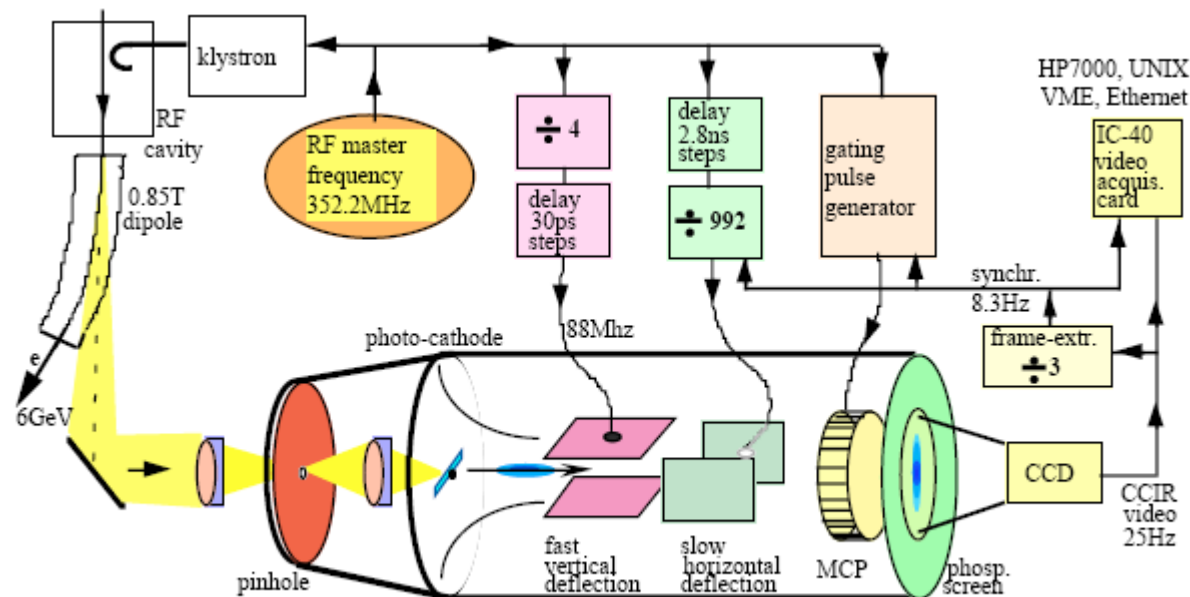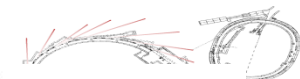
# Principle of streak camera



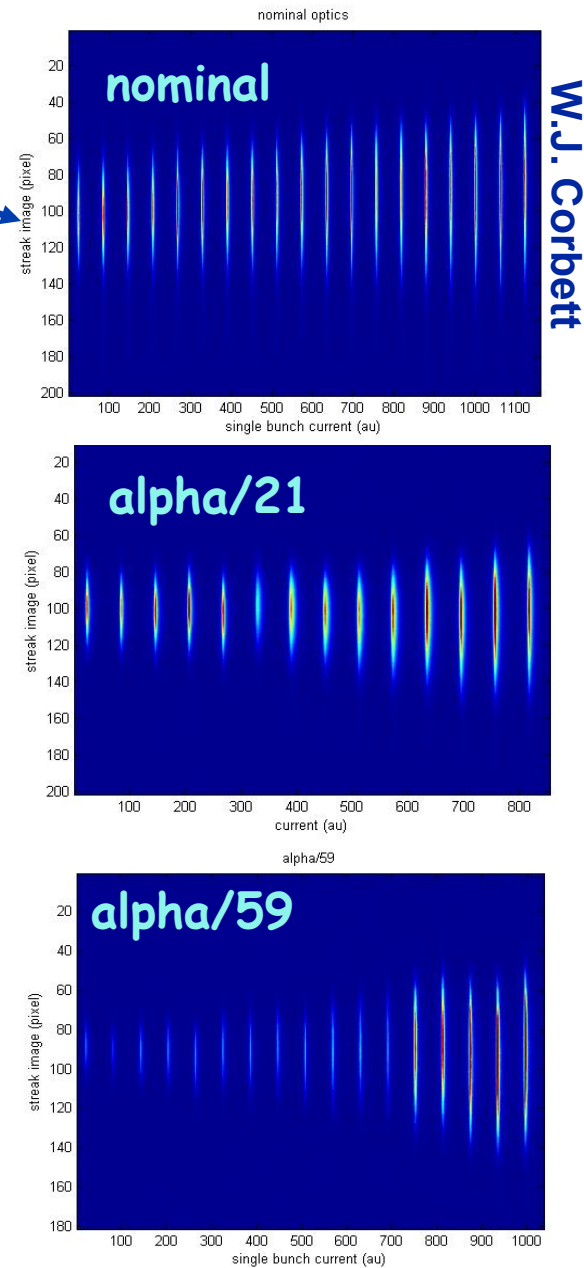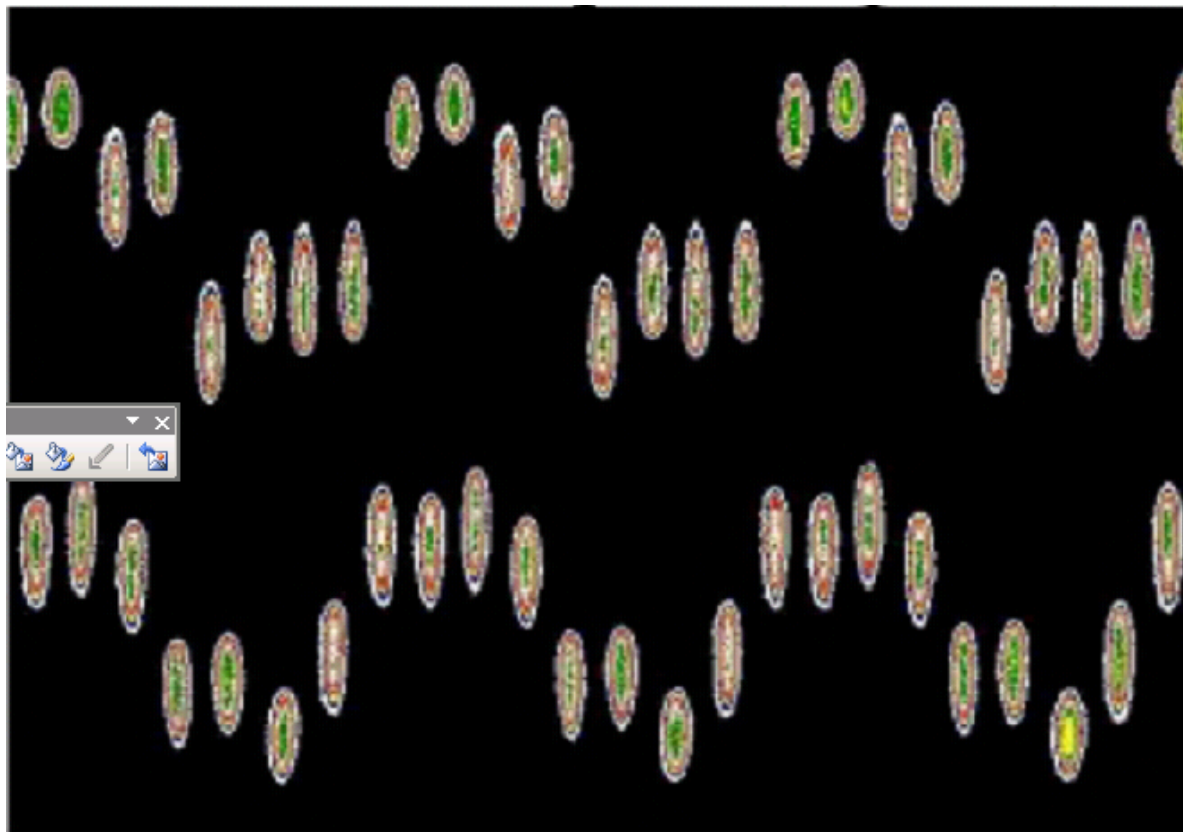Figure: 1 Synchronisation of the Streak Camera system

- Convert light signal into electron beam (photo cathode)
- Accelerate electrons
- Use fast deflection to translate time delay into position difference
- In many ways similar to CRT …
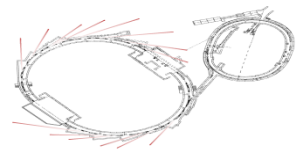
# Streak camera measurements

**Low alpha measurements at SPEAR**
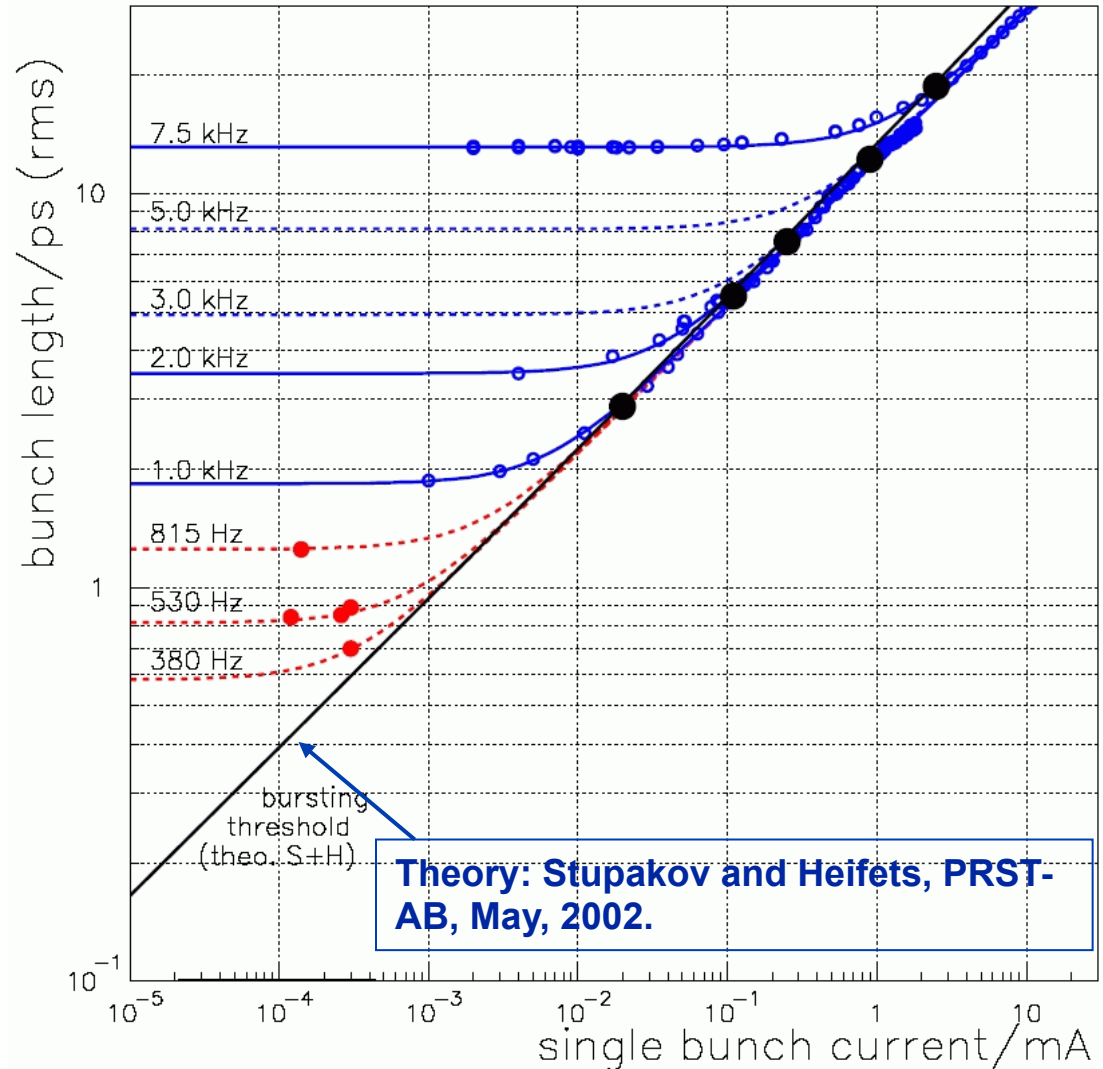
**Longitudinal instabilities at ESRF**



W.J. Corbett

# Streak camera measurements at BESSY

Feikes et al., EPAC2004

- ○ **Streak camera data in blue**

- ○ **Bolometer data in red**



Theory: Stupakov and Heifets, PRST-AB, May, 2002.

# Momentum compaction

**Using the model value of $\alpha$ for $\xi$ and $\eta$ measurements can lead to errors. $\alpha$ itself can be measured in various ways.**

**Indirect measurement from bunch length**

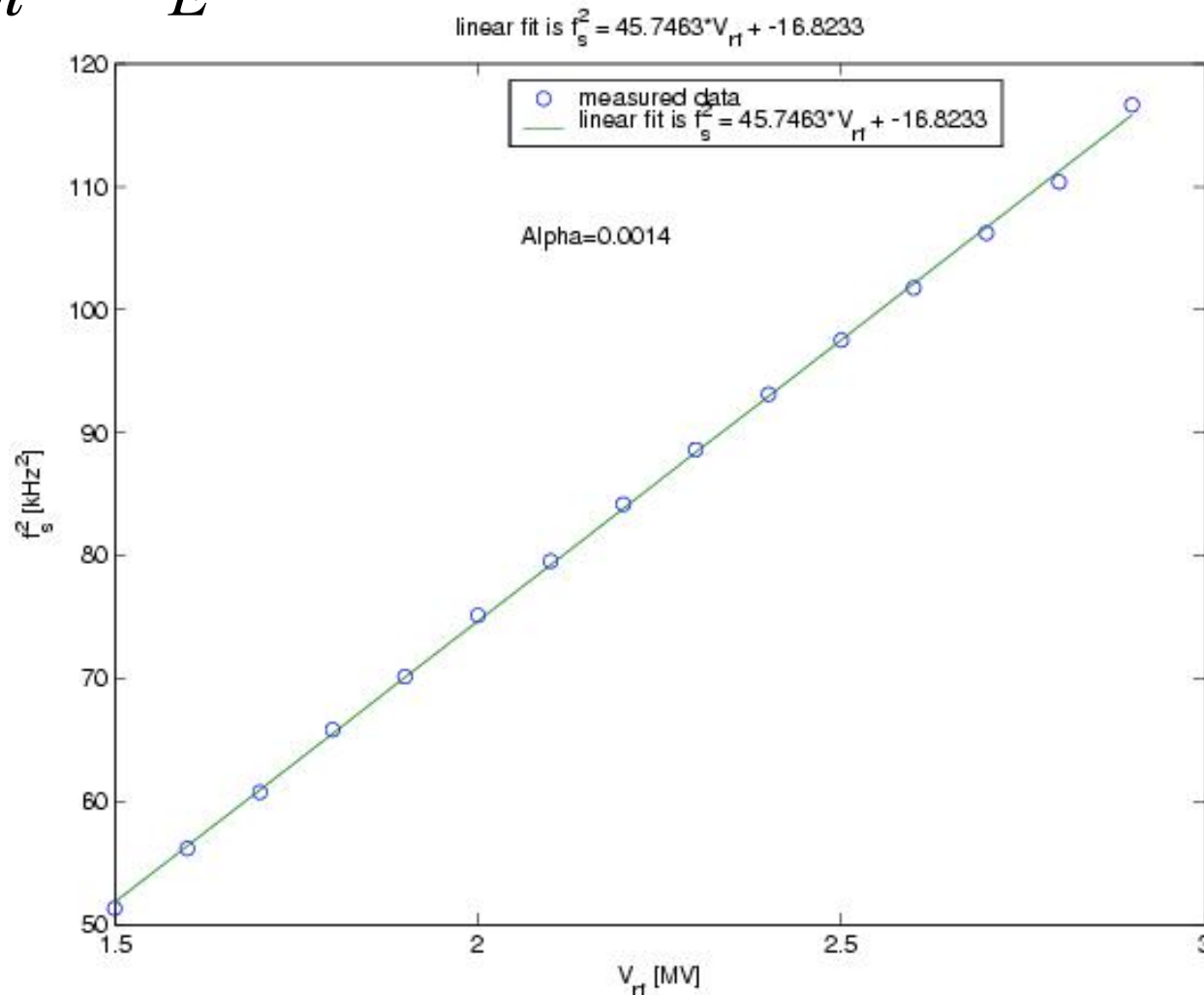$$\sigma_z = \frac{c\sigma_\delta}{2\pi f_{\mathrm{rev}}} \frac{\alpha}{\nu_s}$$



**PEPII-HER a measurement, Wienands et al.**
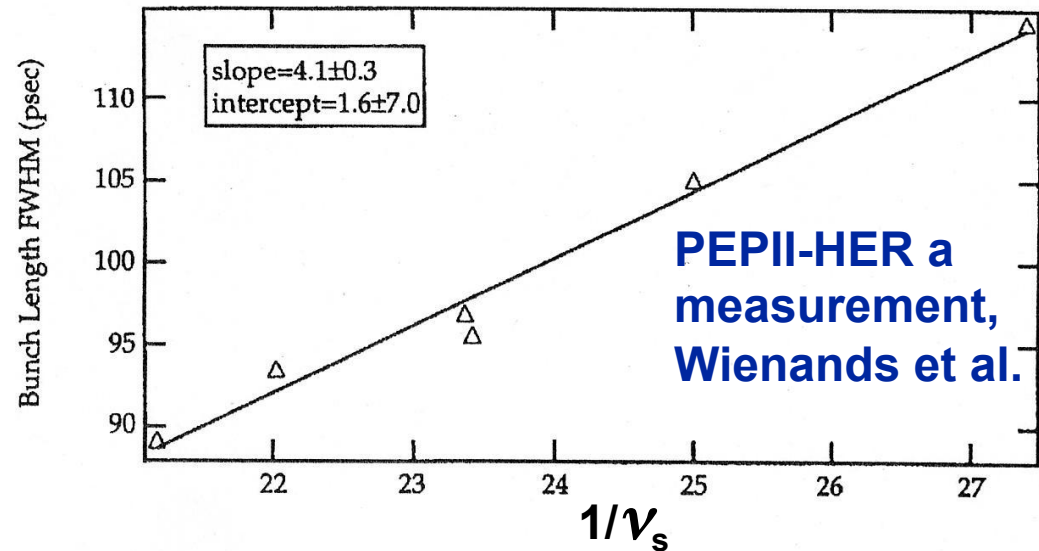
**Direct measurement: measure change in energy with rf frequency.**
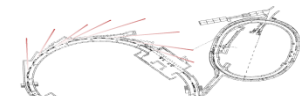
$$\alpha = -\frac{\Delta f_{rf} / f_{rf}}{\Delta p / p}$$

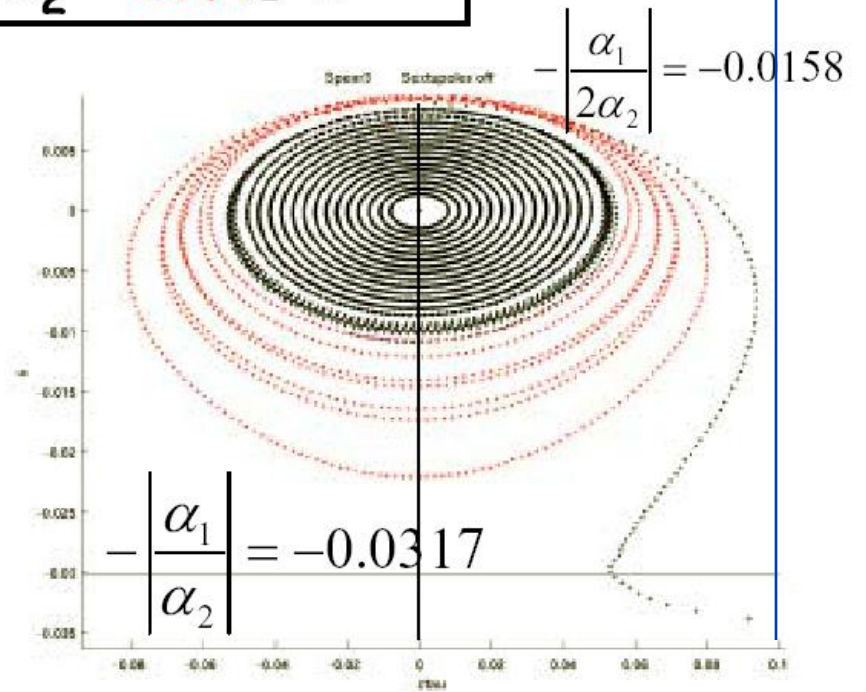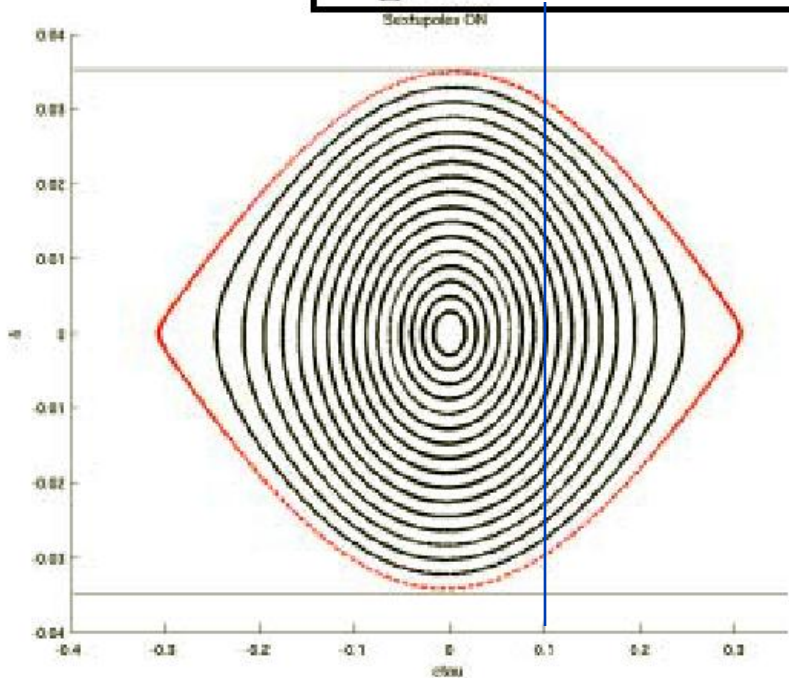$$\nu_s^2 = \frac{\alpha h \cos \phi_s}{2\pi} \frac{eV_{RF}}{E}$$

linear fit is $f_s^2 = 45.7463 * V_{rf} + -16.8233$



Alpha=0.0014

Legend:
- ○ measured data
- —— linear fit is $f_s^2 = 45.7463 * V_{rf} + -16.8233$

Axes: $f_s^2$ [kHz$^2$] vs $V_{rf}$ [MV]

# SPEAR3: Longitudinal Dynamics

| Sextupoles on | Sextupoles off |
|---|---|
| $\alpha_1$ =1.19 E-3 | |
| $\alpha_2$ = −2.1E-3 | $\alpha_2$ =37.4E-3 |

$$-\left|\frac{\alpha_1}{2\alpha_2}\right| = -0.0158$$

$$-\left|\frac{\alpha_1}{\alpha_2}\right| = -0.0317$$

4D tracking using AT
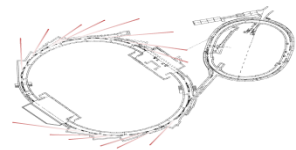
# α₂ measurement

$$\nu_s^2 = \frac{\alpha h \cos\phi_s}{2\pi} \frac{eV_{RF}}{E}$$

○ **|α₂|, sextupoles off >> |α₂|, sextupoles on**

○ **Energy aperture much reduced with sexupoles off**
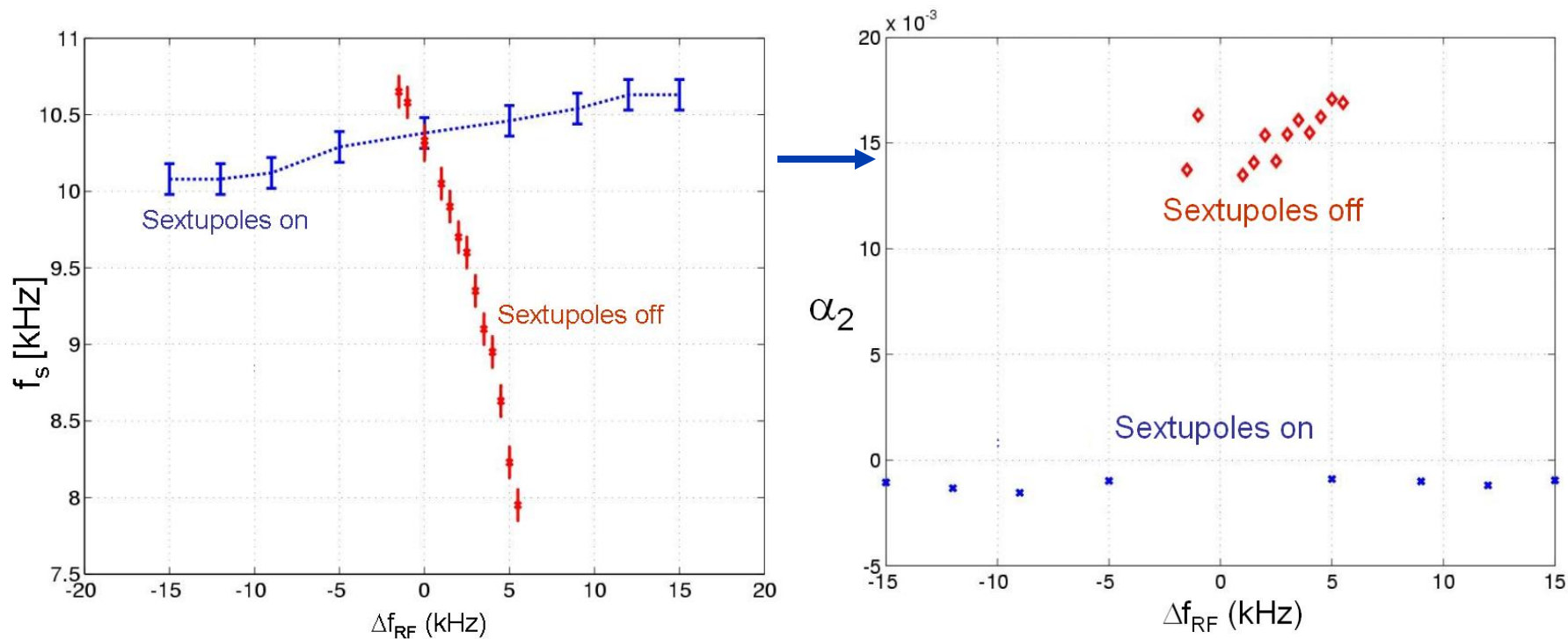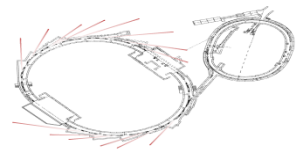
# Further reading

**For more on beam measurements, see:**

**Beam Measurement, Proceedings of the Joint US-CERN-Japan-Russia School on Particle Accelerators, S-I. Kurokawa, S.Y. Lee, E. Perevedentsev & S. Turner, editors, World Scientific (1999).**

**My lecture was in particular derived from lectures in Beam Measurement by Frank Zimmermann and John Byrd. The lectures by Frank Zimmermann are given in more detail in:**

**M.G. Minty and F. Zimmermann, Measurement and control of charged particle beams, Springer (2003).**

# **Natural chromaticity measurement**

- **Turn-by-turn BPM readings during natural chromaticity measurement (sextupoles off)**

- **Beam was kicked with injection kicker to measure $\nu_x$**

- **Why do oscillations disappear and reappear?**