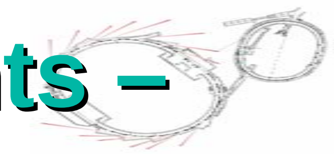
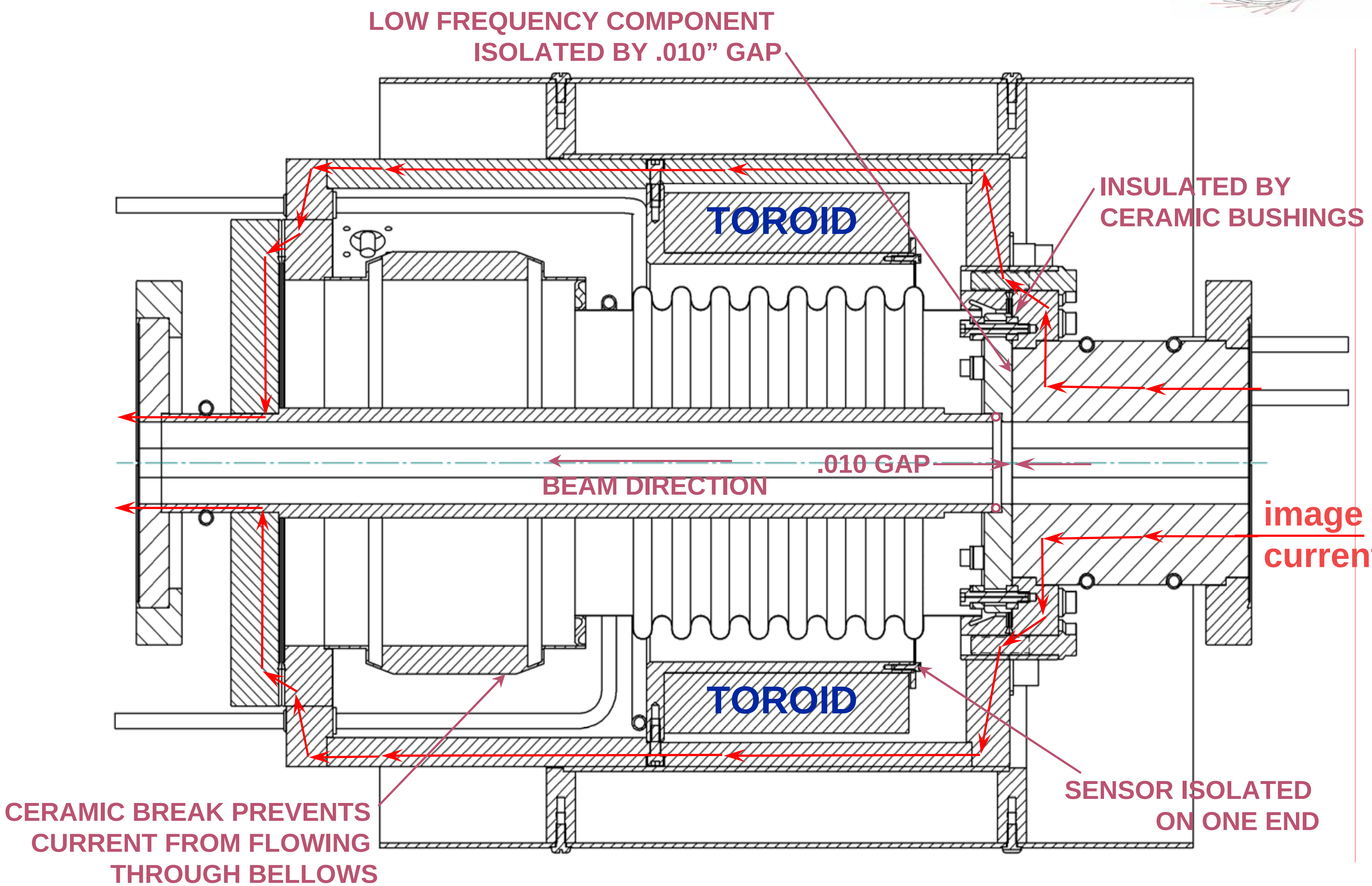
Storage ring measurements – the basics



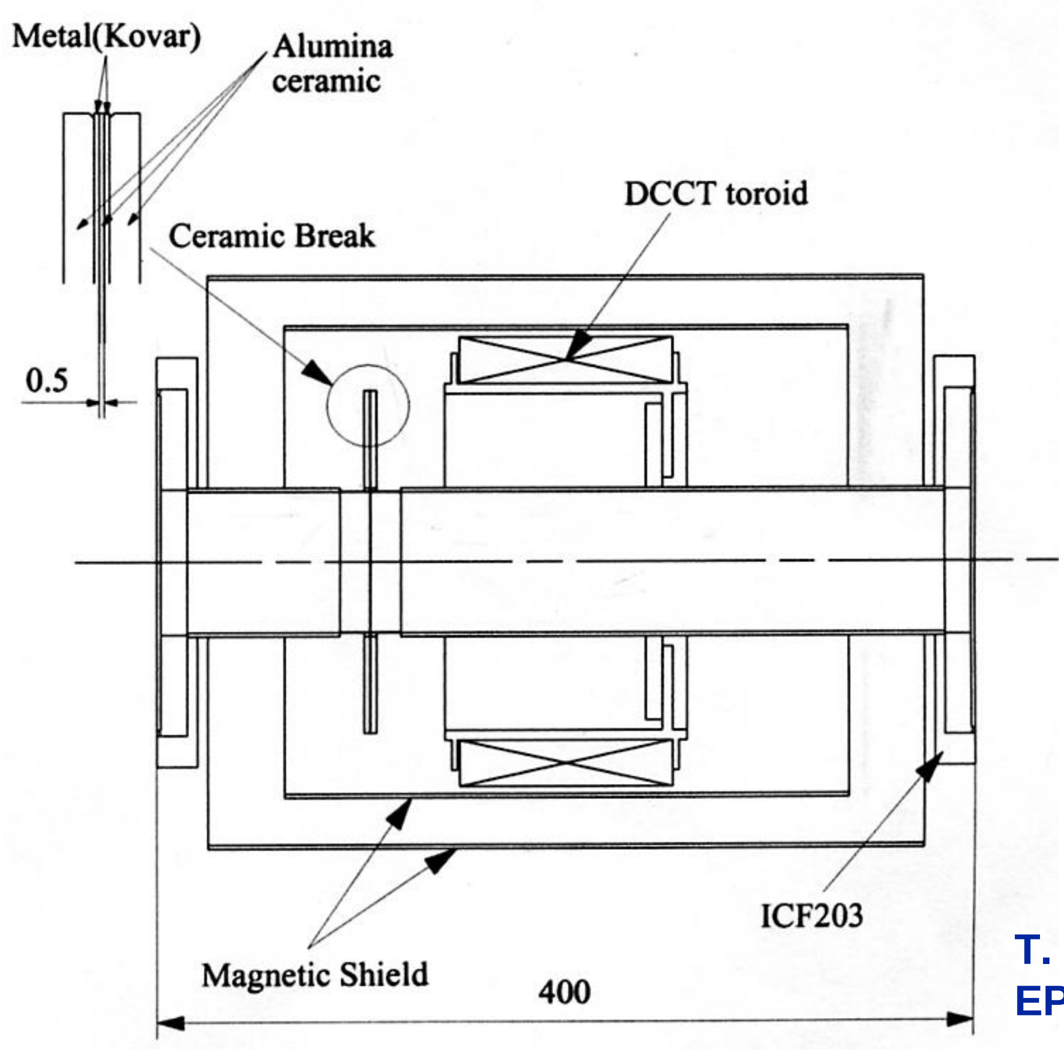
- **Beam Diagnostics**
  - **DCCT**
  - **BPMs**
  - **Synchrotron light monitors**
  - **Scrapers**
  - **Loss monitors**
- **Measuring tunes, β, η, chromaticity, α**

SPEAR3 DCCT



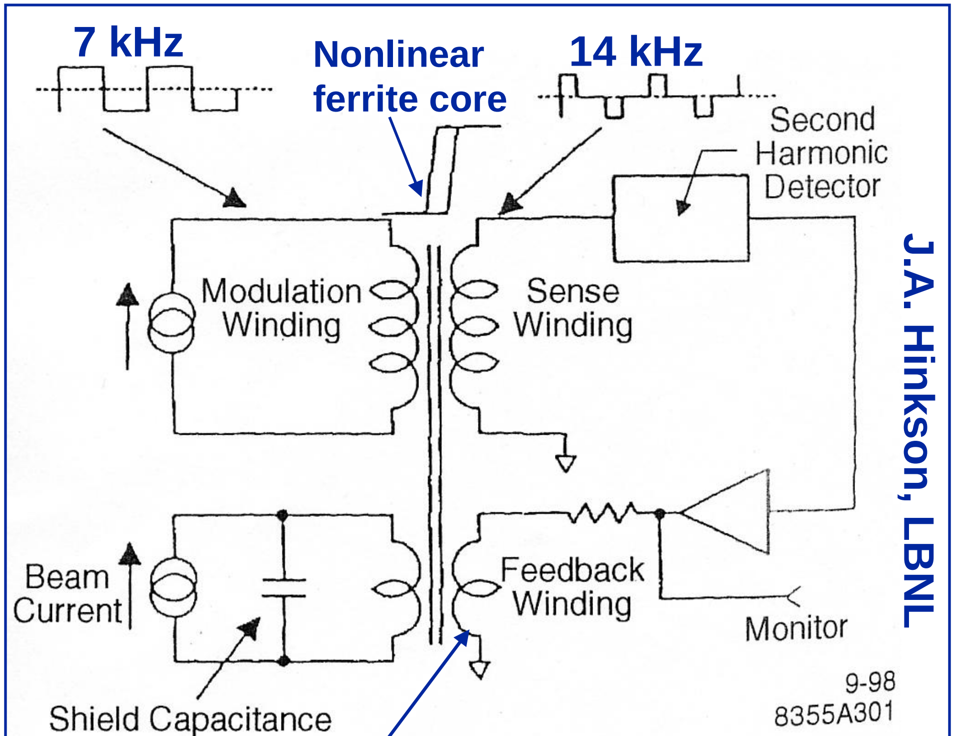
LOW FREQUENCY COMPONENT
ISOLATED BY .010" GAP
INSULATED BY
CERAMIC BUSHINGS
TOROID
TOROID
.010 GAP
BEAM DIRECTION
image
current
CERAMIC BREAK PREVENTS
CURRENT FROM FLOWING
THROUGH BELLOWS
SENSOR ISOLATED
ON ONE END

Photon factory DCCT



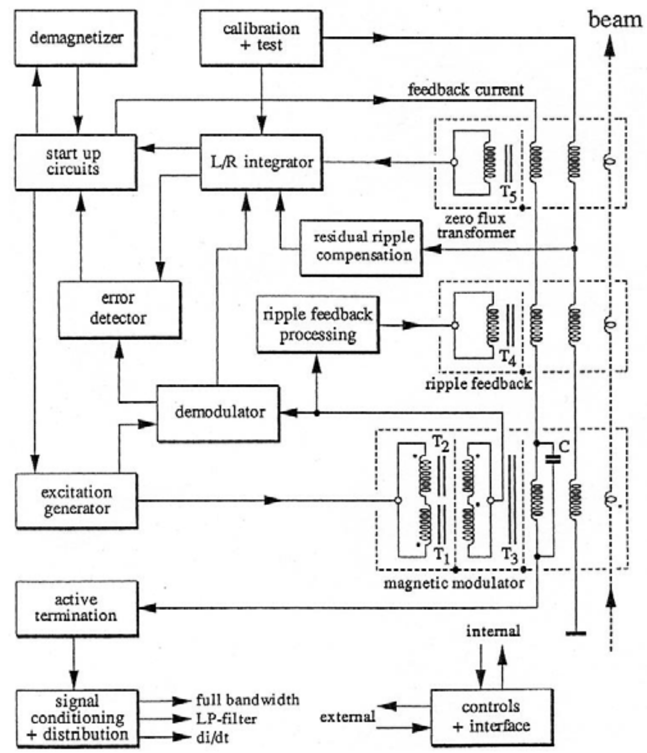
T. Honda et al., EPAC98

DCCT (or PCT) circuit



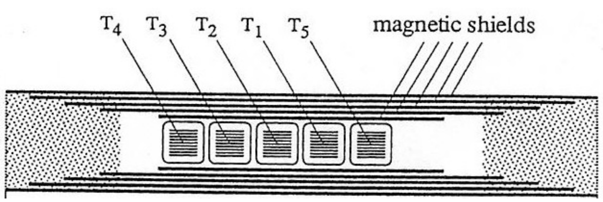
J.A. Hinkson, LBNL

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.

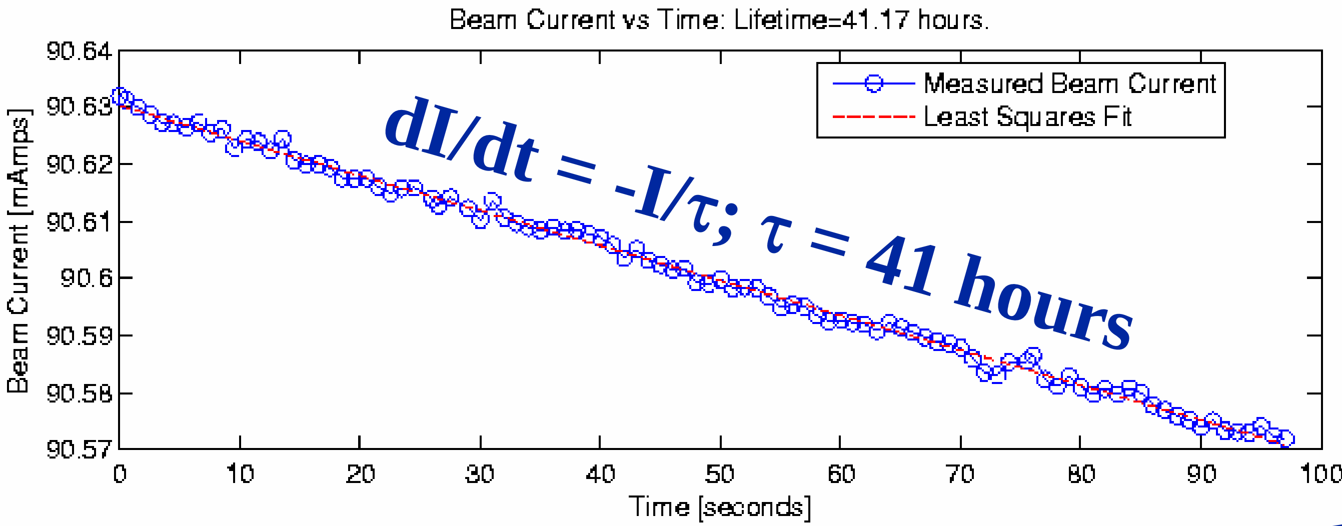


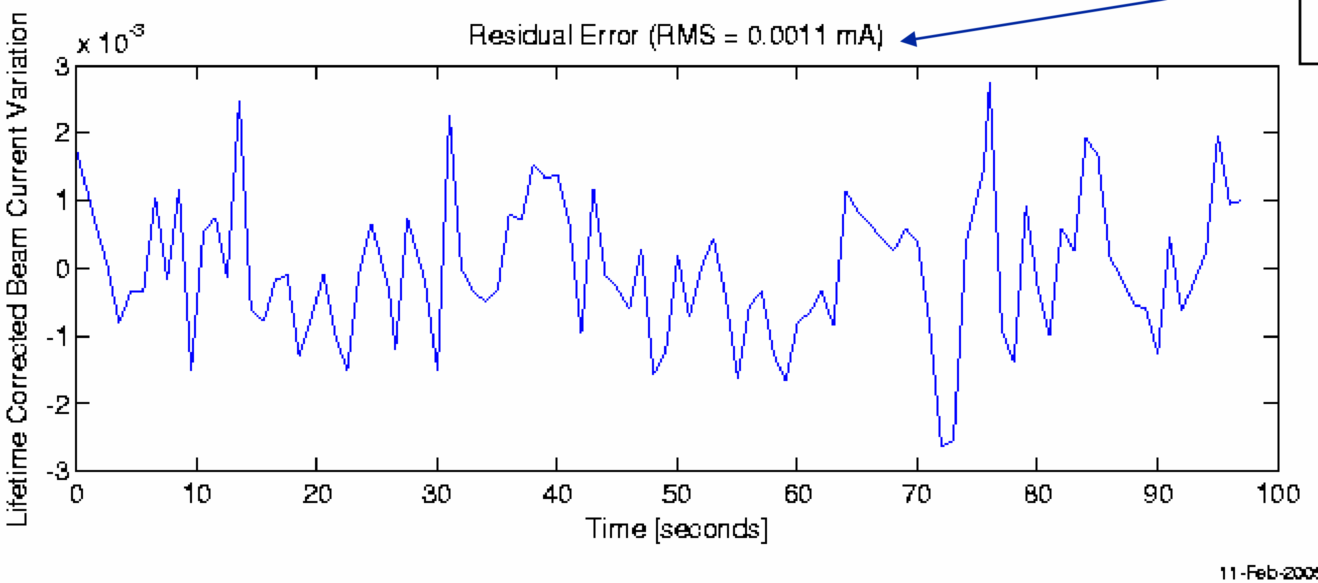
Simplified circuit, K. Unser, 1992

Ferrite core Xsection



SPEAR3 lifetime measurement w/ DCCT



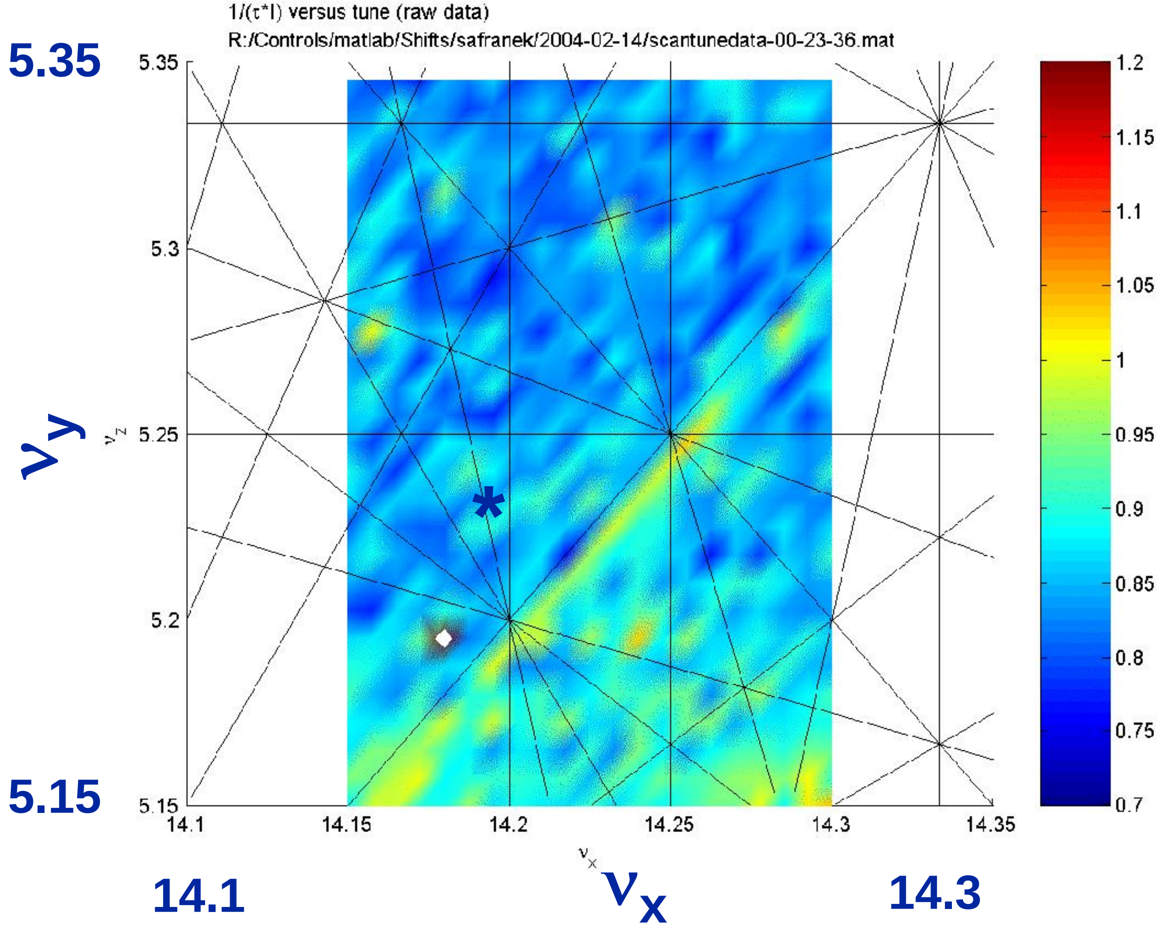


DCCT resolution:

1 μA in 1 second

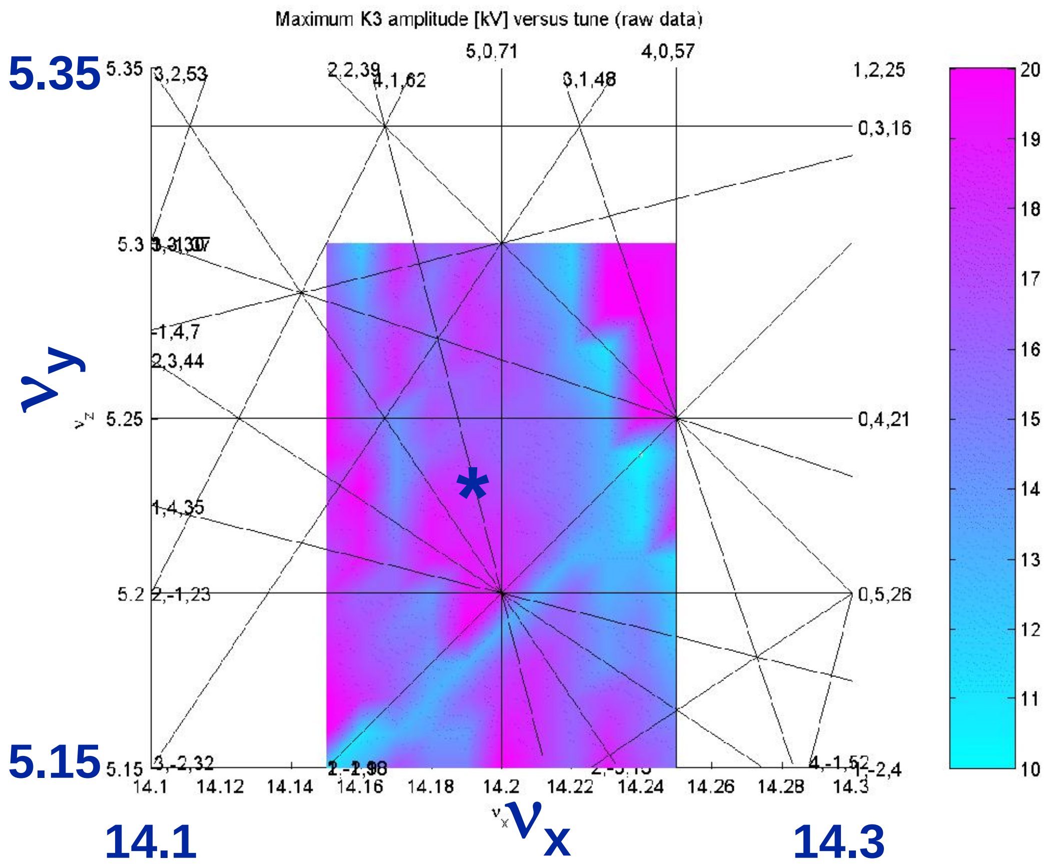
Lifetime vs. tunes

- Resonant line:
  - $\nu_x - \nu_y = 9$
- * = operating tunes (14.19, 5.23)
- Data gathered automatically on owl shift.



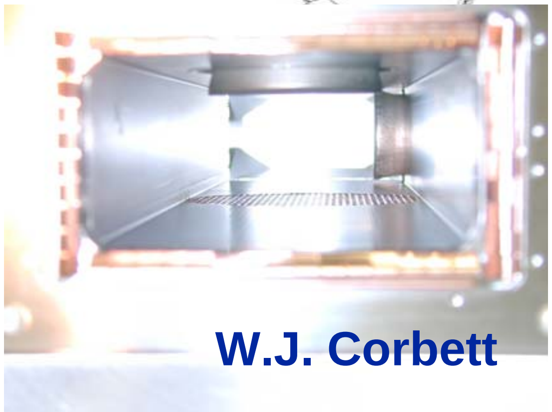
Dynamic aperture vs. tune

- **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.**

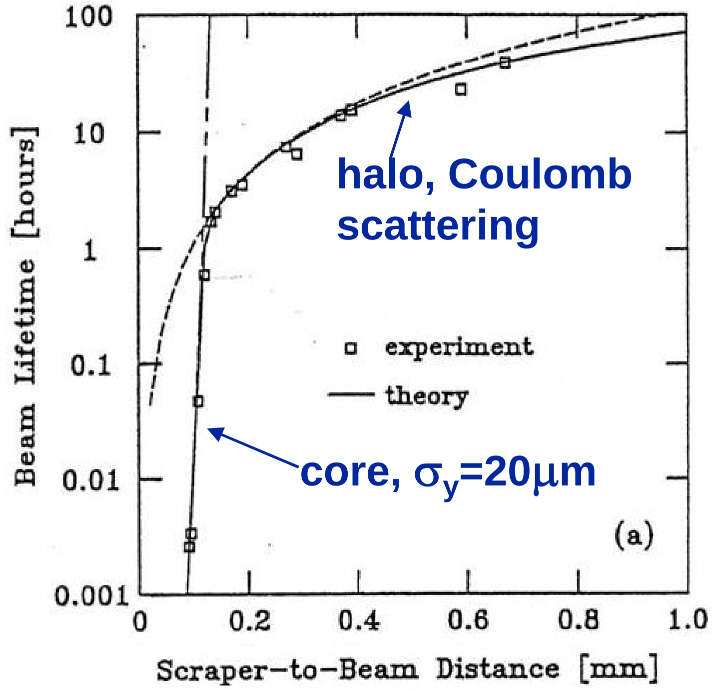


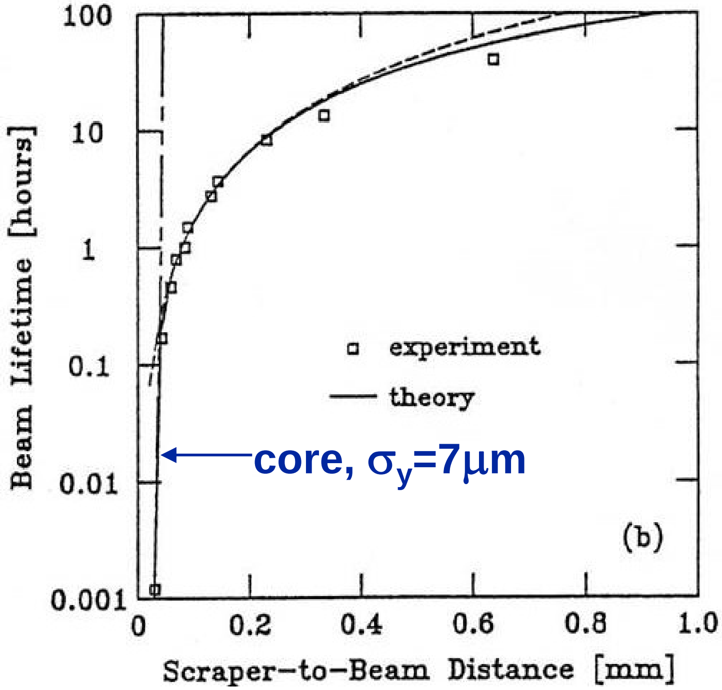
Beam scrapers; lifetime vs. vertical aperture

Scrapers measure beam halo



Peter Stefan et al., NIMA, 1998





SPEAR3 scraper measurements

Three contributions to lifetime:

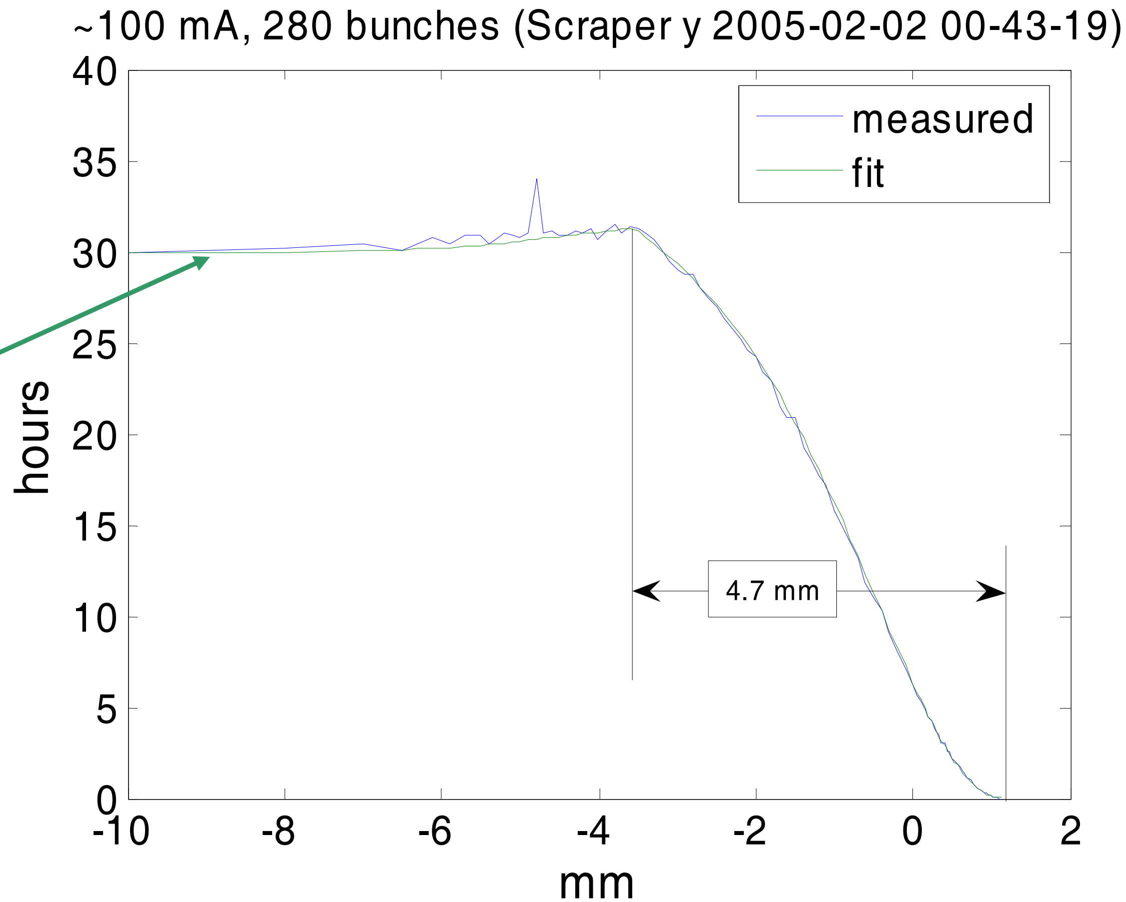
- **Elastic gas scattering (Coulomb)**
- **Brehmsstrahlung**
- **Intrabeam scattering (Touschek)**

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

Five fit parameters:

$$\tau_{C0}, \tau_{B0}, \tau_{T0},$$
$$y_{beam}, y_{ring}$$

$$\tau_C \propto \text{pressure} * \text{y}_{\text{aperture}}{}^2 \approx I_{tot} * y^2$$
$$\tau_B \propto \text{pressure} * f(\text{E}_{\text{aperture}}) \approx I_{tot}$$
$$\tau_T \propto \frac{I_{tot}}{N_{bunch}} * f(\text{E}_{\text{aperture}}) \approx I_b$$

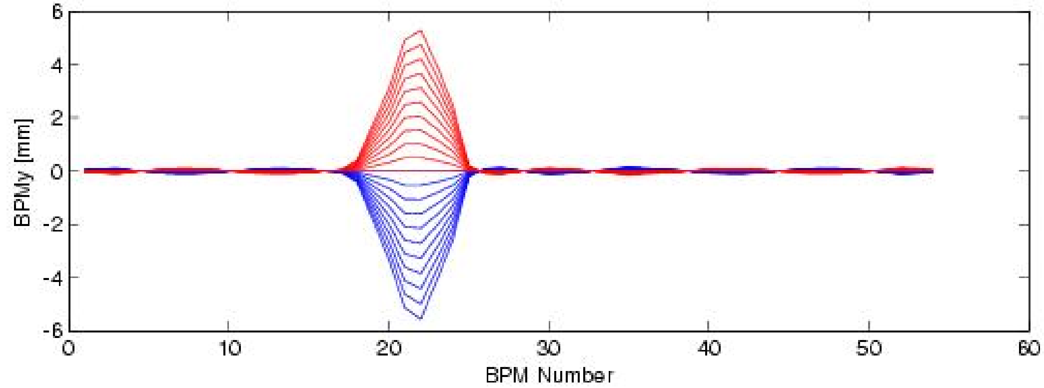


Physical aperture probe

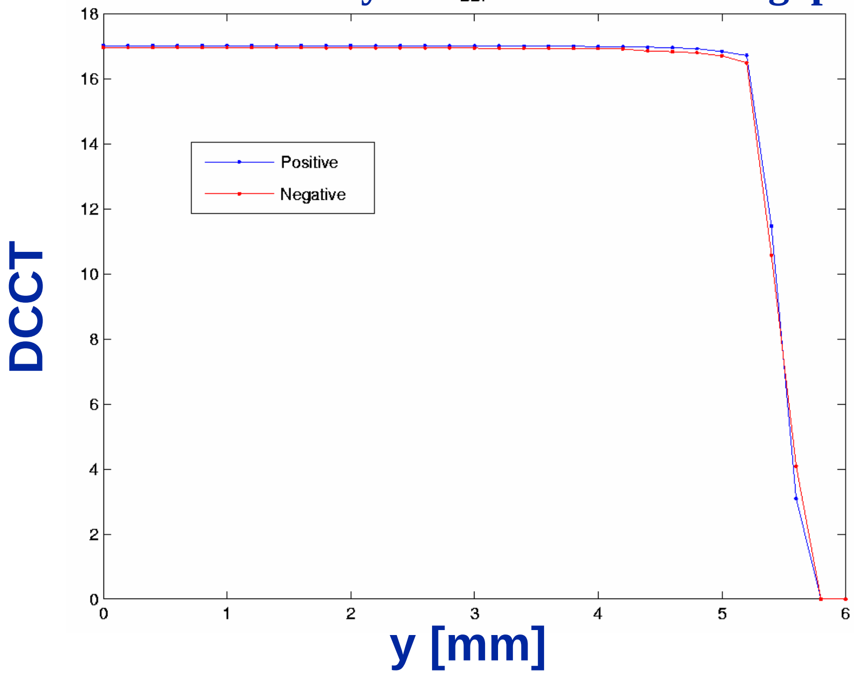
y-bump in ID chamber:

- Bump beam up until lost
- Refill
- Bump beam down until lost

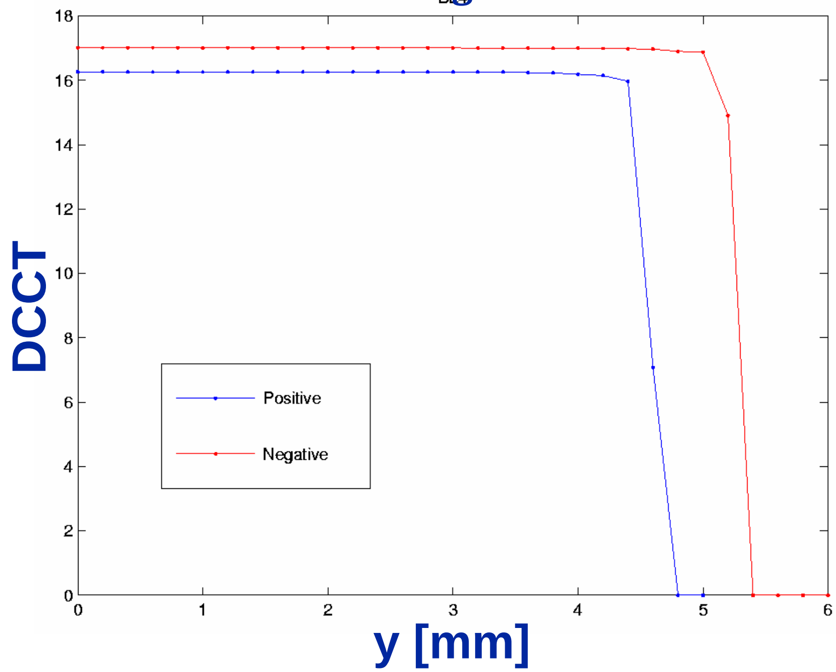
Vertical beam bump in ID chamber



ID7 chamber is symmetric and correct gap

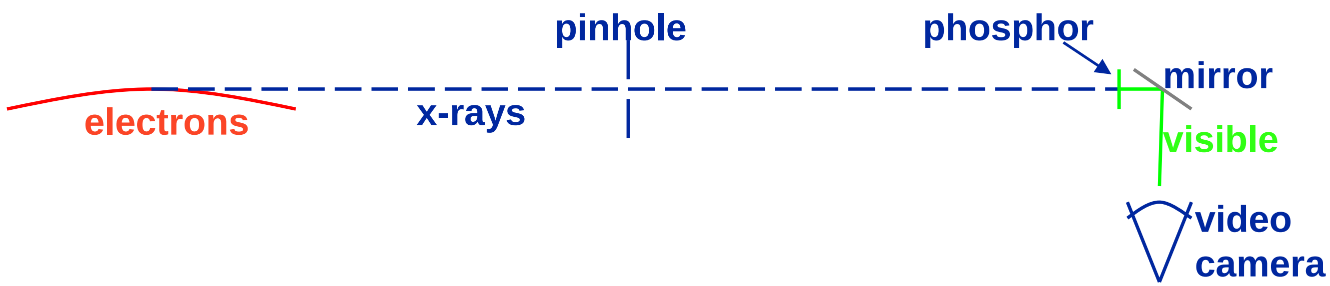


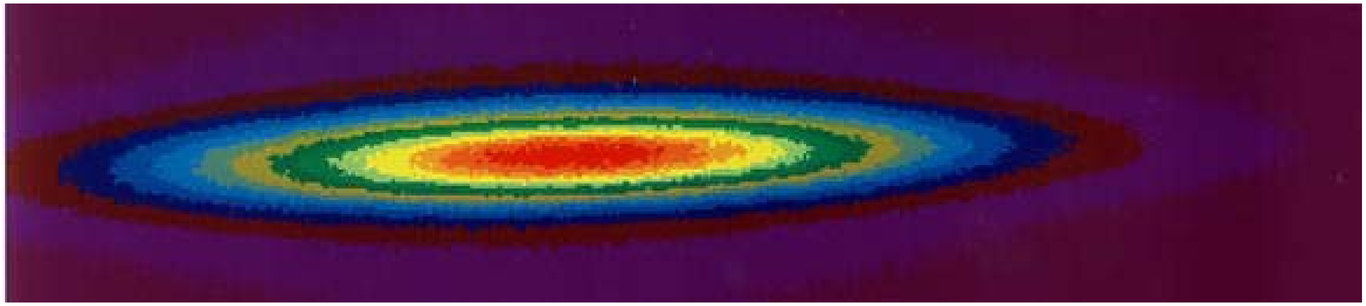
ID4 chamber is mis-aligned and too small



Beam size measurements (more on Thurs.)

Synchrotron light monitors measure beam core





Principle of streak camera

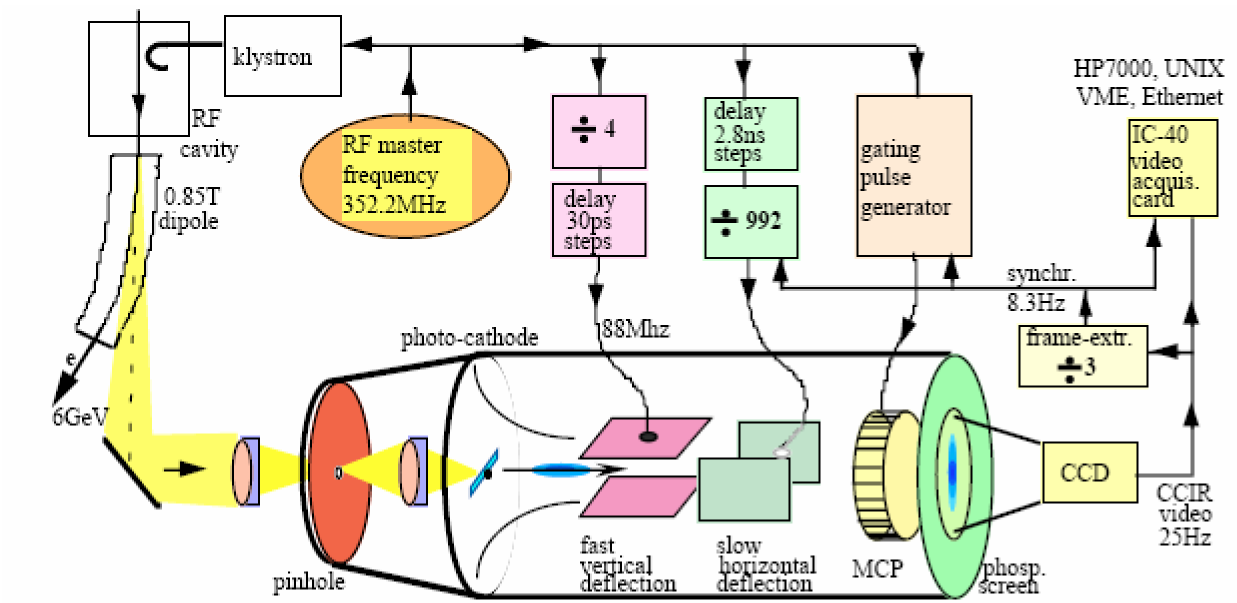
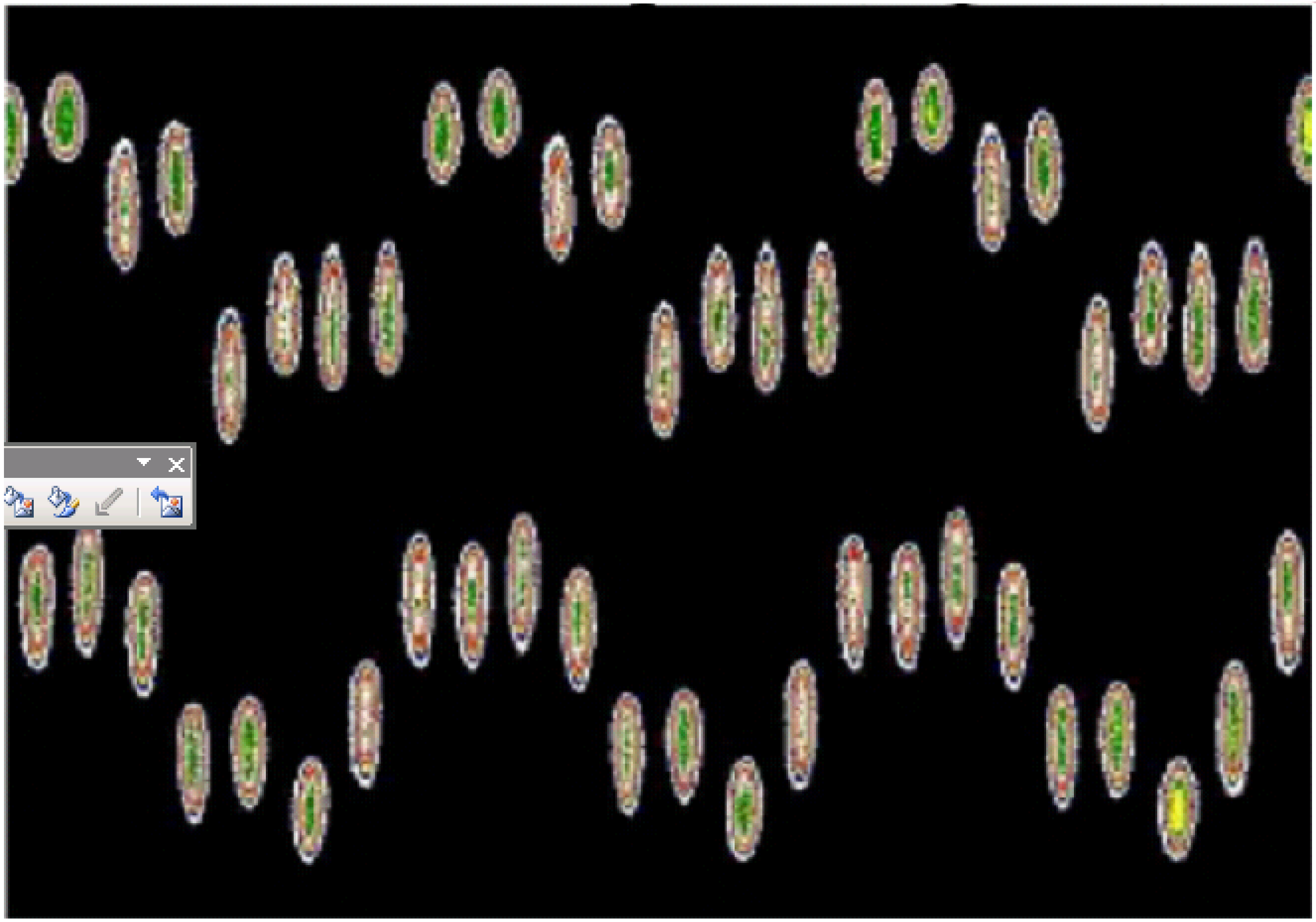


Figure: 1 Synchronisation of the Streak Camera system

- 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 …

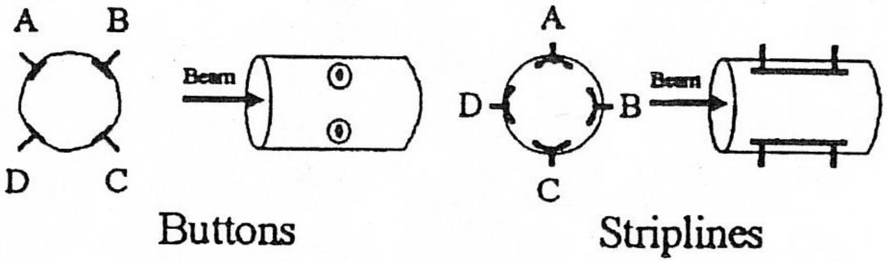
Streak camera



Longitudinal instabilities at ESRF

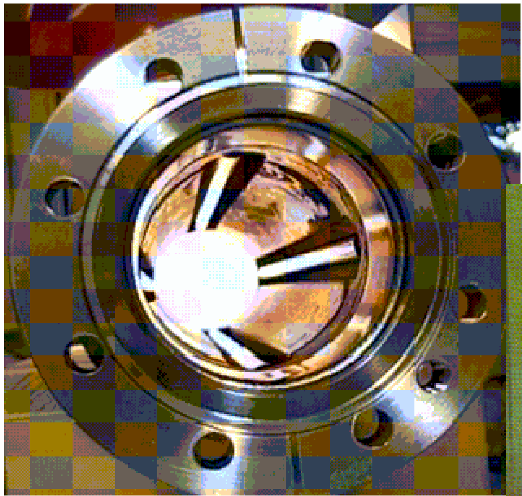
Beam position monitors

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

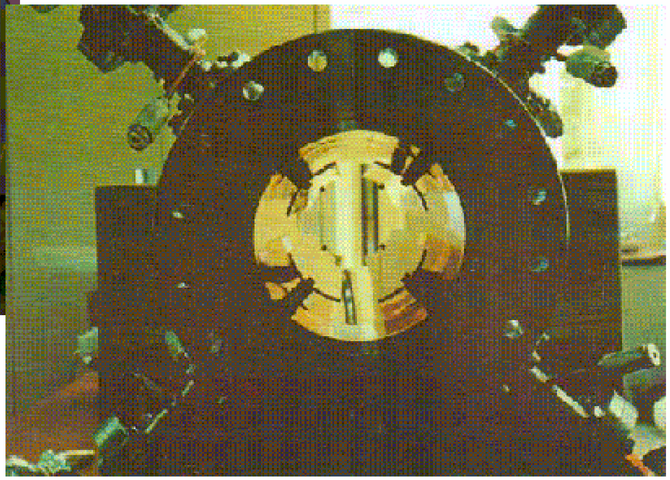


Electron BPM buttons sample electric fields; striplines couple to electric and magnetic fields.

Striplines



M. Wendt, DESY



M. Tobiyama, KEK

Capacitive Pickups, Button BPMs

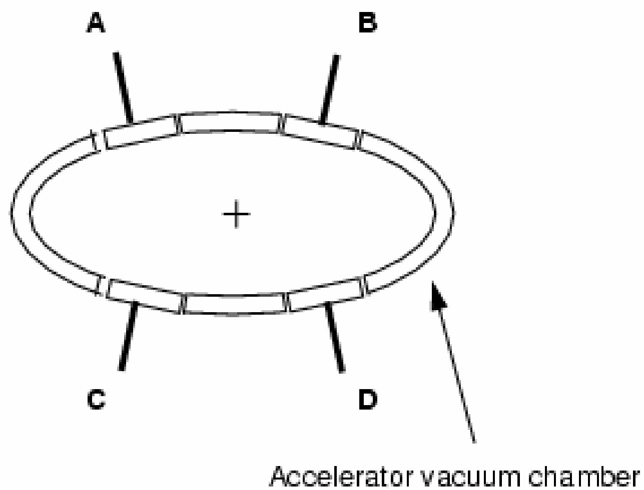
Charged Particle Beam Pickup Electrodes

Capacitive buttons

- Broadband, up to > 10 GHz
- Most effective when button diameter is comparable to the bunch length
- Minimal wakefield interaction with beam

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

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

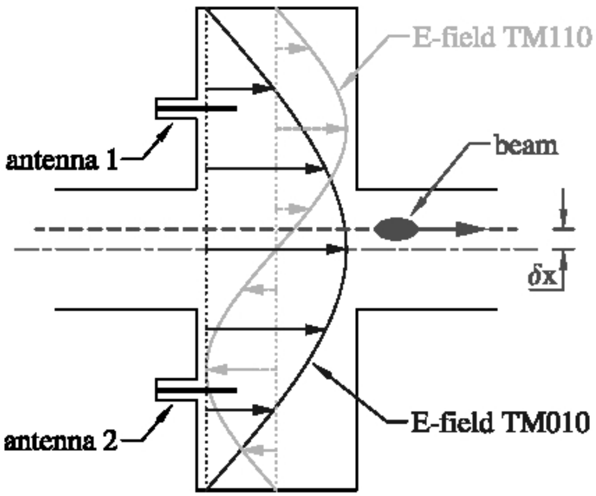


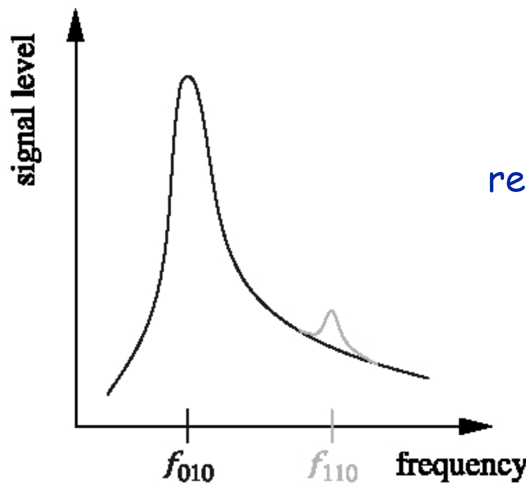
e.g. for round buttons of radius a in round pipe of radius r

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

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

CAVITY BPMs:

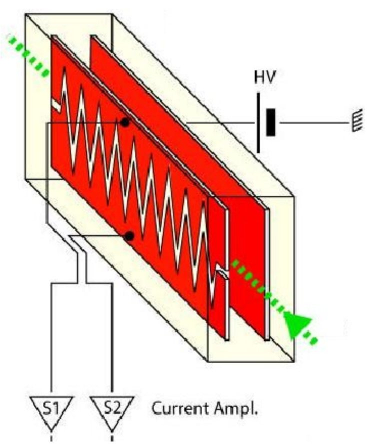




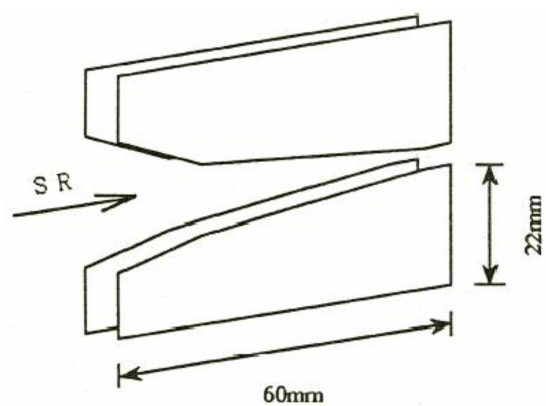
reference:
"Cavity BPMs", R. Lorentz
(BIW, Stanford, 1998)

PHOTON BPMs:

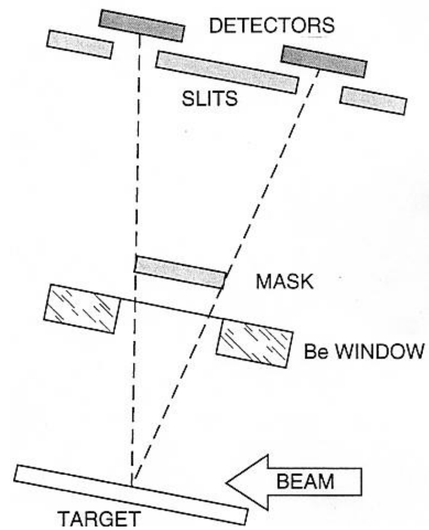
Split ion chamber:



Tungsten blade monitor:



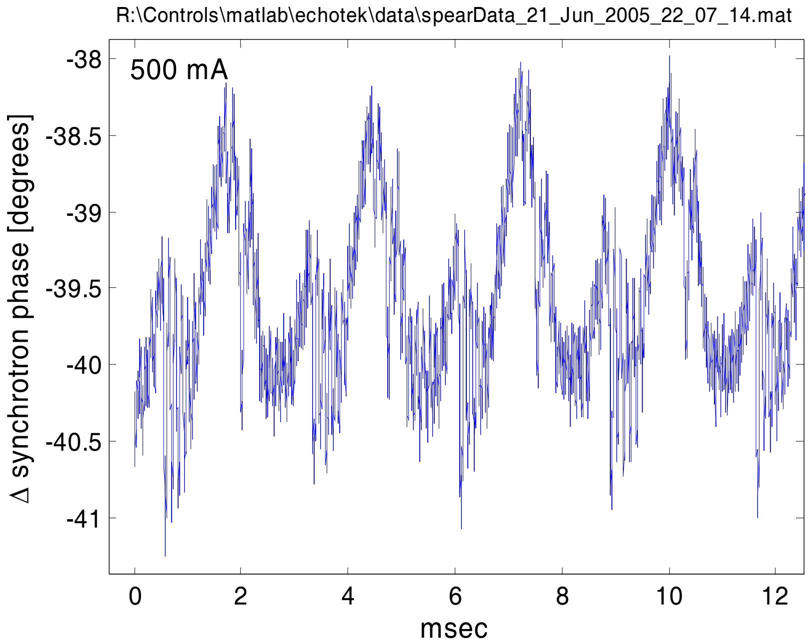
Copper fluorescence bpm:



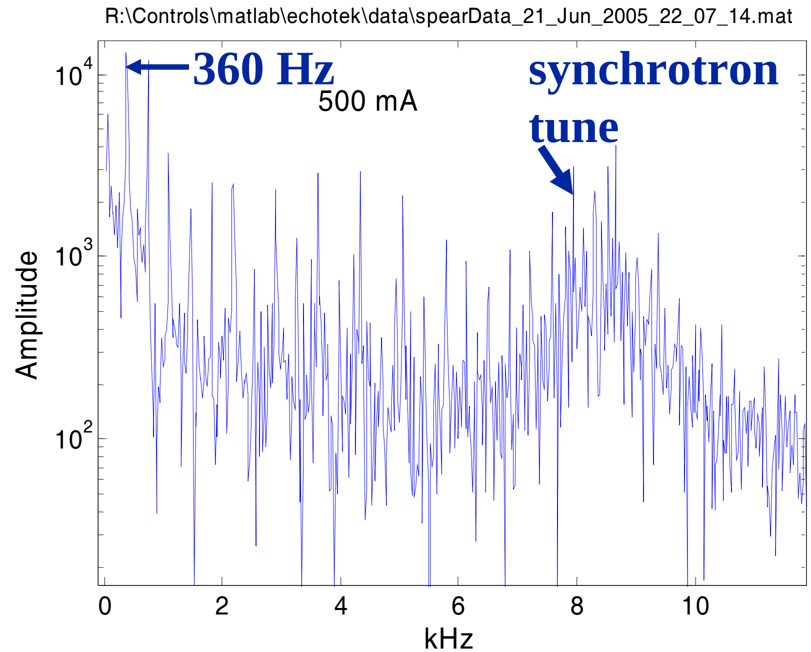
Longitudinal oscillations, BPMs

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



FFT of synchrotron motion

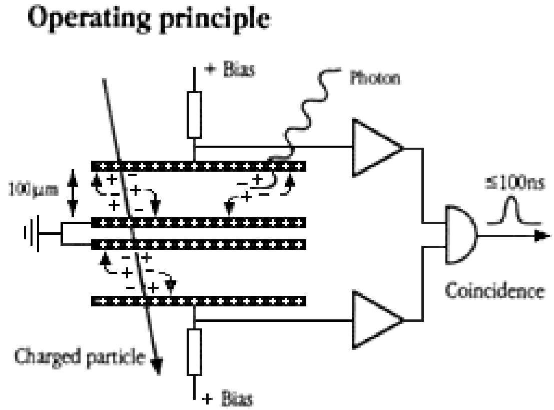


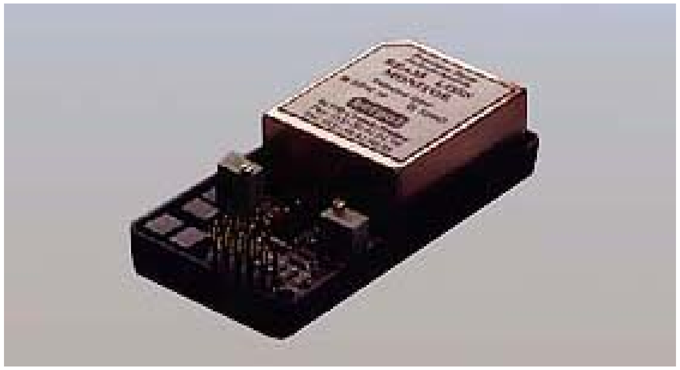
Beam loss monitors

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.

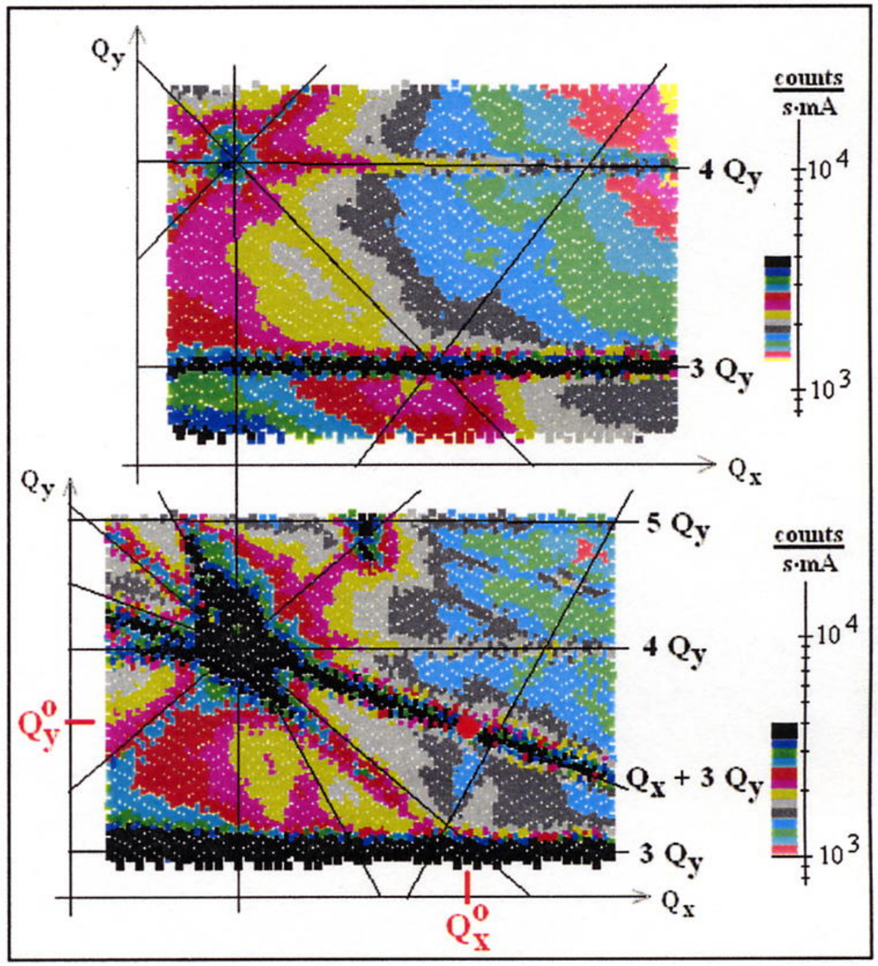




A scintillator with a photomultiplier is another commonly used BLM.

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.

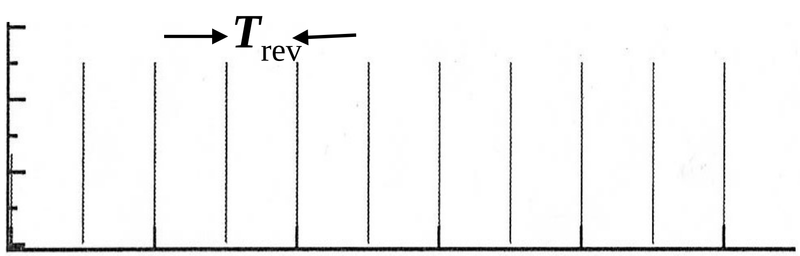
Beam frequencies

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

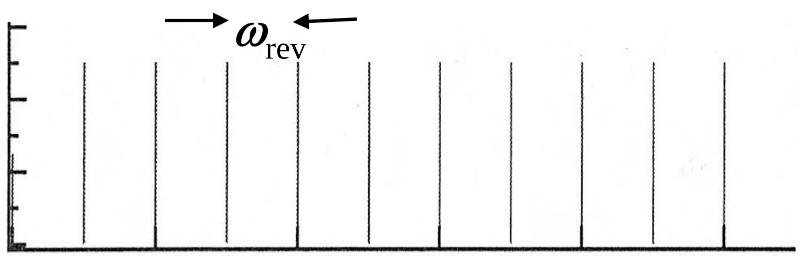
$$I(t) = \sum_{n=-\infty}^{\infty} q\delta(t - nT_{\mathrm{rev}}),$$

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

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



Time

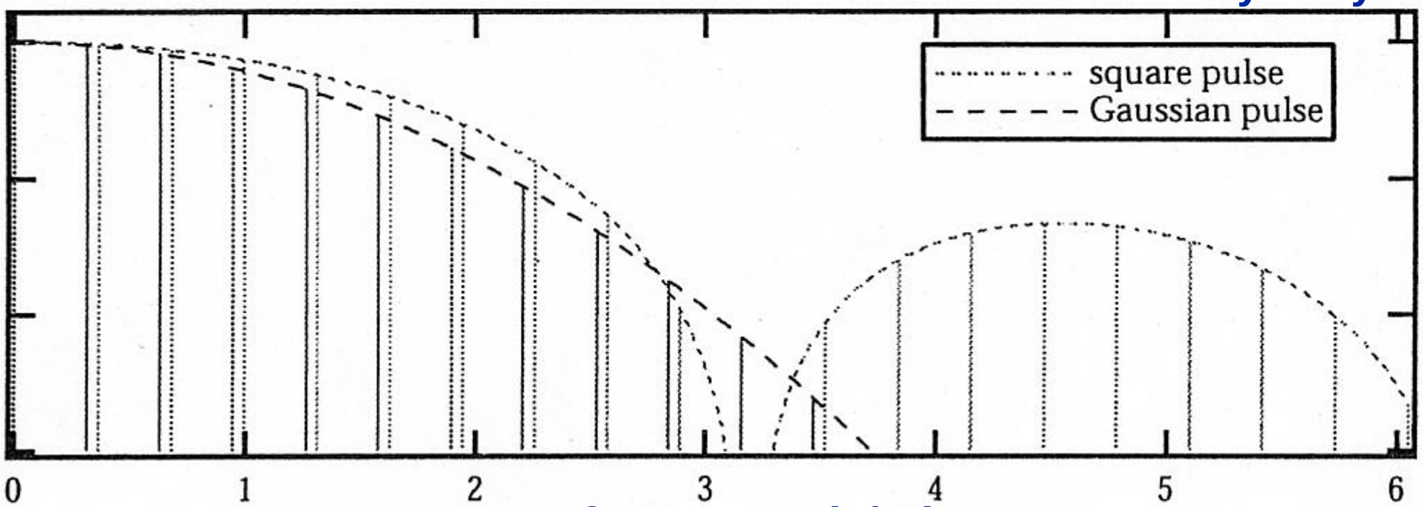


Frequency

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



frequency ($1/\sigma_z$)

For SPEAR3 σ_z = 4.5 mm, so c/σ_z = 67 GHz.

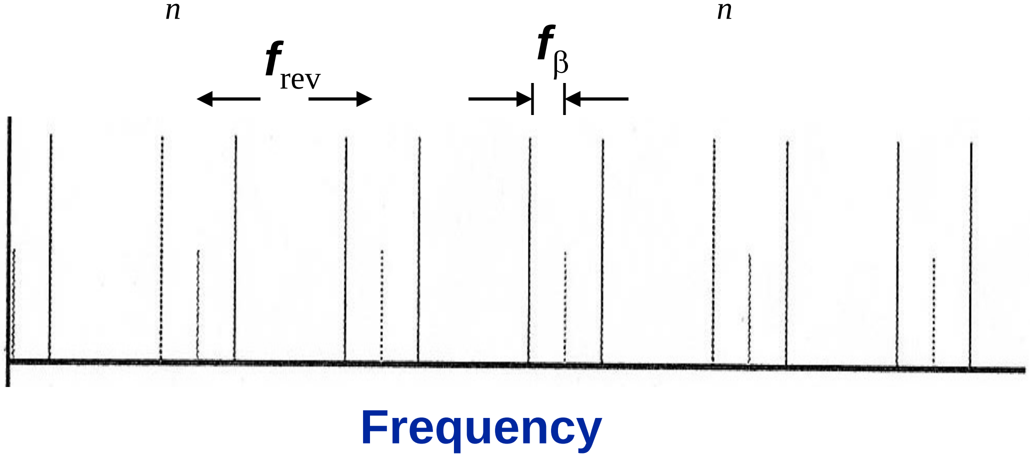
Betatron tune

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_β, 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

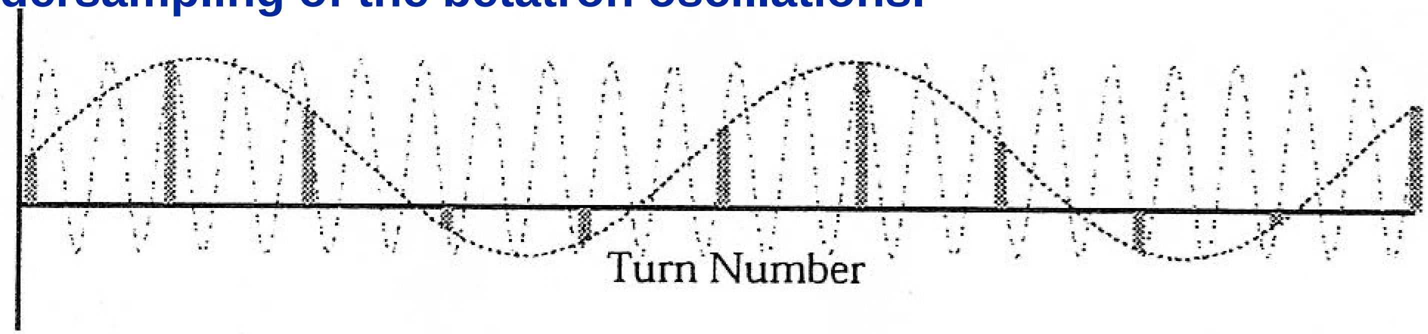
$$d(\omega) = q\omega_{\text{rev}} x_{c.o.} \sum_n \delta(\omega - n\omega_{\text{rev}}) + q\omega_{\text{rev}} x_\beta \sum_n \delta(\omega - (\omega_\beta + n\omega_{\text{rev}}))$$



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

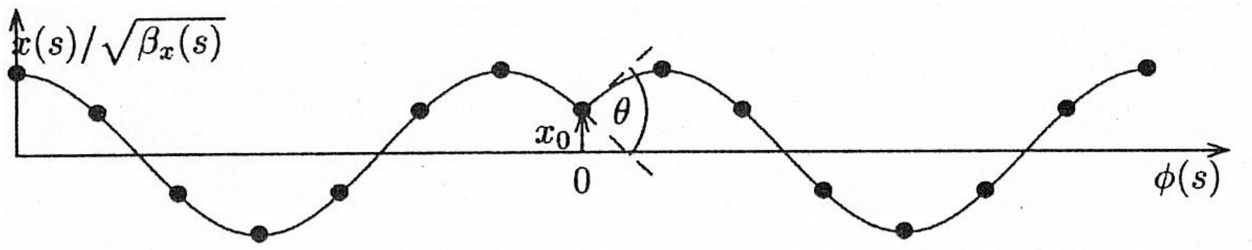
Betatron tune, 2

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



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

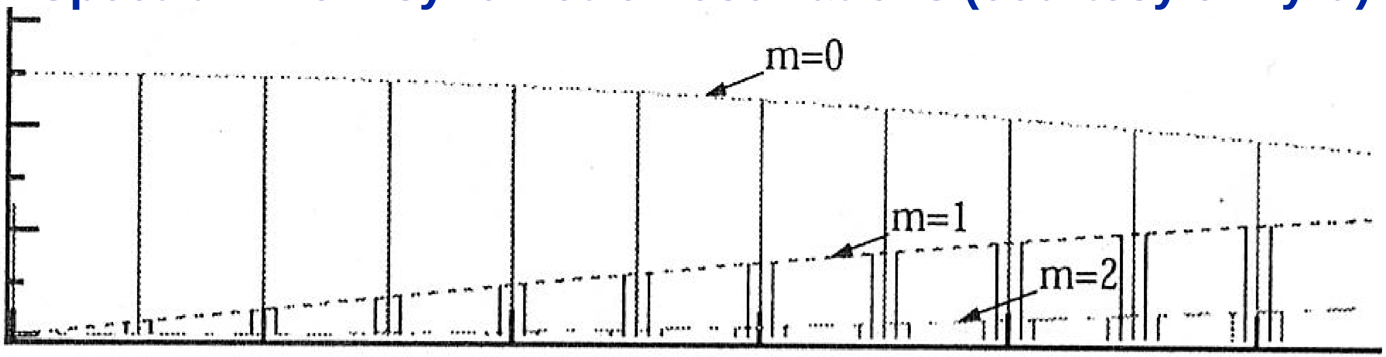
$$\frac{\Delta x_i}{\Delta \theta_j} = \frac{\sqrt{\beta_i \beta_j}}{2\sin(\pi\nu)} \cos(|\phi_i - \phi_j| - \pi\nu)$$



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.

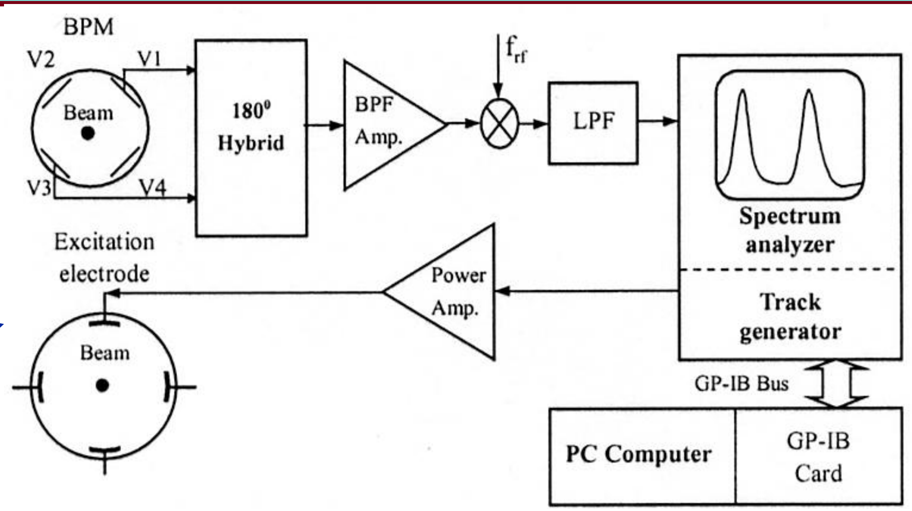
Spectrum from synchrotron oscillations (courtesy J. Byrd)



frequency

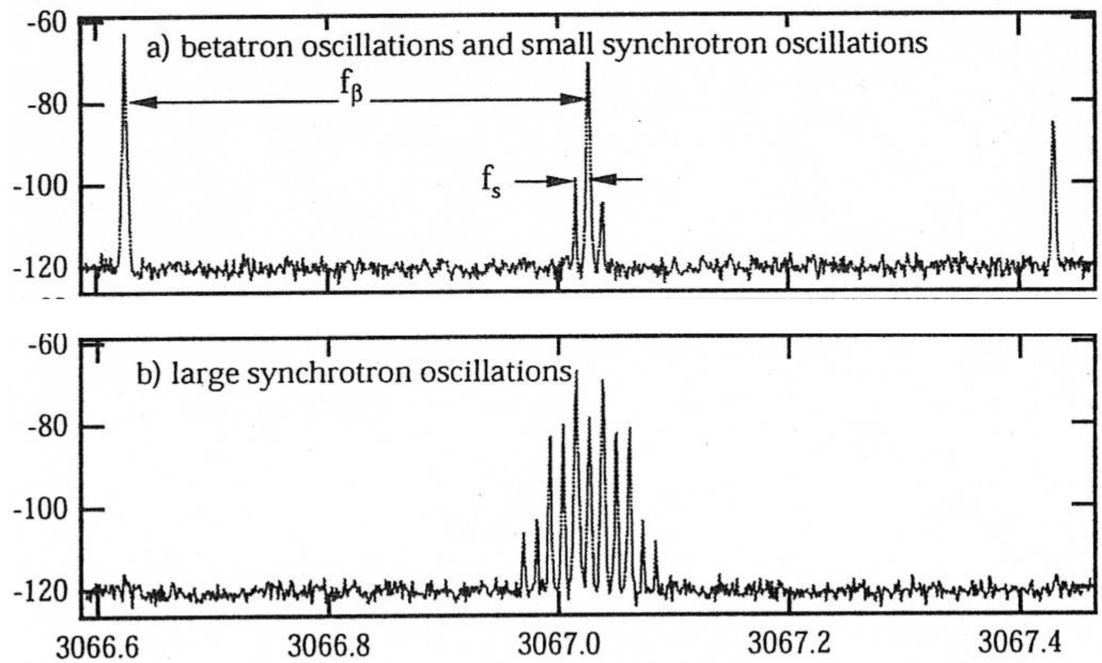
Measured spectra

Typical tune measurement



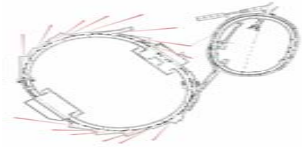
HLS tune meas., Sun et al. PAC01

Typical measured spectra



Multibunch spectra, instabilities, Steier, Friday.

More on spectrum



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

- **Turn by turn measurements, FFT, NAFF**
- **Betatron phase measurement (Tuesday)**
- **Nonlinear dynamics (tune vs. amplitude; tune vs. closed orbit; Thursday)**
- **Impedance measurements (Friday)**
- **Beta function measurements**
- **Chromaticity**

Beta function measurement

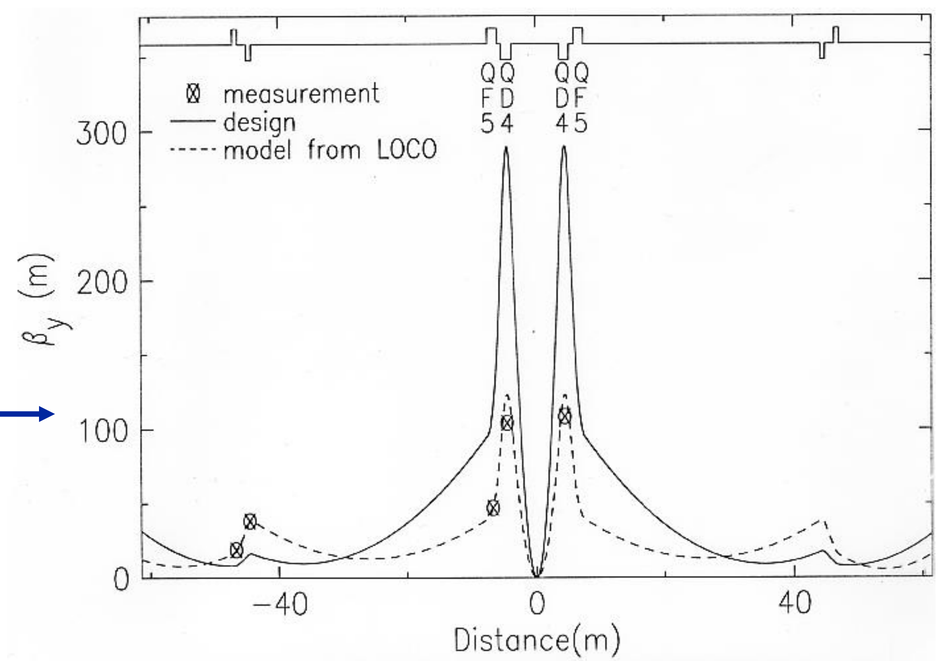
Beta functions can be measured by measuring the change in tune with quadrupole strength:

$$\Delta\nu = \beta \frac{\Delta(KL)}{4\pi}$$

Measurement issues

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

β measurement in PEPII HER IR indicates optics problem.

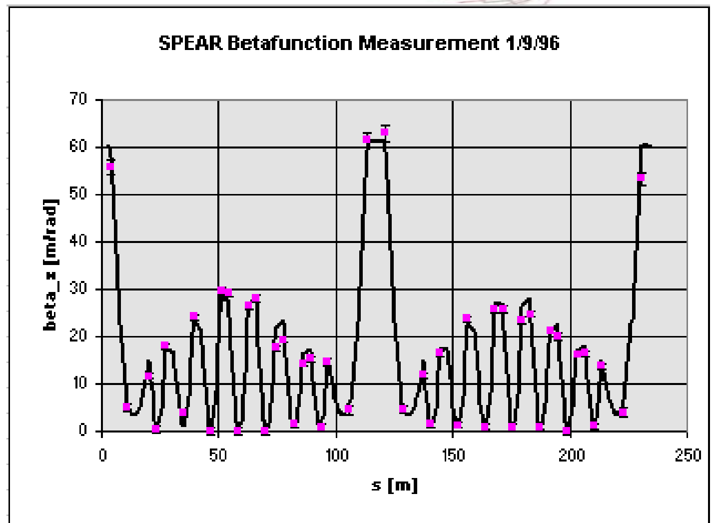


(Methods to be described Tuesday were used to find source of problem and correct it.)

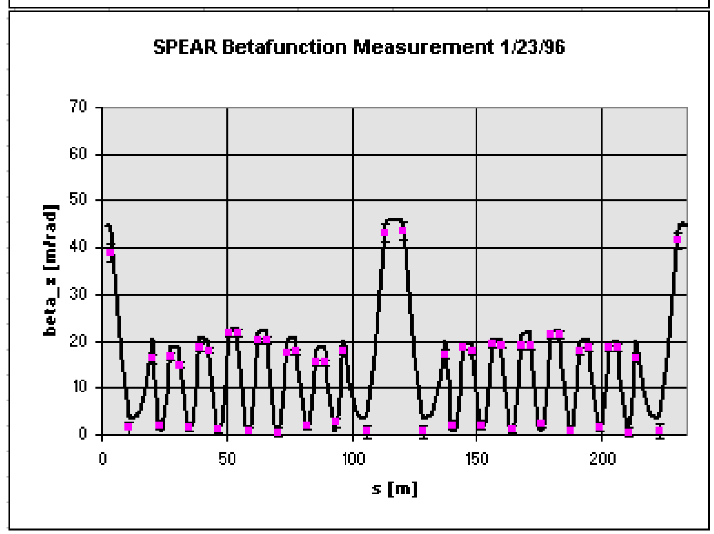
SPEAR β-function correction

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.

before



after



Courtesy Heinz-Dieter Nuhn

Other β measurements

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

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

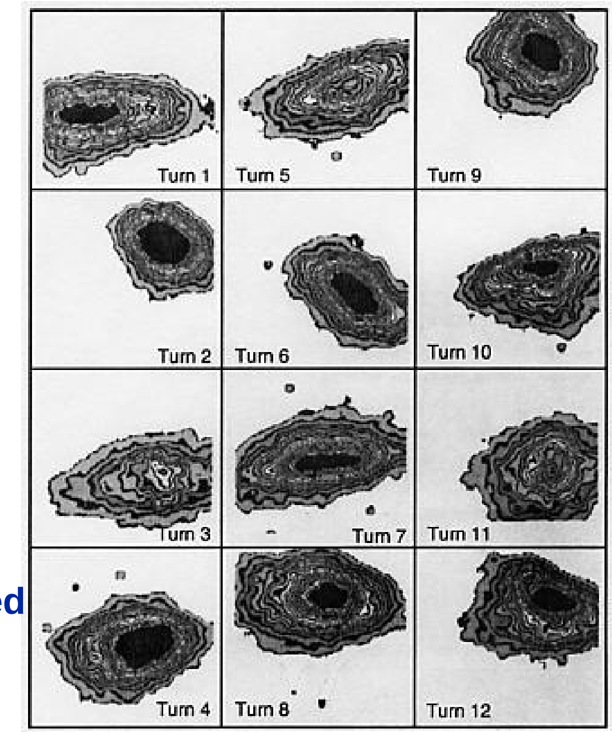
N_{BPM}*$N_{steerer}$ data

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 (Tuesday 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.

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

The energy can be changed by shifting the rf frequency.

$$\alpha \equiv \frac{\Delta L}{L} \Big/ \frac{\Delta p}{p} \qquad \Rightarrow \qquad \frac{\Delta p}{p} = -\frac{1}{\alpha}\frac{\Delta f_{rf}}{f_{rf}}$$

(α = 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

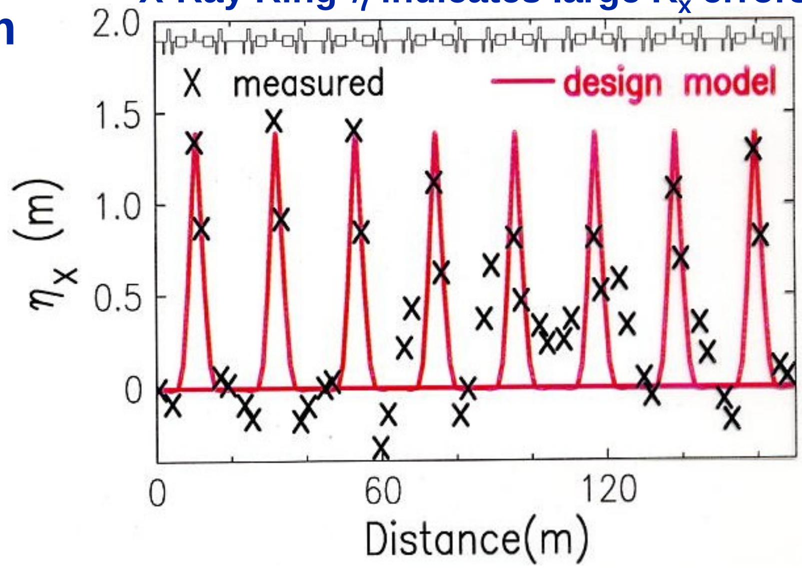
Dispersion distortion can come from quadrupole or dipole errors.

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

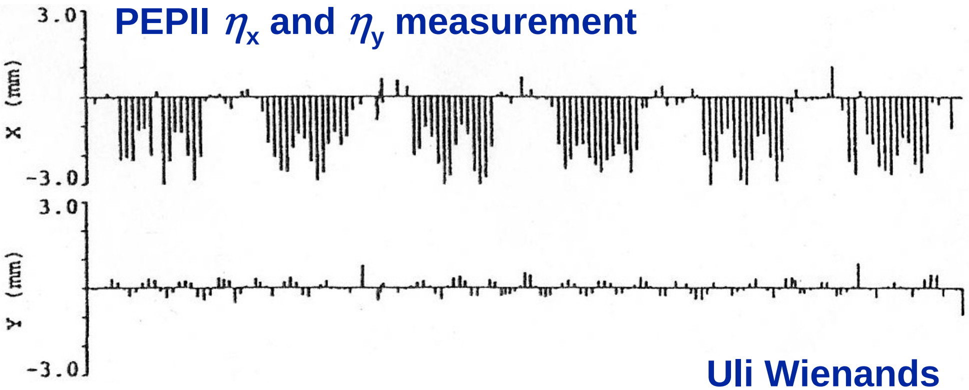
Vertical dispersion gives a measure of vertical bending errors or skew gradient errors in a storage ring.

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

X-Ray Ring η indicates large K_x errors



PEPII η_x and η_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):

$$\xi_N = \Delta\nu \Big/ \frac{\Delta p}{p}$$

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

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

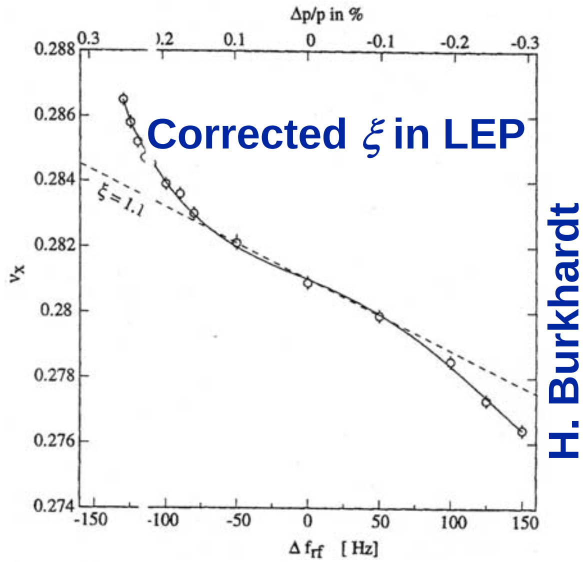
K **is the gradient,** m **is the sextupole strength.**

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:



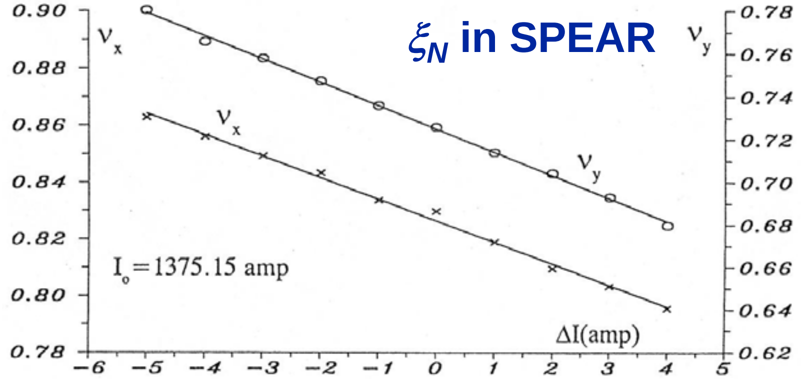
1. **Change the rf frequency. This shifts the orbit in sextupoles, giving the corrected chromaticity.**

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

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

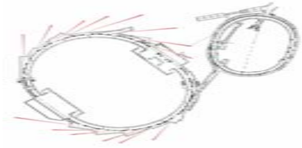
2. **Change the dipole field. This keeps orbit constant, measuring the natural chromaticity.**

$$\xi_N = \frac{\Delta \nu}{\Delta B / B}$$



ξ_N can also be measured from n vs. frf with sextupoles turned off.

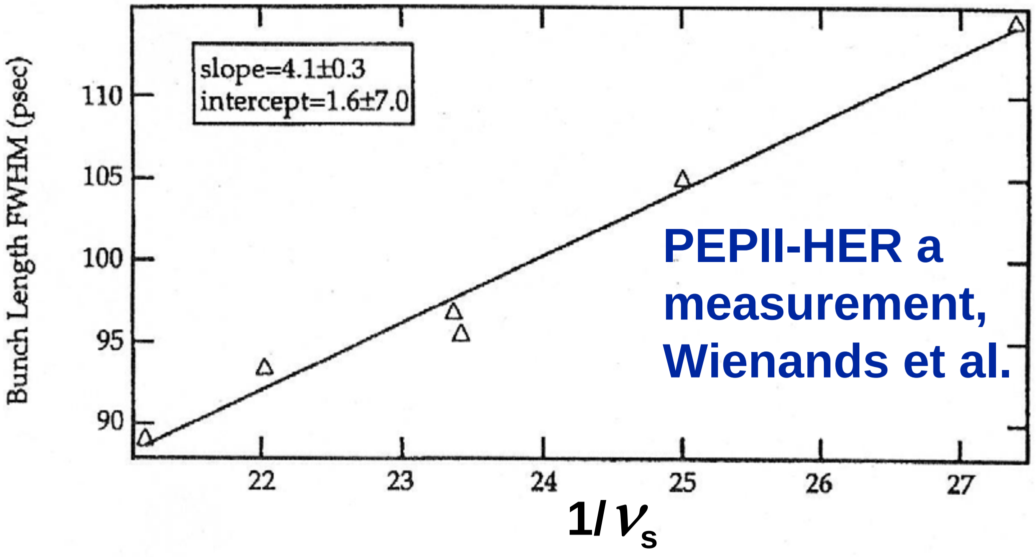
Momentum compaction



Using the model value of α for ξ and η measurements can lead to errors. α itself can be measured in various ways.

Indirect measurement from bunch length

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

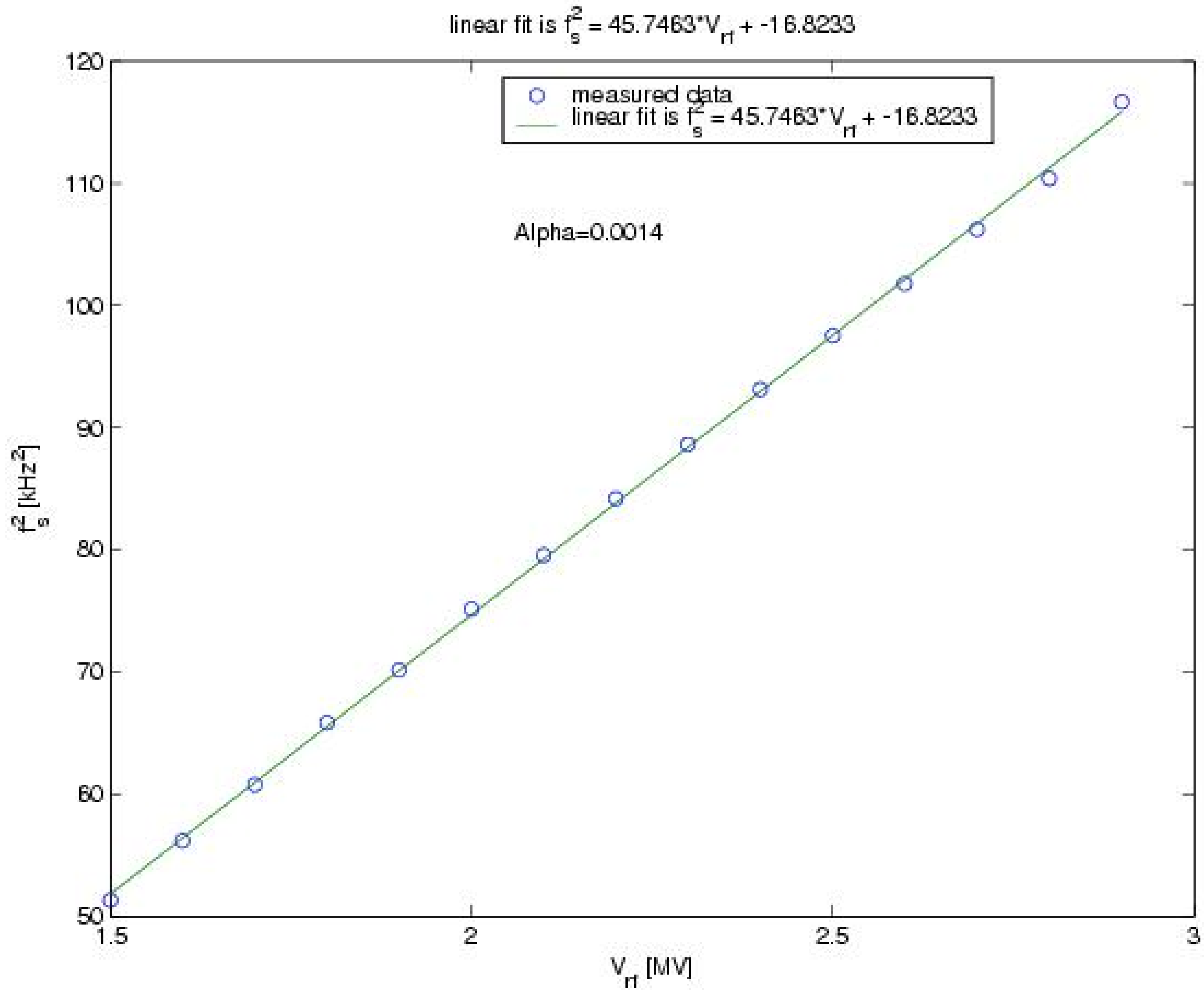


Direct measurement: measure change in energy with rf frequency.

$$\alpha = -\frac{\Delta f_{rf} / f_{rf}}{\Delta p / p}$$

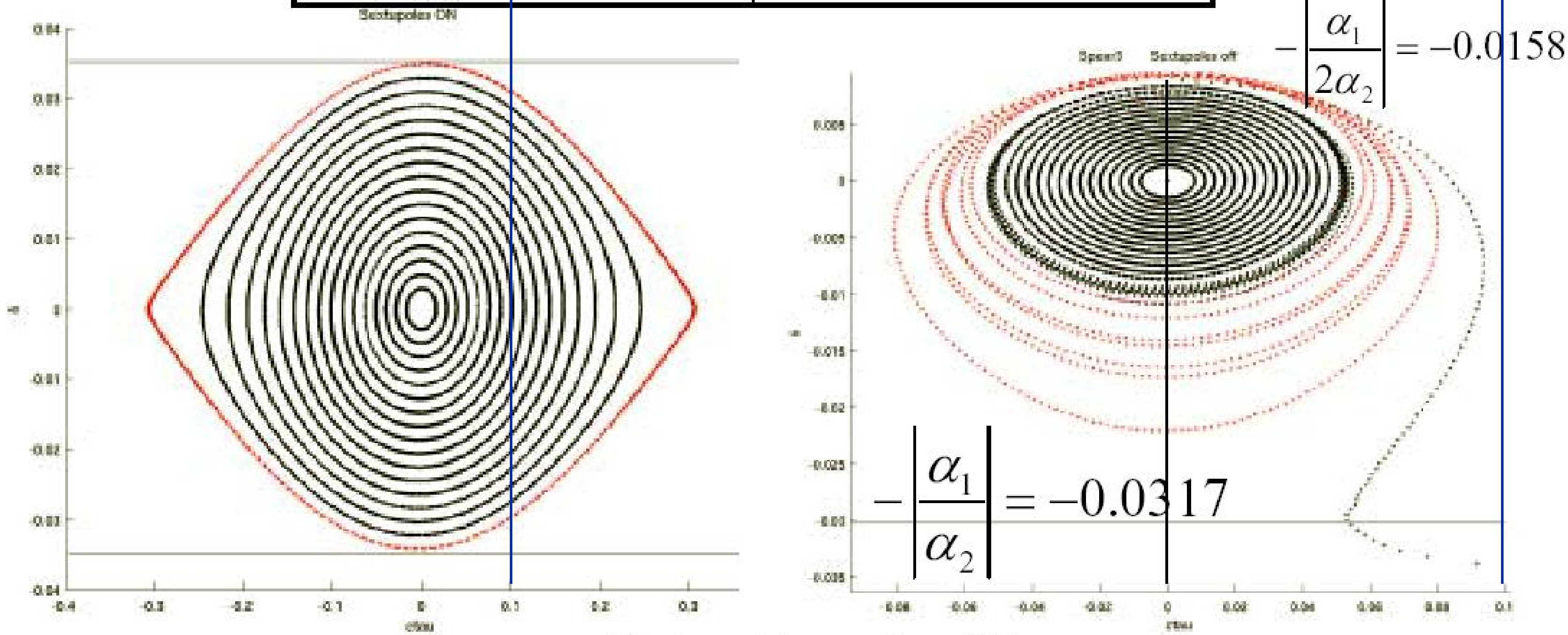
Friday will include lecture on energy measurement.

Momentum compaction measurement



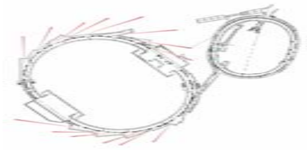
SPEAR3: Longitudinal Dynamics

Sextupoles on	Sextupoles off
α_1 =1.19 E-3	
α_2 = -2.1E-3	α_2 =37.4E-3

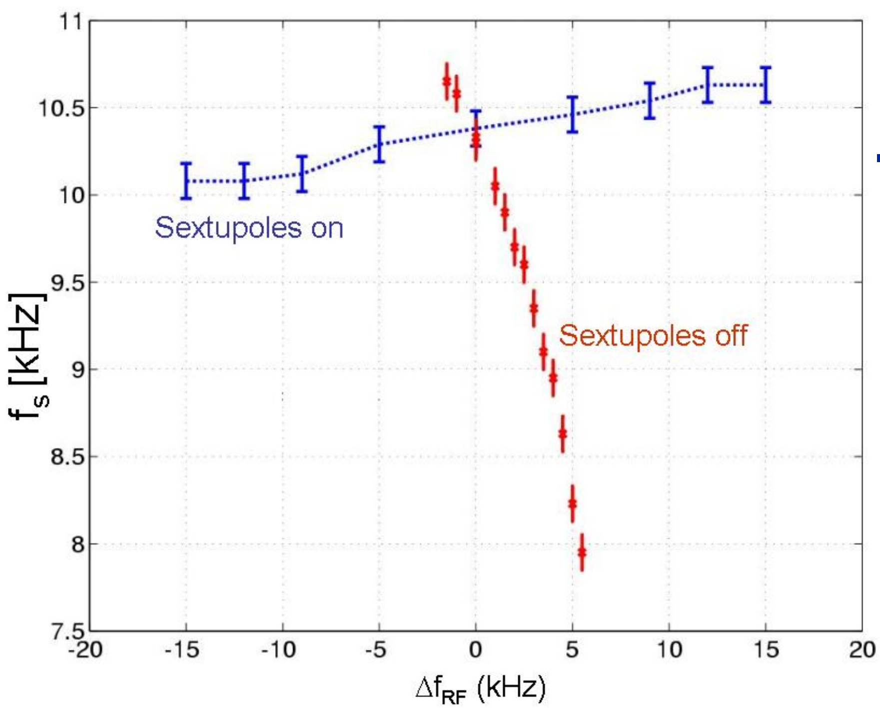


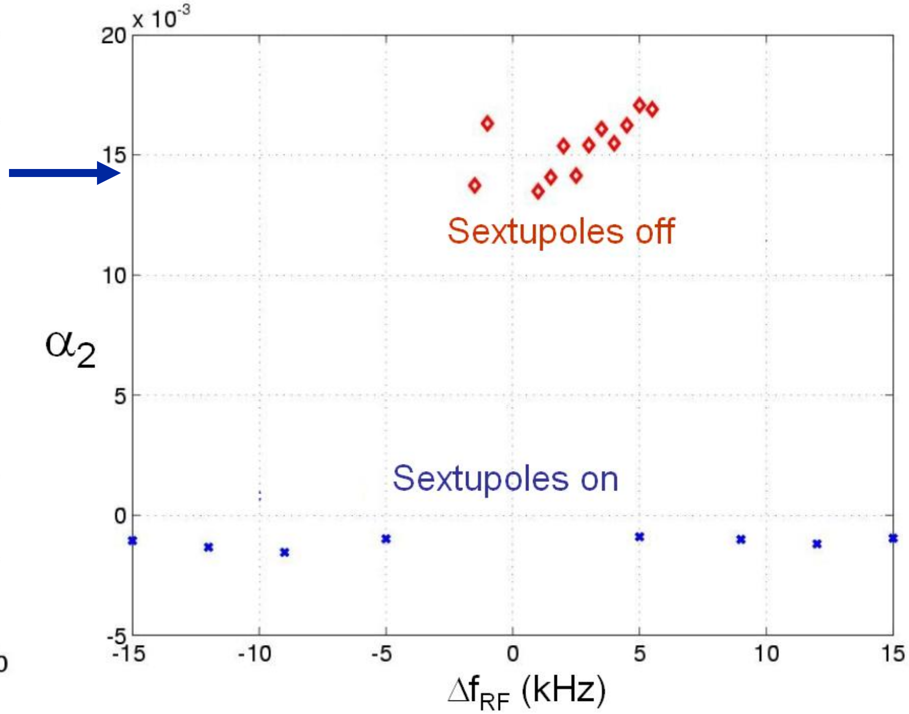
4D tracking using AT

α_2 measurement

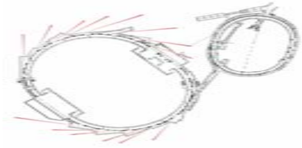


- $|\alpha_2|$, sextupoles off >> $|\alpha_2|$, sextupoles on
- Energy aperture much reduced with sexupoles off





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 a new book:

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