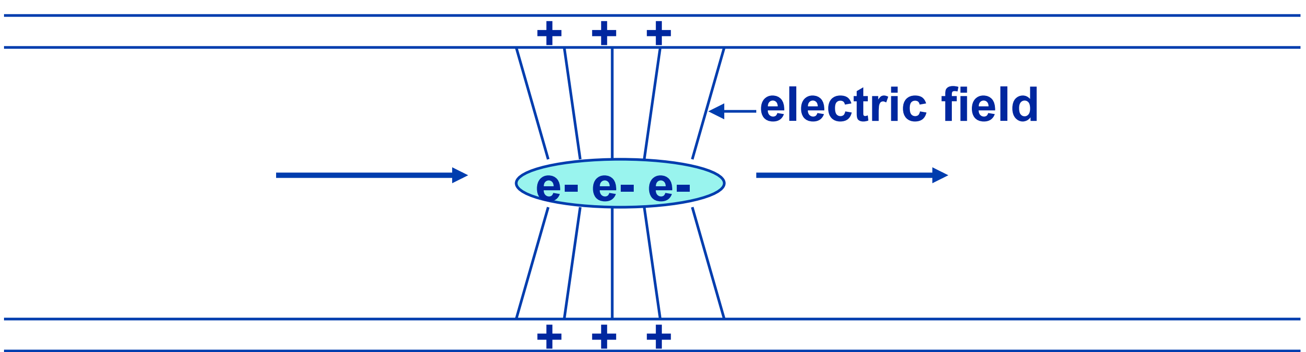
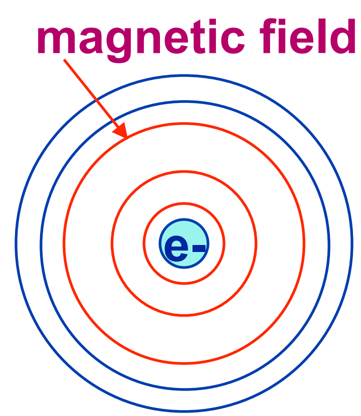
Storage ring measurements, the basics

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

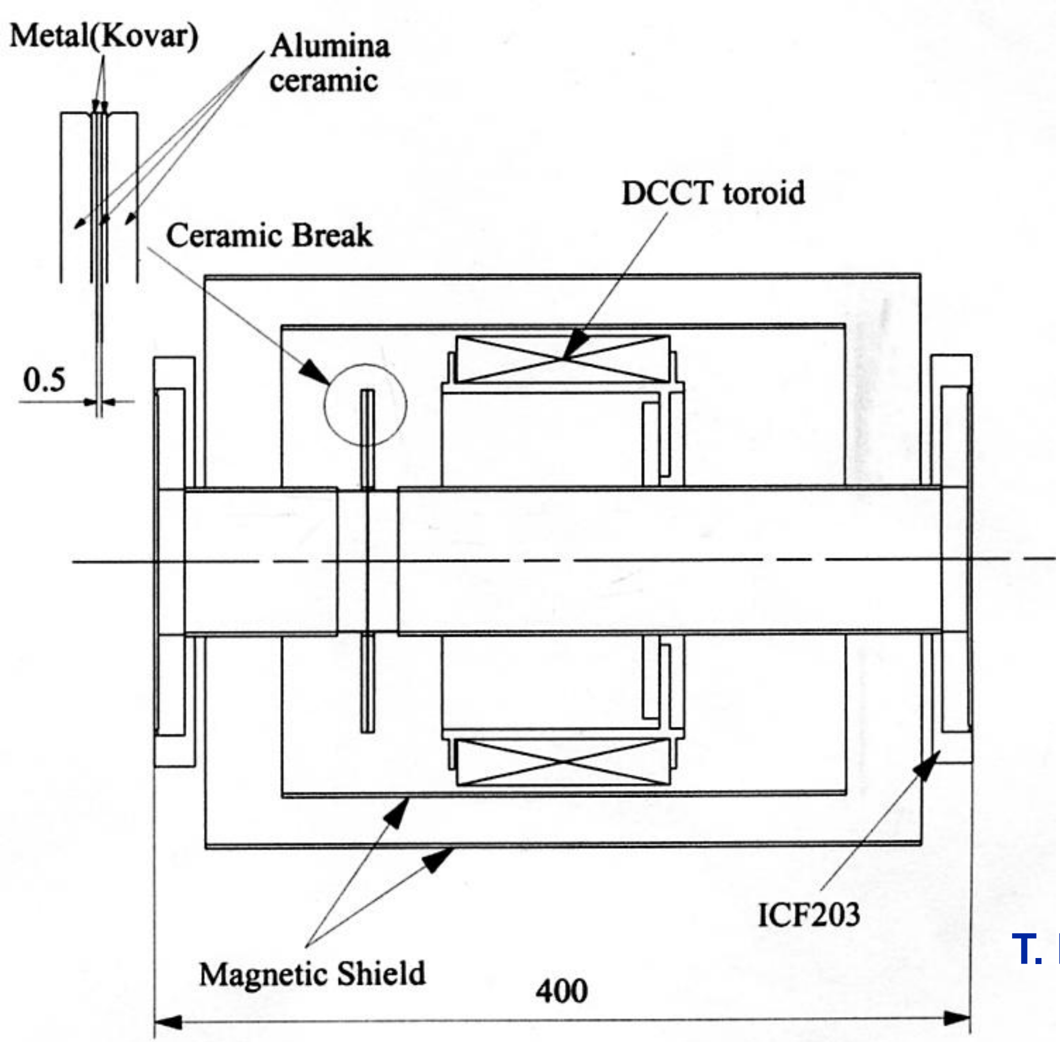
Beam diagnostics: Intensity/current

- 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, …)



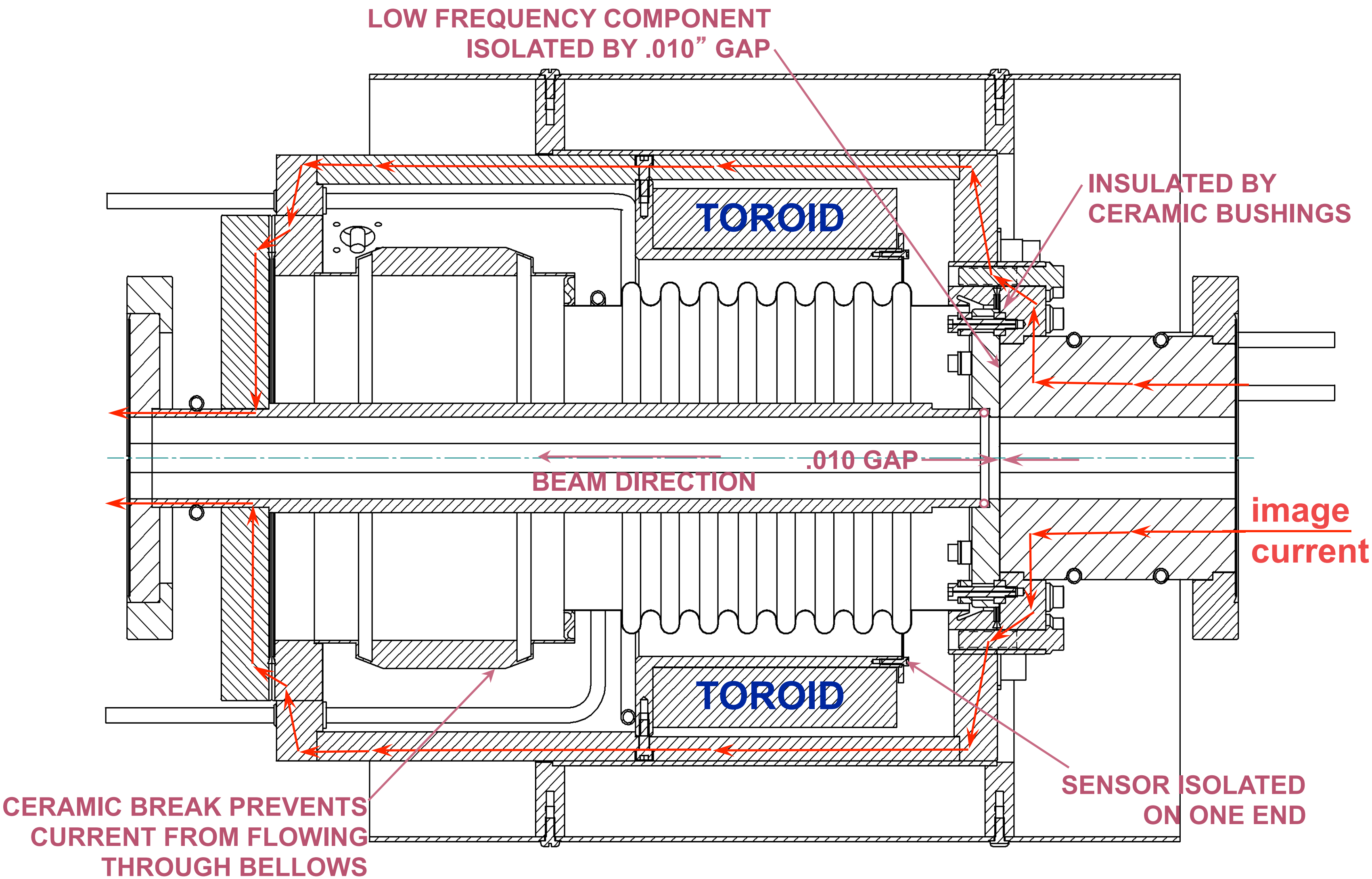


Photon factory DCCT



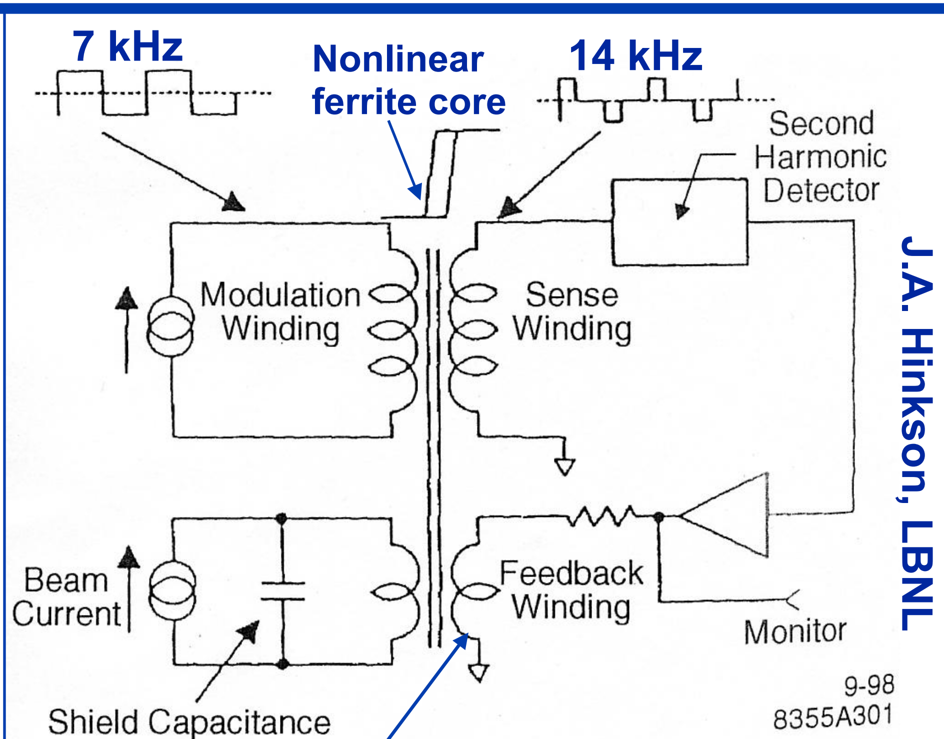
T. Honda et al., EPAC98

SPEAR3 DCCT



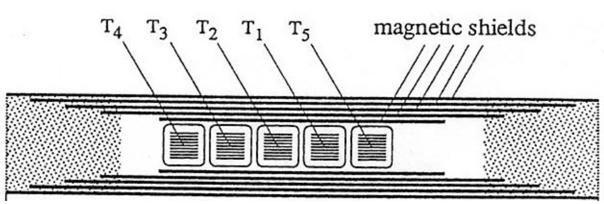
LOW FREQUENCY COMPONENT
ISOLATED BY .010" GAP
TOROID
INSULATED BY
CERAMIC BUSHINGS
.010 GAP
BEAM DIRECTION
image
current
TOROID
CERAMIC BREAK PREVENTS
CURRENT FROM FLOWING
THROUGH BELLOWS
SENSOR ISOLATED
ON ONE END

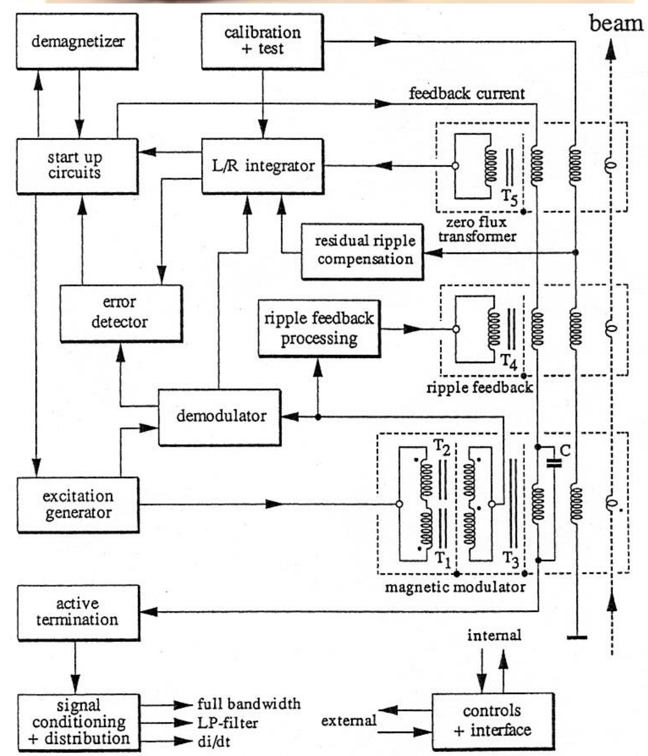
DCCT (or PCT) circuit



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.

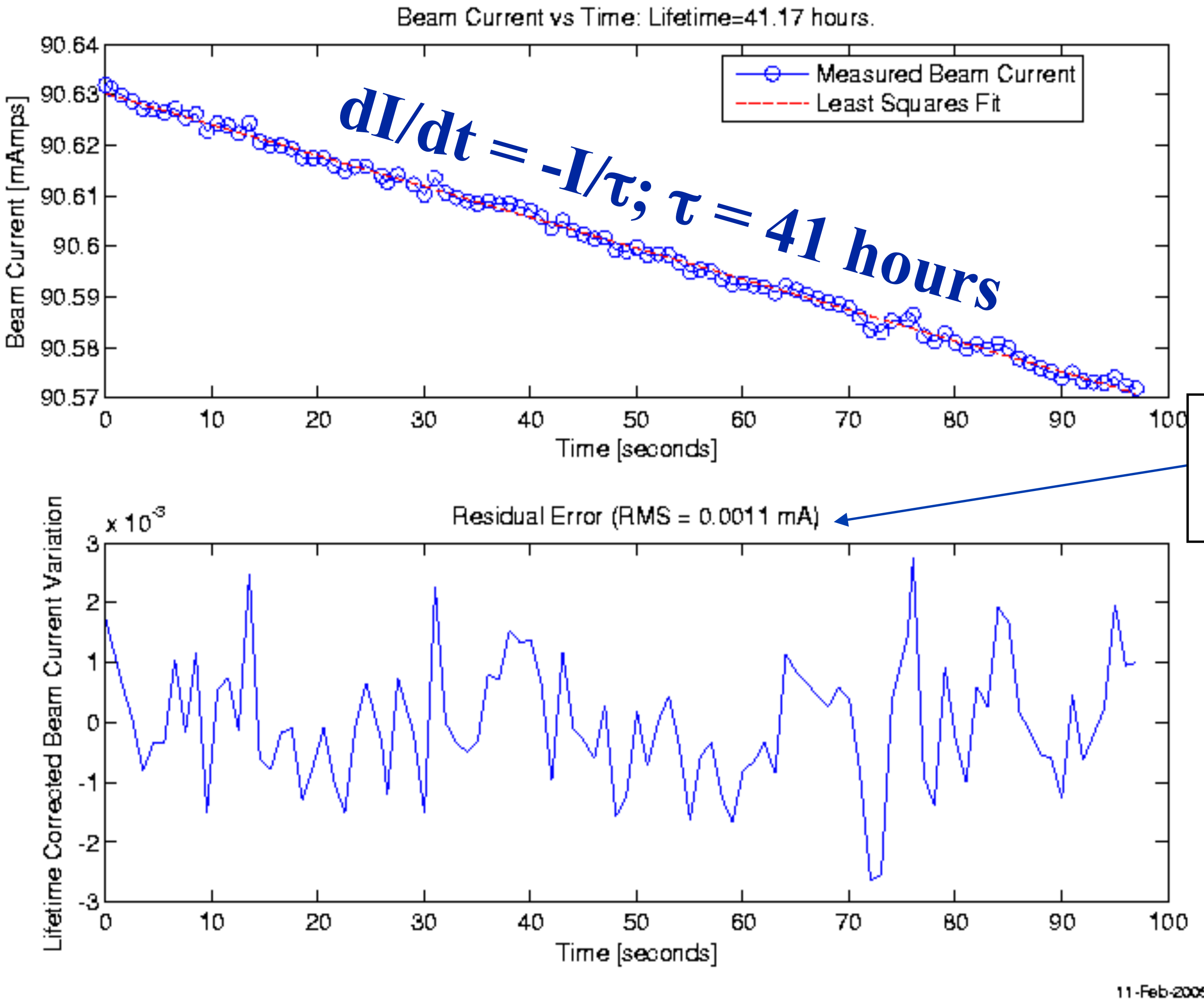
Ferrite core Xsection





Simplified circuit, K. Unser, 1992

SPEAR3 lifetime measurement w/ DCCT

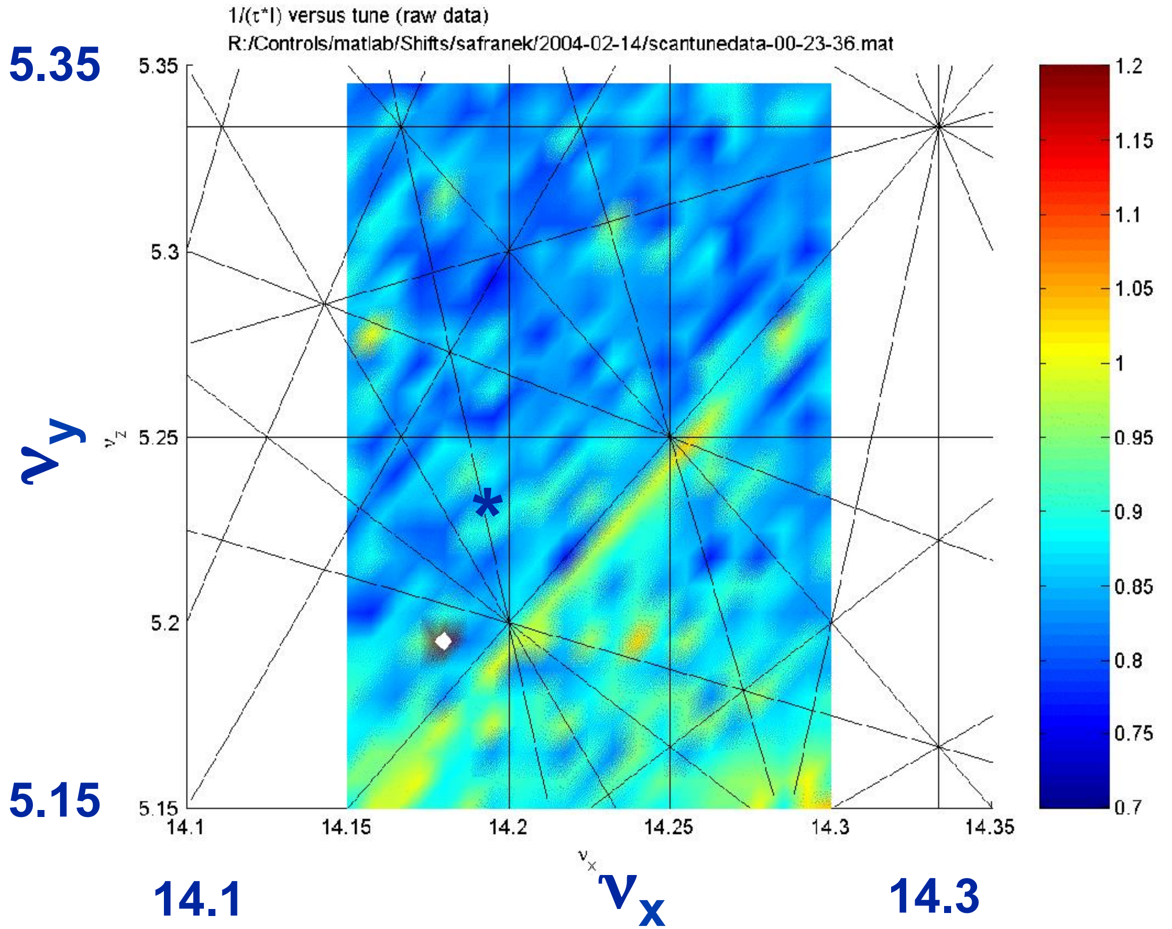


DCCT resolution:

1 μA in 1 second

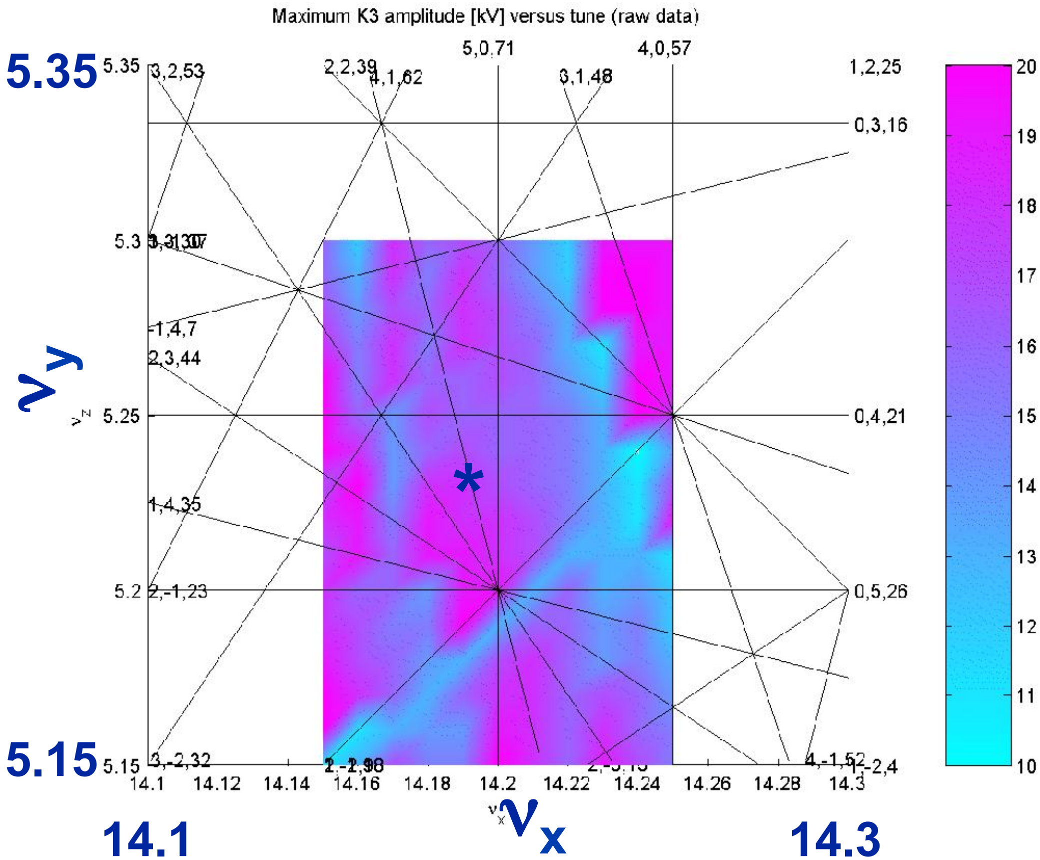
Lifetime vs. tunes

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



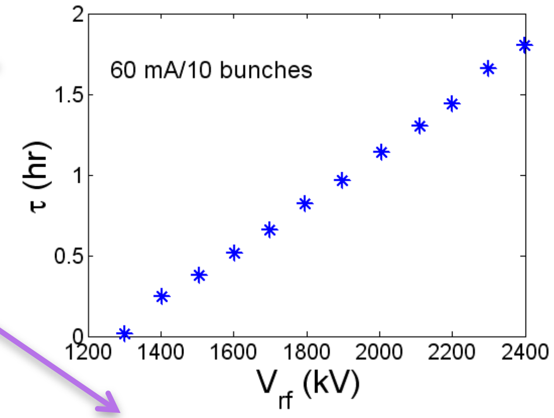
Dynamic aperture vs. tune

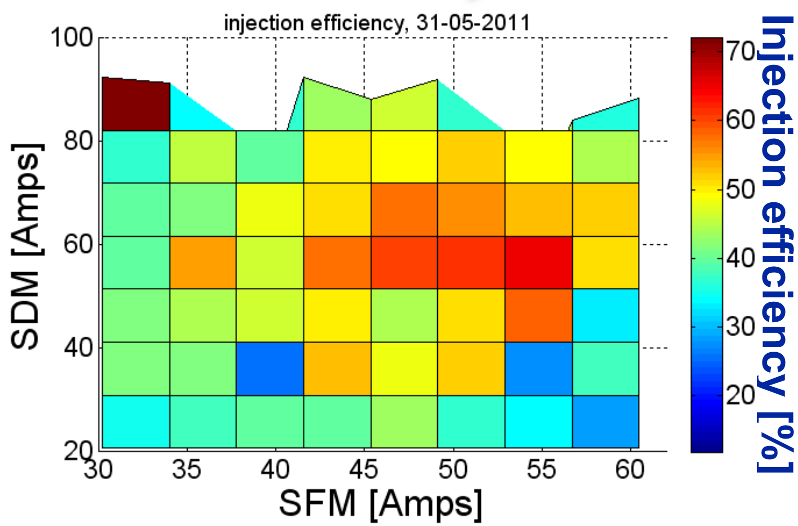
- **Resonant lines:**
  - $\nu_x - \nu_y = 9$
  - $3\nu_x + \nu_y = 48$
  - $4\nu_x + \nu_y = 62$
- **Resonances offset from tune shift with amplitude.**
- *** = operating tunes (14.19, 5.23)**
- **Data gathered automatically on owl shift.**

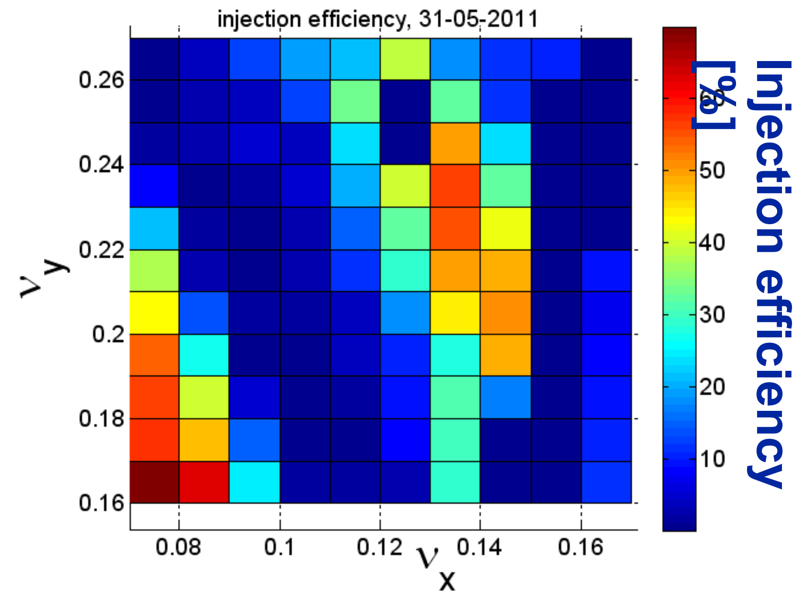


More DCCT-based measurements

- Energy acceptance
- Injection rate vs. tune scan
- Injection rate vs. sextupole scan

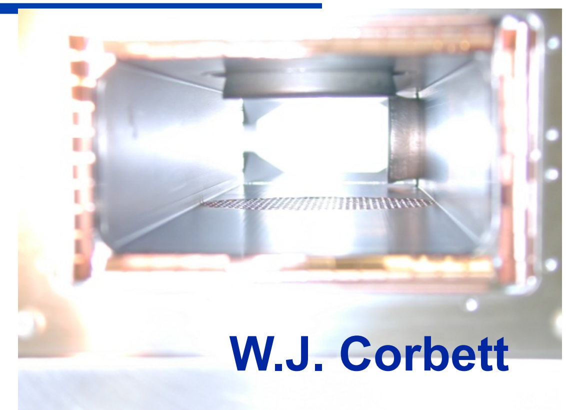






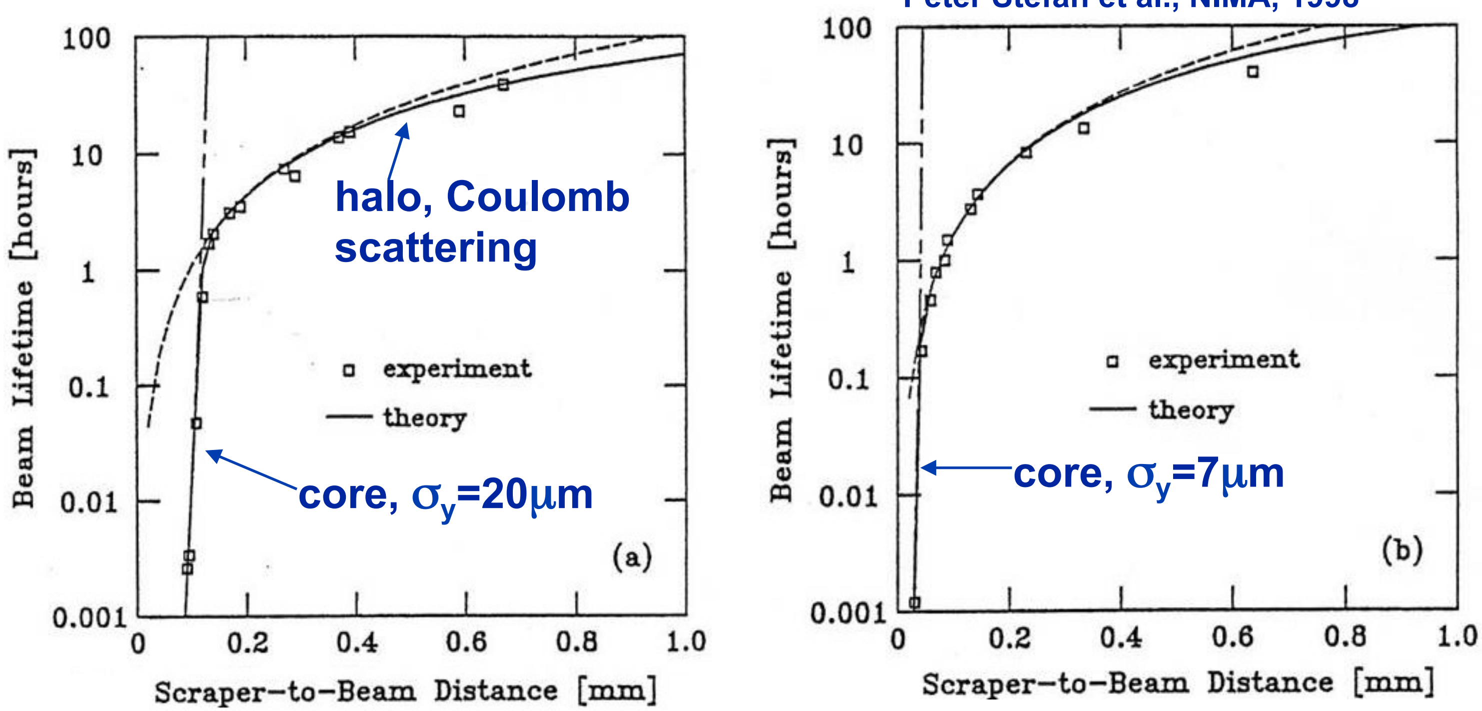
Beam scrapers; lifetime vs. vertical aperture

Scrapers measure beam halo



W.J. Corbett

Peter Stefan et al., NIMA, 1998



SPEAR3 scraper measurements

Three contributions to lifetime:

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

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

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

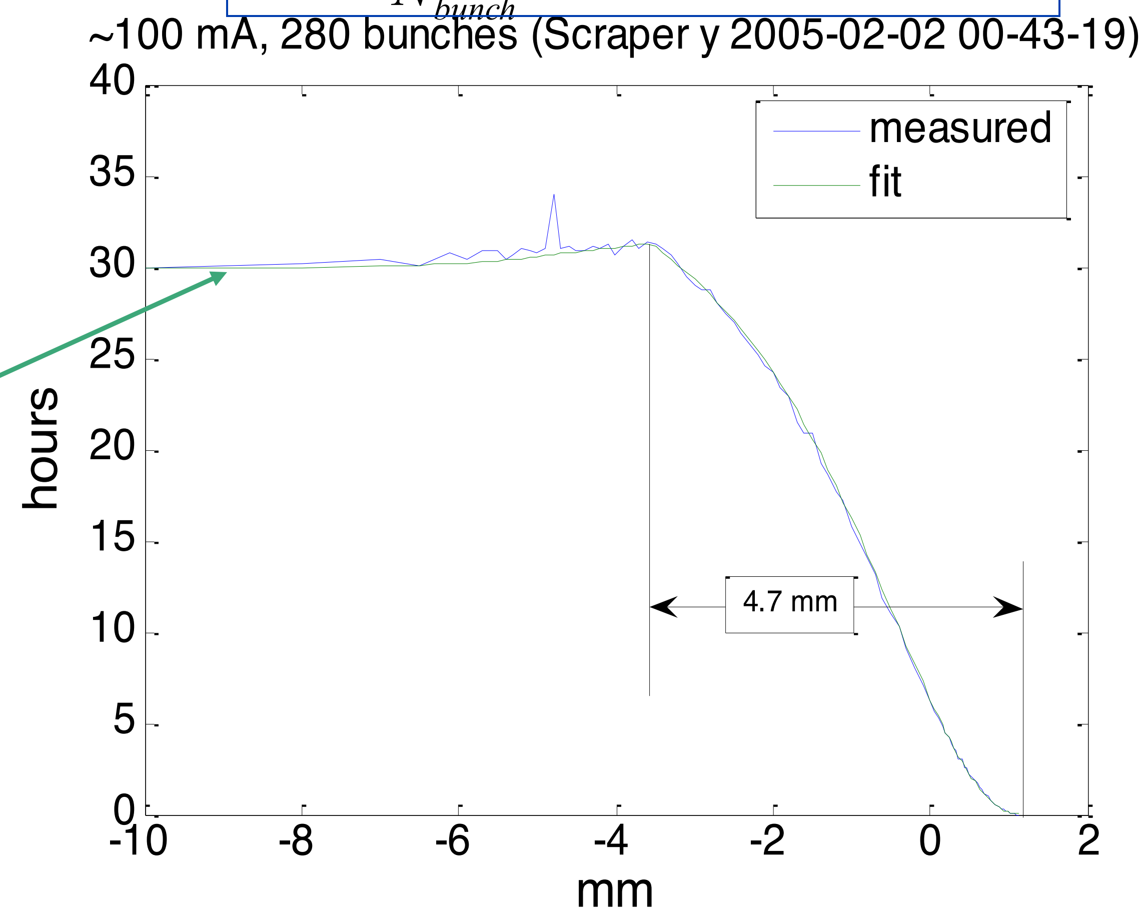
$$\tau_B \propto \text{pressure} * f(\text{E}_{\text{aperture}}) \approx I_{tot}$$

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

Five fit parameters:

$$\tau_{C0}, \tau_{B0}, \tau_{T0},$$

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

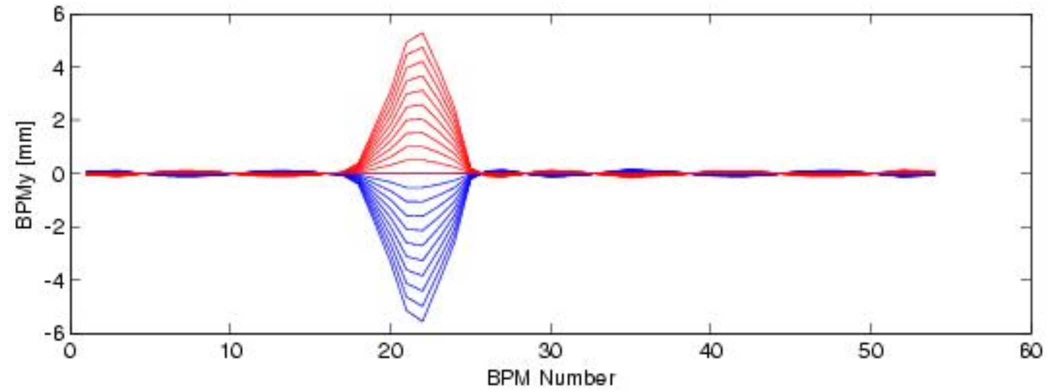


Physical aperture probe

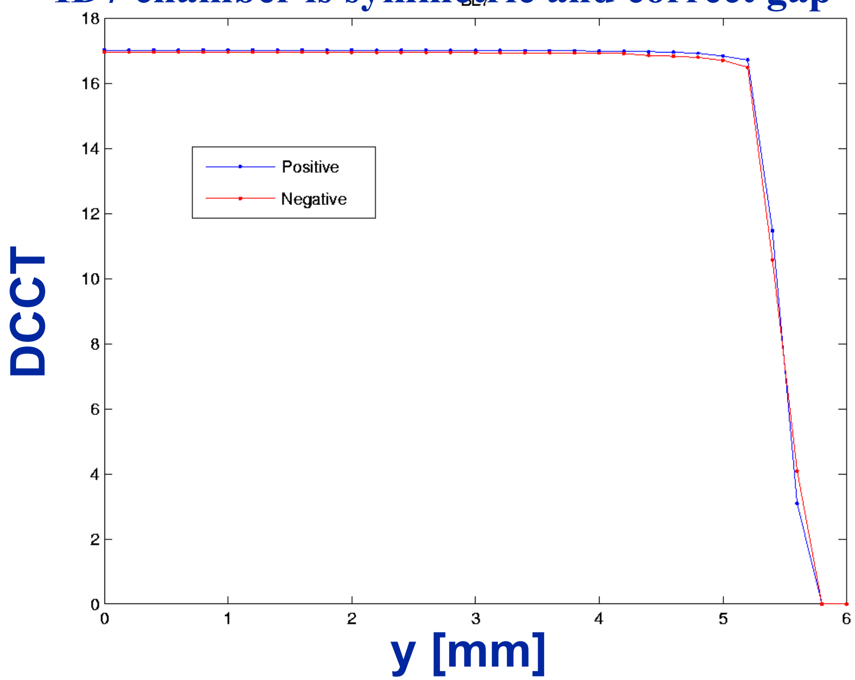
Vertical beam bump in ID chamber

y-bump in ID chamber:

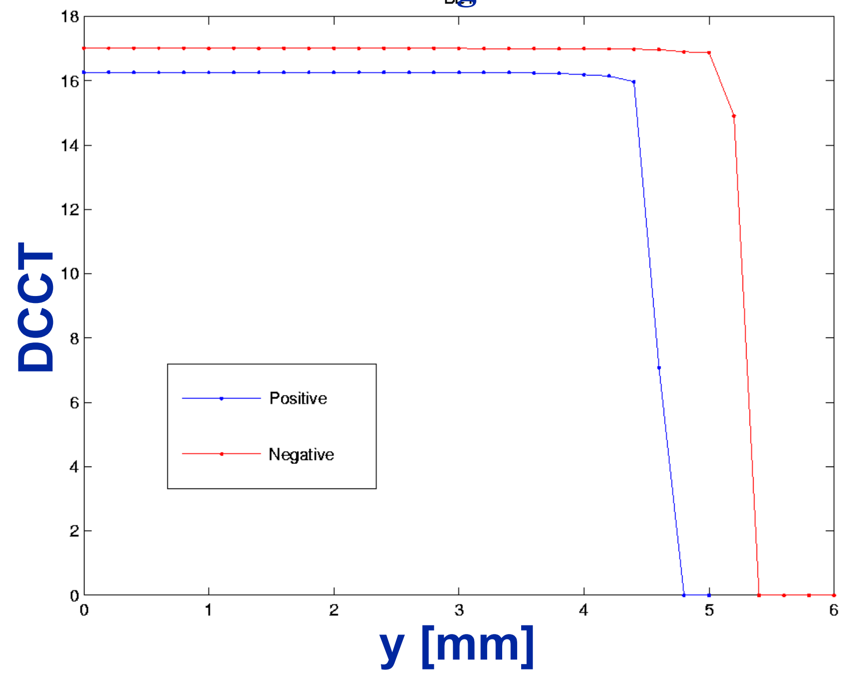
- Bump beam up until lost
- Refill
- Bump beam down until lost



ID7 chamber is symmetric and correct gap



ID4 chamber is mis-aligned and too small

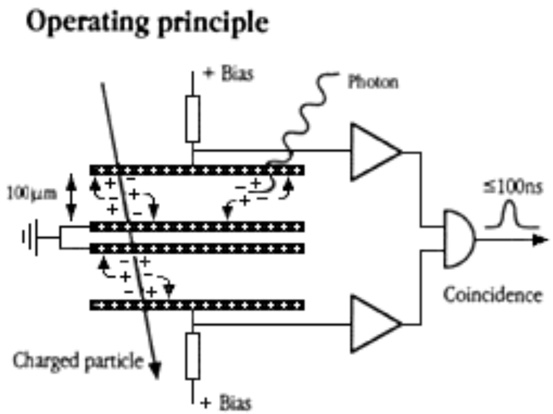


Beam loss monitors

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).

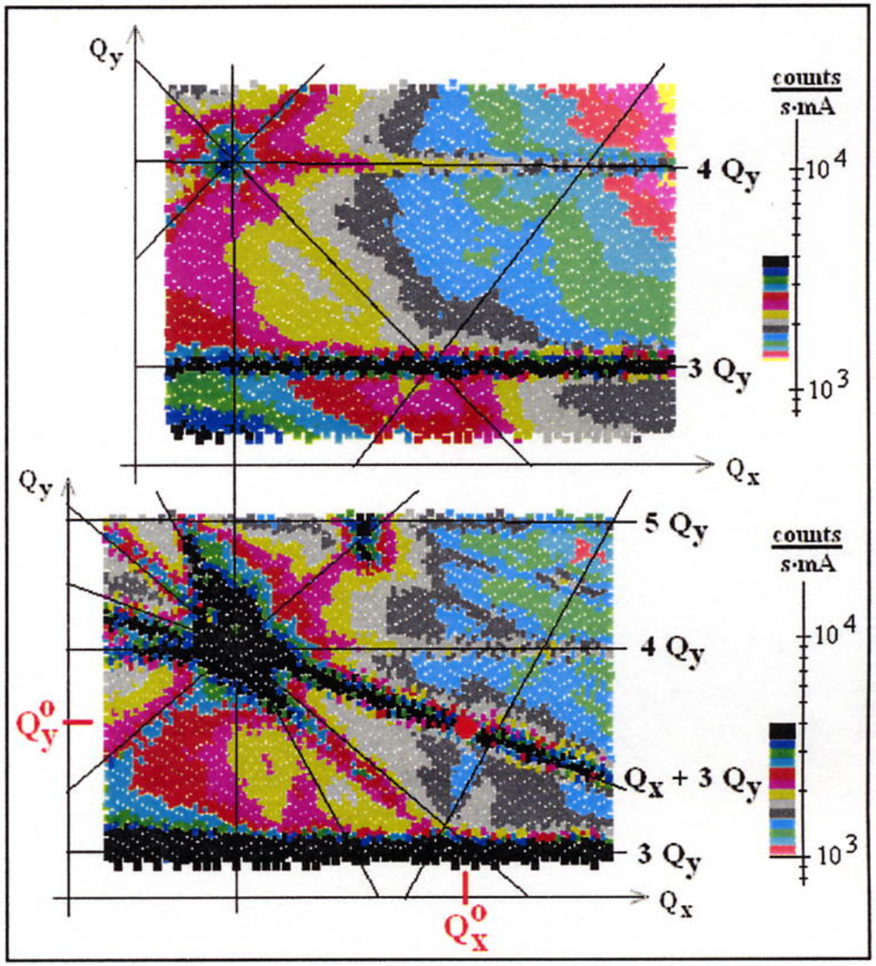
Bergoz PIN diodes generate pulses when from ionizing particles.



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).

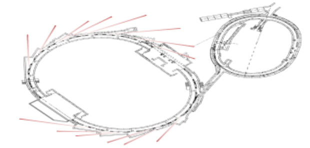


Insertion device open

Insertion device closed

Kuske et al., PAC01.

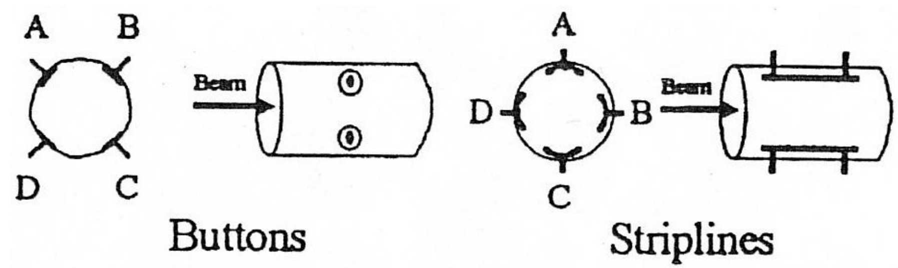
Beam Diagnostics: Position/Closed Orbit



- 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.

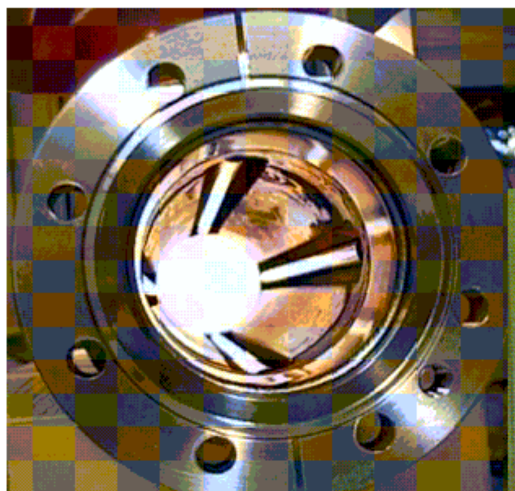
Beam position monitors

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

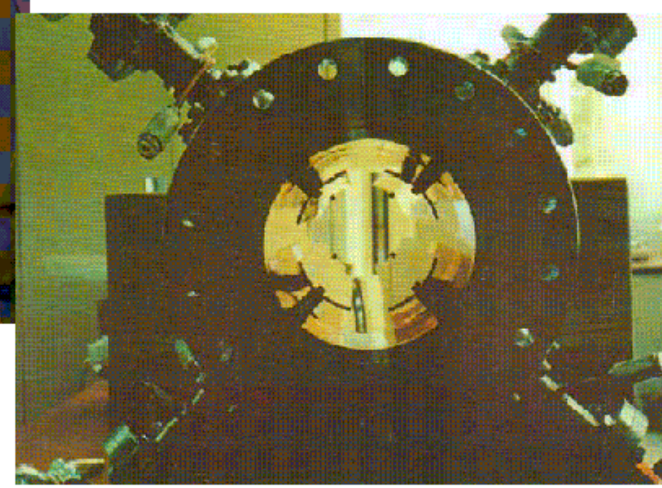


Electron BPM buttons sample electric fields; striplines couple to electric and magnetic fields.

Striplines



M. Wendt, DESY



M. Tobiyama, KEK

Capacitive Pickups, Button BPMs

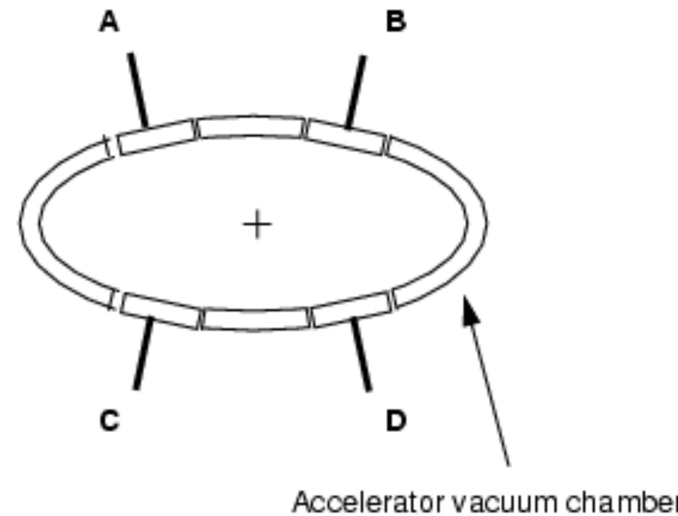
Charged Particle Beam Pickup Electrodes

Capacitive buttons

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

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

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

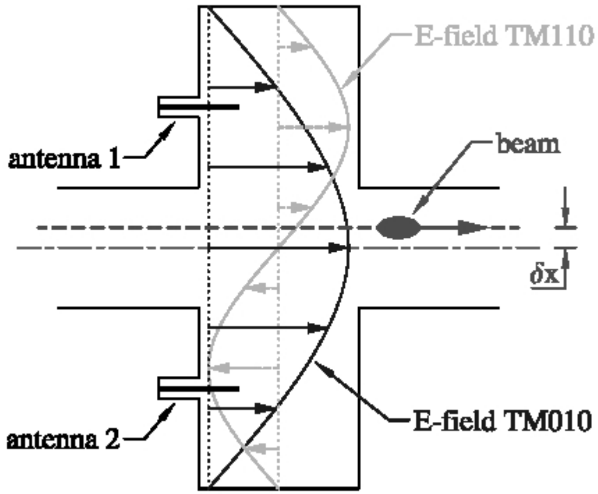


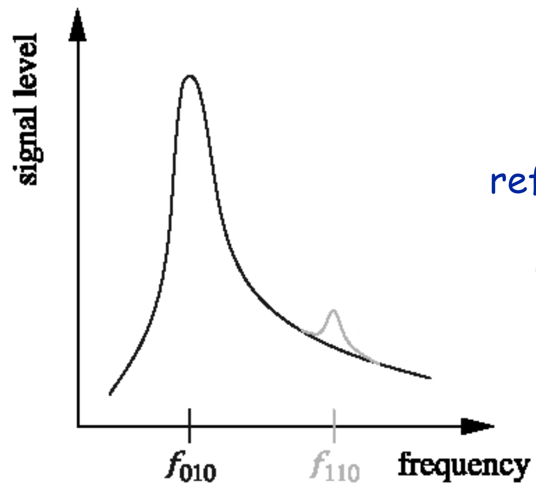
e.g. for round buttons of radius a in round pipe of radius r

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

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

CAVITY BPMs:

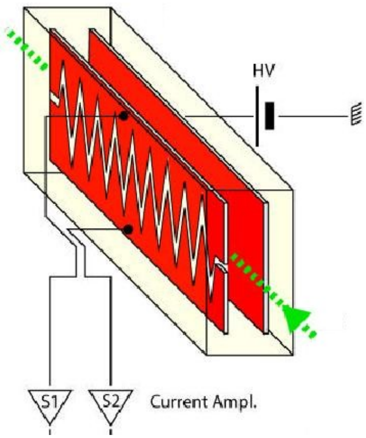




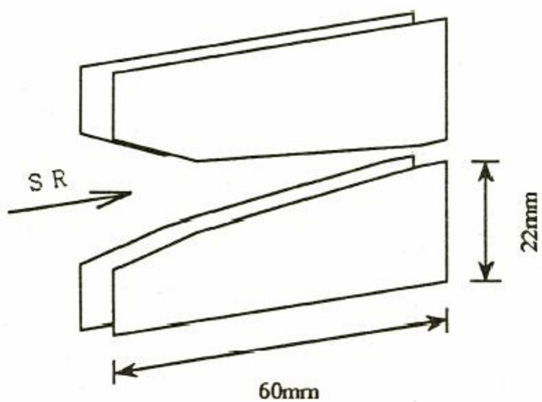
reference:
"Cavity BPMs", R. Lorentz
(BIW, Stanford, 1998)

PHOTON BPMs:

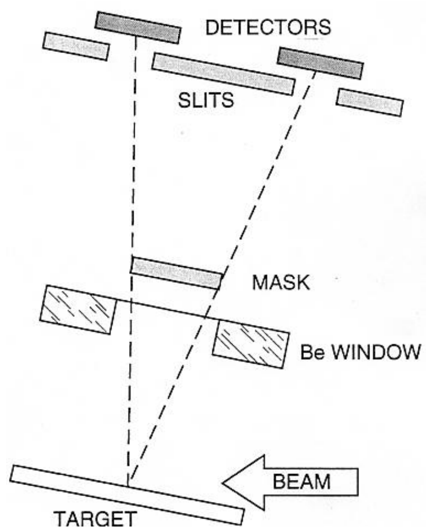
Split ion chamber:



Tungsten blade monitor:



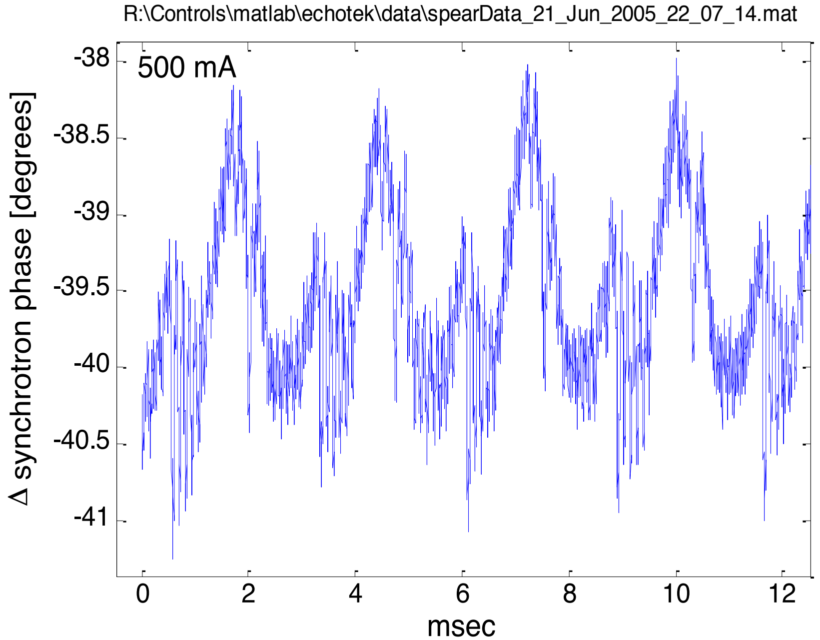
Copper fluorescence bpm:



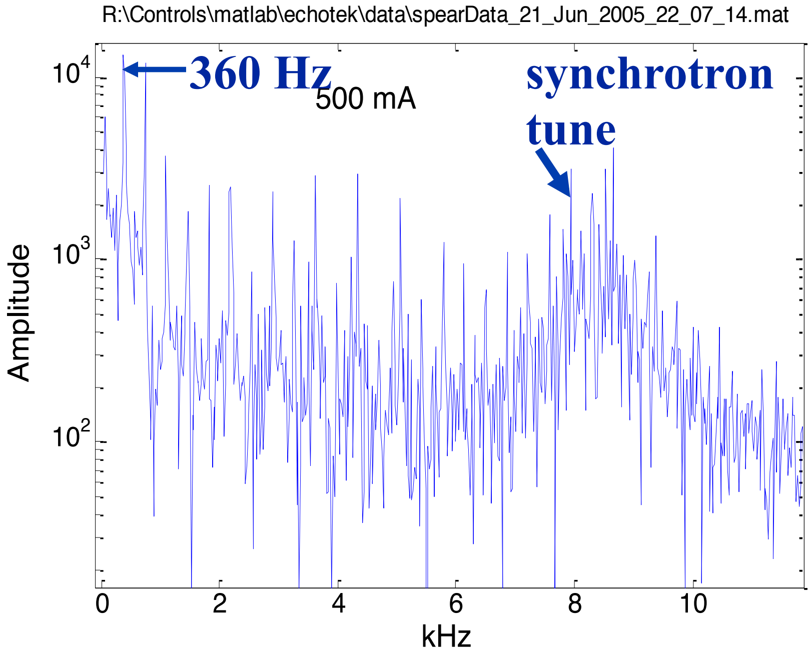
Longitudinal oscillations, BPMs

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



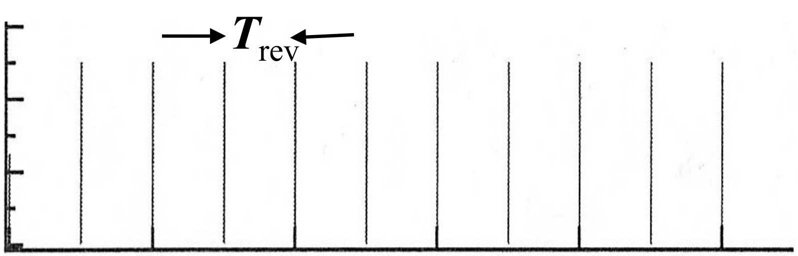
Beam frequencies

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

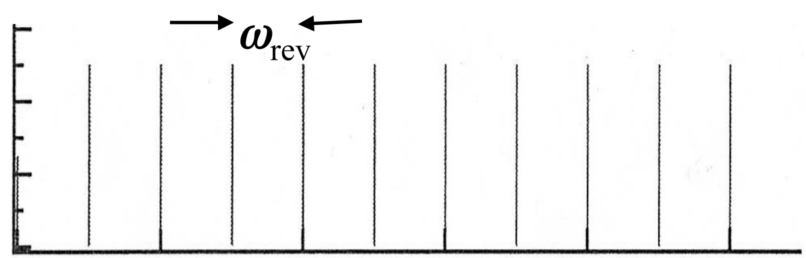
$$I(t) = \sum_{n=-\infty}^{\infty} q\delta(t - nT_{\mathrm{rev}}),$$

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

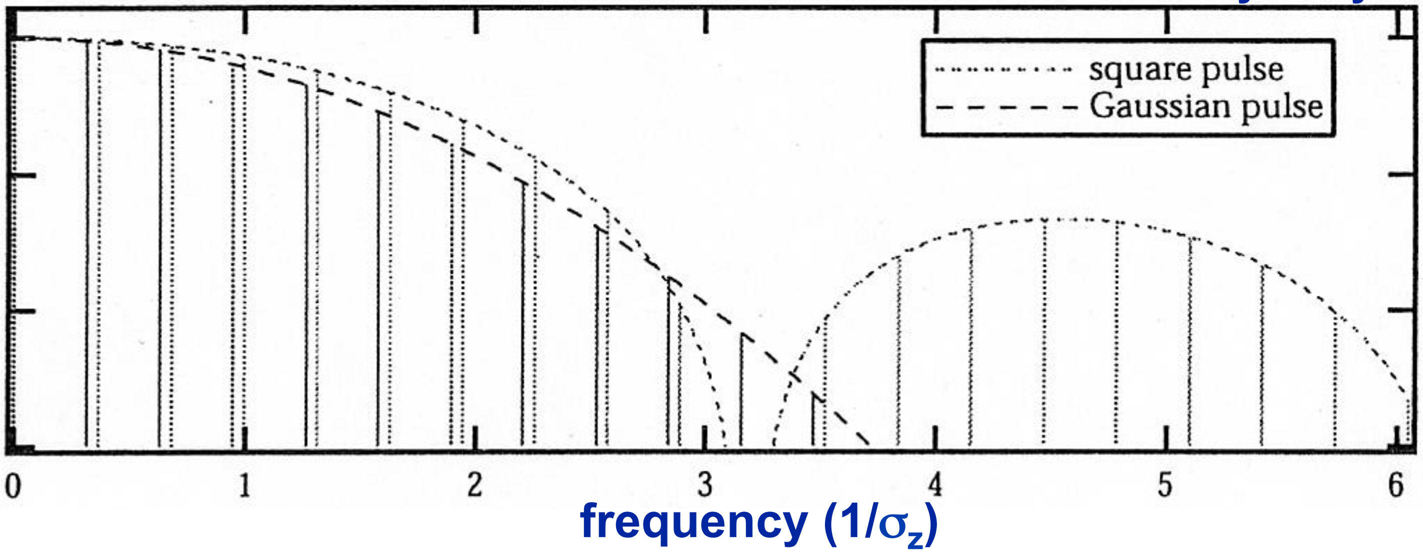


Frequency

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



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

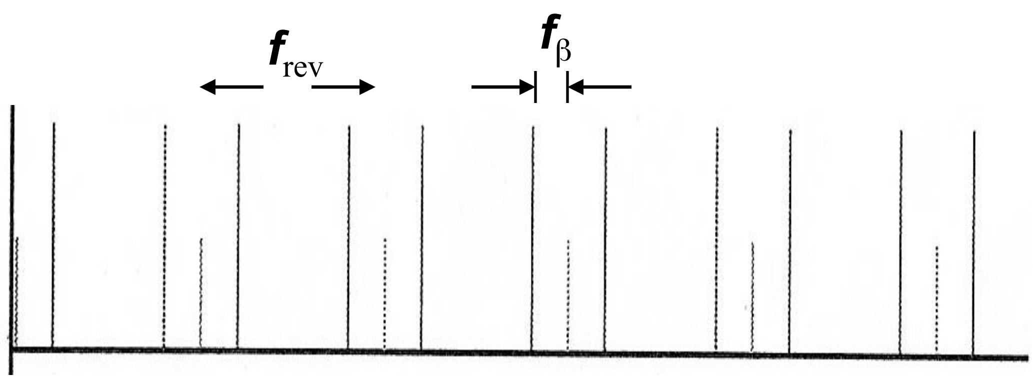
Betatron tune

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

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

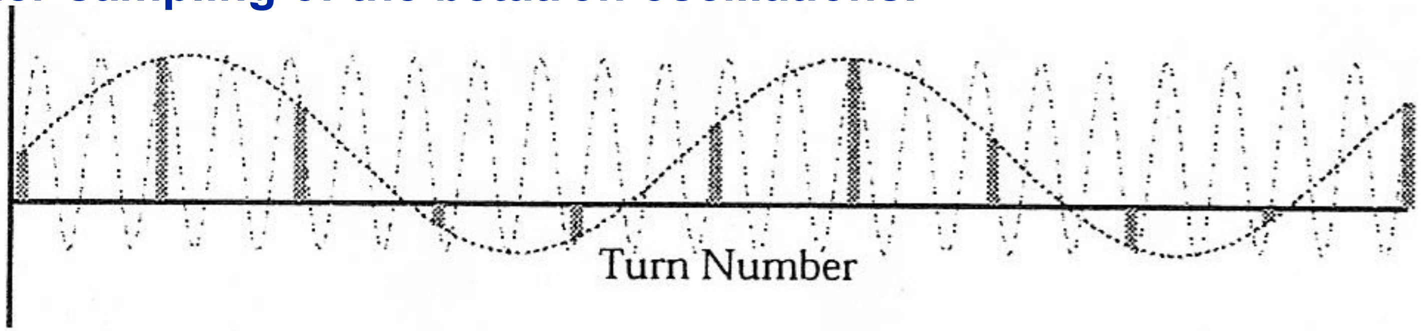


Frequency

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

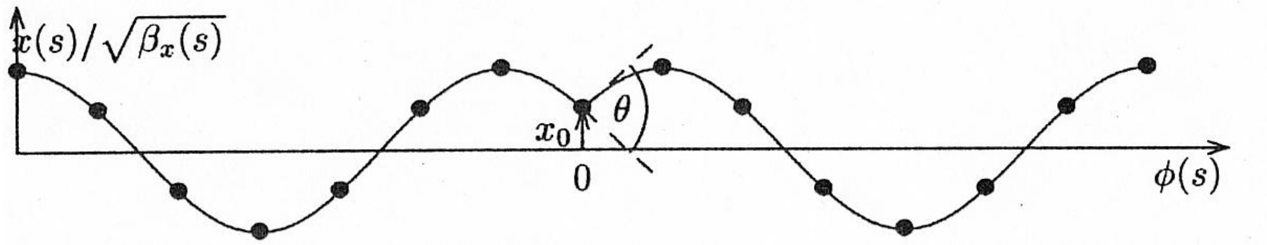
Betatron tune, 2

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



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

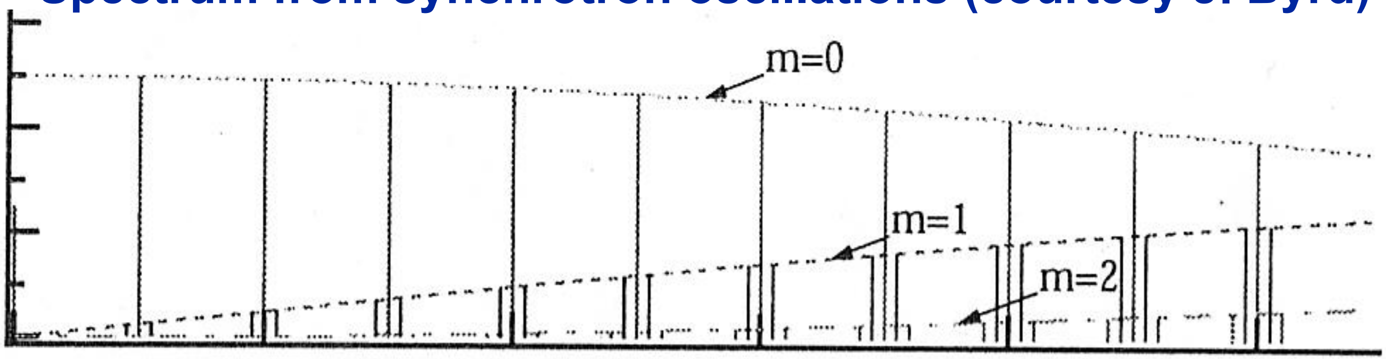
$$\frac{\Delta x_i}{\Delta \theta_j} = \frac{\sqrt{\beta_i \beta_j}}{2\sin(\pi\nu)} \cos(|\phi_i - \phi_j| - \pi\nu)$$



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.

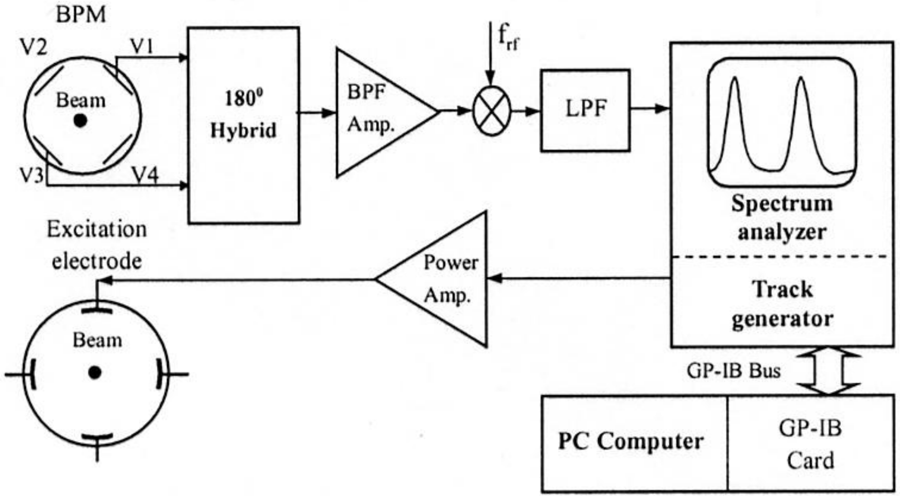
Spectrum from synchrotron oscillations (courtesy J. Byrd)



frequency

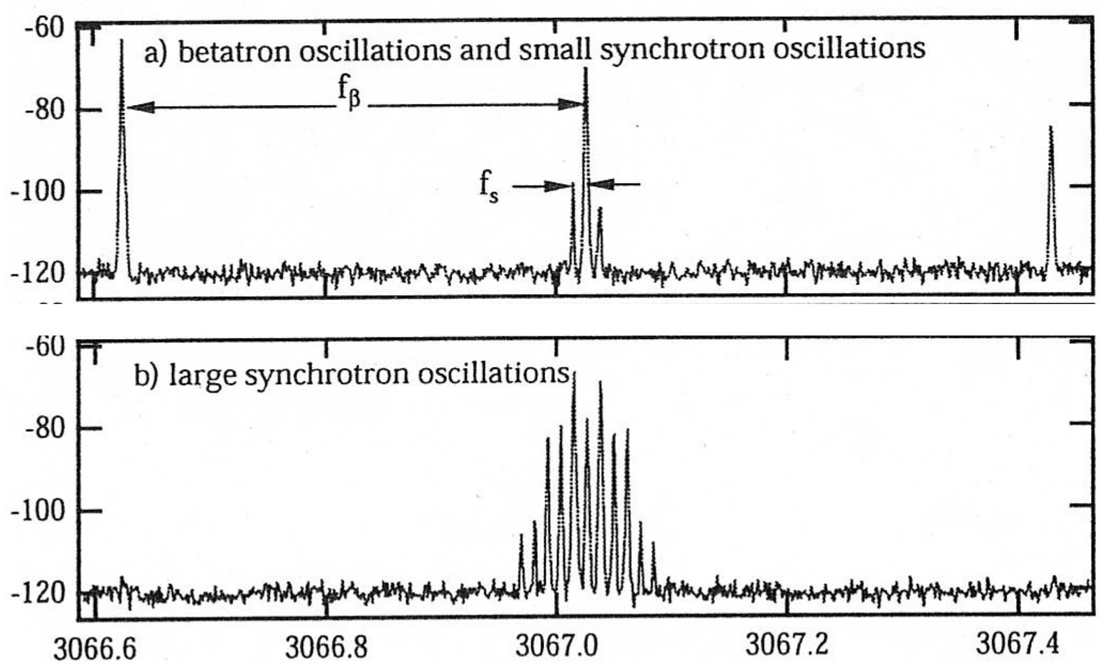
Measured spectra

Typical tune measurement



HLS tune meas., Sun et al. PAC01

Typical measured spectra



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:

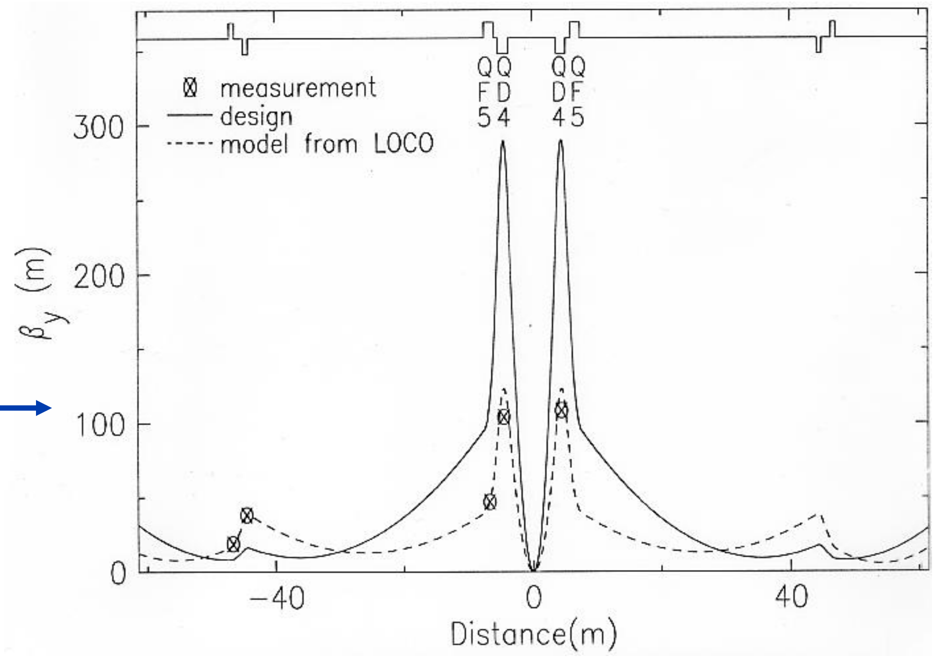
$$\Delta\nu = \beta \frac{\Delta(KL)}{4\pi}$$

Measurement issues

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

β measurement in PEPII HER IR indicates optics problem.

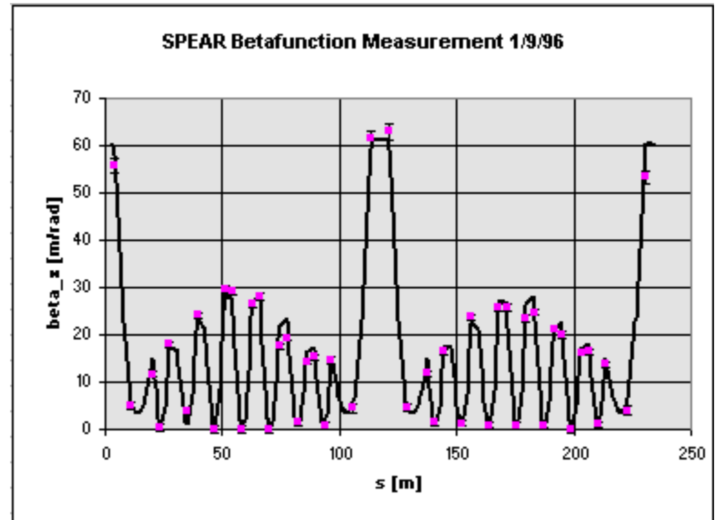
(Methods to be described Tuesday were used to find source of problem and correct it.)



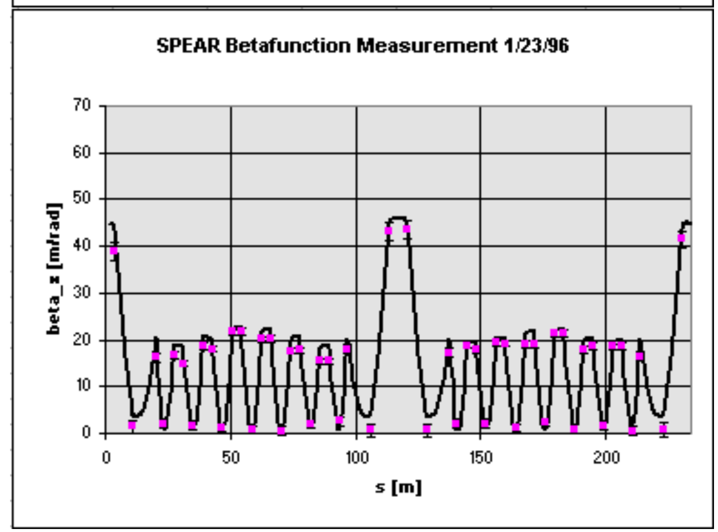
SPEAR β-function correction

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.

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)

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

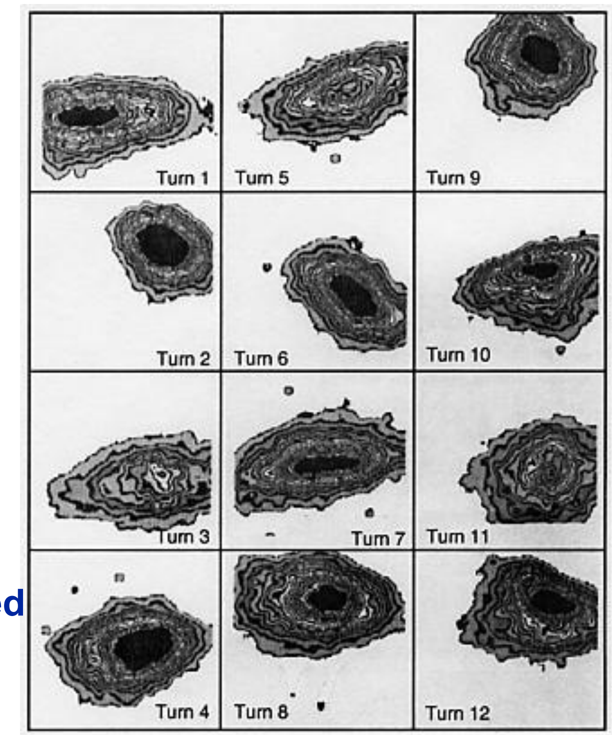
$N_{BPM}*N_{steerer}$ data

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

2. Fit quadrupole gradients, K, to measured orbit response matrix. From K get β (Tuesday lecture).
3. Derive from betatron phase measurements (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.

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

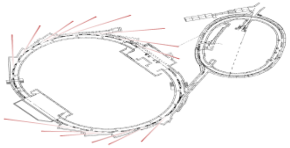
The energy can be changed by shifting the rf frequency.

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

(α = momentum compaction)

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

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

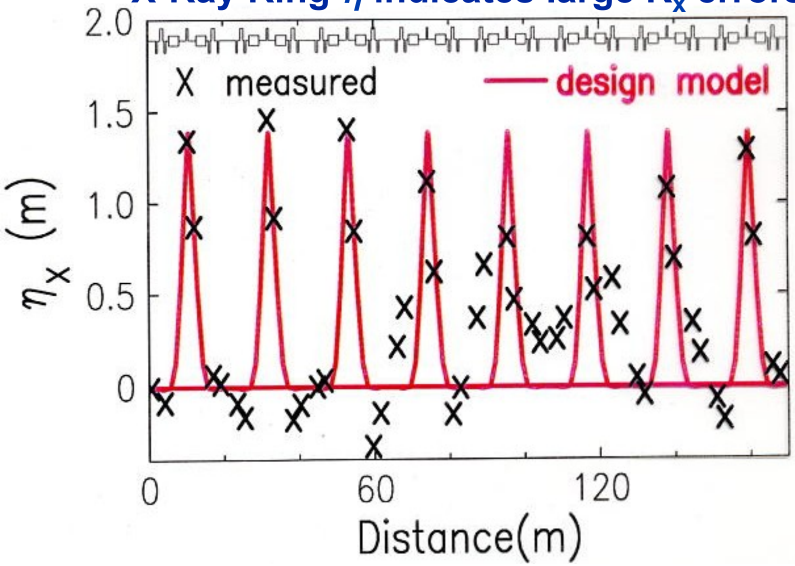


Dispersion measurement

Dispersion distortion can come from quadrupole or dipole errors.

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

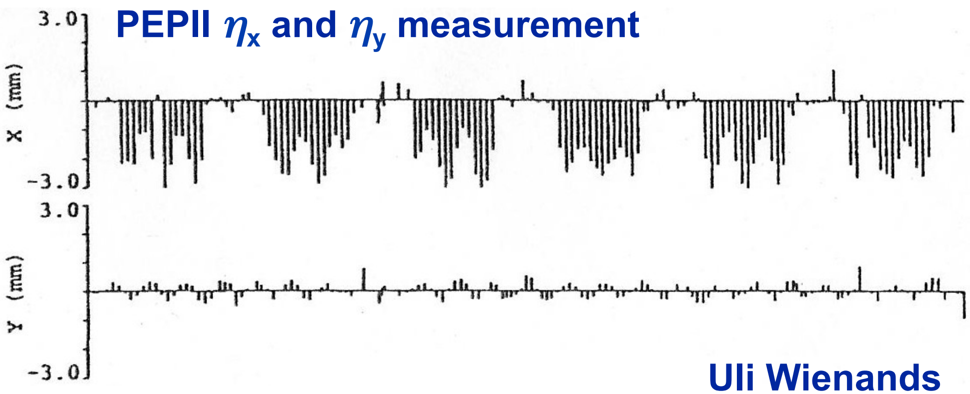
X-Ray Ring η indicates large K_x errors



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

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

PEPII η_x and η_y measurement

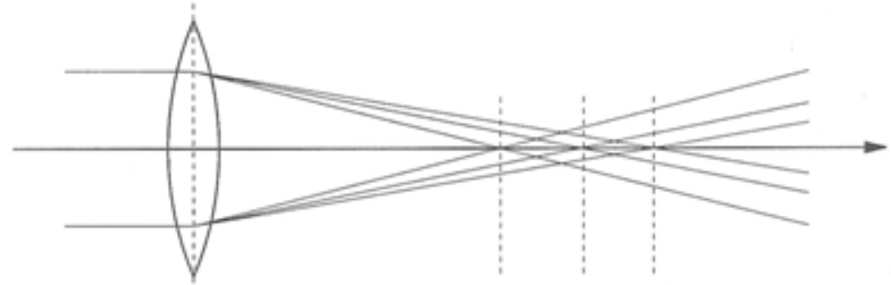


Uli Wienands

Chromaticity

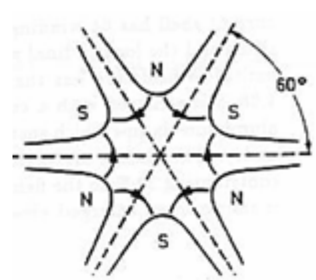
Quadrupoles focus high energy particles less than low energy particles. This leads to a decrease in tune with energy (natural chromaticity):

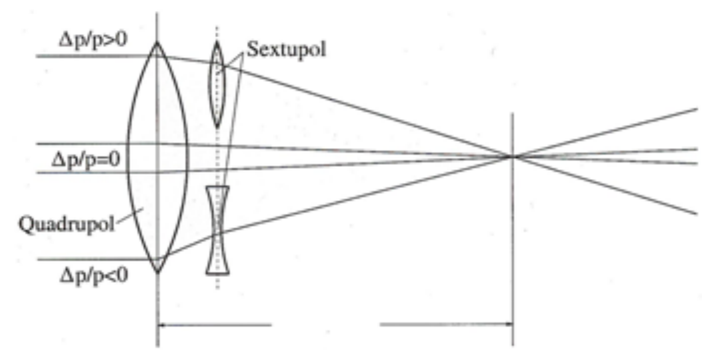
$$\xi_N = \Delta\nu \Big/ \frac{\Delta p}{p}$$



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:

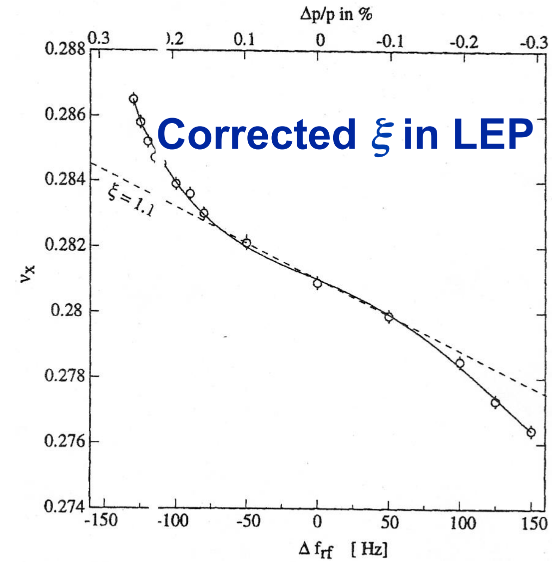
1. Change the rf frequency. This shifts the orbit in sextupoles, giving the corrected chromaticity.

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

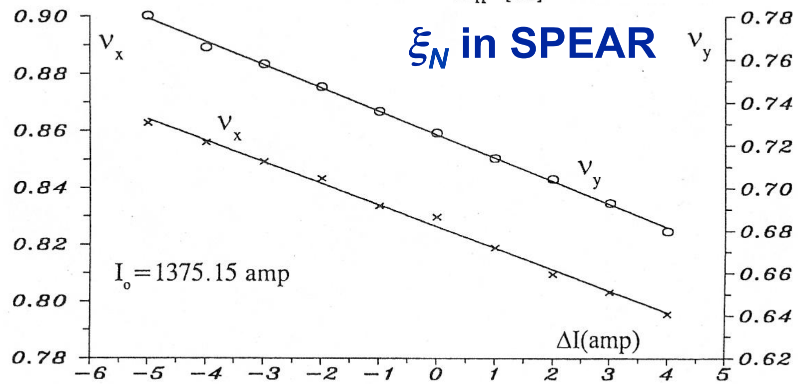
Used to diagnose sextupole mis-wiring in PEPII-HER.

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

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



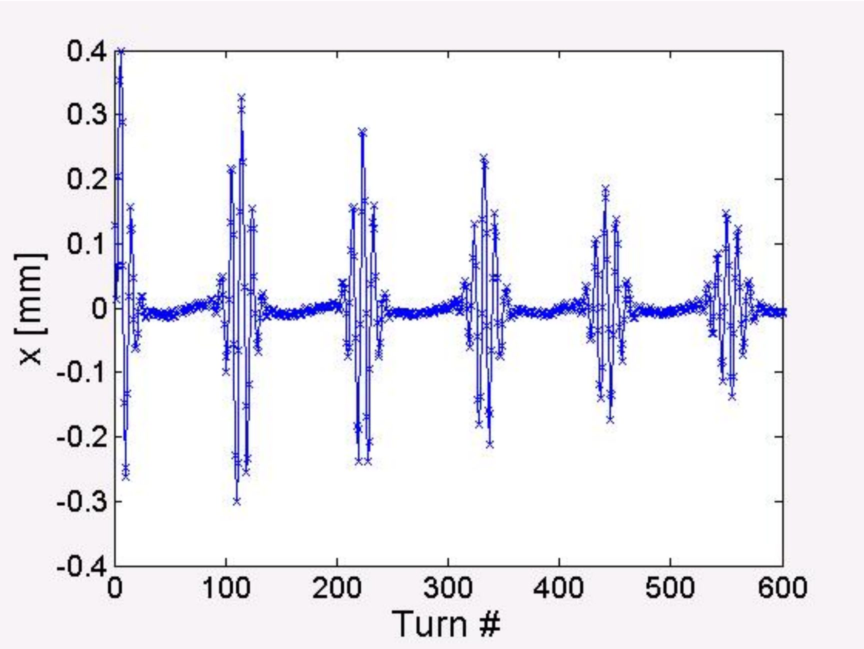
H. Burkhardt



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

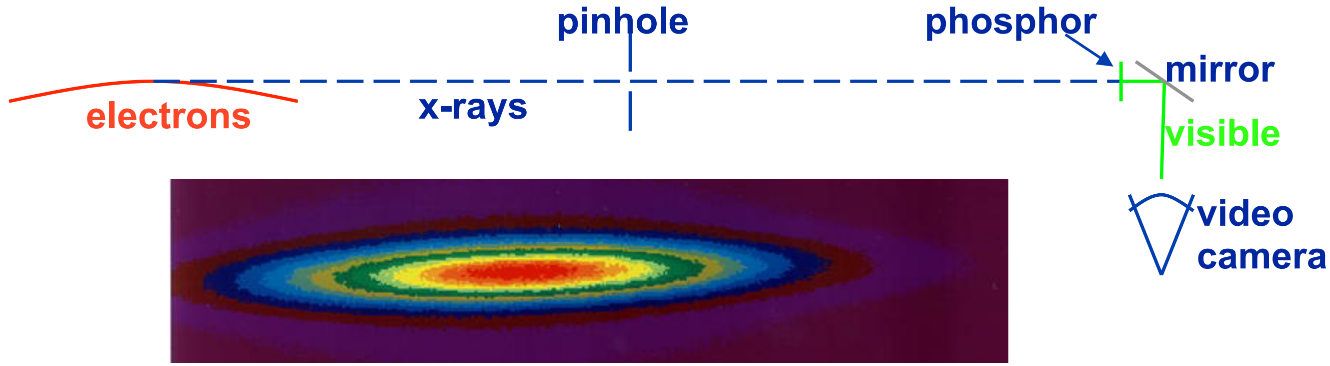
Natural chromaticity measurement

- Turn-by-turn BPM readings during natural chromaticity measurement (sextupoles off)
- Beam was kicked with injection kicker to measure ν_x
- Why do oscillations disappear and reappear?

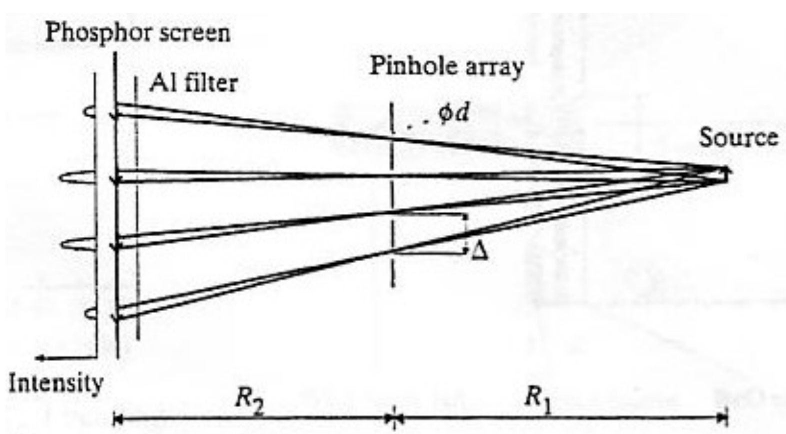


Beam size measurements

X-Ray pinhole camera



Pinhole camera array
(Kuske et al., Bessy)



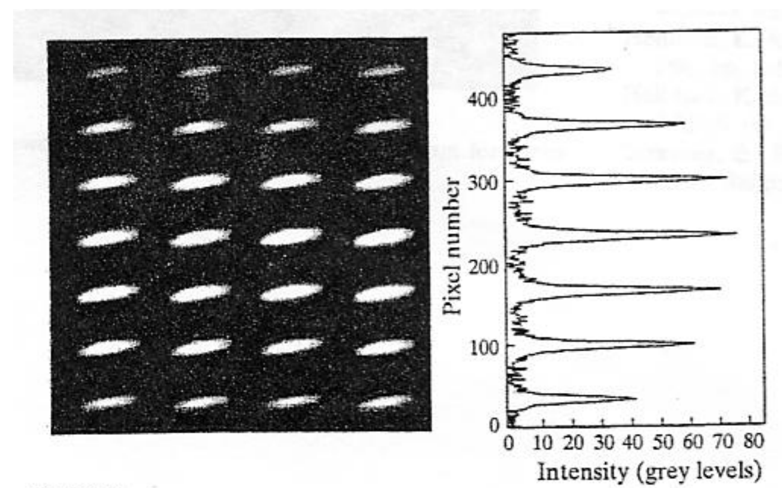
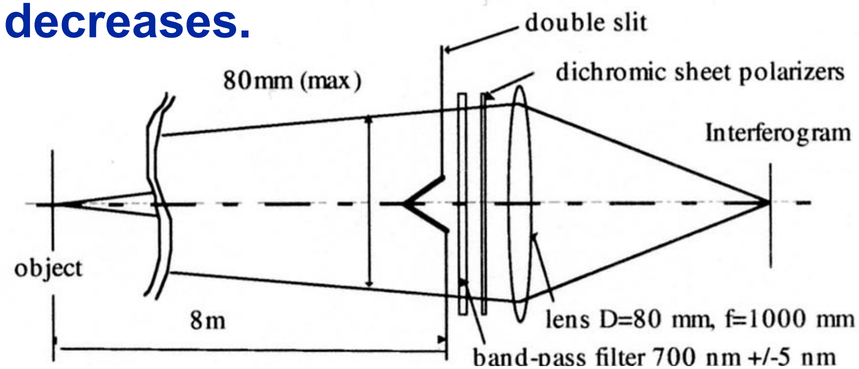


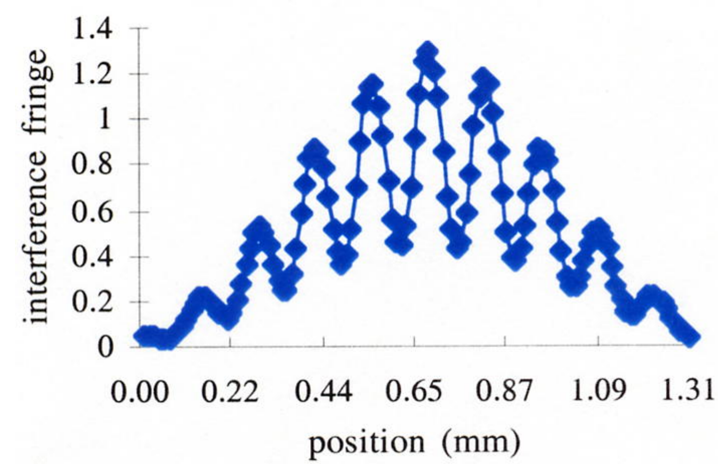
Figure 2
Left: image of a portion of the phosphor observed on a BESSY I bending magnet. Right: integrated intensities of one column of images on the phosphor.

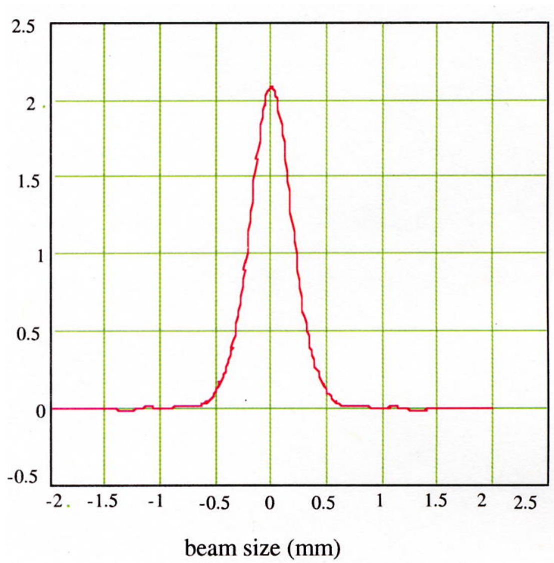
Beam size measurement, spatial coherence

(Mitsuhashi, PAC97)

Michelson's method for measuring the size of stars applied to measuring electron beam size. Spatial cohence increases as beam size decreases.



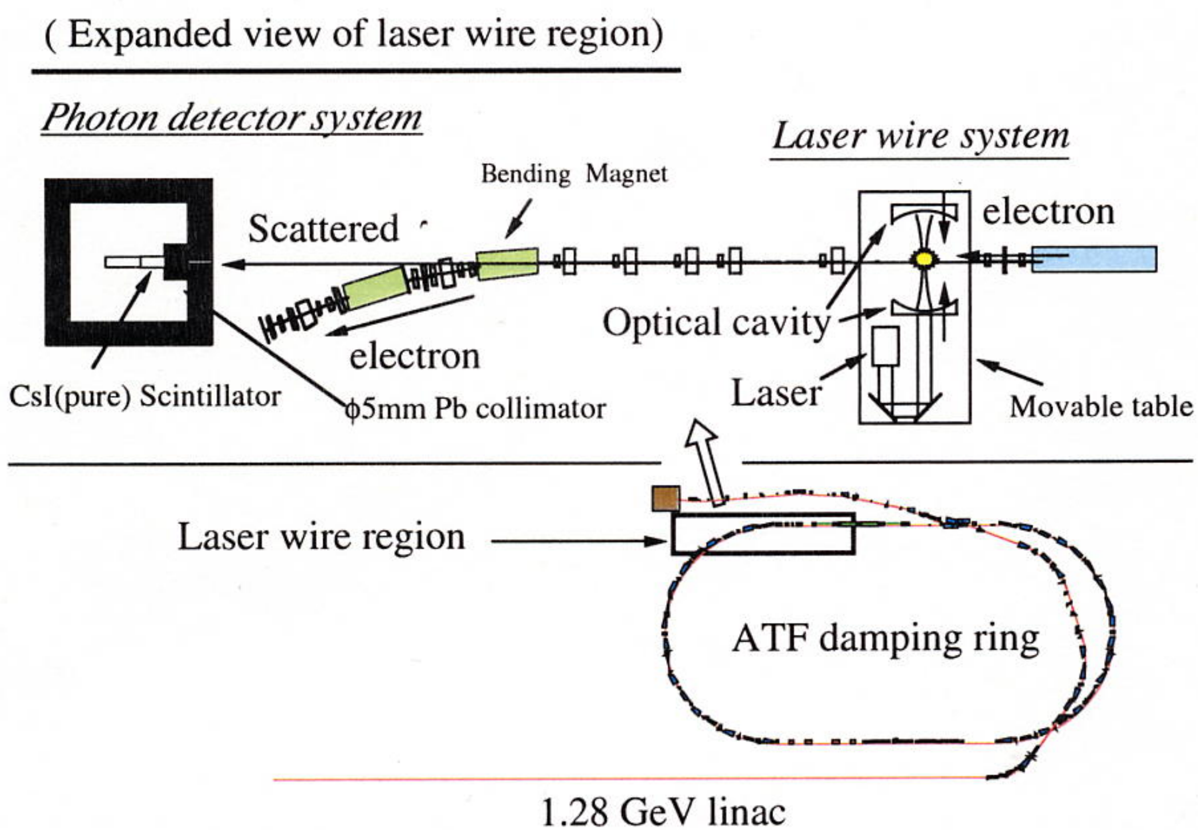




← **Vertical beam size can be obtained from the Fourier transform of the degree of spatial coherence.**

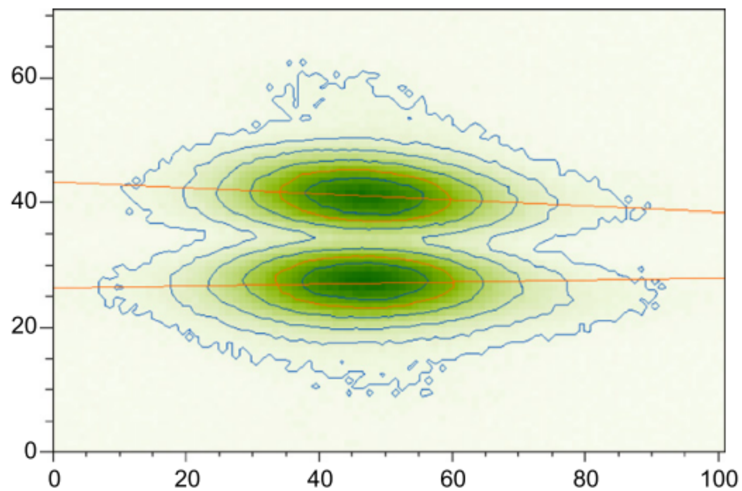
Laser wire beam size measurement

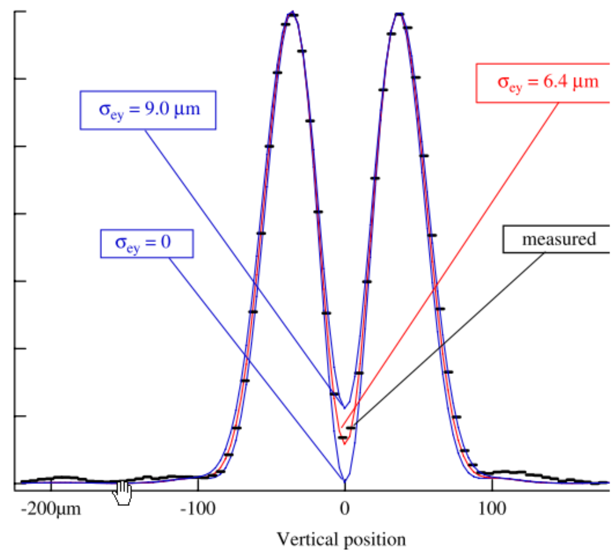
A laser wire successfully measured very small beam sizes at KEK ATF, H. Sakai et al., PRST-AB Volume 5 (2002)

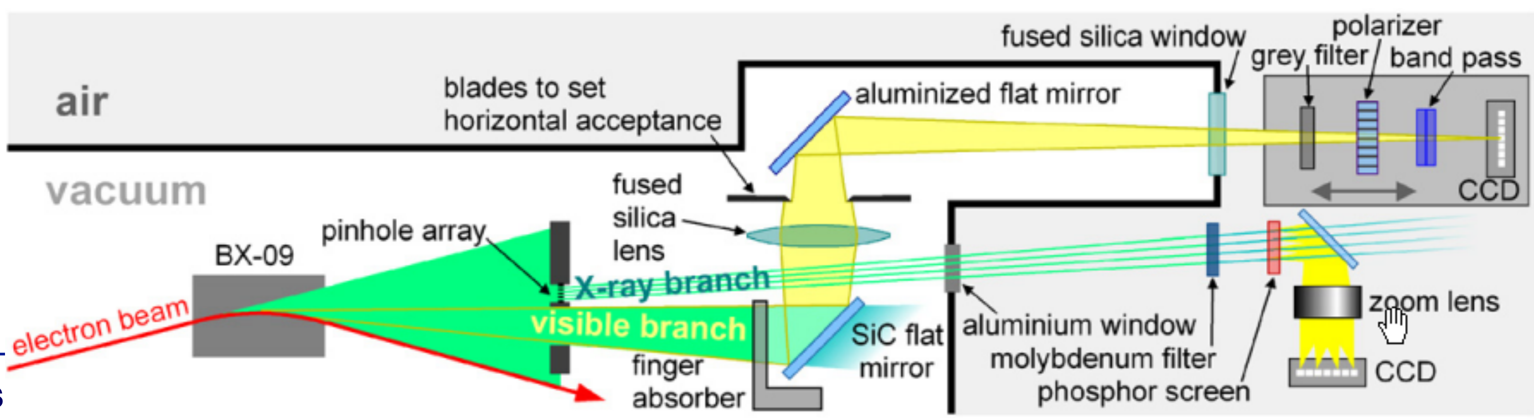


π-mode SR beam size measurement

- Image vertically polarized SR
- Intensity at y=0 determined by ε_y
- Andersson et al., NIMA 591 (2008).

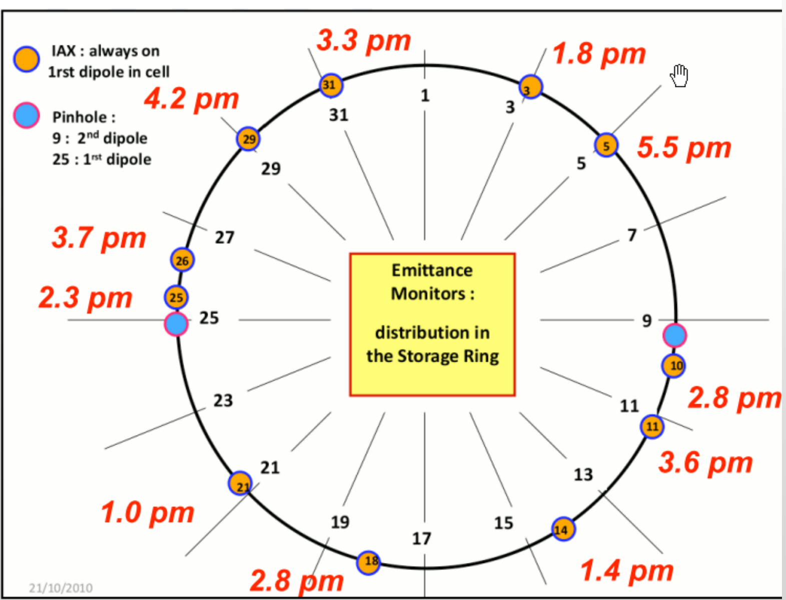


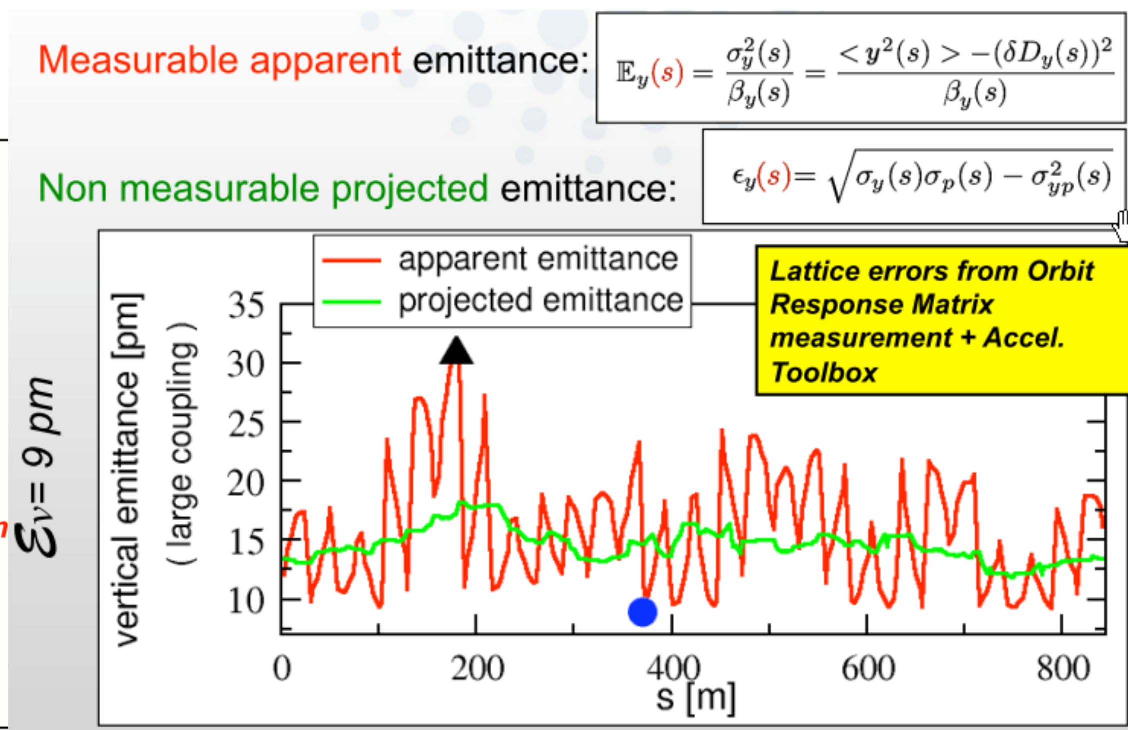




Determining ε_y from measured $<y^2>$

- ESRF – many beam size diagnostics
- See differing σ^2_y/β_y at each location
- A. Franchi et al., PRST-AB-14-012804 (2011).





Principle of streak camera

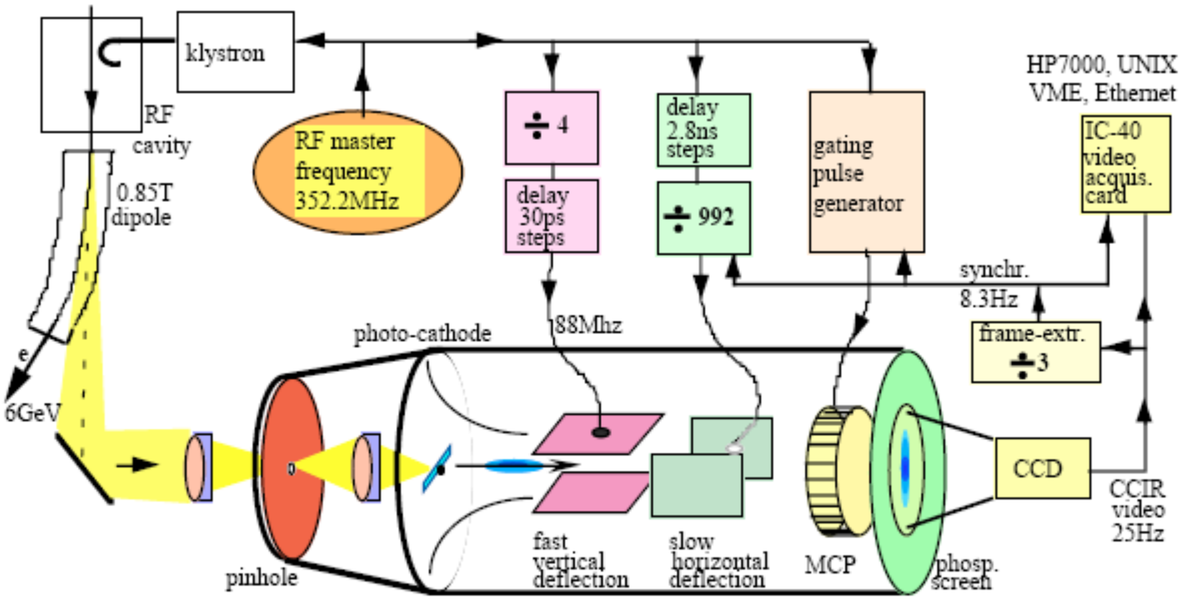
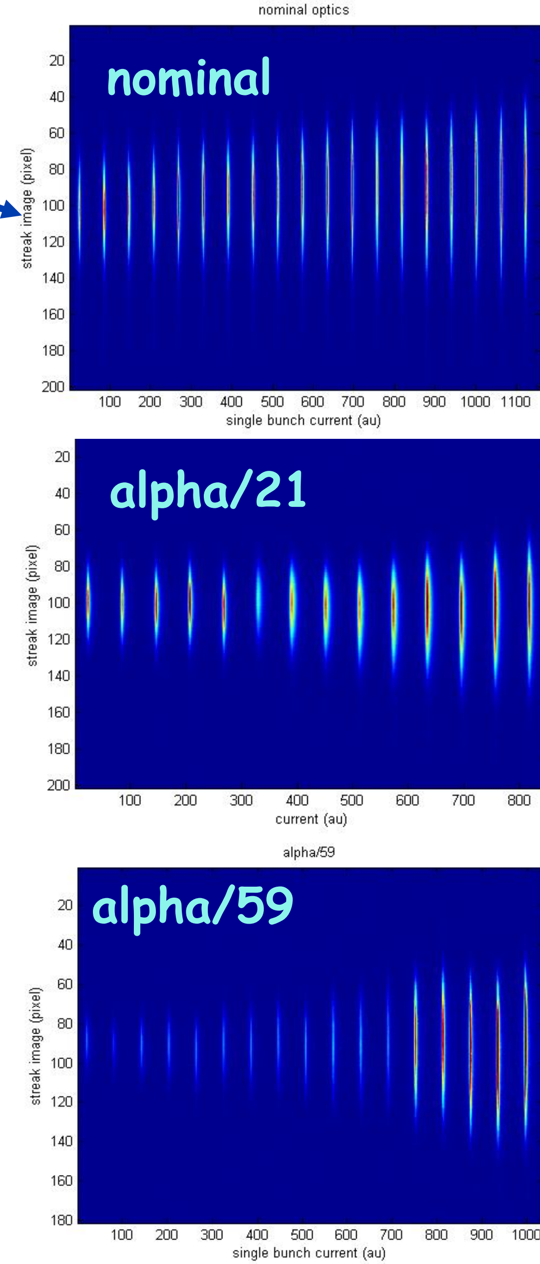


Figure: 1 Synchronisation of the Streak Camera system

- 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 …

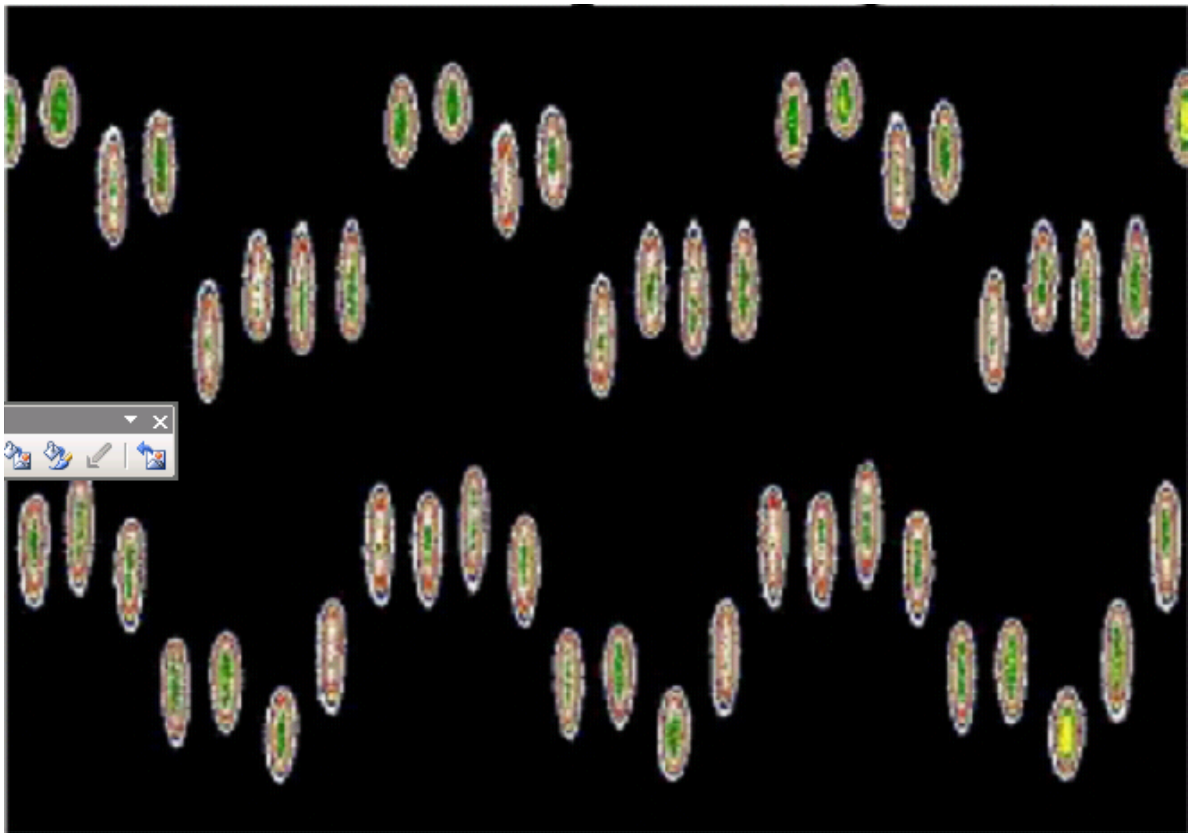
Streak camera measurements

Low alpha measurements at SPEAR



W.J. Corbett

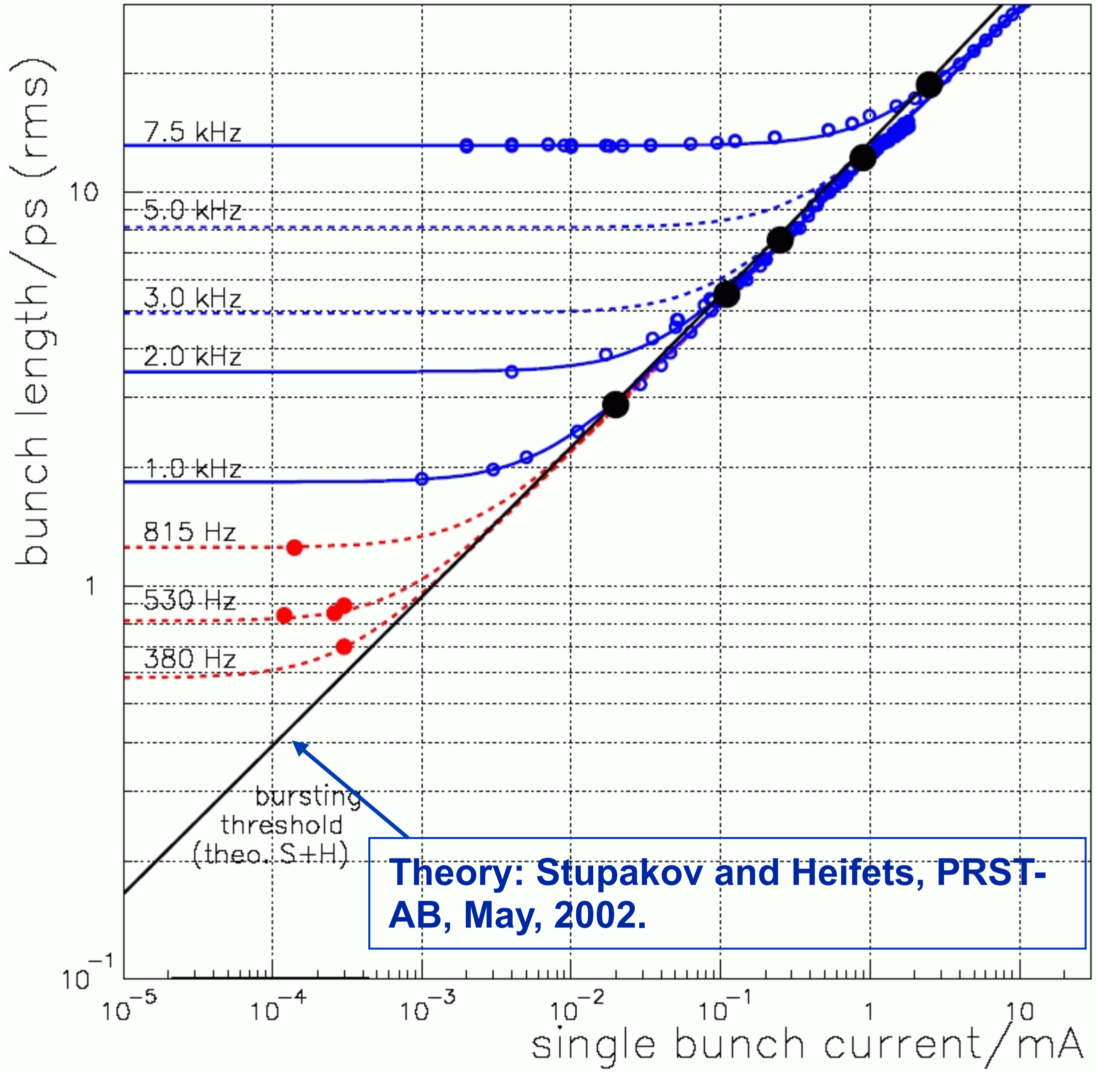
Longitudinal instabilities at ESRF



Streak camera measurements at BESSY

Feikes et al., EPAC2004

- Streak camera data in blue
- Bolometer data in red

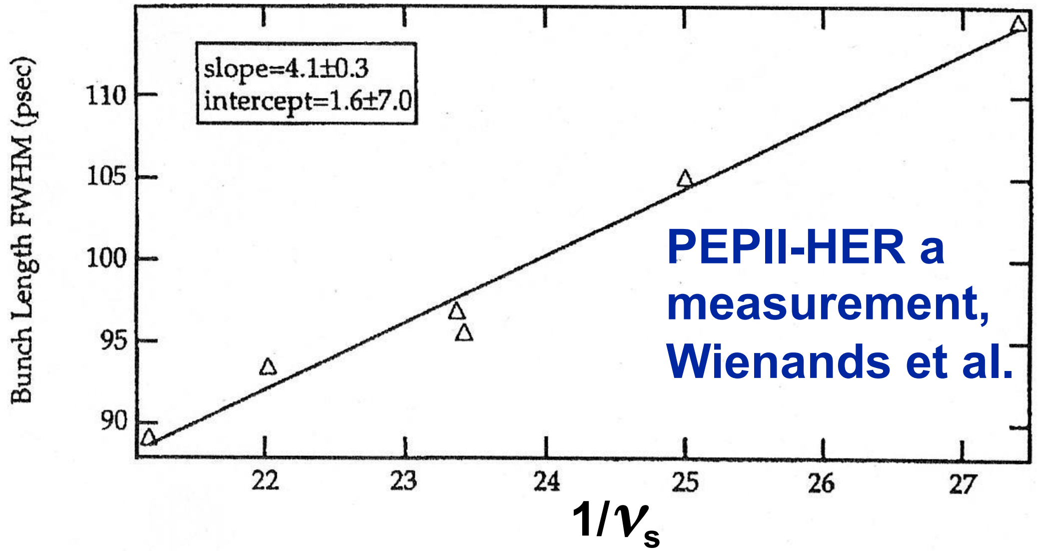


Momentum compaction

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

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



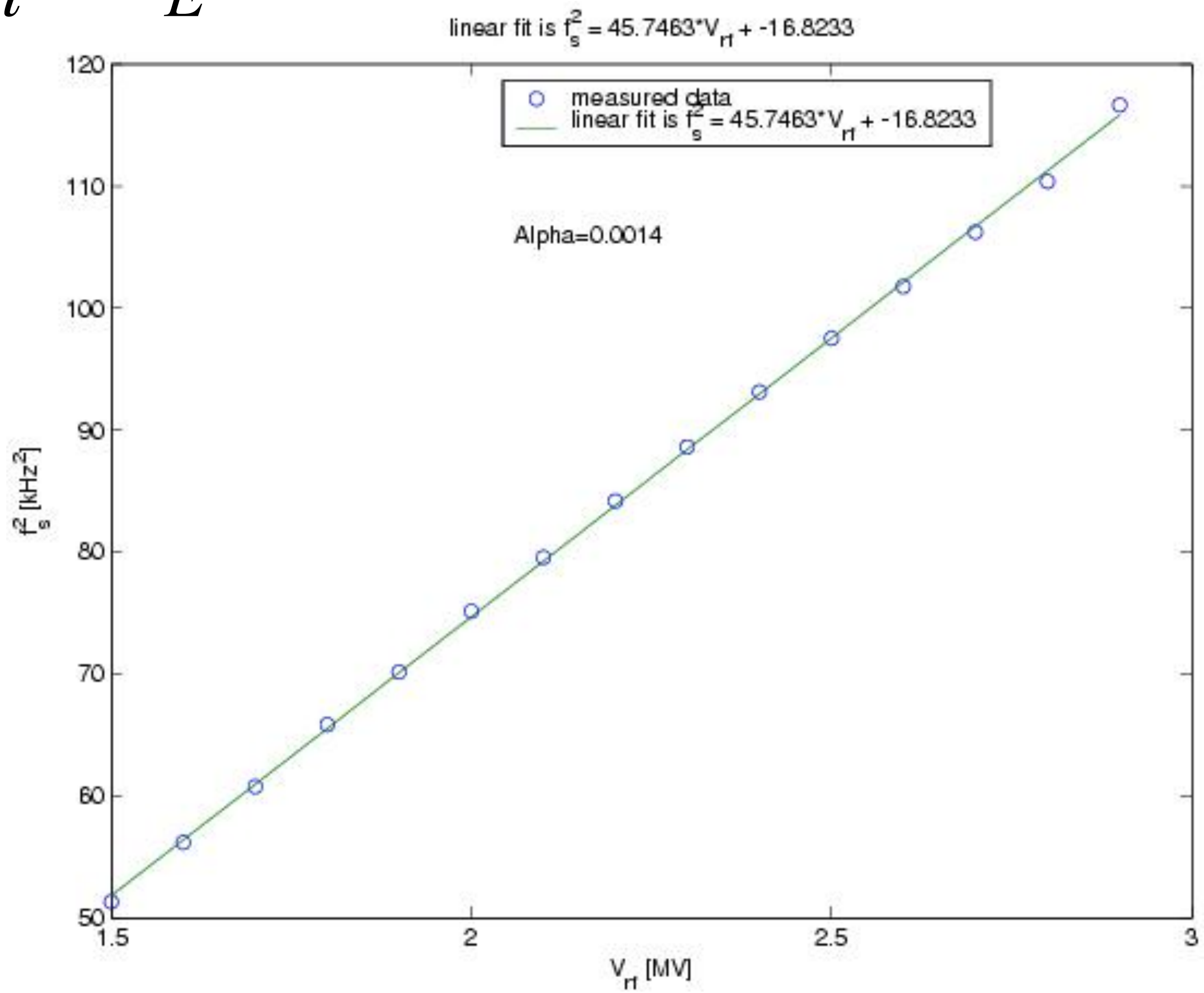
PEPII-HER a measurement, Wienands et al.

Direct measurement: measure change in energy with rf frequency.

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

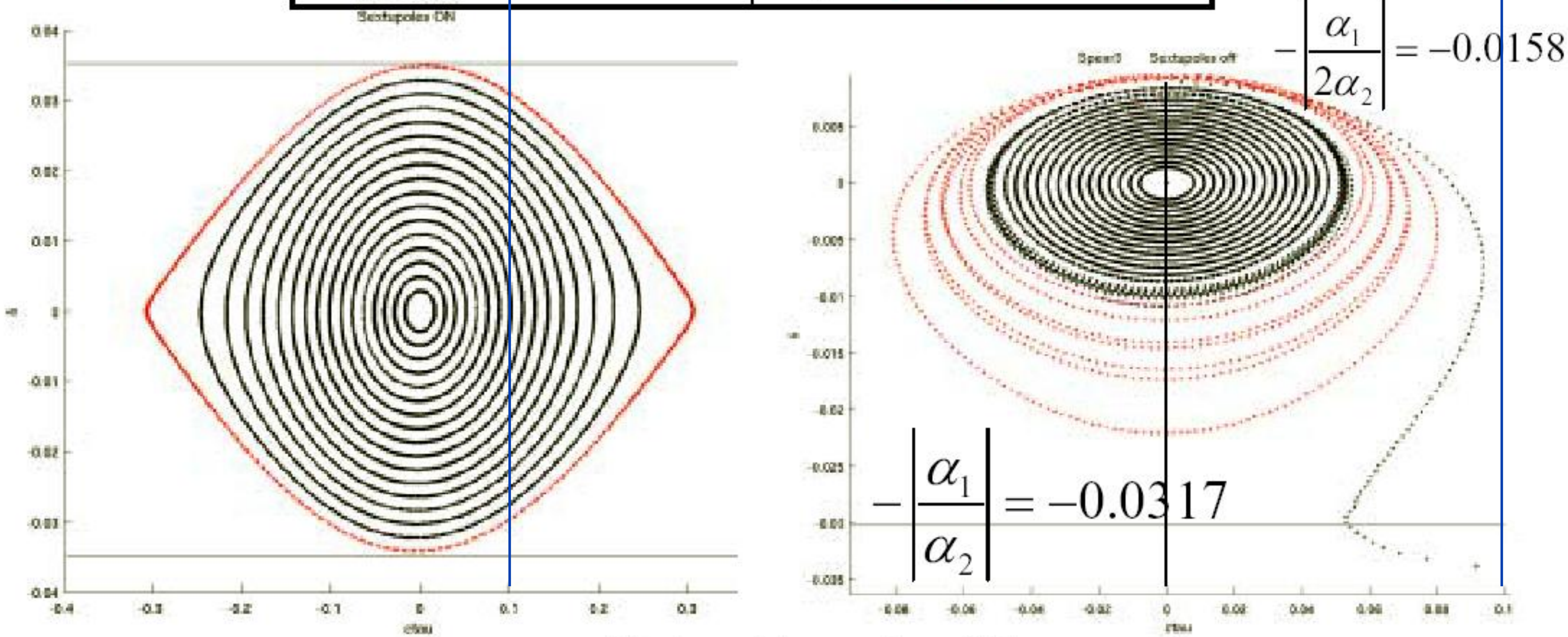
Momentum compaction measurement

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



SPEAR3: Longitudinal Dynamics

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



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

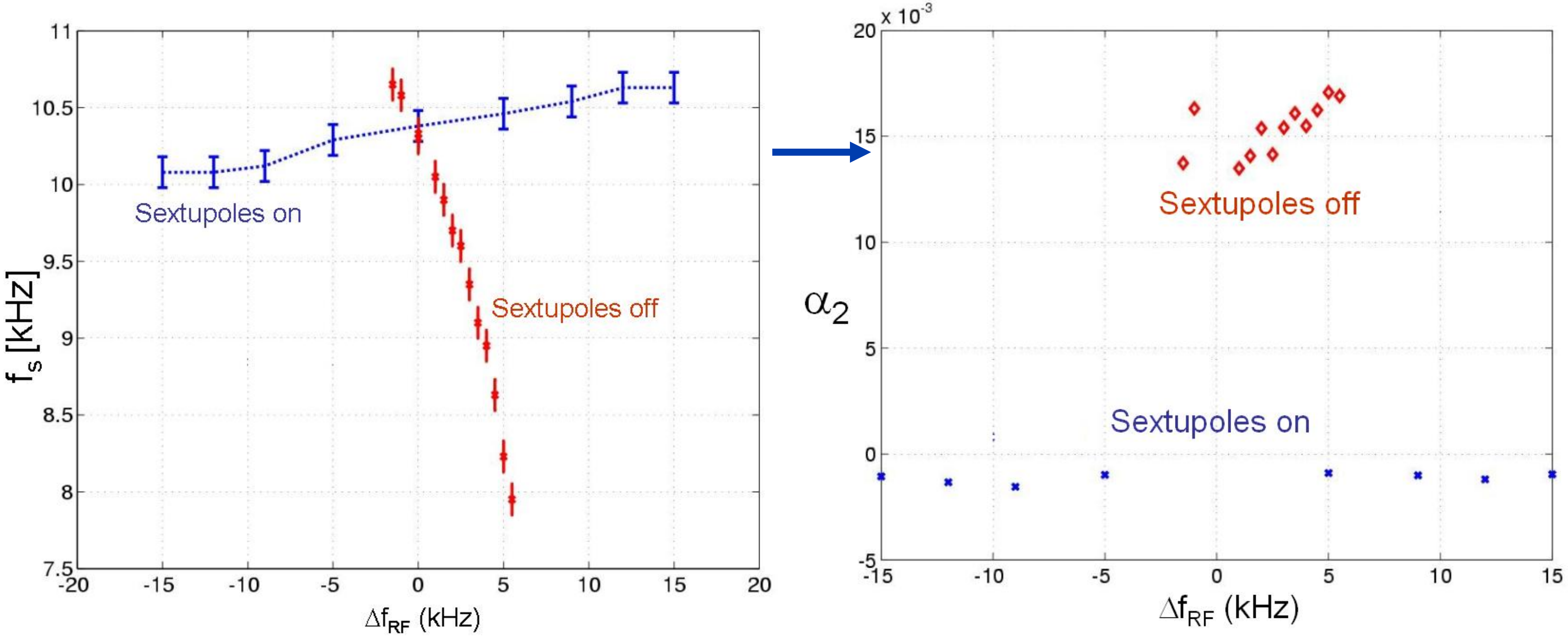
$$-\left|\frac{\alpha_1}{\alpha_2}\right| = -0.0317$$

4D tracking using AT

α_2 measurement

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

- $|\alpha_2|$, 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:

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 ν_x
- Why do oscillations disappear and reappear?