



Storage ring measurements – the basics

○ Beam Diagnostics

↖ DCCT

↖ BPMs

↖ Synchrotron light monitors

↖ Scrapers

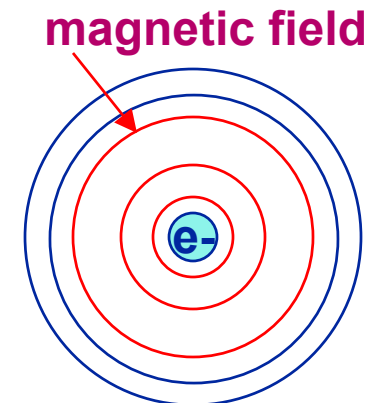
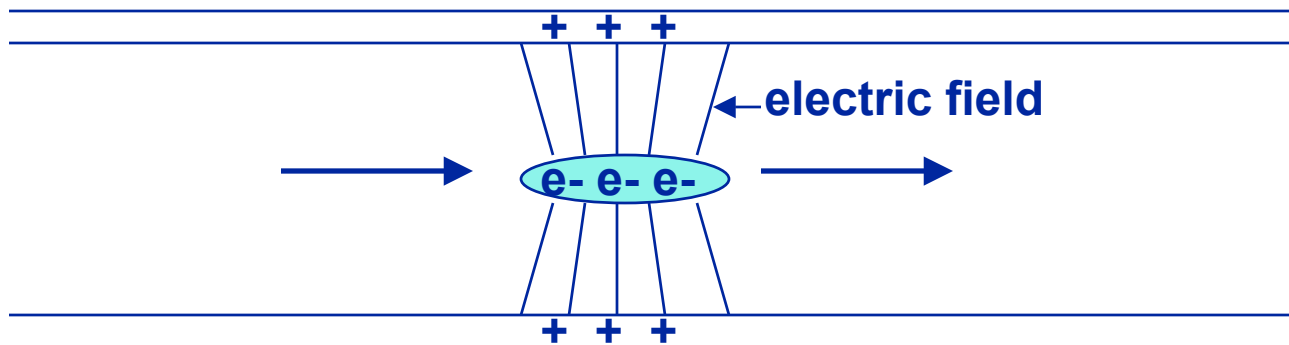
↖ Loss monitors

○ Measuring lifetime, tunes, β , η , chromaticity, α

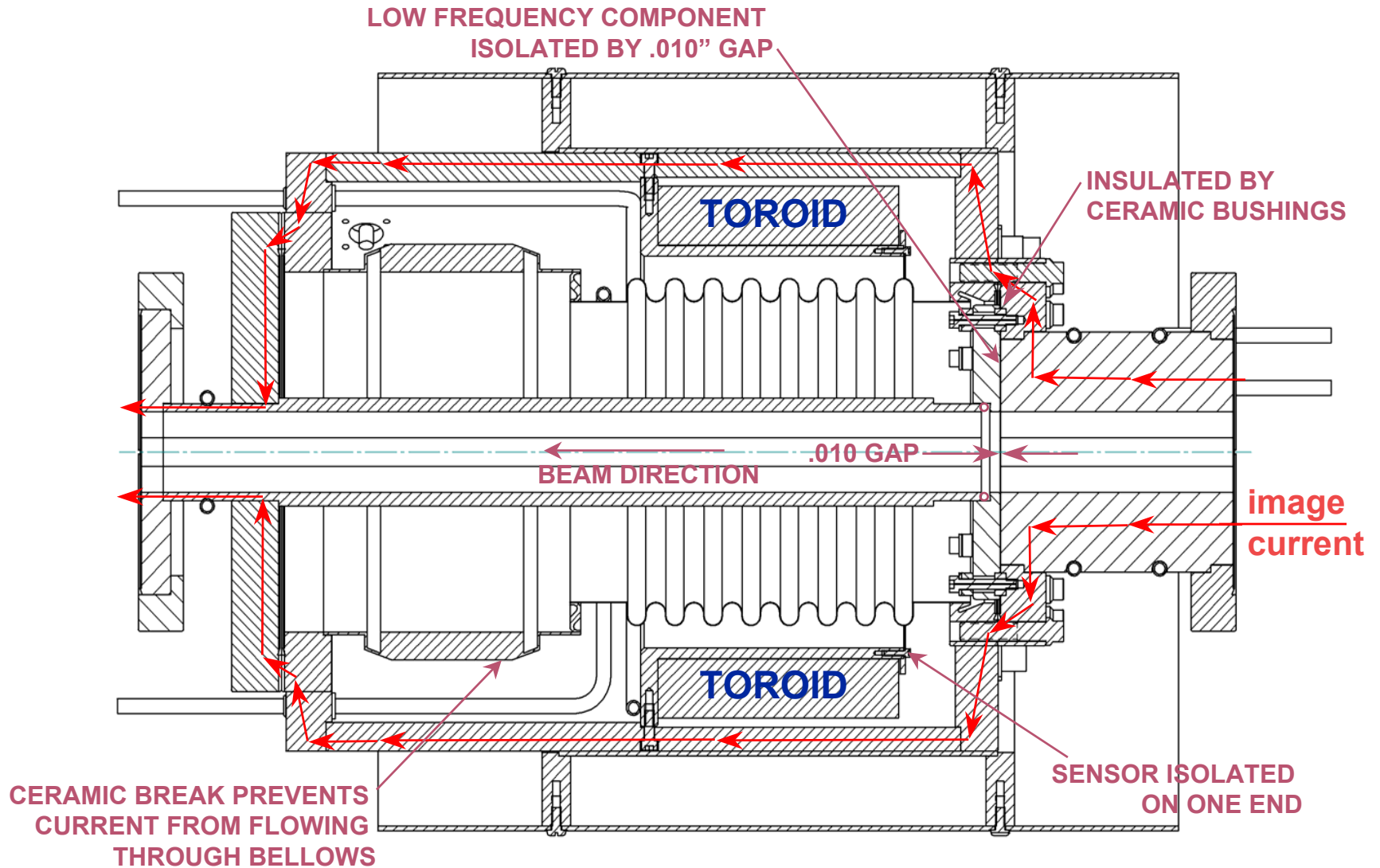
Beam diagnostics: Intensity/current



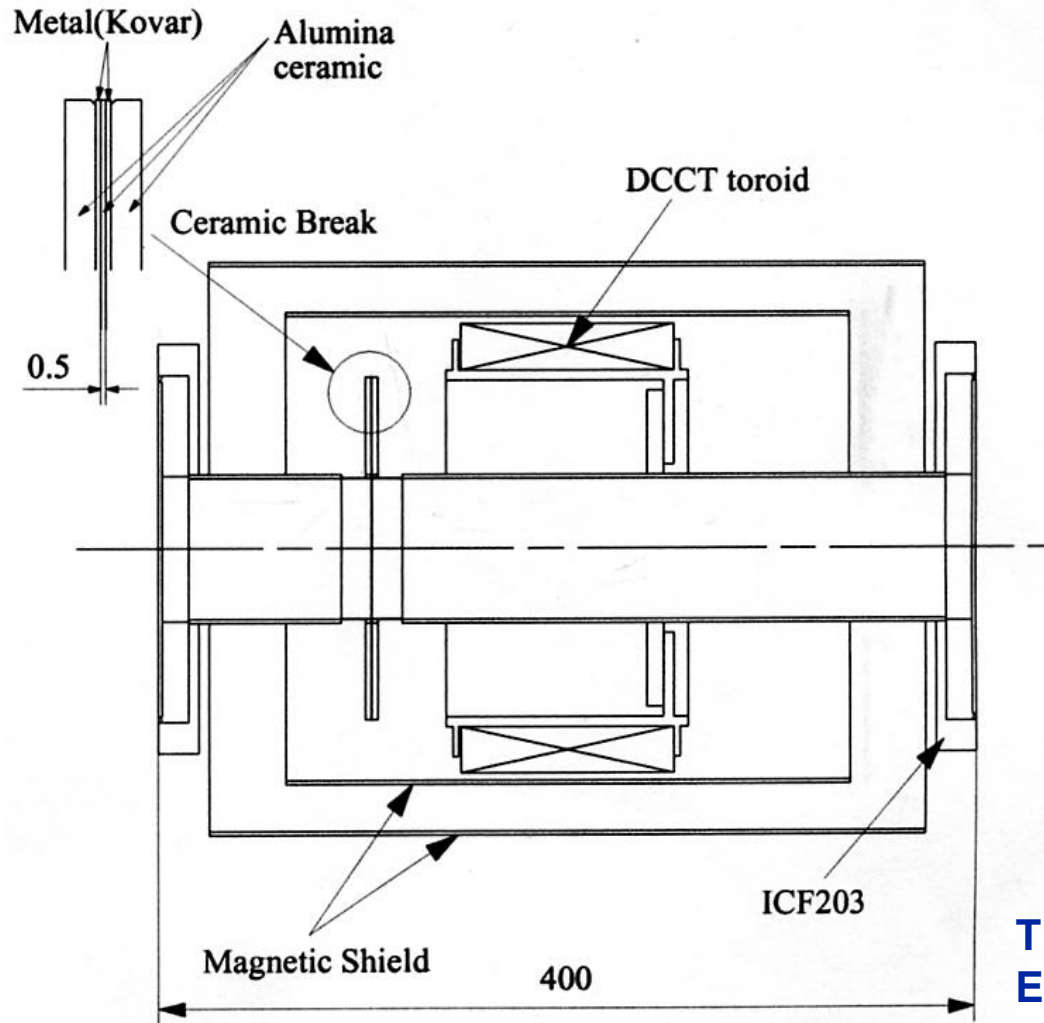
- To measure the intensity of a beam one can apply many methods (capacitive pickups, wall current monitor, toroids, synchrotron radiation based methods ...)
- Most commonly used to measure current in a calibrated way are toroidal monitors (ferrite toroid around beam, coil to pick up induced voltage signal).
 - ↪ 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, ...)



SPEAR3 DCCT

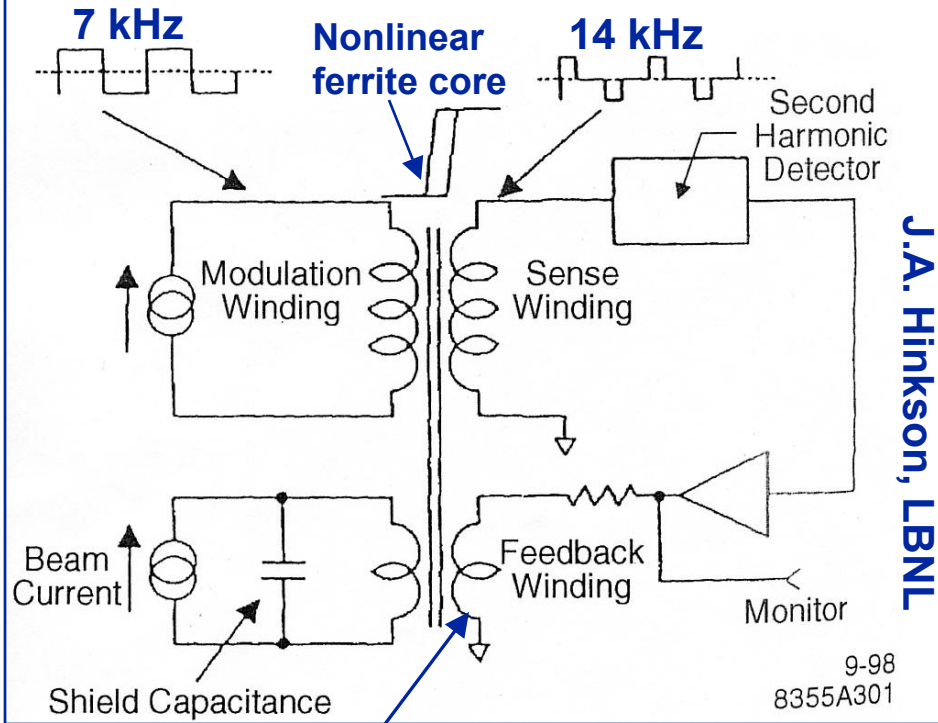


Photon factory DCCT



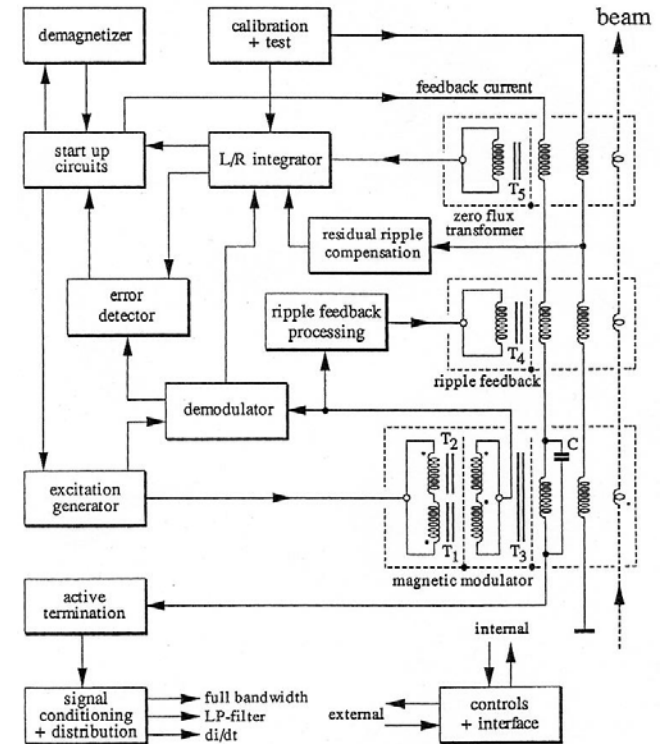
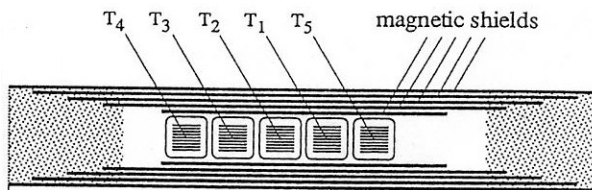
T. Honda et al.,
EPAC98

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

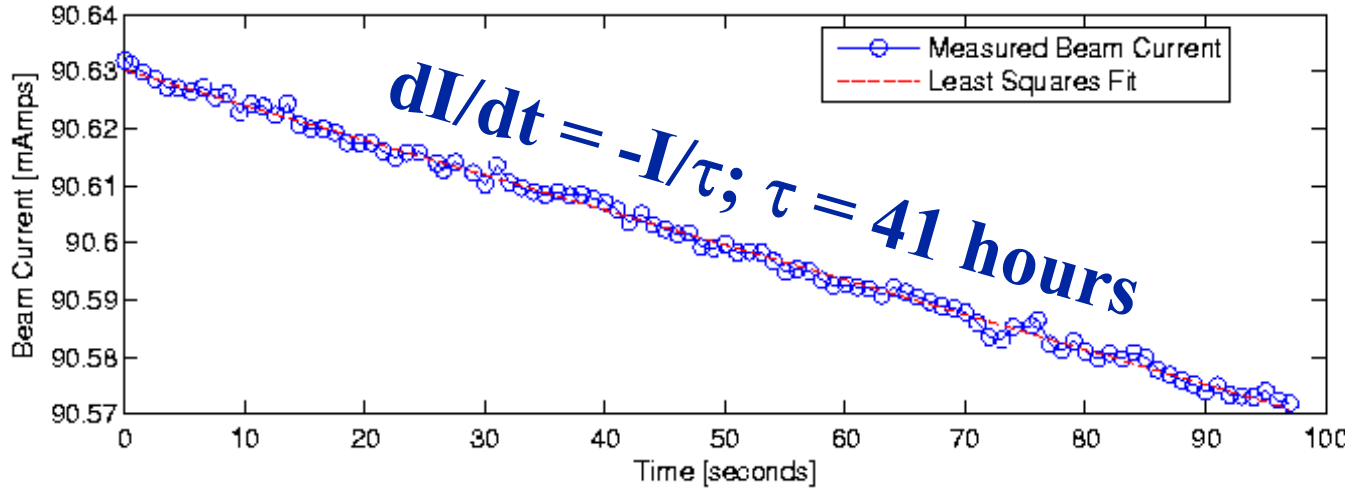


Simplified circuit, K. Unser, 1992

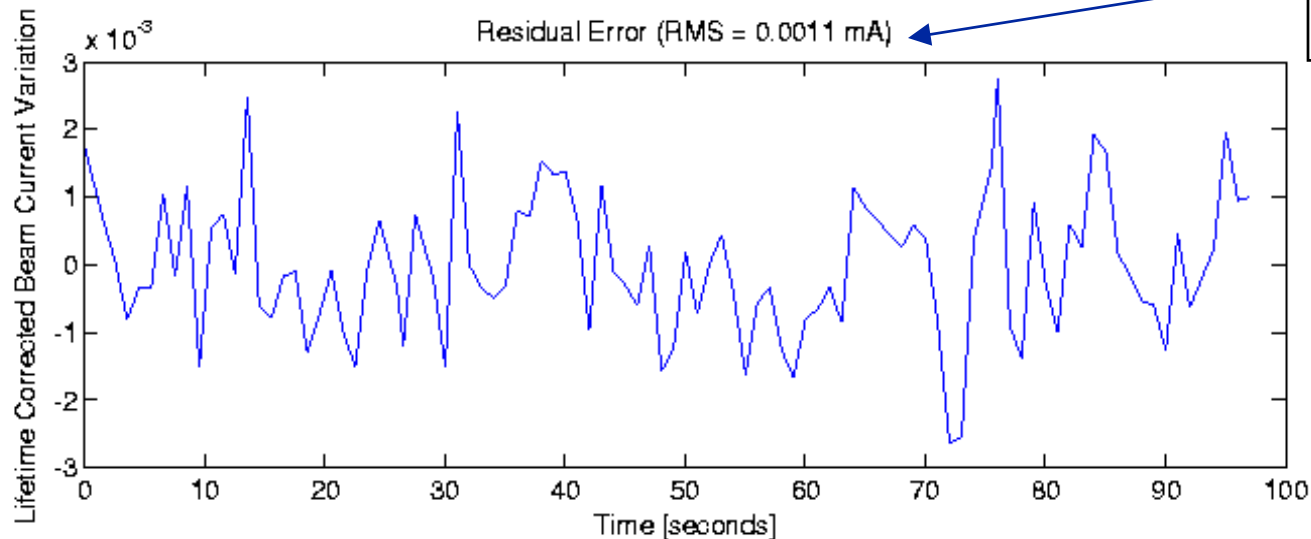
SPEAR3 lifetime measurement w/ DCCT



Beam Current vs Time: Lifetime=41.17 hours.



**DCCT resolution:
1 μ A in 1 second**



11-Feb-2005

Lifetime vs. tunes

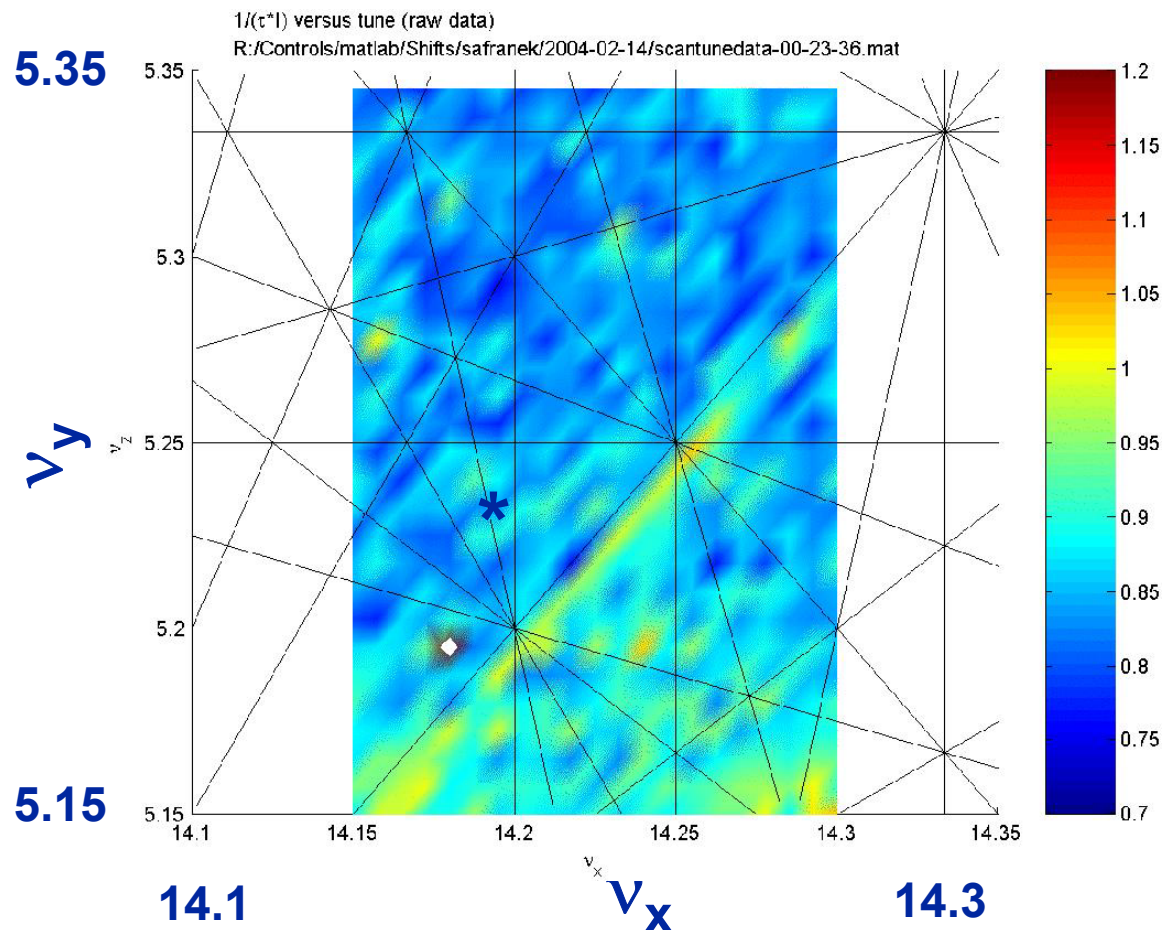


- Resonant line:

$$\leftarrow \nu_x - \nu_y = 9$$

- * = operating tunes (14.19, 5.23)

- Data gathered automatically on owl shift.



Dynamic aperture vs. tune



○ Resonant lines:

$$\Leftrightarrow v_x - v_y = 9$$

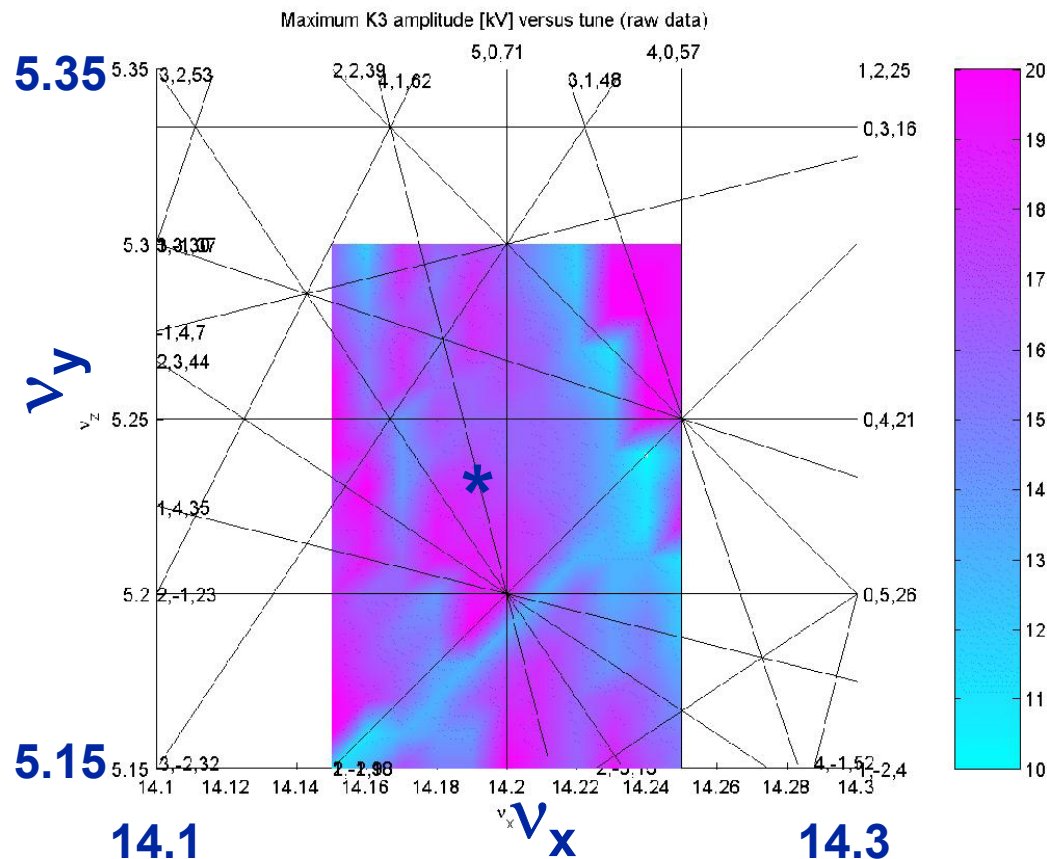
$$\Leftrightarrow 3v_x + v_y = 48$$

$$\Leftrightarrow 4v_x + v_y = 62$$

○ Resonances offset from tune shift with amplitude.

○ * = operating tunes (14.19, 5.23)

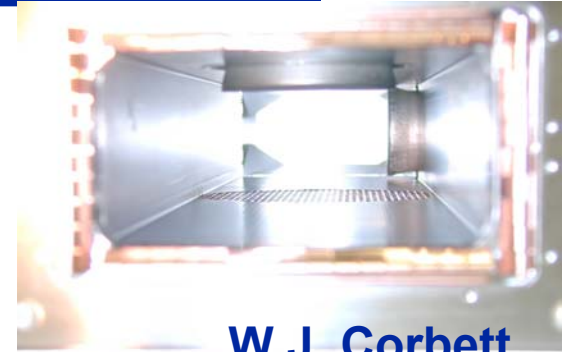
○ Data gathered automatically on owl shift.



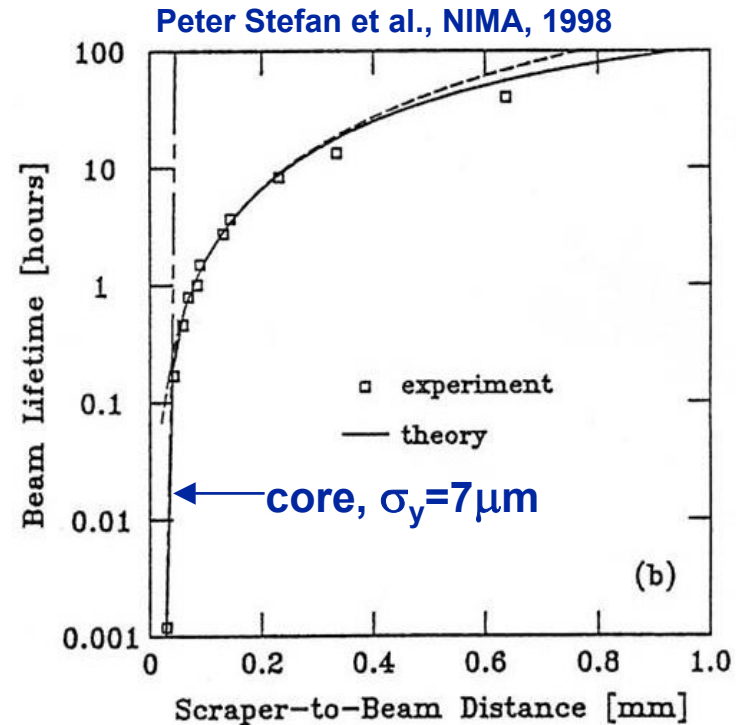
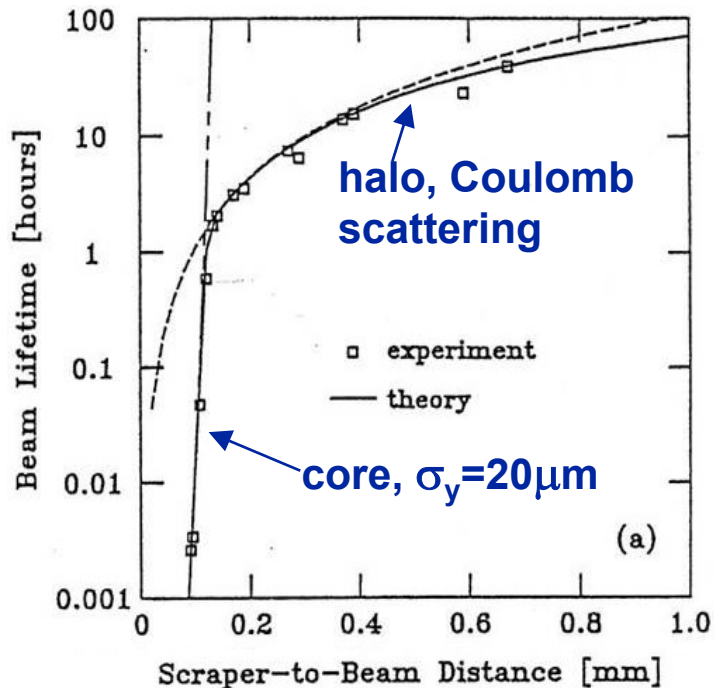
Beam scrapers; lifetime vs. vertical aperture



Scrapers measure beam halo



W.J. Corbett



Peter Stefan et al., NIMA, 1998

SPEAR3 scraper measurements



Three contributions to lifetime:

- Elastic gas scattering (Coulomb)
- Bremsstrahlung
- Intrabeam scattering (Touschek)

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

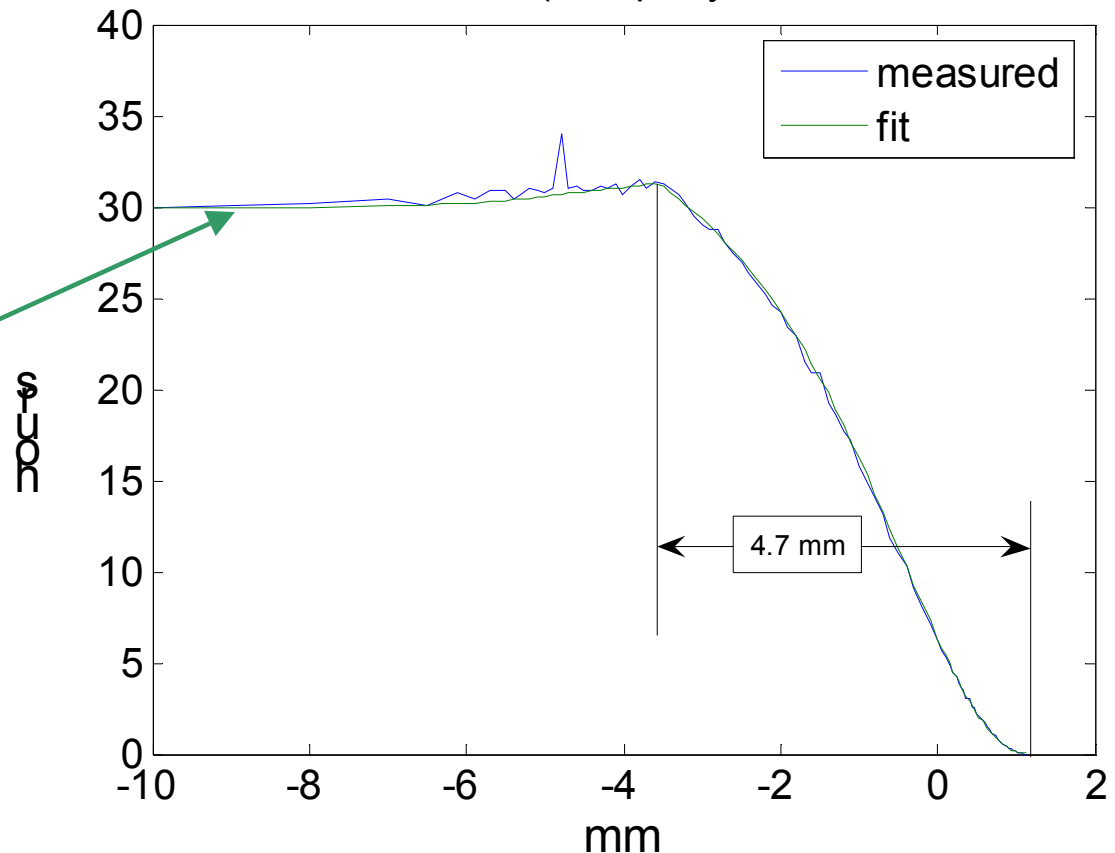


$$\tau_C \propto \text{pressure} * y_{\text{aperture}}^2 \approx I_{\text{tot}} * y^2$$

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

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

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



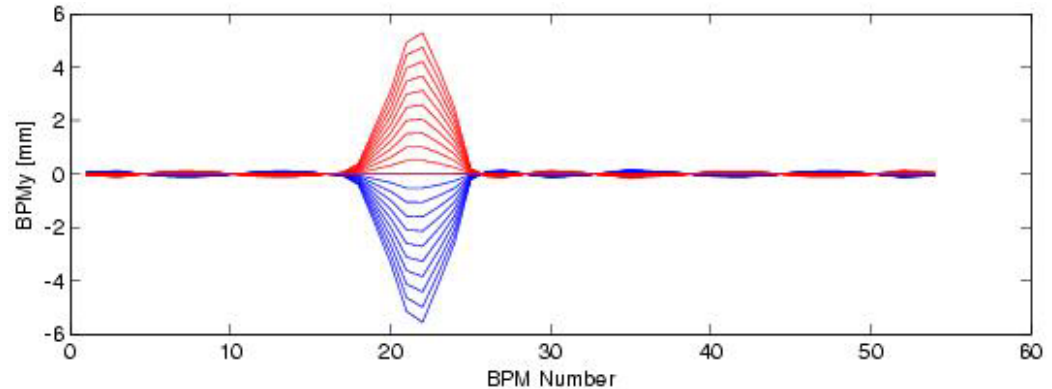
Physical aperture probe

Vertical beam bump in ID chamber

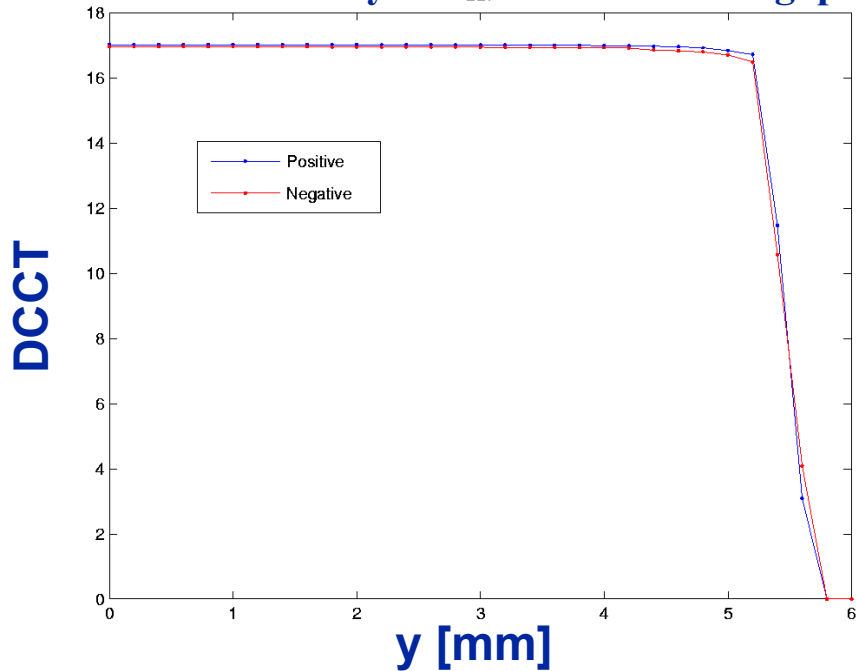


y-bump in ID chamber:

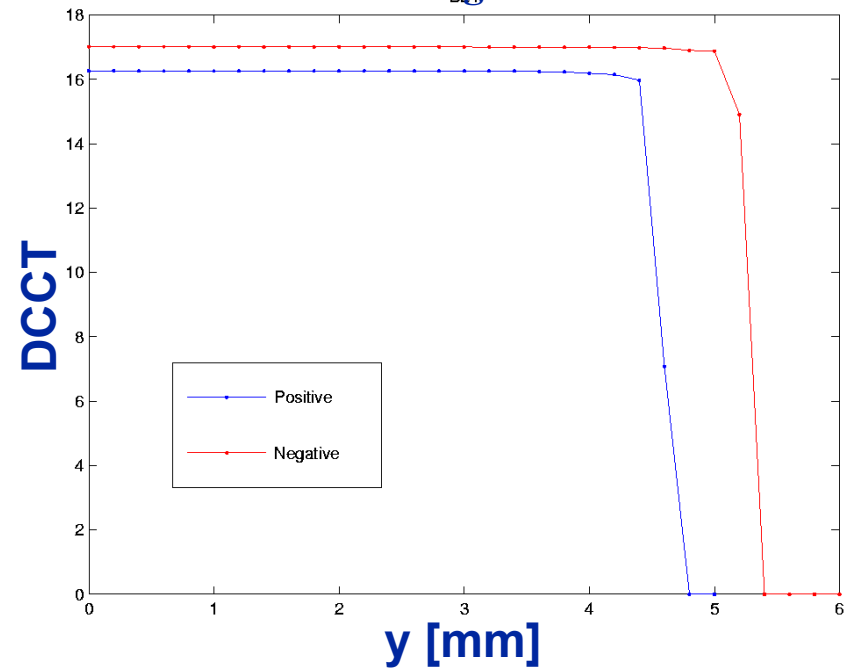
- Bump beam up until lost
- Refill
- Bump beam down until lost



ID7 chamber is symmetric and correct gap



ID4 chamber is mis-aligned and too small



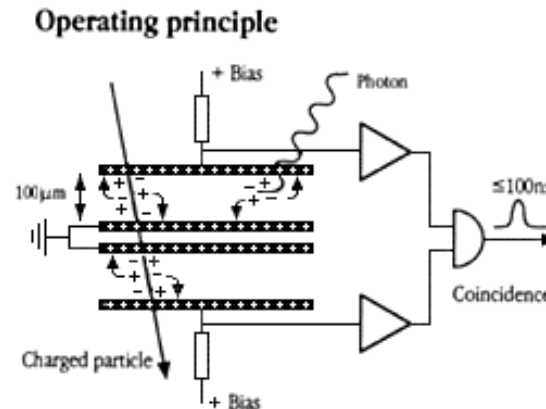
Beam loss monitors



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.

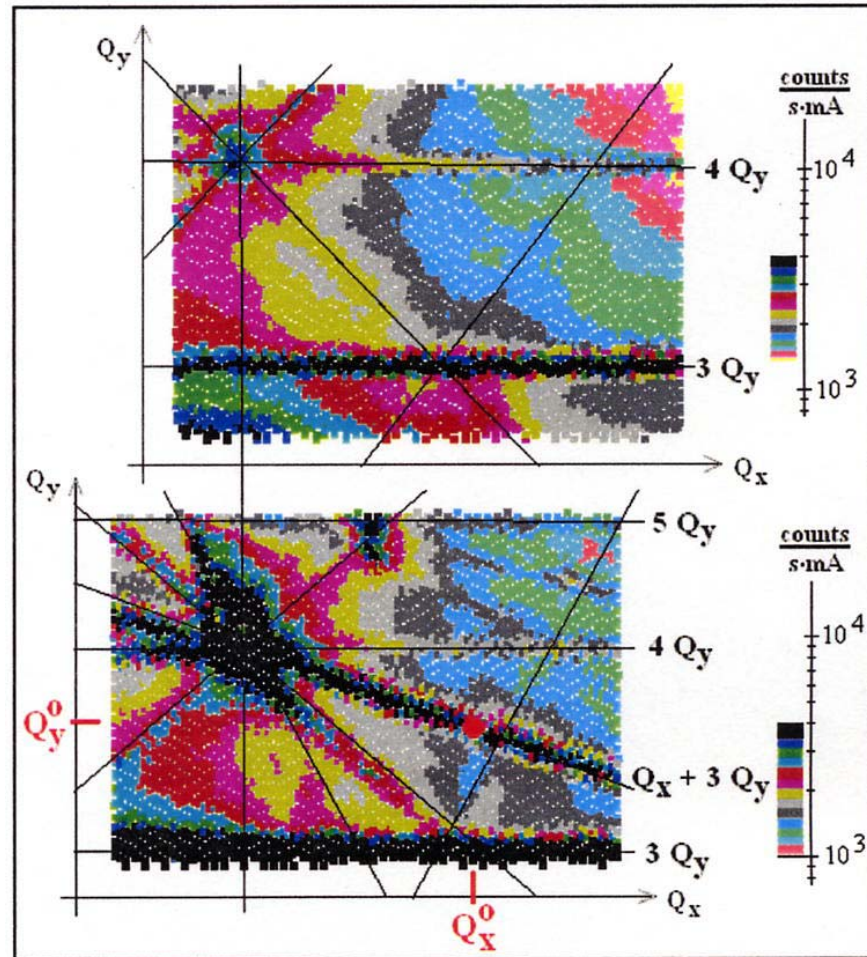


A scintillator with a photomultiplier is another commonly used BLM.

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

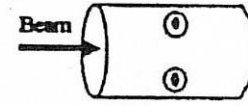
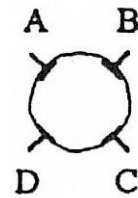


- **BPMs are very important, and very challenging (electronics).**
- **There are many reasons why good orbit stability is necessary:**
- **Accelerator Physics:**
 - ↪ **Changes in orbit cause changes in gradient distribution (e.g. horizontal offset in sextupoles) or coupling (vertical offset in sextupoles)**
 - ↪ **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.**

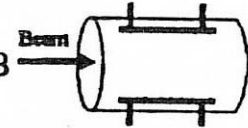
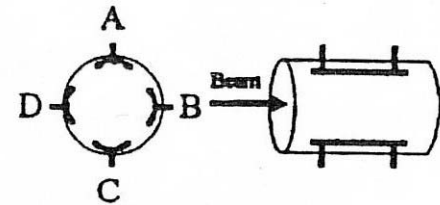
Beam position monitors



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



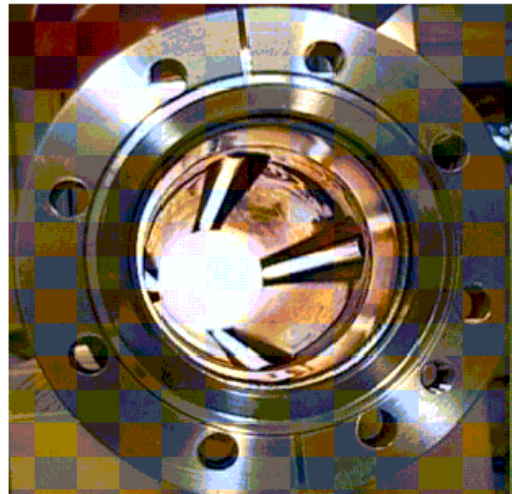
Buttons



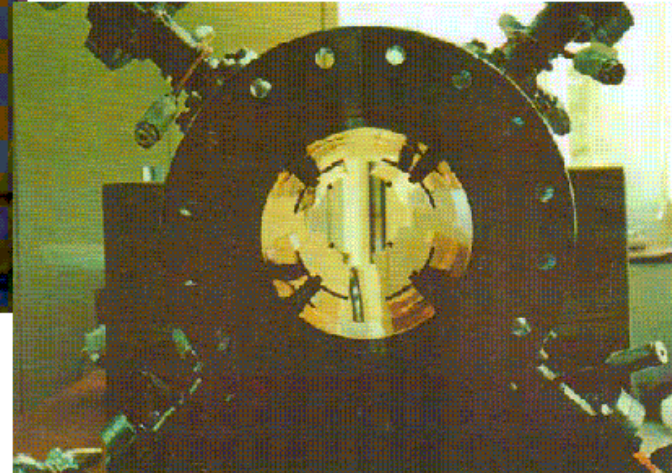
Striplines

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

Striplines



M. Wendt, DESY



M. Tobiyama, KEK

Capacitive Pickups, Button BPMs



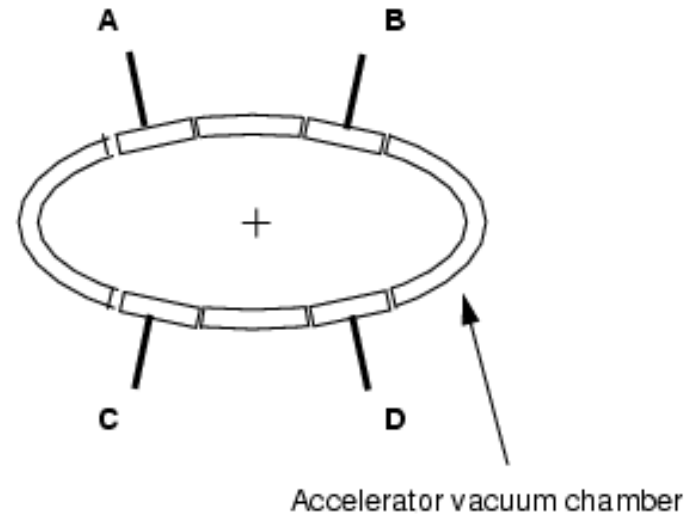
Charged Particle Beam Pickup Electrodes

Capacitive buttons

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

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

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



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

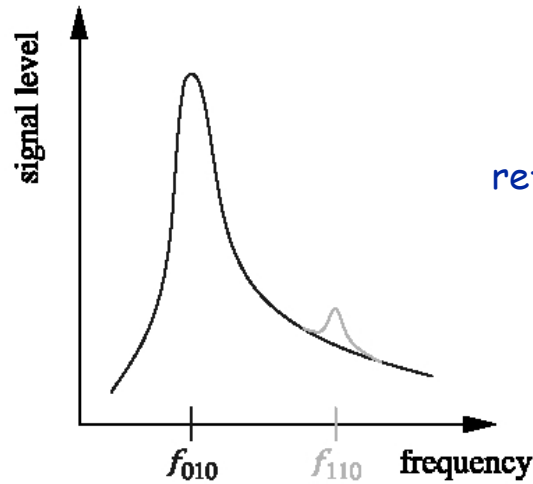
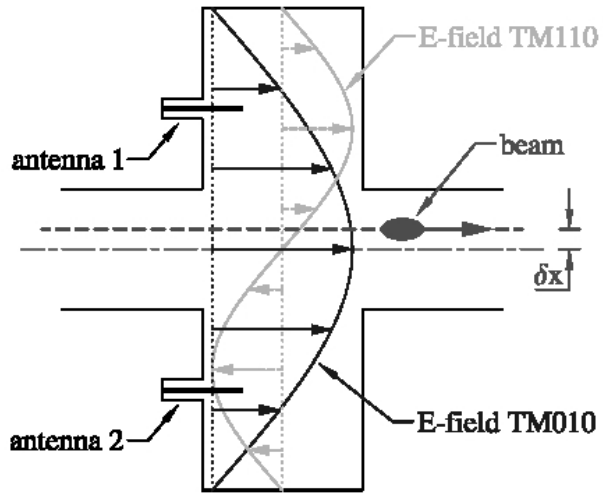
$$Z_t(\omega) = V_p / I_b = \frac{a^2 \omega}{2 r \beta c} \frac{R}{(1 + j\omega RC)}$$

where $\beta = v/c$,

R = Transmission line impedance,

C = Button capacitance

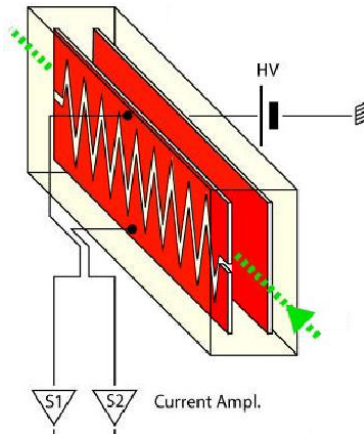
CAVITY BPMs:



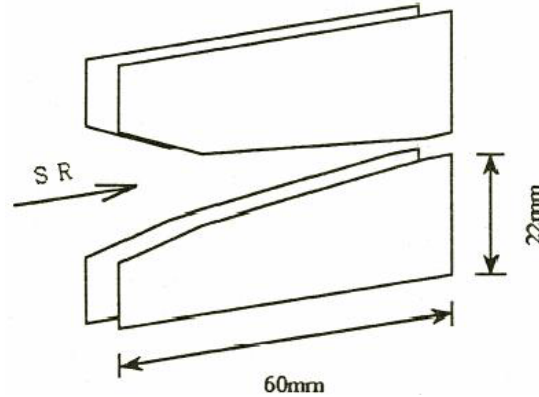
reference:
"Cavity BPMs", R. Lorentz
(BIW, Stanford, 1998)

PHOTON BPMs:

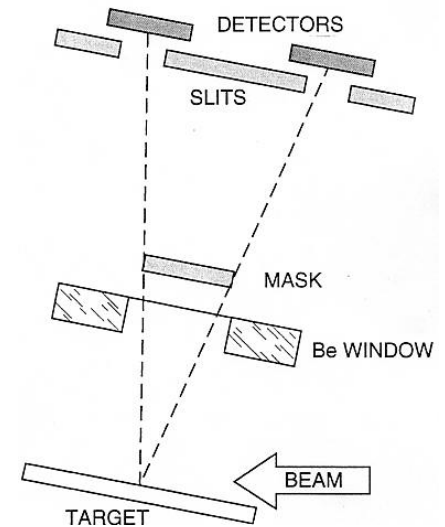
Split ion chamber:



Tungsten blade monitor:



Copper fluorescence bpm:

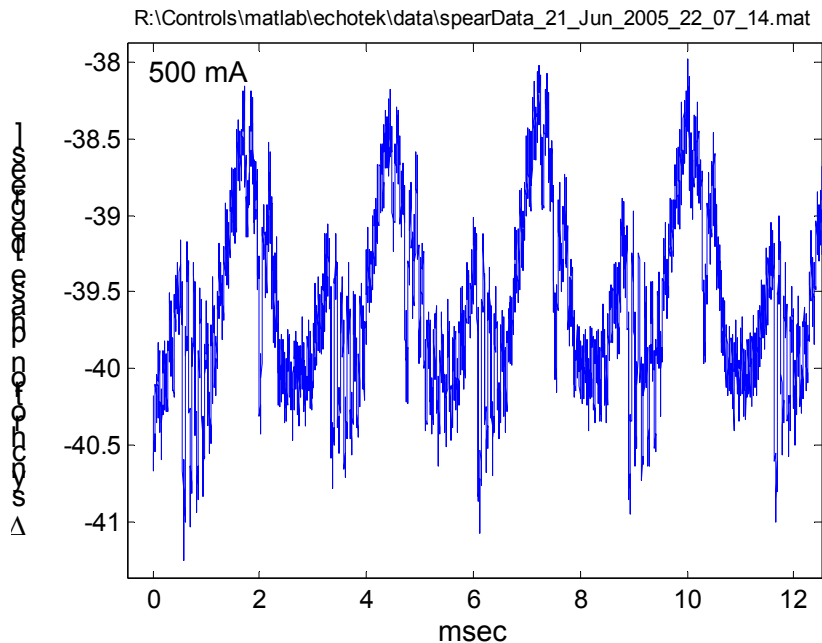


Longitudinal oscillations, BPMs

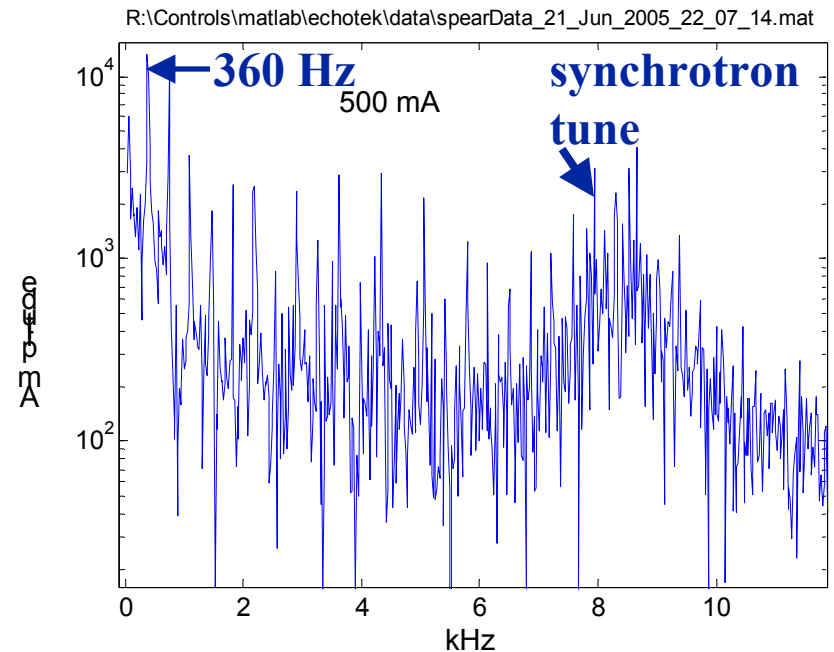


SPEAR3 digital receiver BPMs measure not only the amplitude from each button, but also the phase with respect to the RF, giving the variation in time of arrival of the bunches.

Synchrotron phase vs. time



FFT of synchrotron motion



Beam frequencies

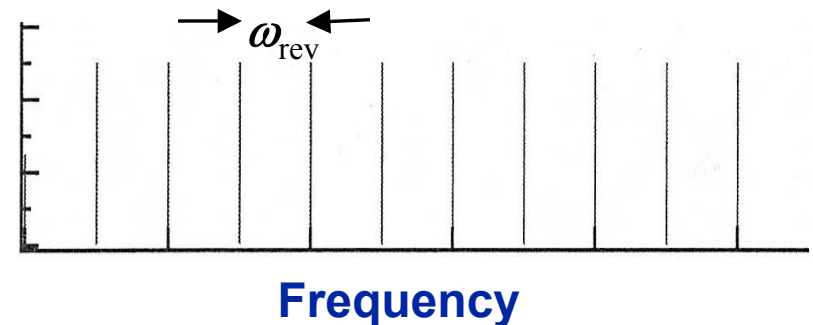
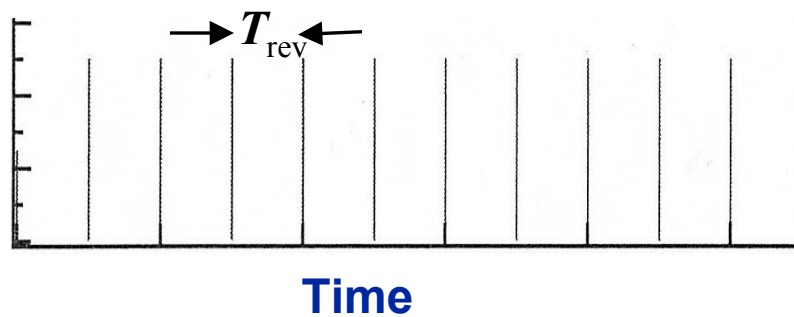


Using a spectrum analyzer with a BPM can yield a wealth of information on beam optics and stability. A single bunch with charge q in a storage ring with a revolution time T_{rev} gives the following signal on an oscilloscope

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

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

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

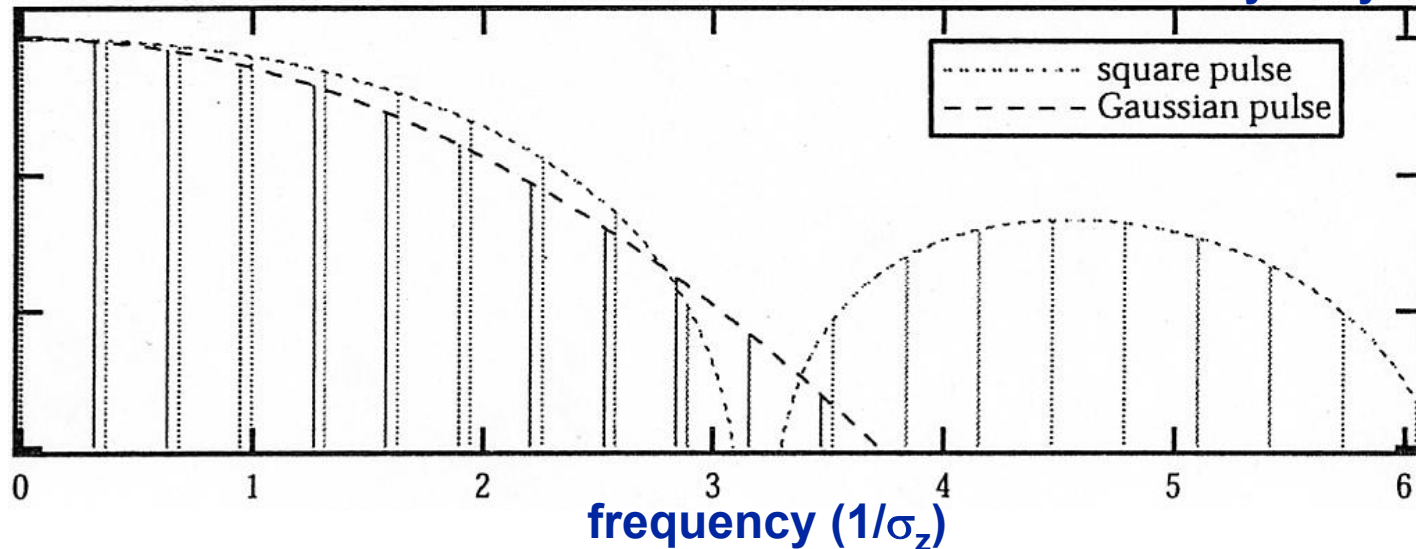


Spectrum for finite bunch length



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 $\sigma_z = 4.5$ mm, so $c/\sigma_z = 67$ GHz.

Betatron tune

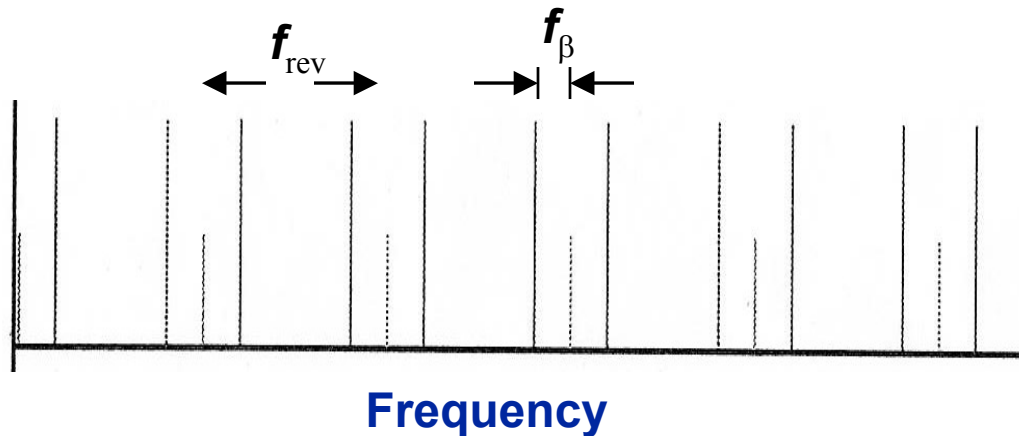


Combining BPM signals, $V_A - V_B - V_C + V_D$, gives a dipole signal that scales as the product of beam current and position. For a closed orbit $x_{c.o.}$ and a betatron oscillation x_β , the signal is

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

The Fourier transform is

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

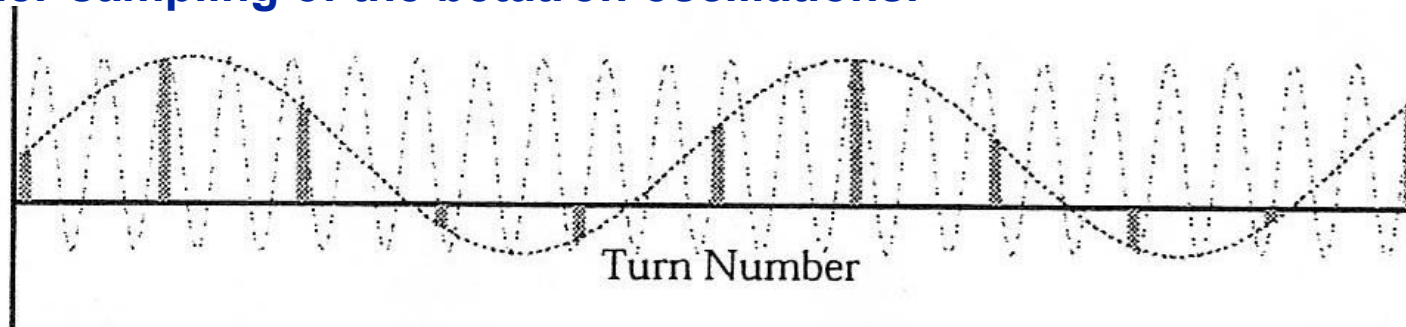


The tune is given by $\nu = f_\beta / f_{\text{rev}}$ (with integer/half-integer ambiguity).

Betatron tune, 2

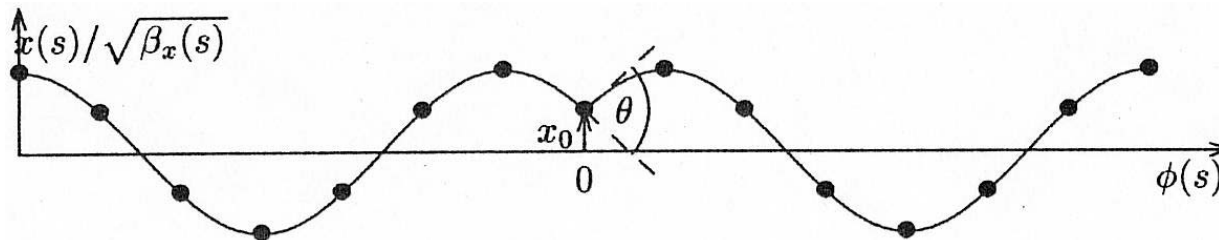


The integer/half-integer ambiguity in tune measurement arises from under-sampling of the betatron oscillations.



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

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

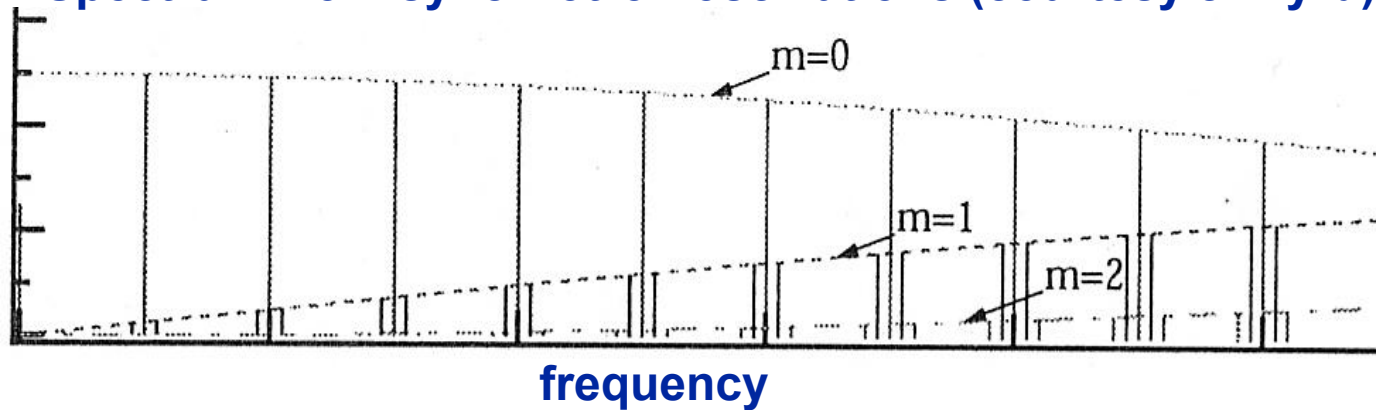


Synchrotron tune



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.

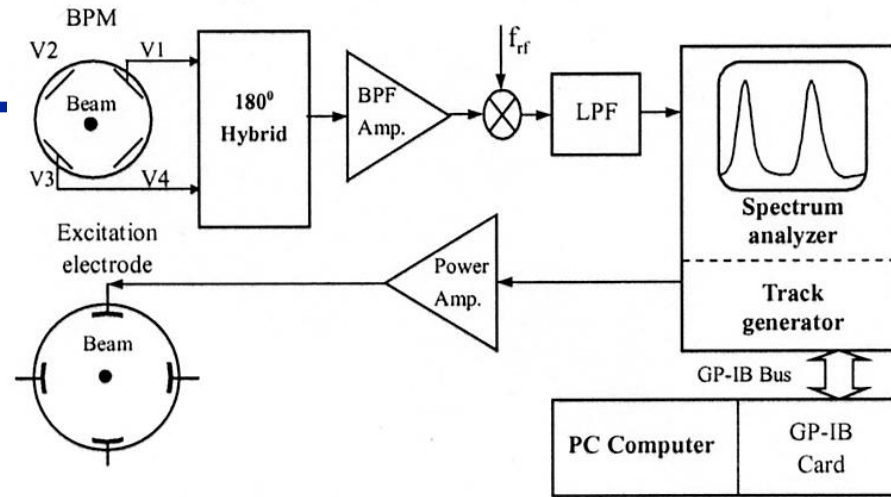
Spectrum from synchrotron oscillations (courtesy J. Byrd)



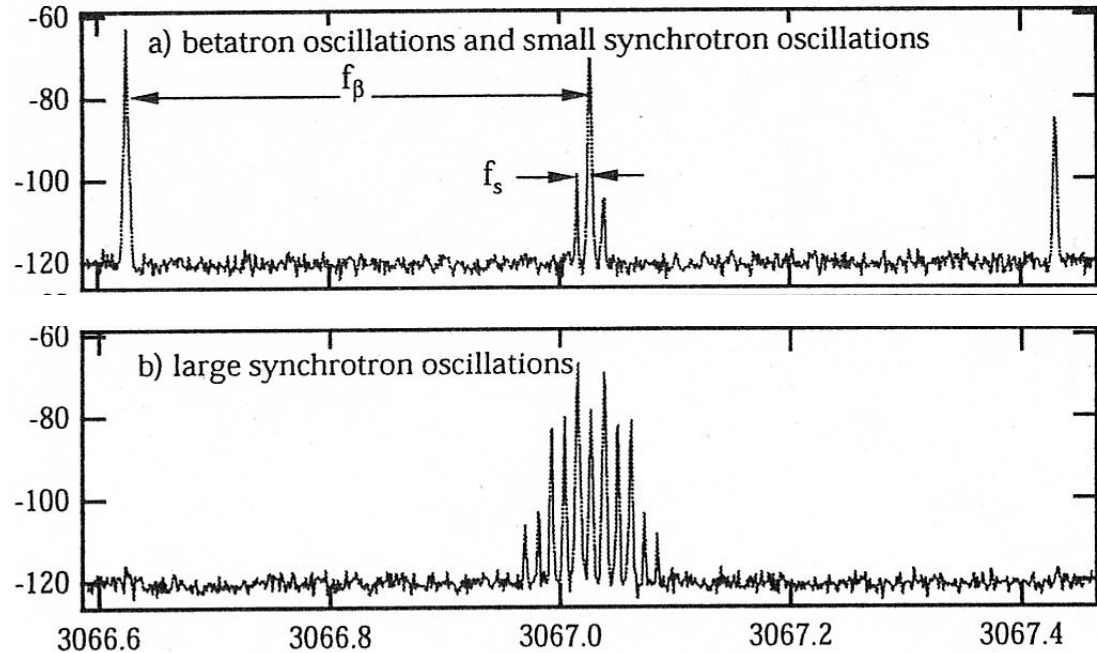
Measured spectra

Typical tune measurement

Typical measured spectra



HLS tune meas.,
Sun et al. PAC01



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:

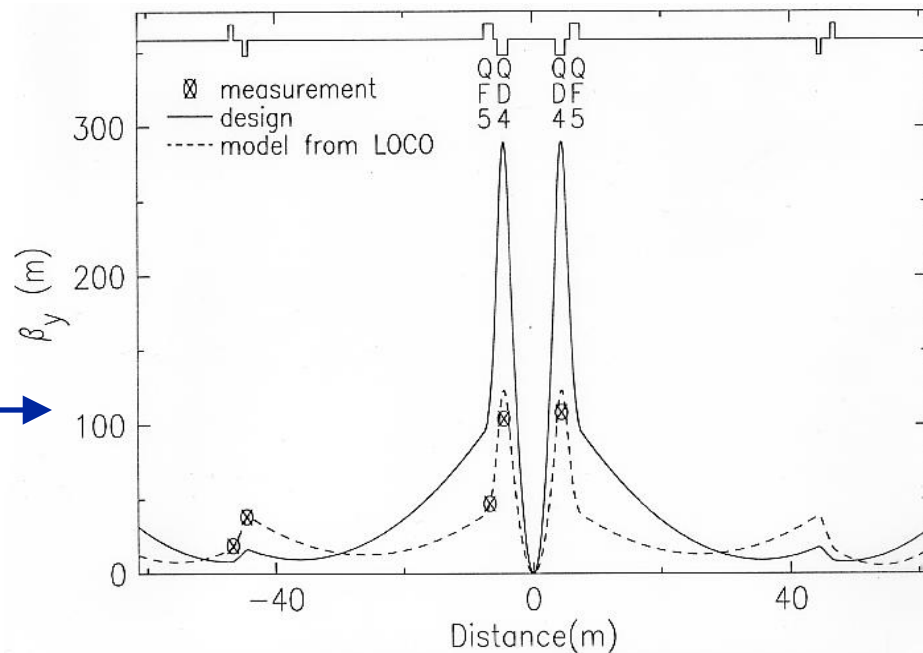
$$\Delta \nu = \beta \frac{\Delta(KL)}{4\pi}$$

Measurement issues

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

β measurement in PEP-II HER IR indicates optics problem.

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

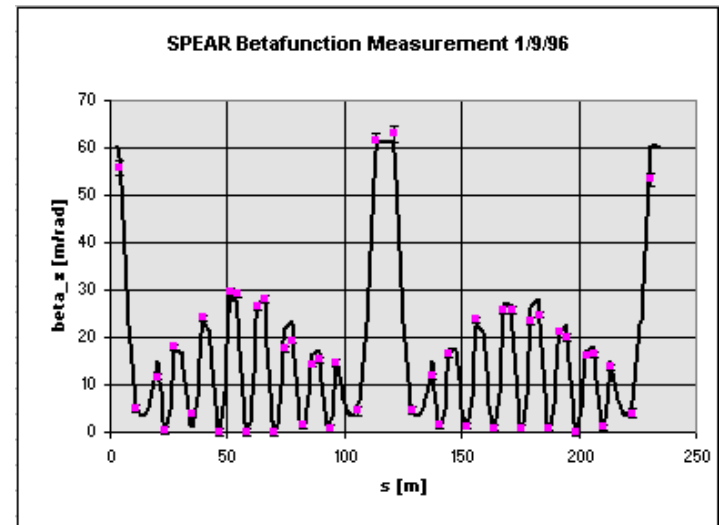


SPEAR β -function correction

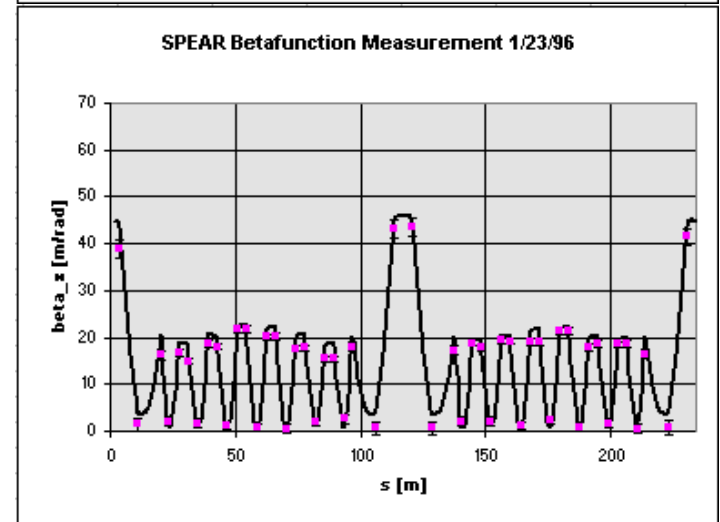


1. β functions measured at quads.
2. MAD model fit to measurements.
3. MAD quadrupoles adjusted to fix β 's.
4. Quadrupole changes applied to ring.
5. β functions re-measured at quads.
6. Iterate.

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)

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

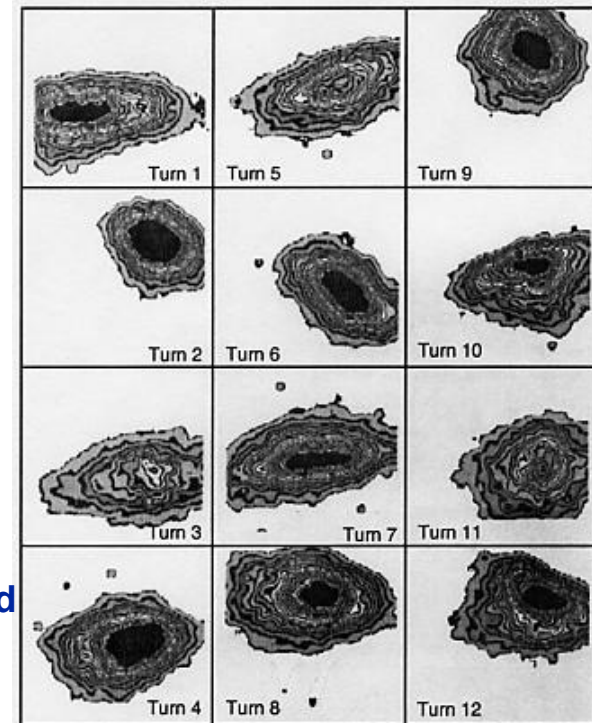
$N_{\text{BPM}} * N_{\text{steerer}}$ data

$2 * N_{\text{BPM}} + 2 * N_{\text{steerer}} + 1$ 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

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

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.

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

The energy can be changed by shifting the rf frequency.

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

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

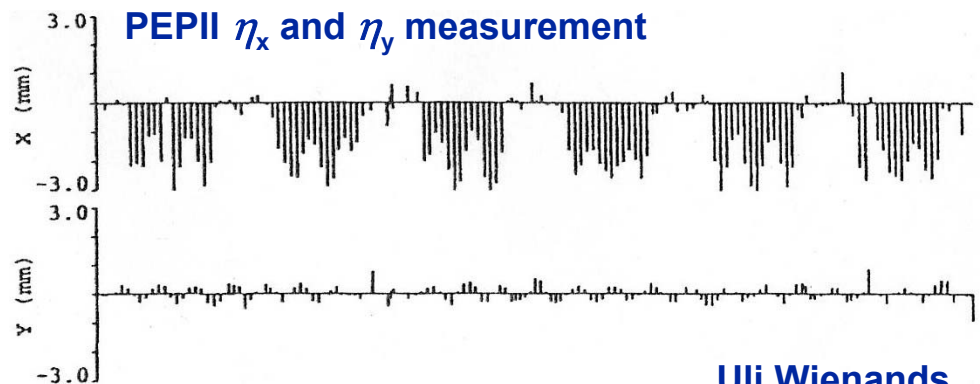
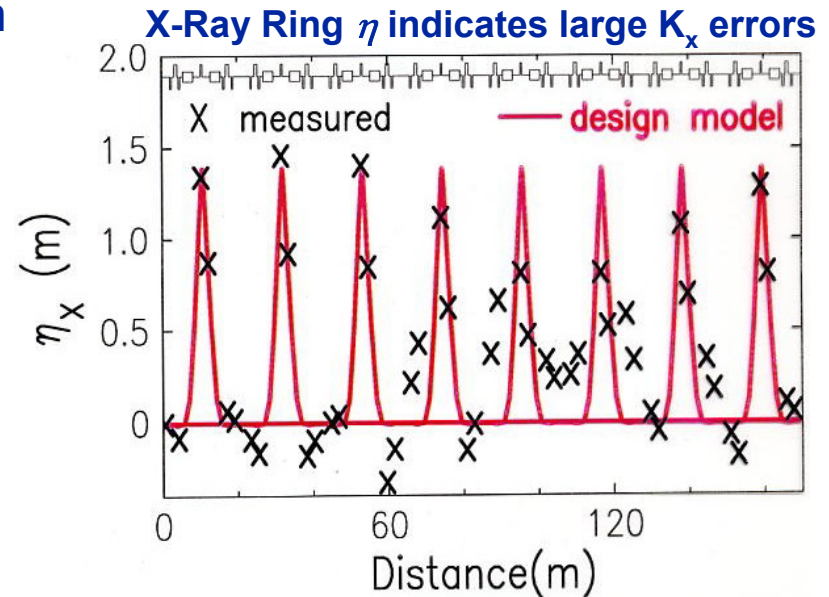


Dispersion distortion can come from quadrupole or dipole errors.

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

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

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



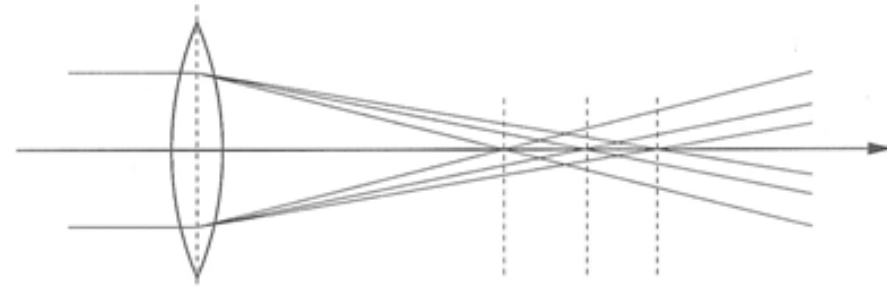
Uli Wienands

Chromaticity



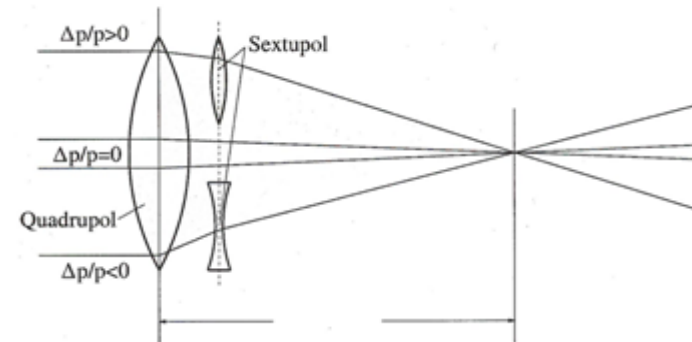
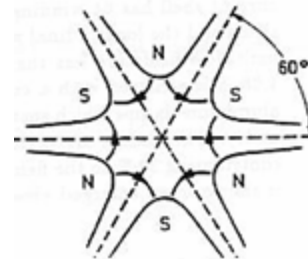
Quadrupoles focus high energy particles less than low energy particles. This leads to a decrease in tune with energy (natural chromaticity):

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



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,

ξ

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.

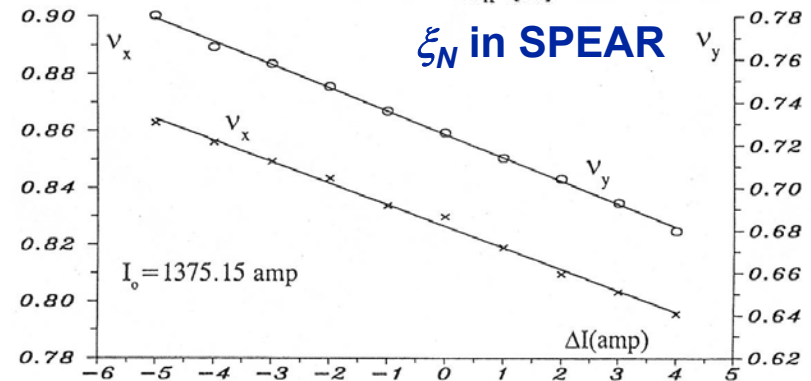
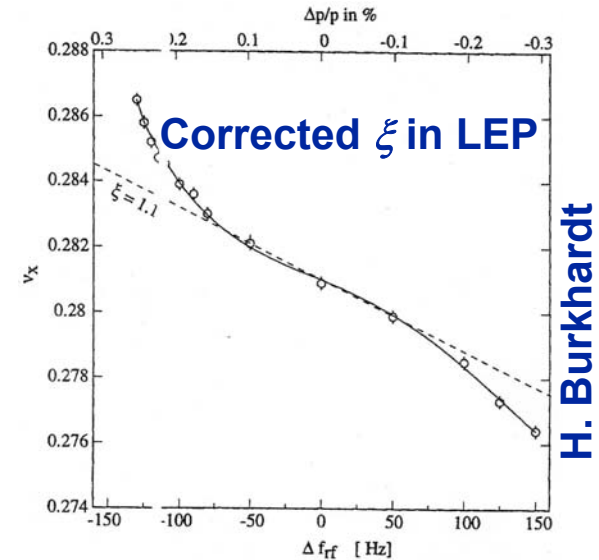
$$\xi = -\alpha f_{rf} \frac{\Delta v}{\Delta f_{rf}}$$

Used to diagnose sextupole miswiring in PEP-II-HER.

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

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

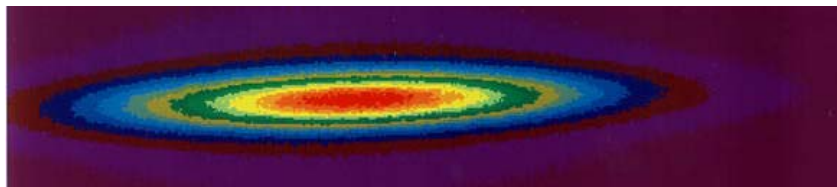
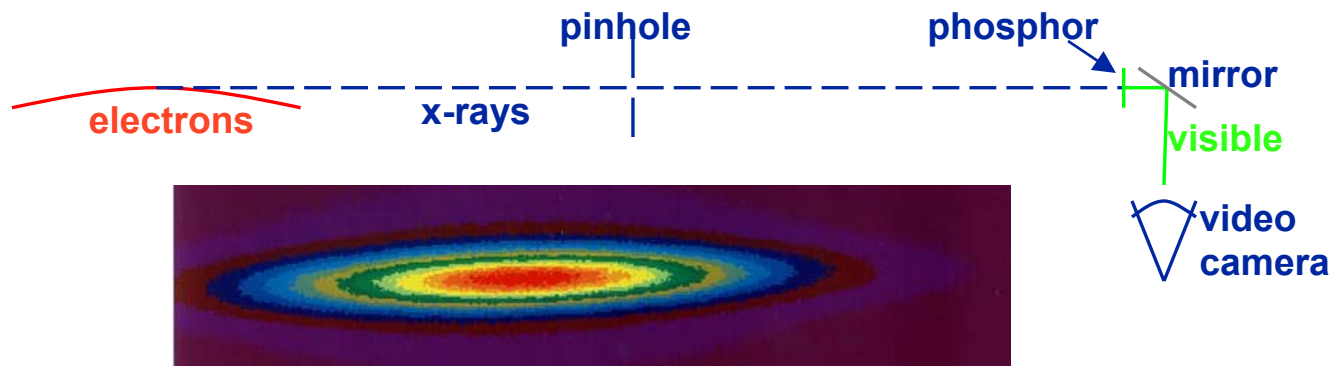
ξ_N can also be measured from n vs. frf with sextupoles turned off.



Beam size measurements



X-Ray pinhole camera



Pinhole camera array (Kuske et al., Bessy)

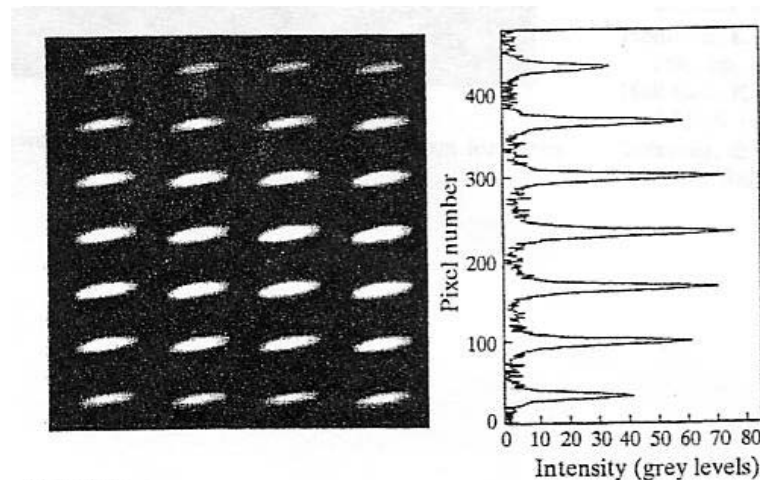
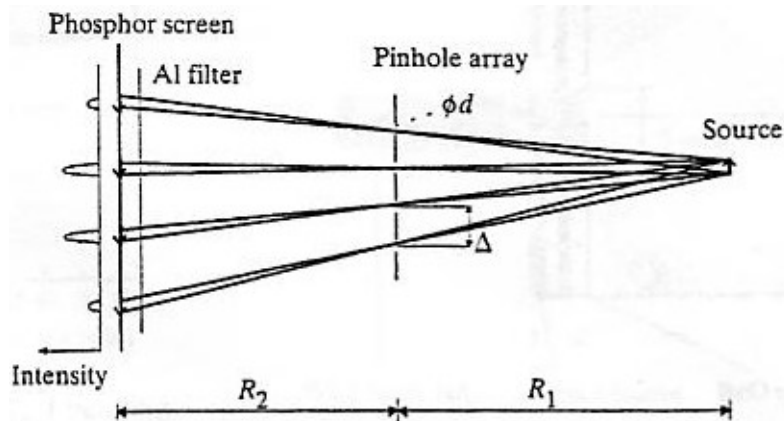


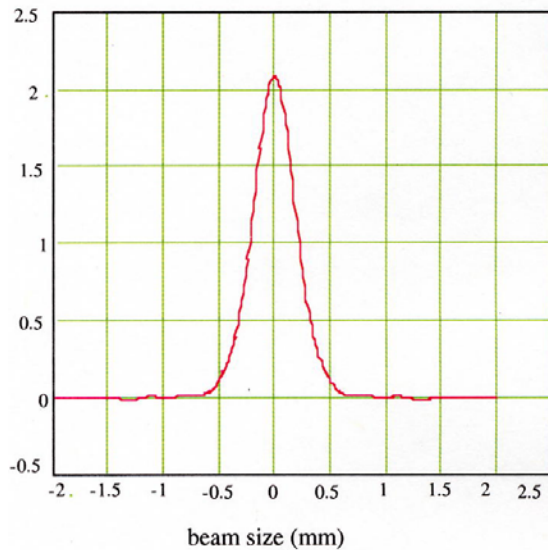
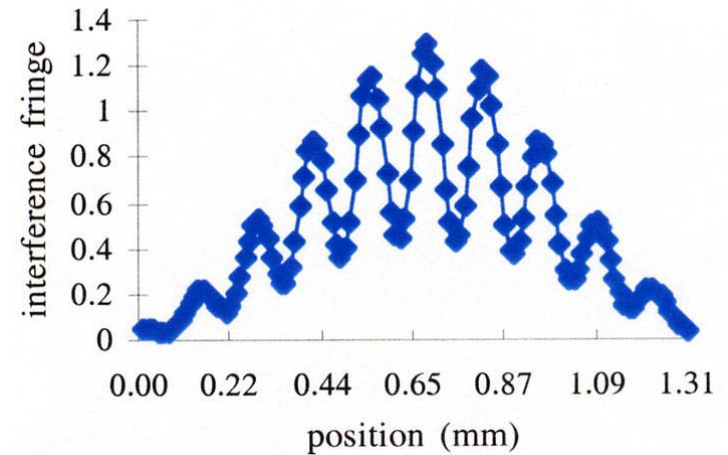
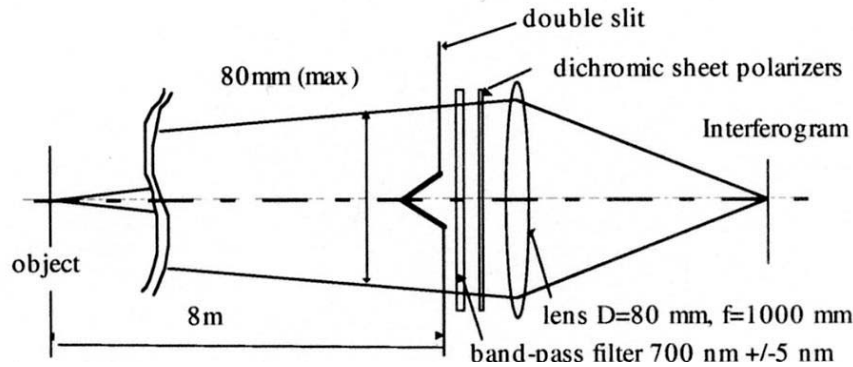
Figure 2
Left: image of a portion of the phosphor observed on a BESSY I bending magnet. Right: integrated intensities of one column of images on the phosphor.



Beam size measurement, spatial coherence

(Mitsubishi, PAC97)

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

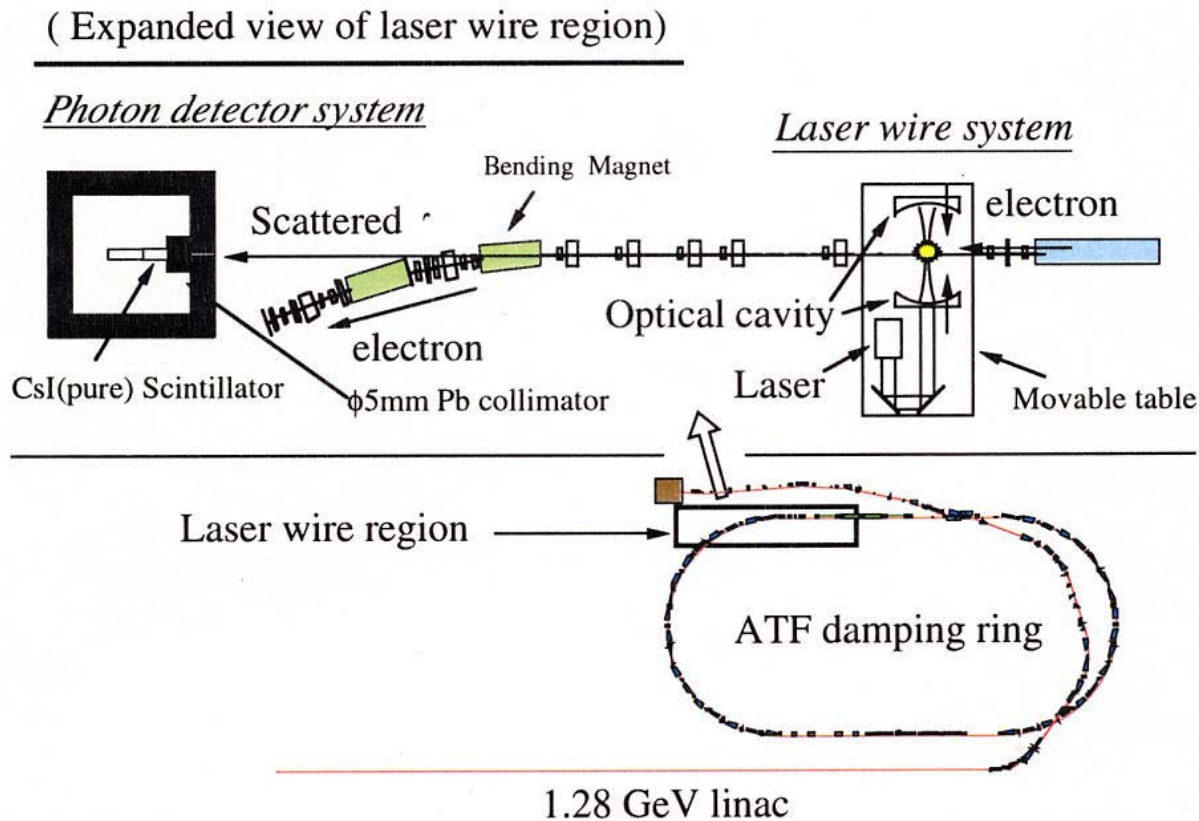


← Vertical beam size can be obtained from the Fourier transform of the degree of spatial coherence.

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)



Principle of streak camera

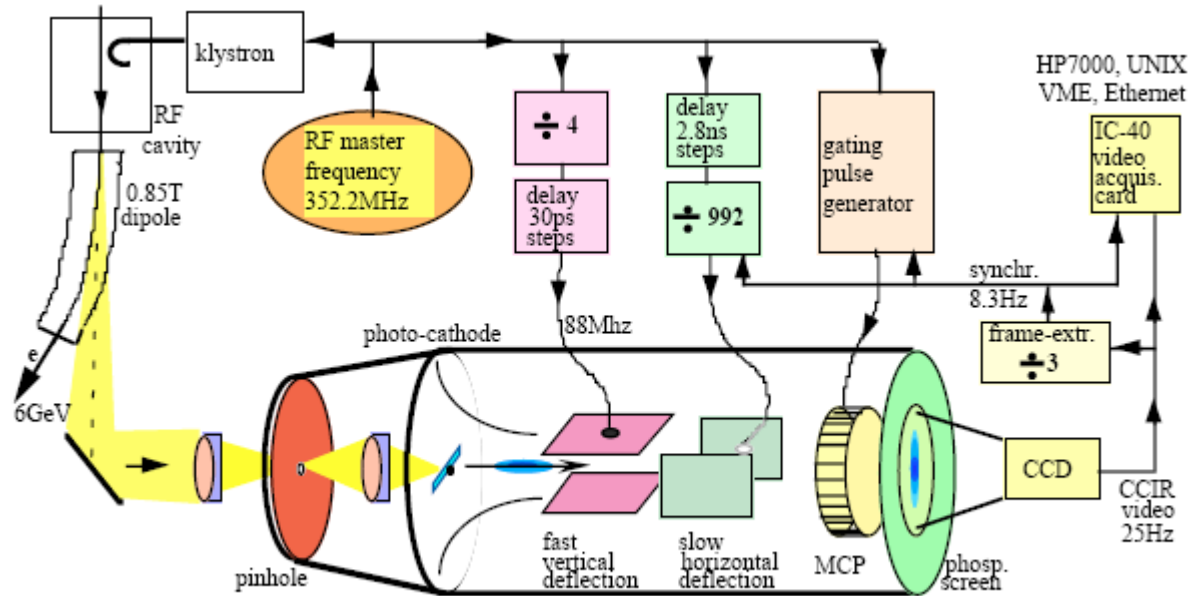
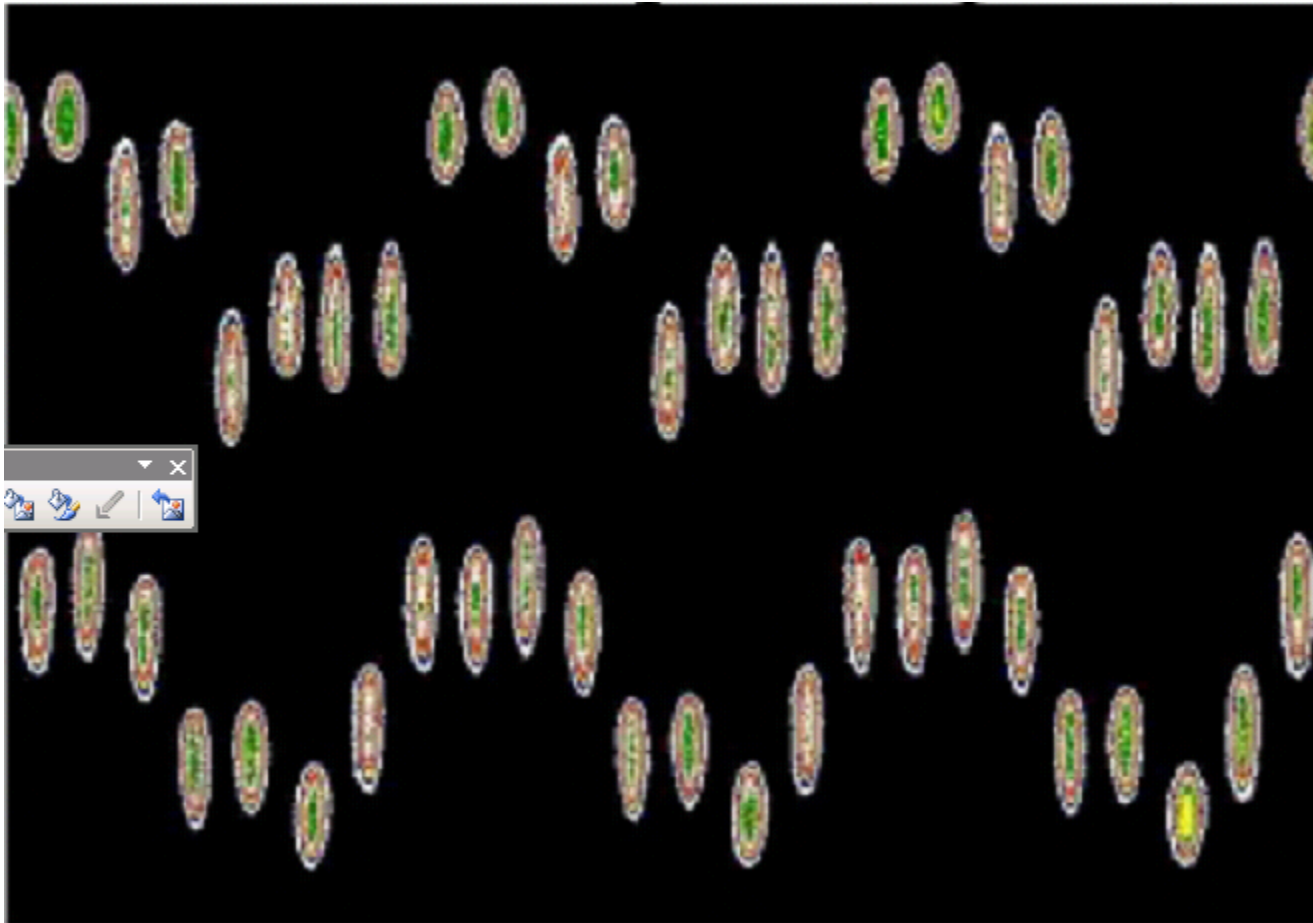


Figure: 1 Synchronisation of the Streak Camera system

- 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

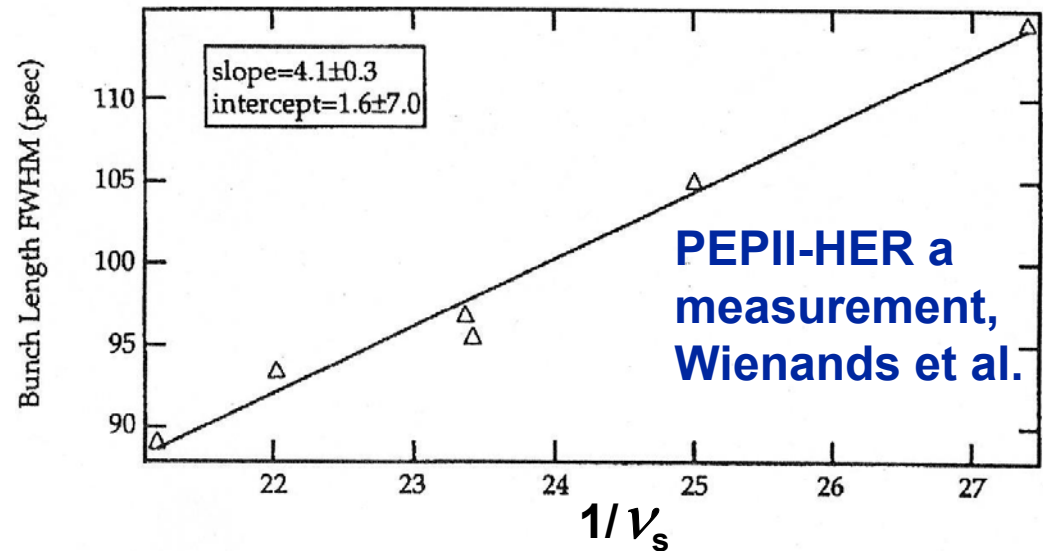
Momentum compaction



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

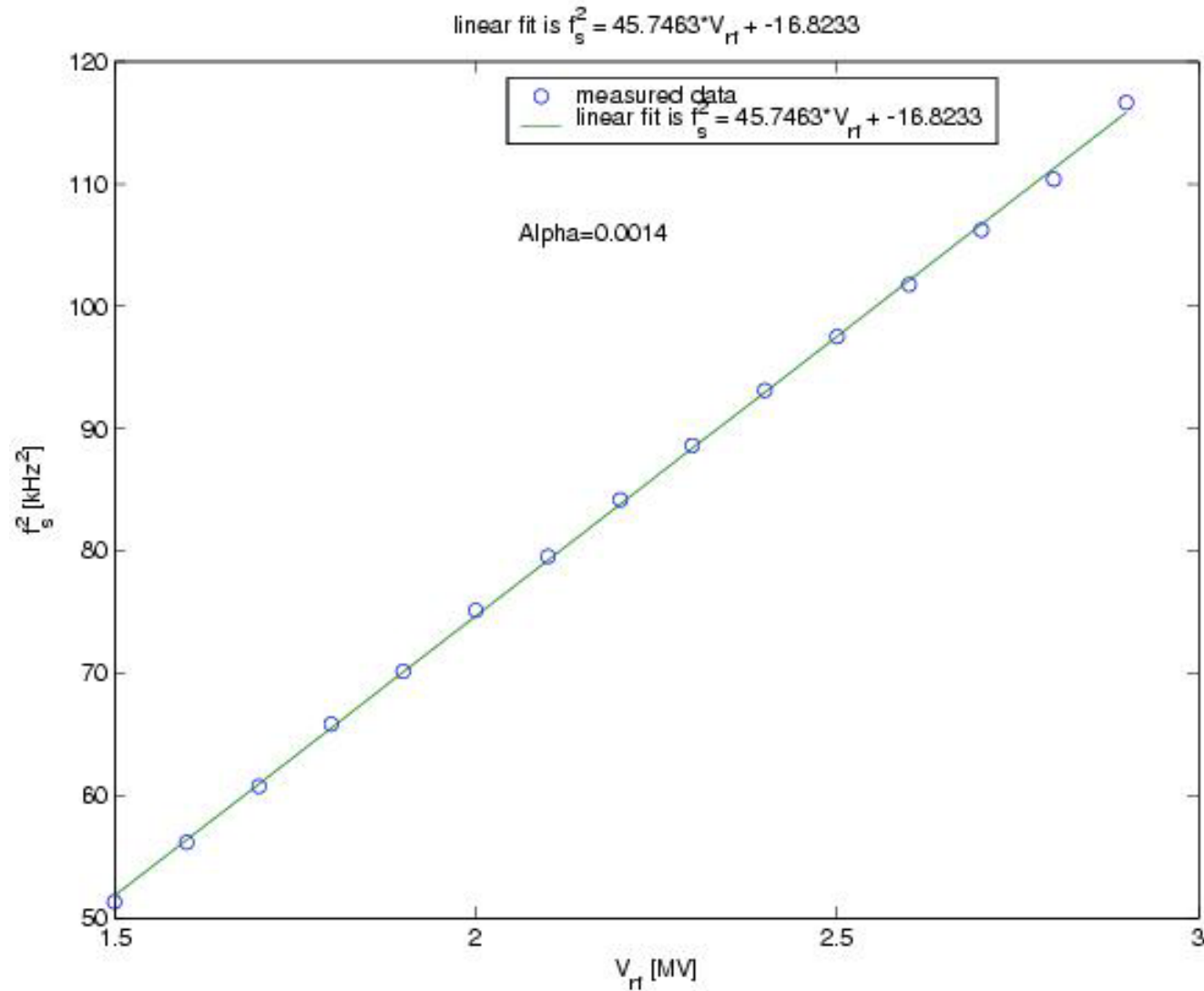
$$\sigma_z = \frac{c \sigma_\delta}{2\pi f_{\text{rev}}} \frac{\alpha}{v_s}$$

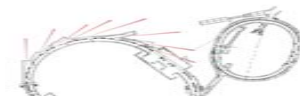


Direct measurement: measure change in energy with rf frequency.

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

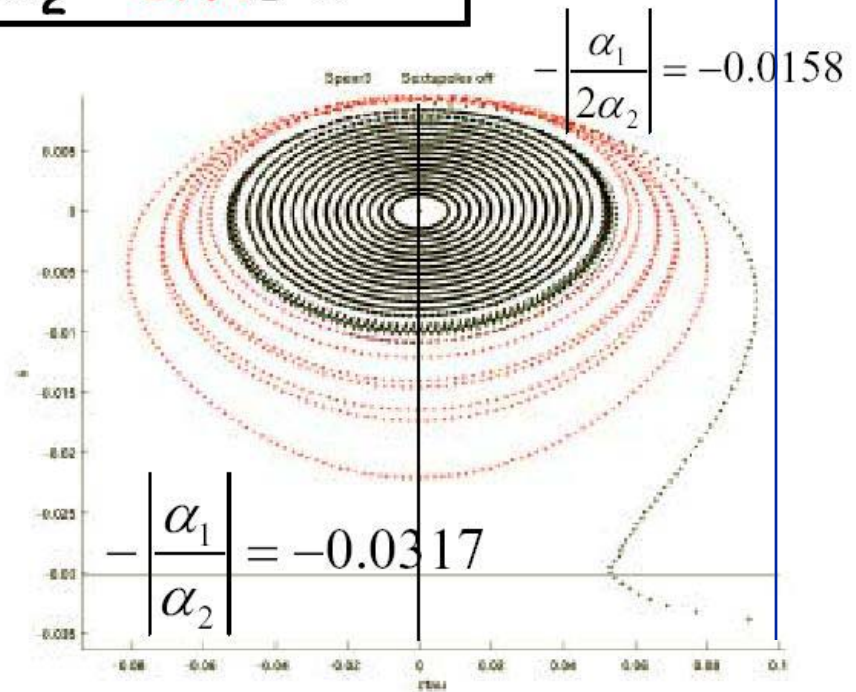
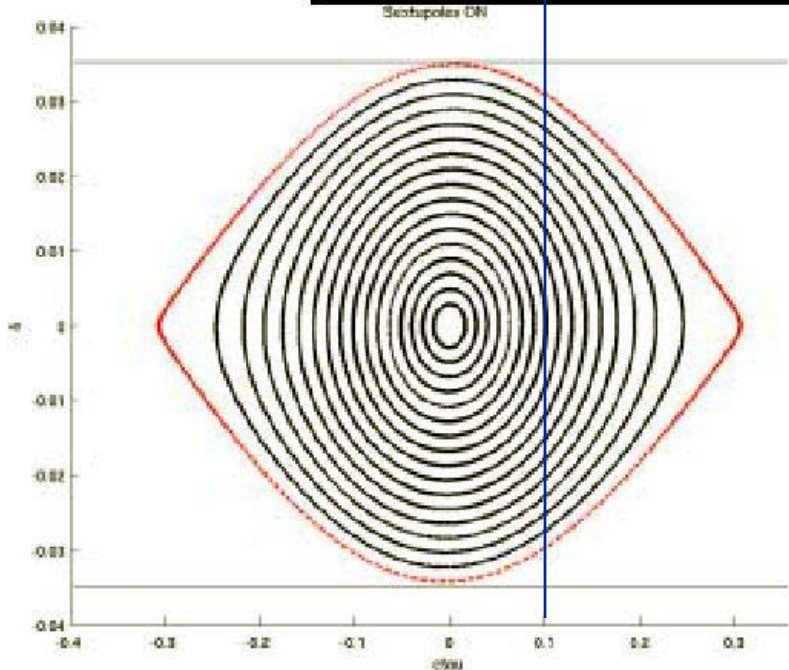
Momentum compaction measurement





SPEAR3: Longitudinal Dynamics

Sextupoles on	Sextupoles off
$\alpha_1 = 1.19 \text{ E-3}$	
$\alpha_2 = -2.1 \text{ E-3}$	$\alpha_2 = 37.4 \text{ E-3}$

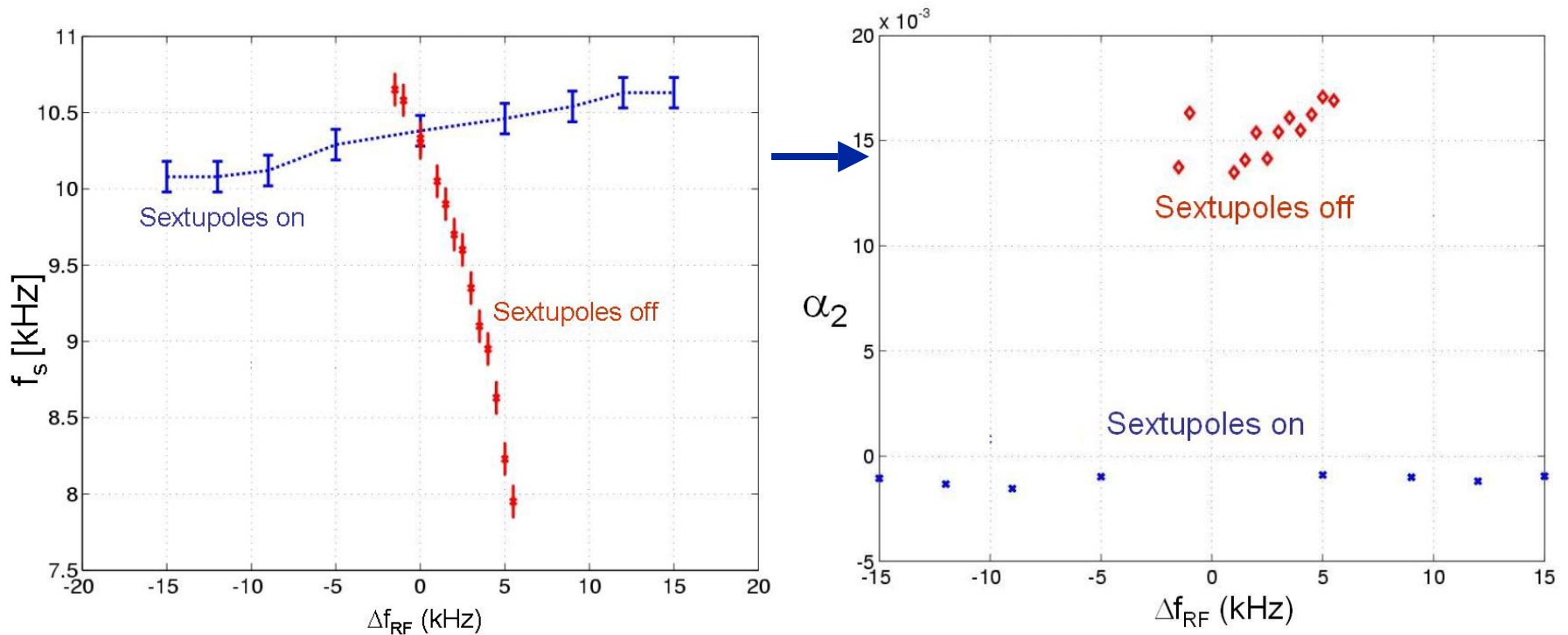


4D tracking using AT

α_2 measurement



- $|\alpha_2|$, sextupoles off \gg $|\alpha_2|$, sextupoles on
- Energy aperture much reduced with sextupoles 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).