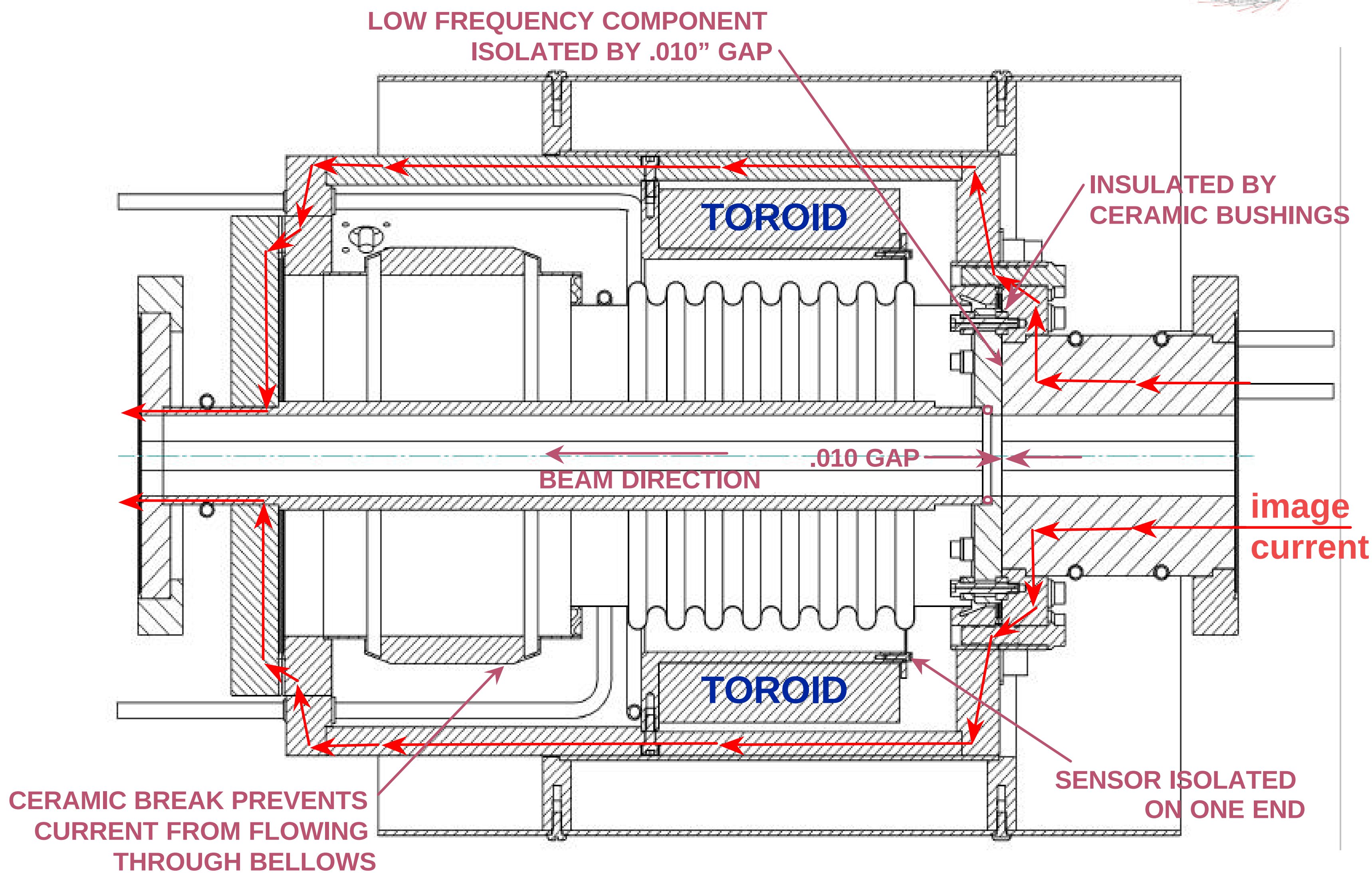
Storage ring optics characterization – the basics

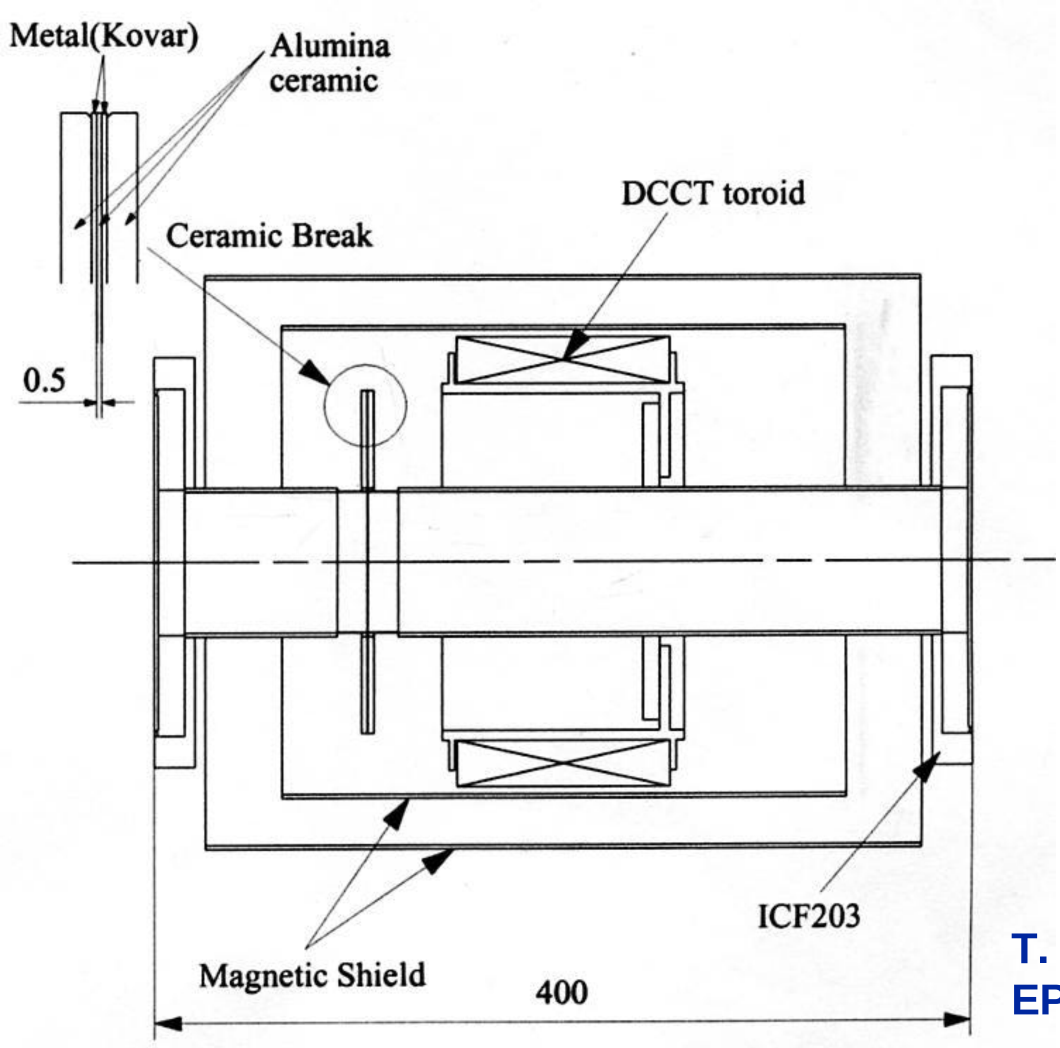
- Beam Diagnostics
  - DCCT
  - BPMs
  - Synchrotron light monitors
  - Scrapers
  - Loss monitors
- Measuring tunes, b, h, chromaticity, a

SPEAR3 DCCT



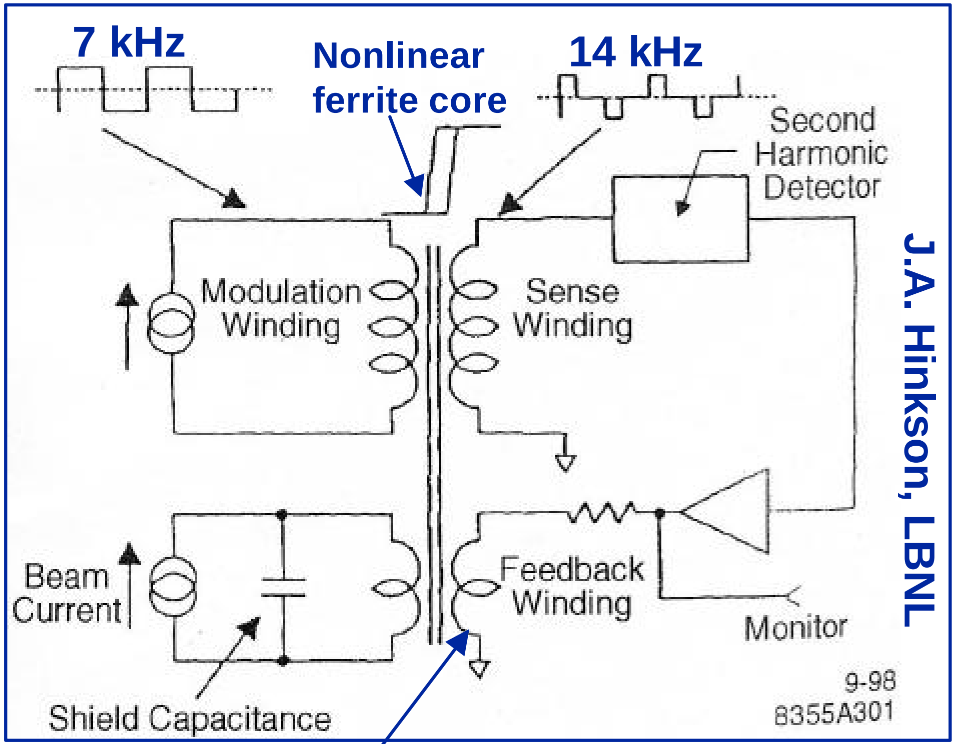
LOW FREQUENCY COMPONENT
ISOLATED BY .010" GAP
INSULATED BY
CERAMIC BUSHINGS
TOROID
TOROID
.010 GAP
BEAM DIRECTION
image
current
CERAMIC BREAK PREVENTS
CURRENT FROM FLOWING
THROUGH BELLOWS
SENSOR ISOLATED
ON ONE END

Photon factory DCCT



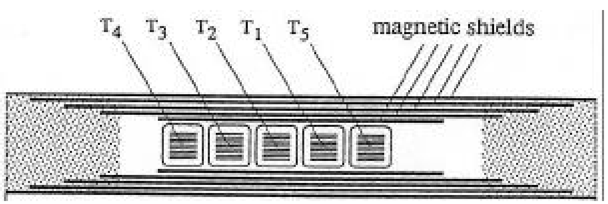
T. Honda et al., EPAC98

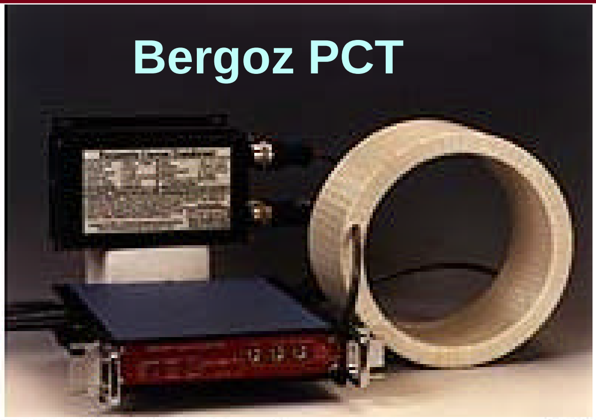
DCCT (or PCT) circuit

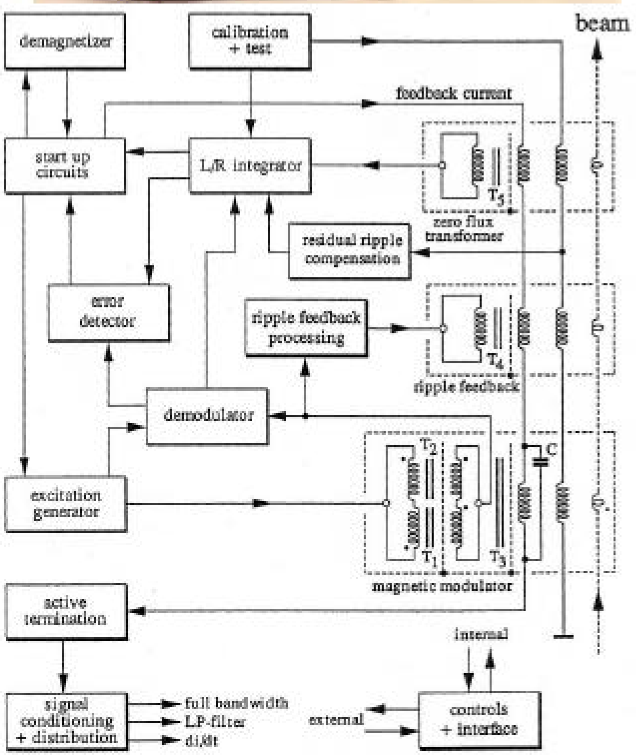


The DC bias current is adjusted to remove the 2nd harmonic (14 kHz) response of toroid. The beam current is proportional to the DC bias current.

Ferrite core Xsection



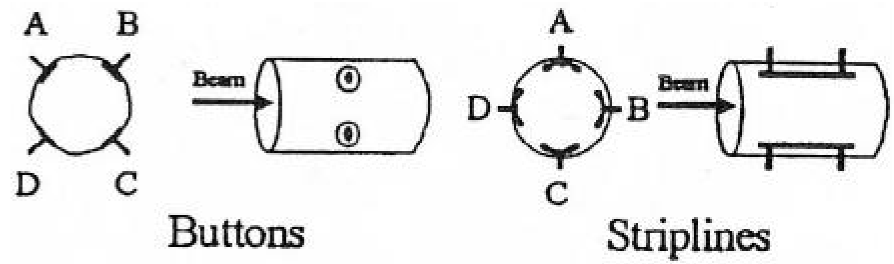




Simplified circuit, K. Unser, 1992

Beam position monitors

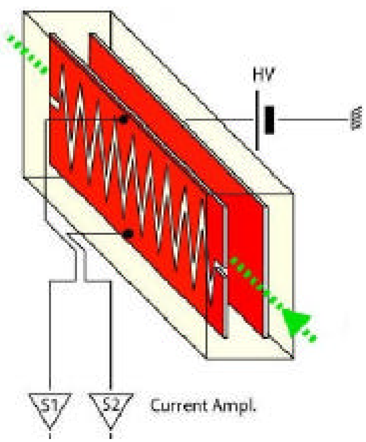
$$x = \frac{r}{\sqrt{2}} \frac{(V_A + V_D - V_B - V_C)}{(V_A + V_B + V_C + V_D)}$$



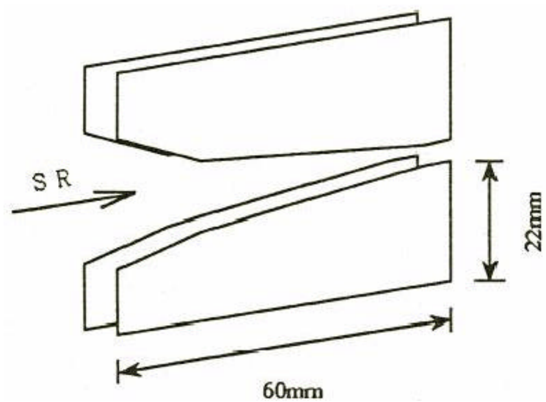
Electron BPM buttons sample electric fields; striplines couple to electric and magnetic fields.

Examples of photon BPMs:

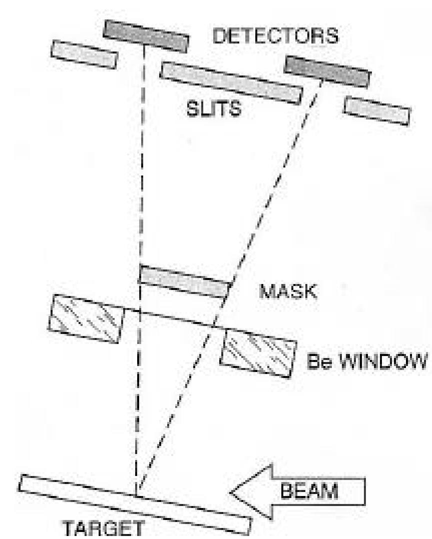
Split ion chamber:



Tungsten blade monitor:

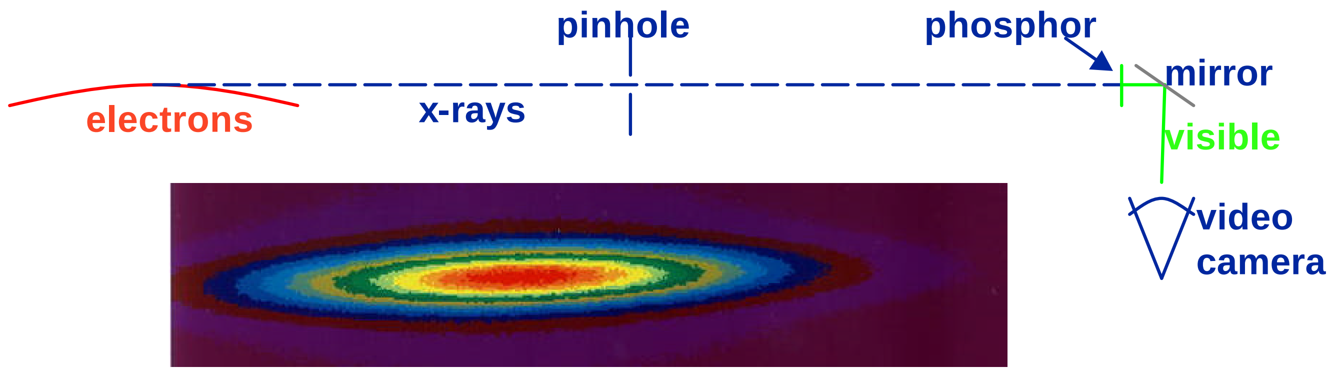


Copper fluorescence bpm:



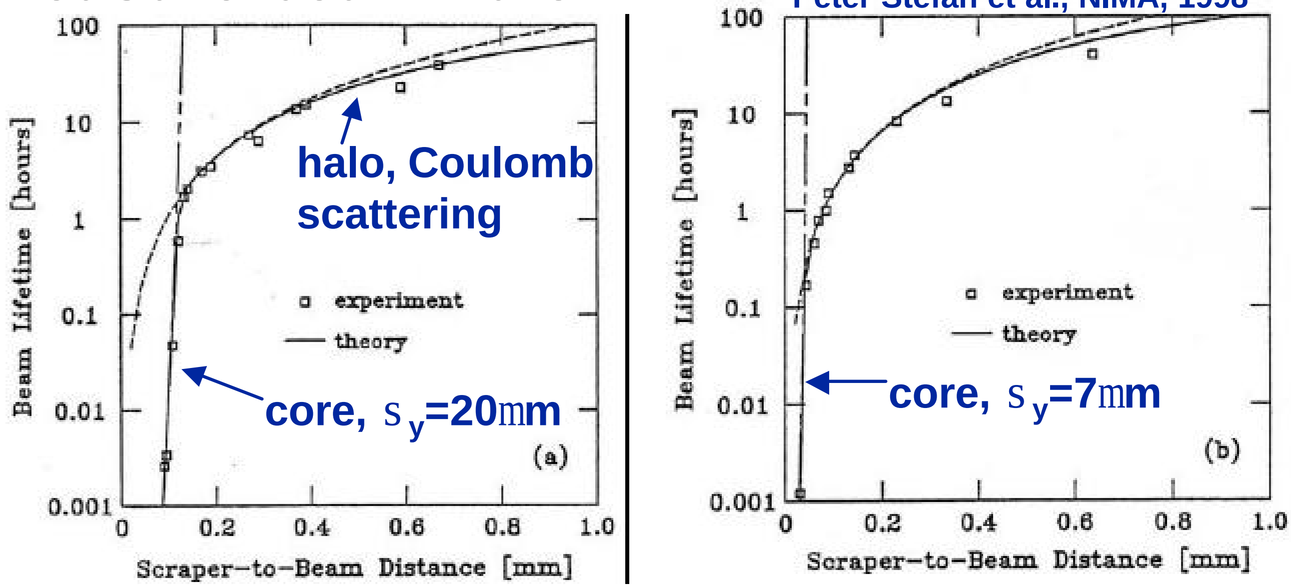
Beam size measurements (more on Thurs.)

Synchrotron light monitors measure beam core

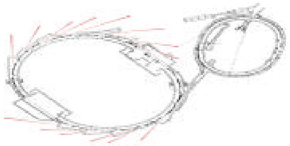


Scrapers measure beam halo

Peter Stefan et al., NIMA, 1998



Beam loss monitors

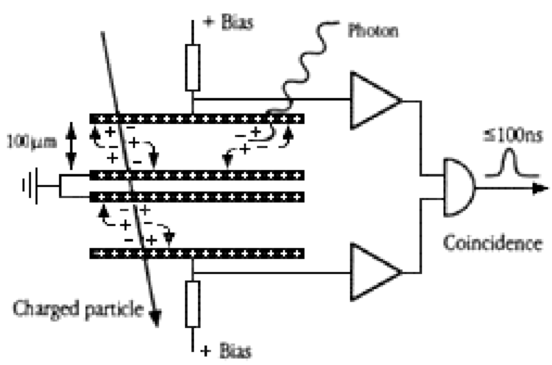


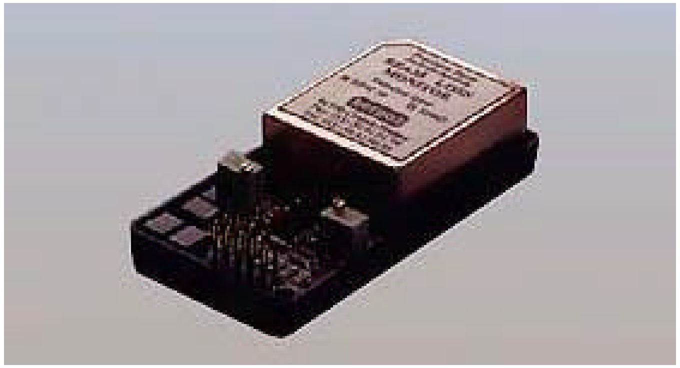
Electrons hit vacuum chamber and generate e+/e- shower which can be detected with beam loss monitors. Advantages over DCCT:

- **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

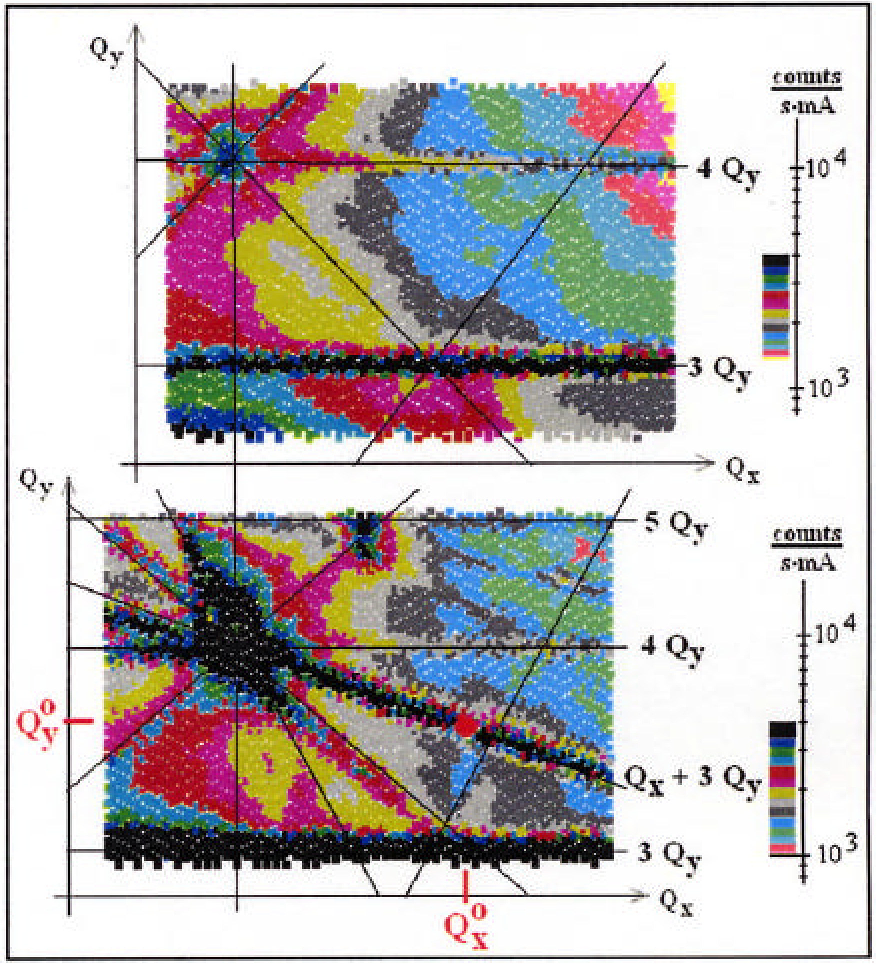




A scintillator with a photomultiplier is another commonly used BLM.

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.

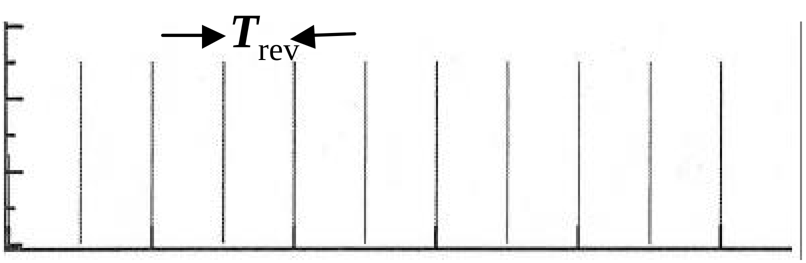
Beam frequencies

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

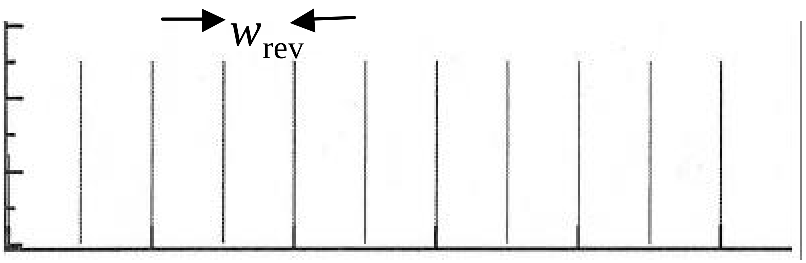
$$I(t) = \sum_{n=-\infty}^{\infty} q d\,(t - nT_{\mathrm{rev}}),$$

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

$$I(w) = \sum_{n=-\infty}^{\infty} q w_{\mathrm{rev}} d\,(w - n w_{\mathrm{rev}})$$



Time

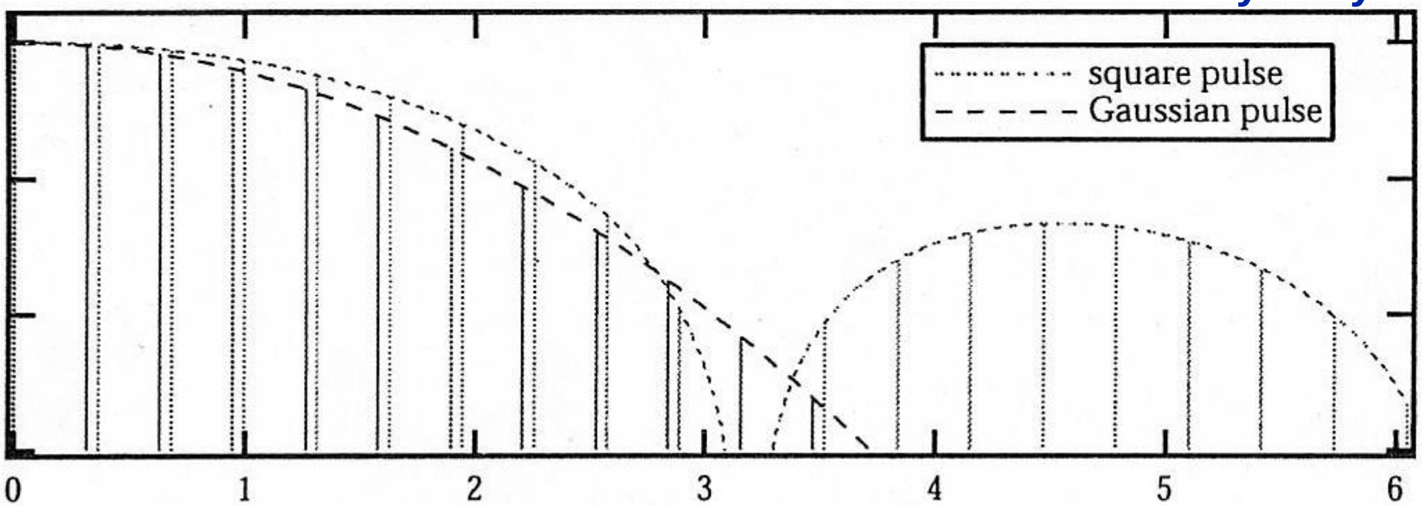


Frequency

Spectrum for finite bunch length

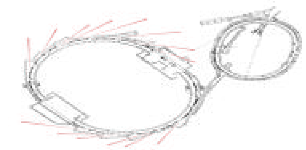
For finite bunch length, the single bunch spectrum rolls off as the Fourier transform of the longitudinal bunch profile (Gaussian for e- rings).

Courtesy J. Byrd



frequency (1/σ_z)

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



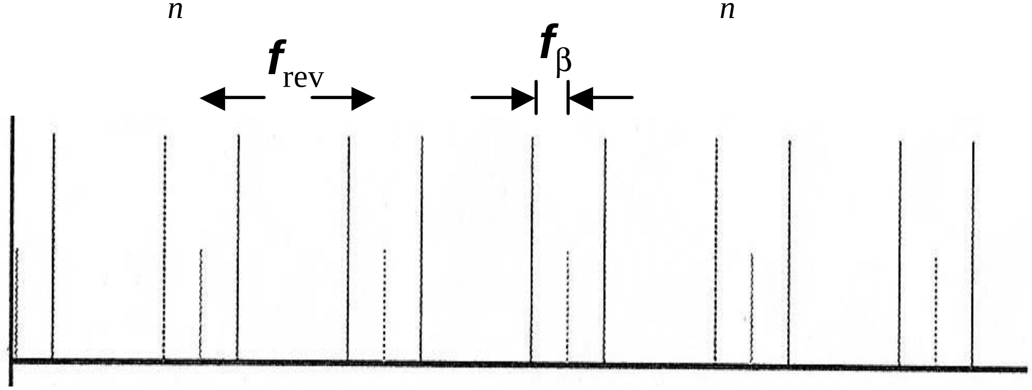
Betatron tune

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_b, the signal is

$$d(t) = (x_{c.o.} + x_b \cos(2pnt)) \sum_{n=-\infty}^{\infty} qd(t - nT_{\mathrm{rev}})$$

The Fourier transform is

$$d(w) = qw_{\mathrm{rev}} x_{c.o.} \sum_n d(w - nw_{\mathrm{rev}}) + qw_{\mathrm{rev}} x_b \sum_n d(w - (w_b + nw_{\mathrm{rev}}))$$

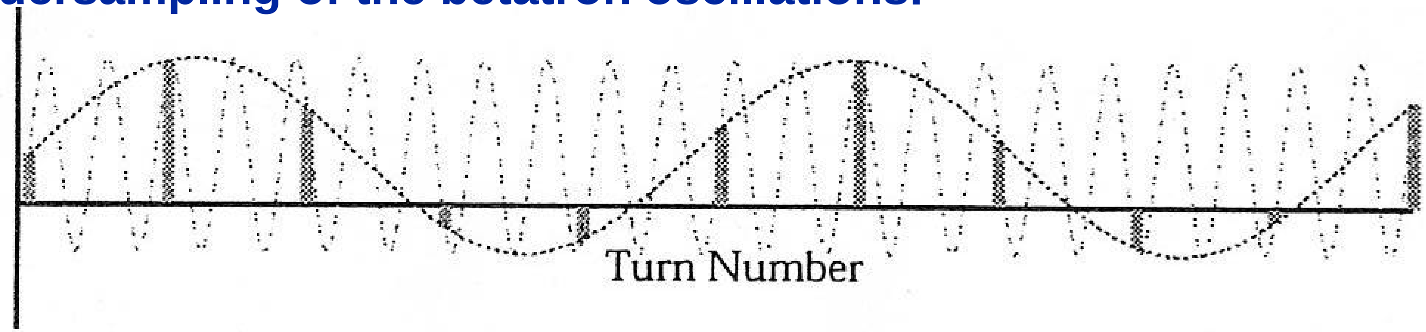


Frequency

The tune is given by $n = f_b / f_{\mathrm{rev}}$ **(with integer/half-integer ambiguity).**

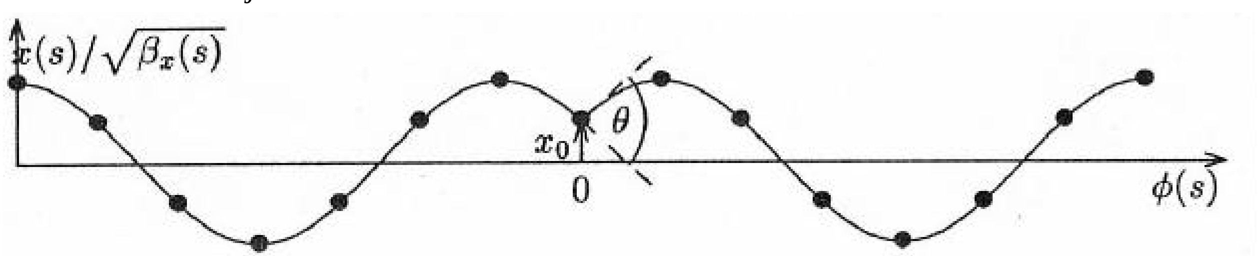
Betatron tune, 2

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.

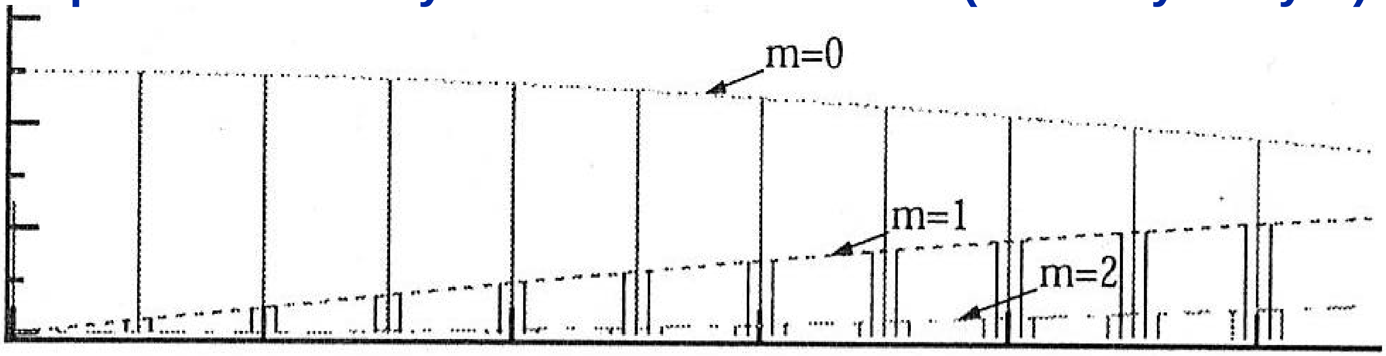
$$\frac{\Delta x_i}{\Delta q_j} = \frac{\sqrt{b_i b_j}}{2\sin(pn)} \cos(|f_i - f_j| - pn)$$



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.

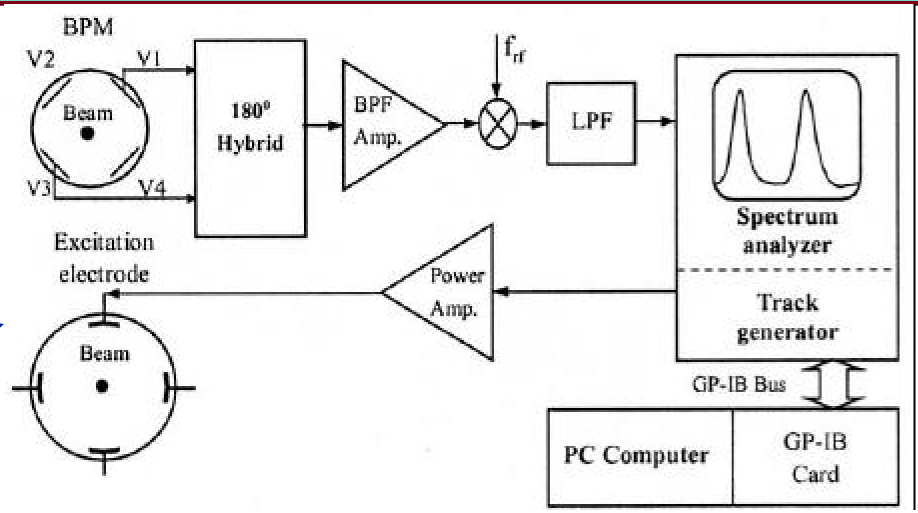
Spectrum from synchrotron oscillations (courtesy J. Byrd)



frequency

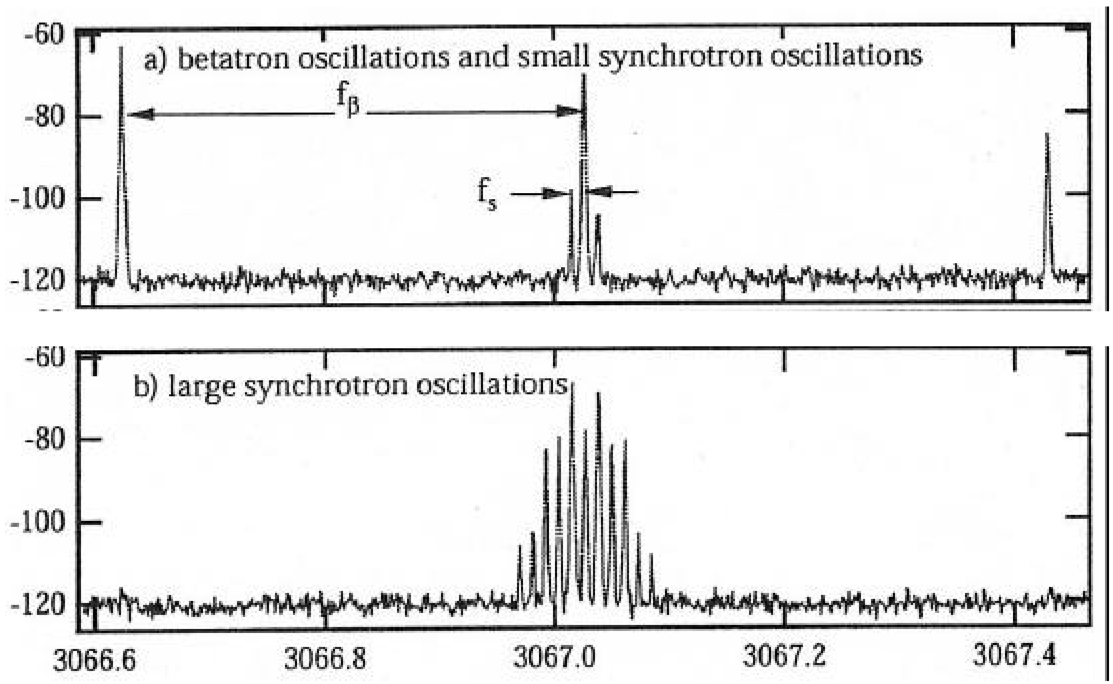
Measured spectra

Typical tune measurement



HLS tune meas.,
Sun et al. PAC01

Typical measured spectra



Multibunch spectra, instabilities, Sebek, 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

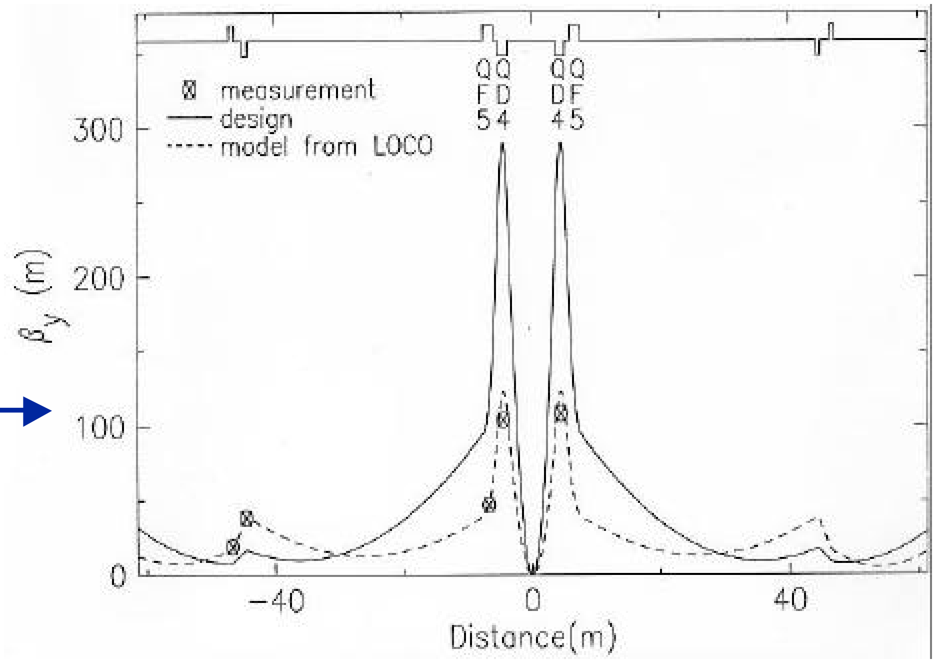
Beta functions can be measured by measuring the change in tune with quadrupole strength:

$$\Delta n = b \frac{\Delta(KL)}{4p}$$

Measurement issues

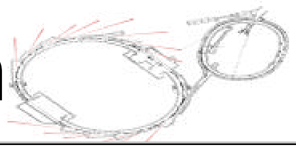
- **Keep orbit constant**
- **Hysteresis**
- **Saturation**
- **Sometimes cannot vary individual quadrupoles**

β measurement in PEPII HER IR indicates optics problem. →



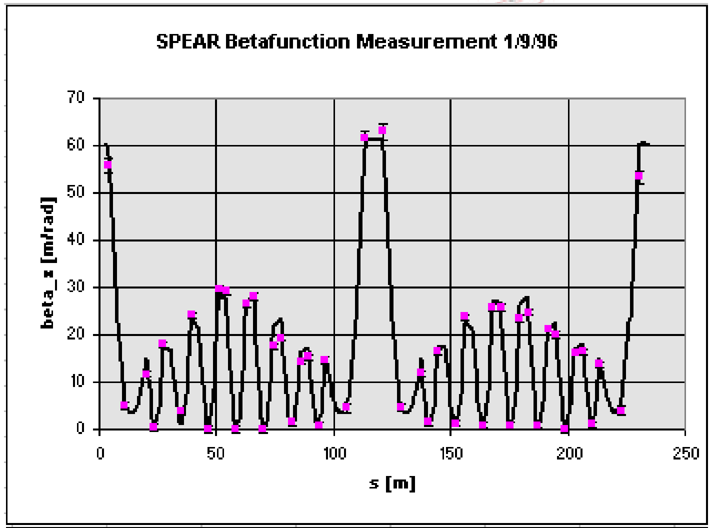
(Methods to be described Tuesday were used to find source of problem and correct it.)

SPEAR b-function correction

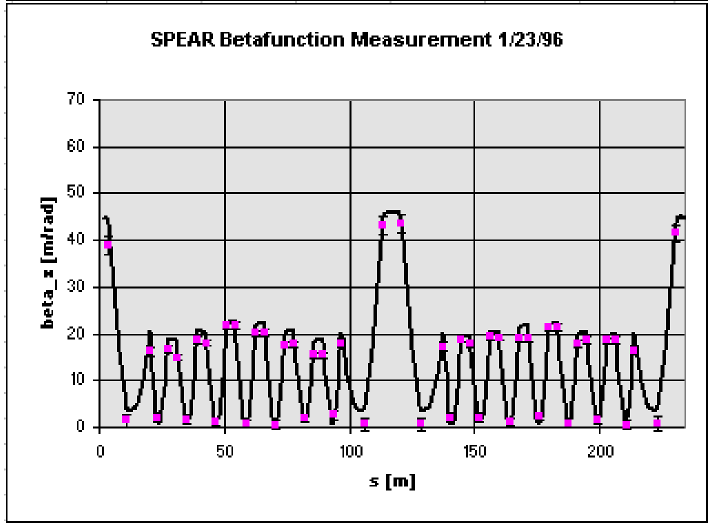


1. b **functions measured at quads.**
2. **MAD model fit to measurements.**
3. **MAD quadrupoles adjusted to fix b's.**
4. **Quadrupole changes applied to ring.**
5. b **functions re-measured at quads.**
6. **Iterate.**

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)

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

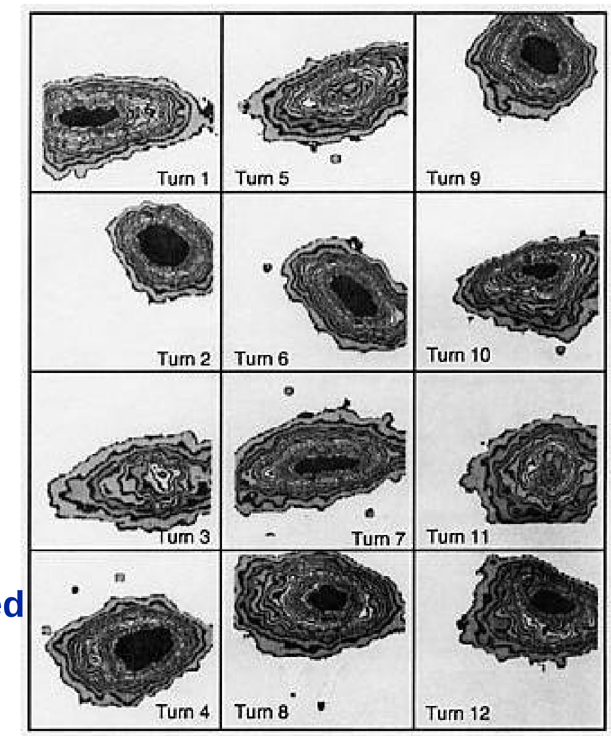
N_{BPM}*$N_{steerer}$ data

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.

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

The energy can be changed by shifting the rf frequency.

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

(a = momentum compaction)

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

$$h = -a f_{rf} \frac{\Delta x}{\Delta f_{rf}}$$

Dispersion measurement

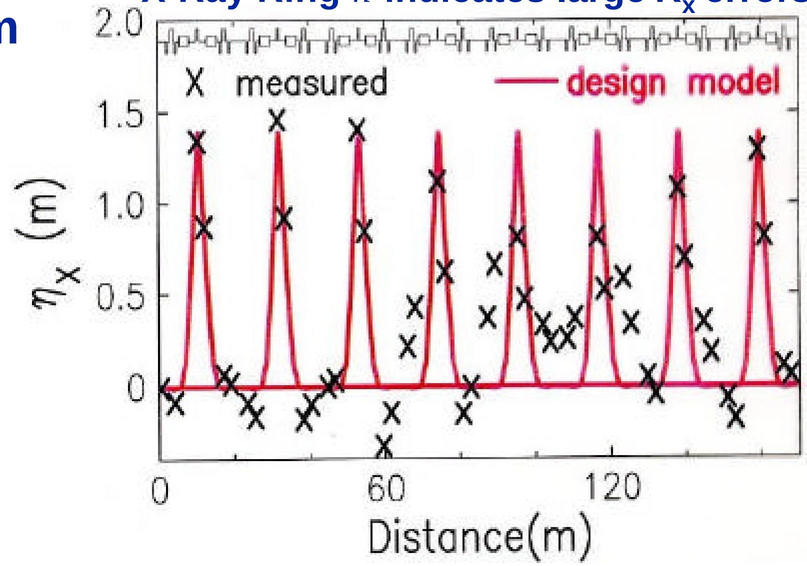
Dispersion distortion can come from quadrupole or dipole errors.

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

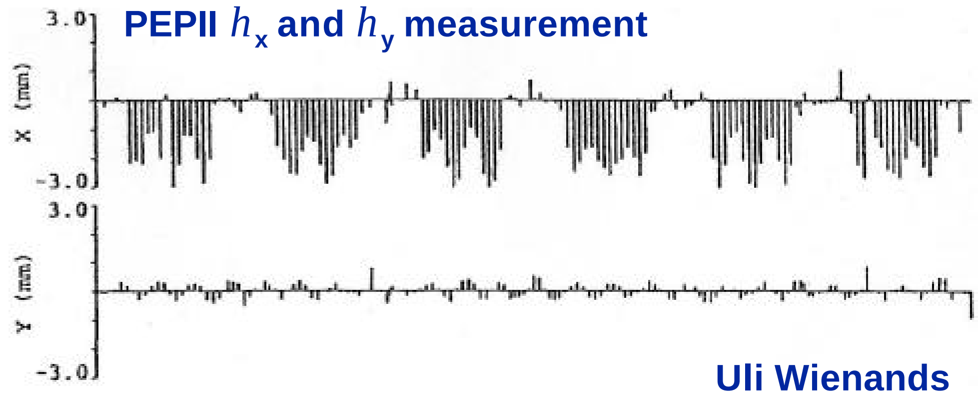
Vertical dispersion gives a measure of vertical bending errors or skew gradient errors in a storage ring.

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

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):

$$x_N = \Delta n \bigg/ \frac{\Delta p}{p}$$

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

$$K = mx = mh\ \Delta p / p$$

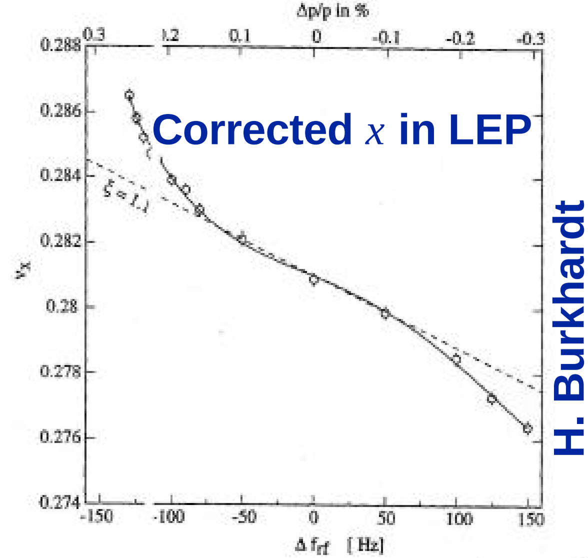
K is the gradient, m is the sextupole strength.

The chromaticity with sextupoles is called the corrected chromaticity,

$$x$$

Chromaticity measurement

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



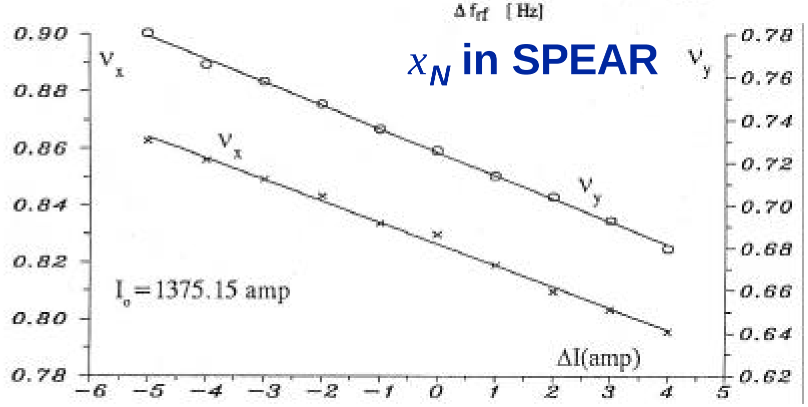
1. Change the rf frequency. This shifts the orbit in sextupoles, giving the corrected chromaticity.

$$x = -a f_{rf} \frac{\Delta n}{\Delta f_{rf}}$$

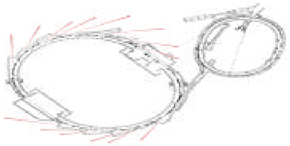
Used to diagnose sextupole mis-wiring in PEPII-HER.

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

$$x_N = \frac{\Delta n}{\Delta B / B}$$



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

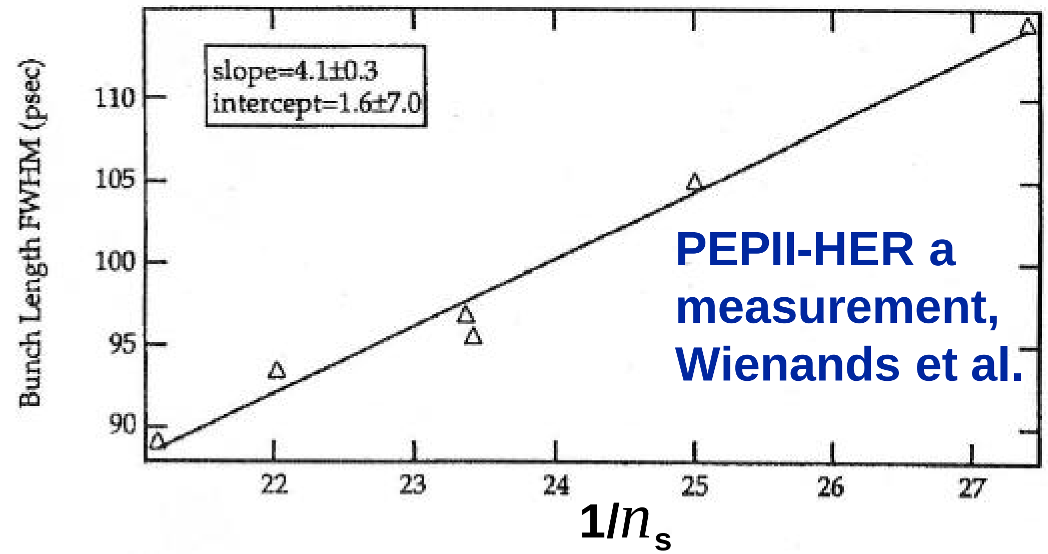


Momentum compaction

Using the model value of a for x and h measurements can lead to errors. a itself can be measured in various ways.

Indirect measurement from bunch length

$$s_z = \frac{c s_d}{2p f_{\mathrm{rev}}} \frac{a}{n_s}$$



Direct measurement: measure change in energy with rf frequency.

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

Friday will include lecture on energy measurement.

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).