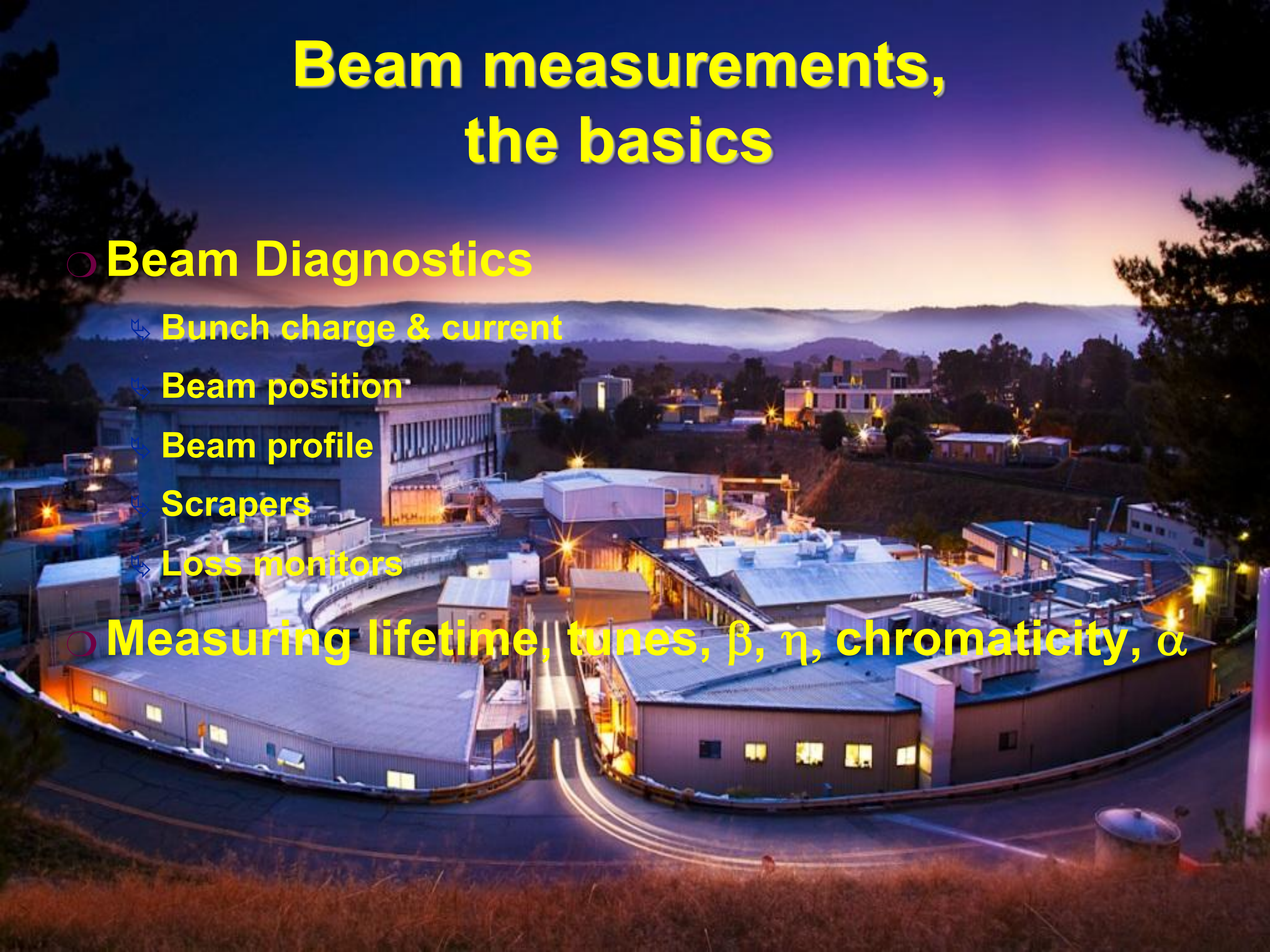
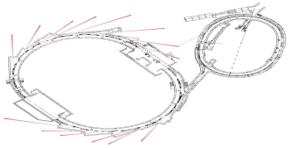
Beam measurements, the basics



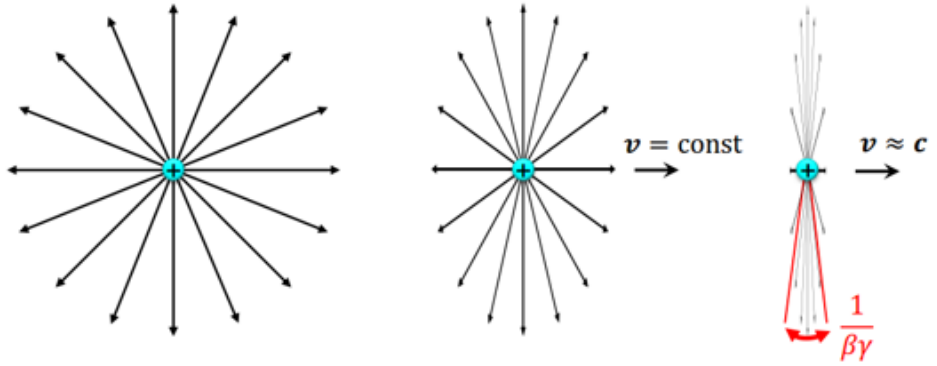
- Beam Diagnostics
  - Bunch charge & current
  - Beam position
  - Beam profile
  - Scrapers
  - Loss monitors
- Measuring lifetime, tunes, β, η, chromaticity, α

Beam fields



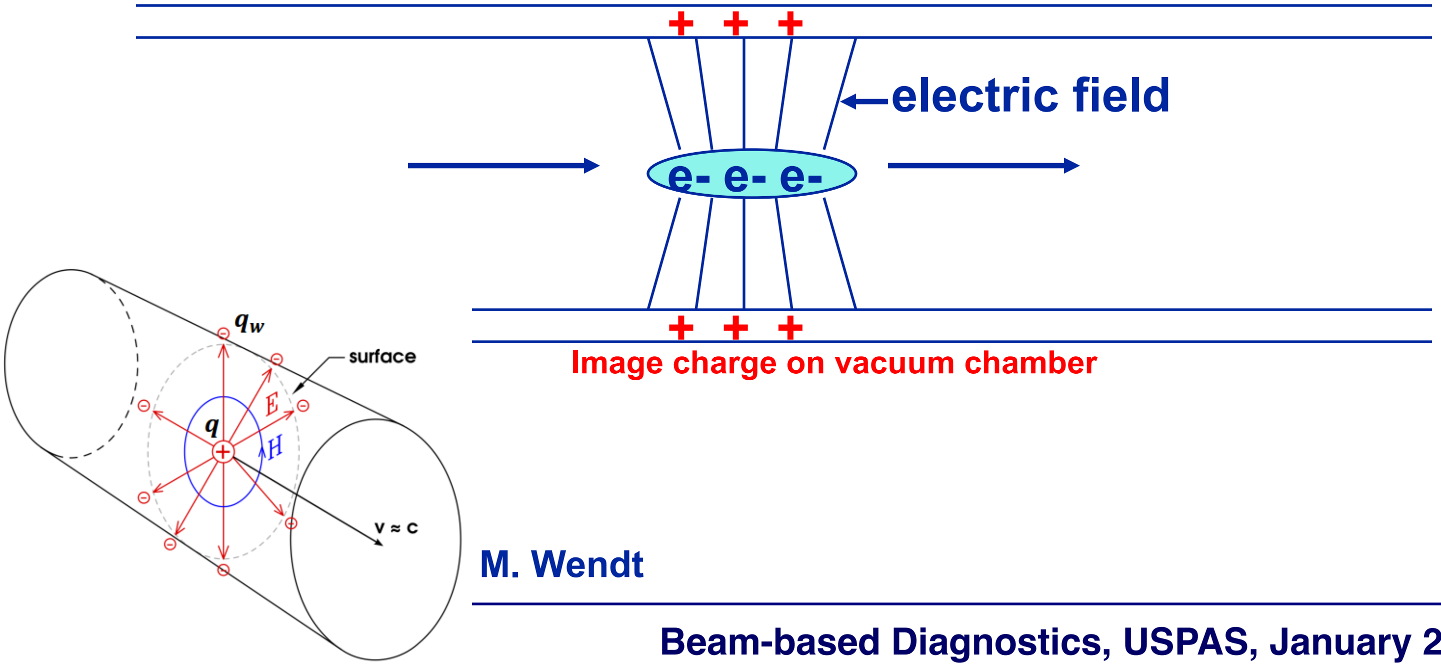
- Coulomb field is compressed for a relativistic electron

At rest: **Relativistic:**

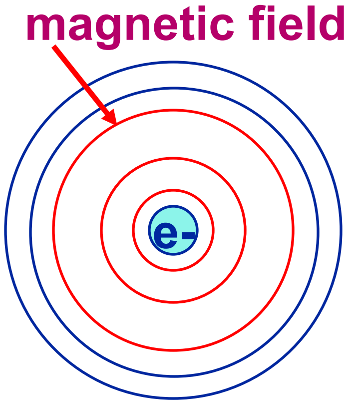


Small E-field opening angle. For SPEAR3, $\gamma = 5871$

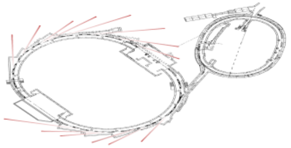
- Electron bunch in a circular vacuum chamber:



M. Wendt

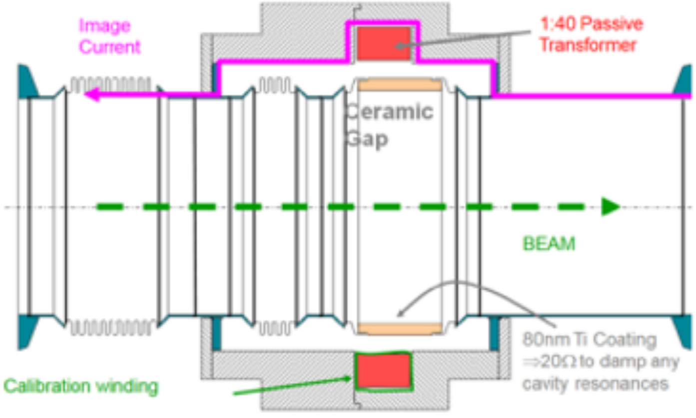


Beam diagnostics: Intensity/current



- Non-destructive intensity measurements usually couple to the E or B fields or the image current – resistive wall monitors, capacitive pickups, or toroids (most often)
- Toroid is a transformer: The primary is the beam and its image current. The secondary is windings around the toroid.

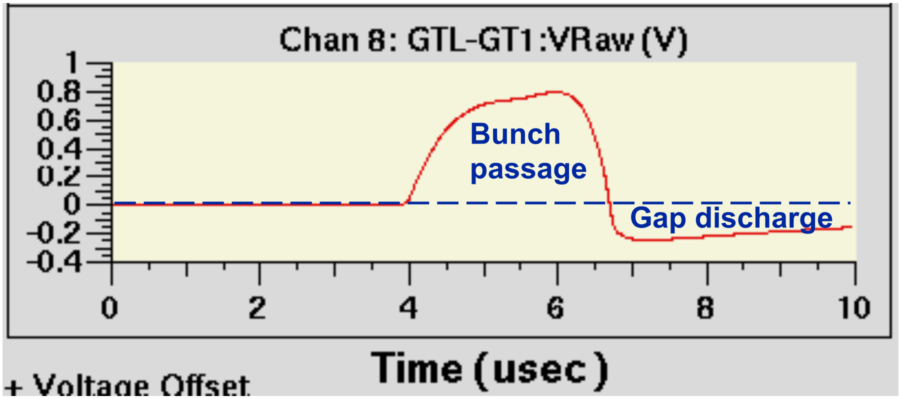
CERN toroid:



- 500MHz Bandwidth
- Low droop (< 0.2%/µs)

courtesy H. Schmickler (CERN)

SSRL toroid signal:



- Gated integral during bunch passage to get charge
- Total integral, including long tail, is zero (transformers do not couple DC)
- Length of tail determined by capacitance and inductance of loop around toroid.
- If the beam current is DC or want to measure DC component, method becomes more complicated – DCCTs are used (also in DC power supplies, …)

Photon factory DCCT

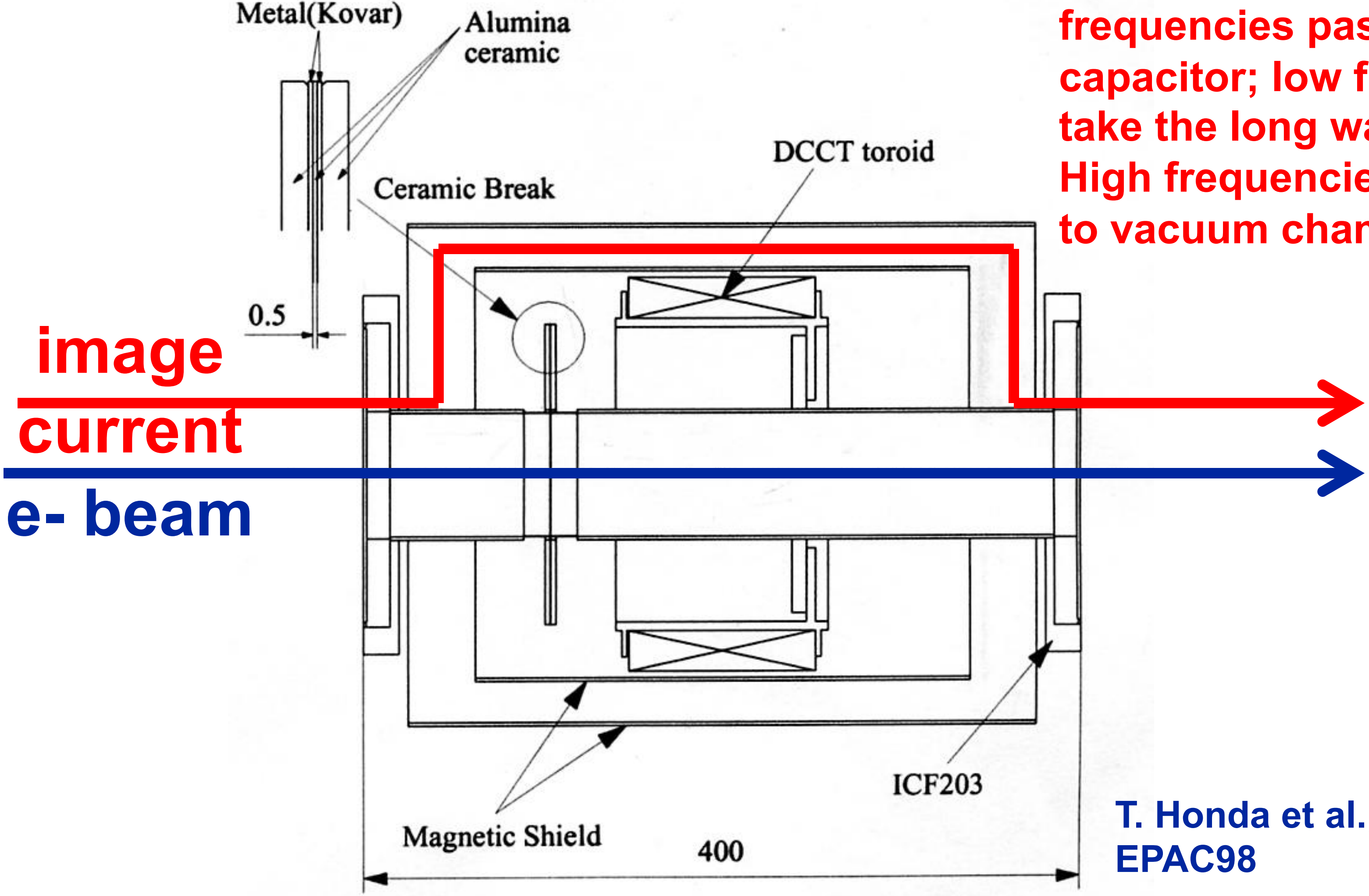
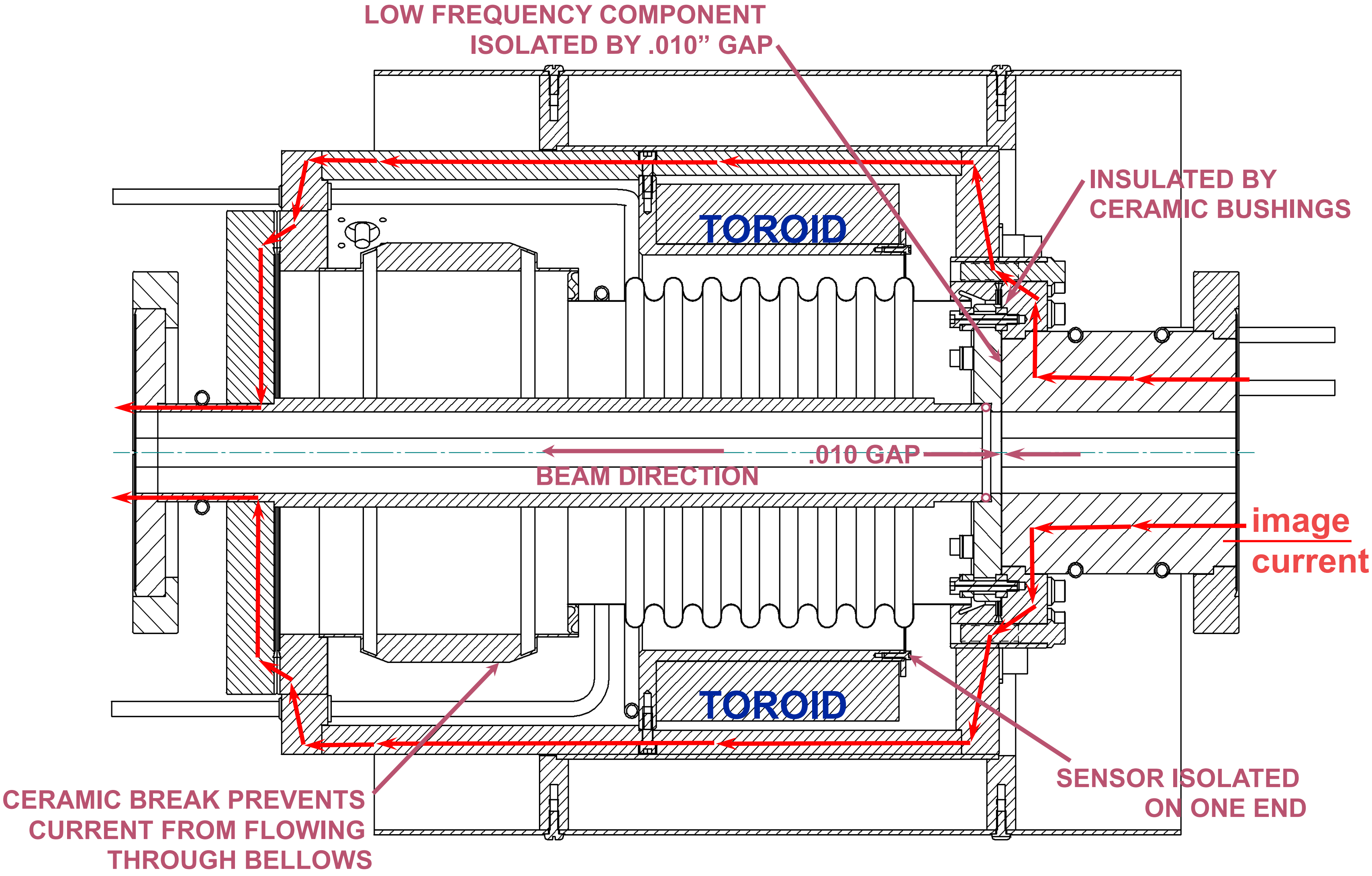


Image current high frequencies pass through capacitor; low frequencies take the long way around. High frequencies confined to vacuum chamber.

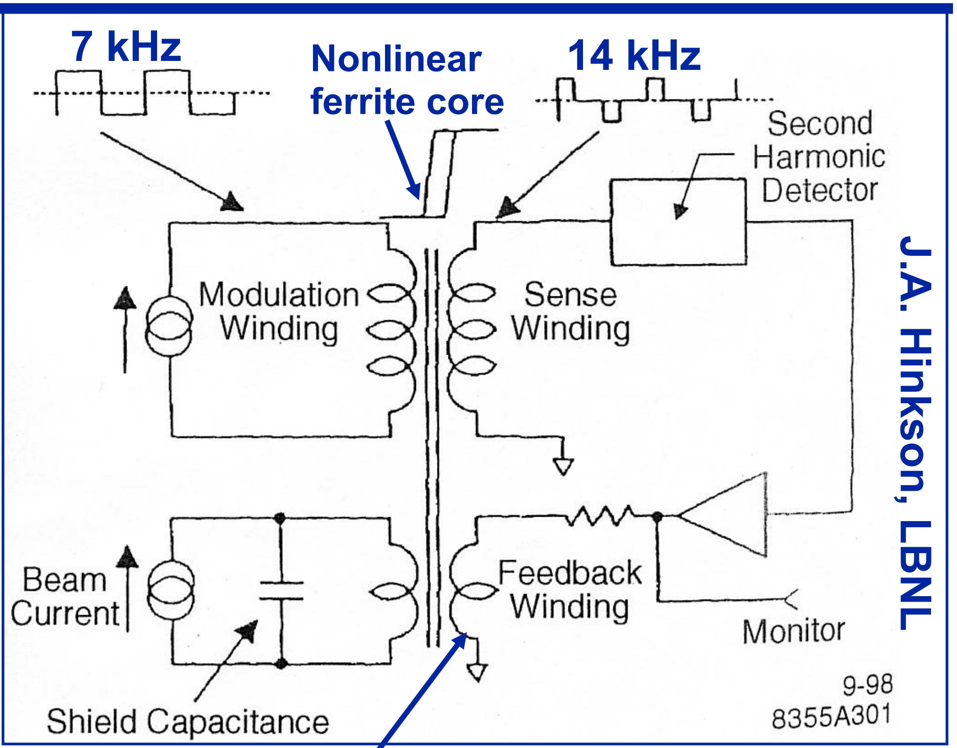
T. Honda et al., EPAC98

SPEAR3 DCCT



In this case, capacitor (electrical break) and ceramic (vacuum) are separate.

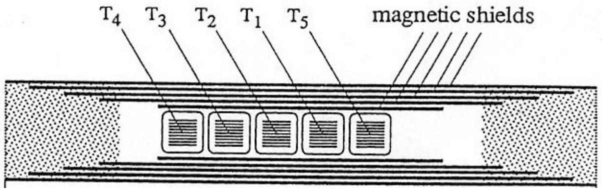
DCCT (or PCT) circuit



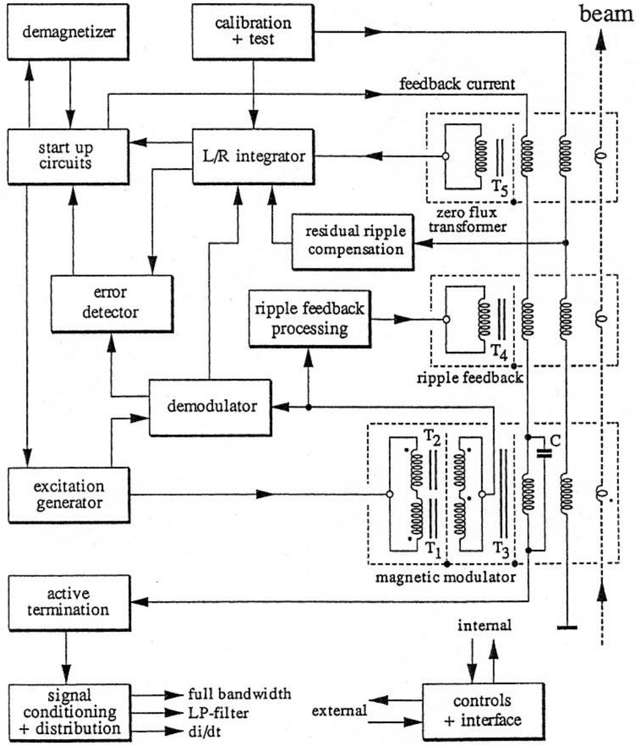
J.A. Hinkson, LBNL

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.

Ferrite core Xsection

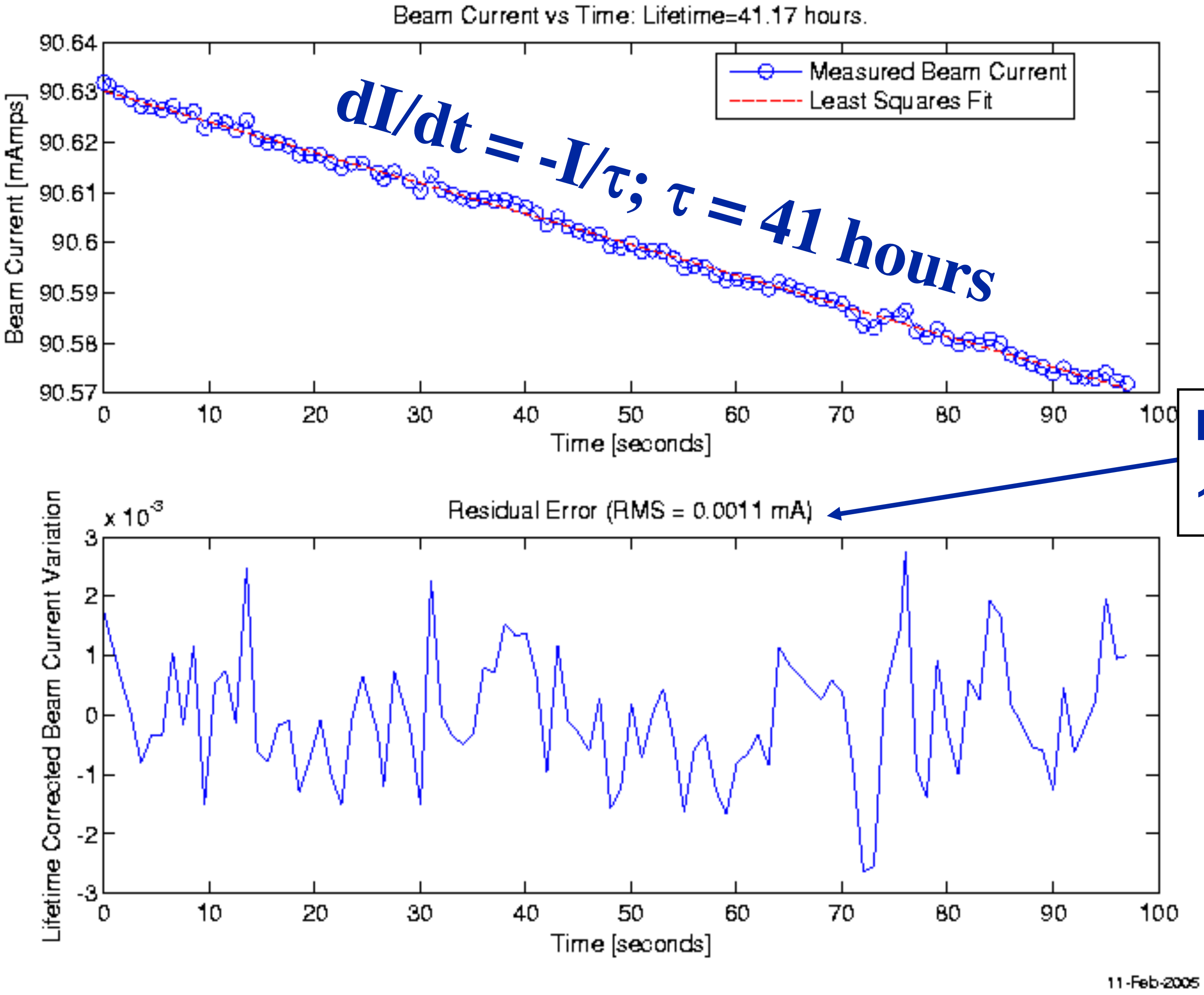


Bergoz PCT



Simplified circuit, K. Unser, 1992

SPEAR3 lifetime measurement w/ DCCT



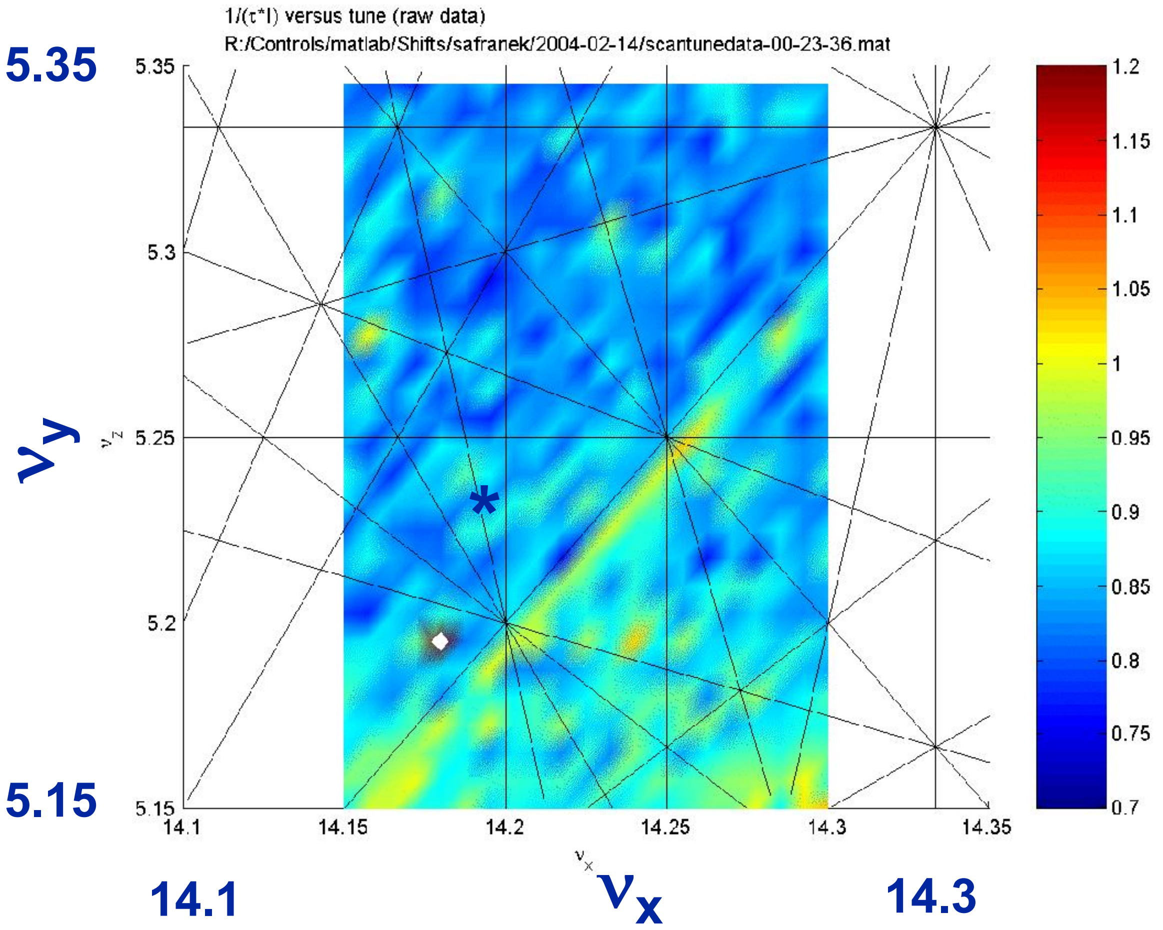
$dI/dt = -I/\tau$; $\tau = 41$ hours

DCCT resolution:

1 μA in 1 second

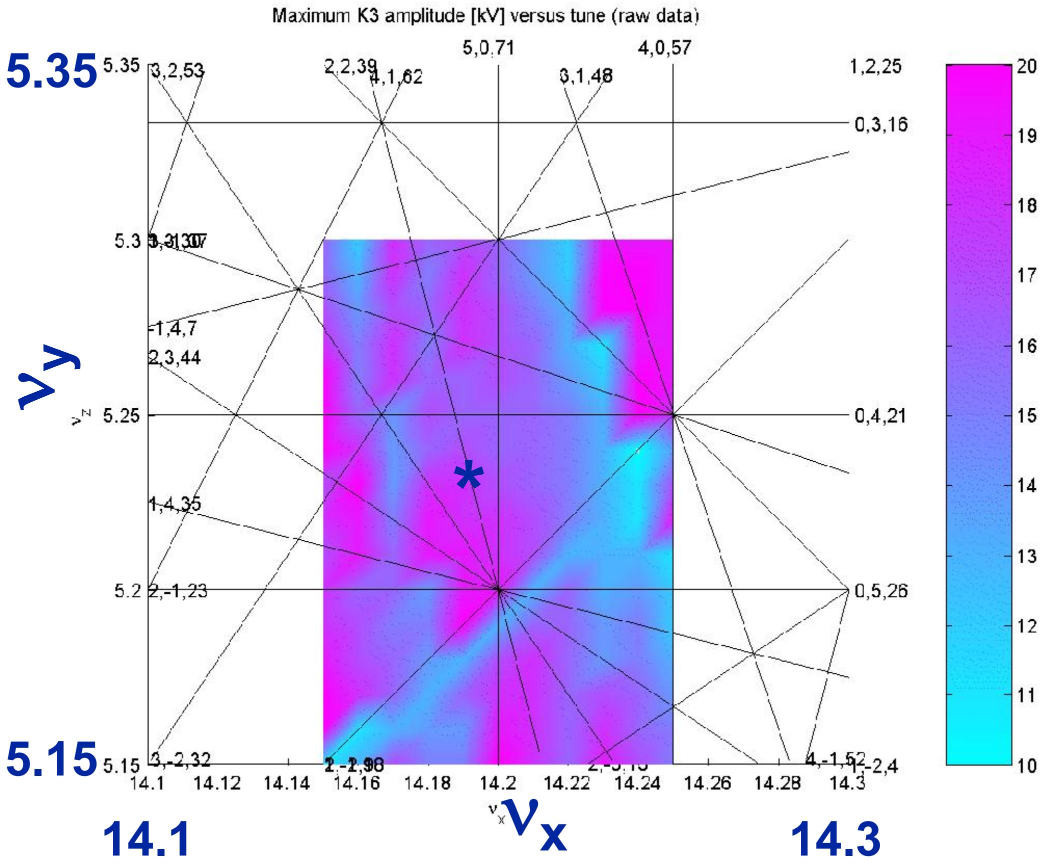
Lifetime vs. tunes

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



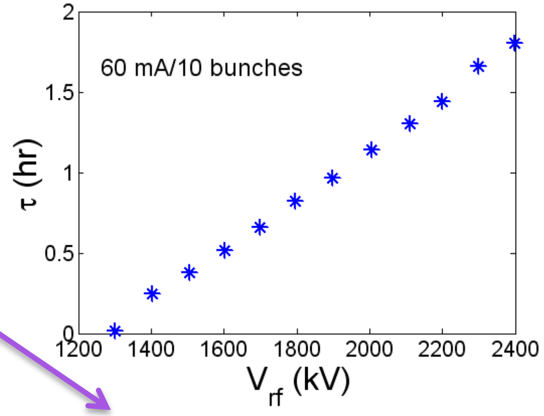
Dynamic aperture vs. tune

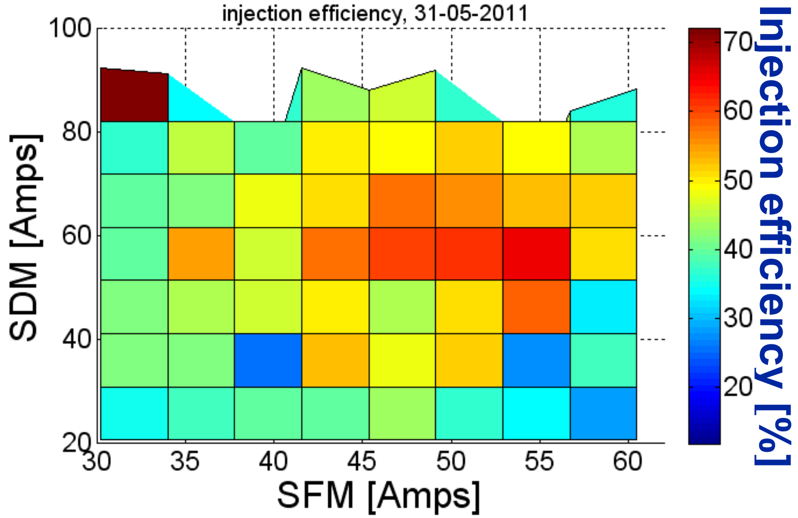
- **Resonant lines:**
  - $\nu_x - \nu_y = 9$
  - $3\nu_x + \nu_y = 48$
  - $4\nu_x + \nu_y = 62$
- **Resonances offset from tune shift with amplitude.**
- *** = operating tunes (14.19, 5.23)**
- **Data gathered automatically on owl shift.**

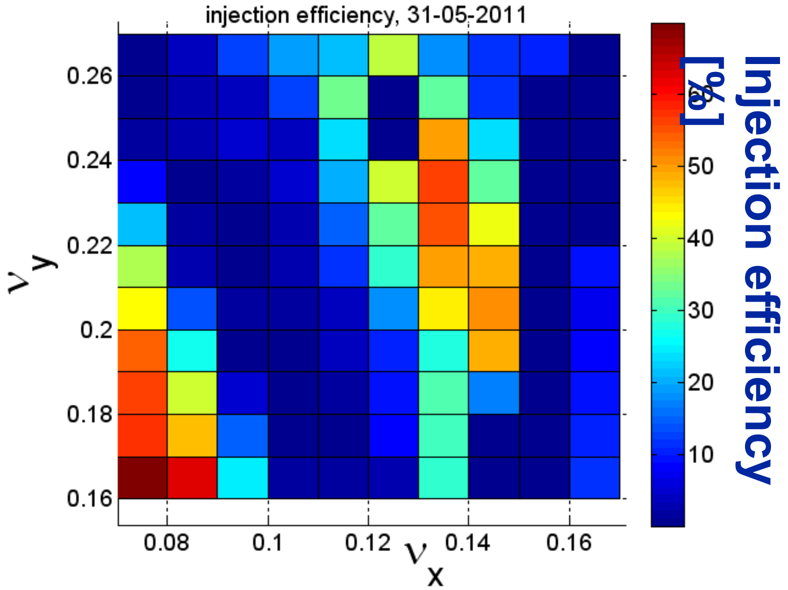


More DCCT-based measurements

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

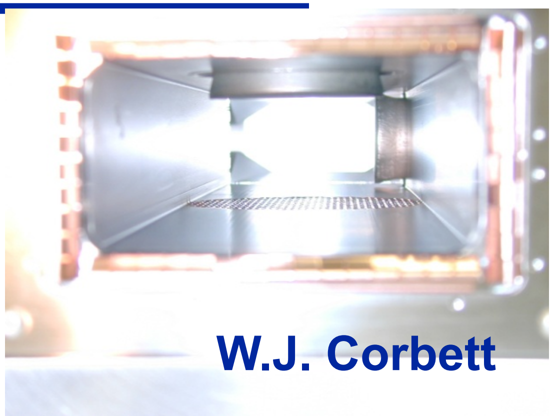






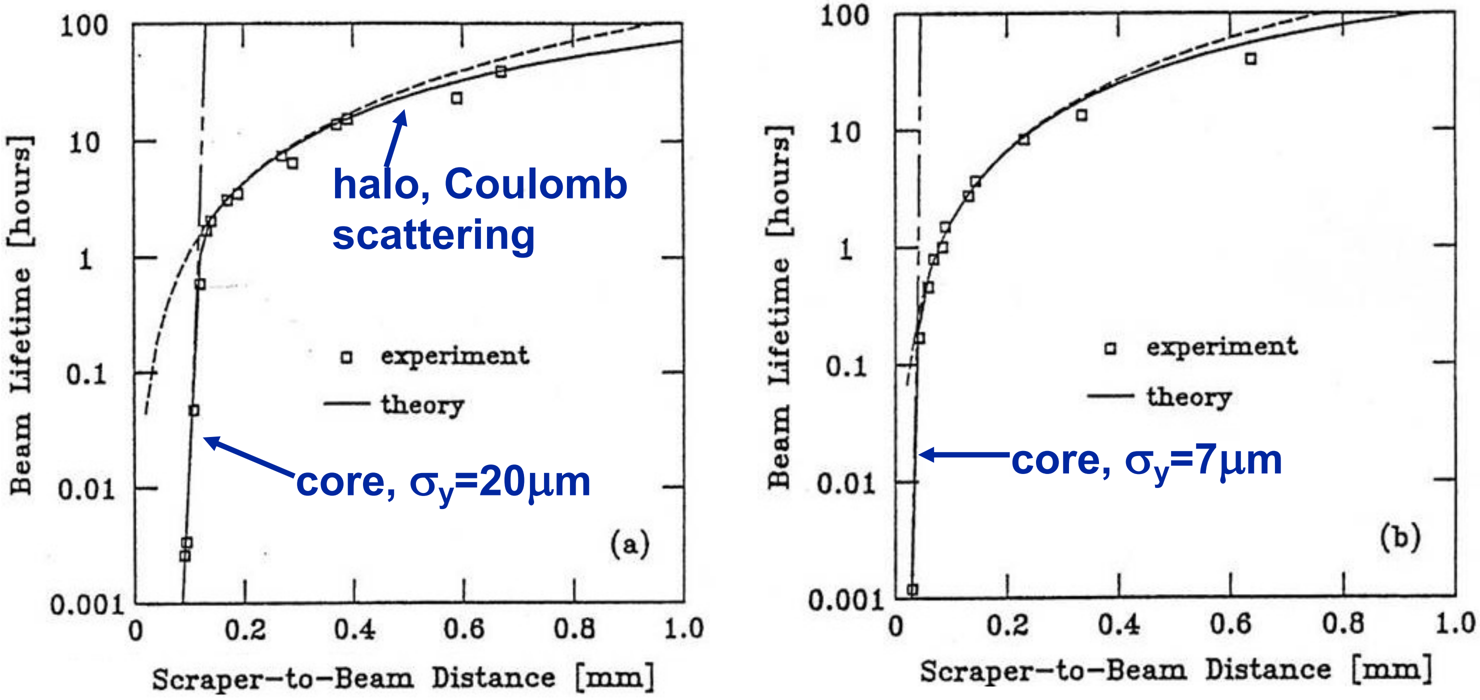
Beam scrapers; lifetime vs. vertical aperture

Scrapers measure beam halo



W.J. Corbett

Peter Stefan et al., NIMA, 1998



halo, Coulomb scattering

core, σ_y=20μm

core, σ_y=7μm

SPEAR3 scraper measurements

Three contributions to lifetime:

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

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

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

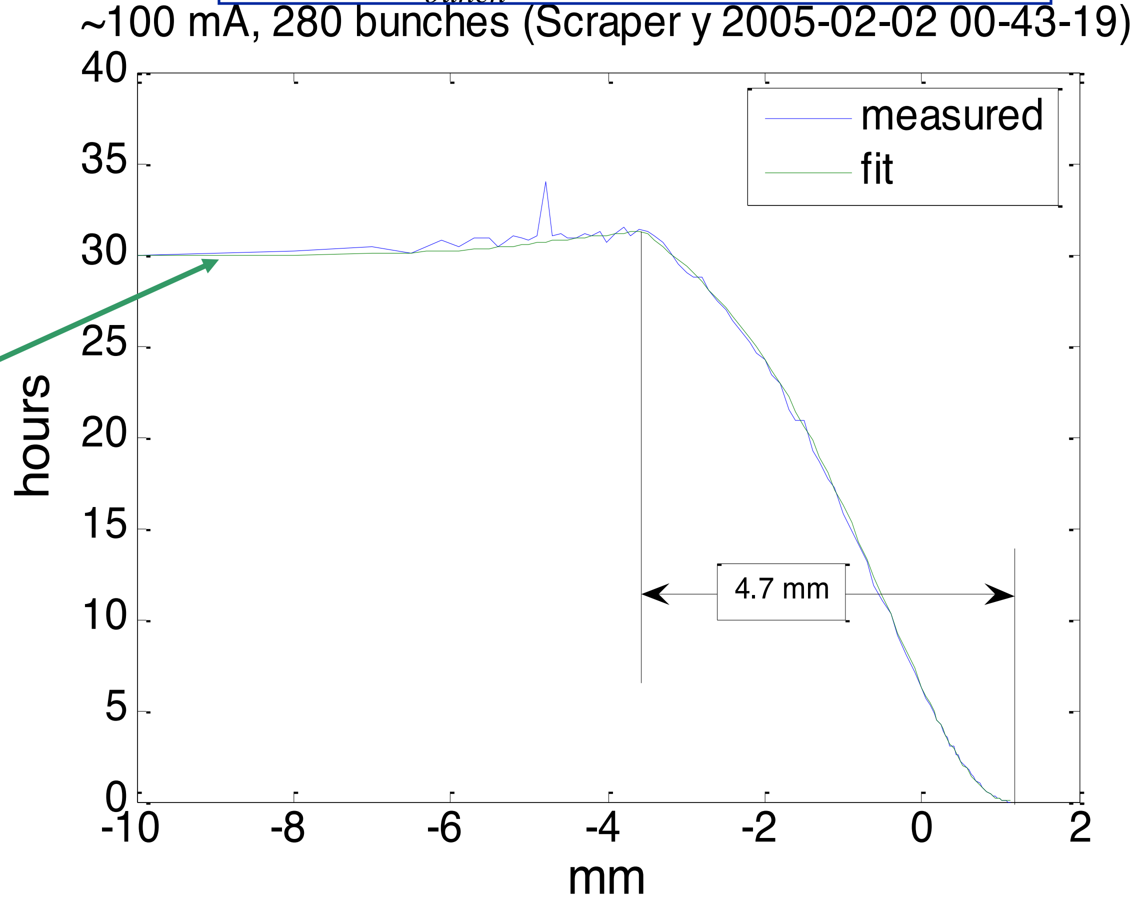
$$\tau_B \propto \mathrm{pressure} * f(\mathrm{E}_{\mathrm{aperture}}) \approx I_{tot}$$

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

Five fit parameters:

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

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

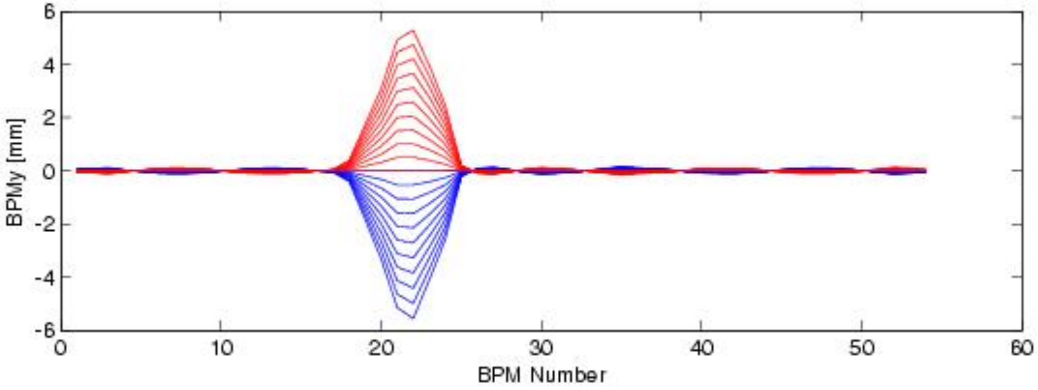


Physical aperture probe

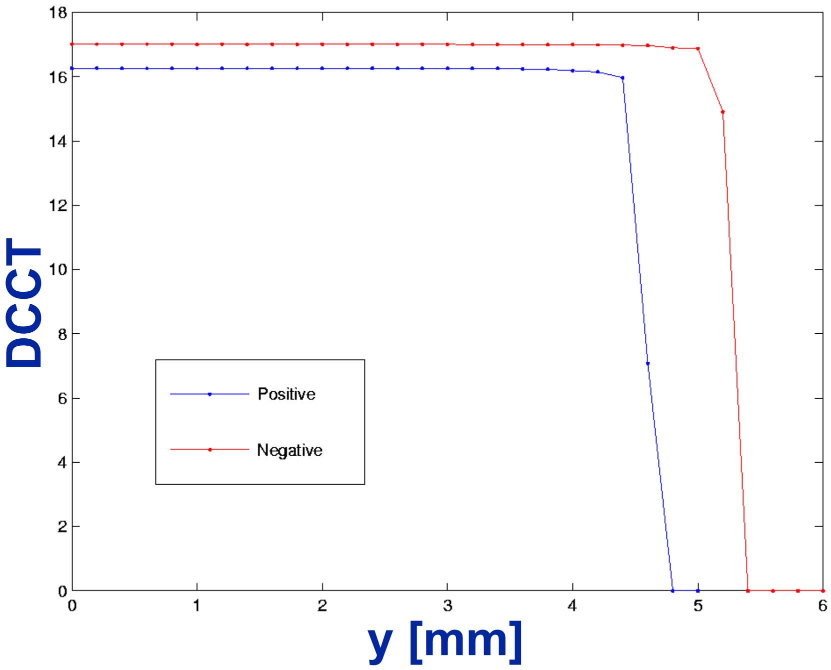
Vertical beam bump in ID chamber

y-bump in ID chamber:

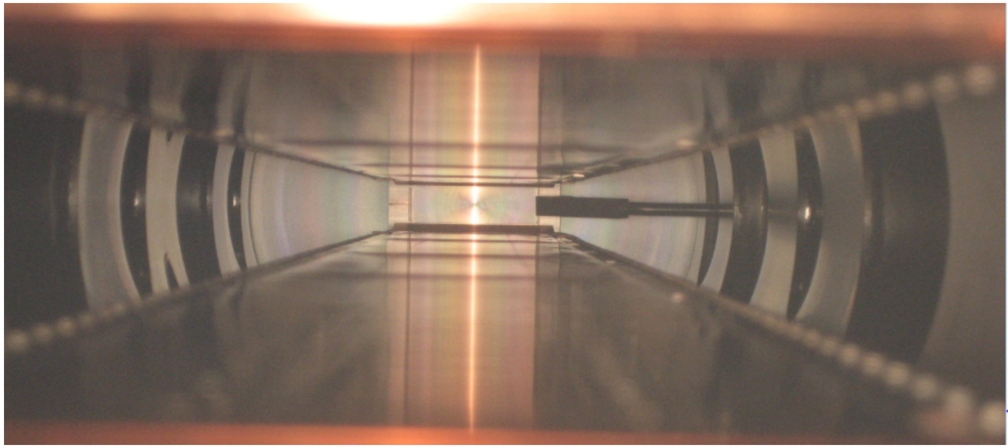
- **Bump beam up until lost**
- **Refill**
- **Bump beam down until lost**



ID4 chamber is mis-aligned and too small



Discovered ¾ mm ripples in in-vacuum undulator copper current sheets:

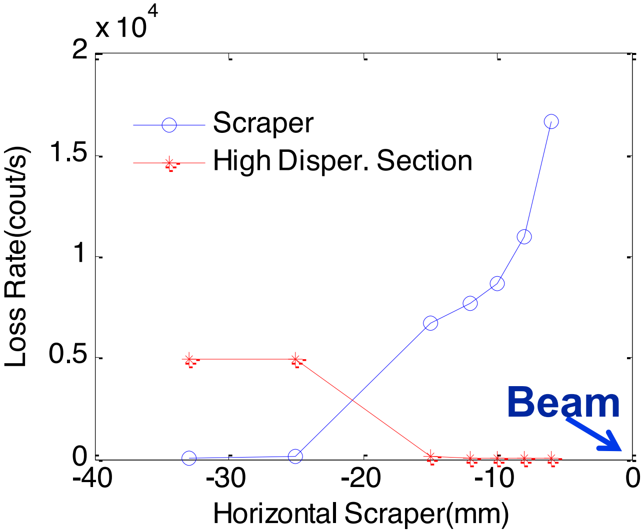


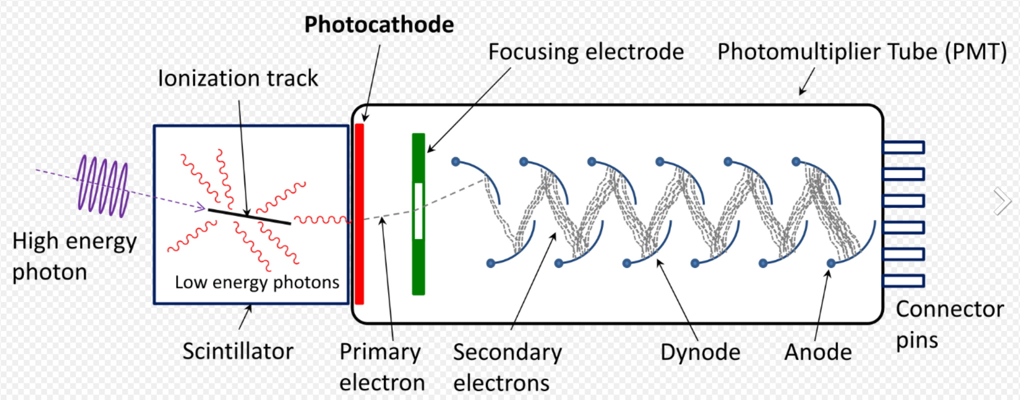
K. Tian

Beam Loss Measurement

- ❖ dc current transformer (DCCT):
  - ✓ Direct measurement of the global beam loss;
  - ✓ ~10% uncertainty for 6 second integration with 500mA stored current

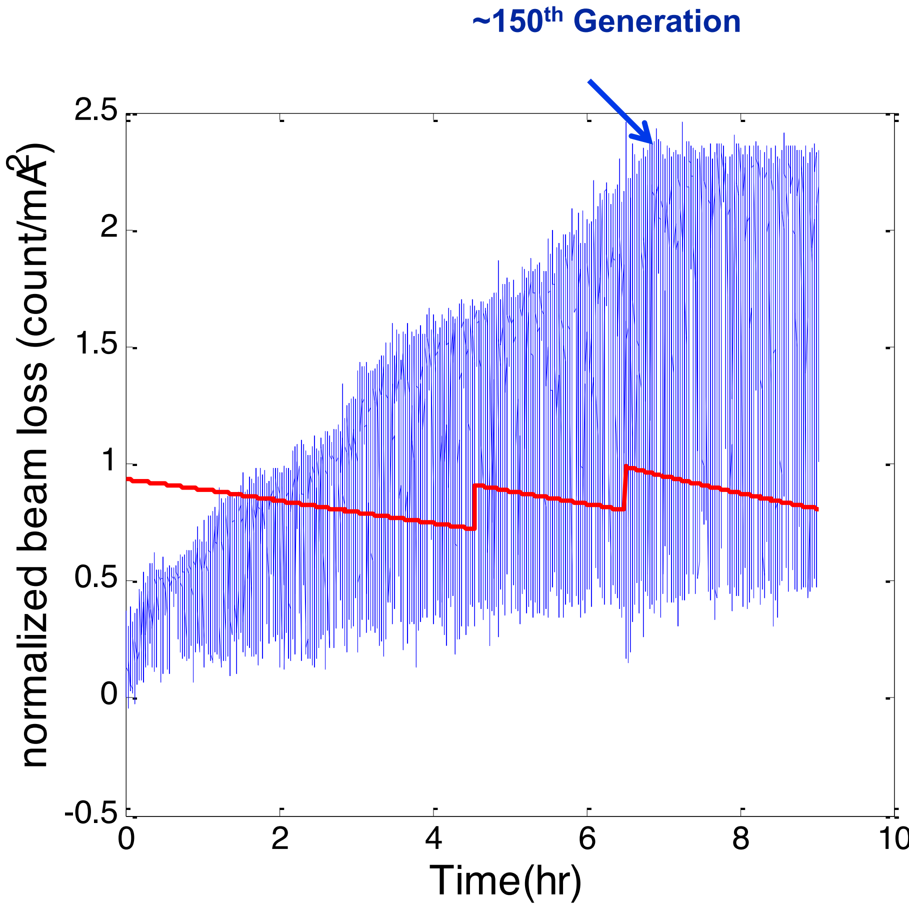
- ❖ Beam Loss Monitor:
  - ✓ Nal Scintillator with PMT tube;
  - ✓ High SNR;
  - ✓ Fast 1Hz rate;
  - ✓ Local beam loss;
  - ✓ Insert scraper to capture most of the beam loss at one location.





GA coupling correction w/ beam loss monitor

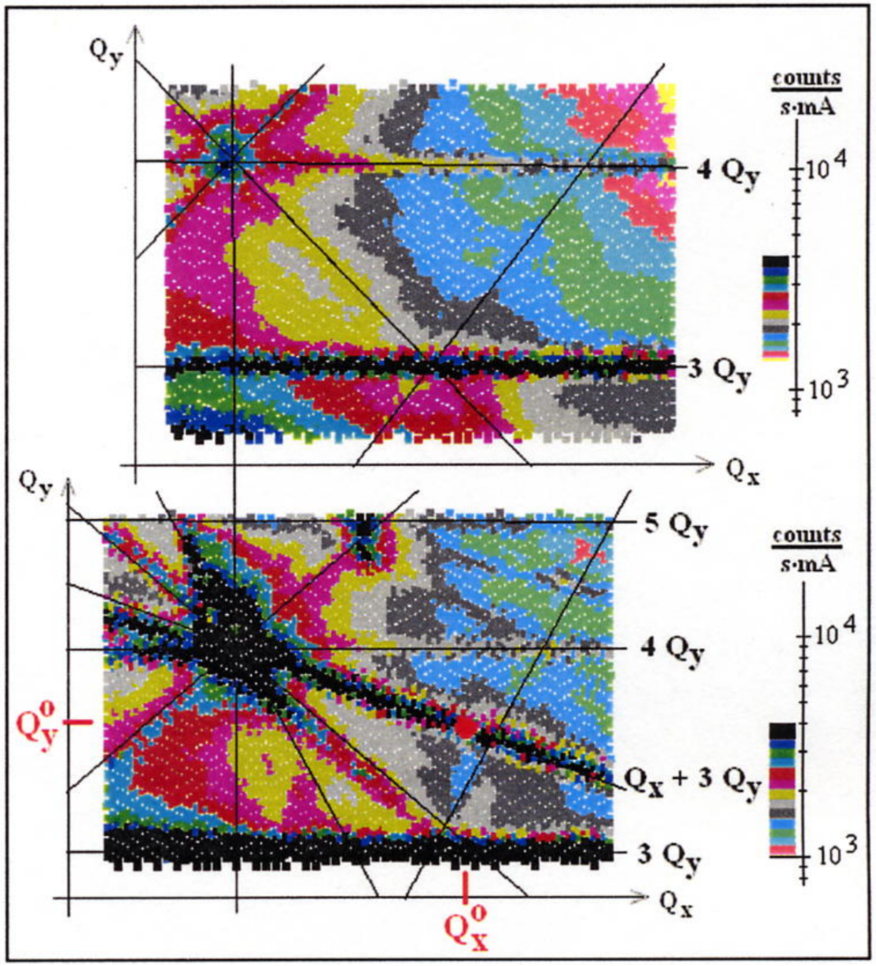
- ❖GA = Genetic Algorithm optimizer
- ❖Adjust 17 skew quadrupoles to maximize measured loss rate.
- ❖ Minimizes vertical beam size.
- ❖211 generations and about 9 hours in total (<3 minutes /generation);
- ❖ Refill the stored current to 100mA twice;
- ❖ The optimization was paused during the fill and restarted by loading the dumped data after the fill



K. Tian

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).

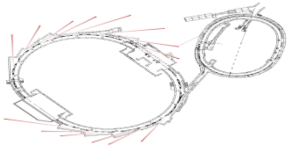


Insertion device open ←

Insertion device closed ←

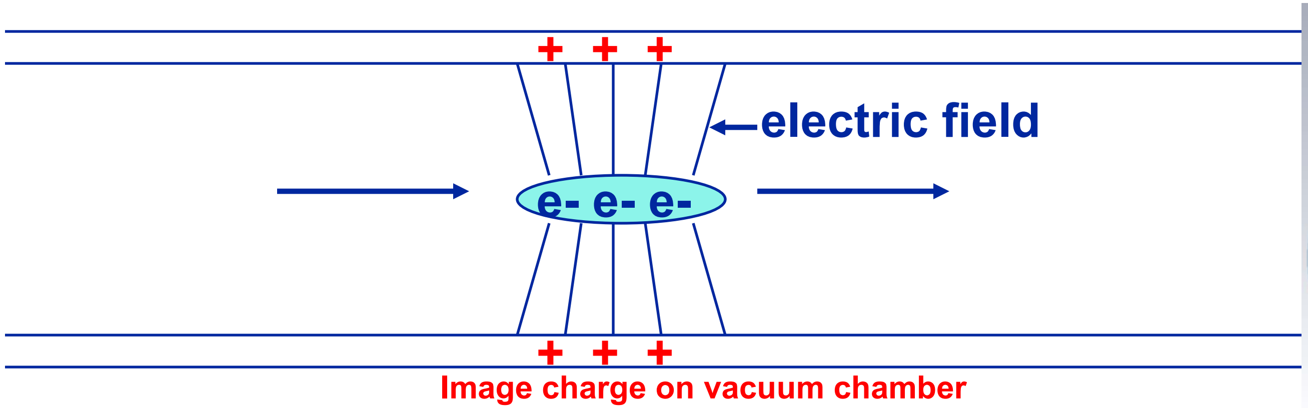
Kuske et al., PAC01.

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 Colliders:
  - Beam-beam overlap at interaction point.
  - 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.
- Synchrotron Light Users:
  - Stability of photon source point (flux through apertures, photon energy after monochromator, motion of beam spot on inhomogenous sample, …)

Beam position monitors



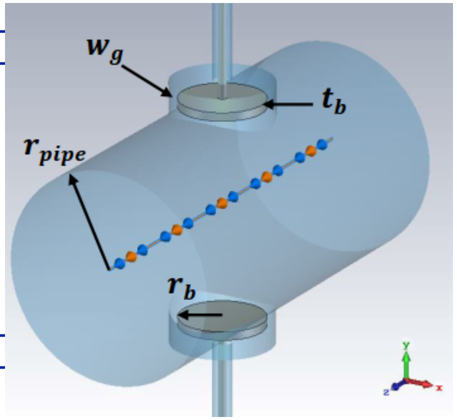


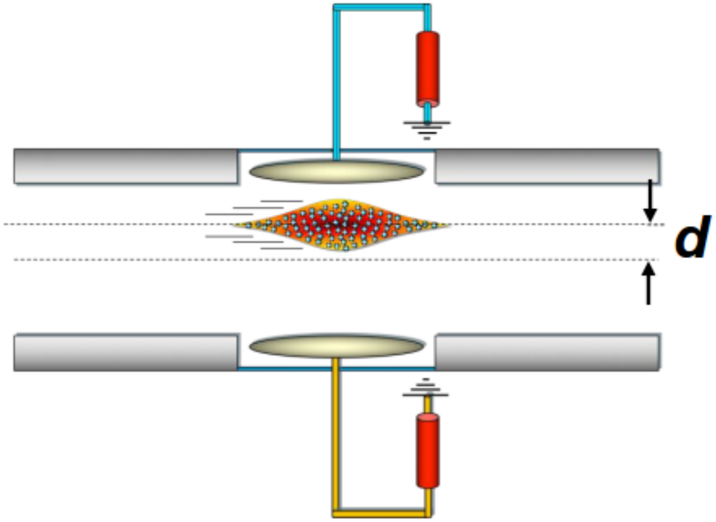
Image charge down wire to capacitor as beam arrives

Image charge flows back up wire as beam leaves

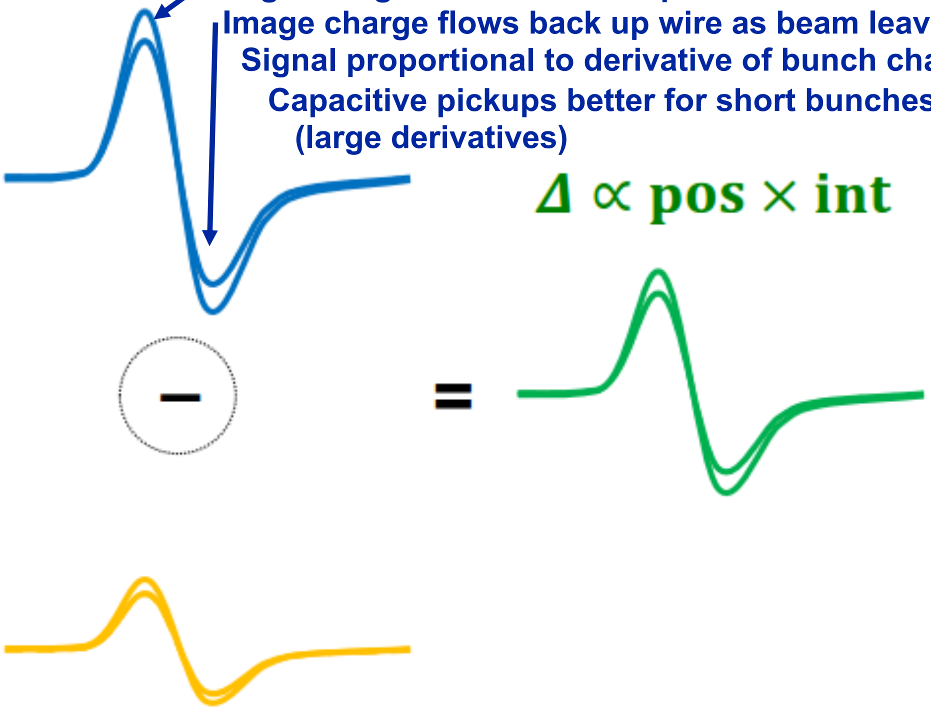
Signal proportional to derivative of bunch charge

Capacitive pickups better for short bunches (large derivatives)

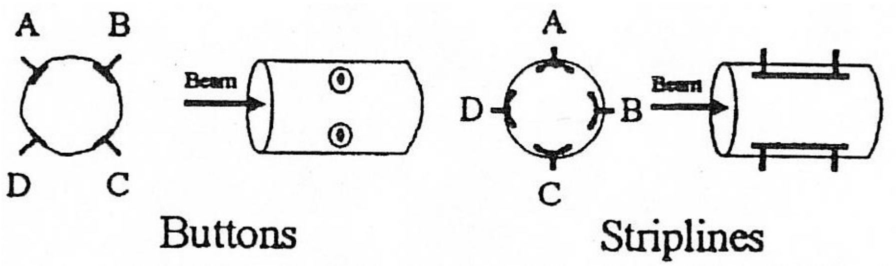
Interrupt chamber with capacitive pickups:



$\Delta \propto \text{pos} \times \text{int}$



Beam position monitors

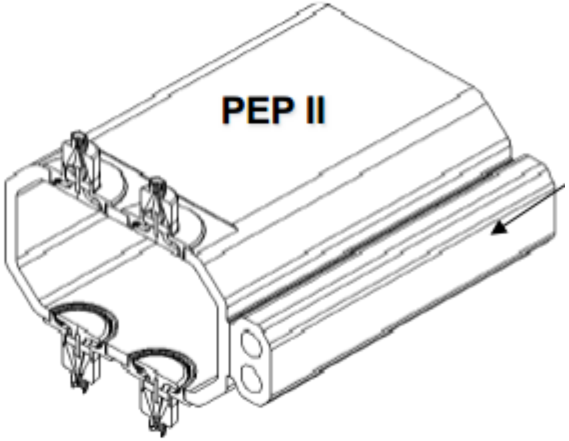


For circular chamber

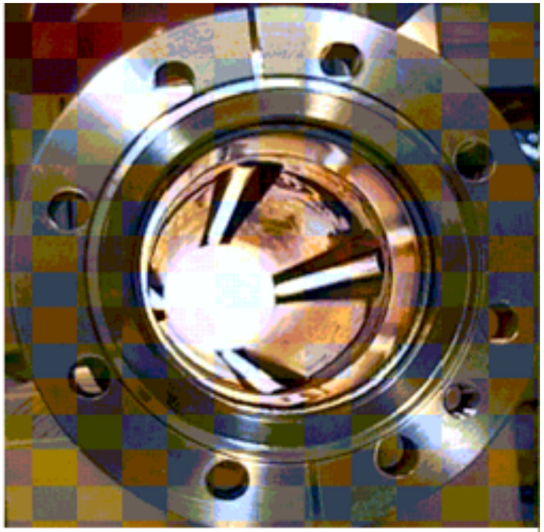
$$x = \frac{r}{\sqrt{2}} \frac{(V_A + V_D - V_B - V_C)}{(V_A + V_B + V_C + V_D)}$$

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

Button capacitive pickups

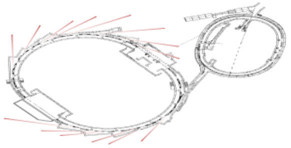


Stripline inductive pickups

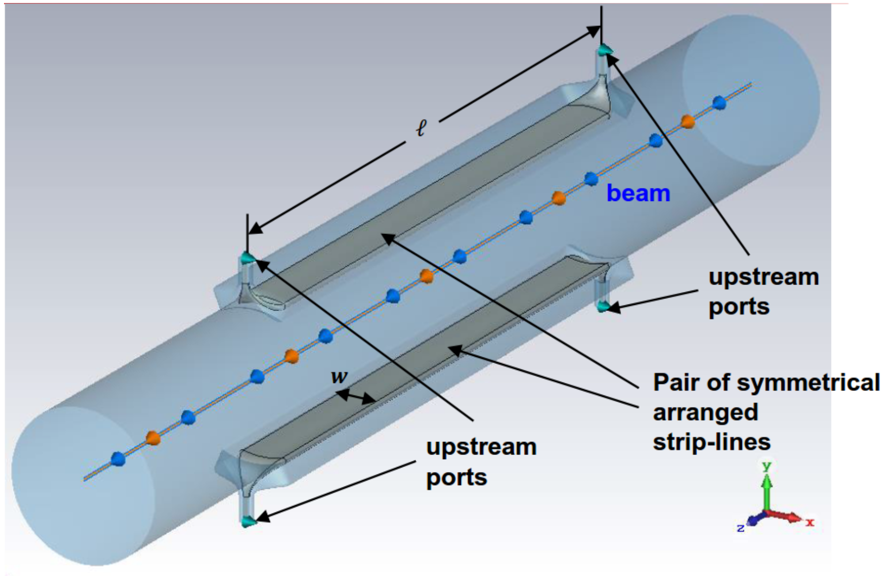


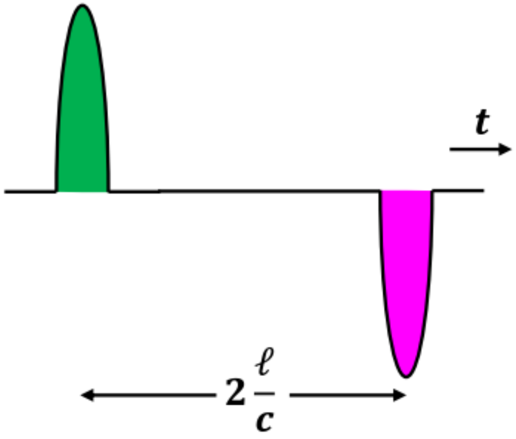
M. Wendt, DESY

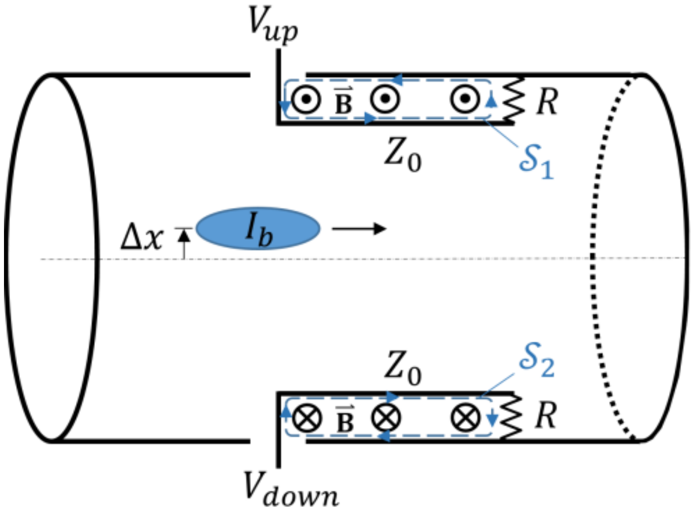
Stripline BPMs



- Stripline to wall is 50 Ω parallel plate waveguide
- At upstream end image charge splits between 50 Ω waveguide and 50 Ω cable.
- At downstream end, charge in stripline waveguide reflects and travels back to the upstream port with opposite charge to initial pulse



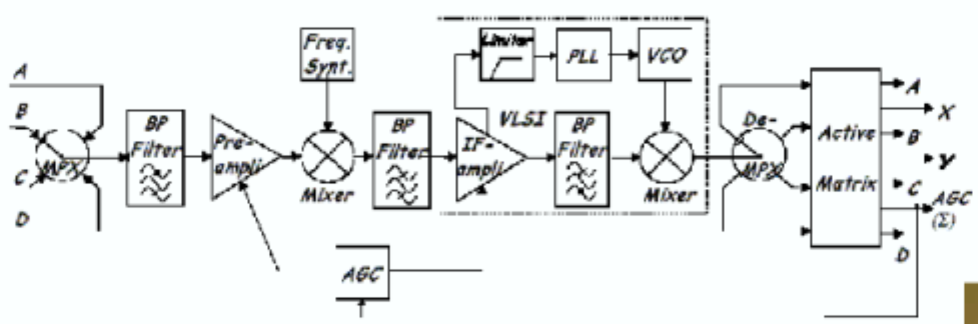


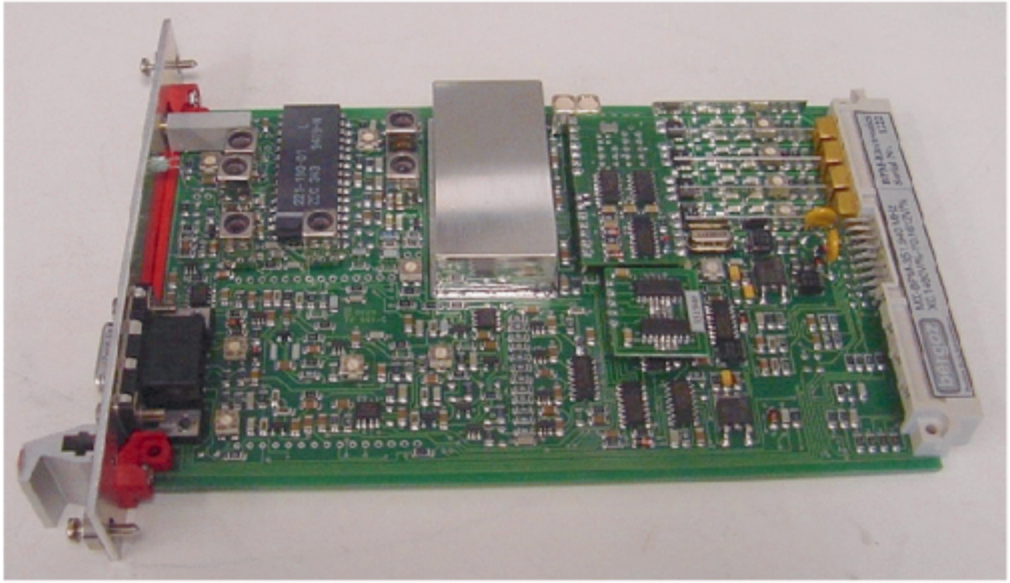


Signal Processing Electronics

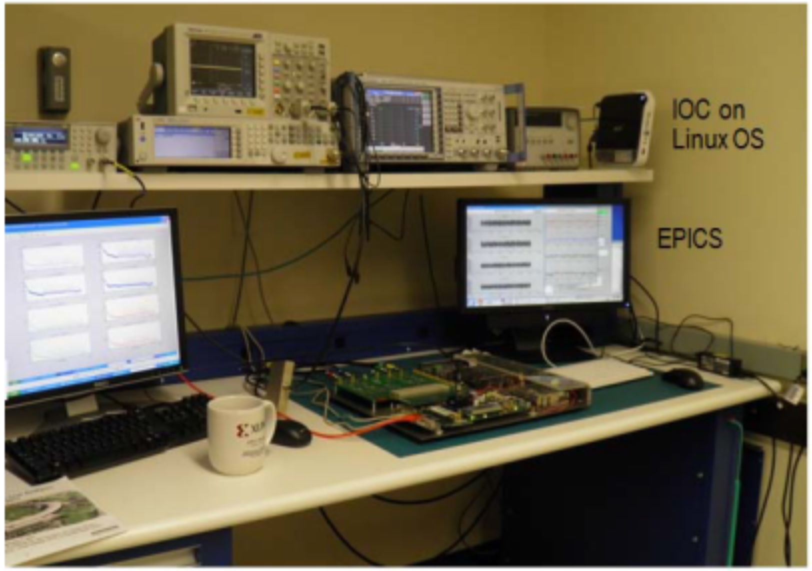
Bittner / Biscardi / Galayda / Hinkson/ Unser / Bergoz Narrowband Receiver

Normalization accomplished via multiplexing plus automatic gain control (AGC)*:



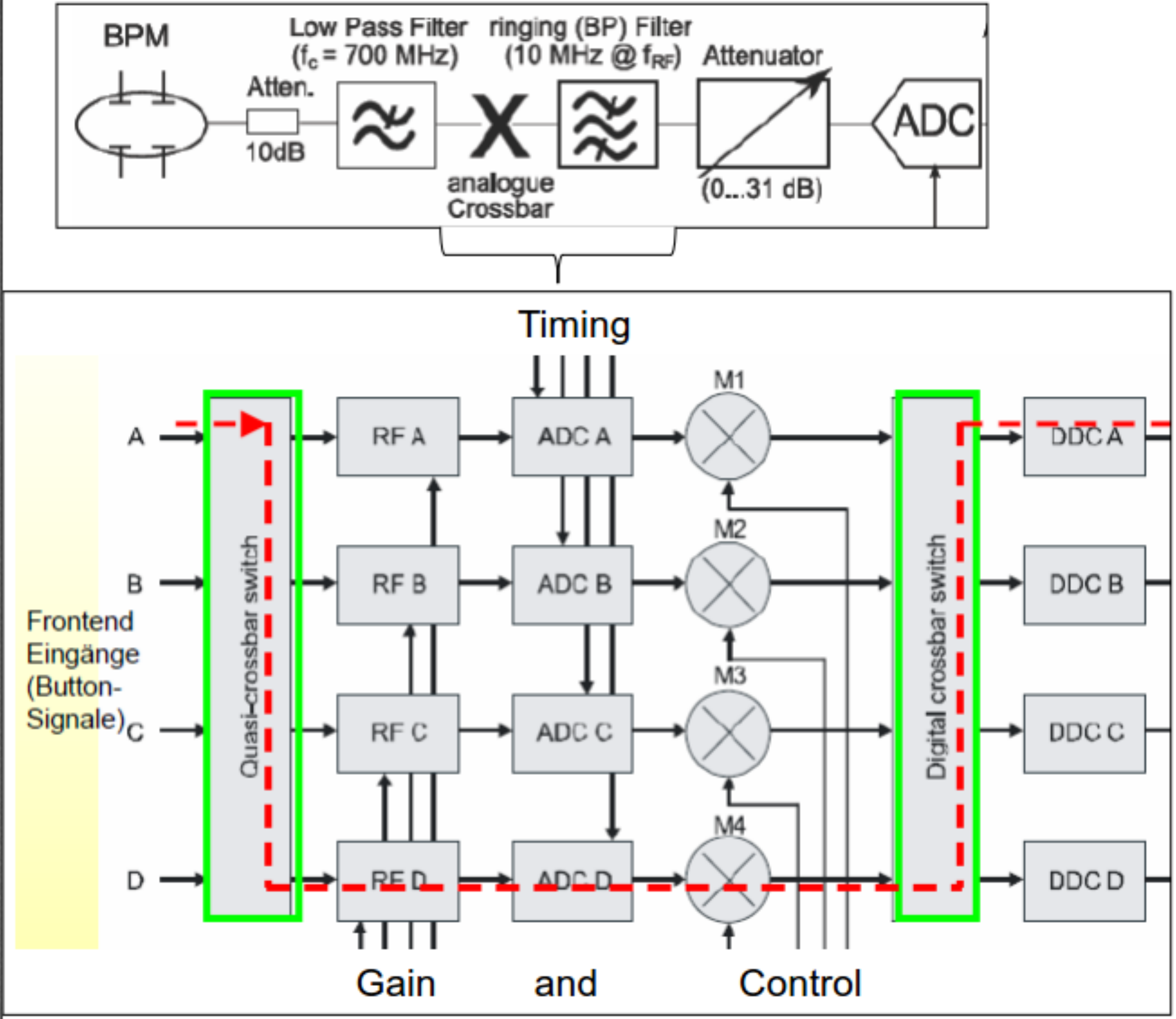


- More recently: Digital BPMs only frontend is analog, followed by ADCs, FPGAs (sometimes DSP) and digital signal processing



Courtesy Kurt Vetter

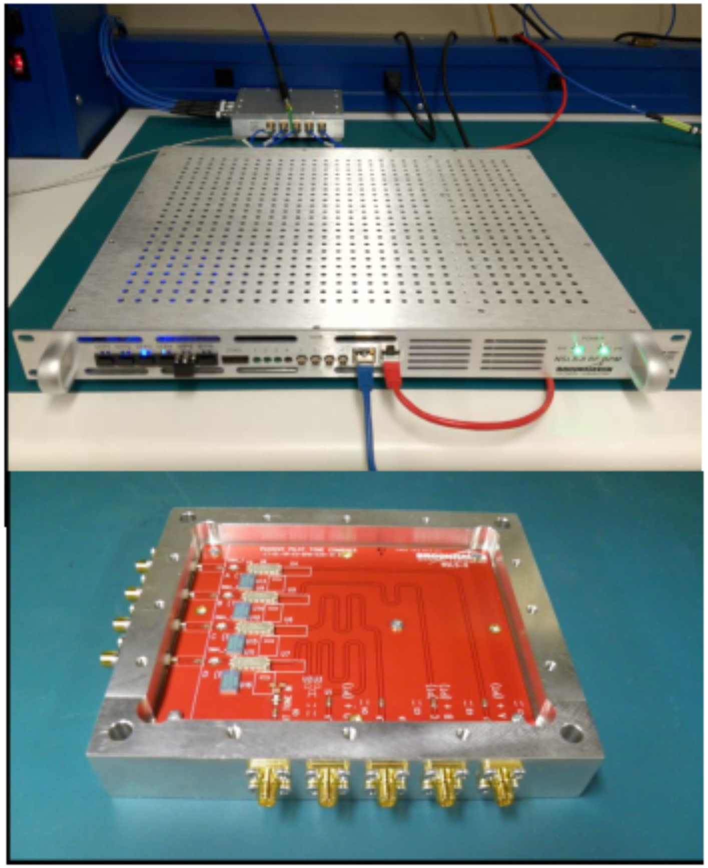
1) Electronic stabilization
a) Libera with switching crossbar for dynamic calibration

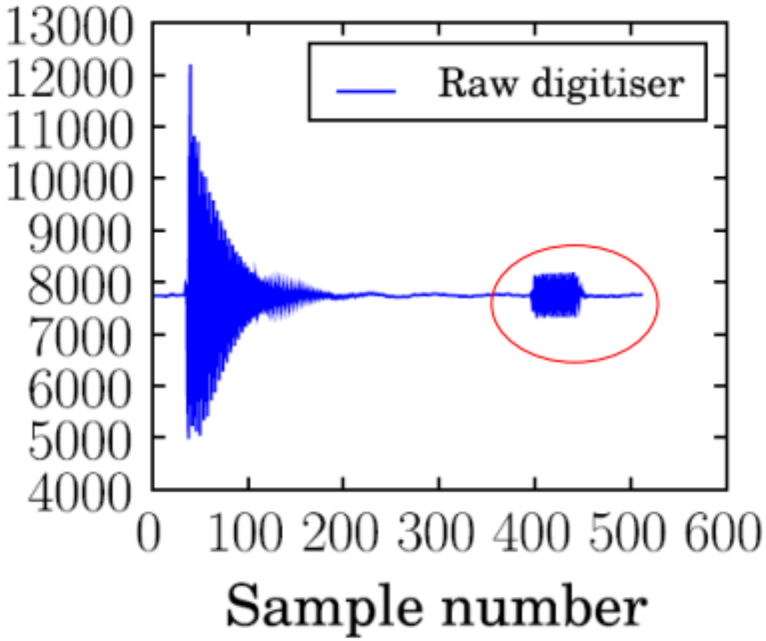


Switching crossbar removes different drifts of channels

⇒ Long term stabilization (I-Tech Patent)

1) Electronic stabilization
b) Pilot tone for dynamic calibration



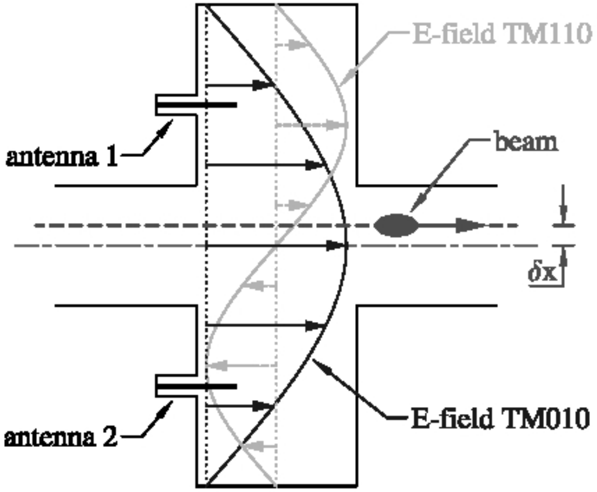


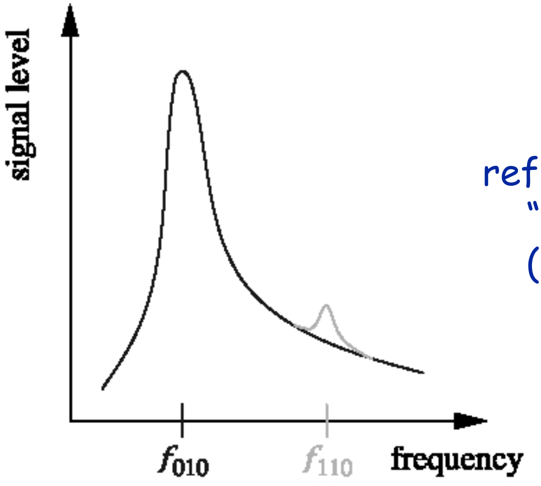
Cavity beam position monitor system for the Accelerator Test Facility 2
Y. I. Kim et al.; Phys. Rev. ST Accel. Beams 15,

An integrated RF synthesizer phase-locked to the ADC clock generates a programmable CW pilot tone for dynamic calibration. The pilot tone is combined with the beam signal within the Pilot Tone Combiner Module.

NSLS-II RF Beam Position Monitor Update
K. Vetter, et al., (BIW12)

CAVITY BPMs:

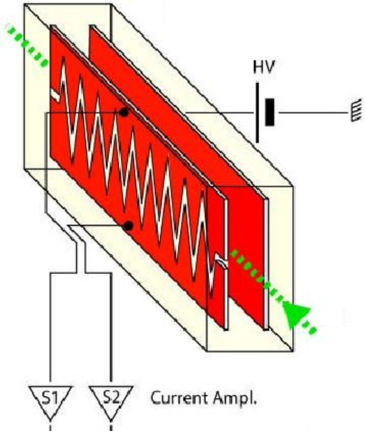




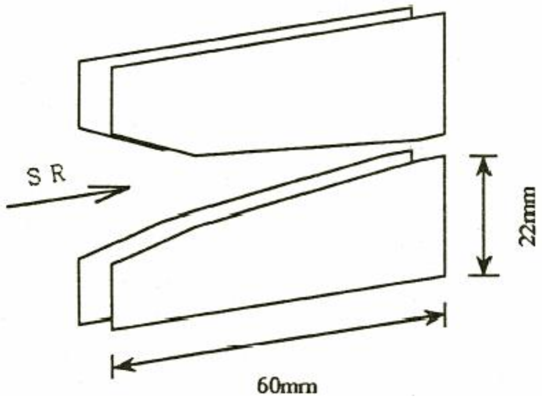
reference:
"Cavity BPMs", R. Lorentz
(BIW, Stanford, 1998)

PHOTON BPMs:

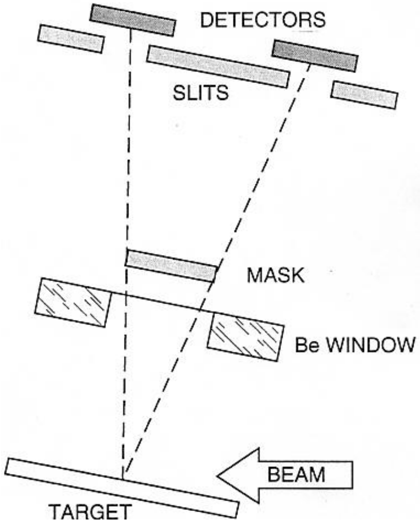
Split ion chamber:



Tungsten blade monitor:



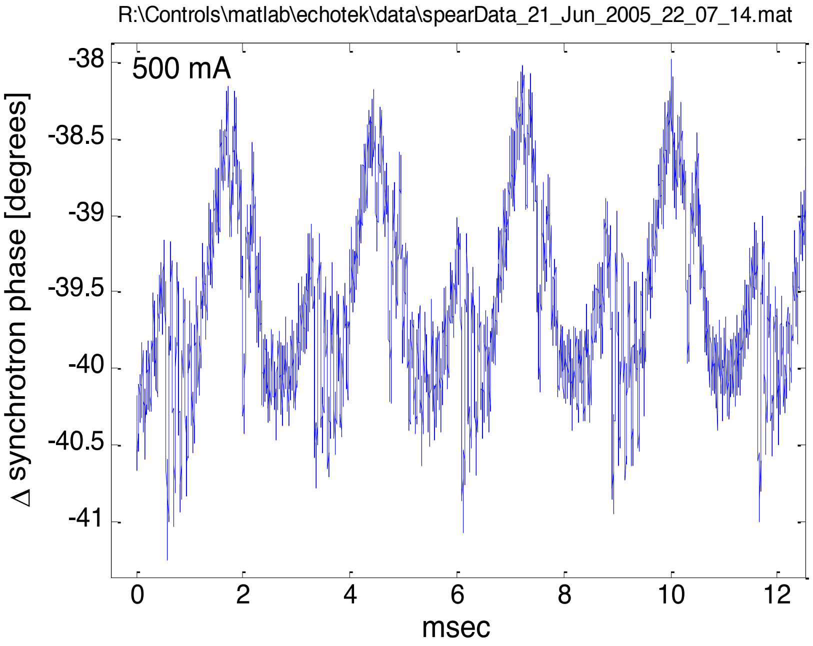
Copper fluorescence bpm:



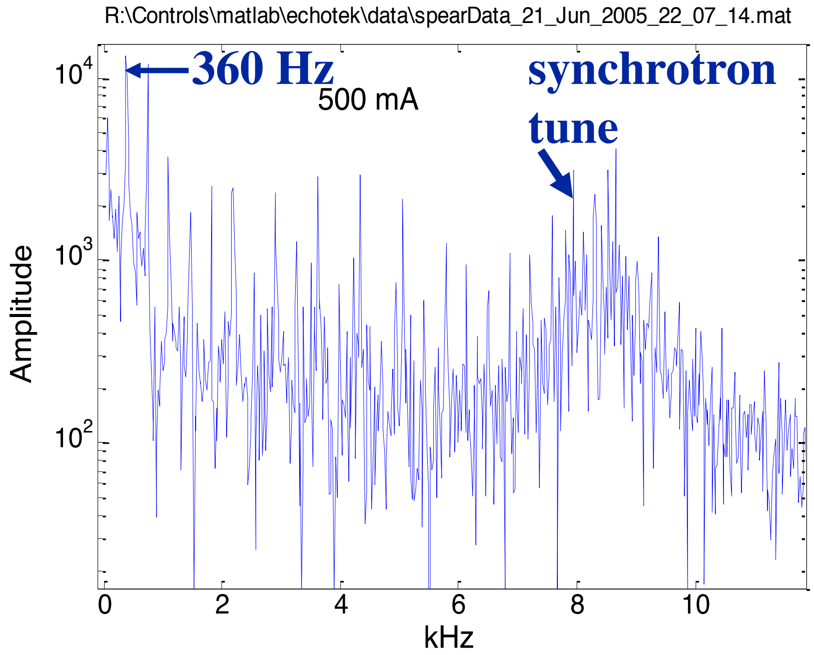
Longitudinal oscillations, BPMs

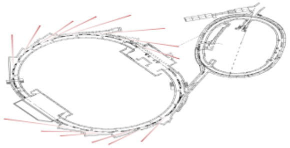
SPEAR3 digital receiver BPMs measure not only the amplitude from each button, but also the phase with respect to the RF, giving the variation in time of arrival of the bunches.

Synchrotron phase vs. time



FFT of synchrotron motion





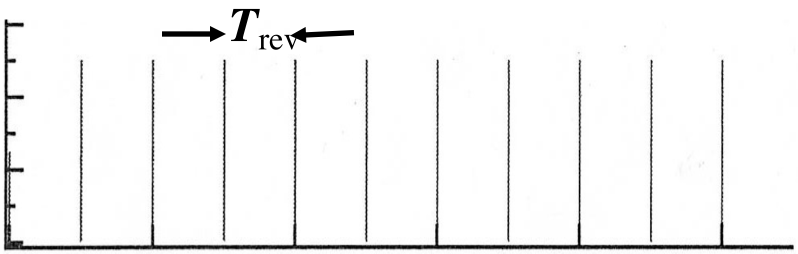
Beam frequencies

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

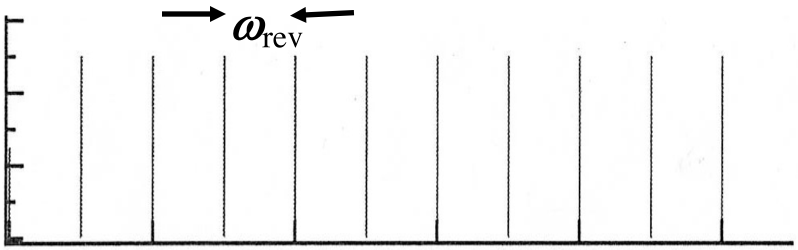
$$I(t)=\sum_{n=-\infty}^{\infty} q\,\delta(t-nT_{\text{rev}}),$$

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

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



Time

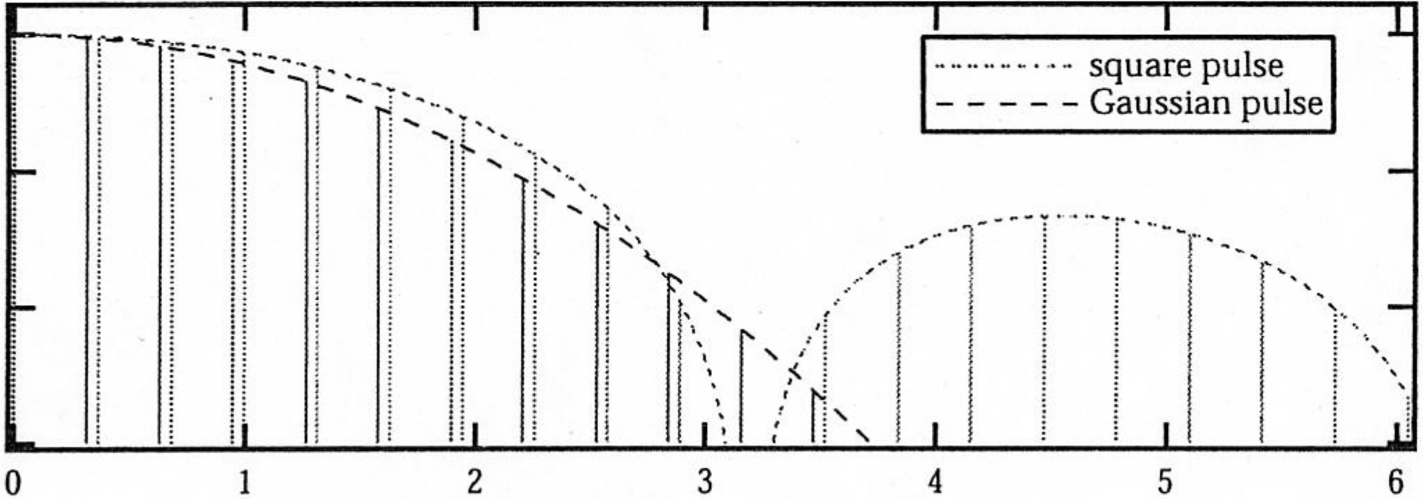


Frequency

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

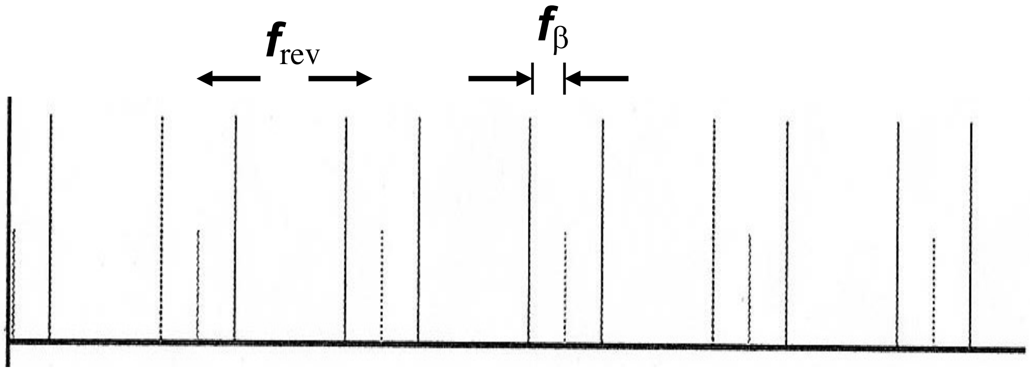
Combining BPM signals, V_A-V_B-V_C+V_D, gives a dipole signal that scales as the product of beam current and position. For a closed orbit $x_{c.o.}$ and a betatron oscillation x_β, the signal is

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

The Fourier transform is

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

$$\omega_\beta = 2\pi\nu$$

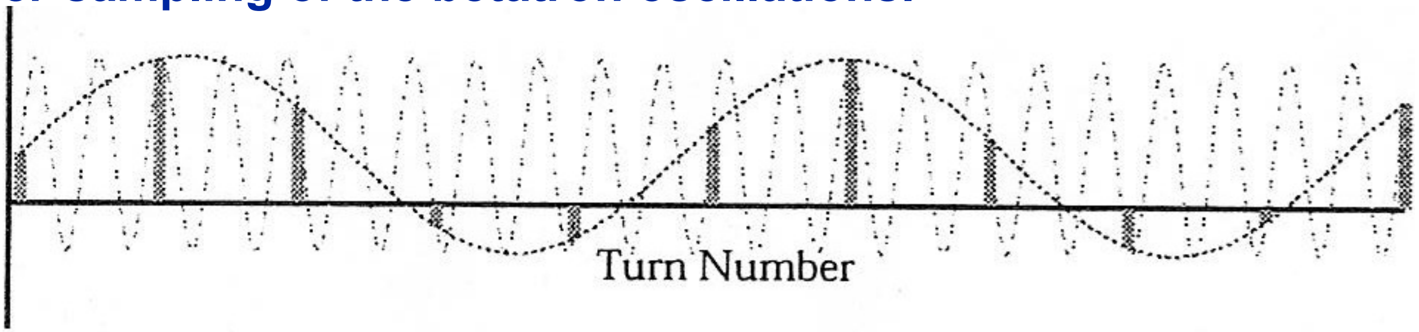


Frequency

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

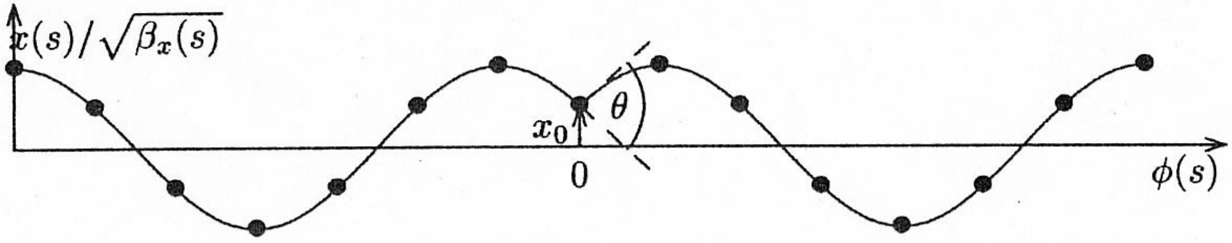
Betatron tune, 2

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.

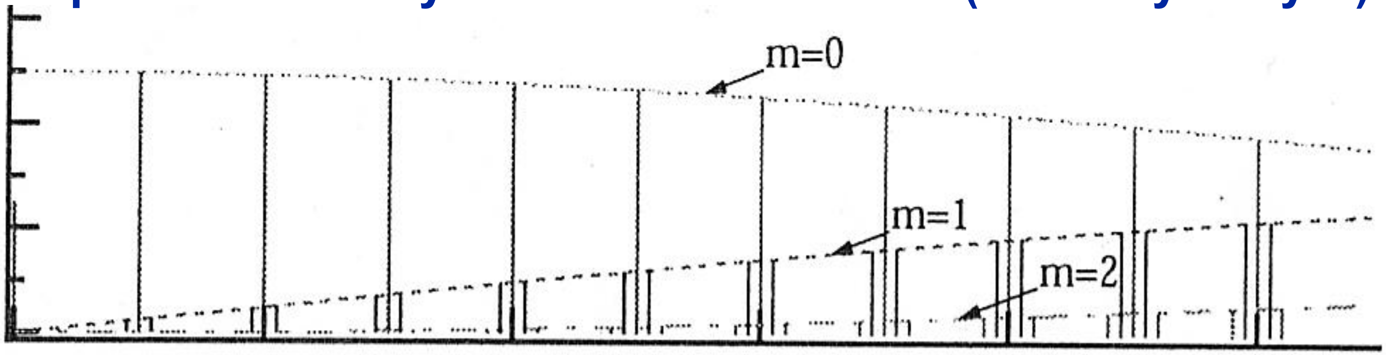
$$\frac{\Delta x_i}{\Delta \theta_j} = \frac{\sqrt{\beta_i \beta_j}}{2\sin(\pi\nu)} \cos(|\phi_i - \phi_j| - \pi\nu)$$



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.

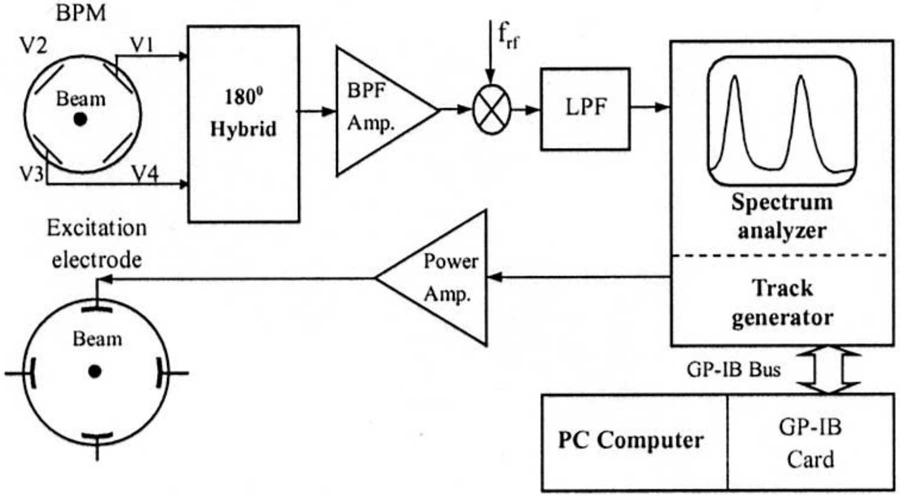
Spectrum from synchrotron oscillations (courtesy J. Byrd)



frequency

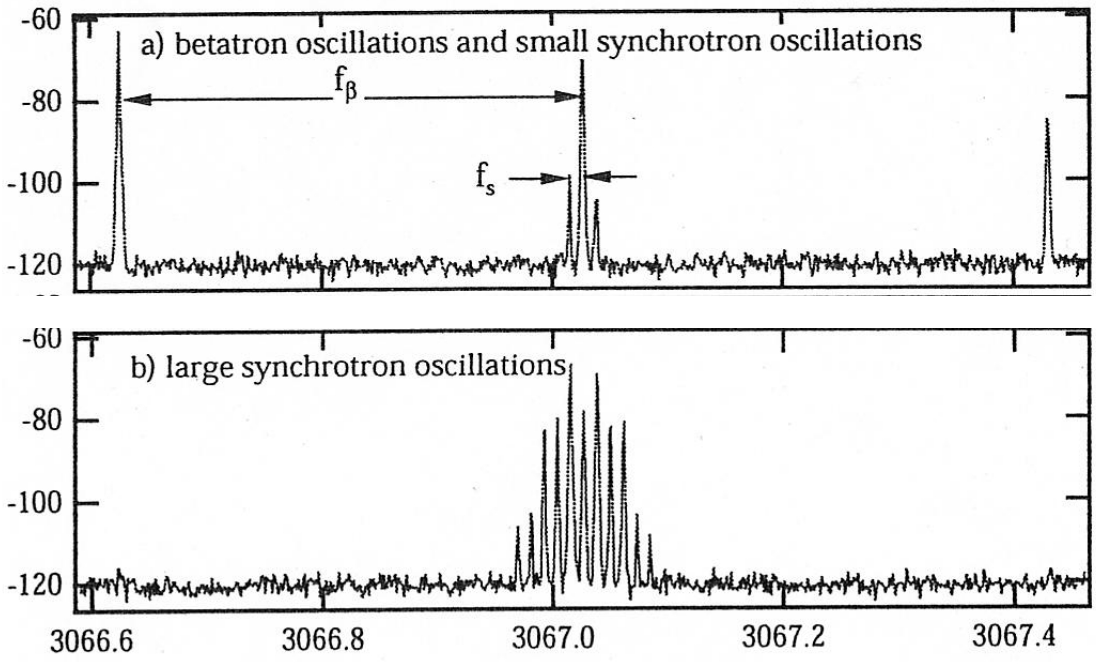
Measured spectra

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 (Tuesday)
- Nonlinear dynamics (tune vs. amplitude; tune maps; tune vs. closed orbit; Wednesday)
- Impedance measurements
- Beta function measurements
- Chromaticity

Beta function measurement

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

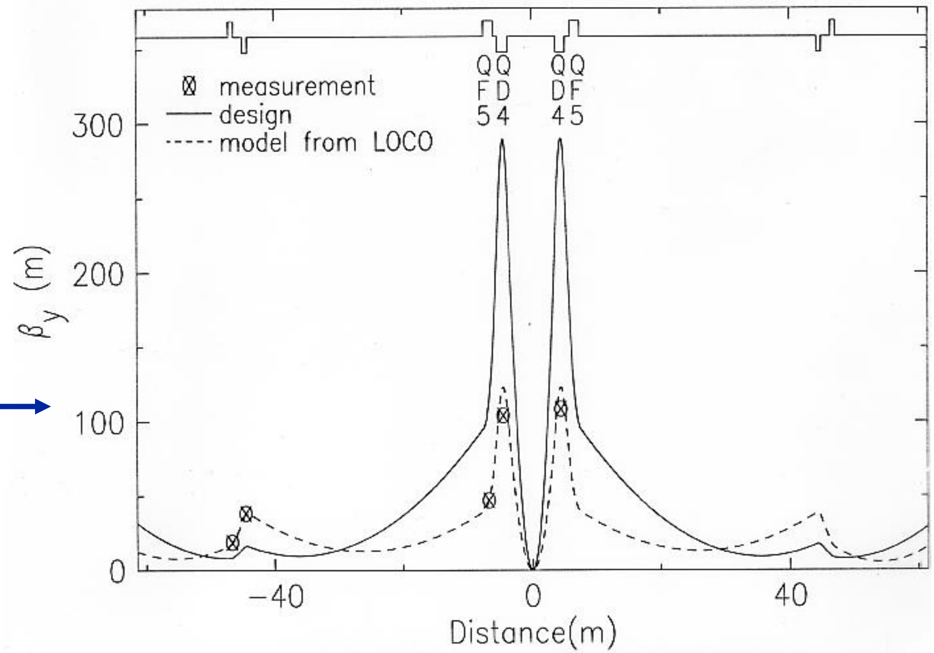
$$\Delta \nu = \beta \frac{\Delta(KL)}{4\pi}$$

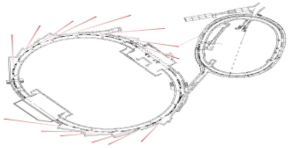
Measurement issues

- 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.)

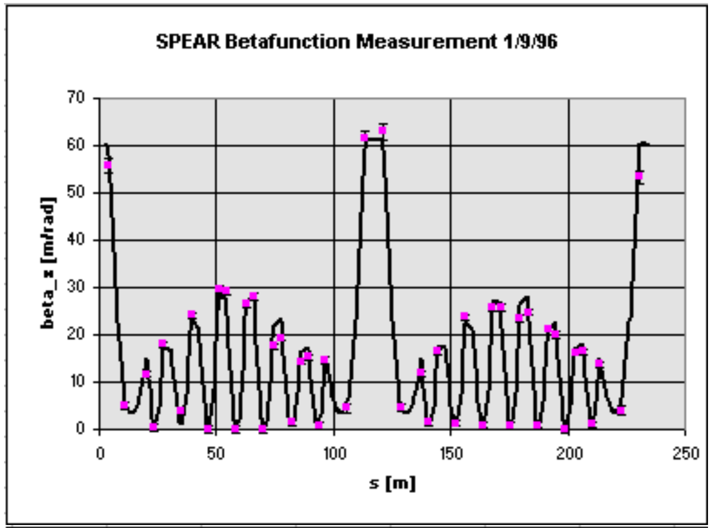




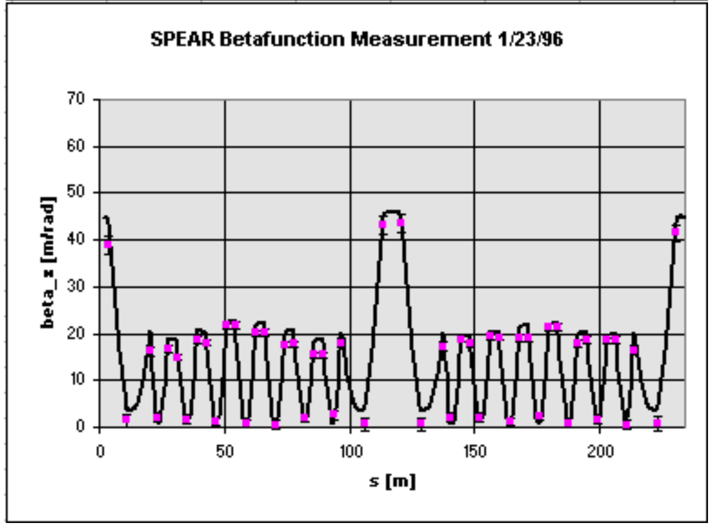
SPEAR β-function correction

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

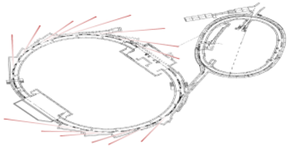


after



Courtesy Heinz-Dieter Nuhn

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

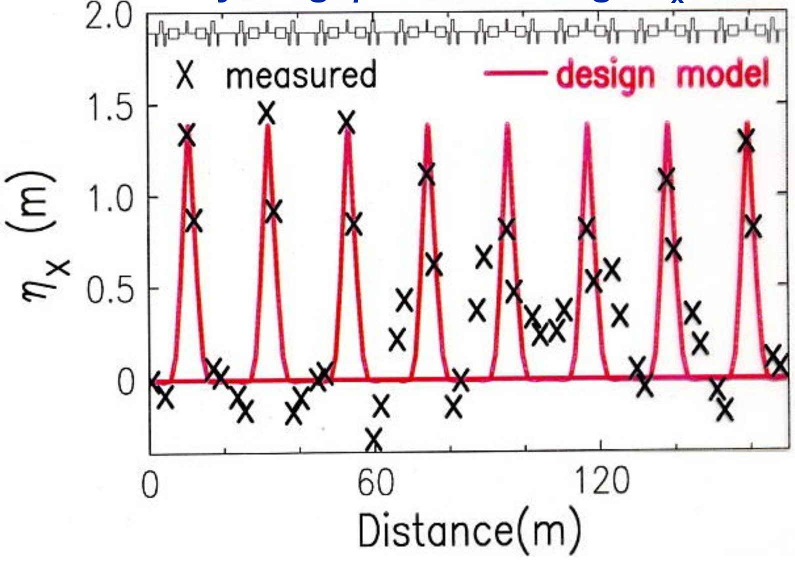
Dispersion distortion can come from quadrupole or dipole errors.

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

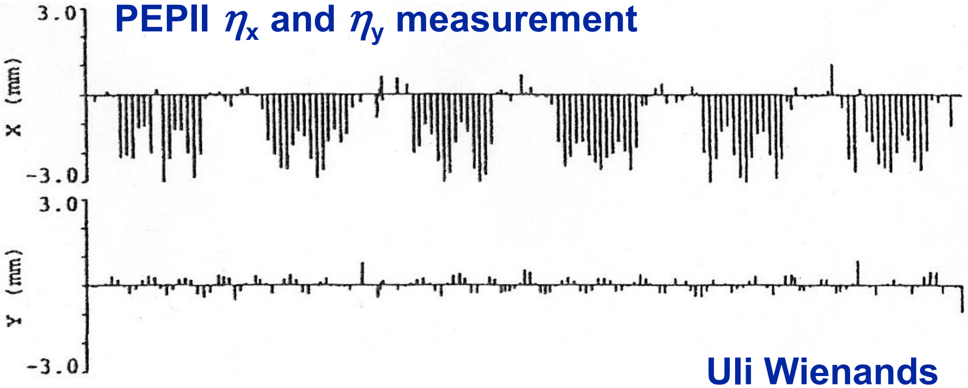
Vertical dispersion gives a measure of vertical bending errors or skew gradient errors in a storage ring.

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

X-Ray Ring η indicates large K_x errors

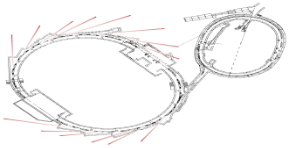


PEPII η_x and η_y measurement

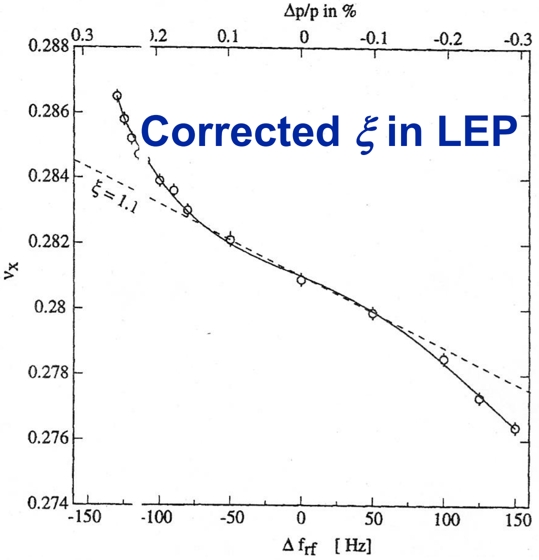


Uli Wienands

Chromaticity measurement, $\xi = d\nu/d\delta_E$



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



Corrected ξ in LEP

H. Burkhardt

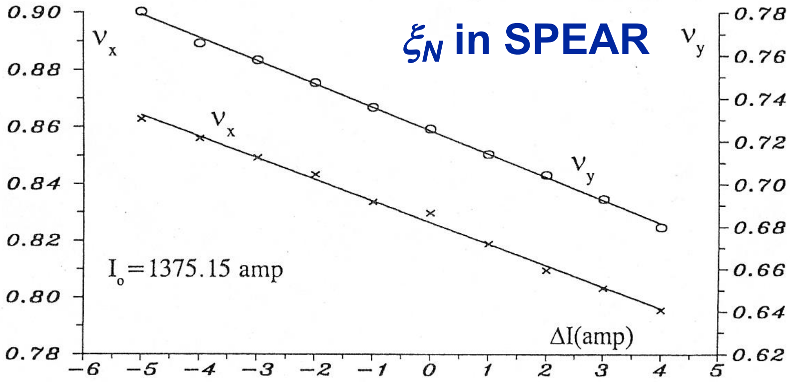
1. Change the rf frequency. This shifts the orbit in sextupoles, giving the corrected chromaticity.

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

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

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

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

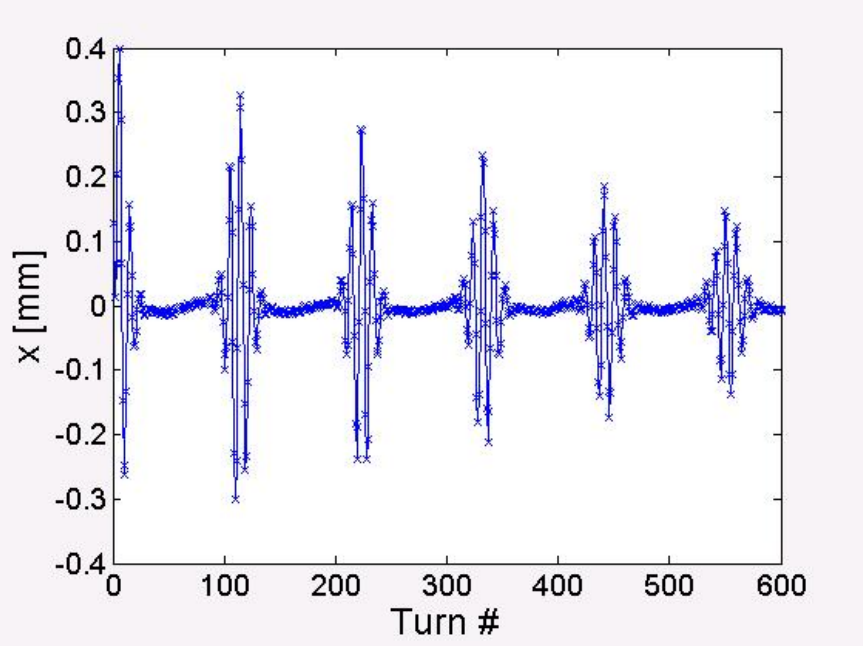


ξ_N in SPEAR

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

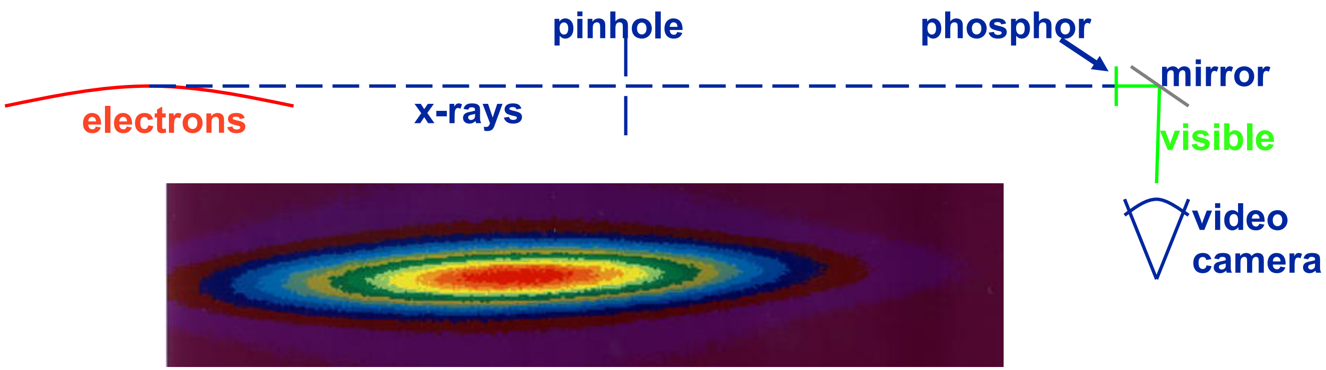
Natural chromaticity measurement

- 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?



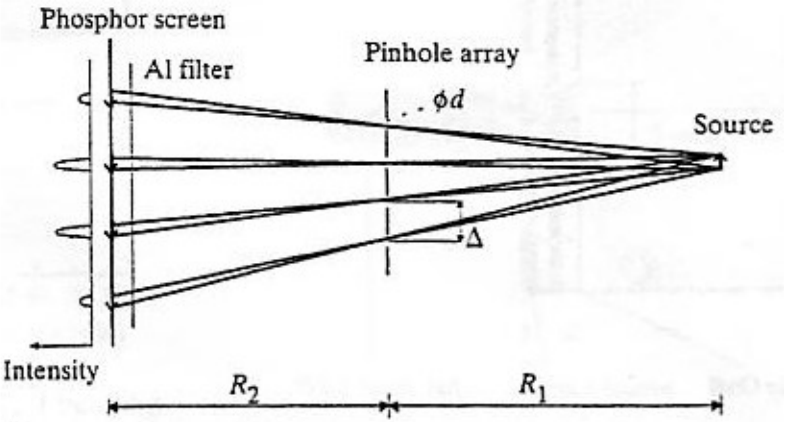
Beam size measurements

X-Ray pinhole camera



Pinhole camera array

(Kuske et al., Bessy)



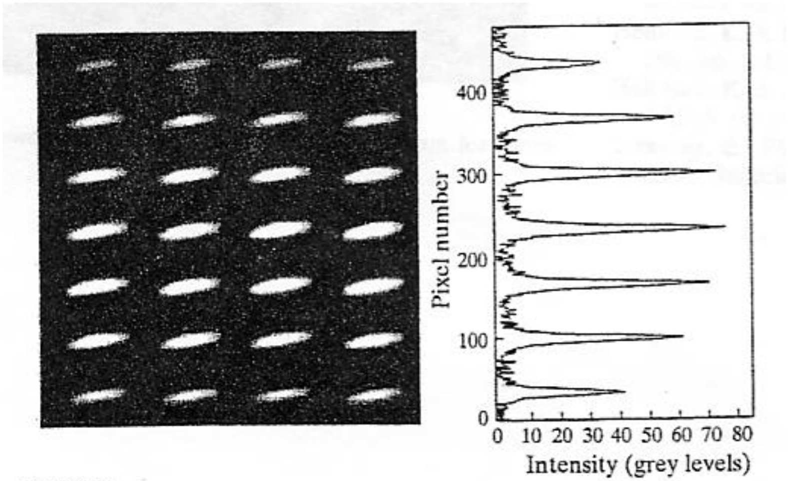


Figure 2
Left: image of a portion of the phosphor observed on a BESSY I bending magnet. Right: integrated intensities of one column of images on the phosphor.

See beam size lecture for more details

Principle of streak camera bunch length measurement

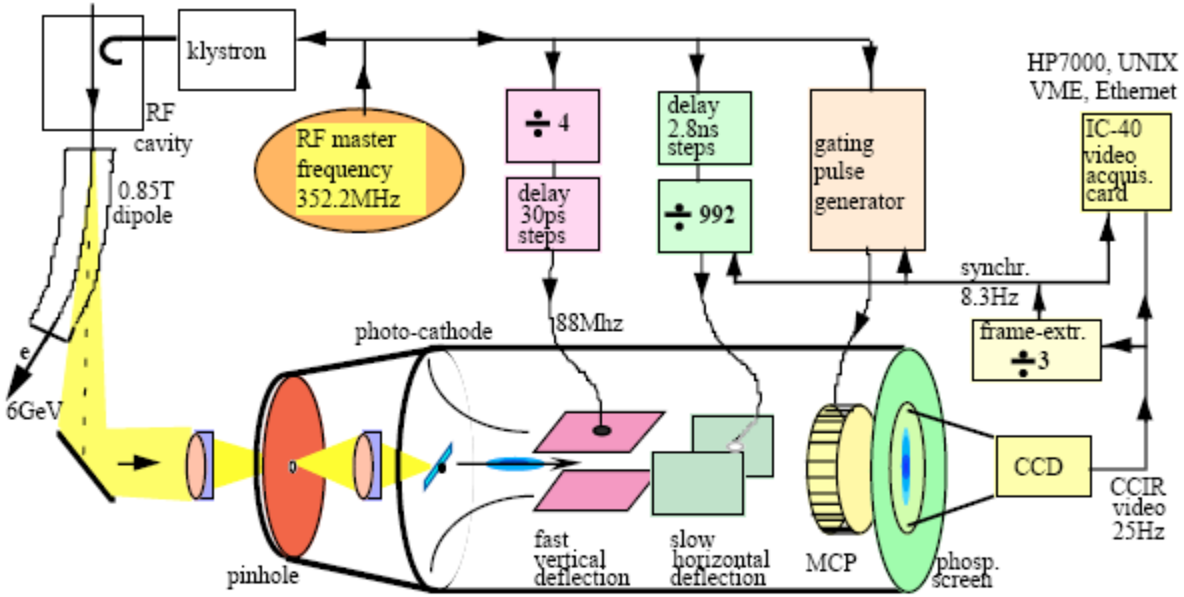
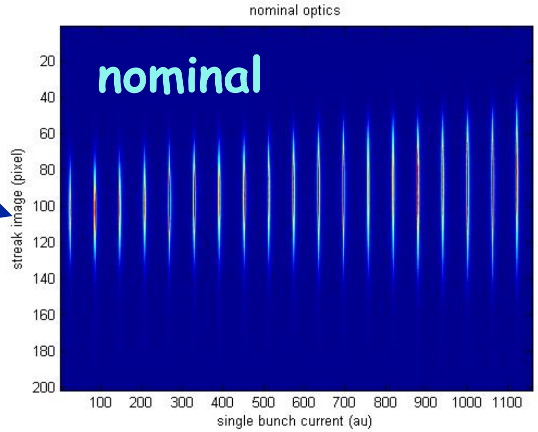


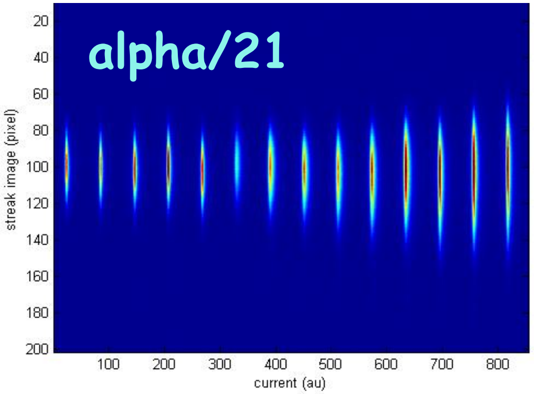
Figure: 1 Synchronisation of the Streak Camera system

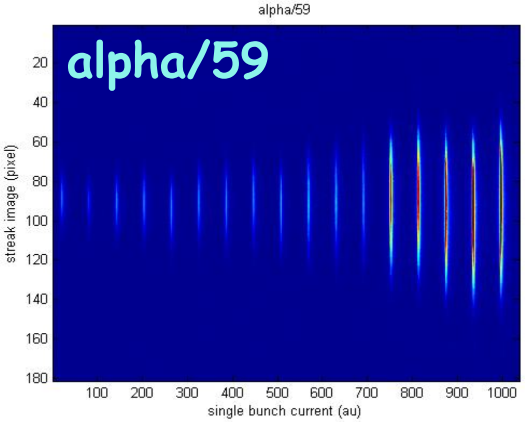
- Convert light signal into electron beam (photo cathode)
- Accelerate electrons
- Use fast deflection to translate time delay into position difference
- In many ways similar to CRT …

Streak camera measurements

Low alpha measurements at SPEAR

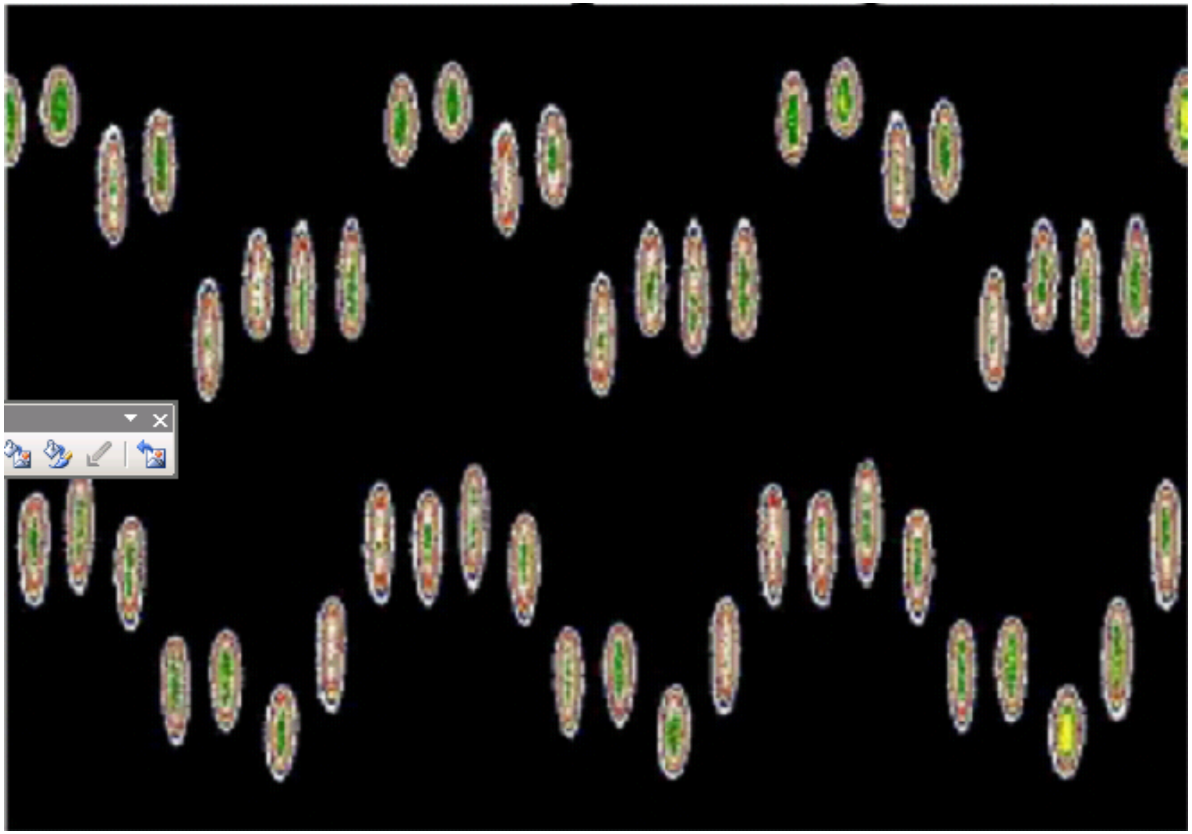






W.J. Corbett

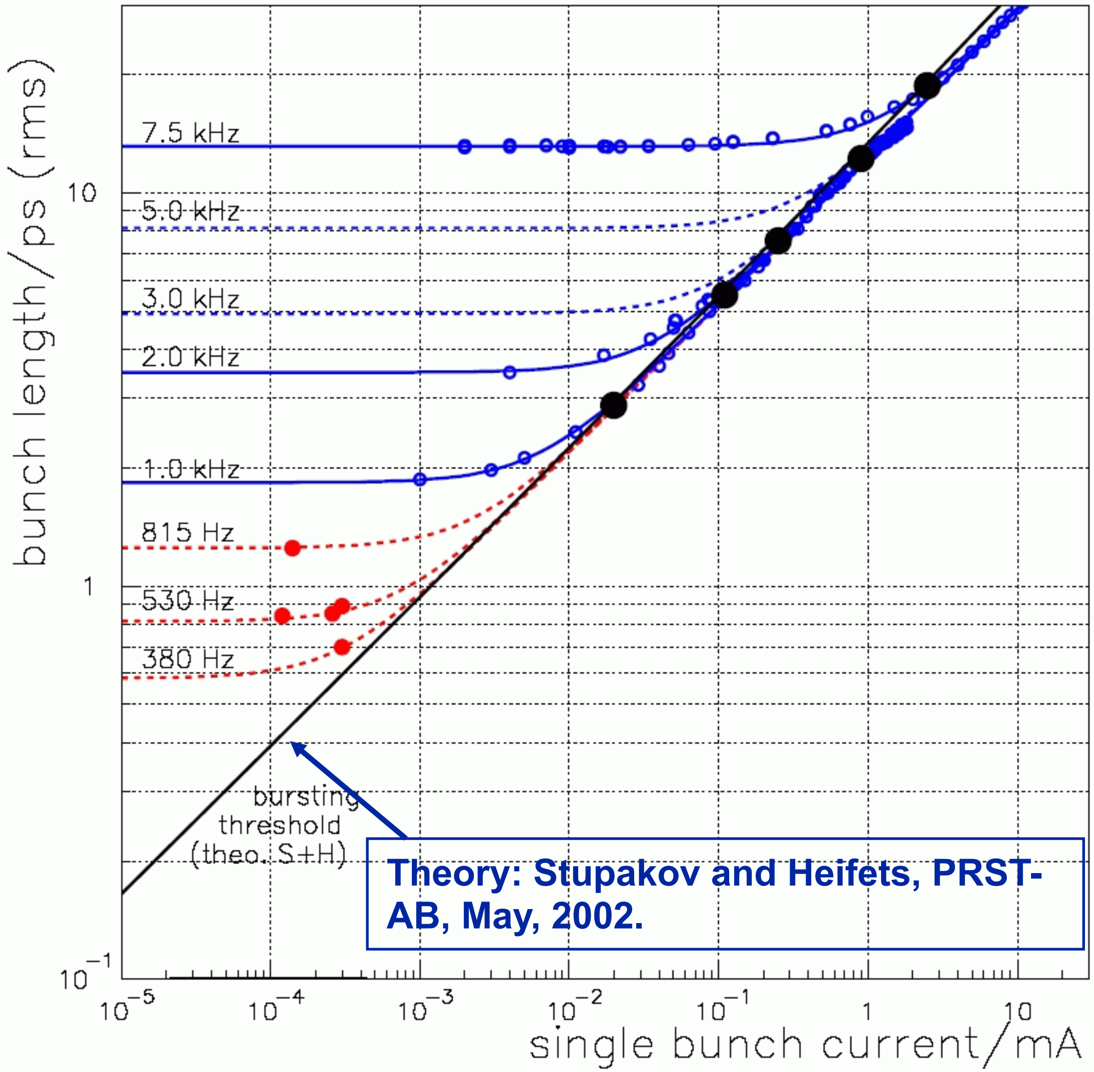
Longitudinal instabilities at ESRF



Streak camera measurements at BESSY

- ❍ **Streak camera data in blue**
- ❍ **Bolometer data in red**

Feikes et al., EPAC2004



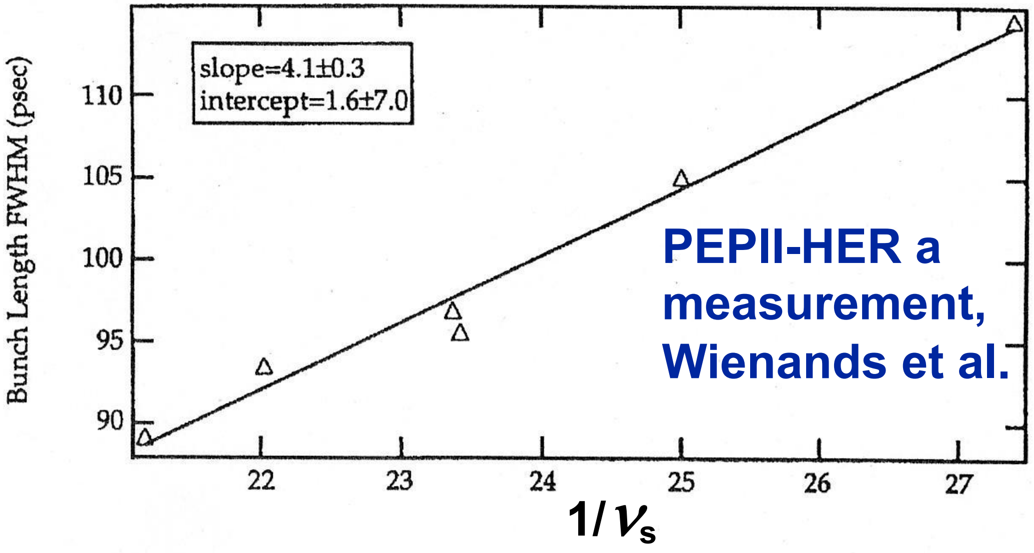
Theory: Stupakov and Heifets, PRST-AB, May, 2002.

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

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



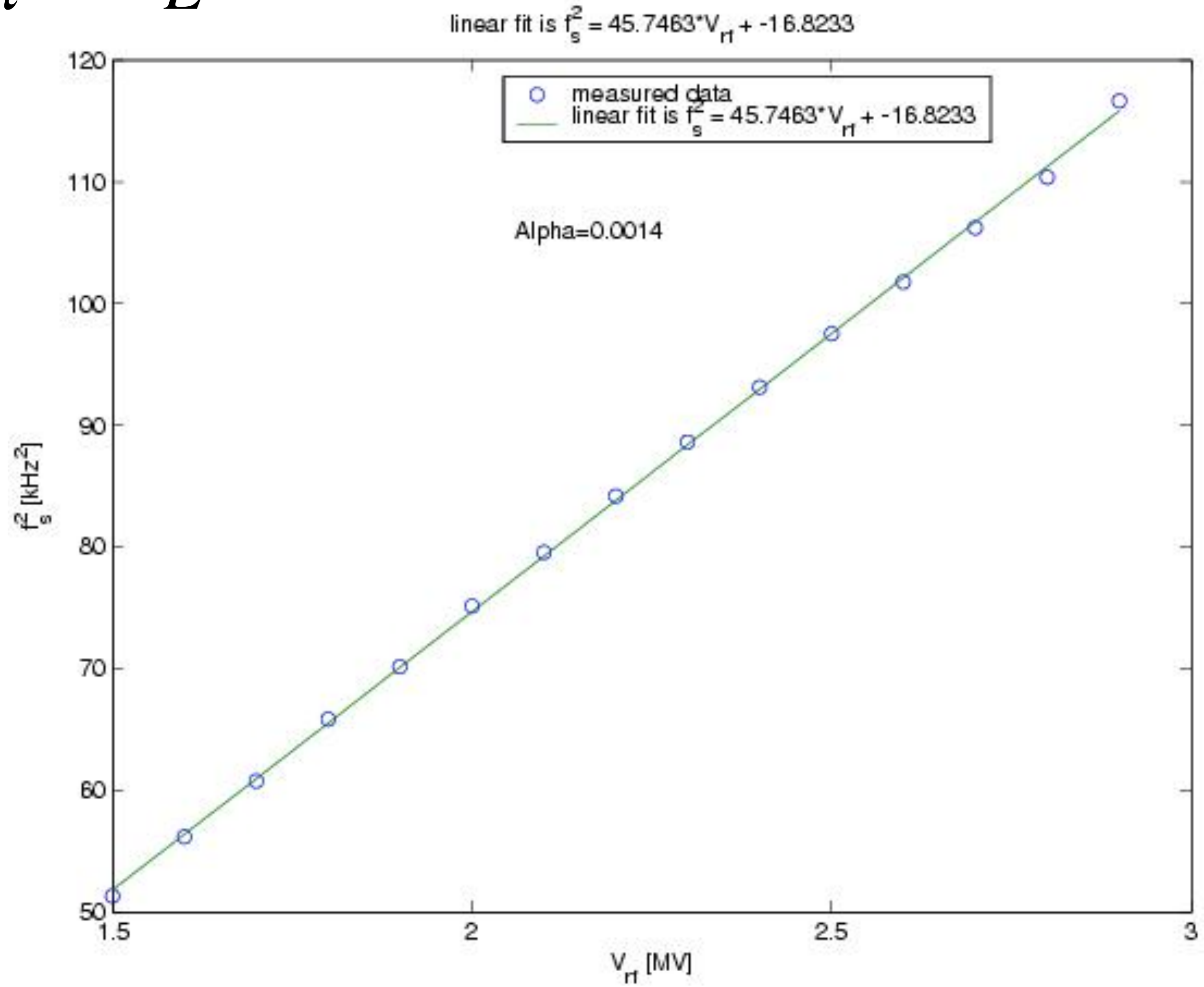
PEPII-HER a measurement, Wienands et al.

Direct measurement: measure change in energy with rf frequency.

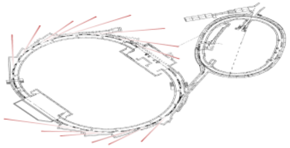
$$\alpha = -\frac{\Delta f_{rf} \big/ f_{rf}}{\Delta p / p}$$

Momentum compaction measurement

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



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).