



國家同步輻射研究中心
National Synchrotron Radiation Research Center



Beam Diagnostics

OCTOBER 20, 2026

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Diagnostics

- Basic Concepts
- Beam Charge/Intensity/Position/Loss monitor
- Transverse Beam Profile and Emittance Monitor
- Longitudinal Beam Profile and Emittance Monitor

References

- 1. 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).
- 2. M.G. Minty and F. Zimmermann, Measurement and control of charged particle beams, Springer (2003).
- 3. Conference proceedings at Joint Accelerator Conferences Website (JACow):
 - <http://accelconf.web.cern.ch/accelconf/>
 - DIPAC
 - PAC
 - EPAC
 - APAC
 - ...
- 4. AIP proceedings for Beam Instrumentation Workshop.
- 5. Paragraph 7.4, “Handbook of Accelerator Physics and Engineering”, edited by Alexander Wu Chao & Maury Tigner.

Introduction

Accelerator performance depends critically on the ability to carefully measure and control the properties of the accelerated particle beams

In fact, it is not uncommon, that beam diagnostics are modified or added after an accelerator has been commissioned

This reflects in part the increasingly difficult demands for high beam currents, smaller beam emittances, and the tighter tolerances placed on these parameters (e.g. position stability) in modern accelerators

A good understanding of diagnostics (in present and future accelerators) is therefore essential for achieving the required performance

A beam diagnostic consists of

- The measurement devices
- Associated electronics and processing hardware/software
- High-level applications (methods, algorithm, ...)

focus of this lecture

subject of many recent publications and internal reports (often application specific)

Missions of the beam diagnostics

- Aids commissioning and efficient running of the machines
 - Improve the machine performance and support various beam physics study
 - **Model/Reality: a lots of improvements this last 20 plus years, nevertheless:**
 - Difficulties to foresee all aspects
 - Static errors (modeled in a statistical way: impossible to get the real distribution)
 - Dynamical errors
 - **High number of perturbation sources**
 - Known sources
 - Unknown sources
 - **By pushing so much accelerator performance, parameters become very sensitive to any drift in temperature, in tunes, ...**
 - **High performance can be reached only with the heavy help of lots of feedforward and feedback systems.**
- Fortunately, high performance diagnostics enable us to get a model close to reality

Diagnostics improvements help us to increase performance

Some Beam Parameters to be monitored

- Intensity

Absolute measure
Relative between bunches (population, ...etc.)
Time dependence properties (bunch length, ...etc.)

- Position

Equilibrium orbit, trajectory, 1st turn, turn-by-turn
Momentum dependence (dispersion)
Time dependence (instabilities, damping after stimulus)
Variation with lattice parameters (bump, lens alignments)
Orbit stability (utility, vibration, power supply, ...etc.)

- Emittance

Transverse (betatron)
Longitudinal (bunch shape)
Momentum spread

- Lattice functions

Betatron tune
 β function
Dispersion function η
Chromaticity ξ
Coupling

- RF related parameters

Synchrotron tune
Parasitic power losses
Potential well distortion

- Instabilities

Diagnostics of process
Stimulated instabilities
Damping times

- Energy/Energy Spread

- Injection/Extraction

Particle trajectories
Available aperture

- Beam loss

Loss pattern
Loss rate
Loss mechanism

- Beam excitation

Kicker, cavity,
stripline, ...

- etc.

Wisdom: An accelerator is just as good as its diagnostic



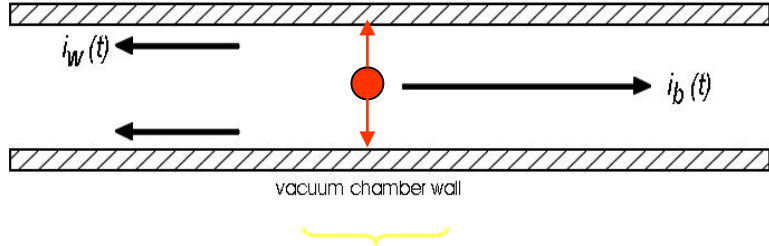
SSRF Diagnostic Devices



	Linac	LTB	Booster	BTS	Ring
BPM (buttons)	—	—	—	—	152
BPM (stripline)	3	3	50	5	—
Tune monitor	—	—	1	—	1
Orbit Feedback System	—	—	—	—	1
Transverse Feedback System	—	—	—	—	1
Synchrotron Radiation Monitor	—	—	—	—	1
Profile Monitor	5	3	4	4	2
DCCT	—	—	1	—	1
Wall Current Monitor	5	2	1	3	—
Integration Current Transformer	1	—	—	1	—
Faraday Cup	1	—	—	—	—
Slit	—	2	—	1	—
Scraper	—	—	—	—	2

Total 257 sets of detectors

Fields of a relativistic particle

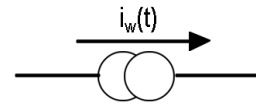


induced wall current $i_w(t)$
has opposite sign of beam
current $i_b(t)$: $i_b(t) = -i_w(t)$

Lorentz-contracted “pancake”

Detection of charged particle beams - beam detectors:

i_w is a current source



with infinite output impedance, i_w will flow through any impedance placed in its path

many “classical” beam detectors consist of a modification of the walls through which the currents will flow

Sensitivity of beam detectors:

beam charge: $S(\omega) = \frac{V(\omega)}{I_w(\omega)}$ (in Ω) = ratio of signal size developed $V(\omega)$ to the wall current $I_w(\omega)$

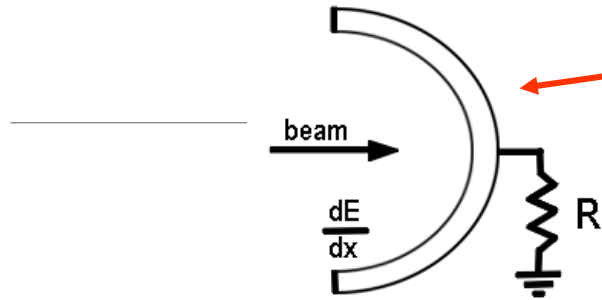
beam
position:

$$S(\omega) = \frac{V(\omega)}{D(\omega)}$$

(in Ω/m)

= ratio of signal size developed / dipole mode of the distribution, given by $D(\omega) = I_w(\omega) z$, where $z = x$ (horizontal) or $z = y$ (vertical)

Beam Charge - the Faraday Cup



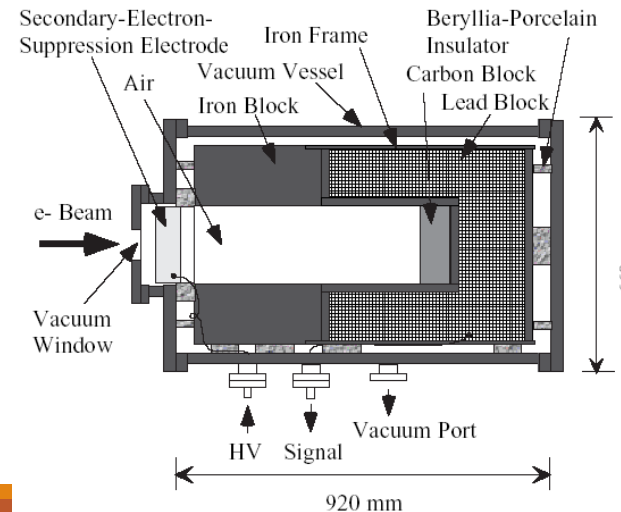
thick (e.g. ~0.4 m copper for 1 GeV electrons) or series of thick (e.g. for cooling) charge collecting receptacles

Principle: beam deposits (usually) all energy into the cup (invasive)
charge converted to a corresponding current
voltage across resistor proportional to instantaneous current absorbed

In practice:

termination usually into 50 Ω ; positive bias to cup to retain e⁻ produced by secondary emission; bandwidth-limited (~1 GHz) due to capacitance to ground

cross-sectional view of the FC of the KEKB injector linac (courtesy T. Suwada, 2003)



cylindrically symmetric
blocks of
lead (~35 radiation lengths)
carbon and iron
(for suppression of EM showers generated by the lead)
bias voltage (~many 100 Volts)
for suppression of secondary electrons

Beam Intensity - Toroids (1)

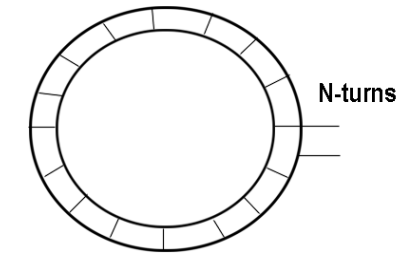
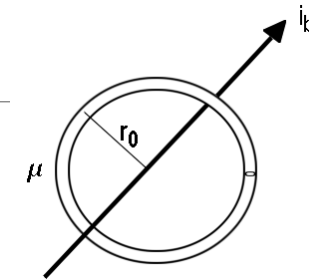
Consider a magnetic ring surrounding the beam, from Ampere's law:

$$\oint \vec{B} \cdot d\vec{l} = \mu I$$

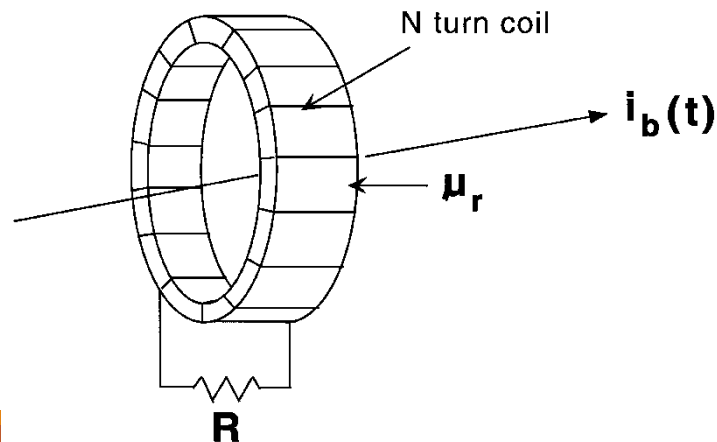
if r_0 (ring radius) $\gg$ thickness of the toroid, $B = \frac{\mu i_b}{2\pi r_0}$

Add an N-turn coil - an emf is induced which acts to oppose B:

$$\begin{aligned} \epsilon &= \frac{d\phi}{dt} \text{ where } \phi = \int \vec{B} \cdot d\vec{a} \\ &= \frac{\mu A}{2\pi r_0} \frac{di_b}{dt} \end{aligned}$$

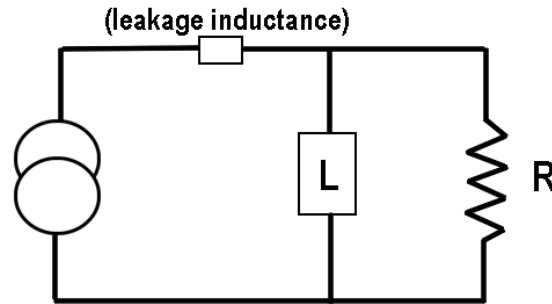


Load the circuit with an impedance; from Lenz's law, $i_R = i_b/N$:



Principle: the combination of core, coil, and R produce a current transformer such that i_R (the current through the resistor) is a scaled replica of i_b . This can be viewed across R as a voltage.

Beam Intensity - Toroids (2)



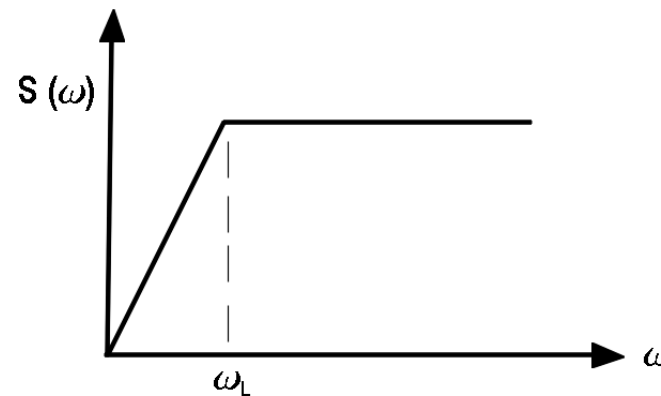
$$L = \frac{N^2}{R_h}$$

with R_h = reluctance of magnetic path

$$R_h = \frac{l}{\mu A} [\text{H}^{-1}] \longrightarrow L = \frac{N^2 \mu_r \mu_0 A}{l}$$

sensitivity:

$$S = \frac{R}{\sqrt{1 + (\frac{\omega_l}{\omega})^2}} \quad \omega_l = \frac{R}{L}$$



cutoff frequency, ω_L , is small if $L \sim N^2$ is large

detected voltage:

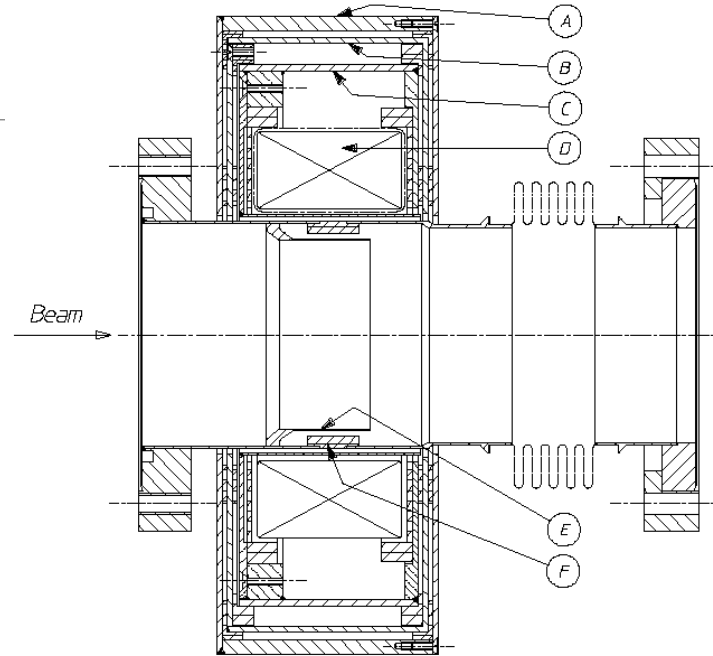
$$V(t) = \frac{i_b R}{N} e^{-(\frac{R}{L})t}$$

trade-off
between
bandwidth
and signal
amplitude

if N is large, the
voltage detected is
small

Beam Intensity - Toroids (3)

schematic
of the toroidal
transformer for the TESLA
Test facility
(courtesy,
M. Jablonka,
2003)



- A iron
 - B Mu-metal
 - C copper
 - D "Supermalloy" (distributed by BF1 Electronique, France) with $\mu \sim 8 \times 10^4$
 - E electron shield
 - F ceramic gap
- } shielding

(one of many)
current trans-
formers available
from Bergoz
Precision Instru-
ments (courtesy
J. Bergoz, 2003)



(based on design of K. Unser
for the LEP bunch-by-bunch
monitor at CERN)

linacs: resolution of 3×10^6
storage rings: resolution
of 10 nA rms

details: www.bergoz.com

Beam Intensity - Toroids (4) - DCCT

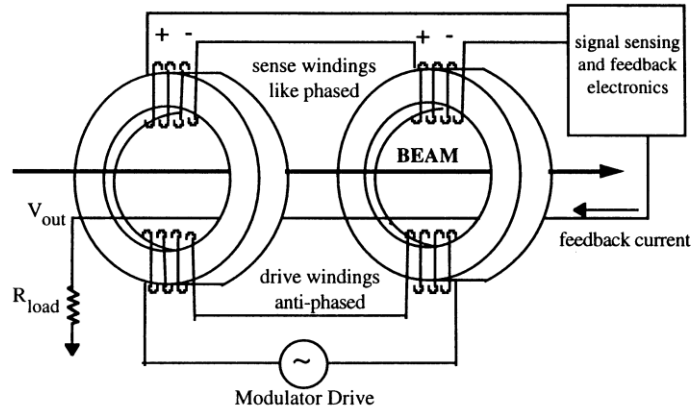


Figure 6. Magnetic modulator section of DC Transformer with flux nulling feedback.

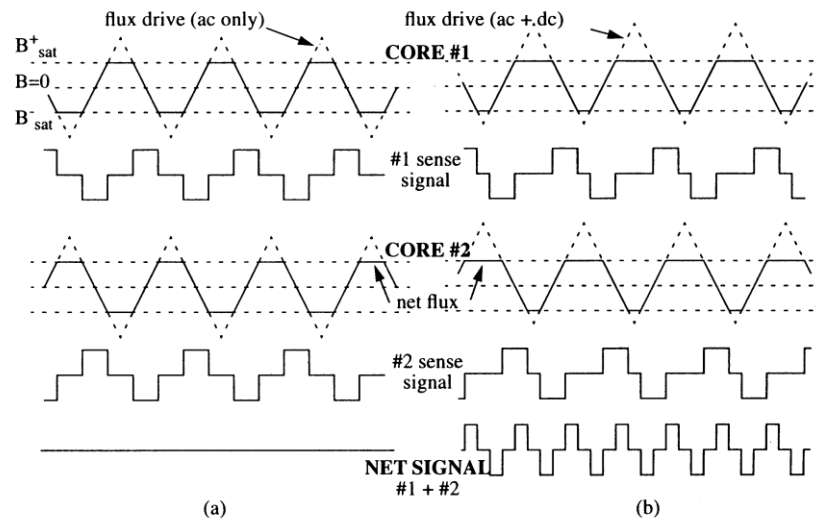


Figure 7. Magnetic modulator signals, (a) with no dc present and (b) with exaggerated dc presence.

State of the Art Commercial DCCT

Full scale range from $\pm 20\text{mA}$ to $\pm 20\text{A}$ controlled by TTL levels

5 $\mu\text{A}/\sqrt{\text{Hz}}$ resolution in every range

1 $\mu\text{A}/\sqrt{\text{Hz}}$ or lower resolution on option

Frequency response DC to 100 kHz

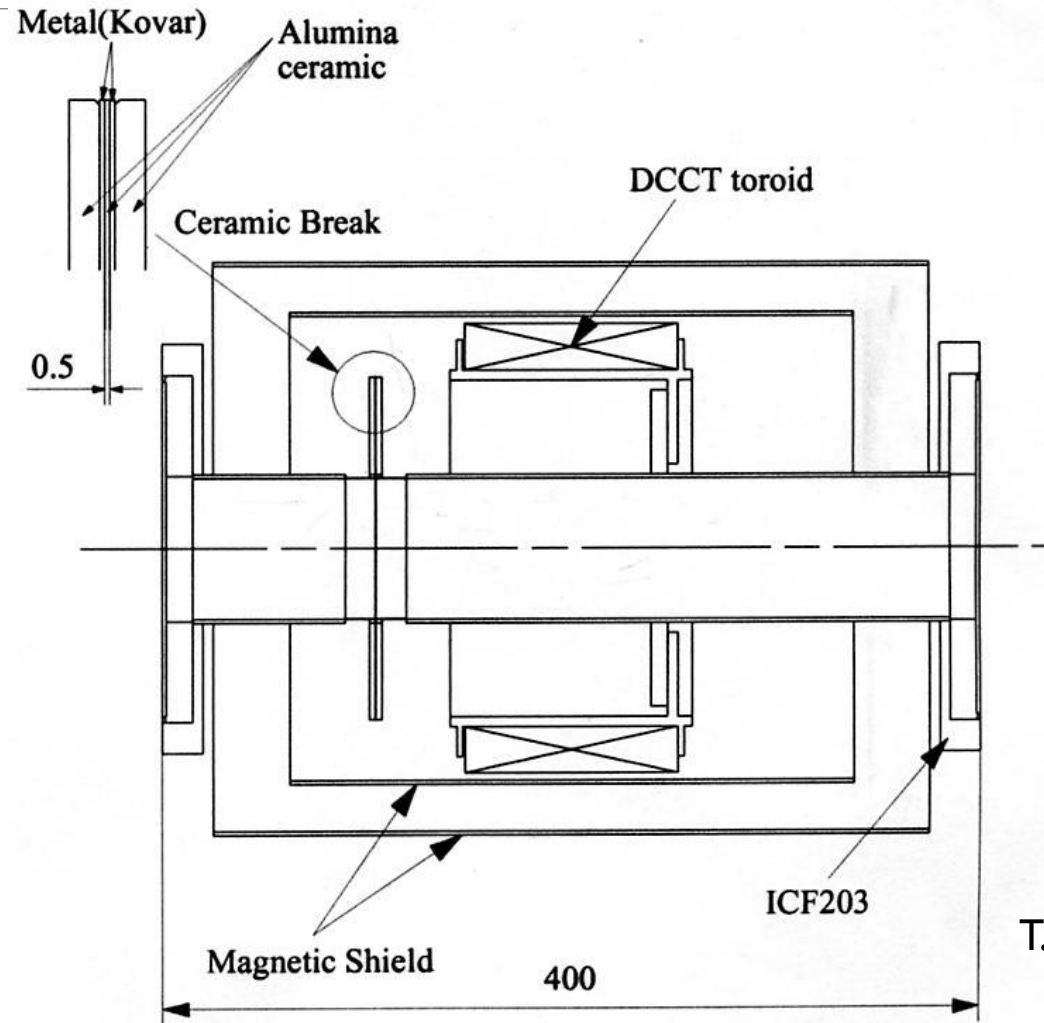
Linearity error $< 0.1\%$

Sensor inner diameter from 55 to 245 mm to fit around any vacuum chamber



*New-PCT with 245-mm sensor head and 130-m cable
Also shown: smaller sensor head*

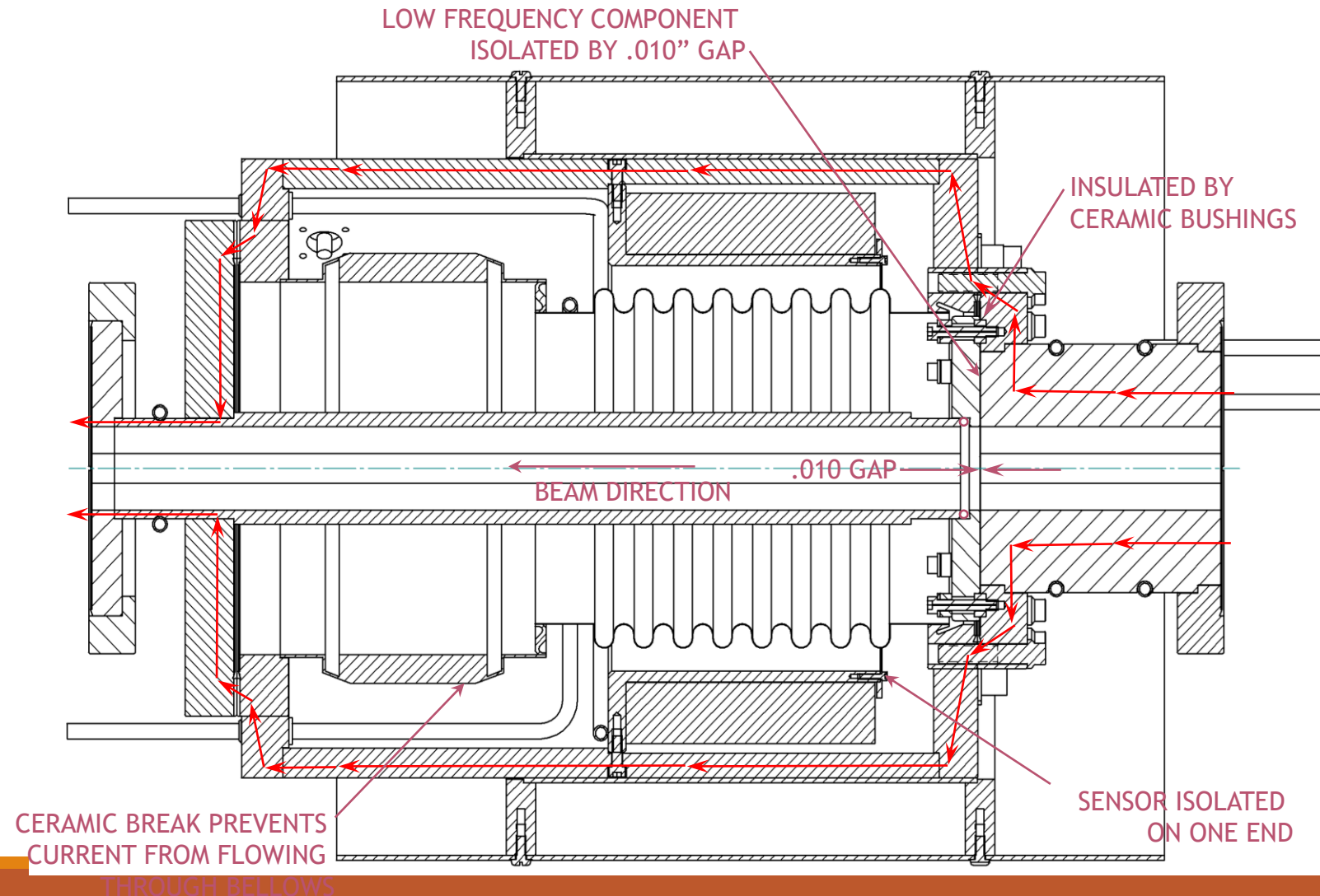
Beam Intensity - Toroids (5) - DCCT



T. Honda et al., EPAC98

Beam Intensity - Toroids (6) - DCCT

SPEAR3 DCCT



Determination of Current Related Parameter - Lifetime

Determination of Current Related Parameter - Lifetime

Once the intensity of the stored beam is recorded the 1/e decay time can be determined:

$$I(t) = I_0 \bullet e^{-t/\tau} \approx I_0 \bullet (1 - t / \tau)$$

Measurement of parameters related to lifetime ::

Varied intensity, fill pattern:

- Lifetime limiting processes

- Varied quadrupoles, tunes:

- Lifetime limiting resonances

- Coupling-cross correlation hor./vet.

Varied magnet gap of ID:

- Resonance driven by ID

Varied scraper position:

- Contributions of the lifetime, dynamical aperture,

- Particles in the halo of the beam, Touschek effect

Varied transverse beam size:

- Touschek contribution

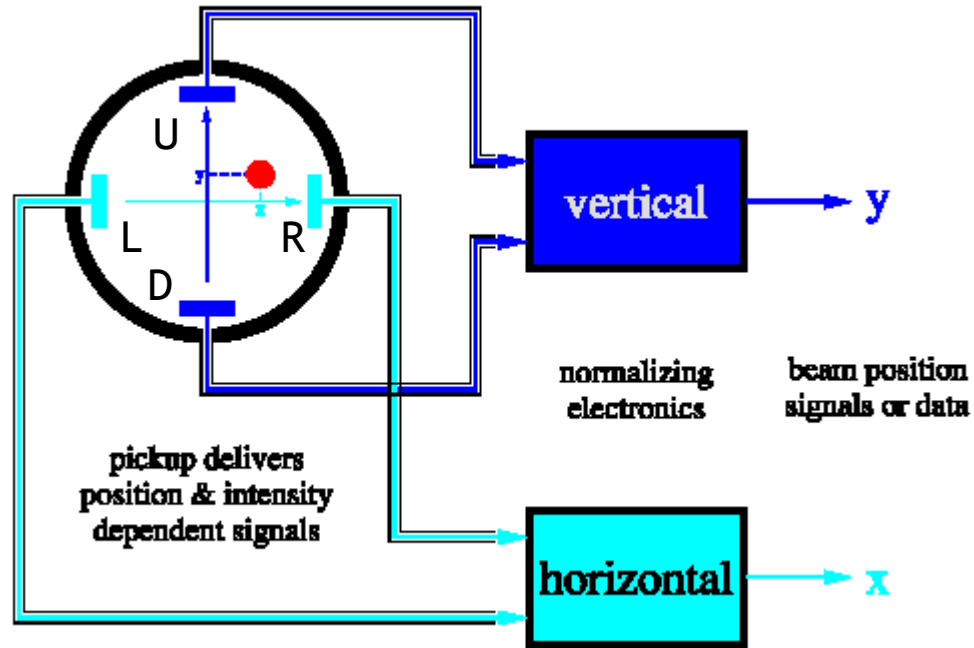
Varied bunch length:

- Touschek contribution

Varied local bump:

- Physical aperture

Beam Intensity - BPM Sum signals



U ~ up
D ~ down
L ~ left
R ~ right

(M. Wendt, 2003)

beam "position" $V_R - V_L$ (horizontal)
 $V_U - V_D$ (vertical)
 beam intensity $V_R + V_L, V_U + V_D, V_R + V_L + V_U + V_D$
 normalized (intensity-independent) beam position = position/intensity

- Remarks:
- 1) as we will see, higher-order nonlinearities must occasionally be taken into account
 - 2) in circular $e^{+/-}$ accelerators, assembly is often tilted by 45 degrees

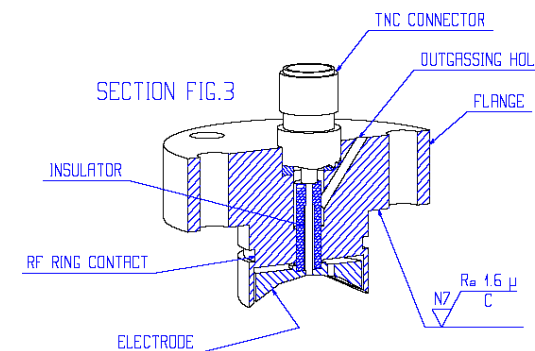
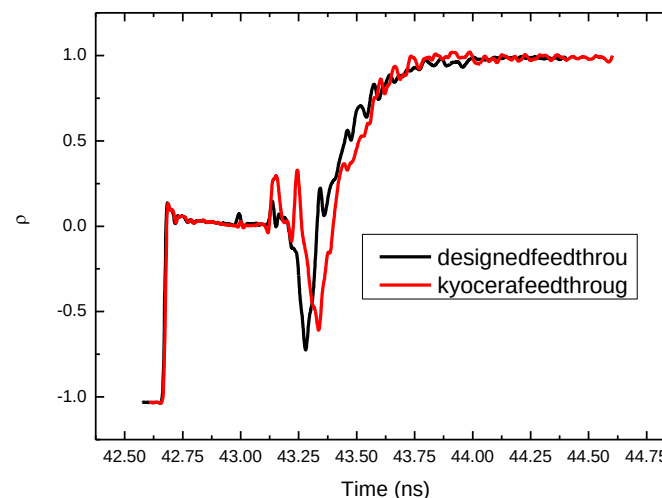
Technical drawing of a pin assembly. The drawing includes a cross-section view (A-A) and a side view. The side view shows a pin (2) inserted into a housing (1). The pin is made of Kovar and the housing is made of Kovar. The pin is brazed to the housing. The drawing includes dimensions for the pin diameter (φA, φB, φC) and the housing diameter (φA, φB, φC). The pin diameter is specified as φA = +0.02 / -0.02, φB = +0.01 / -0.01, and φC = +0.01 / -0.01. The housing diameter is specified as φA = +0.02 / -0.02, φB = +0.01 / -0.01, and φC = +0.01 / -0.01. The drawing also includes a table of materials:

Part	Material	Material
1	Housing	KOVAR
2	Pin	KOVAR
3	Ceramic	Al ₂ O ₃ ≥ 97%

PROFILE: A-A
SCALE 5 : 1

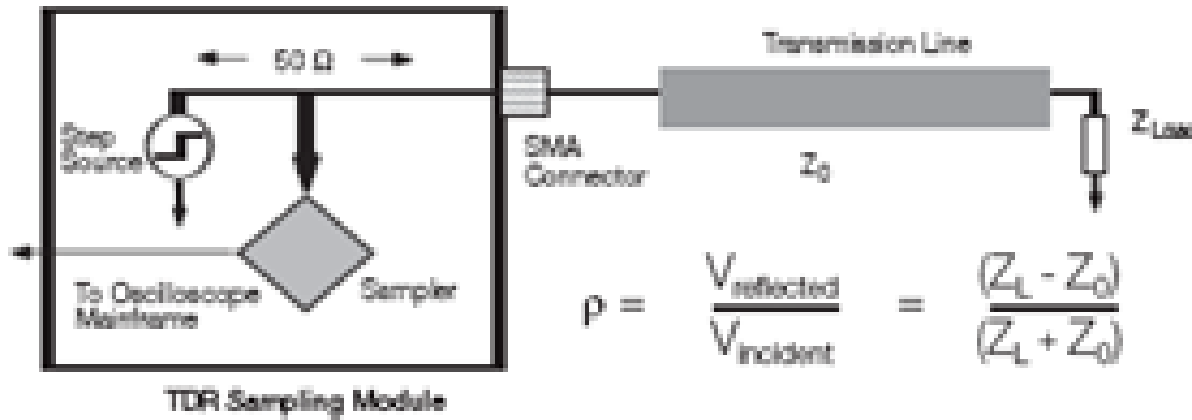
Section	impedance	ρ
A	49.95Ω	-0.0005
B	48.04Ω	-0.01949
C	49.56Ω	0.01557

TPS



LHC

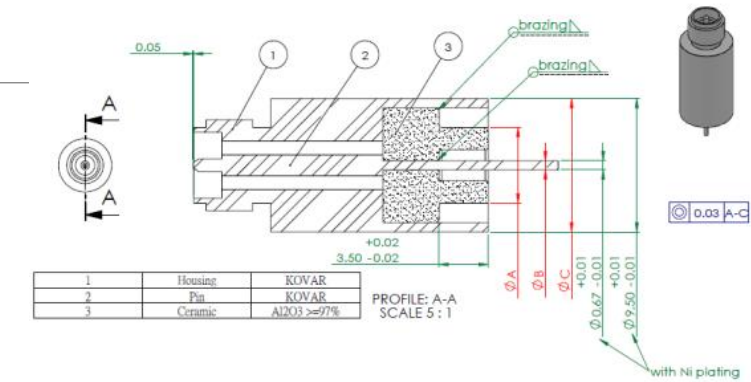
note: monitor has inherent nonlinearities



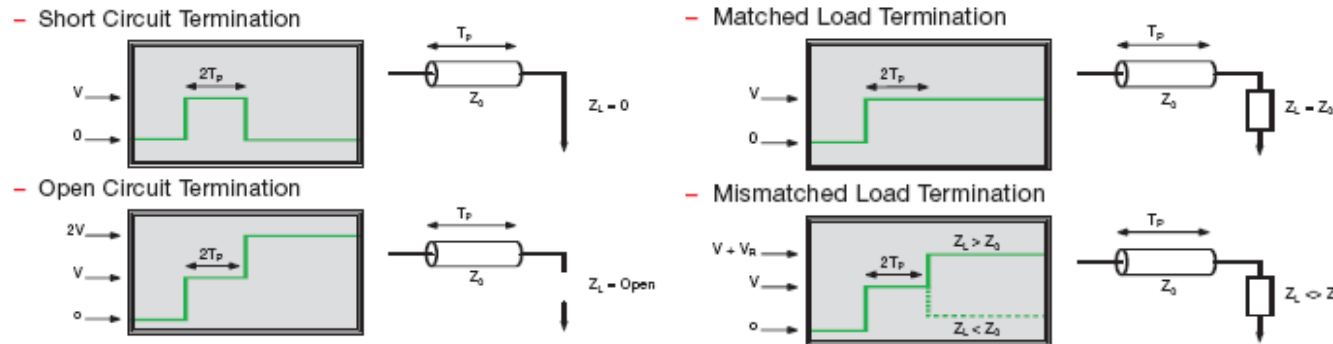
$$C = \frac{2\pi\epsilon L}{\ln \frac{b}{a}}$$

$$L_I = \frac{\mu_0 L}{2\pi} \ln \frac{b}{a}$$

$$Z_C = \sqrt{\frac{L_I}{C}} \rightarrow Z_C = \frac{1}{2\pi} \sqrt{\frac{\mu_0}{\epsilon}} \ln \frac{b}{a}$$

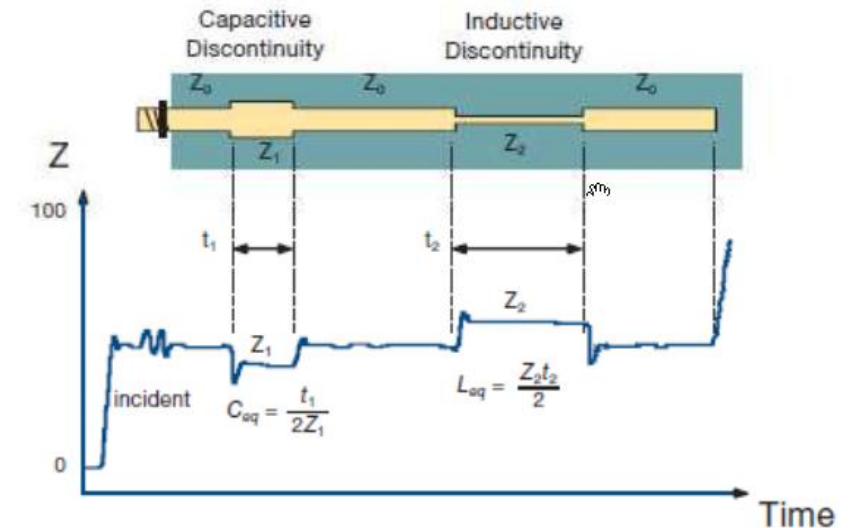


Section	impedance	ρ
A	49.95 Ω	-0.0005
B	48.04 Ω	-0.01949
C	49.56 Ω	0.01557



$$t = \frac{2L}{v}$$

v related to dielectric material



The transfer impedance $Z_t(\omega, \beta)$

At a resistor R the voltage U_{im} from the image current is measured.

The *transfer impedance* Z_t is the ratio between U_{im} and the beam current I_{beam}

in *frequency domain*: $U_{im}(\omega) = R \cdot I_{im}(\omega) = Z_t(\omega, \beta) \cdot I_{beam}(\omega)$

The pick-up has a capacitance C :

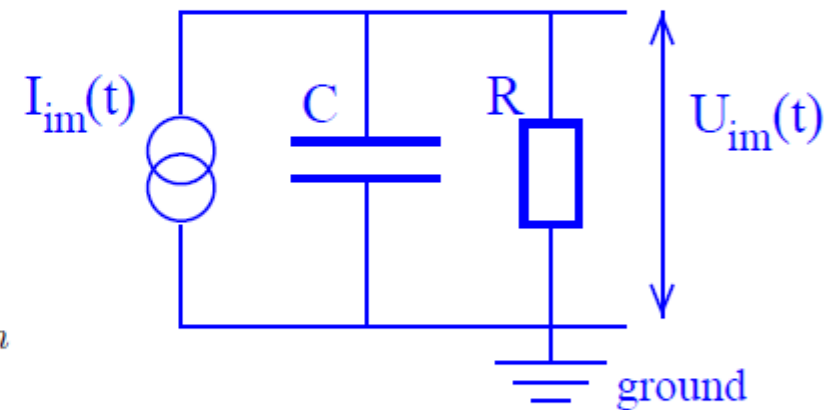
plate $\leftrightarrow$ vacuum-pipe and cable.

The amplifier has an input resistor R .

The equivalent circuit is a current source:

$$\begin{aligned} U_{im} &= \frac{R}{1 + i\omega RC} \cdot I_{im} \\ &= \frac{A}{2\pi a \beta c} \cdot \frac{1}{C} \cdot \frac{i\omega RC}{1 + i\omega RC} \cdot I_{beam} \\ &\equiv Z_t(\omega, \beta) \cdot I_{beam} \end{aligned}$$

equivalent circuit



$$\frac{1}{Z} = \frac{1}{R} + i\omega C \Leftrightarrow Z = \frac{R}{1 + i\omega RC}$$

This is a high pass with $\omega_{cut} = 1/RC$.

It is: $|Z_t(\omega)| = \frac{A}{2\pi a \beta c C} \cdot \frac{\omega/\omega_{cut}}{\sqrt{1 + \omega^2/\omega_{cut}^2}}$ and phase $\varphi(\omega) = \arctan(\omega_{cut}/\omega)$

Sensitivity

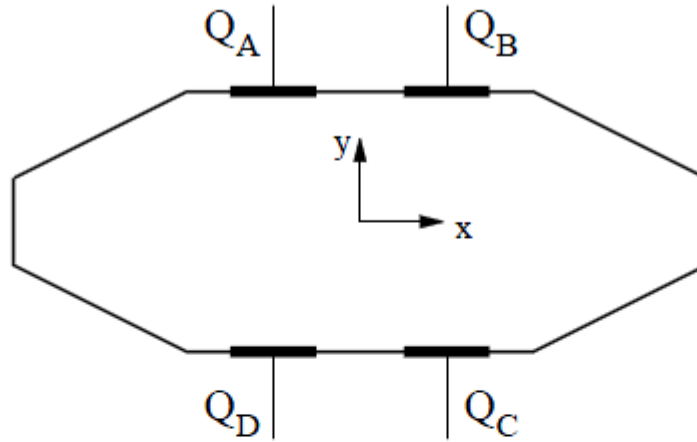


Figure 3: Schematic view of a pickup and definition of the button electrodes.

button electrode. The beam positions are finally received by comparing the induced charges on the four buttons according to the difference over sum (Δ/Σ) method as follows:

$$Q_x = \frac{\Delta_x}{\Sigma} = \frac{(Q_B + Q_C) - (Q_A + Q_D)}{(Q_A + Q_B + Q_C + Q_D)} \quad (19)$$

$$Q_y = \frac{\Delta_y}{\Sigma} = \frac{(Q_A + Q_B) - (Q_C + Q_D)}{(Q_A + Q_B + Q_C + Q_D)} \quad (20)$$

The position sensitivities are determined by the derivatives of Q_x and Q_y with respect to the beam position x_0, y_0 :

$$S_x = \frac{\partial Q_x}{\partial x_0}, \quad S_y = \frac{\partial Q_y}{\partial y_0} \quad (21)$$

The monitor constant which is a characteristic value of an electrostatic monitor is related to the sensitivity by the following formula:

$$k_{x,y} = \frac{1}{S_{x,y}(0,0)} . \quad (22)$$

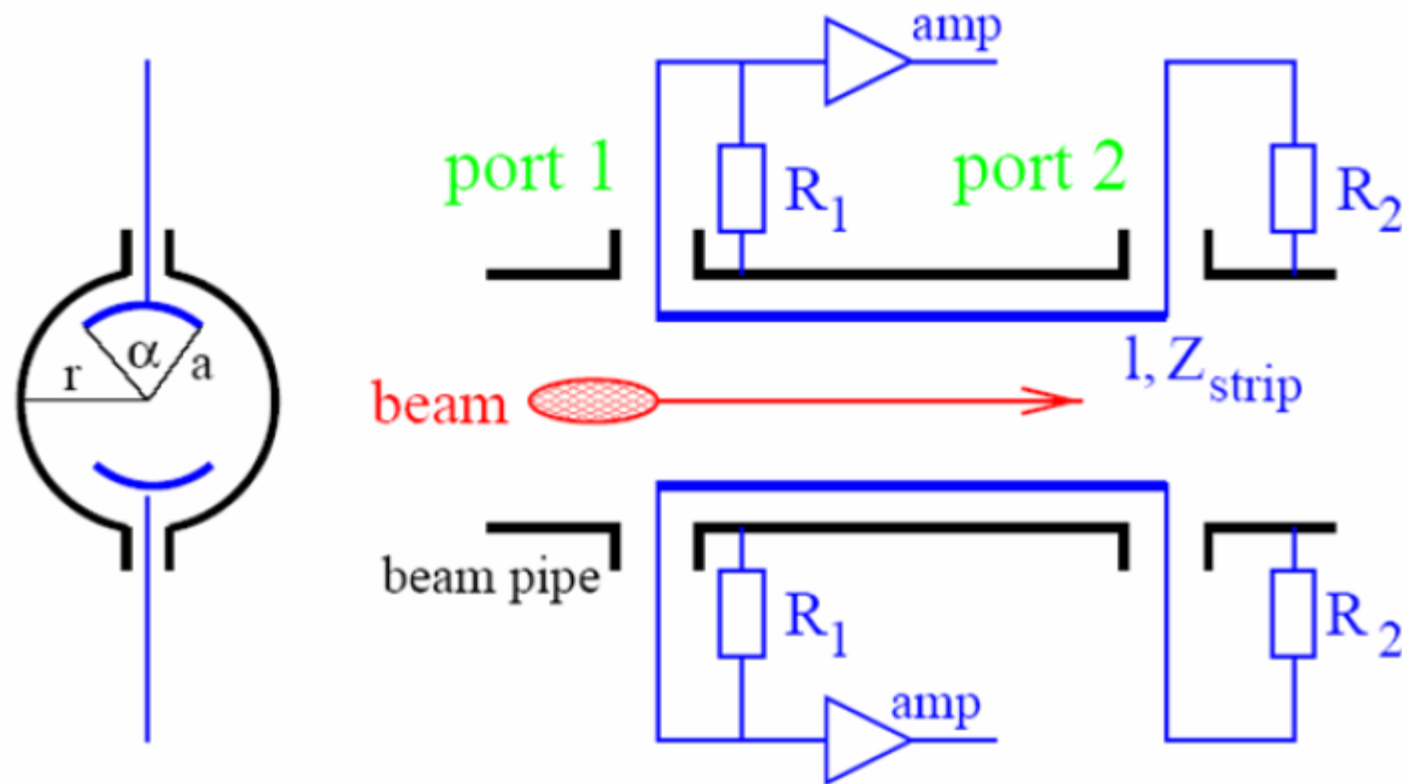
With knowledge of the monitor constant the beam position can be reconstructed from the induced pickup signals in first order by

$$x = k_x \frac{\Delta_x}{\Sigma} = k_x \frac{(Q_B + Q_C) - (Q_A + Q_D)}{(Q_A + Q_B + Q_C + Q_D)} \quad (23)$$

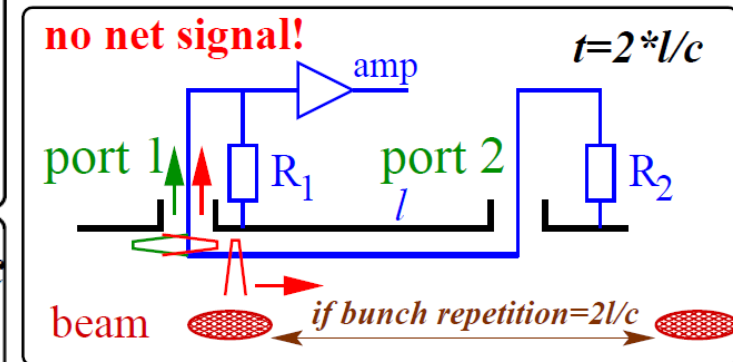
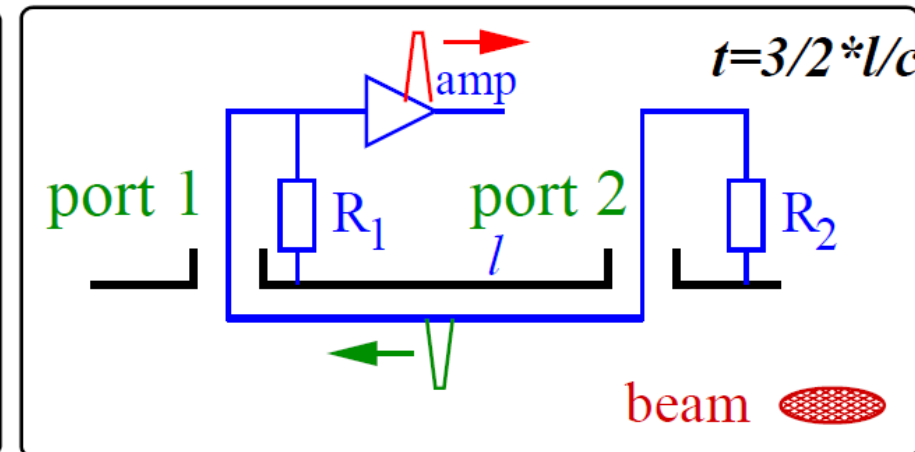
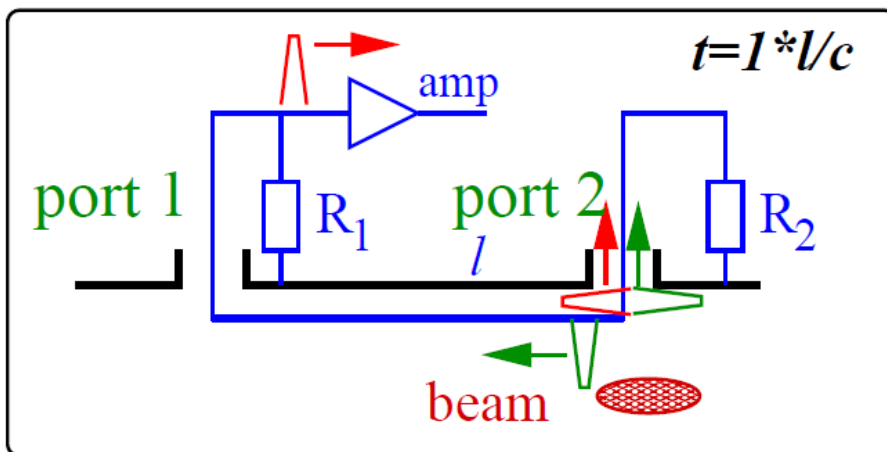
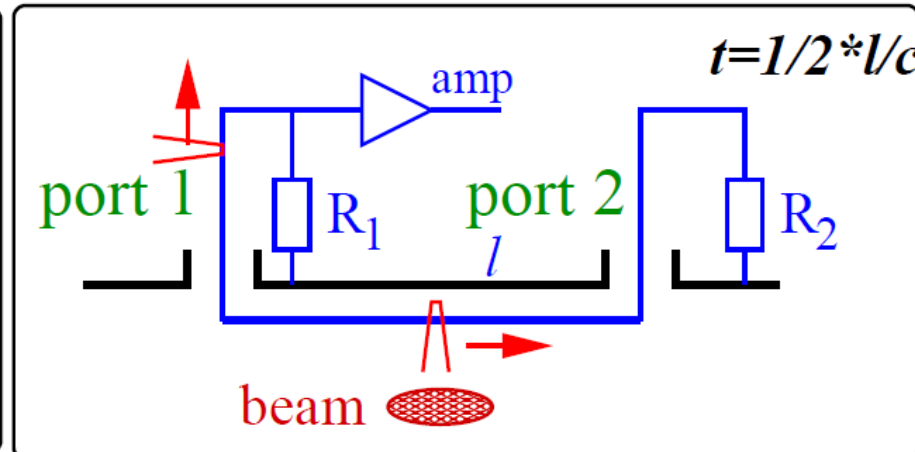
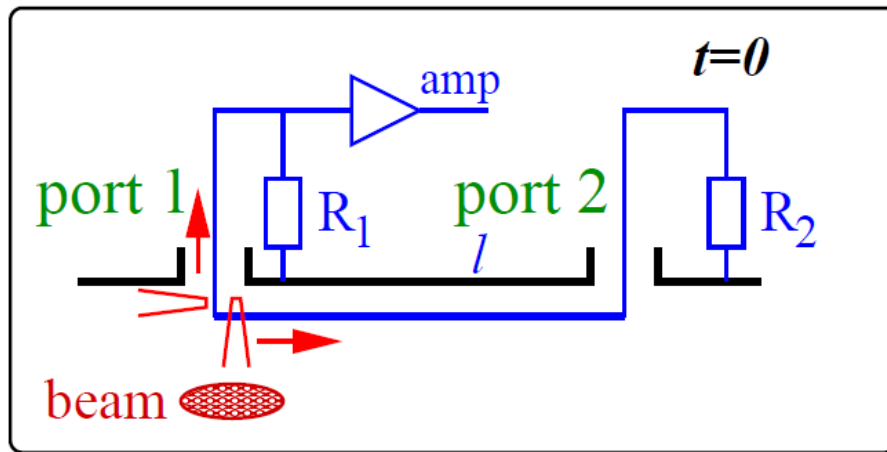
$$y = k_y \frac{\Delta_y}{\Sigma} = k_y \frac{(Q_A + Q_B) - (Q_C + Q_D)}{(Q_A + Q_B + Q_C + Q_D)} \quad (24)$$

Beam Position - Stripline / Transmission Line Detectors (1)

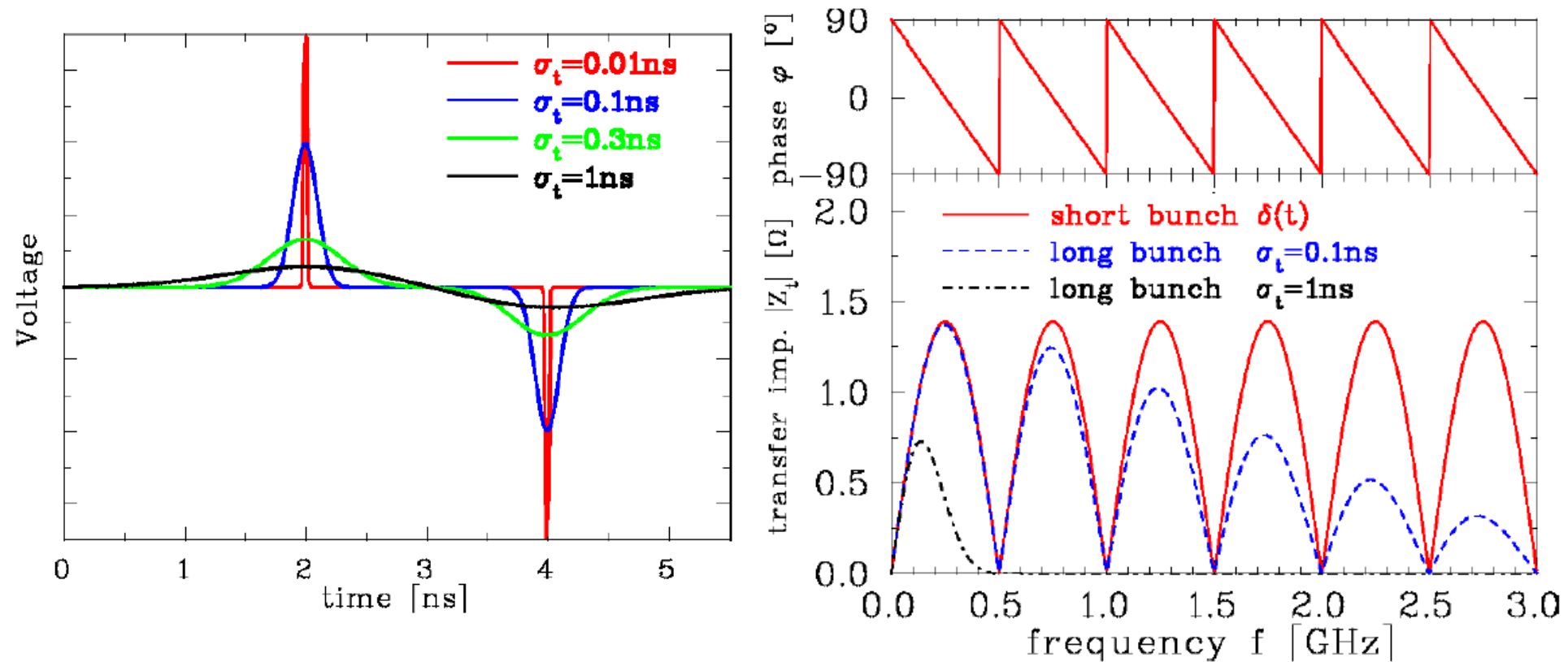
principle: electrode (spanning some azimuth ψ) acts as an inner conductor of a coaxial line; shield acts as the grounded outer conductor $\rightarrow$ signal propagation must be carefully considered



Beam Position - Stripline / Transmission Line Detectors (2)

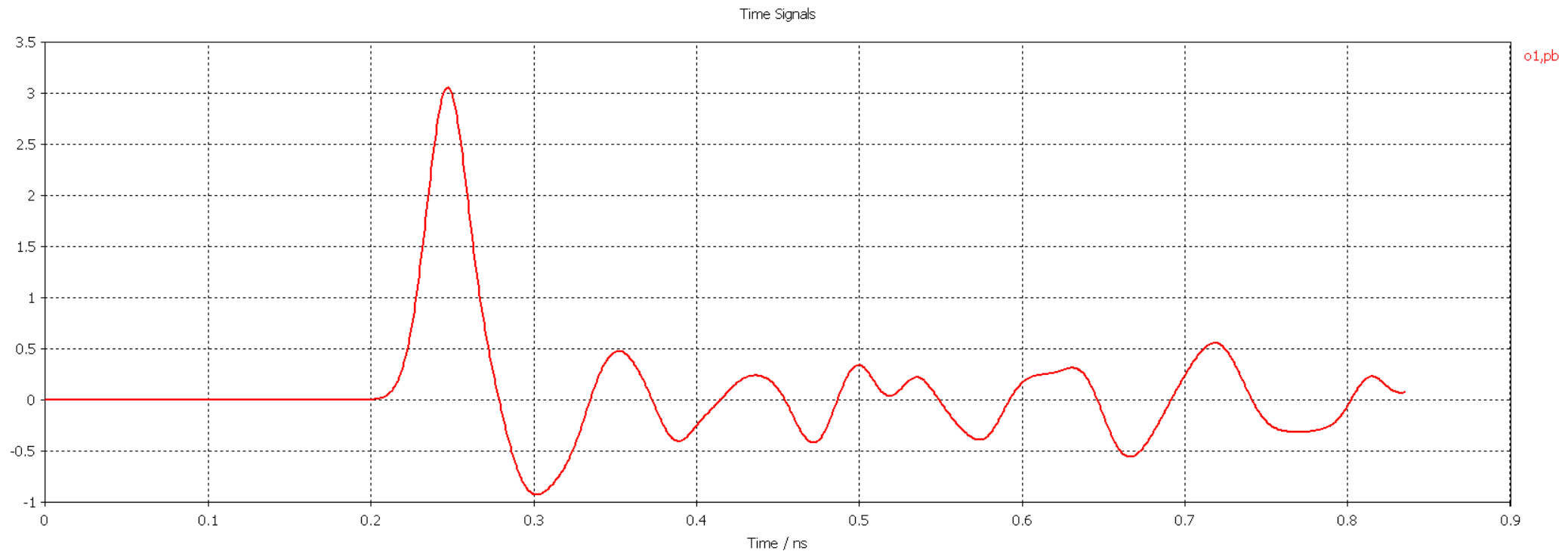


Beam Position - Stripline / Transmission Line Detectors (3)



Beam Position - Stripline / Transmission Line Detectors (4)

CST Particle Studio Simulation



Beam at BPM center

Beam Position - Stripline / Transmission Line Detectors (5)

- Signal at upstream port 1

$$U_1(t) = \frac{1}{2} \cdot \frac{\alpha}{2\pi} \cdot R_1 \left(I_{beam}(t) - I_{beam}(t - 2l/c) \right)$$

- With Gaussian bunch distribution as

$$I_{beam}(t) = I_0 \cdot \exp\left(-t^2/2\sigma_t^2\right)$$

$$U_1(t) = \frac{Z_{strip}}{2} \cdot \frac{\alpha}{2\pi} \left(e^{-t^2/2\sigma_t^2} - e^{-(t-2l/c)^2/2\sigma_t^2} \right) \cdot I_0$$

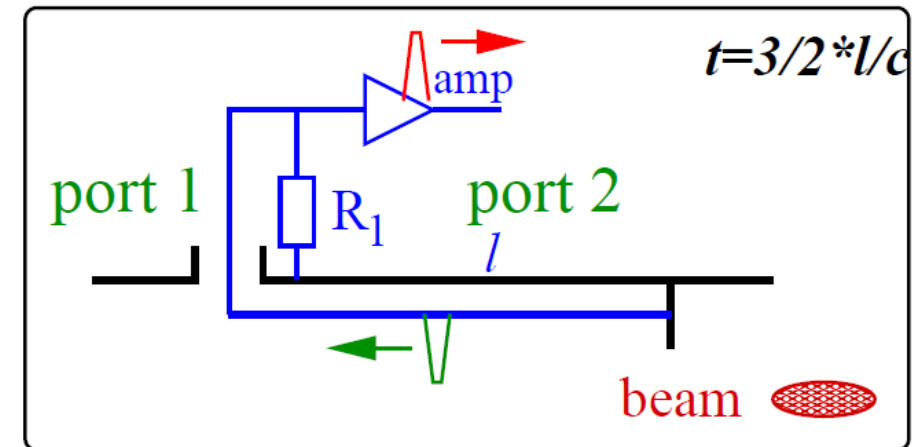
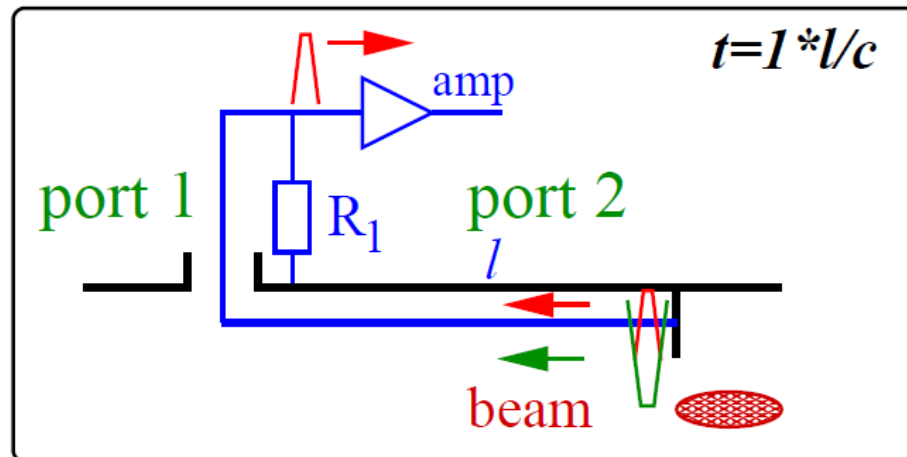
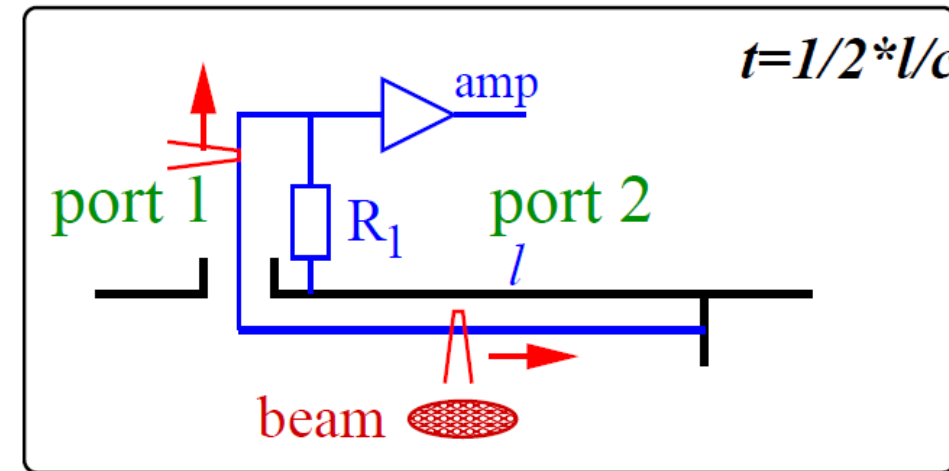
- Transfer impedance

$$Z_t(\omega) = Z_{strip} \cdot \frac{\alpha}{4\pi} \cdot e^{-\omega^2\sigma_t^2/2} \cdot \sin\left(\omega l/c\right) \cdot e^{i(\pi/2 - \omega l/c)}$$

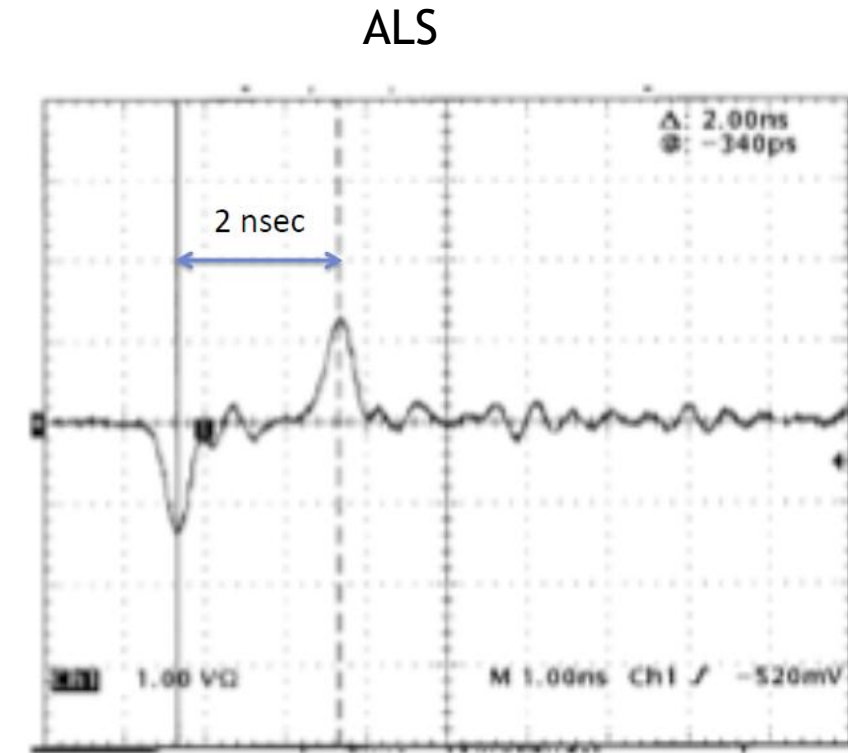
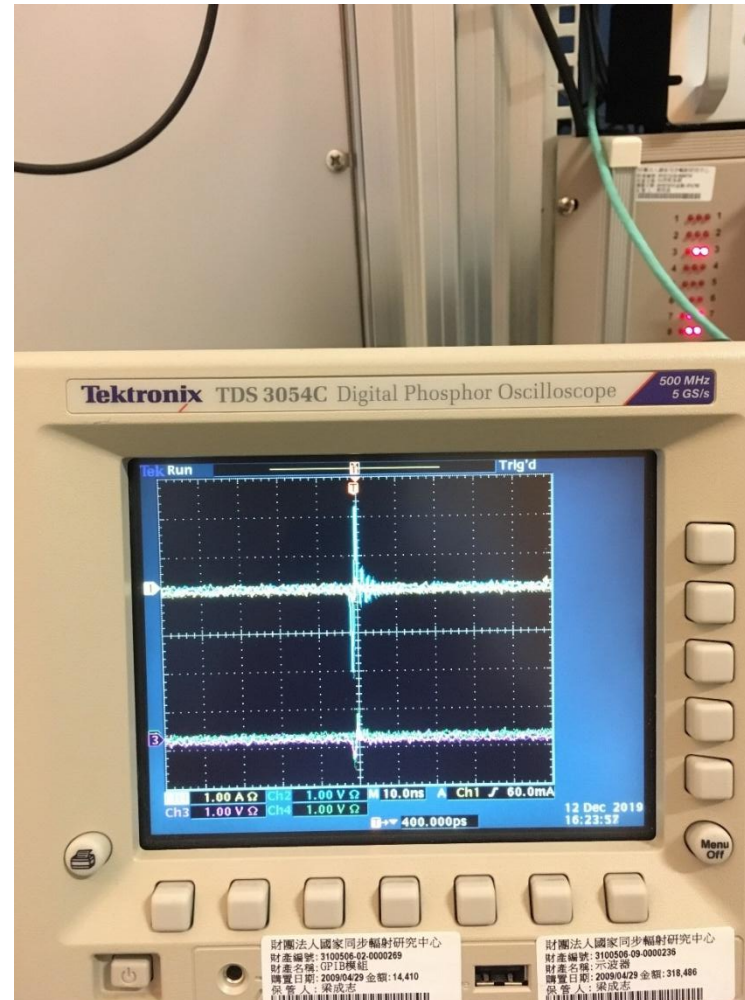
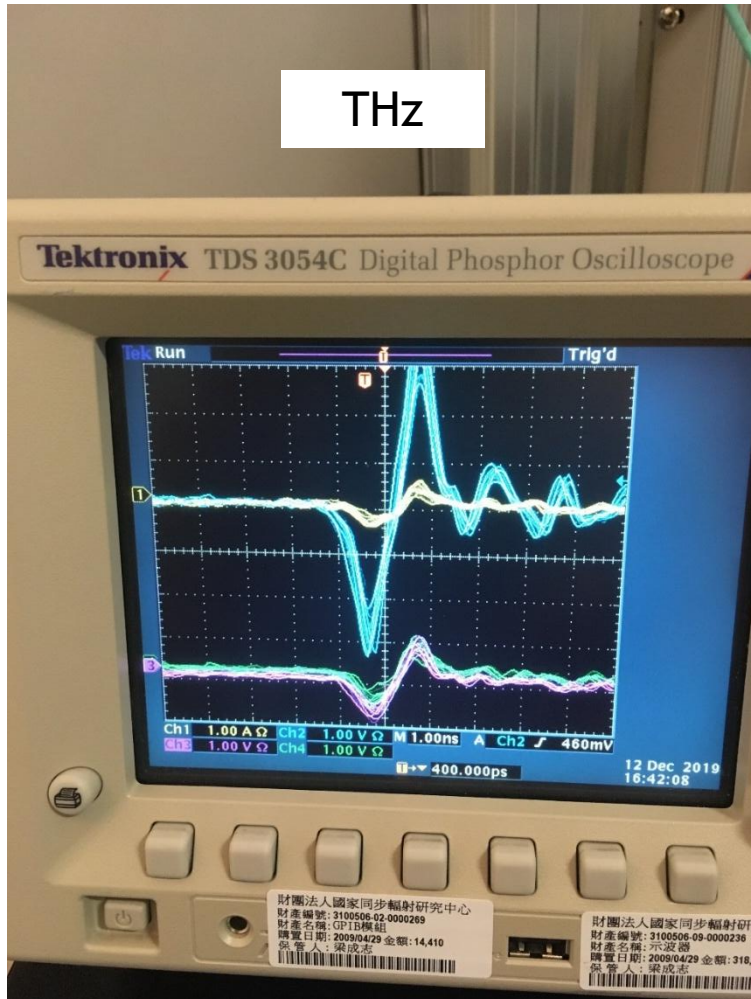
- For very short bunch, $\sigma_t \approx 0$. $|Z_t|$ is composed of a series of maxima for $f_{max} = \frac{c}{4l} \cdot (2n - 1)$ for $n = 1, 2, 3, \dots$
- First maximum is $l = \frac{c}{4f_{acc}} = \frac{\lambda}{4}$, λ is the “wavelength” of bunch repetition.
- Stripline BPM is called quarter wave coupler.
- Coupled line directional coupler

Beam Position - Stripline / Transmission Line Detectors (6)

Downstream Port Shorted Stripline BPM



Beam Position - Stripline / Transmission Line Detectors (7)

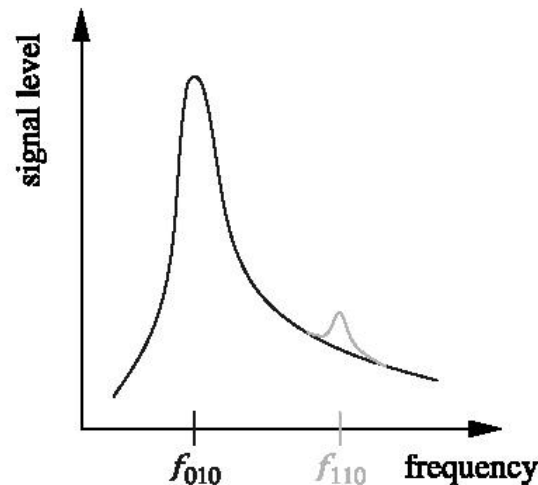
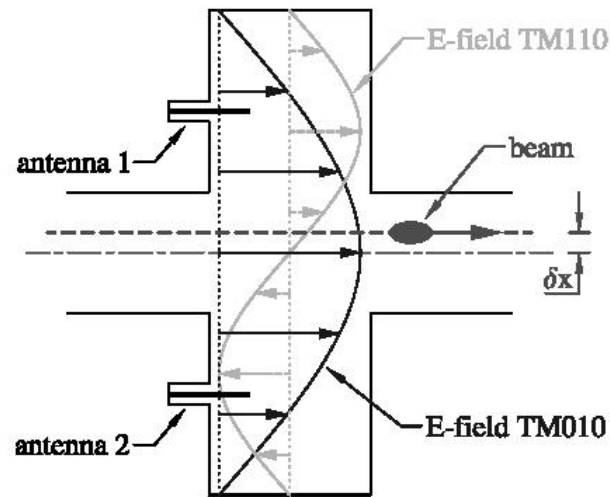


Principle: excitation of discrete modes (depending on bunch charge, position, and spectrum) in a resonant structure; detection of dipole mode signal proportional to bunch charge, qx transverse displacement, δx

Theoretical treatment: based on solving Maxwell's equations for a cylindrical waveguide with perpendicular plates on two ends

Motivation: high sensitivity (signal amplitude / μm displacement) accuracy of absolute position, LCLS design report

dipole mode cavity BPM consists of (usually) a cylindrically symmetric cavity, which is excited by an off-axis beam:



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

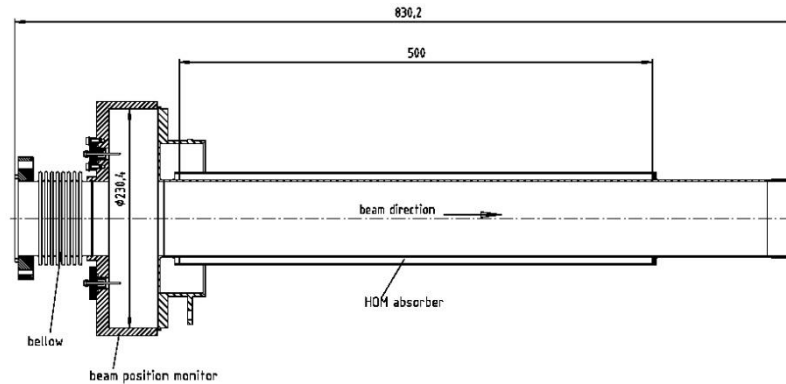
TM_{010} , “common mode” ($\propto I$)
 TM_{110} , dipole mode of interest

} amplitude detected at position of antenna contains contributions from both modes $\rightarrow$ signal processing

$$V_{110}^{out}(\delta x) = V_{110}^{in}(\delta x) \left(\frac{R}{Q}\right)^{-1/2} \sqrt{\frac{50\Omega}{Q_L}} \sqrt{1 - \frac{Q_L}{Q_0}}$$

$$V_{110}^{in} \approx \delta x \cdot q \frac{l T_{tr}^2}{r^3} \cdot 0.2474$$

$$T_{tr} = \frac{\sin \eta}{\eta} \quad \text{with} \quad \eta = \frac{\pi l}{\lambda_{mn0}}$$



schematic of
a “cold” cavity
BPM tested at
TTF I (Lorenz)

for the TTF cavity BPM:

$$r = 115.2 \text{ mm}$$

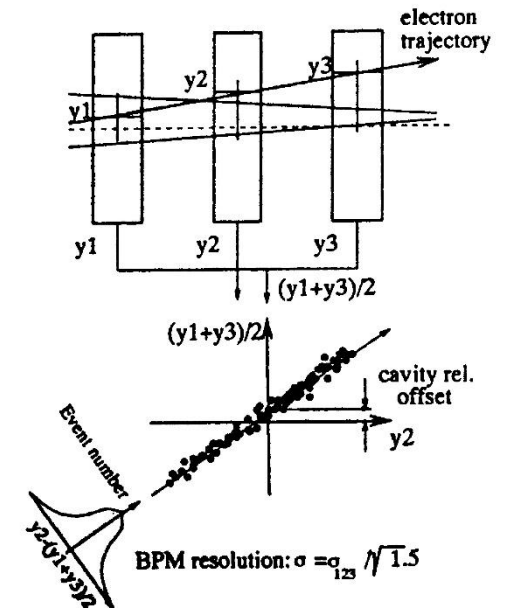
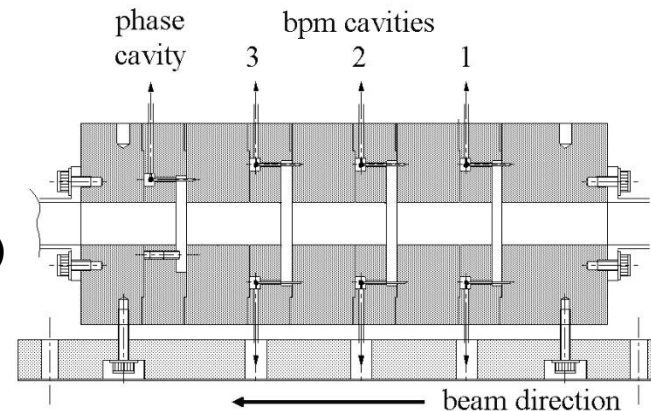
$$L = 52 \text{ mm}$$

$$\rightarrow V_{110}^{out} \sim 115 \text{ mV/mm for } 1 \text{ nC}$$

T_{tr} transit time factor
 (R/Q) geometrical property of cavity
 Q_0, Q_L unloaded and loaded Q-factors
 L cavity length
 r cavity radius
 λ_{mn0} wavelength of mode of interest
 δx transverse displacement

pioneering experiments: 3
 C-band cavity “RF” BPMs in
 series at the FFTB (SLAC)
 $\rightarrow 25 \text{ nm}$ position resolution
 at 1 nC bunch charge

(courtesy, T. Shintake, 2003)



$$X = \frac{(V_1 + V_4) - (V_2 + V_3)}{V_1 + V_2 + V_3 + V_4} \quad Y = \frac{(V_1 + V_2) - (V_3 + V_4)}{V_1 + V_2 + V_3 + V_4}$$

$$x \cong K_x X, \quad y \cong K_y Y \quad (\text{for } \sqrt{x^2 + y^2} \ll R)$$

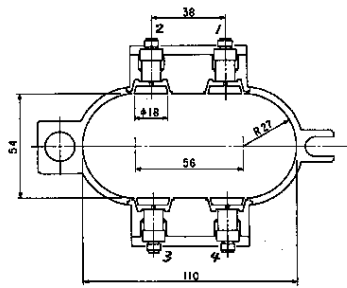


図3-11 トリスタンMRのビーム位置モニタの位置マップ (境界要素法)

(T.Shintake et al. NIM A254(1987) 146より転載)

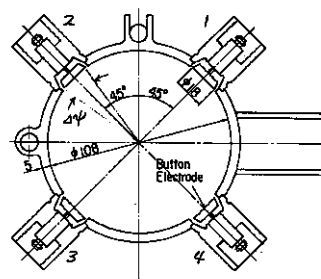
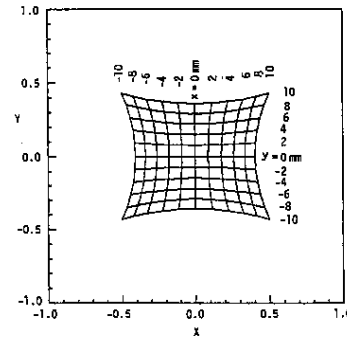


図3-9 静電誘導ピックアップ型ビーム位置モニタ (トリスタンAR) および

位置マップ (境界要素法) (T.Shintake et al. NIM A254(1987) 146 より転載)

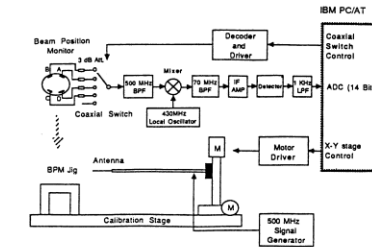
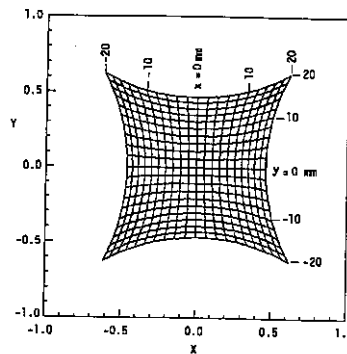


Figure 10 BPM calibration system.

$$H = \frac{(A+C)-(B+D)}{A+B+C+D} \quad (21a)$$

and

$$V = \frac{(A+B)-(C+D)}{A+B+C+D} \quad (21b)$$

$$X = K_x H \quad (22a)$$

$$Y = K_y V \quad (22b)$$

$$X = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} a_{m,n} H^{m-n} V^n \quad (23a)$$

$$Y = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} b_{m,n} H^{m-n} V^n \quad (23b)$$

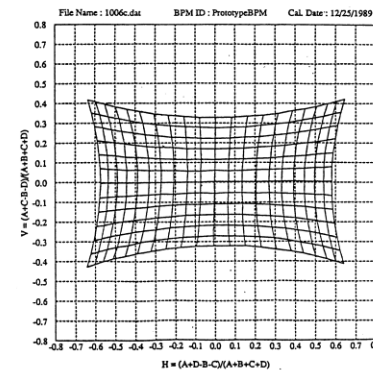


Figure 12 Normalized signal plot of 20 mm x 12 mm area.

$$X = a_0 + a_1 H + a_2 V + a_3 H^2 + a_4 H V + a_5 V^2 + a_6 H^3 + a_7 H^2 V + a_8 H V^2 + a_9 V^3 + a_{10} H^4 + a_{11} H^3 V + a_{12} H^2 V^2 + a_{13} H V^3 + a_{14} V^4 \quad (24a)$$

$$Y = b_0 + b_1 H + b_2 V + b_3 H^2 + b_4 H V + b_5 V^2 + b_6 H^3 + b_7 H^2 V + b_8 H V^2 + b_9 V^3 + b_{10} H^4 + b_{11} H^3 V + b_{12} H^2 V^2 + b_{13} H V^3 + b_{14} V^4 \quad (24b)$$

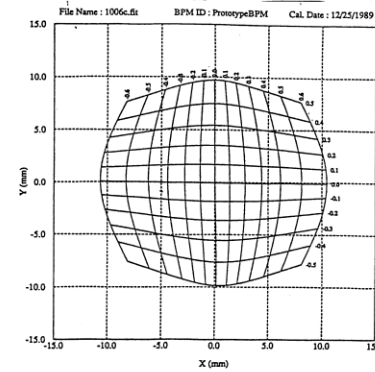


Figure 13 Fitting results of prototype BPM.

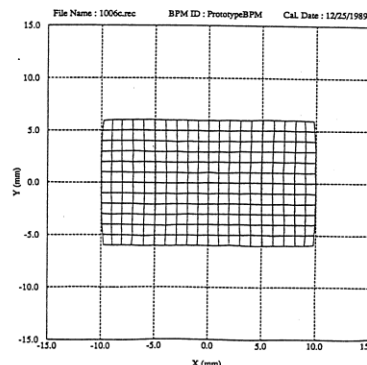
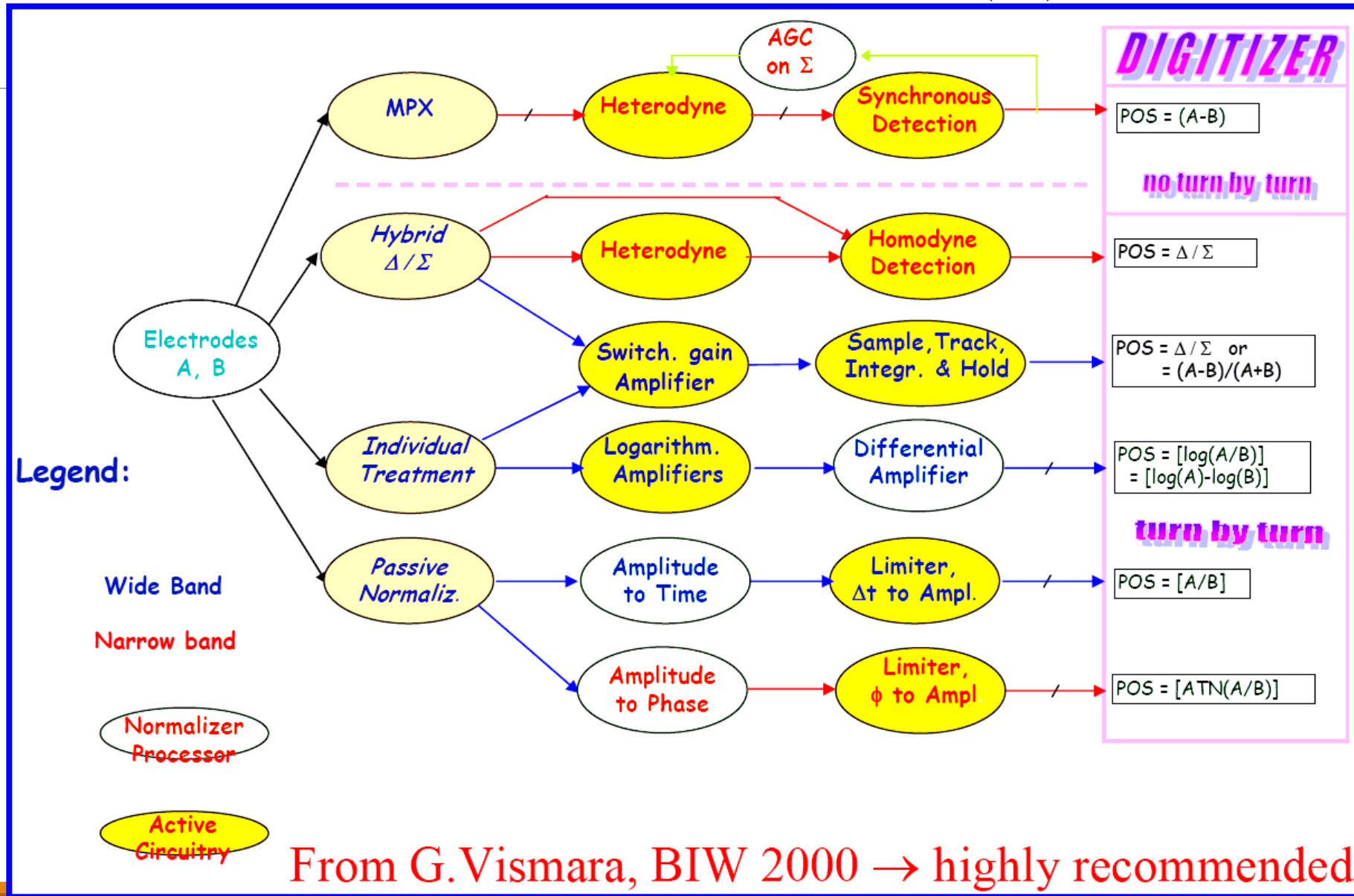
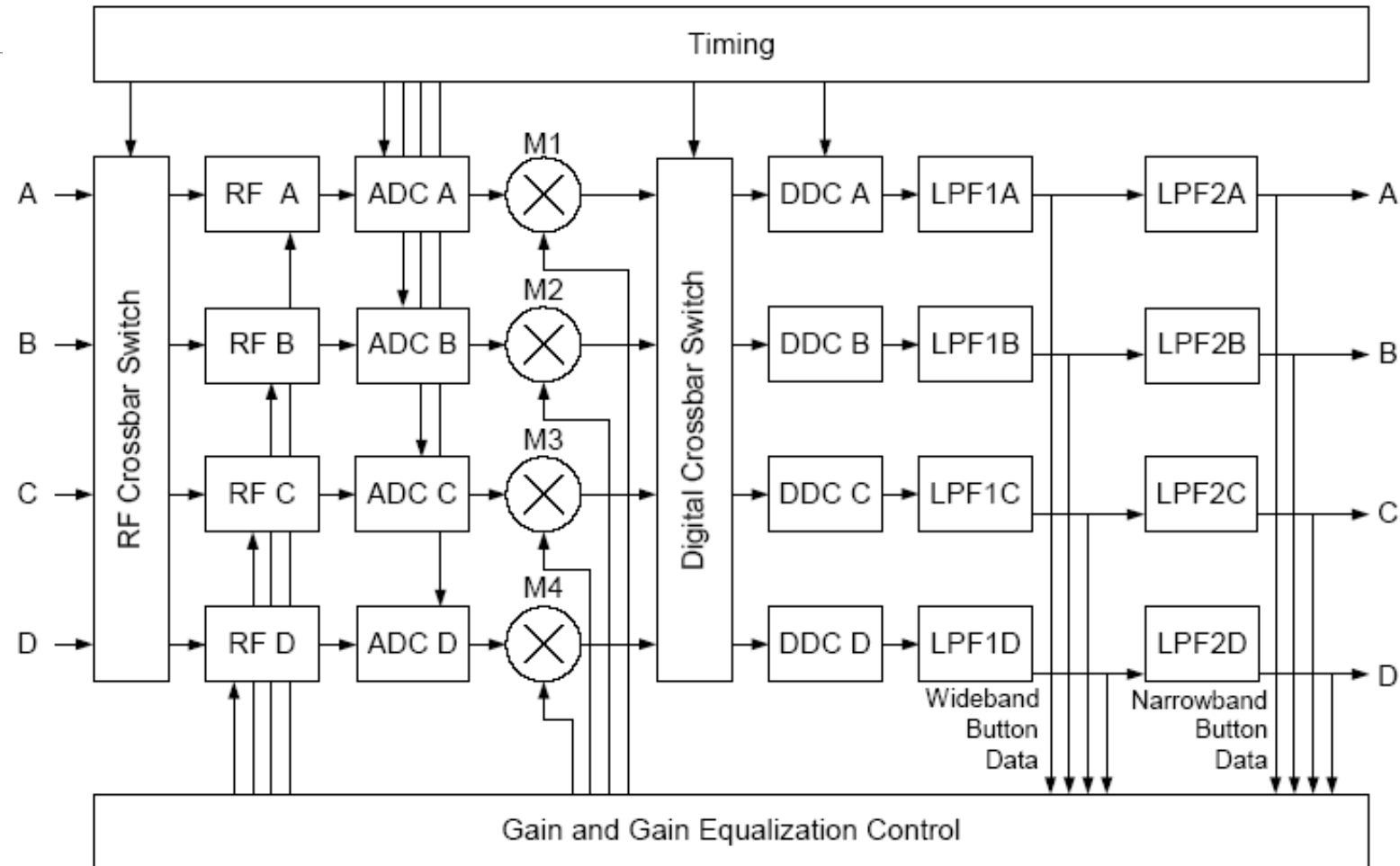


Figure 14 Data reconstruction for 20 mm x 12 mm area.

BPM - Electronics (1)



BPM - Electronics (2)

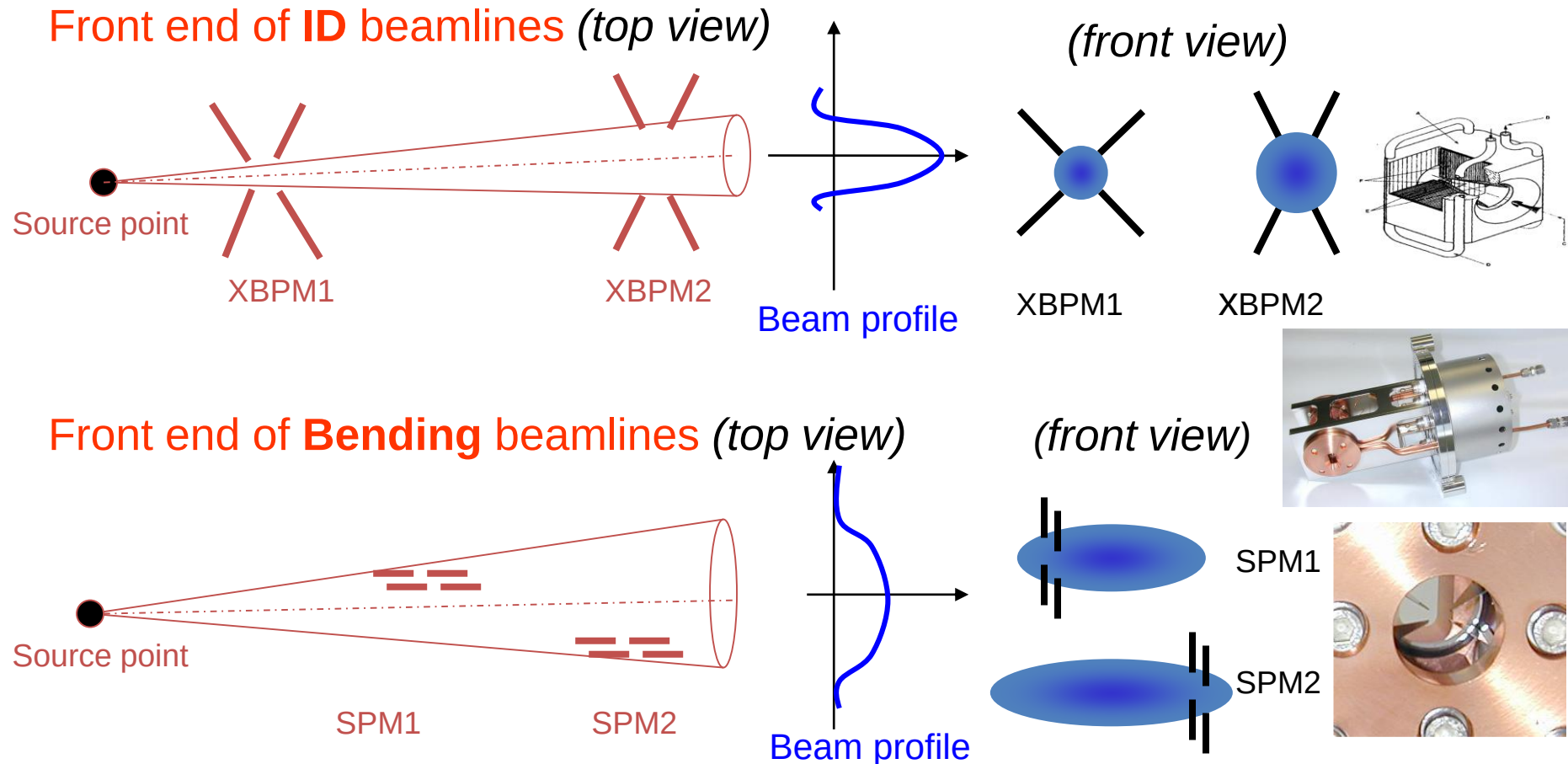


How to calibrate?
=> Quasi-crossbar scheme

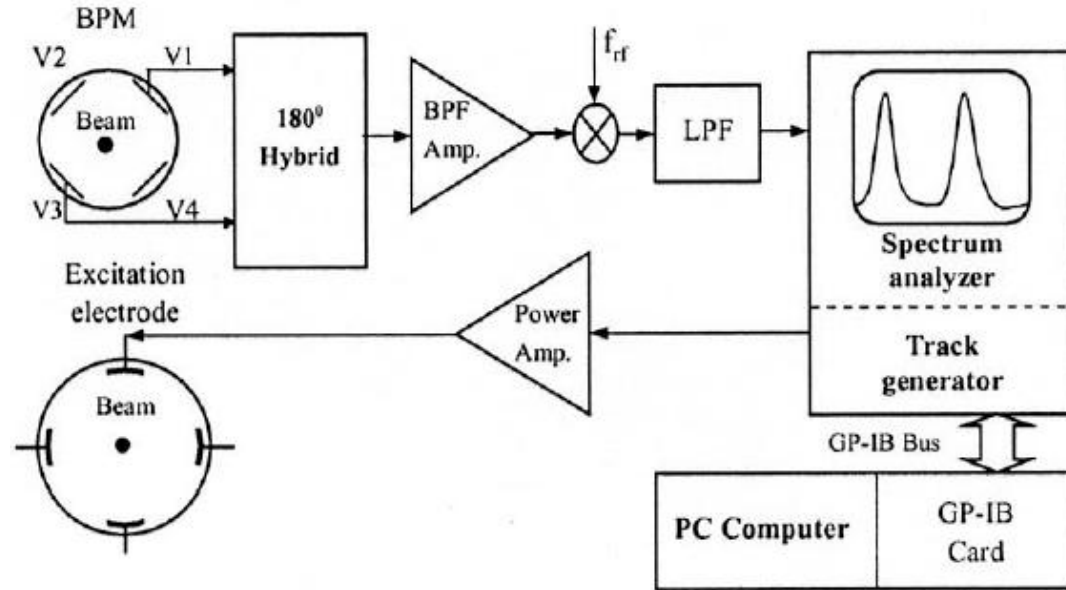
Beam Position Monitor -- Photon BPM

What are the XBPMs?

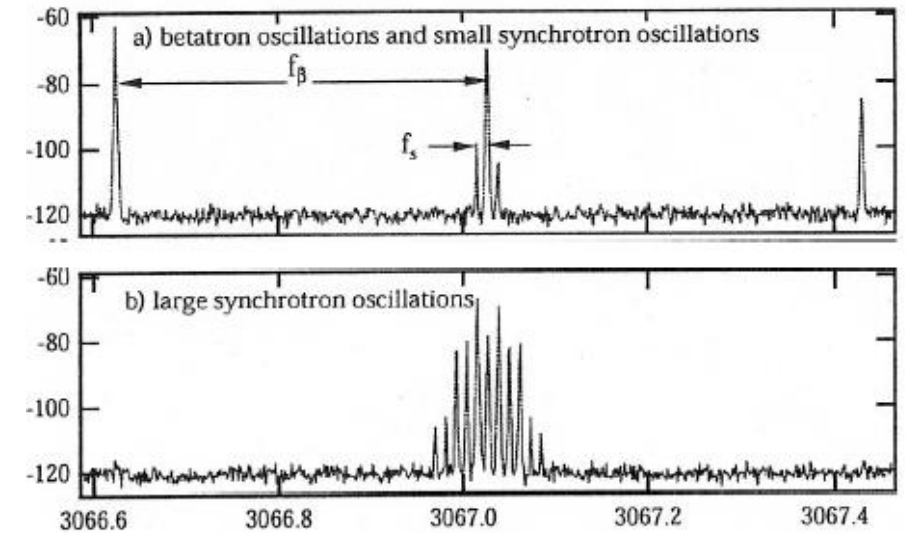
- principle: 4 blades of Tungsten/Diamond read the tails of the photon beam. Beam position deduced by asymmetries. Design of K. Holldack (BESSY), produced by FMB (Berlin).



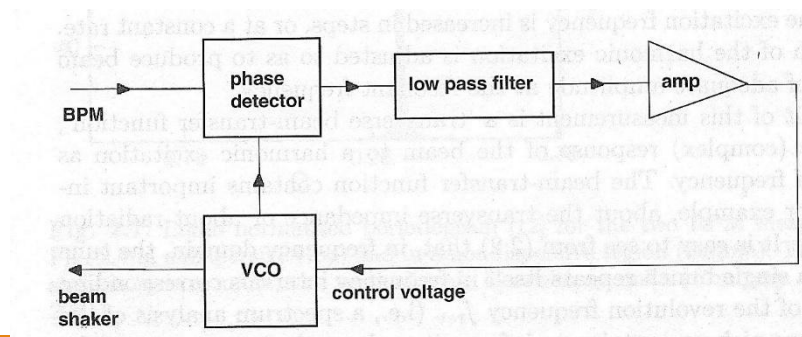
Tune Measurement (1)



HLS Tune Measurement



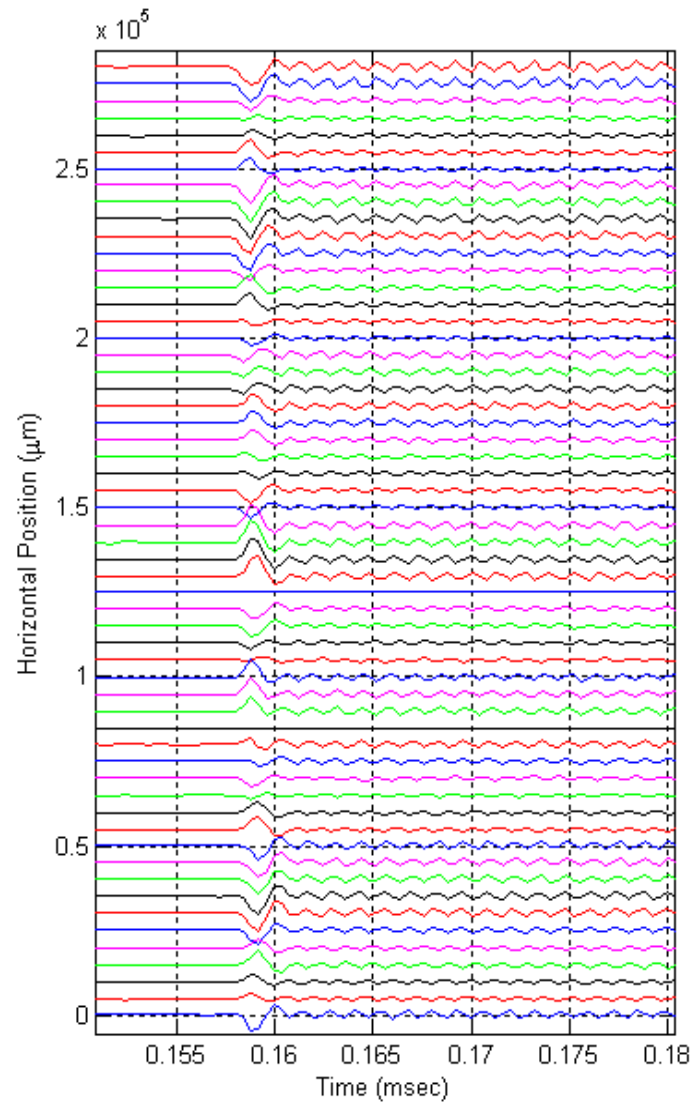
Typical ALS Beam Spectrum



More on spectrum

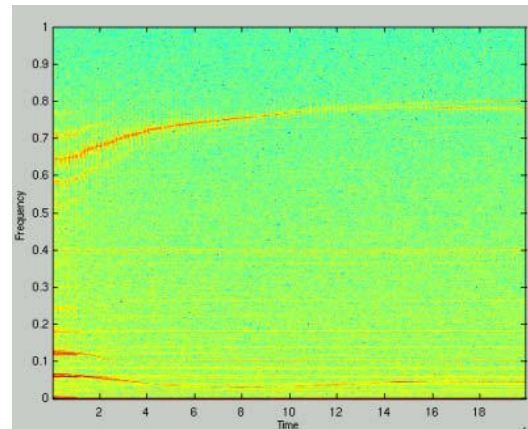
Tune measurements play an important role in many storage ring measurements.

- Turn by turn measurements, FFT, Interpolated FFT, NAFF, ...
- Betatron phase measurement (transverse dynamics)
- Nonlinear dynamics (tune vs. amplitude; tune vs. closed orbit)
- Impedance measurements
- Beta function measurements
- Chromaticity
- Momentum compaction factor

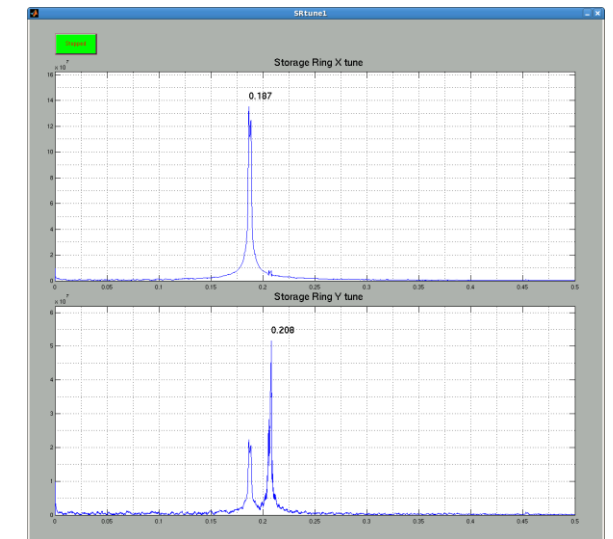


TLS Turn-by-turn data

SSRF Booster Tune Evolution

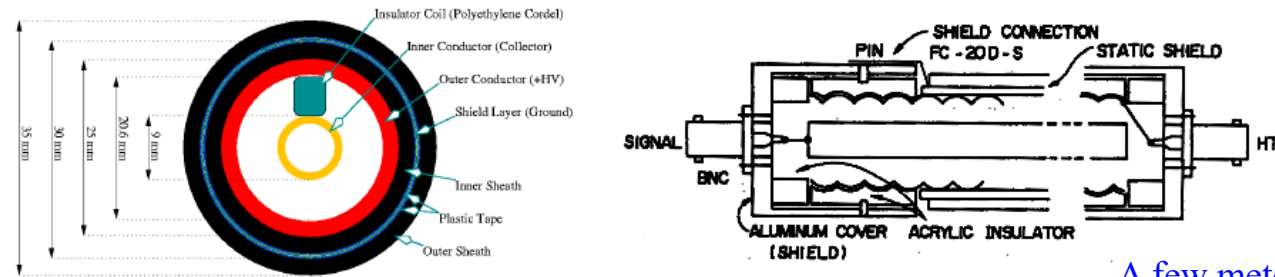


SSRF Storage Ring Tune Monitor



Beam Loss Monitor (1)

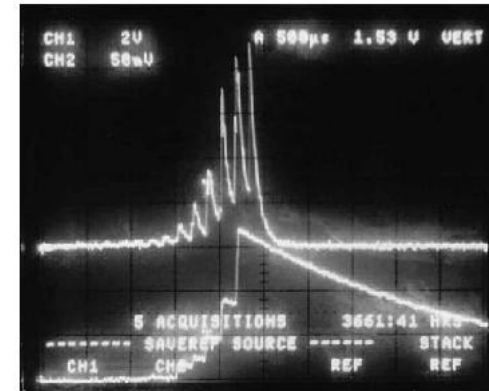
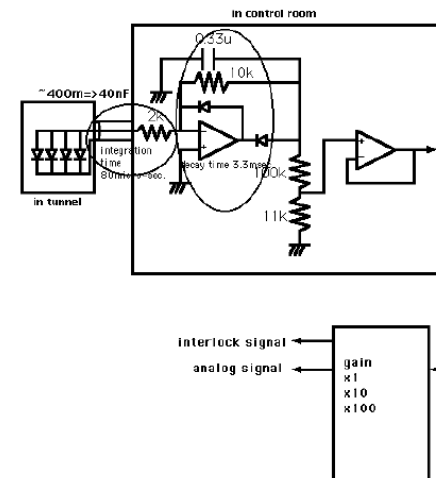
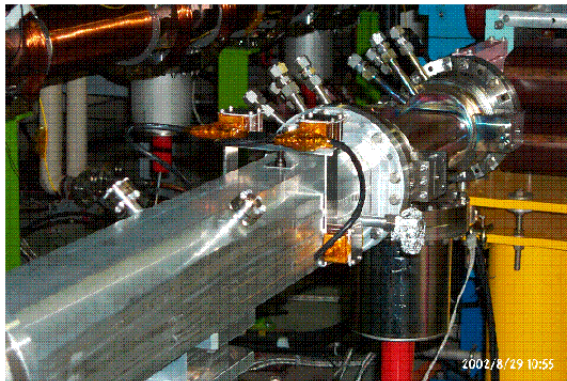
Ionization Chamber — (~100 around tunnel & 23 along BT): response ~msec



A few meter long typically

図5-1 FC-20D-S 中空導軸ケーブルを利用した空気イオンチェンバー

PIN Photodiode (at moving masks): response ~20-80nsec



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).

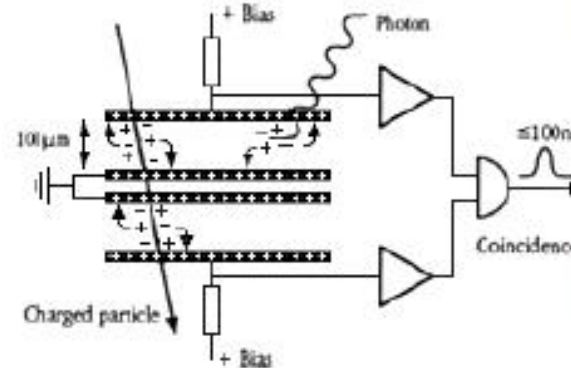
Bergoz PIN diodes generate pulses when from ionizing particles.

- Beam lifetime includes
 - Quantum lifetime
 - Inelastic scattering
 - Touschek lifetime
- Beam lifetime, esp. quantum lifetime became much more worse due to operators' changing the running parameters

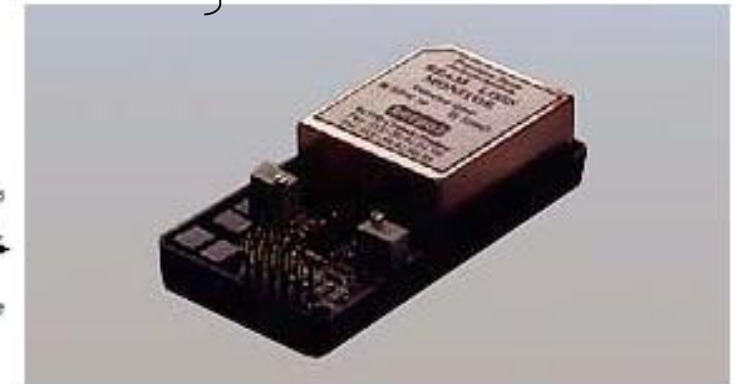
A scintillator with a photomultiplier is another commonly used BLM.

Beam loss monitor is an elegant tool for various beam physics study, e.g. tune scan

Operating principle



Loss
mechanism
study



Yuxiong Li,
et al.
(HLS)

Measurement of the Transverse Beam Emittance

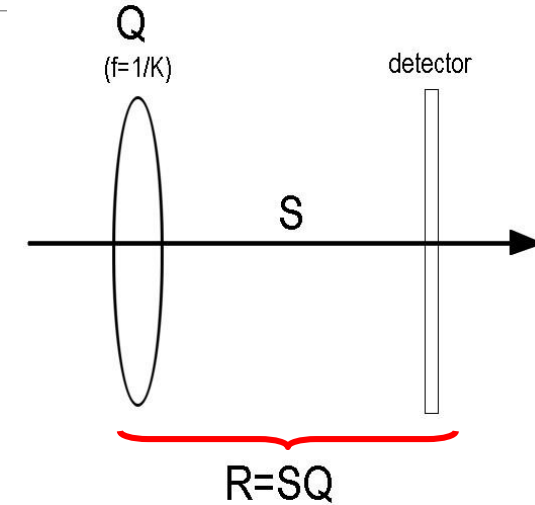
Method I: quadrupole scan

Principle: with a well-centered beam, measure the beam size as a function of the quadrupole field strength

Here

Q is the transfer matrix of the quadrupole

R is the transfer matrix between the quadrupole and the beam size detector



With $Q = \begin{pmatrix} 1 & 0 \\ K & 1 \end{pmatrix}$ then $R = \begin{pmatrix} S_{11} + KS_{12} & S_{12} \\ S_{21} + KS_{22} & S_{22} \end{pmatrix}$ with $\Sigma_{\text{beam}} = R\Sigma_{\text{beam},0}R^t$

The (11)-element of the beam transfer matrix is found after algebra to be:

$$\begin{aligned} \Sigma_{11}(= \langle x^2 \rangle) = & (S_{11}^2 \Sigma_{11_0} + 2S_{11}S_{12} \Sigma_{12_0} + S_{12}^2 \Sigma_{22_0}) \\ & + (2S_{11}S_{12} \Sigma_{11_0} + 2S_{12}^2 \Sigma_{12_0})K + S_{12}^2 \Sigma_{11_0}K^2 \end{aligned}$$

which is quadratic in the field strength, K

Measurement: measure beam size versus quadrupole field strength

data:

again:

$$\Sigma_{11}(=\langle x^2 \rangle) = (S_{11}^2 \Sigma_{11_0} + 2S_{11}S_{12}\Sigma_{12_0} + S_{12}^2 \Sigma_{22_0}) + (2S_{11}S_{12}\Sigma_{11_0} + 2S_{12}^2 \Sigma_{12_0})K + S_{12}^2 \Sigma_{11}K^2$$

fitting function (parabolic):

$$\begin{aligned} \Sigma_{11} &= A(K - B)^2 + C \\ &= AK^2 - 2ABK + (C + AB^2) \end{aligned}$$

equating terms (drop subscripts 'o'),

$$A = S_{12}^2 \Sigma_{11},$$

$$-2AB = 2S_{11}S_{12}\Sigma_{11} + 2S_{12}^2 \Sigma_{12},$$

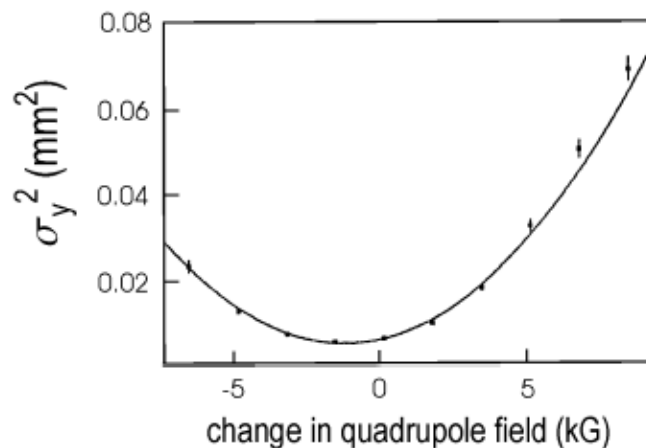
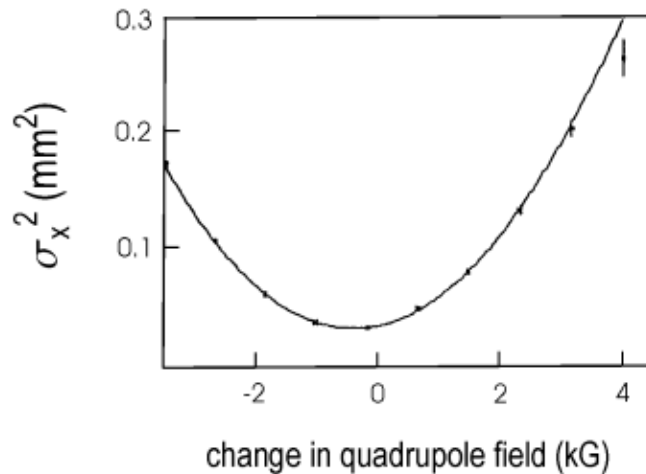
$$C + AB^2 = S_{11}^2 \Sigma_{11} + 2S_{11}S_{12}\Sigma_{12} + S_{12}^2 \Sigma_{22}$$

solving for the beam matrix elements:

$$\Sigma_{11} = A/S_{12}^2,$$

$$\Sigma_{12} = -\frac{A}{S_{12}^2} \left(B + \frac{S_{11}}{S_{12}} \right),$$

$$\Sigma_{22} = \frac{1}{S_{12}^2} \left[(AB^2 + C) + 2AB \left(\frac{S_{11}}{S_{12}} \right) + A \left(\frac{S_{11}}{S_{12}} \right)^2 \right]$$



Measurement of the Transverse Beam Emittance

The (here, horizontal) emittance is given from the determinant of the beam matrix:

$$\epsilon_x = \sqrt{\det \Sigma_{\text{beam}}^x}$$

$$\begin{aligned} \det \Sigma_{\text{beam}}^x &= \Sigma_{11}\Sigma_{22} - \Sigma_{12}^2 \\ &= AC/S_{12}^4, \end{aligned}$$

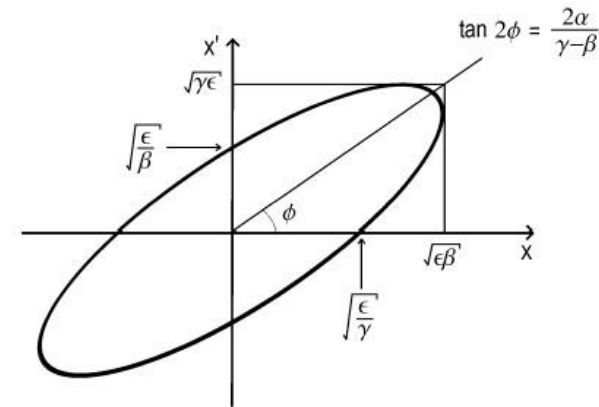
$$\rightarrow \epsilon_x = \sqrt{AC}/S_{12}^2$$

With these 3 fit parameters (A,B, and C), the 3 Twiss parameters are also known:

$$\beta_x = \frac{\Sigma_{11}}{\epsilon} = \sqrt{\frac{A}{C}},$$

$$\alpha_x = -\frac{\Sigma_{12}}{\epsilon} = \sqrt{\frac{A}{C}} \left(B + \frac{S_{11}}{S_{12}} \right),$$

$$\gamma_x = \frac{S_{12}^2}{\sqrt{AC}} \left[(AB^2 + C) + 2AB \left(\frac{S_{11}}{S_{12}} \right) + A \left(\frac{S_{11}}{S_{12}} \right)^2 \right]$$



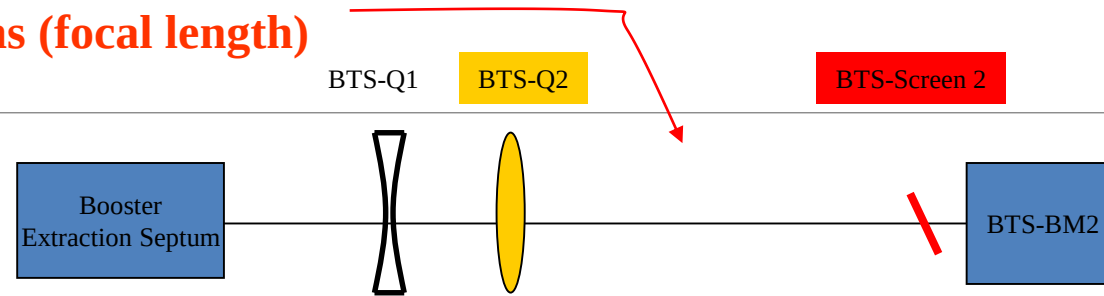
as a useful check, the beam-ellipse parameters should satisfy $(\beta_x \gamma_x - 1) = \alpha_x^2$

1. Variable Quadrupole Strengths (focal length)

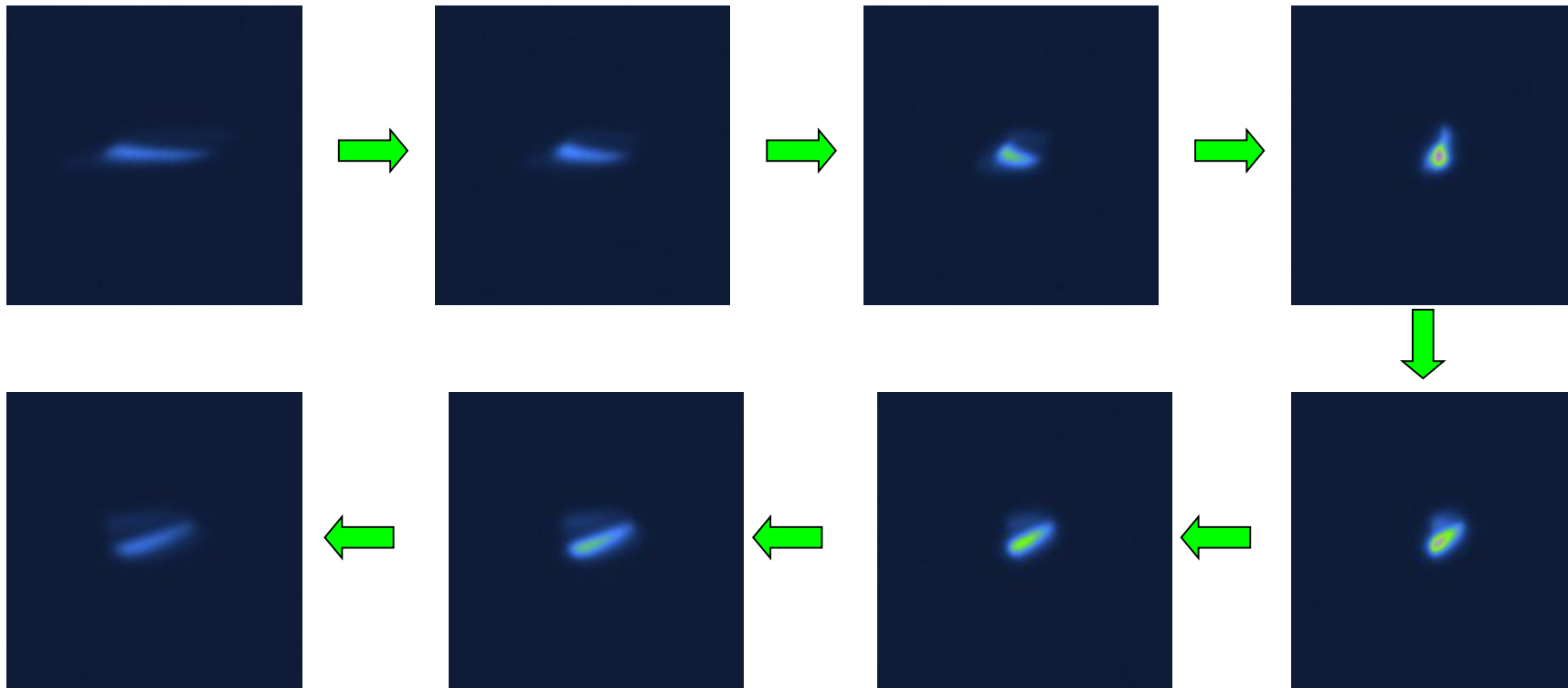
2. Multiple Profile Monitors

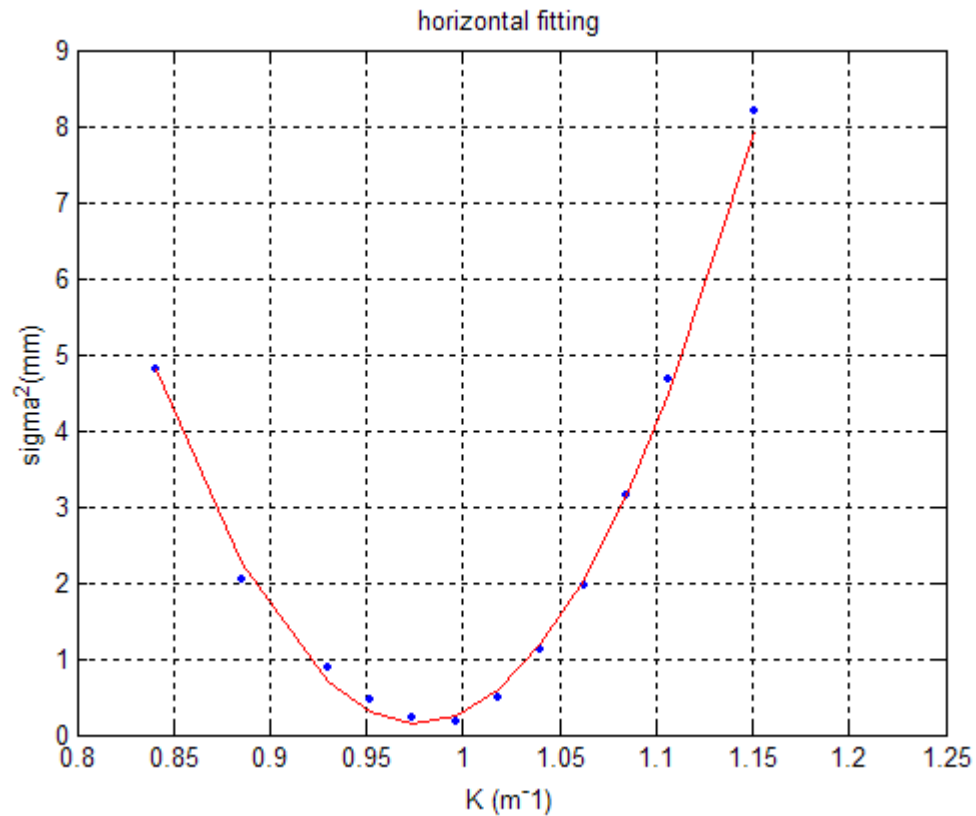
3. The “Pepper-Pot” Technique

4. ...



Quad Scan Method





A: 255.22

B: 0.98

C: 0.15

S_{12} : 5.109

$$\varepsilon_x = \sqrt{AC} / S_{12}^2$$

Emittance Fitting Equation

$$\sum_{11} = \langle \sigma^2 \rangle = A(K - B)^2 + C$$

Beam emittance = 238.3 nm.rad

Method II: fixed optics, measure beam size using multiple measurement devices

Recall: the matrix used to transport the Twiss parameters:

$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_f = \begin{pmatrix} R_{11}^2 & -2R_{11}R_{12} & R_{12}^2 \\ -R_{11}R_{21} & 1 + 2R_{12}R_{21} & -R_{12}R_{22} \\ R_{21}^2 & -2R_{21}R_{22} & R_{22}^2 \end{pmatrix}_{fi} \begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_i$$

with fixed optics and multiple measurements of σ at different locations:

subscripts: matrix elements
superscripts: "measurement number"

$$\underbrace{\begin{pmatrix} (\sigma_x^{(1)})^2 \\ (\sigma_x^{(2)})^2 \\ (\sigma_x^{(3)})^2 \\ \dots \\ (\sigma_x^{(n)})^2 \end{pmatrix}}_{\Sigma_x} = \underbrace{\begin{pmatrix} (R_{11}^{(1)})^2 & 2R_{11}^{(1)}R_{12}^{(1)} & (R_{12}^{(1)})^2 \\ (R_{11}^{(2)})^2 & 2R_{11}^{(2)}R_{12}^{(2)} & (R_{12}^{(2)})^2 \\ (R_{11}^{(3)})^2 & 2R_{11}^{(3)}R_{12}^{(3)} & (R_{12}^{(3)})^2 \\ \dots & \dots & \dots \\ (R_{11}^{(n)})^2 & 2R_{11}^{(n)}R_{12}^{(n)} & (R_{12}^{(n)})^2 \end{pmatrix}}_{\mathbf{B}} \underbrace{\begin{pmatrix} \beta(s_0)\epsilon \\ -\alpha(s_0)\epsilon \\ \gamma(s_0)\epsilon \end{pmatrix}}_{\mathbf{o}}$$

simplify notation:
 $\Sigma_x = \mathbf{B} \cdot \mathbf{o}$

goal is to determine the vector $\mathbf{o}$ by minimizing the sum (least squares fit):

$$\chi^2 = \sum_{l=1}^n \frac{1}{\sigma_{\Sigma_x}^{(l)}} \left(\Sigma_x^{(l)} - \sum_{i=1}^3 B_{li} o_i \right)^2$$

with the symmetric $n \times n$ covariance matrix, $\mathbf{T} = (\hat{\mathbf{B}}^t \cdot \hat{\mathbf{B}})^{-1}$

→ the least-squares solution is $\mathbf{o} = \mathbf{T} \cdot \hat{\mathbf{B}}^t \cdot \hat{\Sigma}_x$

(the 'hats' show weighting: $\hat{B}_{li} = \frac{B_{li}}{\sigma_{\Sigma_x}^{(l)}}$ $\hat{\Sigma}_x^{(l)} = \frac{\Sigma_x^{(l)}}{\sigma_{\Sigma_x}^{(l)}}$)

Methods of Emittance Measurement

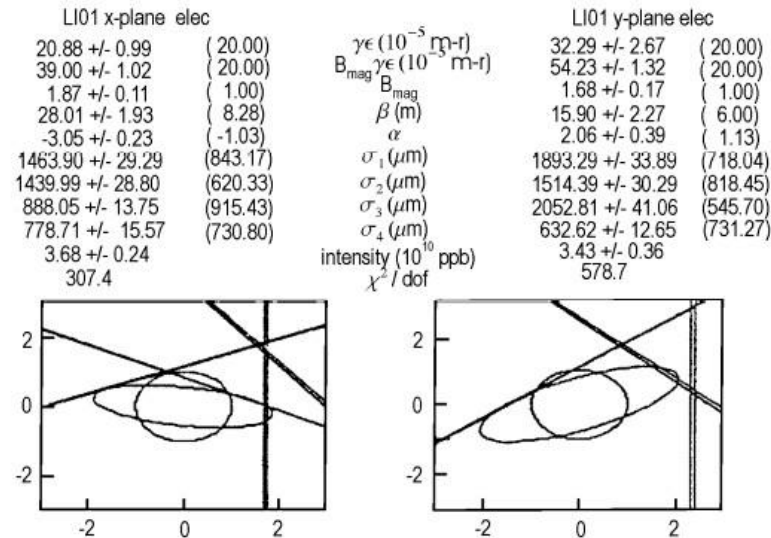
graphical representation of results:

once the components of σ are known,

$$\epsilon = \sqrt{\sigma_1 \sigma_3 - \sigma_2^2},$$

$$\beta = \sigma_1 / \epsilon, \text{ and}$$

$$\alpha = -\sigma_2 / \epsilon.$$



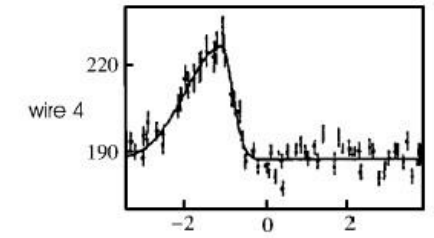
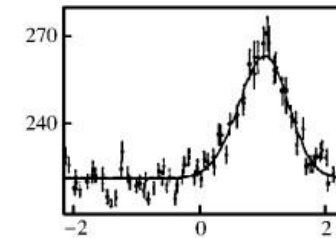
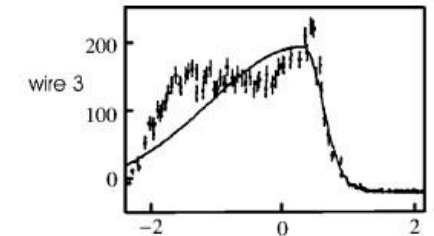
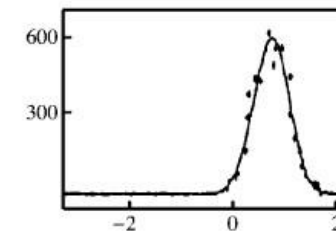
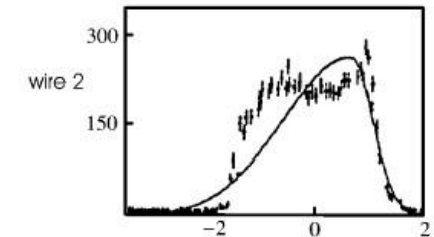
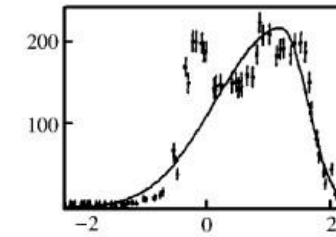
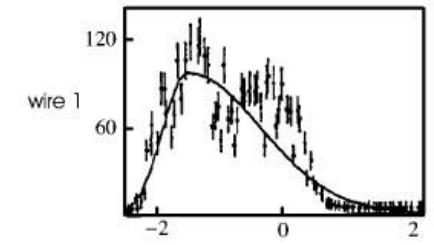
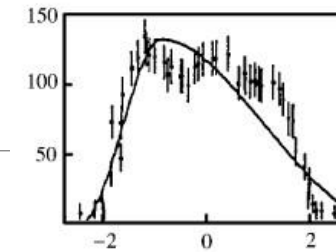
note: coordinate axes are so normalized (design phase ellipse is a circle):

$$\left(\frac{x}{\sqrt{\beta_x}}, \frac{\alpha_x x + \beta_x x'}{\sqrt{\beta_x}} \right)$$

lines show phase space coverage of wires:

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{\text{ref point}} = R^{-1} \begin{pmatrix} \sigma_{x,w} \\ x'_w \end{pmatrix}$$

With methods I & II, the beam sizes may be measured using e.g. screens or wires



horizontal position (mm)

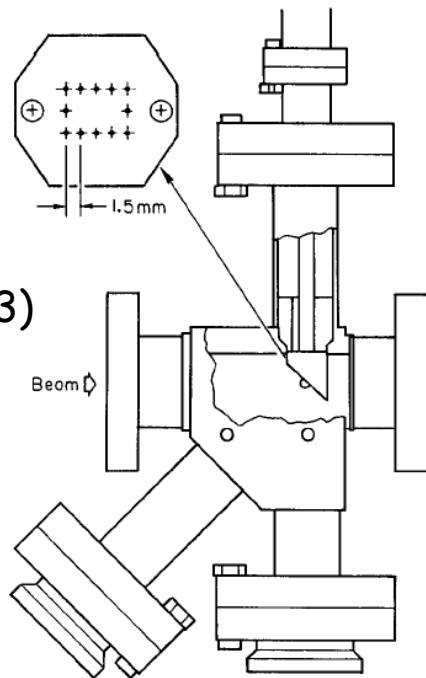
vertical position (mm)

principle: intercepting screen (e.g. $\text{Al}_2\text{O}_3\text{Cr}$ possibly with phosphorescent coating)
inserted into beam path (usually 45°); image viewed by camera $\rightarrow$ direct
observation of x-y ($\eta = 0$) or y- δ ($\eta \neq 0$) distribution

R. Jung et al, "Single
pass optical profile
monitoring"
(DIPAC 2003)

fluorescence - light emitted ($t \sim 10$ ns) as excited atoms decay to ground state
phosphorescence - light continues to emit ($\sim \mu\text{s}$) after exciting mechanism has ceased (i.e. oscilloscope "afterglow")
luminescence - combination of both processes

(courtesy P. Tenenbaum, 2003)



emittance measurement

image is digitized, projected, fitted with Gaussian
calibration: often grid lines directly etched
onto screen or calibration holes drilled, either
with known spacing

issues

spatial resolution ($20\text{-}30 \mu\text{m}$) given by phosphor
grain size and phosphor transparency
temporal resolution - given by decay time
radiation hardness of screen and camera
dynamic range (saturation of screen)

Screen Types

→ Luminescence Screens

destructive (thick) but work during setting-up with low intensities

→ Optical Transition Radiation (OTR) screens

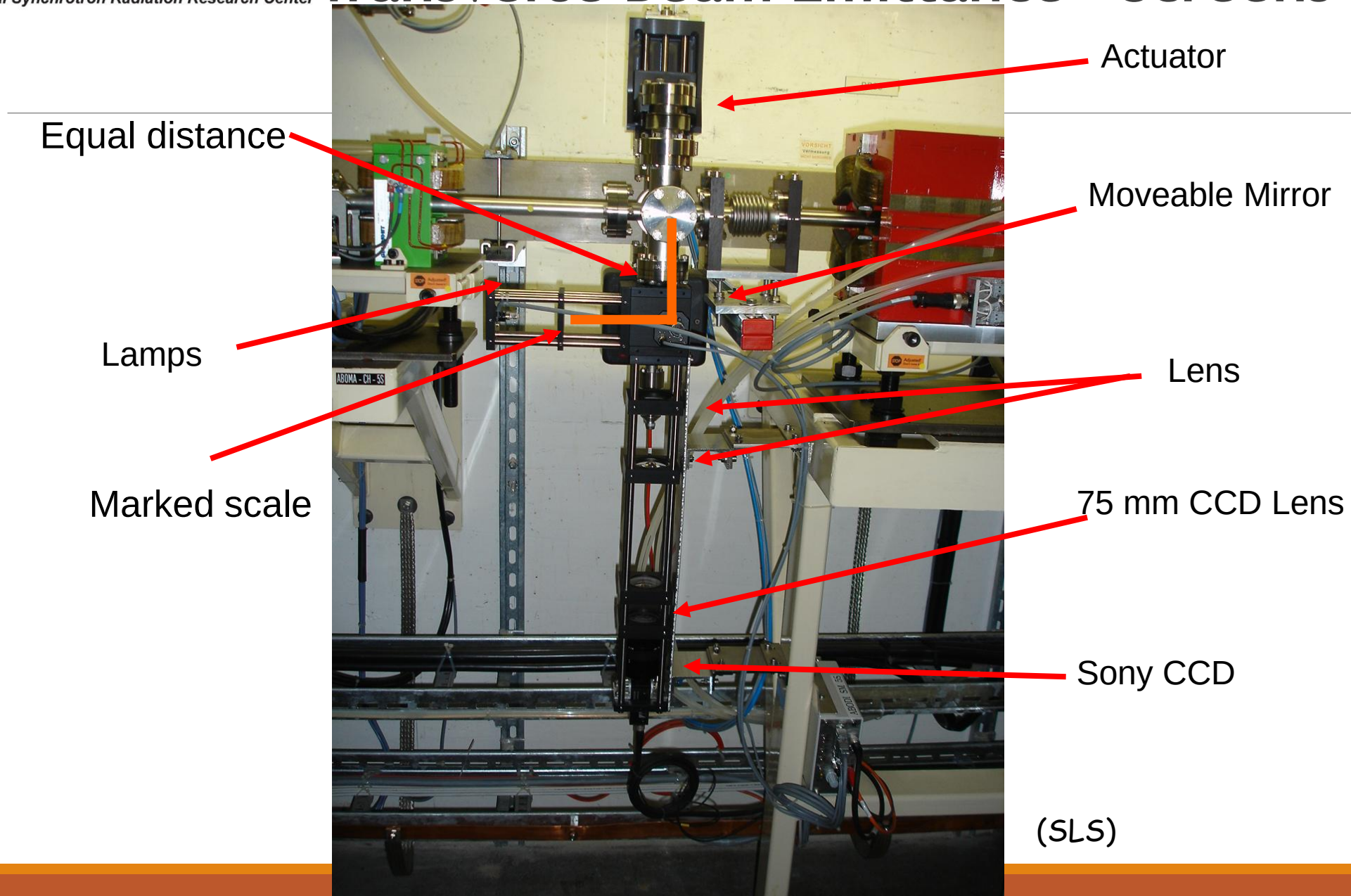
much less destructive (thin) but require high intensity

Sensitivities measured with protons with previous screen holder,
normalised for $7 \text{ px}/\sigma$



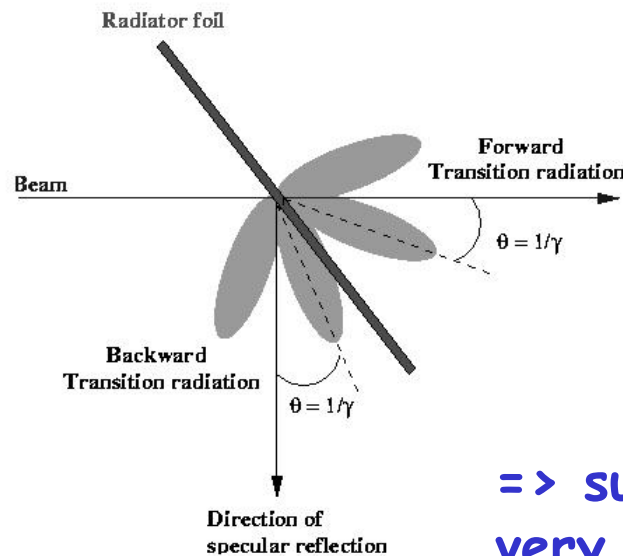
Type	Material	Activator	Sensitivity
Luminesc.	CsI	Tl	$6 \cdot 10^5$
++	Al_2O_3	0.5%Cr	$3 \cdot 10^7$
++	Glass	Ce	$3 \cdot 10^9$
++	Quartz	none	$6 \cdot 10^9$
OTR [bwd]	Al		$2 \cdot 10^{10}$
++	Ti		$2 \cdot 10^{11}$
++	C		$2 \cdot 10^{12}$
Luminesc. GSI	P43: $\text{Gd}_2\text{O}_2\text{S}$	Tb	$2 \cdot 10^7$





Transverse Beam Emittance - Transition Radiation (1)

principle: when a charged particle crosses between two materials of different dielectric constant (e.g. between vacuum and a conductor), transition radiation is generated, temporal resolution is ~ 1 ps $\rightarrow$ useful for high bunch repetition frequencies



forward and backward transition radiation with foil at 45° allowing for simple vacuum chamber geometry (courtesy K. Honkavaara, 2003)

foil: Al, Be, Si, Si + Al coating, for example

=> surface phenomenon allows the use of very thin screens ($\sim 10\mu\text{m}$)

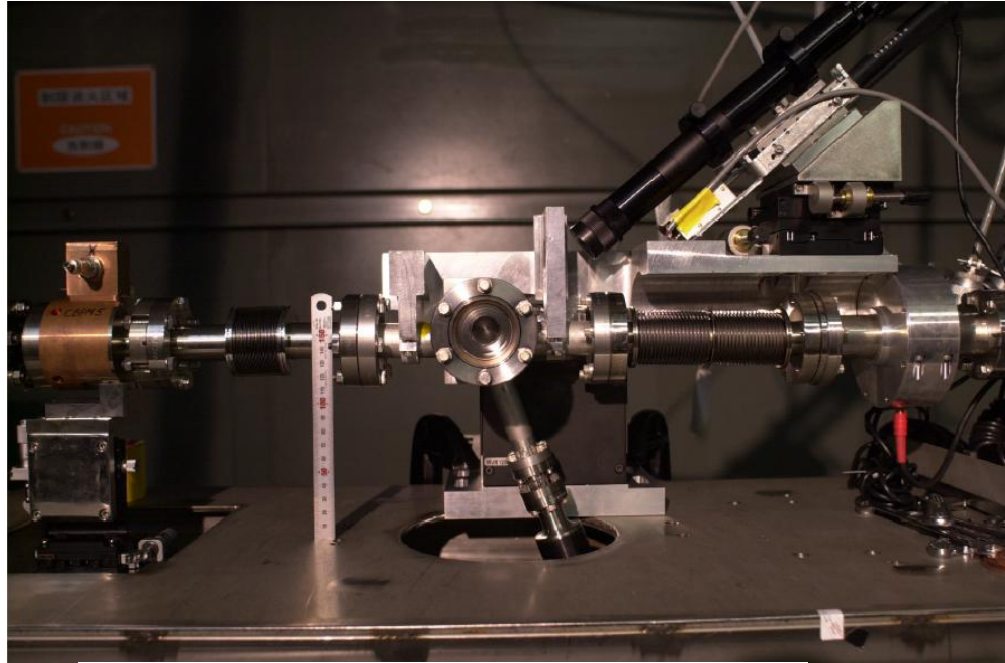
issues:

emittance measurement (as for screens):
digitized and fitted image
calibration: also with etched lines of known spacing

spatial resolution ($< 5 \mu\text{m}$) as introduced by the optics
damage to radiator with small spot sizes
geometrical depth of field effect when imaging backward

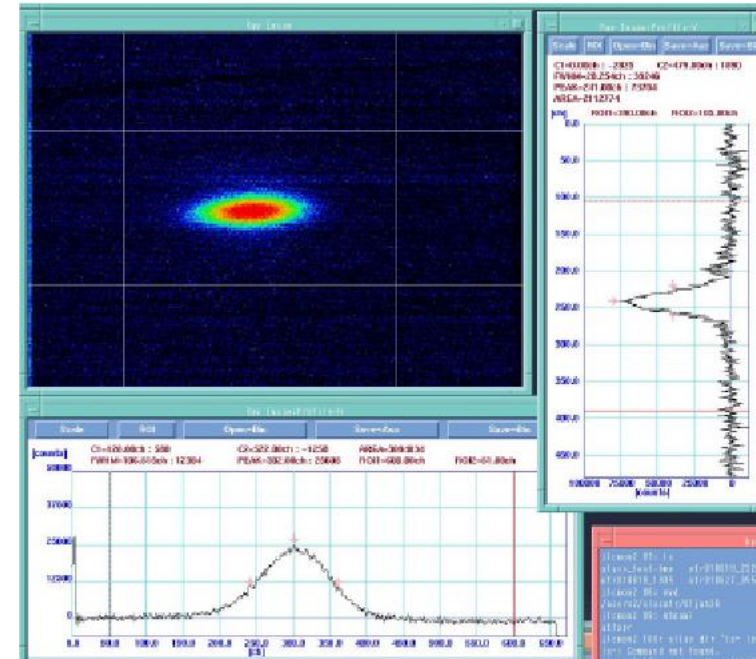
TR

Transverse Beam Emittance - Transition Radiation (2)

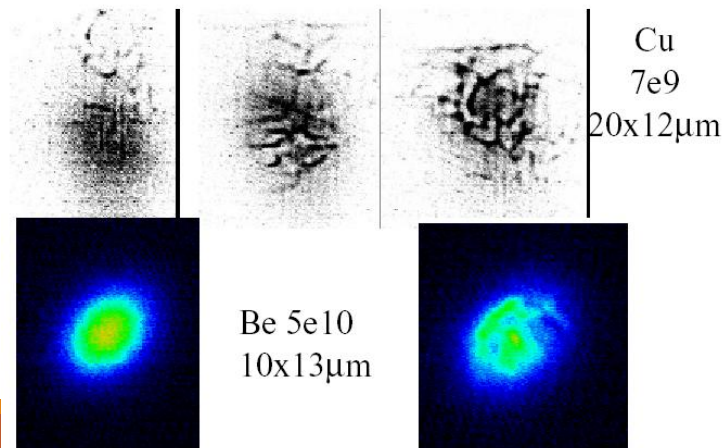


the SLAC-built OTR as installed
in the extraction line of the ATF

beam spot as measured with the
OTR at the ATF at KEK



successive images illustrating damage:



(all figures courtesy M. Ross, 2003)

Transverse Beam Emittance - Wire Scanners (1)

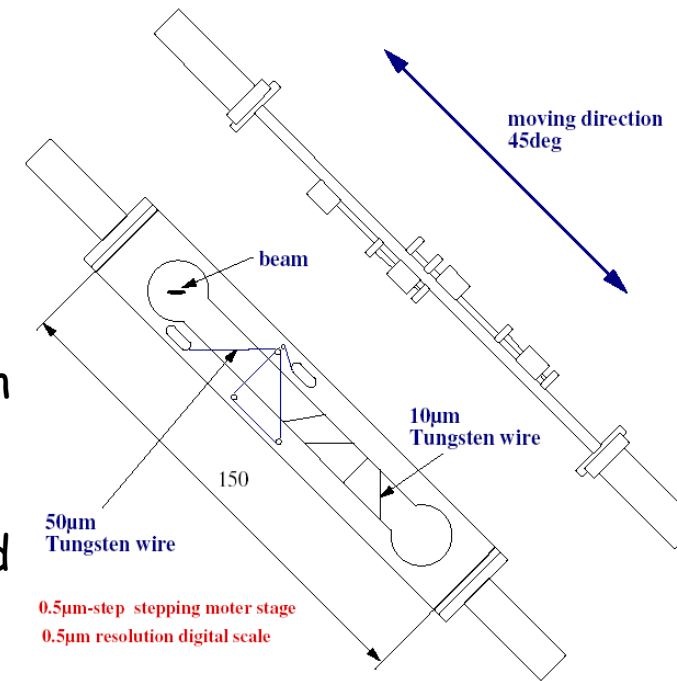
principle: precision stage with precision encoder propels shaft with wire support
wires (e.g. C, Be, or W) scanned across beam (or beam across wire)
interaction of beam with wire detected, for example with PMT

wire mount used at the ATF (at KEK) with thin W wires and 5 μm precision stepper-motors and encoders (courtesy H. Hayano, 2003)

wire velocity: depends on desired inter-point spacing and on the bunch repetition frequency

detection of beam with wire:

1. change in voltage on wire induced by secondary emission
2. hard Bremsstrahlung - forward directed γ 's which are separated from beam via an applied magnetic field and converted to e^+/e^- in the vacuum chamber wall and detected with a Cerenkov counter or PMT (after conversion to γ 's in front end of detector)
3. via detection at 90° (δ -rays)
4. using PMTs to detect scattering and electromagnetic showers
- (5. via change in tension of wire for beam-tail measurements)



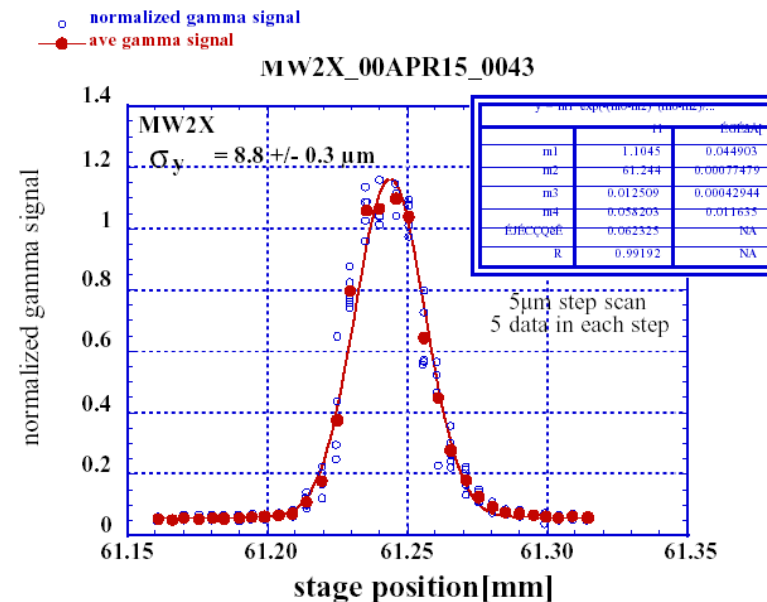
emittance measurement: as for screens
(quad scan or 3-monitor method)

Transverse Beam Emittance - Wire Scanners (2)

issues:

- different beam bunch for each data point
- no information on x-y coupling with 1 wire (need 3 wires at common location)
- dynamic range: saturation of detectors (PMTs)
- single-pulse beam heating
- wire thickness (adds in quadrature with beam size)
- higher-order modes

(left) wire scanner chamber installed in the ATF (KEK) extraction line and (right) example wire scan (courtesy H. Hayano, 2003)



Transverse Beam Emittance - Laser Wire Scanners (1)

principle: laser wire provides a non-invasive and non-destructible target
— wire scanned across beam (or beam across wire)

constituents: laser, optical transport line, interaction region and optics, detectors

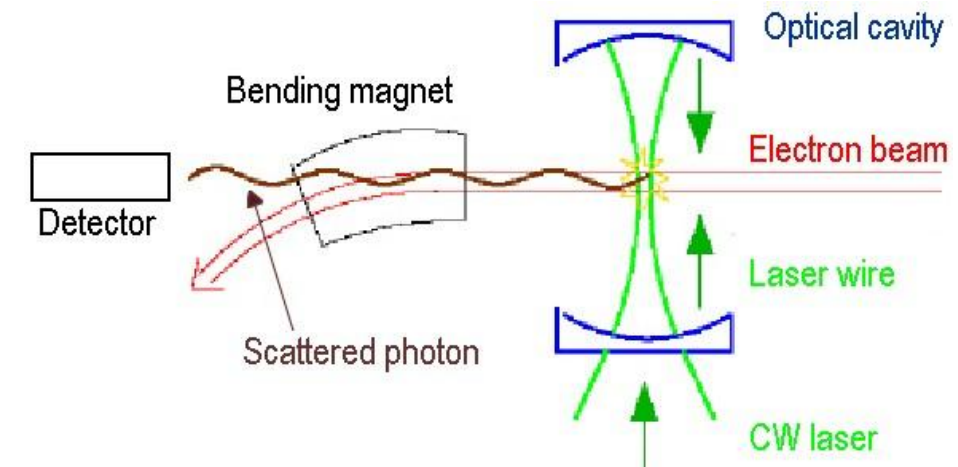
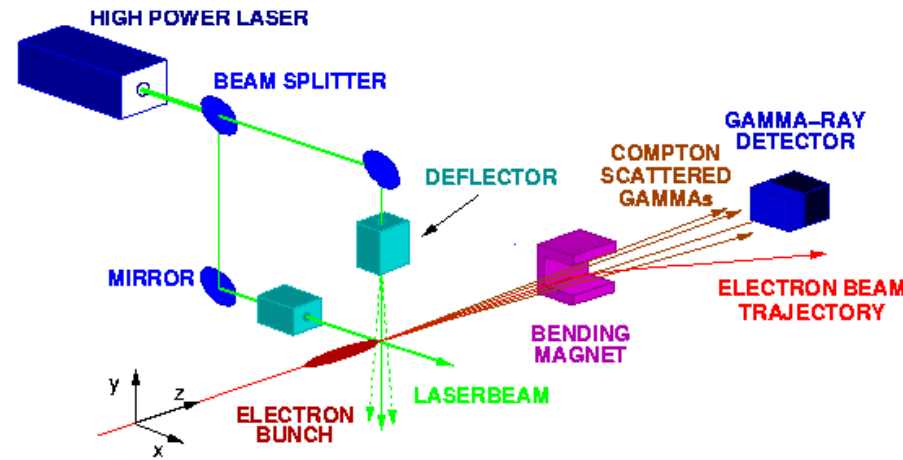
beam size measurements: forward scattered Compton γ 's or
lower-energy electrons after deflection by a magnetic field

schematic of the laser wire system planned for use at PETRA and for the third generation synchrotron light source PETRA 3 (courtesy S. Schreiber, 2003)

high power pulsed laser

overview of the laser wire system at the ATF (courtesy H. Sakai, 2003)

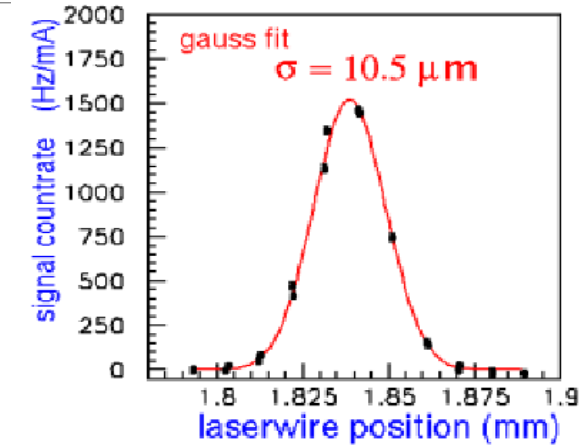
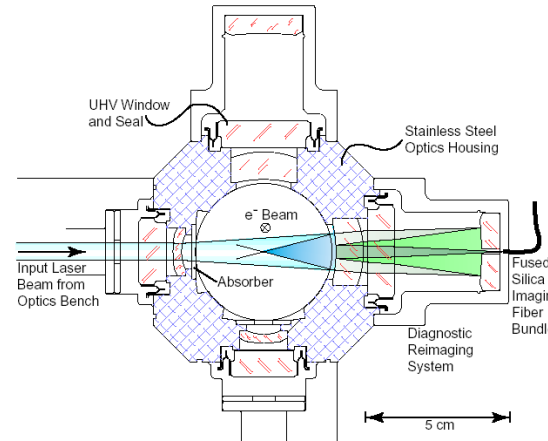
optical cavity pumped by
CW laser (mirror reflectivity ~99+%)



Transverse Beam Emittance - Laser Wire Scanners (2)

laser-electron interaction point
from the pioneering experiment
at the SLC final focus (courtesy
M. Ross, 2003)

beam size measured at the
laser wire experiment of the
ATF (courtesy H. Sakai, 2003)



$$\sigma_y = \sqrt{\sigma_{\text{obs}}^2 - \left(\frac{w_0}{2}\right)^2}$$

$$\beta_y \epsilon_y = (\sigma_y)^2 - \left(\eta_y \frac{\sigma_p}{p}\right)^2$$

(as with normal
wires, the wire
size must be taken
into account)

(here w_0 is the 2σ wire thickness)

issues: photon density
waist of laser < beam size (in practice, waist size $\sim \lambda$)
background and background subtraction
depth of focus large so that sensitivity of σ_y on x_e is minimized
synchronization (for pulsed lasers)

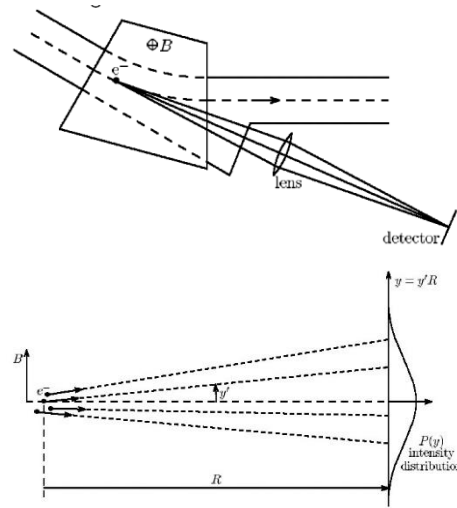
Transverse Beam Emittance - Synchrotron Radiation (1)

principle: charged particles, when accelerated, emit synchrotron radiation

measurements:

imaging → beam cross section

direct observation
→ angular spread

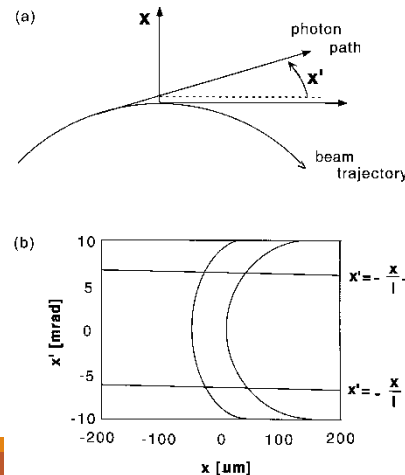


A. Hofmann,
CERN accelerator
school, 2003

depth of field effect in direct imaging (ref. A. Sabersky)

phase space
coordinates
of the photon
beam

photon beam
phase space at
distance l from
source (for a
 $100 \mu\text{m}$ beam
at emission point)



a = half-width of and
 l = distance to defining aperture

measured beam parameters correspond
to a projection of this phase space onto
the horizontal axes

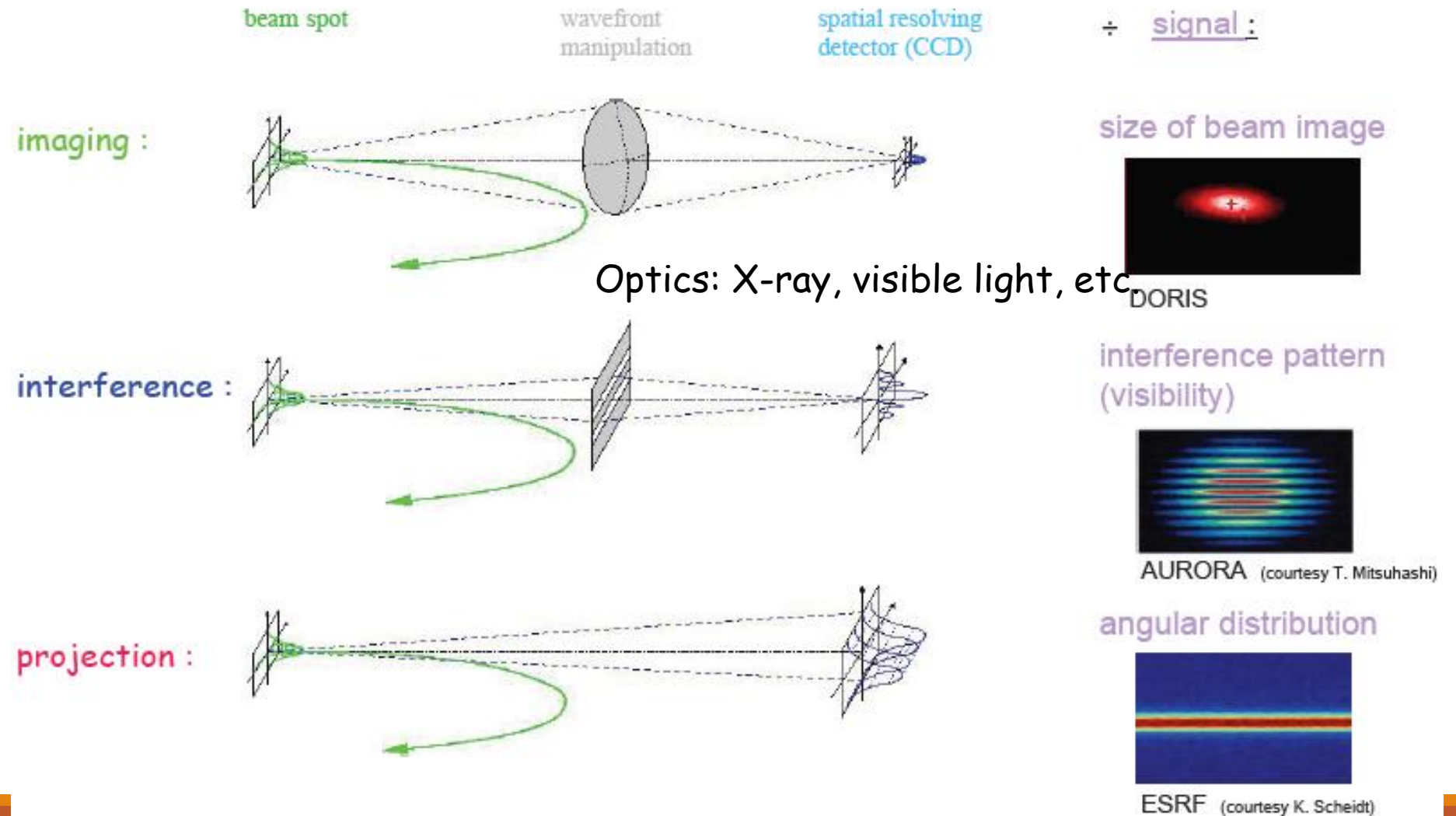
$$\bar{x} = \frac{\int I(x)x dx}{\int I(x) dx}$$

$$\sigma_{r,x}^2 = \frac{\int I(x)(x - \bar{x})^2 dx}{\int I(x) dx}$$

Transverse Beam Emittance - Synchrotron Radiation Monitor (2)

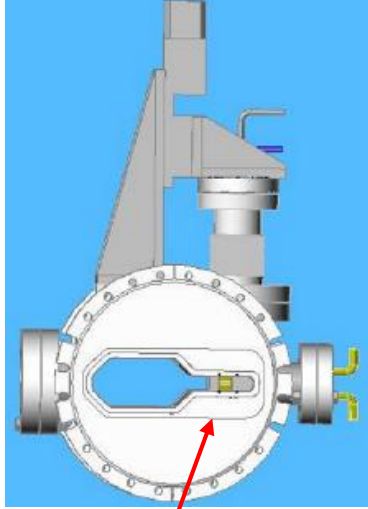
O. Chubar: *Novel Applications of Optical Diagnostics*, Proc. EPAC 2000, p.117

Classification

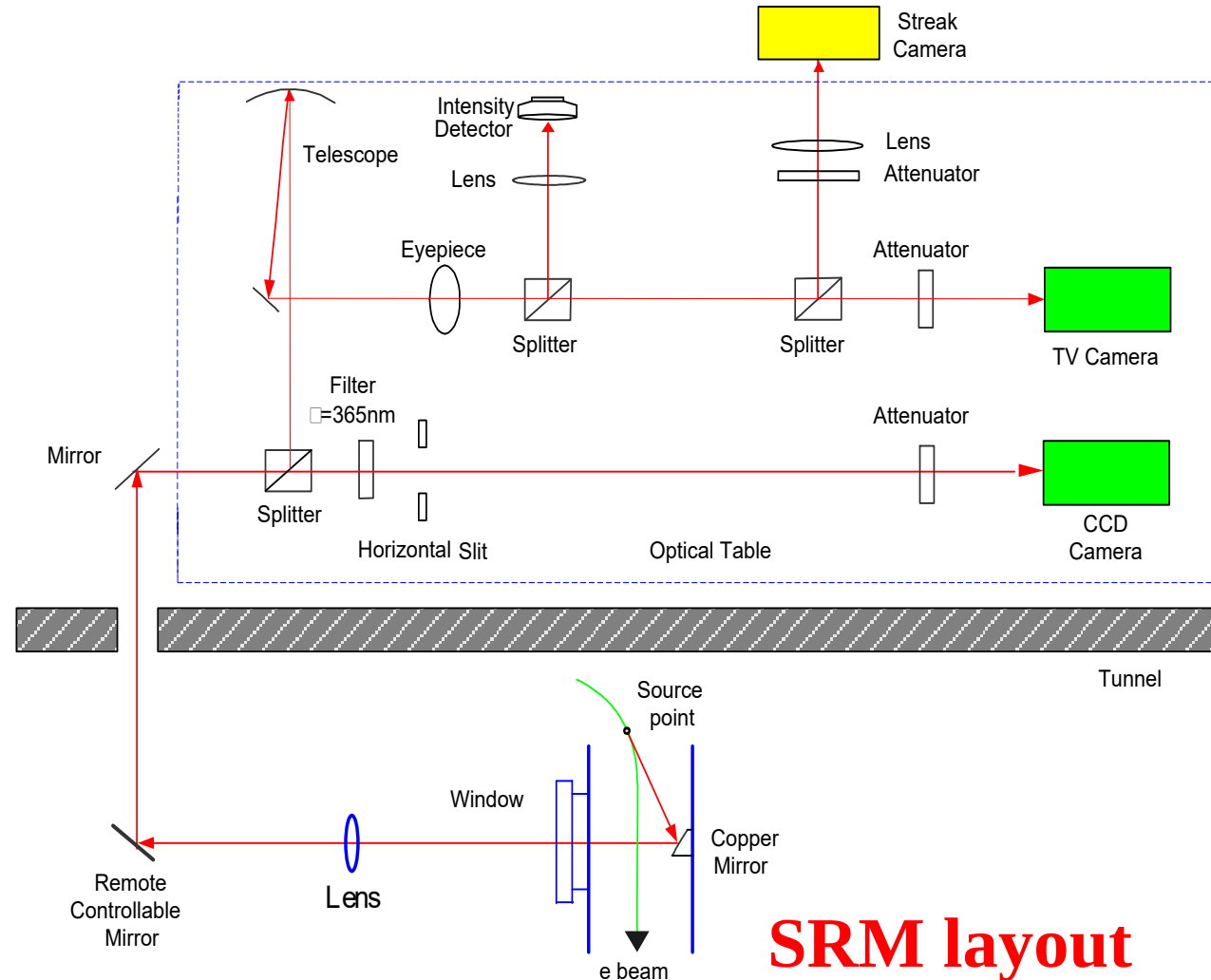


Transverse Beam Emittance - Synchrotron Radiation (3)

Synchrotron Light Monitor Optic Layout (BEPC II)

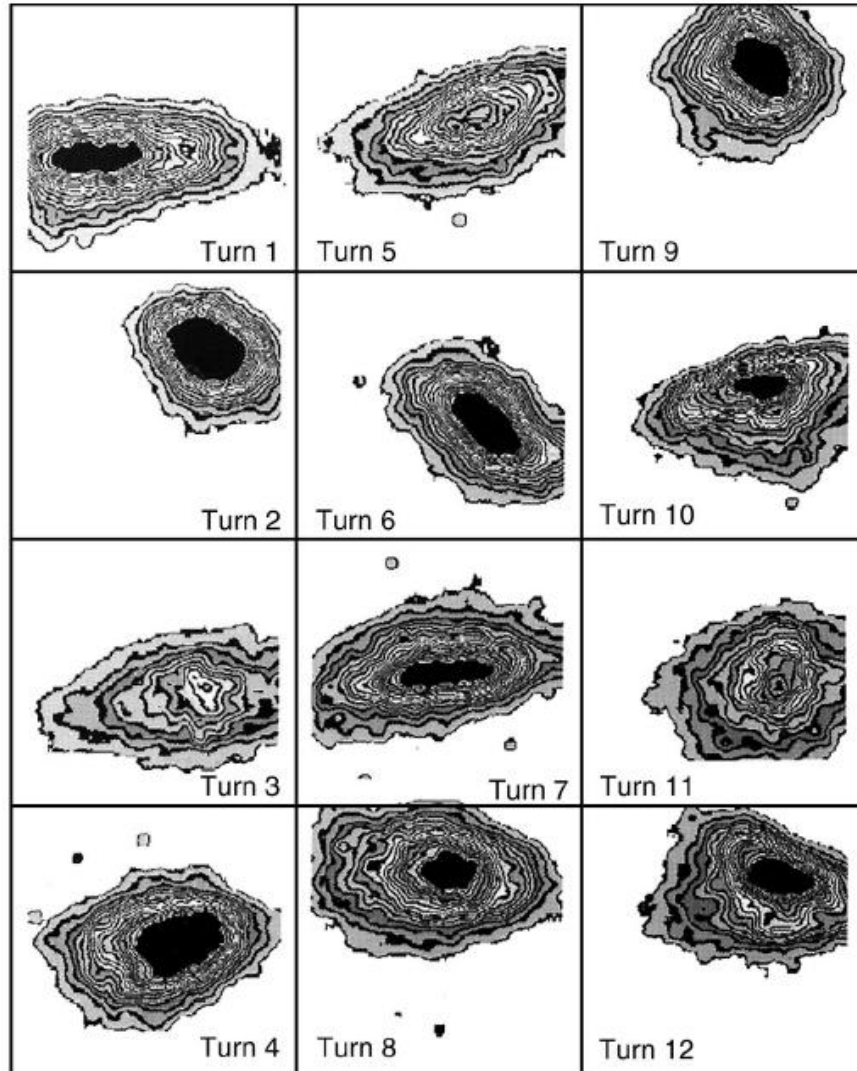


First mirror



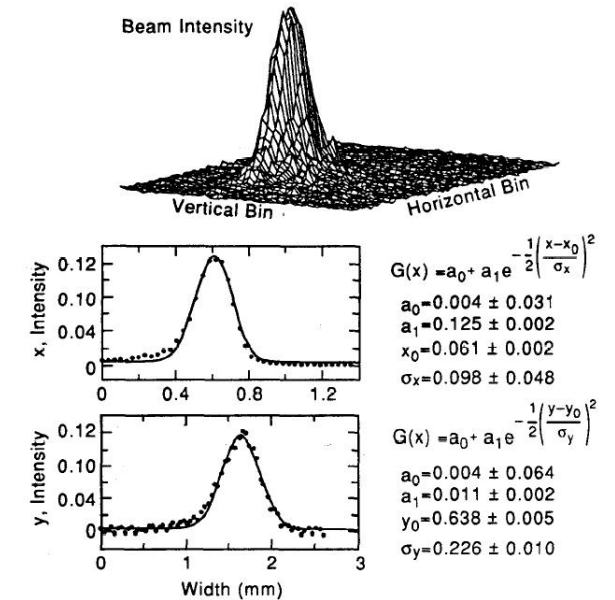
SRM layout

Transverse Beam Emittance - Synchrotron Radiation (4)



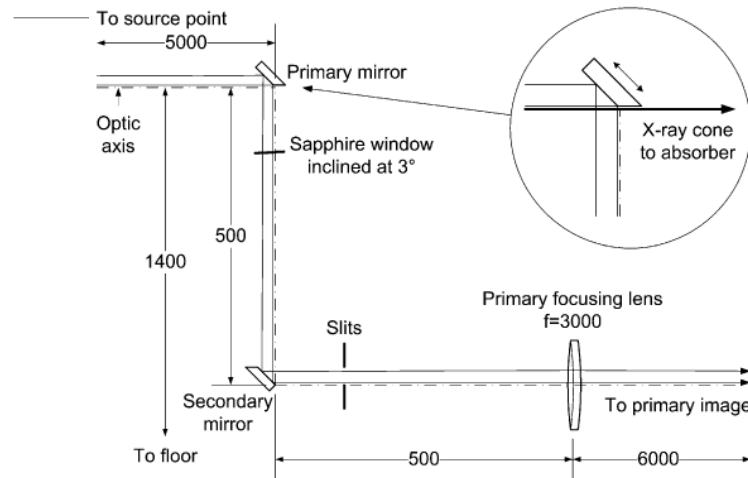
(left) raw data showing turn-by-turn images at injection (average over 8 pulses)

(bottom) digitized image in 3-D and projections together with Gaussian fits (bottom)



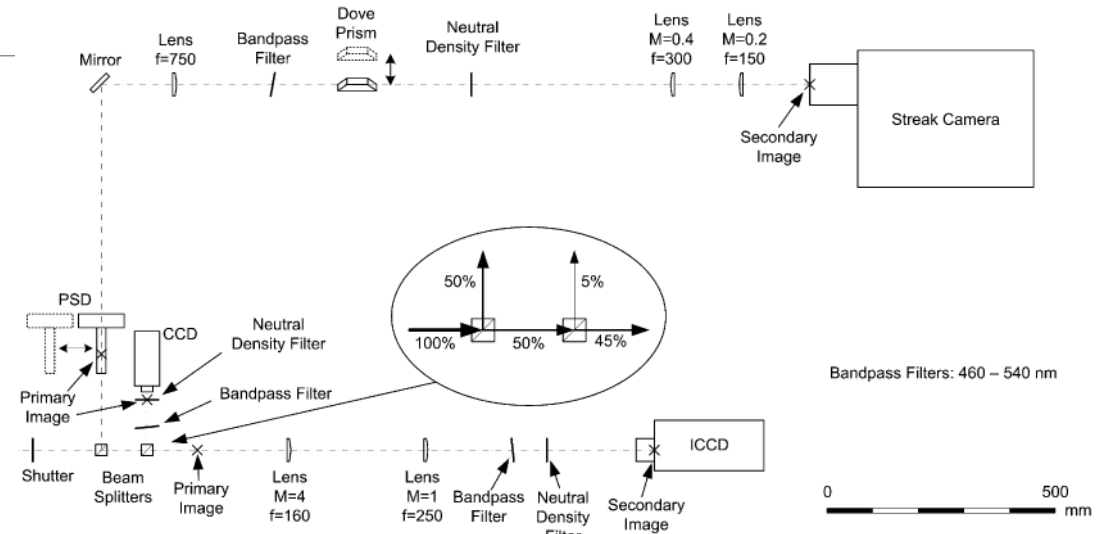
originally, these studies aimed at measuring the transverse damping times, but were then extended to measure emittance mismatch and emittance of the injected beams ...

Transverse Beam Emittance - Synchrotron Radiation (5)



Schematic of the vertical chicane that is used to separate the optical synchrotron radiation from the X-ray component. Not shown are the various shutters that are part of the safety system. The primary mirror, secondary mirror, slit system and primary lens are all motorized for remote control. All components upstream of the sapphire vacuum window share the storage ring UHV.

Nuclear Instruments and Methods in Physics Research A 562 (2006) 495-512



Layout of the optical table inside the OSR hut, showing the disposition of the three cameras and the position-sensitive detector. The primary lens within the vertical chicane creates a real image of the source-point at the indicated primary-image positions, with magnification $M=1$. The other lenses relay these images to the cameras with various magnifications. All components are centered 200mm above the optical table.

Transverse Beam Emittance - Synchrotron Radiation (6)

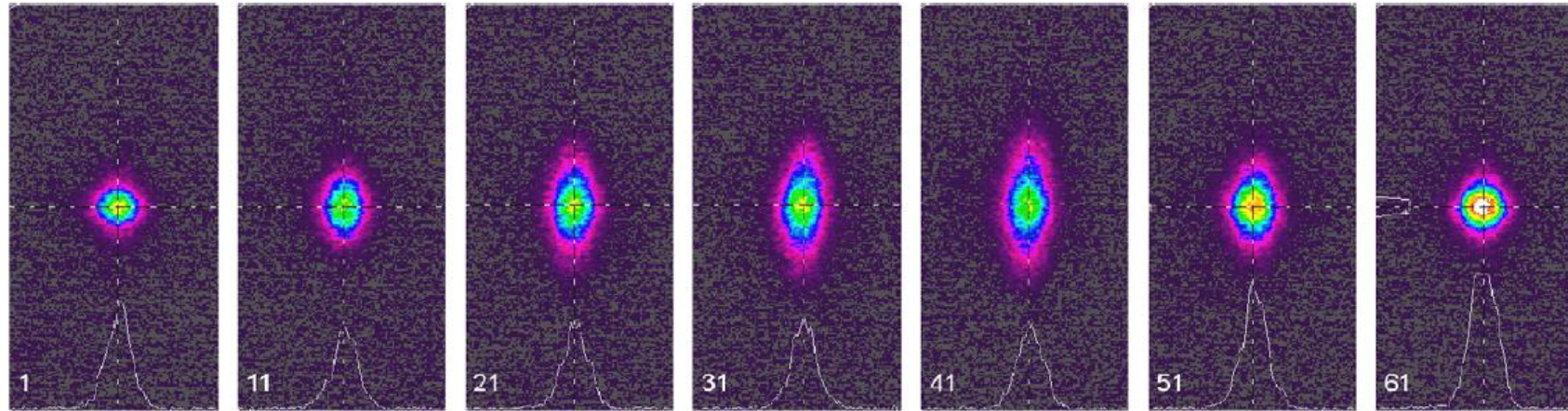


Fig. 8. Walking along a bunch train with the ICCD camera. This sequence shows every 10th bunch, and was made during the early commissioning phase of the CLS. The camera gate width is about 400 ps here. One sees a gradual increase in the vertical profile resembling a quadrupole mode, followed by a collapse. We interpret this as evidence for the Fast Beam-Ion Instability (FBII) that occurred before the vacuum had fully conditioned.

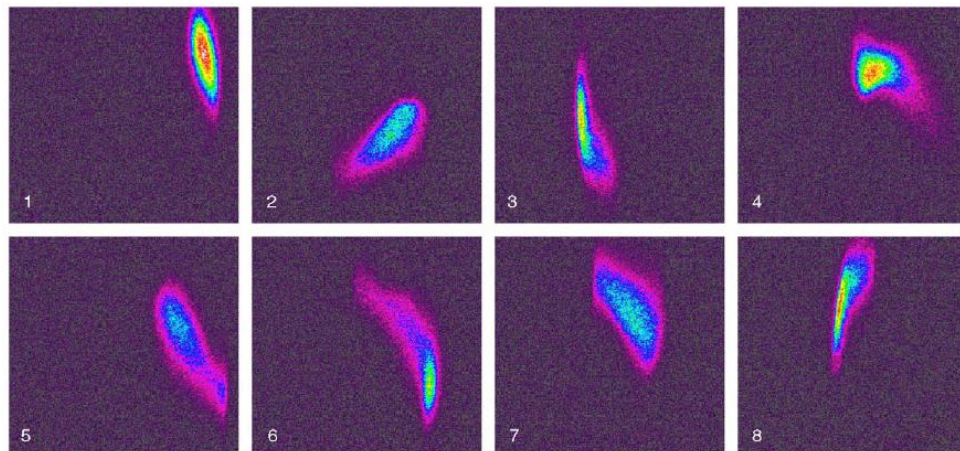


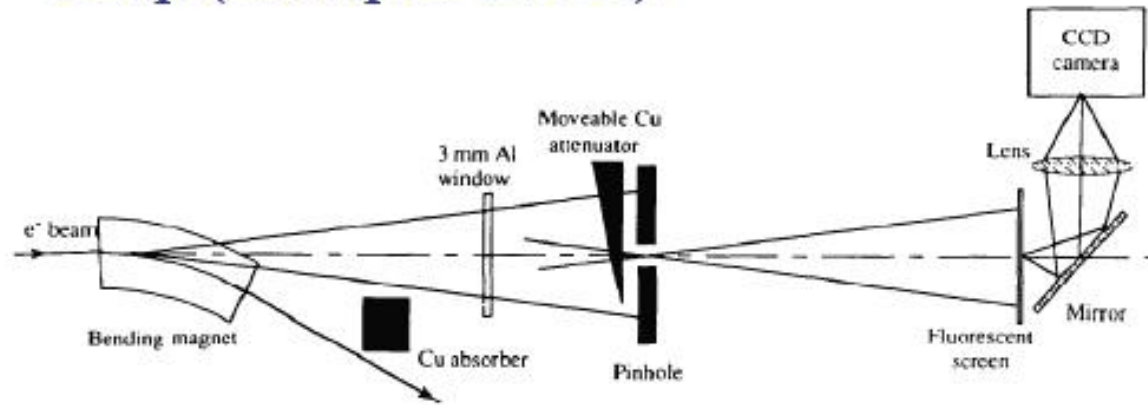
Fig. 9. Injection study with the ICCD camera. This sequence shows the beam on turns 1-8 immediately following injection. The M=1 relay lens was used here, and the corresponding field of view is roughly 15mm square. The horizontal breathing is indicative of a b-mismatch. A vertical steering error at the injection point is also apparent from the vertical oscillations.

Nuclear Instruments and Methods in Physics Research A 562 (2006) 495-512

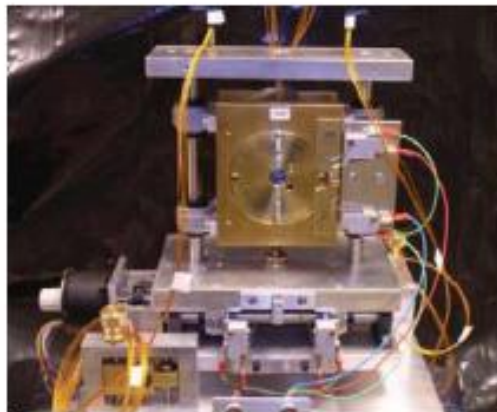
Transverse Beam Emittance - Synchrotron Radiation (7)

- „Camera Obscura“
description of phenomenon already by Aristoteles (384-322 b.C.) in „Problemata“
- Setup (example: ESRF)

P.Elleau, C.Fortgang, C.Penel and E.Tarazona, J.Synchrotron Rad. 2 (1995) , 209



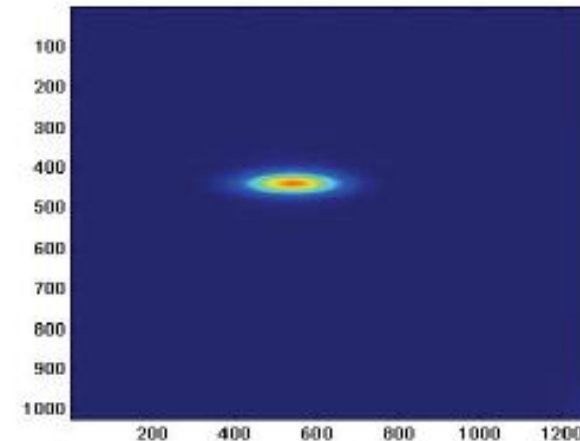
ID-25 X-ray
pinhole camera:



pinhole setup
@ DORIS

resolution:

$$\sigma_{res} \approx 20 \mu m$$



courtesy of K.Scheidt, ESRF

Transverse Beam Emittance - (multiple-pass) interferometric monitor (T. Mitsuhashi)

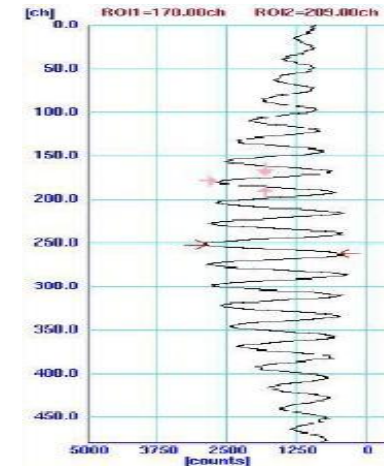
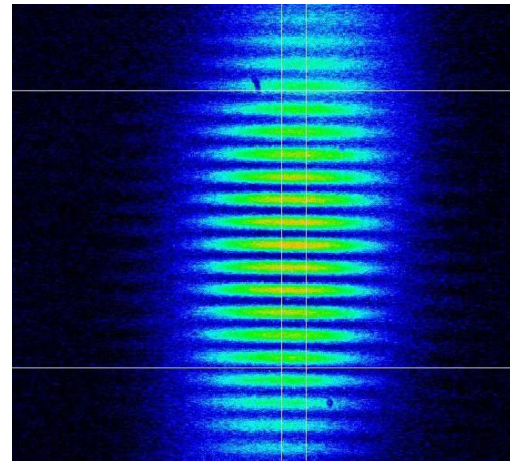
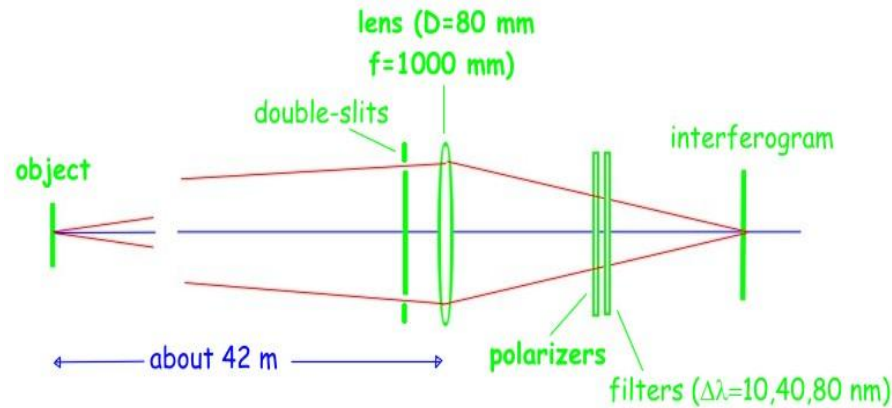
Principle: detection of interference pattern generated by synchrotron radiation after passage through "double-slits" (Michelson's stellar interferometer)

The van Cittert-Zernike theorem

=> The complex degree of coherence (γ) is equal to the diffraction pattern of an aperture of the same size and shape as the source and illuminated by a spherical wave whose amplitude distribution is proportional to the intensity distribution across the source.

=> Fourier transform (γ) -> Profile

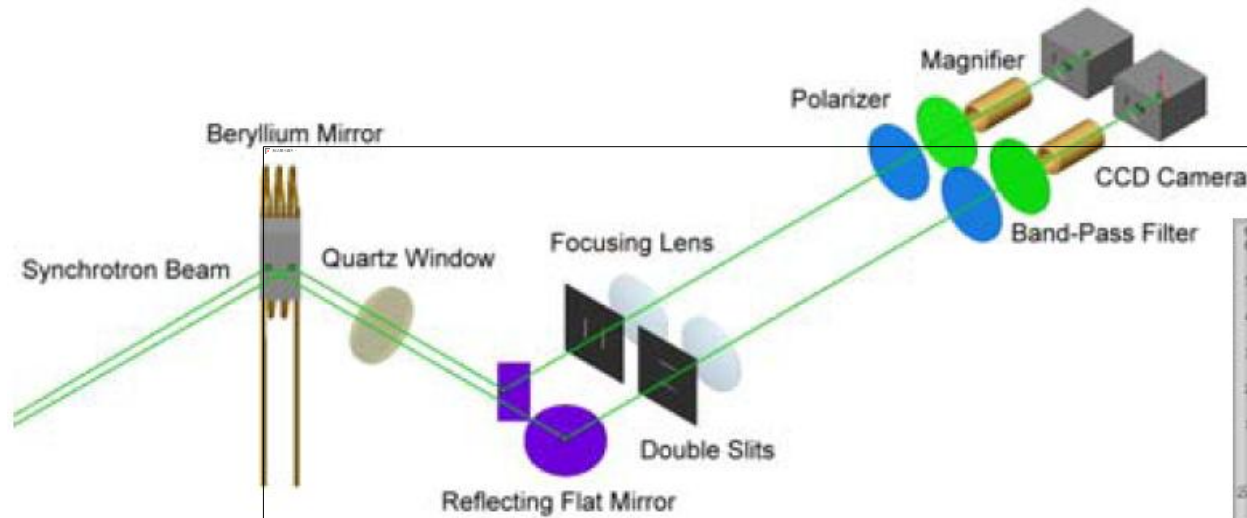
constituents: bending dipole and exit chamber for synchrotron light, photon beam optics, detector (i.e. a CCD)



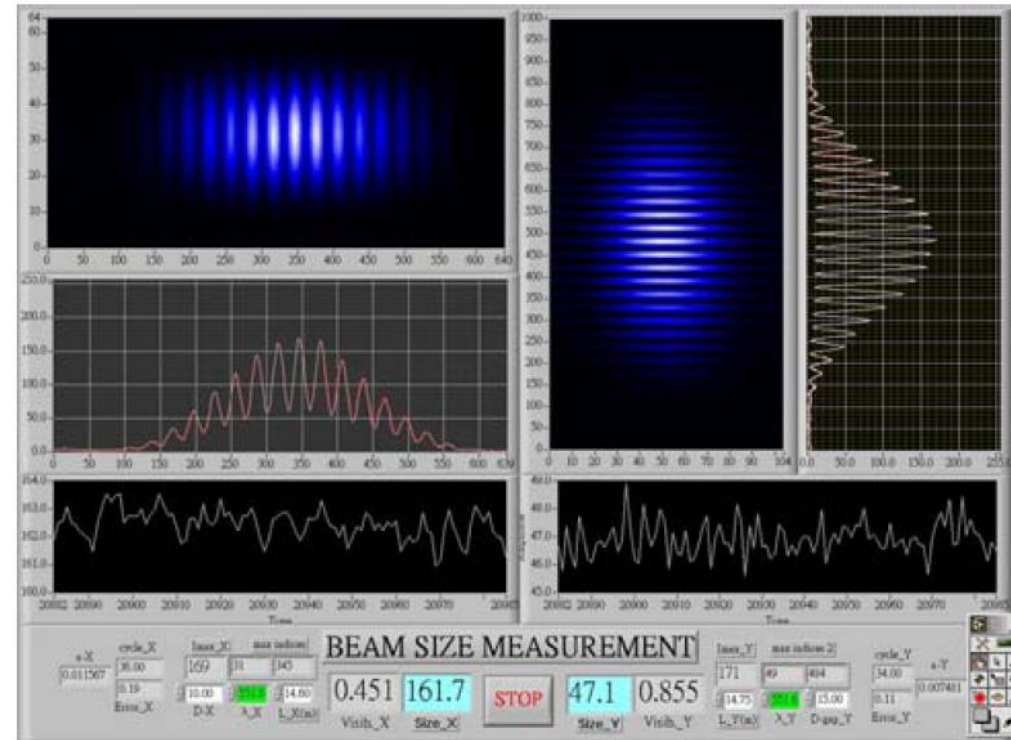
beam size measurement: modulation depth of interference pattern

issues: thermal mirror distortions (KEK-B uses dedicated weak bending magnets), precision control of slit width, and depth of field effects (leads to intensity imbalance in the 2 slits)

Transverse Beam Emittance - (multiple-pass) interferometric monitor for TLS



General optical layout of the SRI
beam size Monitor.



$$\sigma_{beam} = \frac{\lambda}{\pi} \frac{R_o}{D} \sqrt{\frac{1}{2} \ln \left(\frac{1}{\gamma} \right)}$$

R_o : distances from the source point to the double slits

D : slit separation

γ : visibility

λ : wavelength

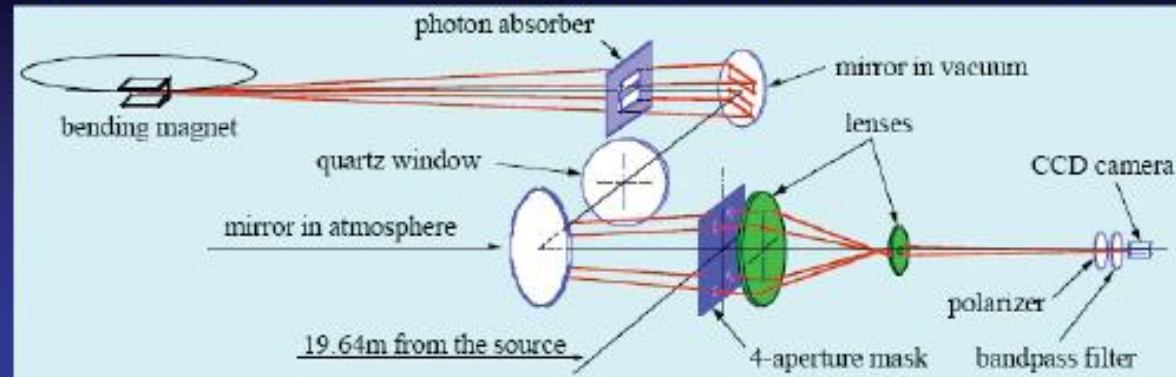
T.C. Tseng, et al.

The software control panel of the beam size monitor.

Transverse Beam Emittance - (multiple-pass) interferometric monitor for SPring-8

SPring-8 2D Synchrotron Light Interferometer

M. Masaki & S. Takano,
J. Sync. Rad. (2003). 10, p295



Resolution

$$\sigma_{inter,X} = 121 \mu\text{m}, \quad \sigma_{inter,Y} = 52 \mu\text{m}$$

2D Beam Profiling

model function: $\tilde{I}(x,y) = \int_{-\infty}^{\infty} I(x,y;x_e,y_e) \rho(x_e,y_e) dx_e dy_e$

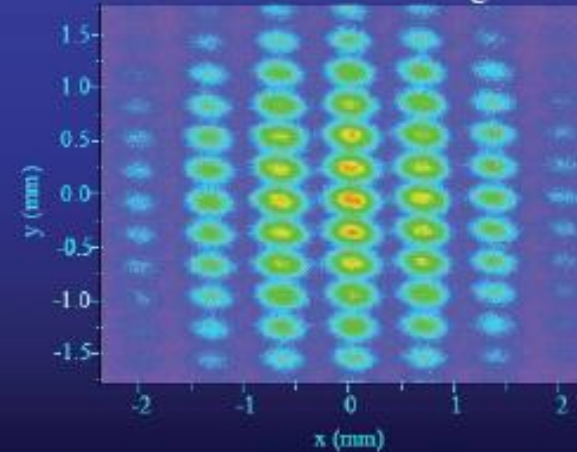
point-spread function: $I(x,y;x_e,y_e)$

electron beam: $\rho(x_e,y_e)$

elliptical Gaussian distribution



Observed interferogram



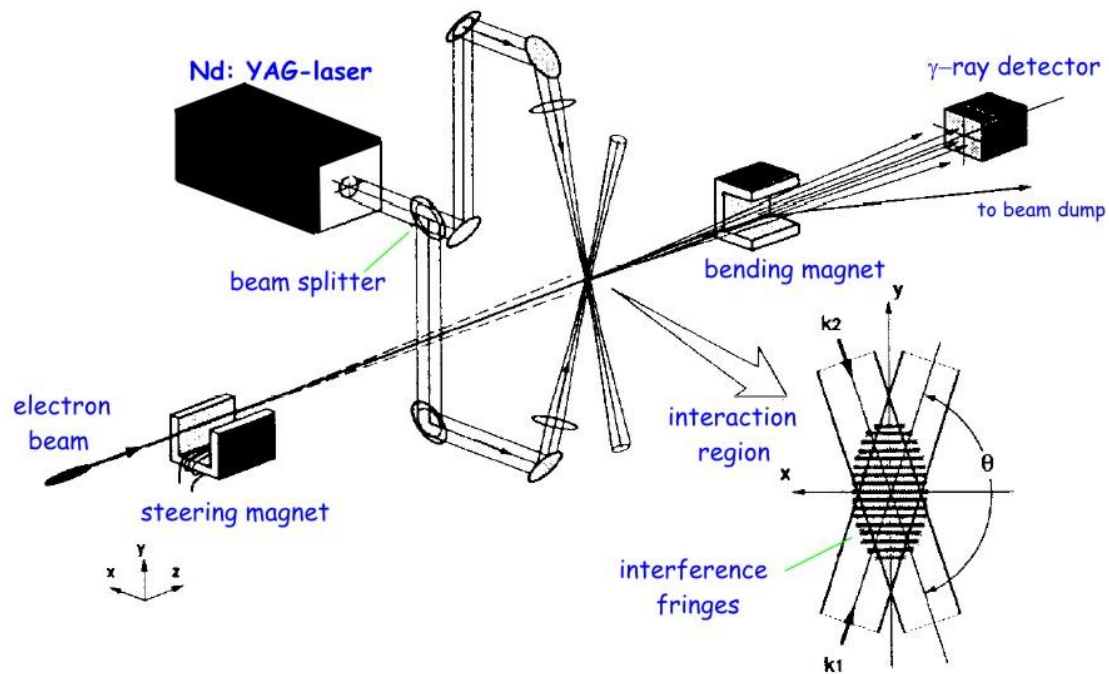
$$\sigma_I = 116(\mu\text{m}), \quad \sigma_{II} = 64(\mu\text{m}), \quad \theta = -18(\text{deg.})$$

courtesy of S. Takano, Spring-8

Transverse Beam Emittance - (single-pass) interferometric monitor (T. Shintake)

principle: laser provides a non-invasive and non-destructable target by splitting and recombining the laser light a standing wave (sw) is made the intercepting beam produces Compton-scattered photons of high density in the sw-peaks and of low density in the sw-valleys

constituents: laser and laser beam splitter, optical transport line, particle beam steering magnet, interaction region and optics, detectors



beam size measurements: scattered Compton γ 's as a function of beam position

Transverse Beam Emittance - (single-pass) interferometric monitor (T. Shintake)

by scanning the beam position along the standing wave, the modulation depth of the observed photon spectrum gives information about the beam size
(arbitrary phase)

number of
scattered
photons

$$\langle N_\gamma \rangle = A + B \cos(2k_L \Delta x + \psi)$$

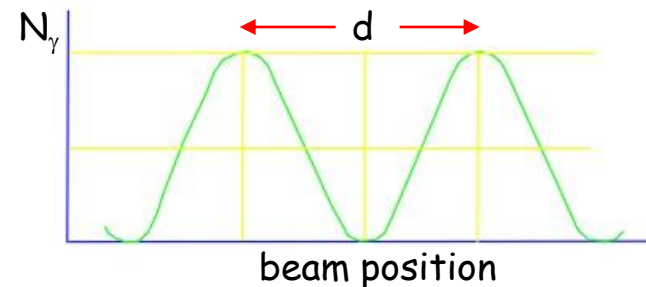
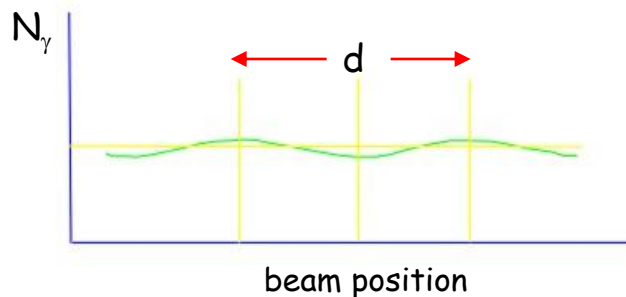
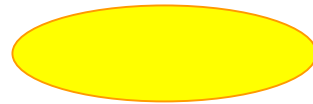
laser wave number ($=2\pi/\lambda_L$)

beam size small compared to
fringe spacing, d : $B/A \rightarrow 1$

horizontal
beam size:

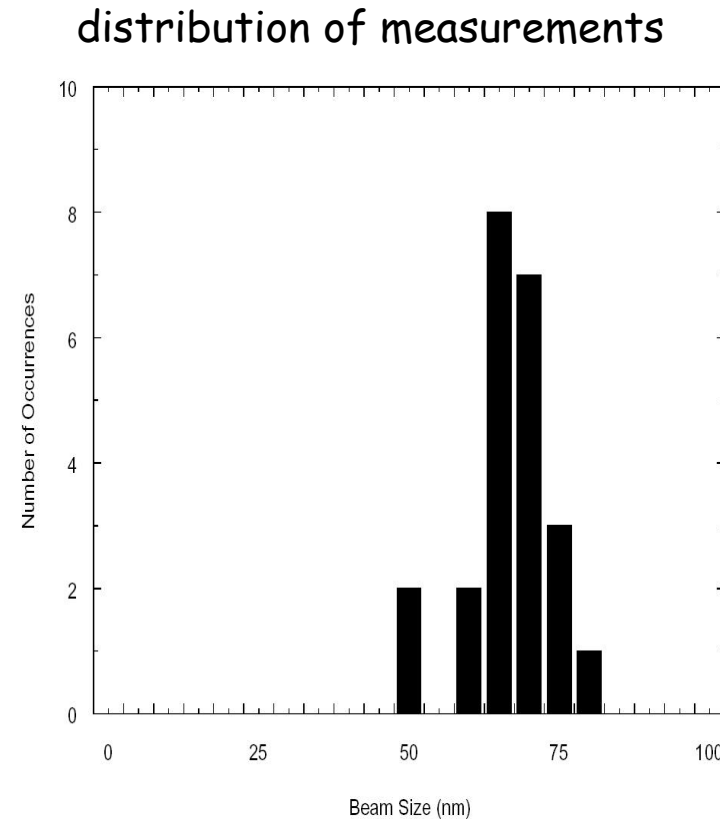
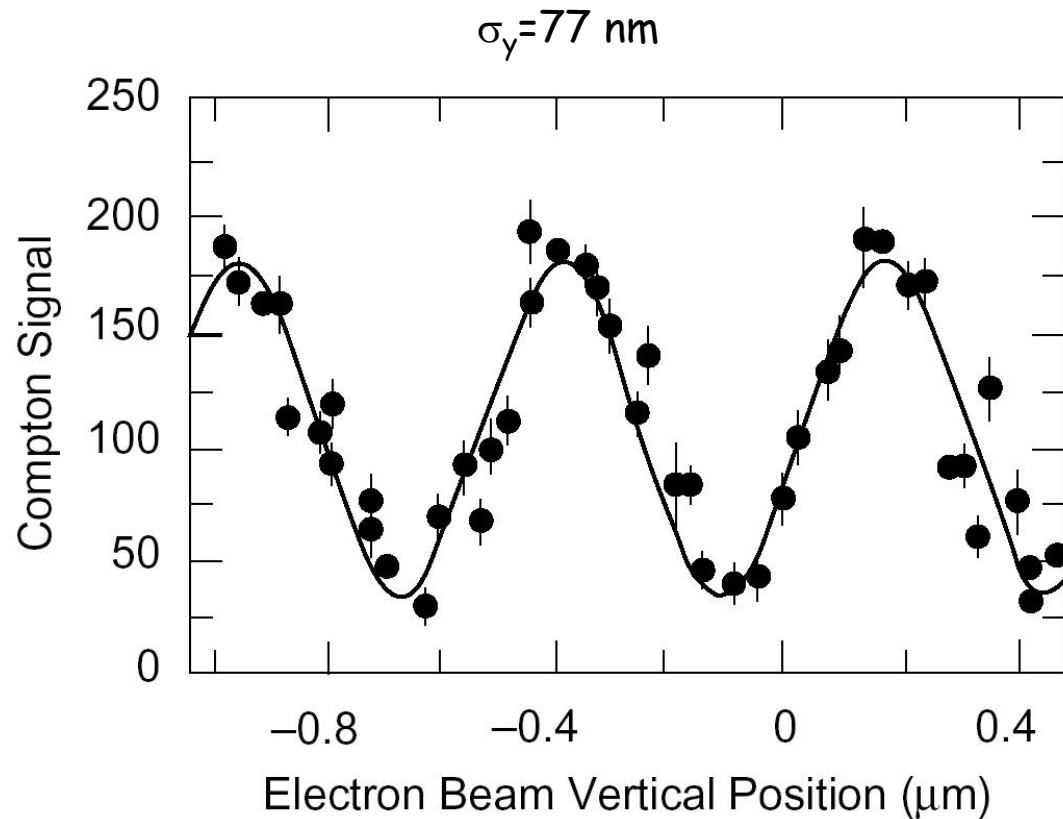


vertical
beam size:



in practice, the optimum fringe
spacing (for best resolution)
depends on the beam size itself

Measurements of small beam sizes at the FFTB (courtesy T. Shintake, 2004)



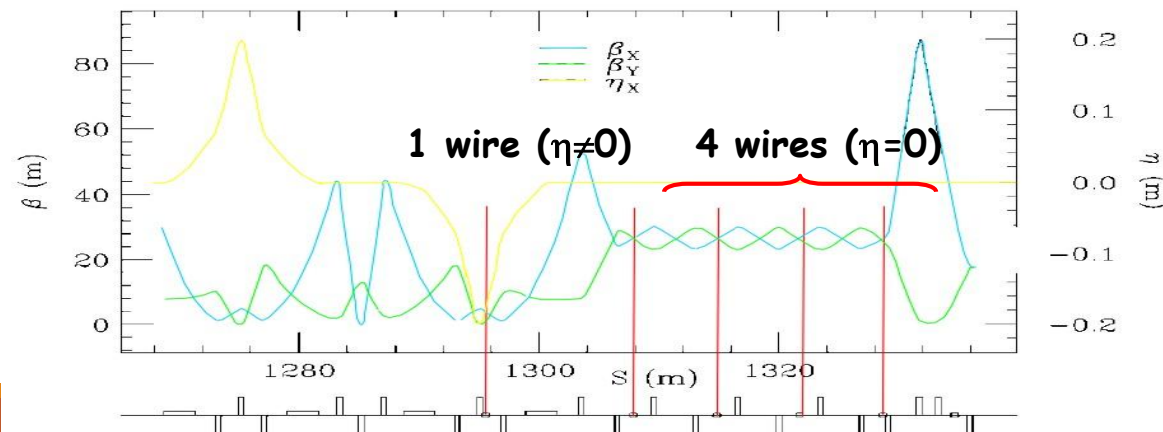
issues for the single-pass interferometric monitor:

laser power imbalance (mirror "asymmetries") and laser alignment electron beam crossing angle (electron beam not parallel to the plane of the fringes) longitudinal extent of the interference pattern (compare "hour-glass" effect) spatial and temporal coherence of the laser (alignment distortions) laser jitter

A closing thought concerning emittance measurements: "diagnostic sections"
the layout of diagnostics for emittance measurements should
be considered together with the particle beam optics

Examples

- KEK-B (Japan): dedicated weak bending magnets (to minimize heat loading)
- TTF-I (DESY): 4 wire scanners/plane placed in symmetric fashion as geometry allowed between permanent magnet undulators; phase advance between scanners energy-dependent (quadrupoles focus less strongly higher energy beams); result: desired SASE wavelength dictated beam energy for which each pair of wires was separated by $180^\circ \rightarrow$ only 2 unique measurements
 $\rightarrow$ no measurement of emittance at certain beam energies
- LCLS (SLAC): design optics at 15 GeV with equal beam sizes at all scanners ; optimum wire scanner spacing with 45° separation between wires



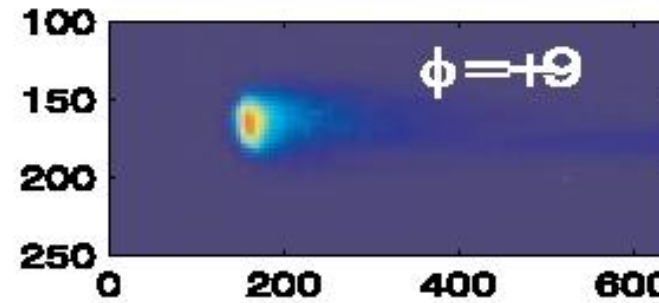
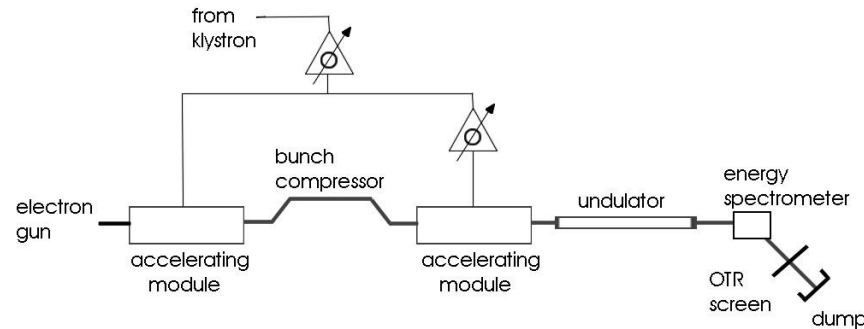
principle: the beam size as measured, e.g. with a screen or wire, is the convolution of the natural beam size σ_β , and the contribution from the energy spread $\delta = \Delta E/E$:

$$\sigma = \sqrt{\sigma_\beta^2 + (\eta\delta)^2}$$

dispersion function (property of lattice)

By proper selection of location (for a screen /wire), where η is large, the beam energy spread δ can be directly measured

example: TTF, single-bunch OTR images following spectrometer (courtesy F. Stulle, 2003)



energy spread measurement (as for screens):

digitized and fitted image

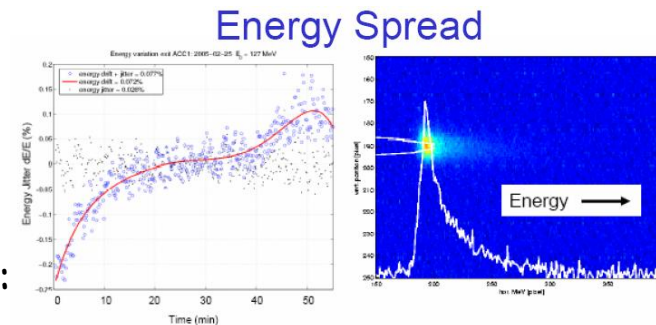
calibration: with etched lines of known spacing

issues (same as those for normal screen measurements):

spatial and temporal resolution

radiation hardness of optics and camera

dynamic range (saturation of screen)

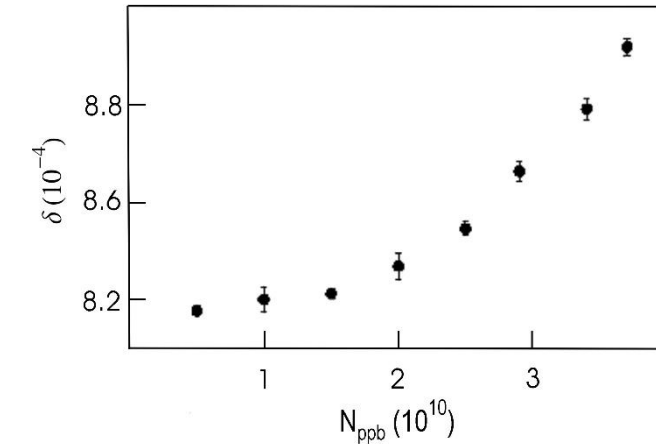
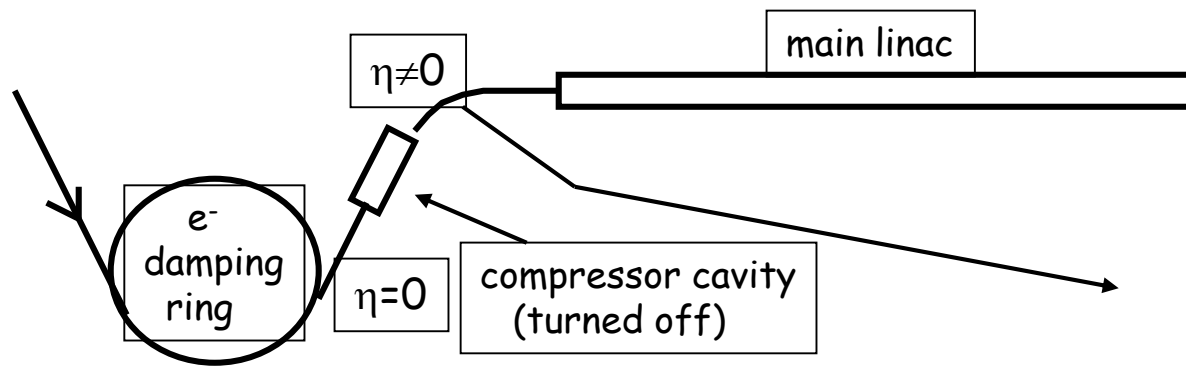


- Energy measured using the OTR screen in the dispersive section of the first bunch compressor
- Energy jitter w/o drift $dE/E = 2.6 \cdot 10^{-4}$ at 127 MeV
- Including the drift yields $7 \cdot 10^{-4}$
- Uncorrelated energy spread < 25 keV (resolution limited)

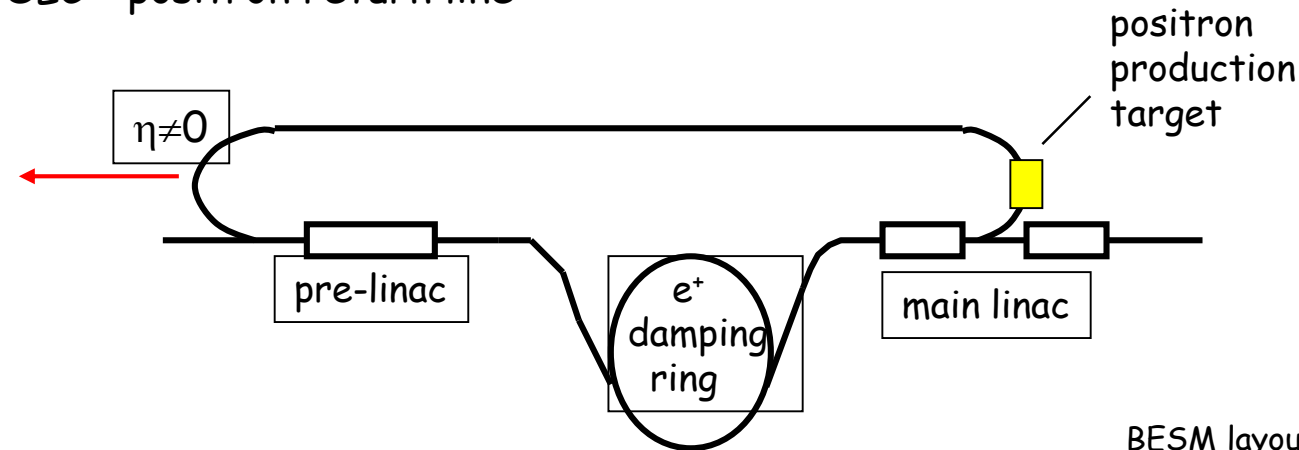
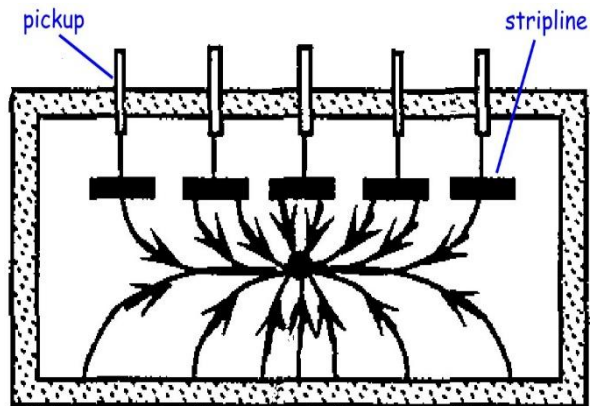
Beam Energy Spread (2)

$$\sigma = \text{sqrt} [\sigma_{\beta}^2 + (\eta\delta)^2]$$

example: energy spread in the SLC e^- damping ring (after extraction) — (wire scanner data)



example: energy spread in the SLC "positron return line"



BESM layout (courtesy T. Suwada, 2004)

Beam Energy Spread (3)

principle: in a storage ring, particles within the bunch perform phase and energy oscillations (out of phase by 90 deg) about a common reference point defined by the rf; measurement of the longitudinal distribution may therefore be used to determine the energy distribution of the bunch

$$\sigma_t = \frac{\alpha}{2\pi f_s} \left(\frac{\sigma_\delta}{E} \right) \rightarrow \frac{\sigma_\delta}{E} = \frac{2\pi f_s}{\alpha} \sigma_t$$

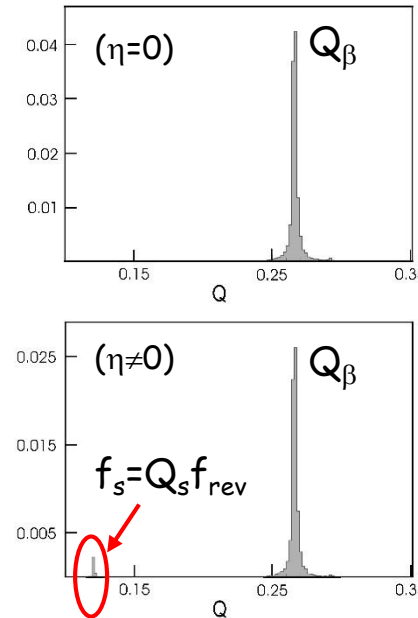
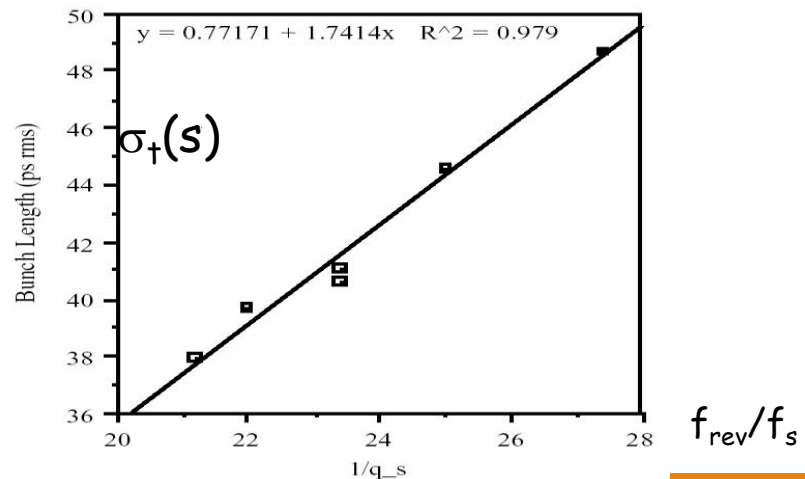
(ref: H. Wiedemann, Eq. 8.70)

synchrotron frequency

bunch length

momentum compaction

example: energy spread in PEP-II B-Factor
streak camera data (courtesy A. Fisher, 2004)



synchrotron
frequency
measured using
FFT of turn
by turn data
in LEP (courtesy
A. Müller, 2001)

Beam Energy Spread (4)

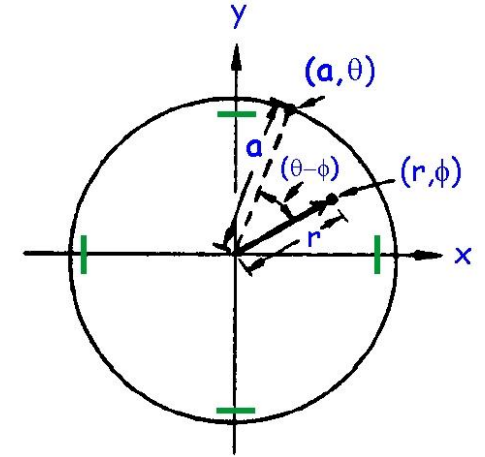
“Nonintercepting emittance monitor” R.H. Miller et al SLAC-PUB-3186
principle: measure the multipole moments induced by the passage of a charged particle beam

$$J_{image}(r, \phi, a, \theta) = \frac{I(r, \phi)}{2\pi a} \left[1 + \sum_{k=1}^{\infty} \left(\frac{r}{a}\right)^k \cos k(\theta - \phi) \right]$$

$$= \frac{I(r, \phi)}{2\pi a} \left\{ 1 + 2\left[\frac{x}{a} \cos \theta + \frac{y}{a} \sin \theta\right] + 2\left[\frac{x^2 - y^2}{a^2} \cos 2\theta + 2\frac{xy}{a^2} \sin 2\theta\right] + 2\left[\left(\frac{x^3}{a^3} - 3\frac{xy^2}{a^3}\right) \cos 3\theta - \left(\frac{y^3}{a^3} - 3\frac{yx^2}{a^3}\right) \sin 3\theta\right] + \text{higher order terms} \right\}$$

← integral of surface line density over area of electrode (see first lecture)

(expansion of integral)



$$J_{image}(a, \theta) = \frac{I_{beam}}{4\pi^2 a \sigma_x \sigma_y} \int \int_{area \text{ of pipe}} \left[1 + 2 \sum_{k=1}^{\infty} \left(\frac{r}{a}\right)^k \cos k(\theta - \phi) \right] \times \exp\left[-\frac{(x-x')^2}{2\sigma_x^2}\right] \exp\left[-\frac{(y-y')^2}{2\sigma_y^2}\right] da$$

← integrate over assumed Gaussian beam distributions in both transverse planes

Result:

$$J_{image}(a, \theta) \simeq \frac{I_{beam}}{2\pi a} \left\{ 1 + 2\left[\frac{x}{a} \cos \theta + \frac{y}{a} \sin \theta\right] + 2\left[\left(\frac{\sigma_x^2 - \sigma_y^2}{a^2} + \frac{x^2 - y^2}{a^2}\right) \cos 2\theta + 2\frac{xy}{a^2} \sin 2\theta\right] + 2\left[3\left(\frac{\sigma_x^2 - \sigma_y^2}{a^2}\right) + \frac{x^2 - y^2}{a^2}\right] \left(\frac{x}{a} \cos 3\theta + \frac{y}{a} \sin 3\theta\right) + \text{higher order terms} \right\}$$

← monopole terms ~ beam intensity

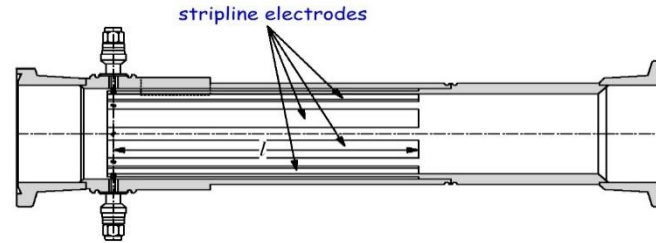
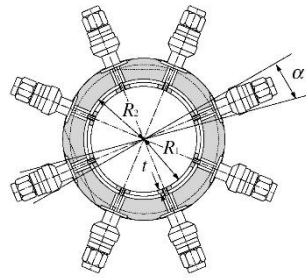
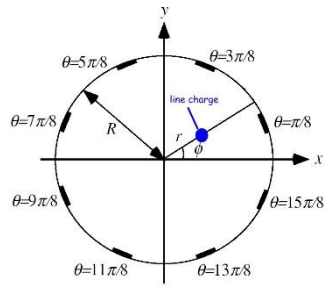
← dipole terms ~ beam position

← quadrupole terms ~ beam size

← sextupole terms

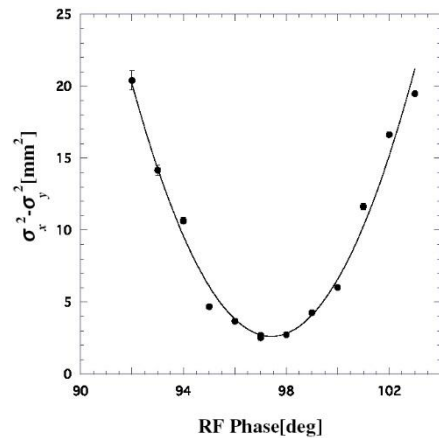
T. Suwada, M. Satoh, K. Furukawa “Nondestructive beam energy-spread monitor using multi-strip-line electrodes” PRSTAB 6, 032801

principle: measure the energy spread derived from the quadrupole moments of the beam in regions of nonzero dispersion

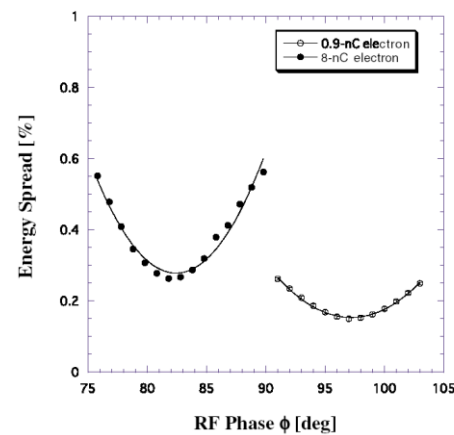


cylindrically symmetric with 8 electrodes
length (as long as possible) constrained
by geometrical considerations (space)
50 Ohm output impedance
rotation to avoid synchrotron radiation

cross-calibration
using OTR screen



energy spread
measurements



energy spread found by solving:

measured with BESM (correction for gain imbalance and geometrical errors)

$$\langle x^2 \rangle - \langle y^2 \rangle$$

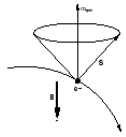
$$\approx \beta_x \epsilon_x + (\eta_x \Delta E / E)^2 - \beta_y \epsilon_y + g$$

derived from independent measurement

(all figures courtesy T. Suwada, 2004)

Energy Calibration With High Precision

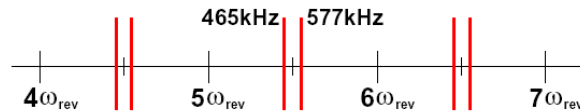
- Bending magnet field measurements (Hall Probes): $\rightarrow \frac{\Delta E}{E} = (1 - 2) \cdot 10^{-3}$
- For higher precision $\rightarrow$ Resonant Spin Depolarization
- In a flat machine the ideal electron sees $\vec{B}_\perp \rightarrow$ spin vector precesses according to Thomas-BMT equation:



$$\omega_{spin} = \omega_{rev} \nu_{ST} = \omega_{rev} \cdot a \gamma$$

$$a = \frac{g-2}{2} = 0.00115965(2)$$

- SLS: $E = 2.4$ GeV, $\omega_{rev} = 1042$ kHz
 $\rightarrow \nu_{ST} = 5.4465$ corresponding to $\omega_{res-depol} \approx 465/577$ kHz



Polarization

- Spin-flip synchrotron radiation (only $\approx 10^{-11}$ of total radiation power) $\rightarrow$ polarization build-up anti-parallel to main bending field:

$$P(t) = P_0(1 - e^{-\frac{t}{\tau}}) \quad \frac{1}{\tau} = \frac{1}{\tau_p} + \frac{1}{\tau_d} \quad P_0 = P_{ST} \frac{\tau_d}{\tau_p + \tau_d}$$

$P_{ST} = 92.4\%$ theoretical maximum for a flat ring

$$\tau_p = \left(\frac{5\sqrt{3}}{8} \cdot \frac{e^2 \hbar}{m_e^2 c^2} \right)^{-1} \cdot \frac{\rho^3}{\gamma^5} \quad @SLS: \tau_p = 1873 \text{ s } (\gamma = 4700)$$

$$@LEP: \tau_p = 360 \text{ min } (\gamma = 86000)$$

$$\tau_d \propto (a\gamma)^{-2} \quad \tau_d \gg \tau_p \text{ for low-energy machines}$$

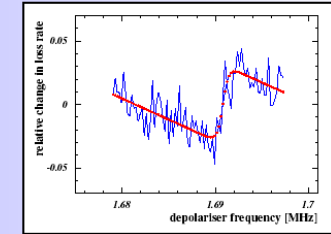
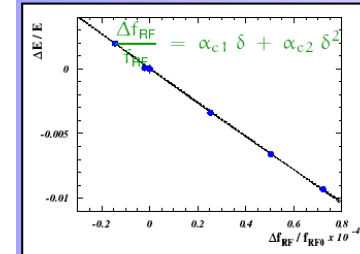
- How to measure polarization without a polarimeter?
 - Touschek lifetime is polarization dependent: $\sigma_{ts} = f_1 - P^2 f_2$
 - Choose filling with high bunch current $\rightarrow \tau$ is dominated by τ_{ts}
 - Identify changes in $I \cdot \tau_{ts}$ with changes in P

Some RDP Results

- Fit to loss rate scans using

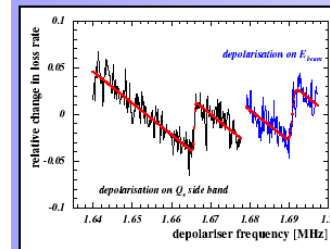
$$\tau = a - \frac{\partial \tau_l}{\partial t} + \frac{\Delta \tau}{1 + \exp \left\{ -\frac{t - t_d}{\sigma_d} \right\}}$$

- Measure α_c using RDP scans for different f_{RF} :



- Expectation for linear term:
 $7.2 \cdot 10^{-3}$
- $\alpha_{c1} = (7.39 \pm 0.01) \cdot 10^{-3}$
- Quadratic term:
 $\alpha_{c2} = (4.1 \pm 0.2) \cdot 10^{-2}$
 $\rightarrow$ highly significant but small

Bunch Lengthening & RDP

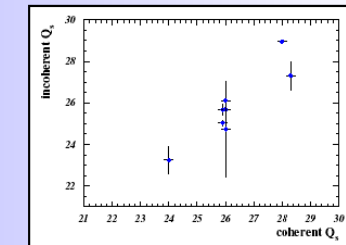


- Depolarisation can also occur on synchrotron side bands
- Due to the single particle nature of the depolarisation process, this happens at $f_{dep}/f_{rev} = [v] \pm Q_s^{inc}$
- RMS bunch length: $\sigma_s \propto 1/Q_s^{inc}$

- The coh./inc ratio is a measure for bunch lengthening with current

$$\frac{Q_s^{coh}}{Q_s^{inc}} = 1 - \lambda I_{bunch}$$

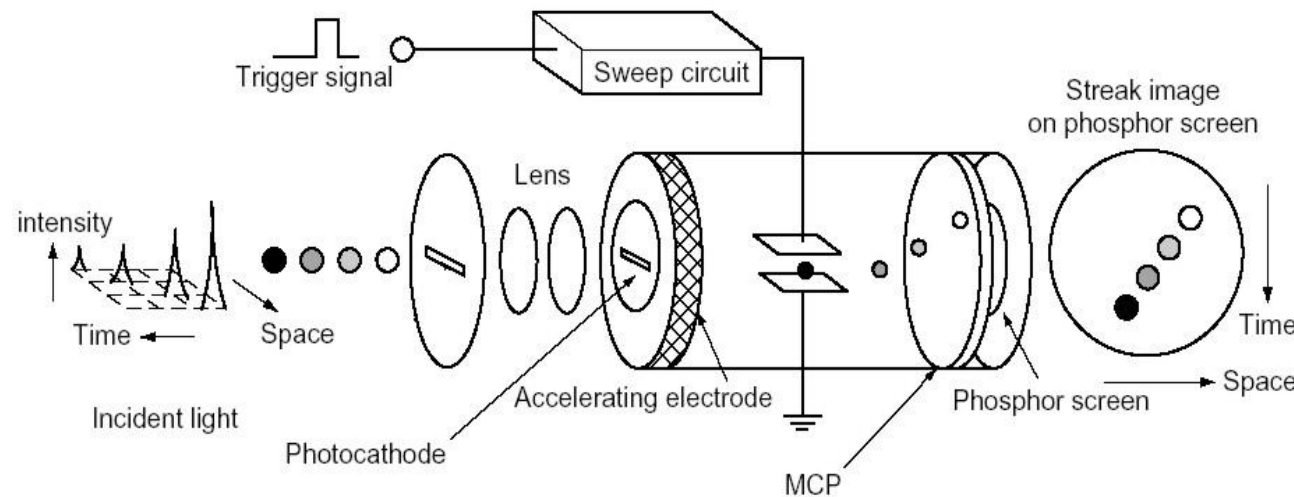
- Average coherent/incoherent ratio:
 (1.02 ± 0.03)
 $\rightarrow$ no significant lengthening



Bunch Length (1)

conventional methods: streak camera

principle: photons (generated e.g. by SR, OTR, or from an FEL) are converted to e^- (photocathode), which are accelerated and deflected using a time-synchronized, ramped HV electric field; e^- signal is amplified (MCP), converted to γ 's (phosphor screen) and detected using an imager (e.g. CCD array), which converts the light into a voltage

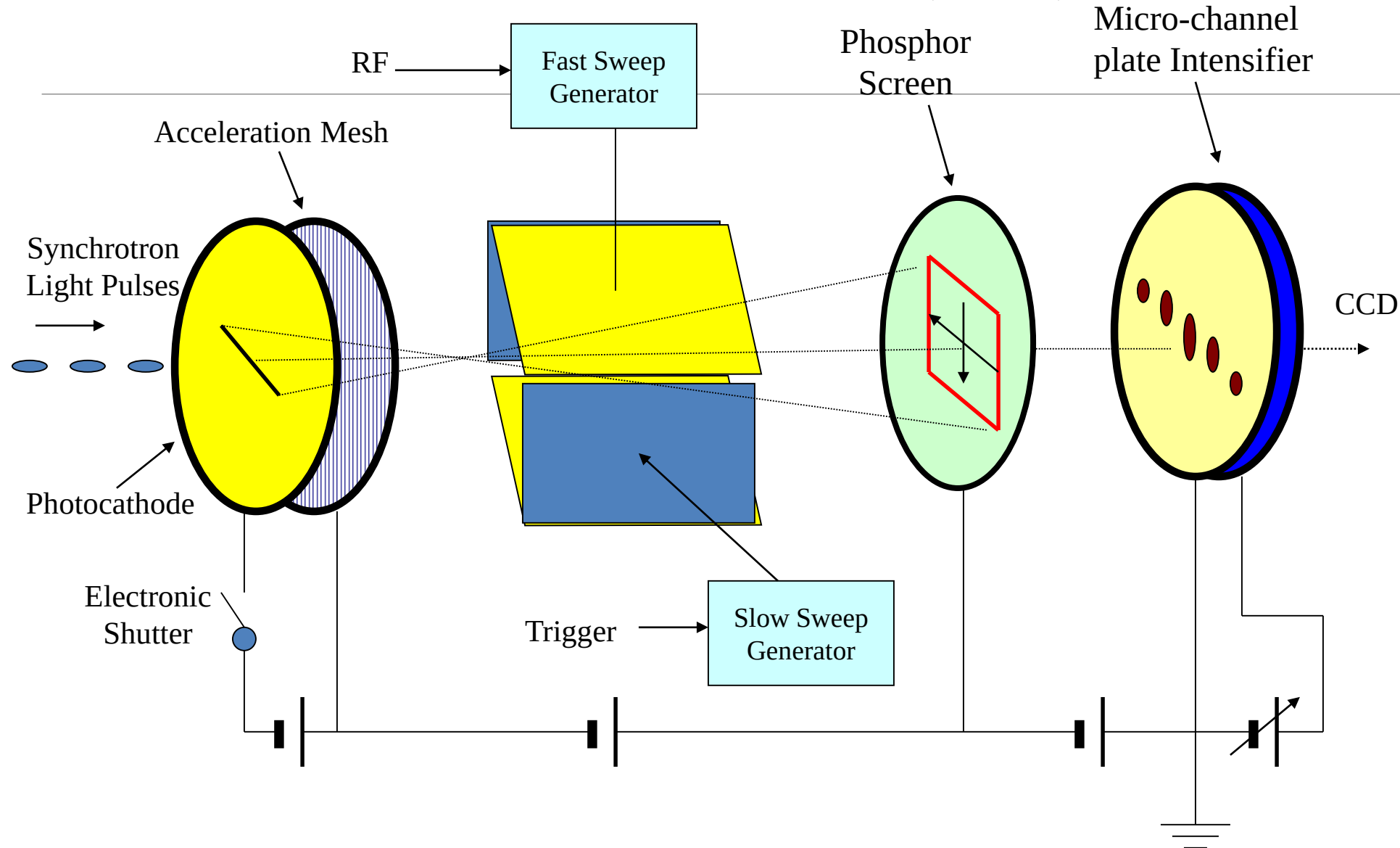


from Hamamatsu home page, C5680 series
(www.hama-comp.com)

issues: energy spread of e^- from the photocathode
(time dispersion)
space charge effects following the photocathode
chromatic effects ($dt/dE_\gamma(\lambda)$) in windows
trigger jitter

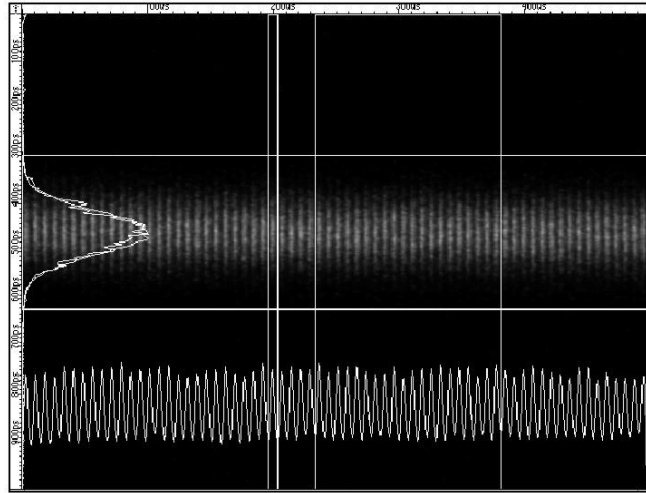
lower limit
on resolution
 ~ 0.5 ps

Bunch Length (1-1)

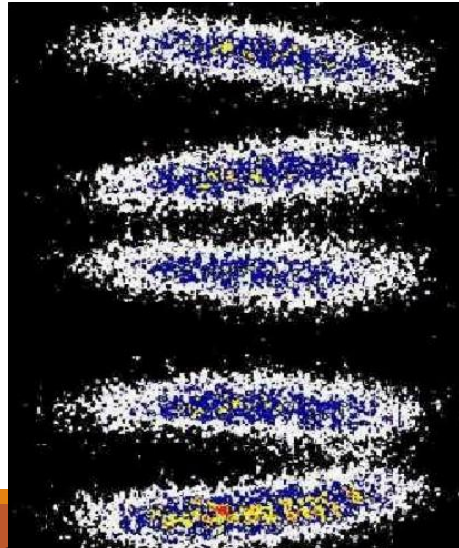


Bunch Length (1-2)

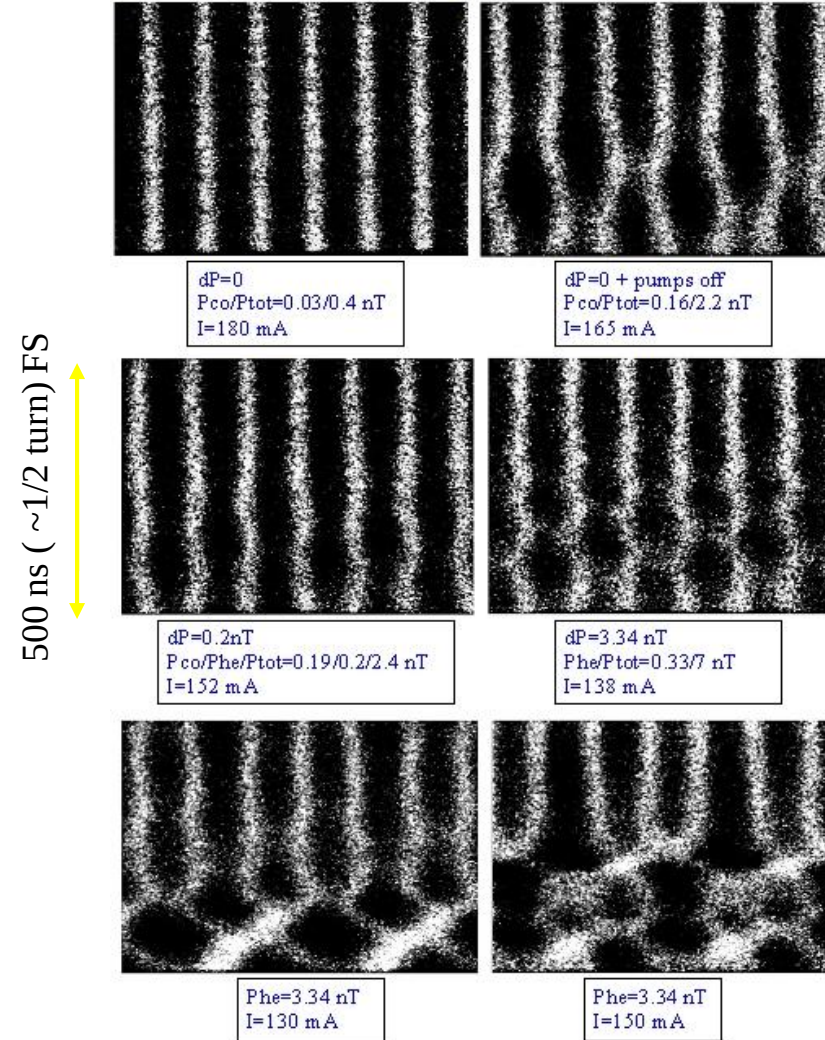
example: bunch length in PEP-II B-Factory (courtesy A. Fisher, 2004)



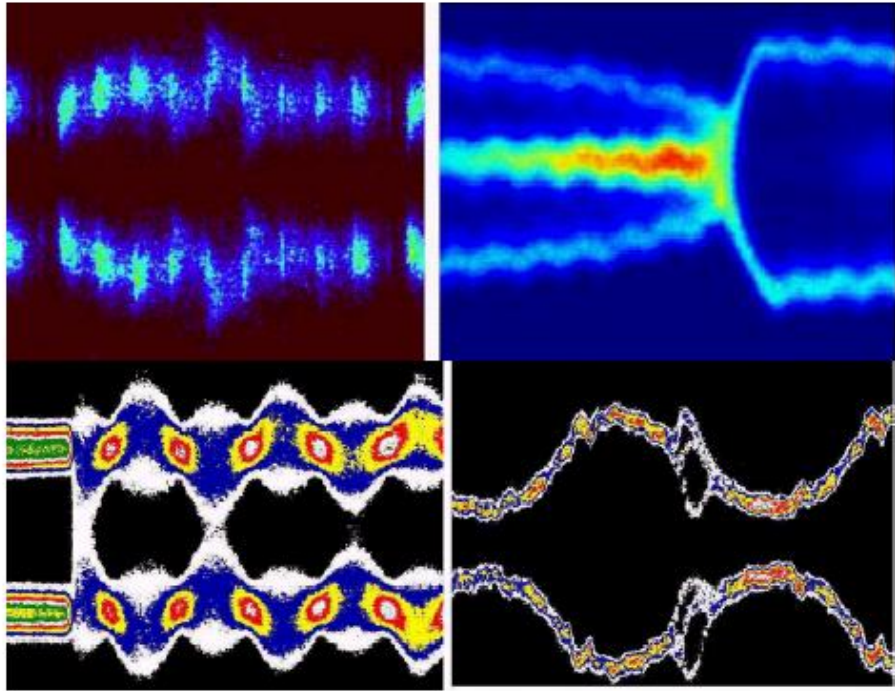
example: bunch length in ESRF over 5 turns (courtesy K. Scheidt, 2004)



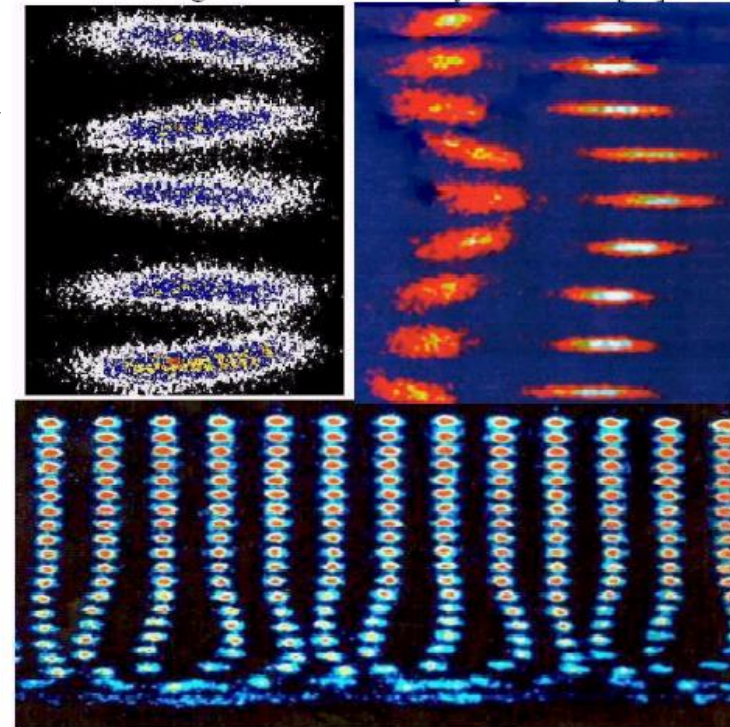
example: streak camera images from the Pohang light source evidencing beam oscillations arising from the fast-ion instability (courtesy M. Kwon, 2000)



Bunch Length (1-3)



(top-left) PEP-2 HER: phase jumps in center of 1658 bunch train fill , (top-right) Spear: full cycle of bunch filamenting with cavity tuning at Robinson instability, (bottom-left) ESRF: longitudinal oscillations of the beam at injection into the Storage Ring, (bottom-right) : ESRF phase jumps with the beam undergoing RF Voltage modulation to obtain Landau damping.



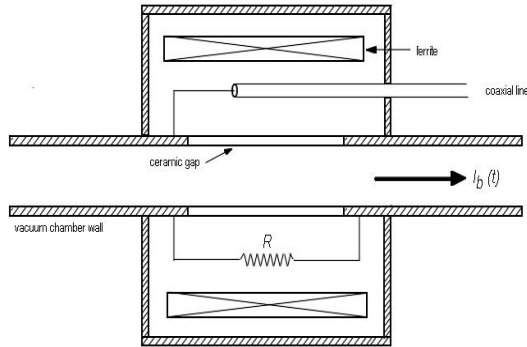
(left) : ESRF five turns of single bunch showing vertical Head-Tail instability, (right) : LEP top & side views of bunch over 9 turns showing vertical Head-Tail effects, transverse motions and bunch length fluctuations, (bottom) : APS horizontal coherent motions at trail of the 60ns filling pattern over 13 turns.

K.Scheidt

Bunch Length (2)

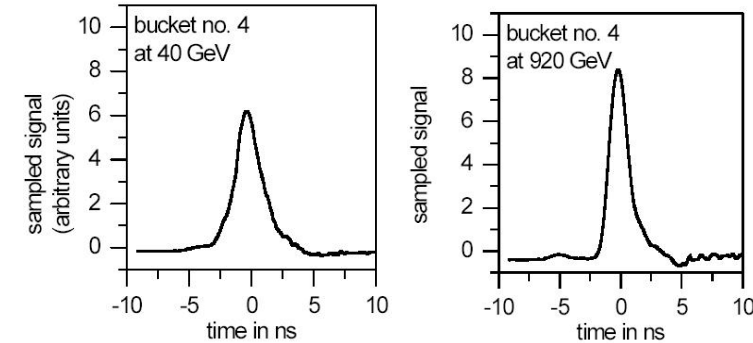
conventional methods: wall gap monitor

recall: resistive wall gap monitor:

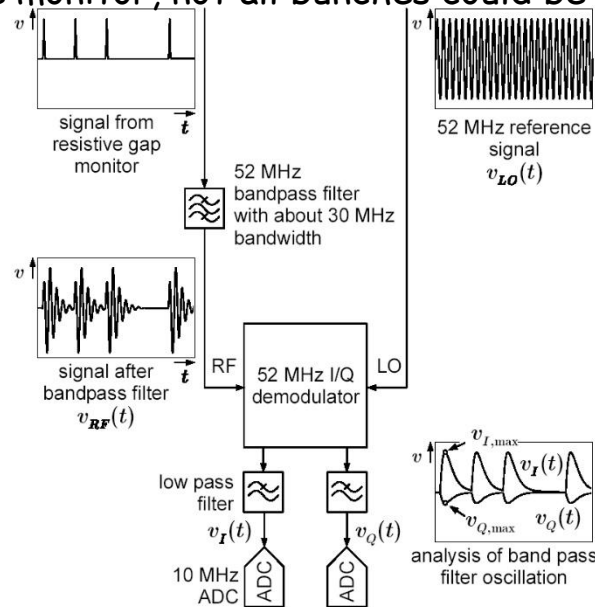


the wall current, after conversion to voltage, is measured with a high bandwidth ($\sim$ GHz) scope

example: R-WGM bunch length measurements at HERA (courtesy E. Vogel, 2004)



with only a single monitor, not all bunches could be simultaneously measured (here $\sim$ s, possible: $\sim$ ms) $\rightarrow$ processing of rf signals for real-time measurements:

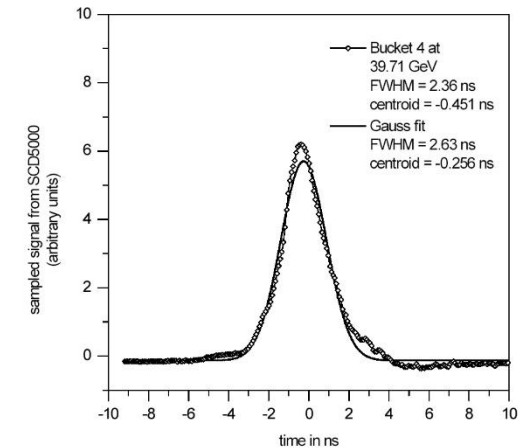


measurement of in-phase (I) and out-of-phase (Q) component of bunch spectrum at some frequency yields signal amplitude, $A(t)$:

$$A(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{t^2}{2\sigma^2}}$$

ratio of signals at two different frequencies
 $\rightarrow$ simple solution for the bunch length σ

example: bunch length measurements at HERA from frequency mixing (courtesy E. Vogel 2004)



measured by comparing two Fourier components of the beam => Real-time measurement

If the longitudinal distribution of electron bunch is Gaussian with an rms length σ_l , the Fourier component of the n th harmonic can be expressed as

$$V(n\omega_0) = 2V_0 e^{(-n^2\omega_0\sigma_l^2/2)}$$

where ω_0 is the revolution frequency of particle, $V(n\omega_0)$ the induced voltage obtained on an ideal beam pickup and V_0 the DC component. Thus, the rms bunch length can be obtained by comparing the Fourier components as

$$\sigma_l = \frac{1}{\omega_0} \sqrt{\frac{2}{(n_2^2 - n_1^2)} \ln \frac{V_1(n_1\omega_0)}{V_2(n_2\omega_0)}}$$

Here, V_1 and V_2 are Fourier components at the n_1 th and n_2 th harmonics of the revolution frequency with $n_2 > n_1$.

Q. Qin*, Z.Y. Guo, G. Xu, L. Ma, Z. Zhao, NIM A463 (2001) 77-85

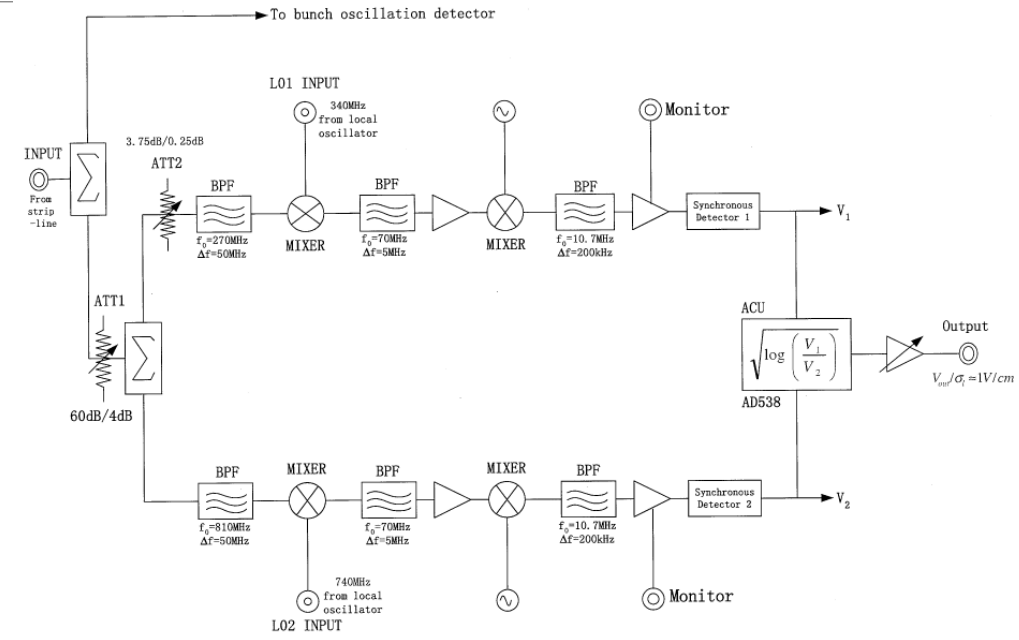
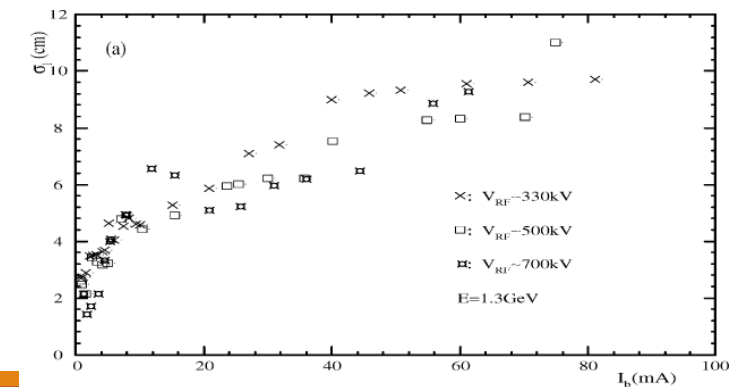
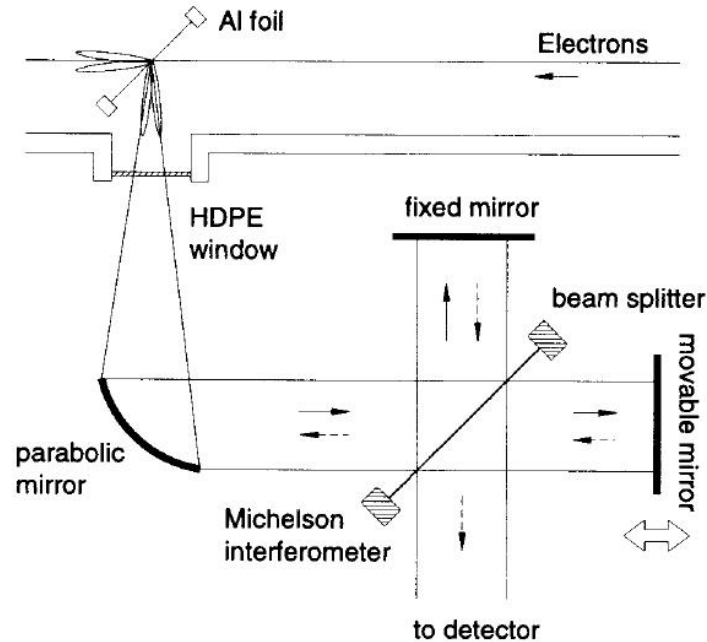


Fig. 1. Block diagram of the beam spectrum analysis system.



newer methods: the Michelson interferometer

principle: use the interferometer to probe the bunch-length dependent frequency spectrum of the bunch



spectrum of a monochromatic wave:

$$\frac{2\pi}{\lambda}$$

$$S(\Delta x) = I(k)(1 + \cos k\Delta x)$$

intensity of
incoming radiation

path length difference
between two arms of
the spectrometer

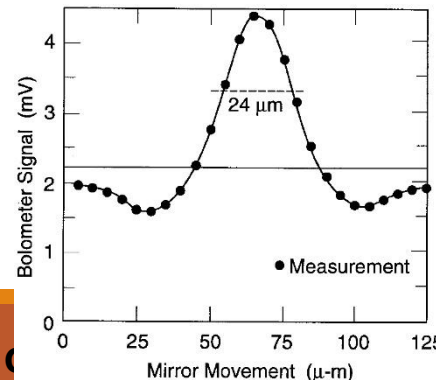
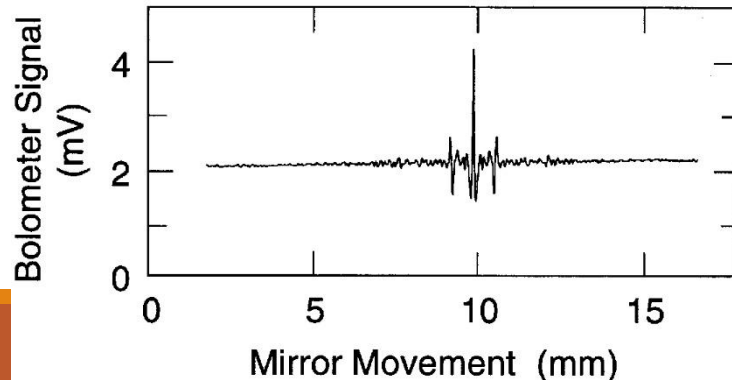
finite spectrum:

$$\begin{aligned} S(\Delta x) &= \int_0^\infty I(k)(1 + \cos k\Delta x) dk \\ &= S_0 + \int_0^\infty I(k) \cos k\Delta x dk \end{aligned}$$

signal with large Δx

interferogram: $S(\Delta x) - S_0$

examples: interferograms measured at the Stanford "sunshine facility" (courtesy H. Wiedemann, 2004)

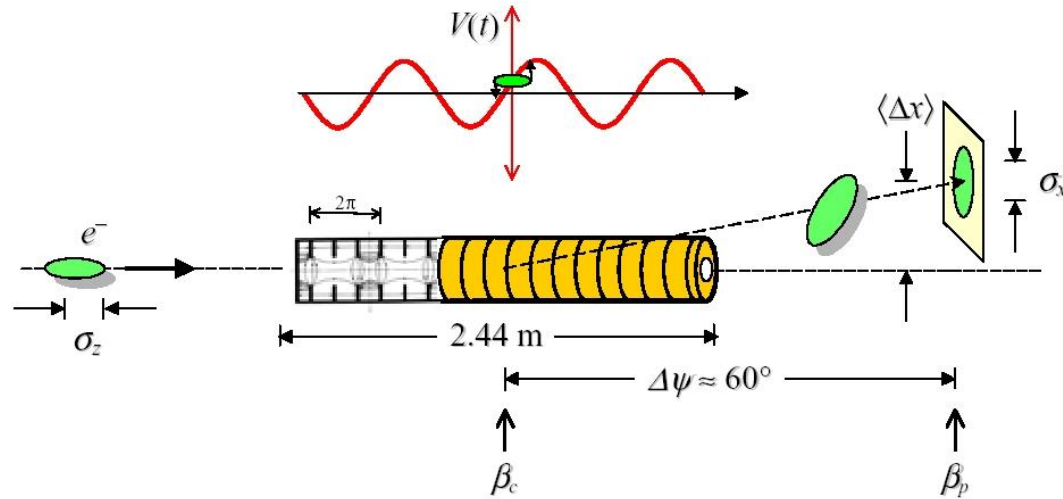


signal FWHM in interferogram (assuming Gaussian bunches):

$$\left(\frac{2.35}{\sqrt{2}}\right)\sigma_z$$

issues: long time averaging water absorption lines

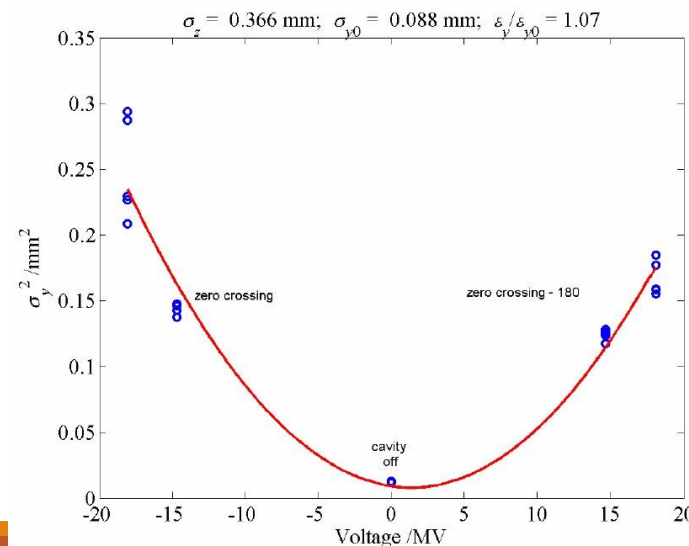
Principle: use transverse mode deflecting cavity to "sweep"/kick the beam, which is then detected using standard profile monitors



Principle of the TM_{11} transverse mode deflecting cavity

introduce x-z correlation

oriented to displace beam vertically while a horizontal bending magnet deflects the beam onto the screen



$$\sigma_y^2 = A(V_{rf} - V_{rf,min})^2 + \sigma_{y0}^2$$

$$\sigma_z = A^{1/2} E_0 \lambda_{rf} / 2\pi R_{34}$$

(R. Akre, 2003)

σ_z expressed in terms of fit parameter, A

newer methods: transverse-mode cavity

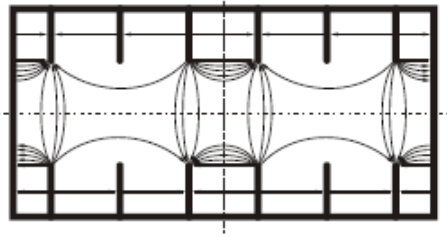
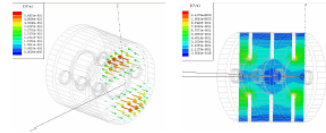


Figure 2.9: Time snap-shot of the electric field distribution of the TM_{11} -mode [Emm00]. The period spans three cells, so it is a $2\pi/3$ -mode. LOLA is given by Eq. (2.69).

Beam bunch length measurement

✓ SLAC - LOLA studying by IHEP



Vertical RF deflecting structure (one period) HFSS simulation

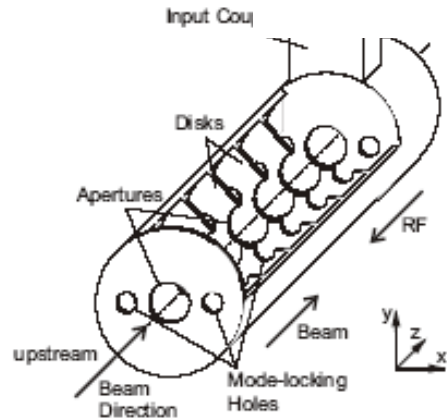


Figure 3.2: Cut-away view of the cavity LOLA. The RF is led into the cavity via an input coupler at the downstream end. The RF travels against the beam direction. Due to the negative group velocity of $v_g < 0$ with respect to the phase velocity, the wave travels downstream as fast as the beam. The big apertures in the disks cause a very strong coupling of the fields. The mode-locking holes avoid a possible rotation of the TM_{11} -mode.

Transverse deflecting RF structure (LOLA) : O. H. Altenmueller, R. R. Larsen, and G. A. Loew, *Investigations of Traveling-Wave Separators for the Stanford Two-Mile Linear Accelerator*, The Review of Scientific Instruments, Vol. 35, Number 4, April 1964.

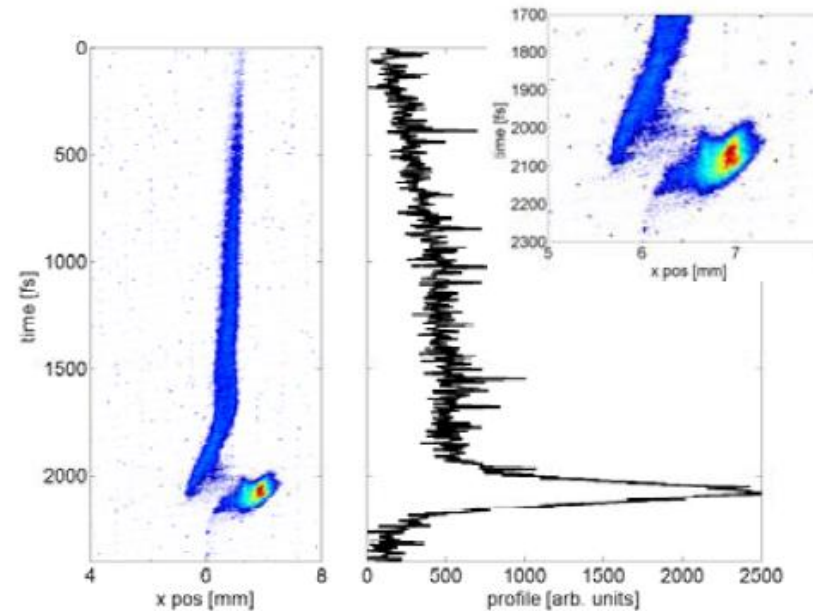


Figure 2: Image of the streaked bunch; inset: zoom on the spike at the head. The streak was approximately 4 fs/px.

Investigation of the longitudinal charge distribution of electron bunches at the VUV-FEL using the transverse deflecting cavity LOLA, (Diploma Thesis) Andy Bolzmann - Department of Physics of the Bayerische Bolzmann, Julius-Maximilians Universität

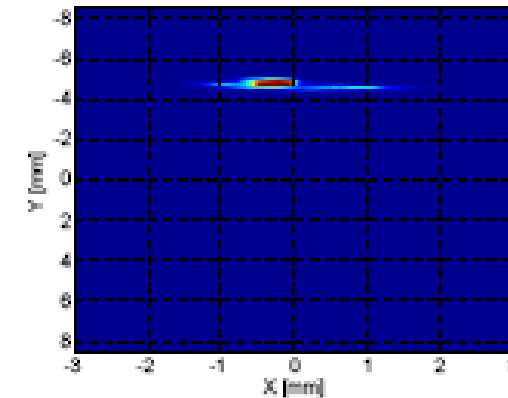
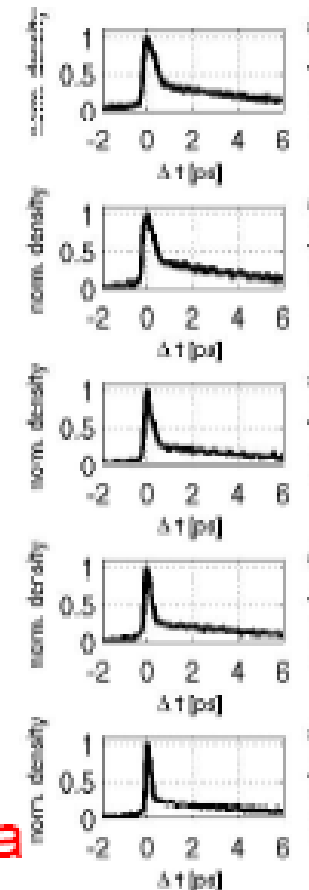
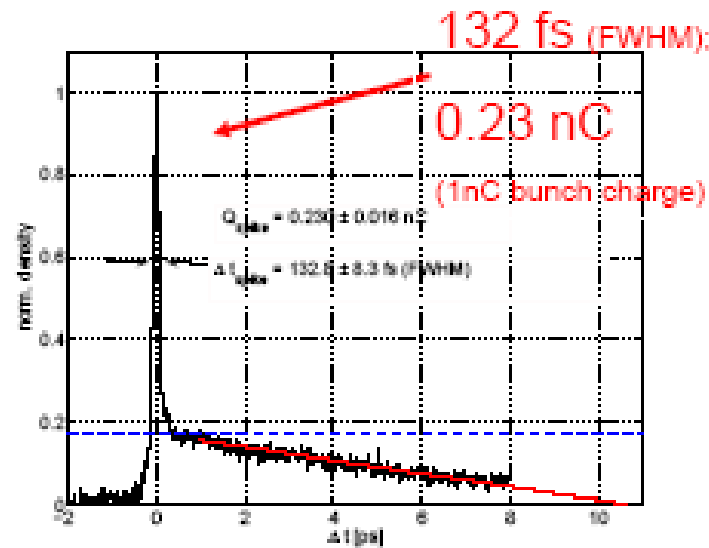
Bunch Length (5-1)

newer methods: transverse-mode cavity

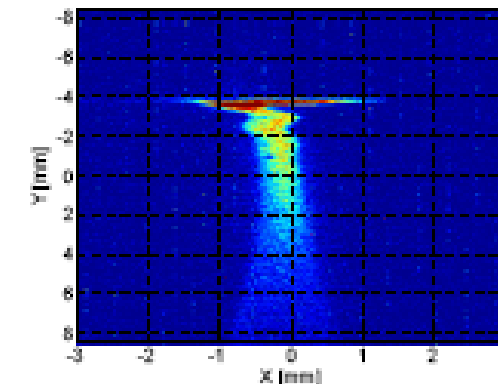
Measurements with LOLA:

Longitudinal density profile

LOLA off:



LOLA on:



→ Resolution depends on the vertical beam size at the screen

Horizontal slice emittance

Energy-time correlation (via dispersion)

Bunch Length (5)

Coherent Smith Purcell Radiation Bunch Length Diagnostic

The radiation is angularly dispersed in frequency according to the SPR dispersion relation

$$\lambda = \frac{l}{n} \left(\frac{1}{\beta} - \cos \theta \right)$$

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ACCELERATORS AND BEAMS 9, 022802 (2006)

where

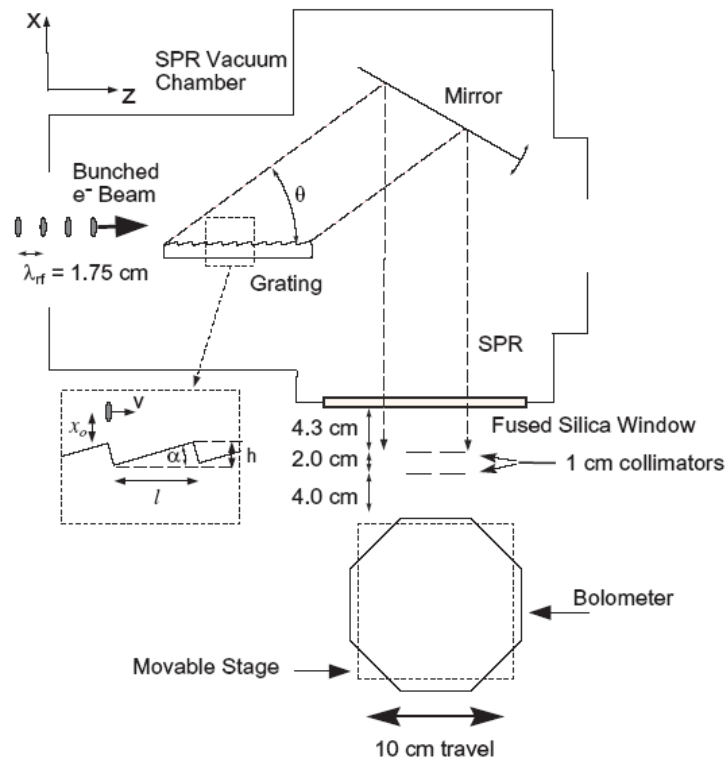
λ is the wavelength of the radiation

n is the order of the radiation,

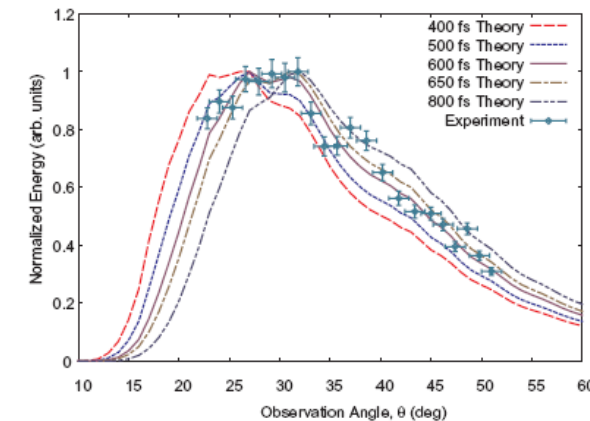
l is the grating period,

β is the ratio of the electron velocity to the
speed of light

θ is the observation angle



SPR experimental setup. The train of bunched electrons is traveling along the z direction above a metallic echelle grating. The diffracted radiation is measured by a detector located outside of the vacuum chamber.

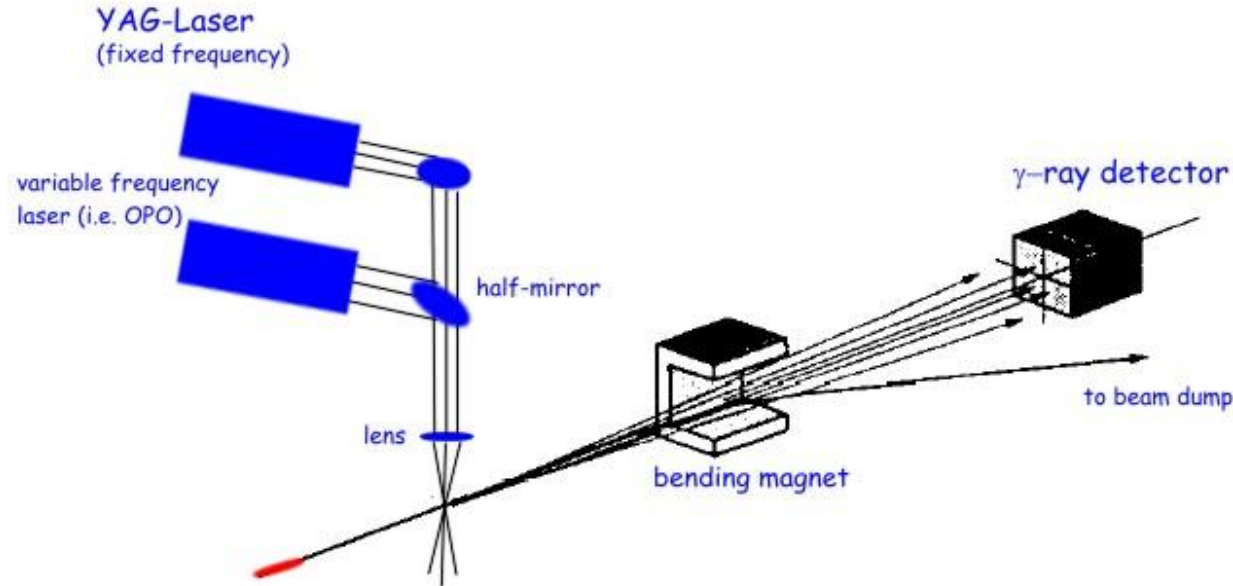


Plot of the angular distribution of SPR normalized energy from the 6 mm grating as measured by the Si bolometer. The theoretical curve is shown for a 15 MeV beam with various Gaussian longitudinal distributions, and 1 mm FWHM Gaussian transverse distribution.

Bunch Length (6)

proposed methods: “beat wave” interferometer (T. Shintake)

principle: the light of a tunable laser is combined with a fixed wavelength laser providing a “beat-wave” (intensity modulation with frequency equal to the frequency difference of the two laser beams) with which the bunch interacts; signal amplitude measured as a function of variable frequency laser (or bunch arrival time)



bunch length measurements: scattered Compton γ 's as a function of frequency

issues:

laser power imbalance (mirror “asymmetries”) and laser alignment electron beam crossing angle (electron beam not parallel to the plane of the fringes) longitudinal extent of the interference pattern (compare “hour-glass” effect) spatial and temporal coherence of the laser (alignment distortions) laser jitter