Diagnostics for Light Sources

Introduction

Diagnostics Systems & Related Measurements

- Electron Beam Position Monitors
- Photon Beam Position Monitors
- Current Monitors
- Synchrotron Light Monitors

V. Schlott (PSI)

Acknowledgements

… to be able to present a state-of-the-art overview of light source diagnostics, I have been relying on the outstanding work of many colleagues from various synchrotron radiation facilities

… this presentation is far from being complete ! It tries to give an overview of light source diagnostics with a number of – hopefully instructive – examples and (latest) measurements

… for their support in discussing the topics, which are presented, and for the provision of information material and measurement results, I would like to explicitly thank the following colleagues…:

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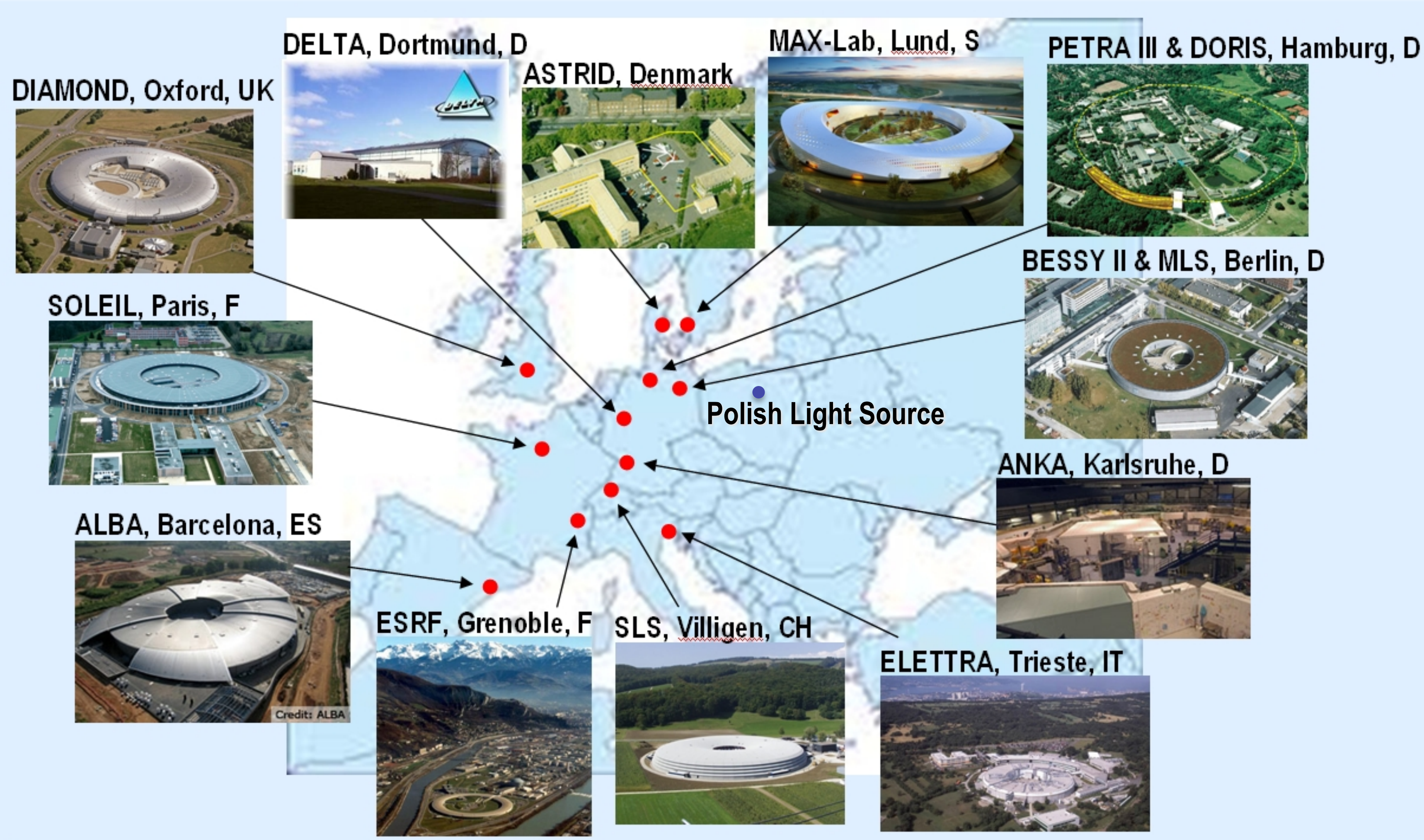
Peter Kuske (BESSY)
Karsten Holldack (BESSY)
Mario Ferianis (ELETTRA)

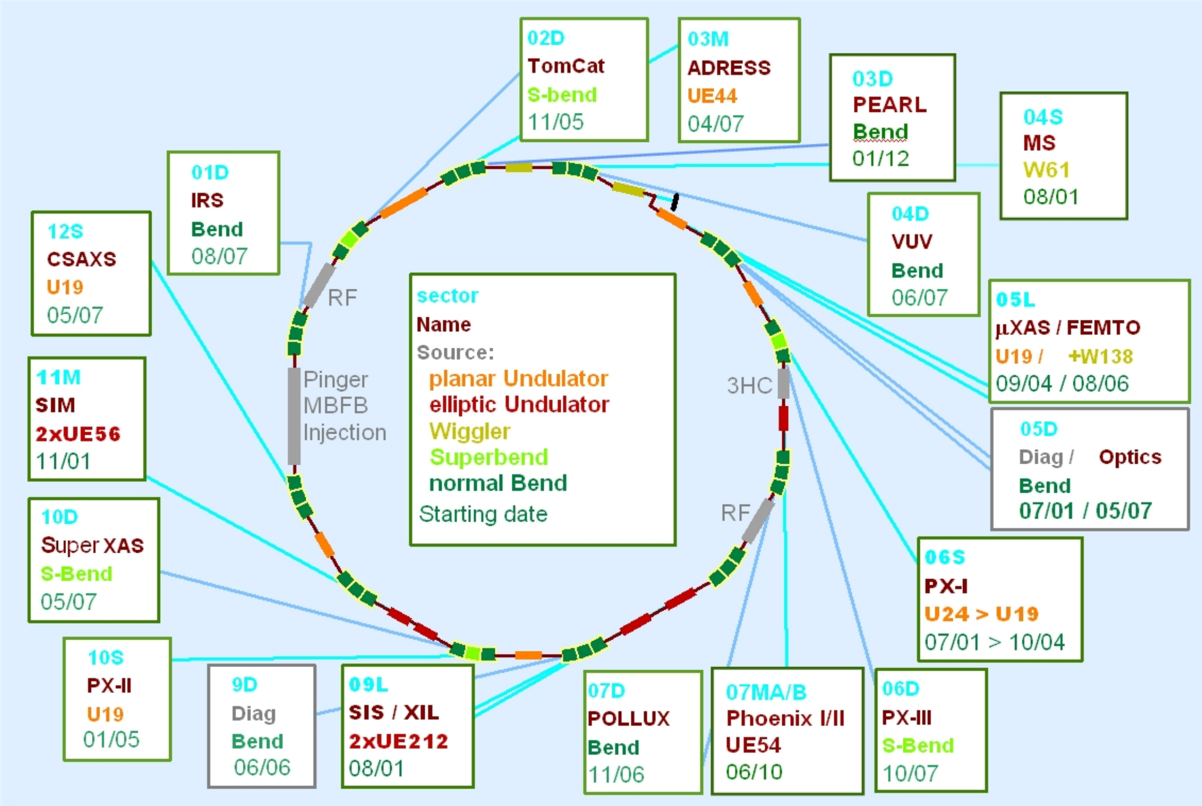
and many more…!!!

3rd Generation Synchrotron Radiation User Facilities in Europe



3rd Generation Light Source User Facilities: SLS Beamlines (2010)

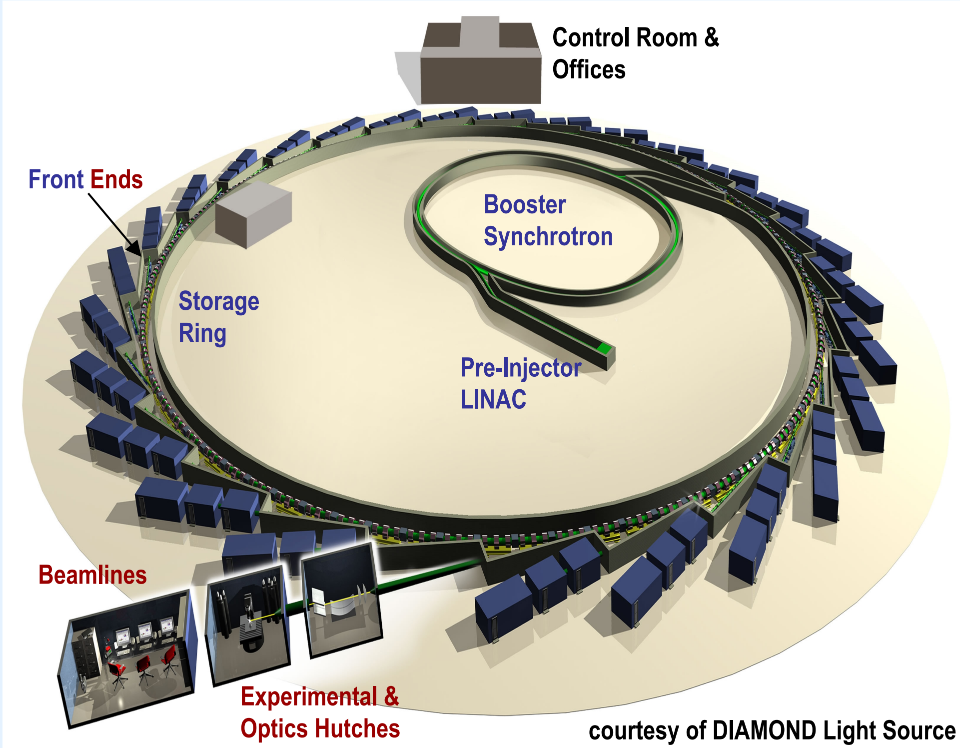
Number of Beamlines:	several tens	Photon Spot Sizes:	sub-µm – few 100 µm
Photon Energies:	THz – > 100 keV	Photon Beam Stability:	σ / 10 (≥ 1 µm)
Flux:	$\leq 10^{13}$ ph / (s 0.1%BW)	Photon Pulse Widths:	few ps – 300 ps
Brilliance:	$\leq 10^{21}$ ph / (s mm^2 mrad^2 0.1%BW)		~ 100 fs (FEMTO-slicing)



Typical Layout & Accelerator Parameters of a 3rd Generation Light Source

Pre-Injector LINAC Parameters

Operation Modes:	single bunch / bunch train
Typ. Energy:	100 – few MeV
Max. Charge:	≤ 2 nC / ≤ 5 nC
ΔE/E:	< 0.5% (0.2 %)
Energy Stability:	< 0.1% (0.1%)
Timing Jitter:	< 100 ps (10 ps)
Typ. Emittance:	< 50 mm mrad
Rep.-Rate:	< 10 Hz



courtesy of DIAMOND Light Source

Booster Synchrotron Parameters

Energy Ramp:	few 100 MeV – few GeV
Ramp Times:	~ 100 ms
Design Current:	≤ 3 mA
Design Emittance:	< 250 nm mrad
Efficiency:	~ 80%
Rep.-Rate:	< 10 Hz

Storage Ring Parameters (European Light Sources)

Electron Energies:	105 MeV – 6 GeV	Horiz. Emittances:	1 – 100 nm rad	Filling Pattern:	single & multiple bunches camshaft to uniform
Beam Currents:	100 pA – 500 mA	Coupling:	< 0.1 – 1 %		
Life Times:	10 – 75 h top-up operation	Vert. Emittances:	≥ 3 pm rad	RF Frequencies:	100 – 500 MHz
		Horiz. Beam Sizes:	few tens of μm	Bunch Spacings:	10 – 2 ns
MTBF / Beam Loss:	< 175 h	Vert. Beam Sizes:	few μm	Bunch Lengths:	few ps – 300 ps
Circumferences:	48 – 2300 m	Horiz. Divergence:	few tens of μrad	Orbit Stability:	< 1 μm (MTF to 200 Hz)
Revolution Frequ.:	6.25 – 0.130 MHz	Vert. Divergence:	few μrad		

Diagnostics Requirements for 3rd Generation Light Sources

the key parameter to be optimized in 3rd generation light sources is the spectral brilliance

$$B \propto \frac{N_{photons}}{\sigma_x \sigma_{x'} \sigma_y \sigma_{y'}} \propto \frac{I_{beam}}{\varepsilon_x \varepsilon_y} \left[\frac{Number\ of\ Photons}{s\, mm^2\, mrad^2\, 0.1\%\, bandwidth} \right]$$

→ high beam current - ideally „top-up“ operation
highly efficient, low loss injector chain

→ small beam emittances - ideally low coupling (< 0.1%)
measurement of small beam sizes with high resolution SR monitors

→ high beam stability - ideally „top-up“ operation with fast and slow orbit feedbacks
high resolution electron and photon BPM systems

Overview of Diagnostics Devices for 3rd Generation Light Sources

Beam Position Monitors:

Button BPMs: x_k, y_k, I_k (k = BPM index)
- → commissioning & injection studies
- → orbit correction & FOFB
- → tunes and chromaticity
- → local and global coupling / resonances

Bunch Charge & Current Monitors:

ICT / BCM in LINAC and TLs
- → transmission and injection efficiency

MPCT in booster synchrotron
- → beam current and transmission on the ramp

DCCT / PCT in storage ring
- → injection efficiency and stored current
- → beam lifetime

Transverse Profile Monitors:

OTR and scintillator screens
- → beam profiles, emittance & ΔE/E in LINAC & TLs
- → injection matching in booster & storage ring

synchrotron radiation monitors
- → beam size, emittance & coupling

Longitudinal Profile Monitors:

Wall Current Monitors, FCTs
- → bunch pattern in LINAC & TLs
- → bunch purity in LINAC & TLs

Streak Camera
- → bunch length / lengthening in storage ring
- → longitudinal instabilities in storage ring

Fast Diodes / PMs
- → bunch pattern / bunch pattern FB in storage ring
- → bunch purity (in photon counting mode)

Beam Loss Monitors & Scrapers:

- → local and global beam loss (low gap undulators)
- → lifetime
- → dynamic aperture studies
- → limitation of storage ring aperture

Photon Beam Monitors:

- → photon beam position (undulator gap compensation)
- → absolute orbit reference & long term stability
- → FOFB „out of loop monitors“
- → more potential…!

Beam Position Monitors: Modes of Operation & Specifications

injection & commissioning mode:

→ x_k, y_k and I_k upon injection trigger (k = BPM index)
→ data processing & transfer in batches

→ position resolution:	< 500 μm (rms)
→ absolute accuracy:	< 500 μm (with respect to quad)
→ intensity / charge res.:	~ 10 % / ≥ 50 pC
→ dynamic range:	< 0.5 – 5 mA
→ current dependency:	< 500 μm (within 10dB range)

turn-by-turn mode:

→ x_k, y_k for several thousand turns (k = BPM index)
→ data processing & transfer in batches

→ position resolution:	~ 1 μm (rms)
→ absolute accuracy:	< 200 μm (with respect to quad)
→ measurement bandwidth:	< 1 MHz
→ dynamic range:	5 – 100 mA
→ current dependency:	not critical for BD studies
→ drift (8h – 1 month):	not critical for BD studies
→ reproducibility (bunch pattern):	< 500 μm

closed orbit correction mode:

→ x_k, y_k (k = BPM index)

→ measurement rate:	few samples per second
→ position resolution:	< 0.2 μm (rms)
→ absolute accuracy (after BBA):	< 1 μm (with respect to quad)
→ measurement bandwidth:	few kHz
→ dynamic range:	10 – 100 mA 100 – 500 mA
→ current dependency:	< 1 μm (10 dB range)
→ drift (8h – 1 month):	< 1 μm / < 5 μm
→ reproducibility (bunch pattern):	< 1 μm

global fast orbit feedback mode:

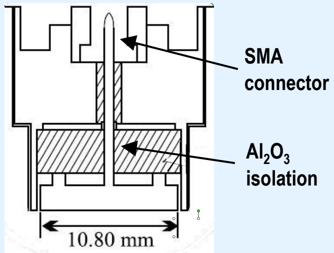
→ x_k, y_k (k = BPM index)

→ measurement rate:	10 kSamples per second
→ position resolution:	< 0.2 μm (rms)
→ absolute accuracy (after BBA):	< 1 μm (with respect to quad)
→ measurement bandwidth:	few kHz
→ dynamic range:	10 – 100 mA 100 – 500 mA
→ current dependency:	< 5 μm (10 dB range)
→ drift (8h – 1 month):	< 1 μm / < 5 μm
→ reproducibility (bunch pattern):	< 1 μm

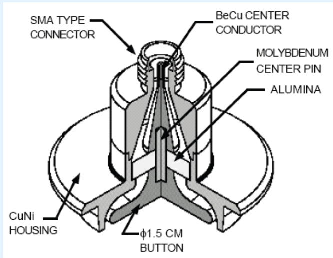
Beam Position Monitors: Signal Considerations for Button Electrodes

Examples of Button Electrodes:

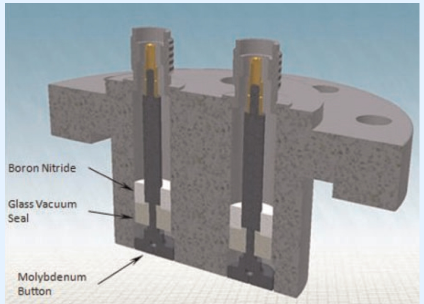
Welded ESRF / DELTA Button



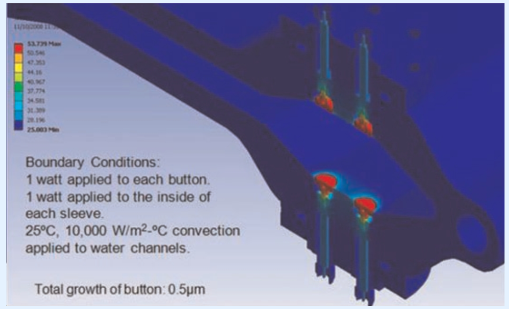
HERA Button



Flanged NSLS-II Button



Heat Load Simulation for NSLS-II Button



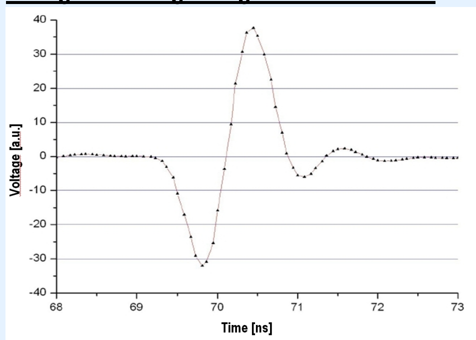
Induced Voltage on Electrode

with a = button radius (typ. 5 – 10 mm)
b = BPM chamber radius (typ. 15 - 20 mm)
$\beta \approx 1$
c = speed of light
R = 50 Ω (termination, dominated by cable)
f = processing frequency (typ. ≤ 500 MHz)

$$V_{button} = \frac{\pi a^2}{2\pi b} \cdot \frac{R}{\beta c} \cdot \frac{dI}{dt}$$

$$= \frac{2\pi a^2}{b} \cdot \frac{R}{\beta c} \cdot f \, I_{avg}$$

Voltage at Storage Ring Button Electrode



courtesy of P. Hartmann, DELTA

Signal Power for 100 mA Beam:

$$P_{signal} = \frac{1}{2} \frac{V_{button}^2}{R}$$

$$\approx 0.67 \, \mu W \approx -32 \, dBm$$

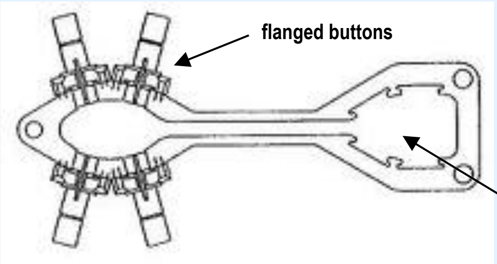
with noise power in 1 MHz BW: ~ 114 dBm
in 10 kHz BW: ~ 134 dBm

For further reading see e.g.: R.E. Schafer, „Beam Position Monitoring“, AIP Conf. Proc. Vol. 212, pp. 26-58 (1989)
AIP Conf. Proc. 249, vol. 1, 612 (1992)
S. R. Smith, „Beam Position Monitor Engineering”, SLAC-PUB-7244, July 1996
P. Forck et al., „Beam Position Monitors“, CAS Beam Diagnostics 2008, 187, CERN-2009-005

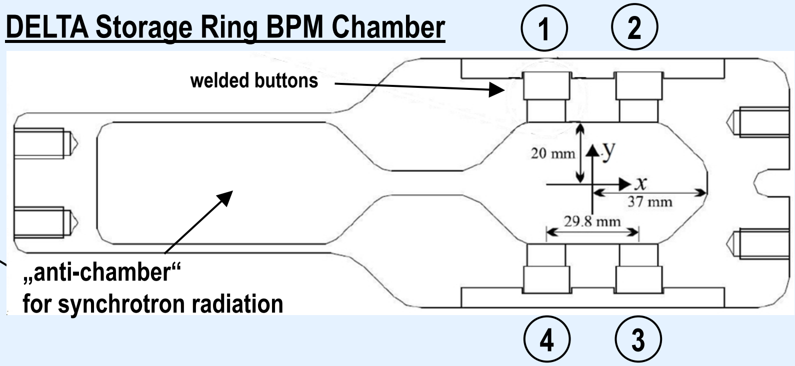
Beam Position Monitors: Storage Ring Chamber Geometries

Examples of Storage Ring BPM Chambers:

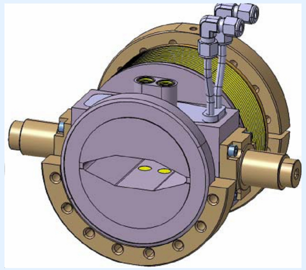
APS Storage Ring BPM Chamber



DELTA Storage Ring BPM Chamber



SOLEIL Arc Chamber



Note…:

… due to heat load from synchrotron radiation, button electrodes have been placed outside of the beam plane

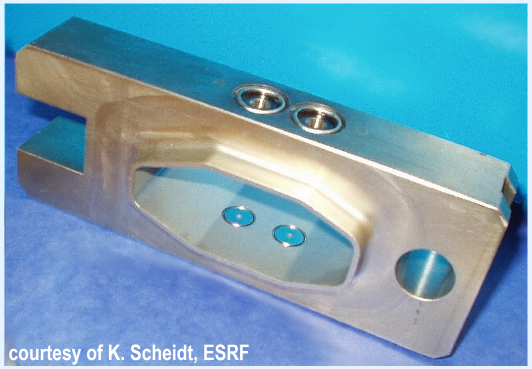
… BPM chamber is typically a massive SS block, which is welded or flanged to the storage ring vacuum chamber

… storage ring vacuum chamber should typically be supported at the locations of the BPM chamber for minimum displacements

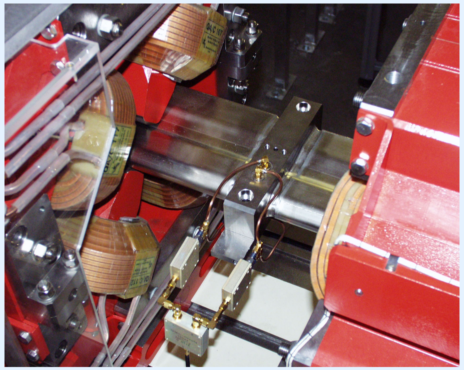
Inside View of DELTA BPM Chamber


courtesy of P. Hartmann, DELTA

ESRF Storage Ring BPM Chamber


courtesy of K. Scheidt, ESRF

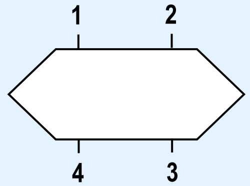
SLS MBF BPM Chamber (with Hybrids)



Light Source BPMs: Position Sensitivity & Non-Linearities

Determination of Horizontal Position:

$$X_{pos} = \frac{1}{S_x} \cdot \frac{(V_1 + V_4) - (V_2 + V_3)}{V_1 + V_2 + V_3 + V_4}$$



Determination of Vertical Position:

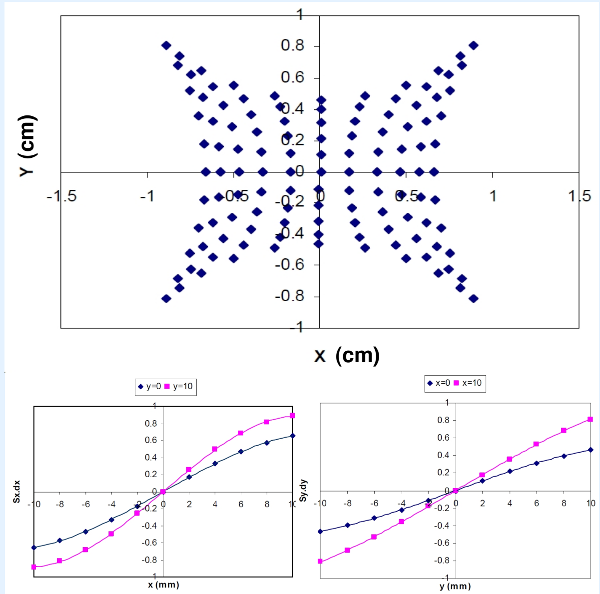
$$Y_{pos} = \frac{1}{S_y} \cdot \frac{(V_1 + V_2) - (V_3 + V_4)}{V_1 + V_2 + V_3 + V_4}$$

Sensitivity parameters S_x, S_y depend on geometry of vacuum chamber, size and distance between electrodes

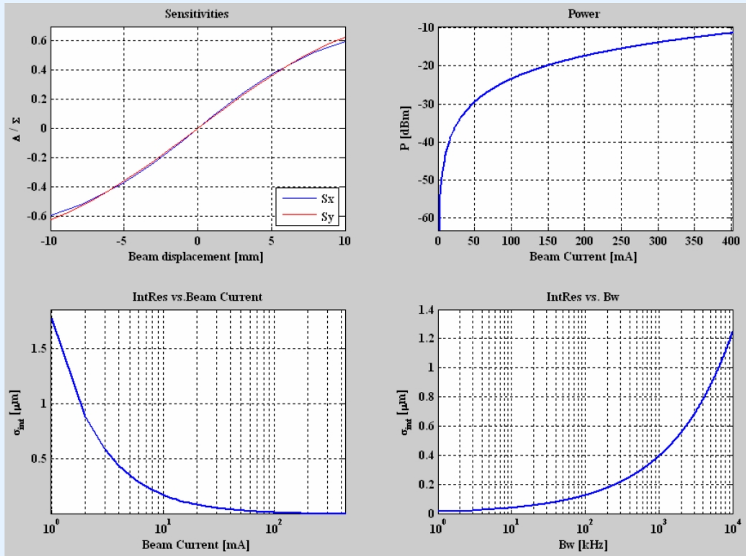
→ general optimization of geometry is obtained by numercal simulations

→ S_x, S_y are typically determined by polynomial fits and given in [% / mm]

SESAME BPM Sensitivity Map (Varnasseri et al., DIPAC 2005)



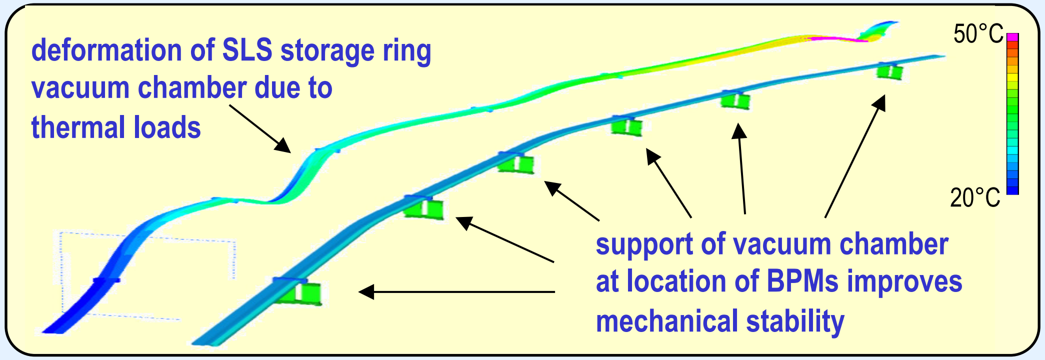
ALBA BPM Simulation Toolbox (Olmos et al., DIPAC 2007)



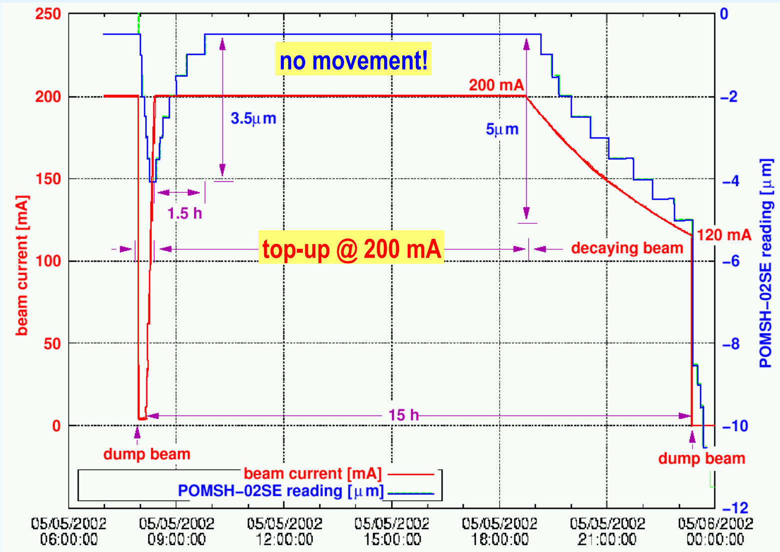
http://www.cells.es/Divisions/Accelerators/RF_Diagnostics/Diagnostics/OrbitPosition/Tools/BPMs_GUI

Storage Ring BPMs: Some Mechanical Considerations & Stability Issues

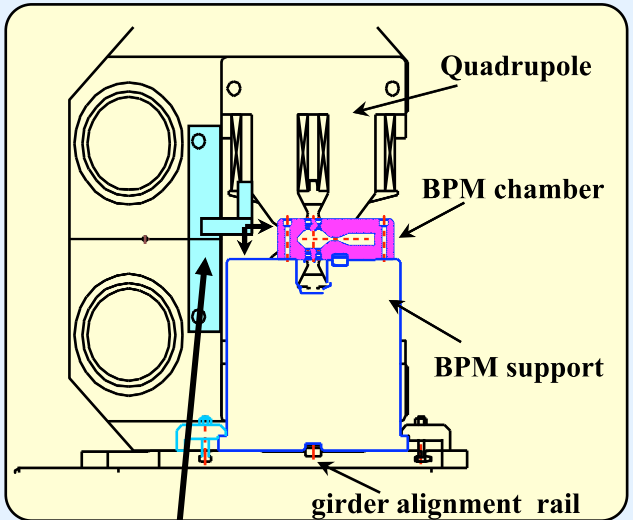
Thermal Load on SLS Vacuum Chamber due to Synchrotron Radiation

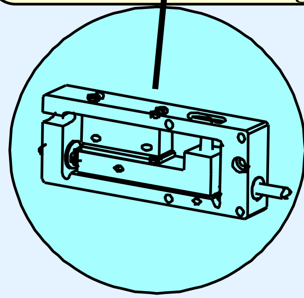


Mechanical Movements of SLS BPM Chambers



Monitoring Mechanical Movements at SLS





dial gauges equipped with linear encoders (0.1 - 0.5 μm resolution) as sensing devices are attached to adjacent quadrupole magnets

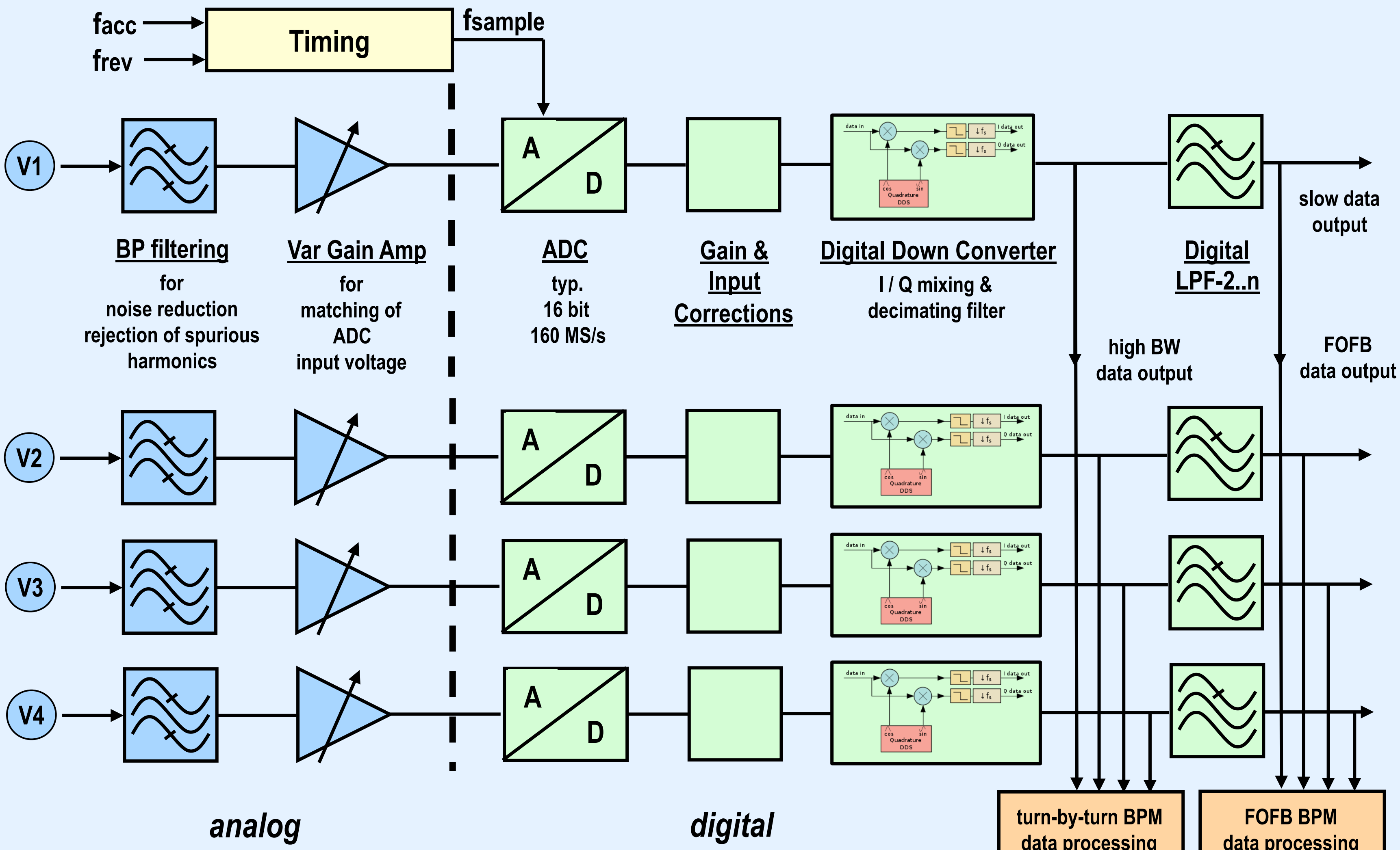
BBA results provide absolute reference positions

Top-Up Operation is the Cure…!!!

→ thermal & mechanical stability

→ no BPM current dependency

Schematic of Light Source Beam Position Monitor Electronics

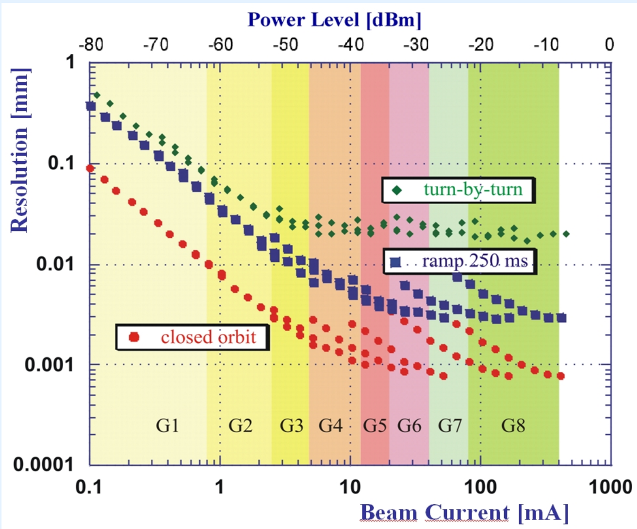


Typical Performances of Light Source Beam Position Monitor Electronics

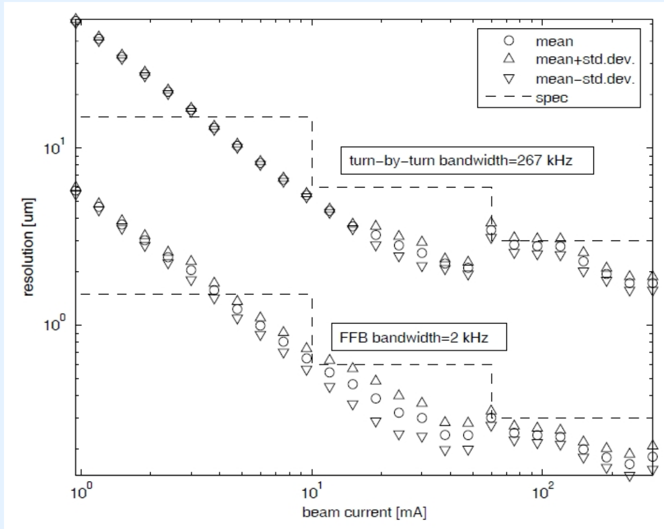
Digital BPM Systems provide: ... selectable bandwidth of BPM data (turn-by-turn, ramp, FOFB...)
... high resolution, low current dependency, low drift and high reproducibility
... in future direct sampling of BPM pick-up signals should be possible

Examples of Light Source BPM System Performances for Different Operation Modes

SLS DPBM Performance (measurements from 2003)



DIAMOND Libera Performance (G. Rehm et al., DIPAC 2005)



Some Remarks: ... due to „top-up“ operation, SLS DBPM system is operated at constant gain levels
... position resolution follows the bandwidth restriction (~ $\sqrt{\text{BW relation}}$)
... next generation DBPM system Libera (Brilliance) provides already improved position resolution

BPM Applications I: Measurement & Optimization of Storage Ring Injection

Pinciple of „4 Kicker Injection“:

1 all 4 kickers „fired“:

the stored beam performs a „closed bump“,

the injected beam enters the storage ring through the septum

2/3 all 4 kickers turned off:

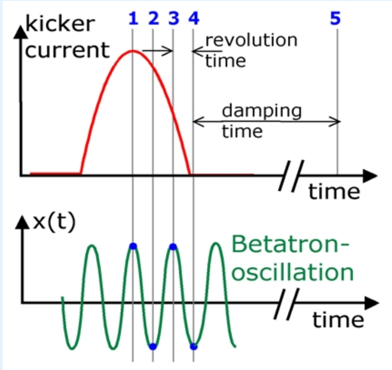
the „closed bump“ of the stored beam fades away,

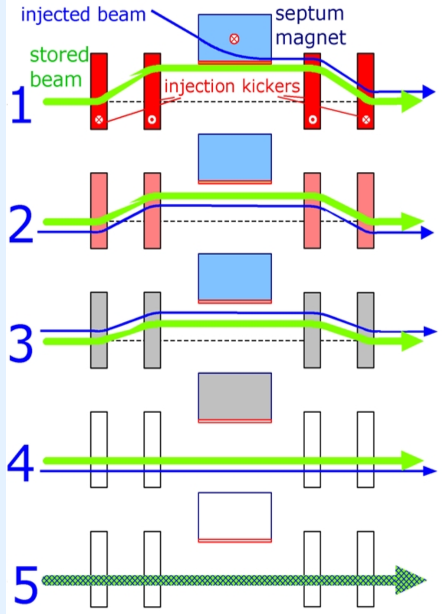
the orbit of the injected beam oscillates around the stored beam

4/5 all 4 kickers off:

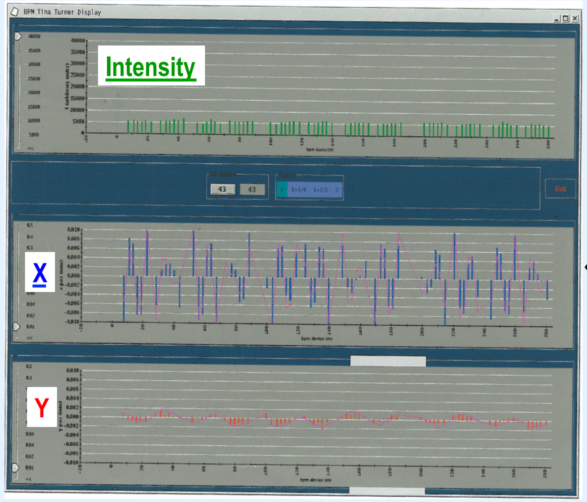
betatron oscillation of injected beam damps down

→ beam is injected and stored on closed orbit

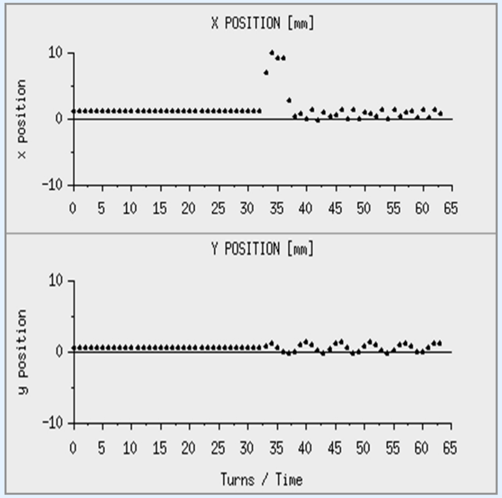




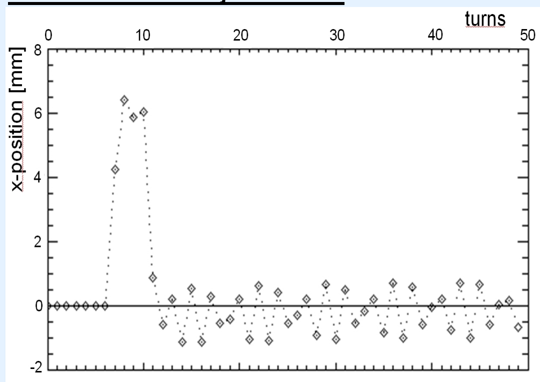
Establishment of Closed Obit from all BPMs (I, X and Y)



Single BPM Turn-by-Turn Meas. of Injection Kick



Simulation of SLS Injection Kick



BPM Applications II: Tune Measurement

Pinciple of Tune Measurement:

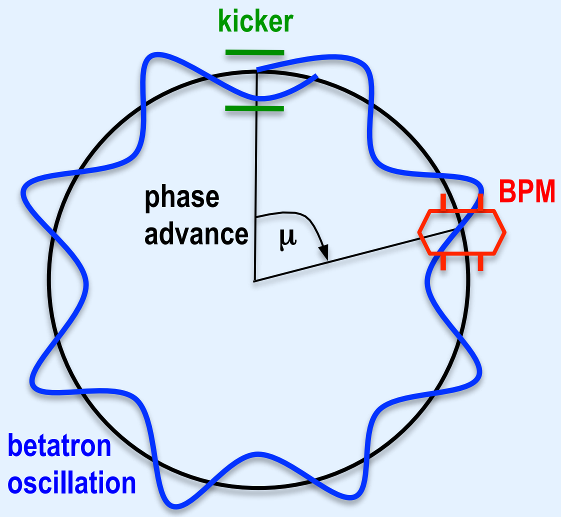
→ excitation of betatron oscillation by kicker magnet (e.g.: septum, MBF kicker)

→ BPM measures turn-by-turn data (e.g.: 4096 horizonatl & vertical psitions)

→ FFT on position readings provides integer part of the tune

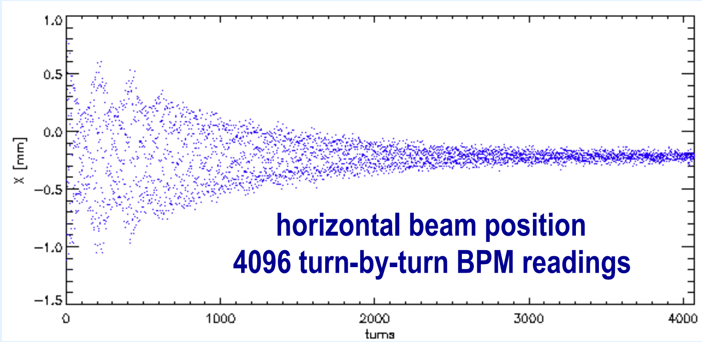
Tune Definition:

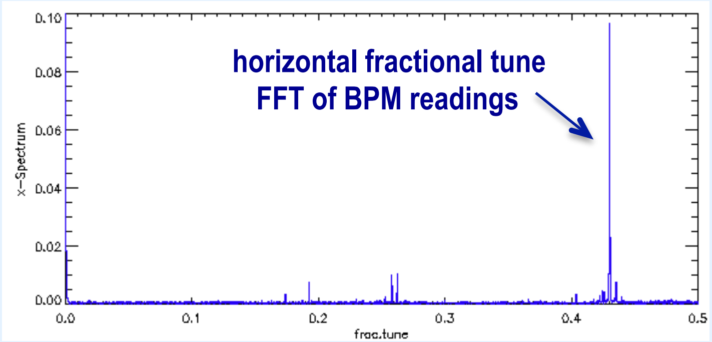
betatron phase advance over one turn



$$Q = \frac{1}{2\pi}\oint_C \mu(s)\,ds$$

$$\Delta x_\beta = \sqrt{\varepsilon\beta}\,\boxed{\sin\left(\mu+\phi_i+2\pi Q n\right)}$$



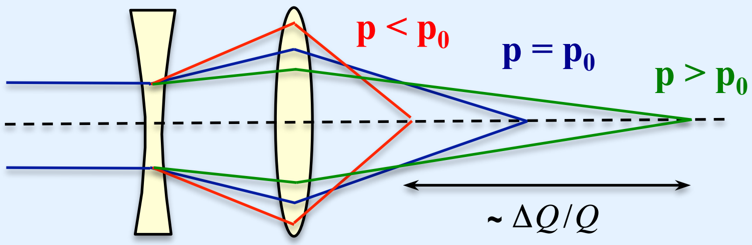


BPM Applications III: Chromaticity and Beta Function / Orbit Response

Chromaticity is a momentum-induced tune shift

→ tune spread depends on momentum spread

$$\frac{\Delta Q}{Q} = \xi \frac{\Delta p}{p}$$



Pinciple of Chromaticity Measurement:

→ measure tune Q_1
→ change $\Delta p/p$ (e.g. RF frequency) and measure tune Q_2
→ determine tune shift $\Delta Q = Q_2 - Q_1$

} BPMs measure in turn-by-turn mode

β-Function / Orbit Response Measurement Methods

→ determination of tune shift induced by quadrupole strength modulation

$$\Delta Q = \frac{1}{4\pi}\int_{s_0}^{s_0+L} \Delta K\,\beta(s)\,ds \cong \frac{\Delta K\,\overline{\beta}L}{4\pi}$$

→ each BPM records position change induced by orbit kick from each corrector
→ orbit response matrix A_{ij} relates orbit positions & corrector deflections
→ fit of β-functions by „linear optics from closed orbit“ (LOCO)

$$\vec{u} = A_{ij}\,\vec{\theta}$$

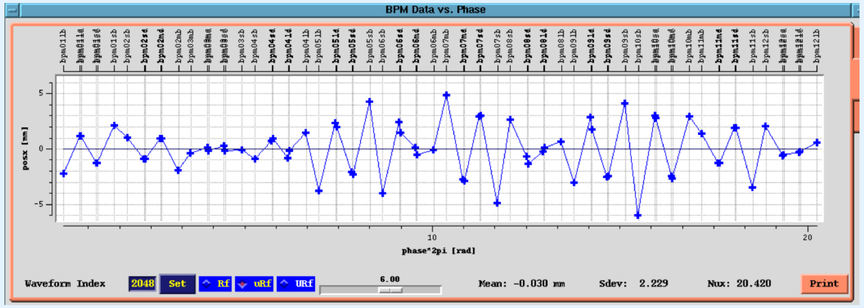
$$A_{ij} = \frac{\sqrt{\beta_i \beta_j}\cos\left(\left|\mu_i - \mu_j\right| - \pi Q\right)}{2\sin(\pi Q)}$$

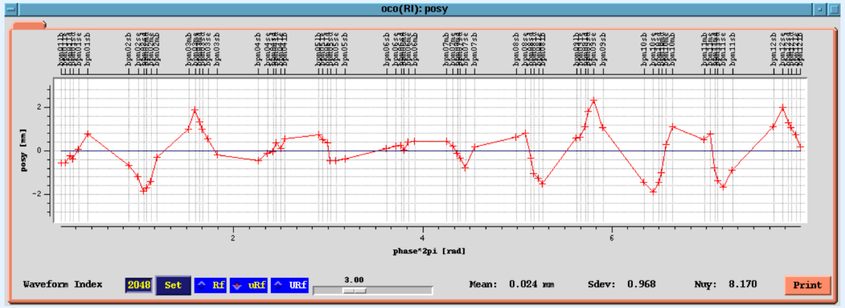
BPM Applications IV: Orbit Correction & Establishment of Golden Orbit

courtesy of Michael Boege, PSI

SLS „bare orbit“ without corrections: x_{rms} = 2.3 mm, y_{rms} = 1 mm

→ upper limit of sextupole & quadrupole alignment errors of < 30 μm

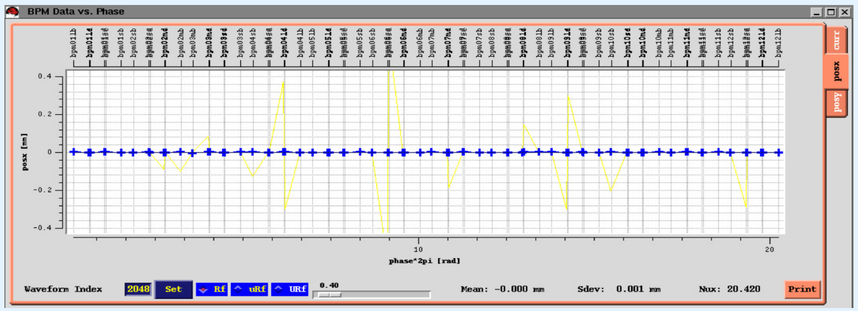


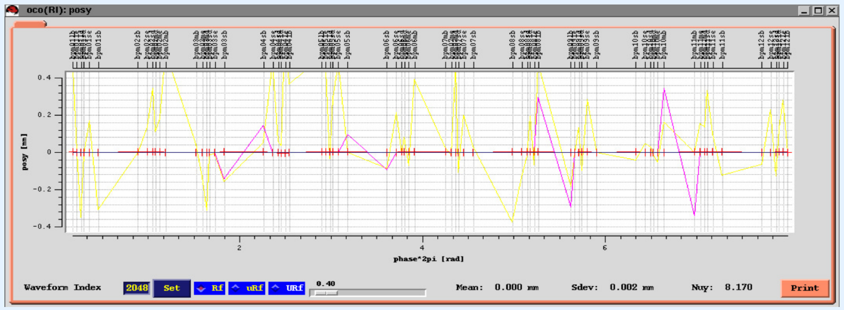


→ global orbit correction is achieved by „single value decomposition“ (SVD) of response matrix A_{ij}

SLS „golden orbit“ after CO correction: x_{rms} = 1 μm, y_{rms} = 1 μm

→ each beamline receives its individual position and angle settings



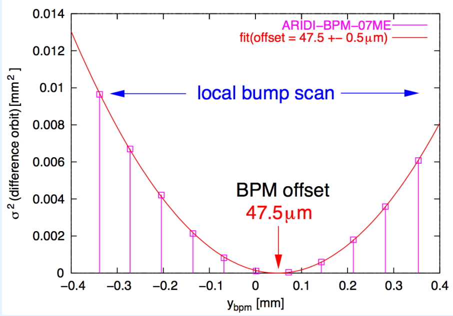


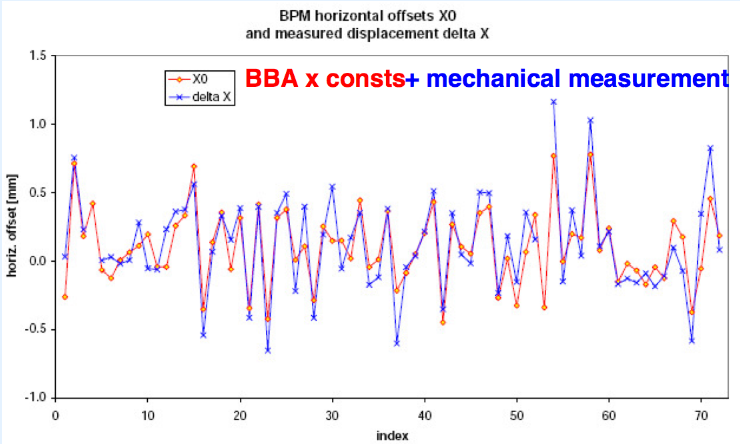
BPM Applications V: BBA & Reproducibility of Golden Orbit

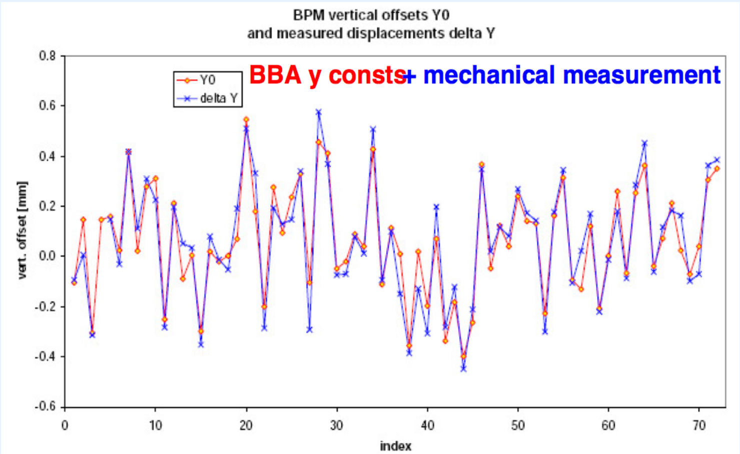
courtesy of Michael Boege, PSI

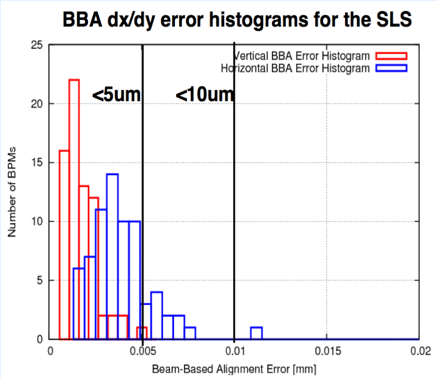
→ scan local bumps through each quadrupole

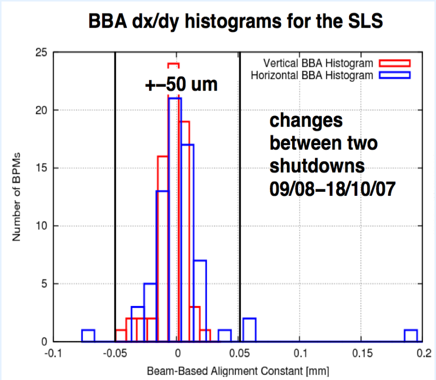
→ variation of quadrupole strengths to minimize global rms orbit











Beam Based Alignment

... aligns orbit to quadrupole axes

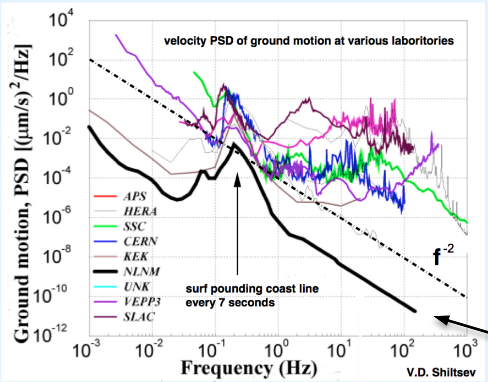
... accounts for mechanical & electrical BPM errors

BPM Applications VI: Global Fast Orbit Feedback & Short Term Stability

→ ground motions below few hundred Hz typically define the short term stability at light sources

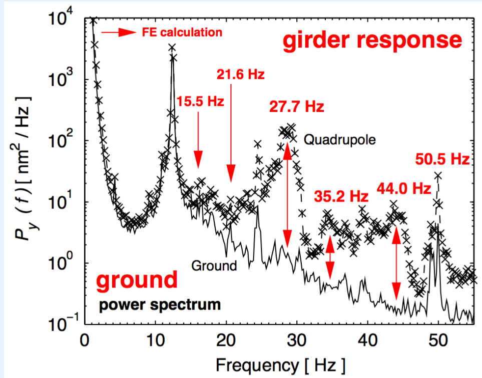
→ amplification by girder response and beam optics cause disturbing beam motions for the users

Typical PSDs due to Ground Motion



lowest observed seismic noise levels

SLS Girder Response to Ground Motion



courtesy of Michael Boege, PSI

global fast orbit feedback system (FOFB) stabilizes electron beam to the „golden orbit“

Ingredients of Global Fast Orbit Feedbacks

→ BPM data acquisition rate of a few (typically 10) kHz with only a few hundred nm integrated noise

→ low noise corrector magnet power supplies with a few kHz bandwidth

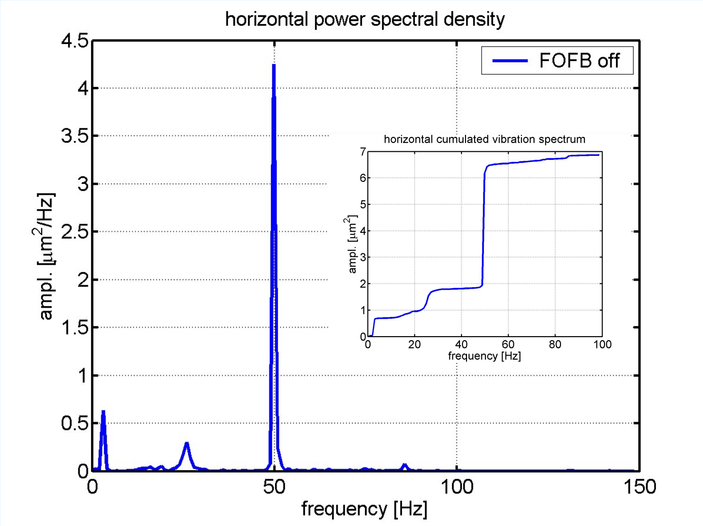
→ a centralized or distributed fast data distribution network for BPMs and corrector magnets

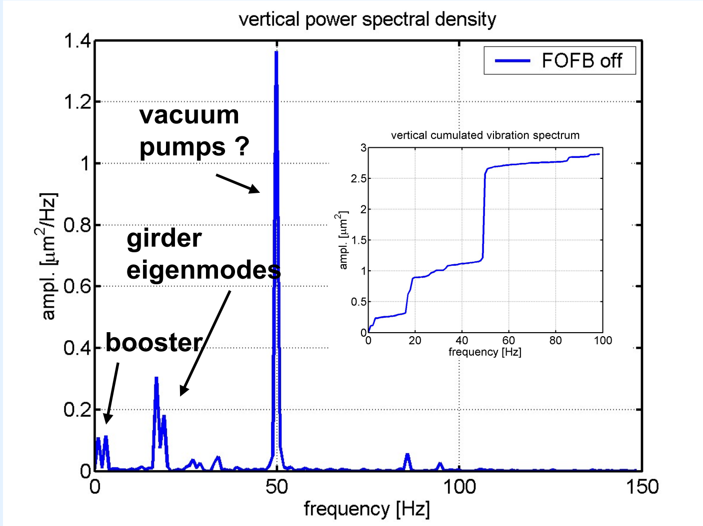
→ calculation of orbit corrections through SVD or matrix inversion

→ feedback loop is closed by (digitally implemented) PID controller

BPM Applications VII: Global Fast Orbit Feedback & Short Term Stability

SLS Global Orbit Distortions without Fast Orbit Feedback

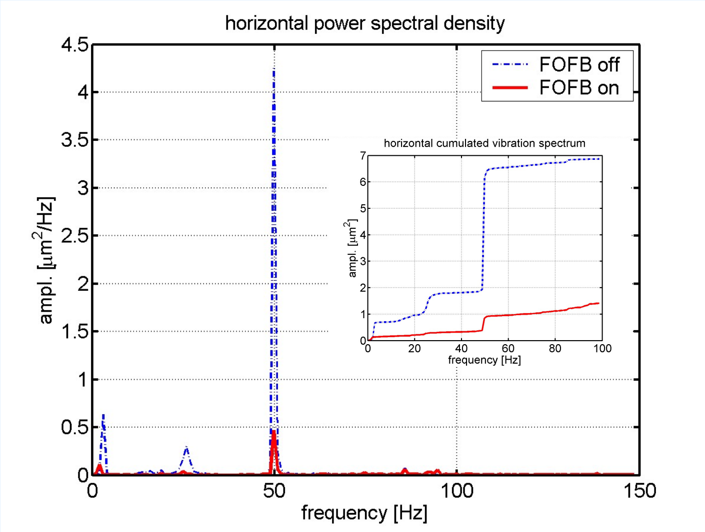


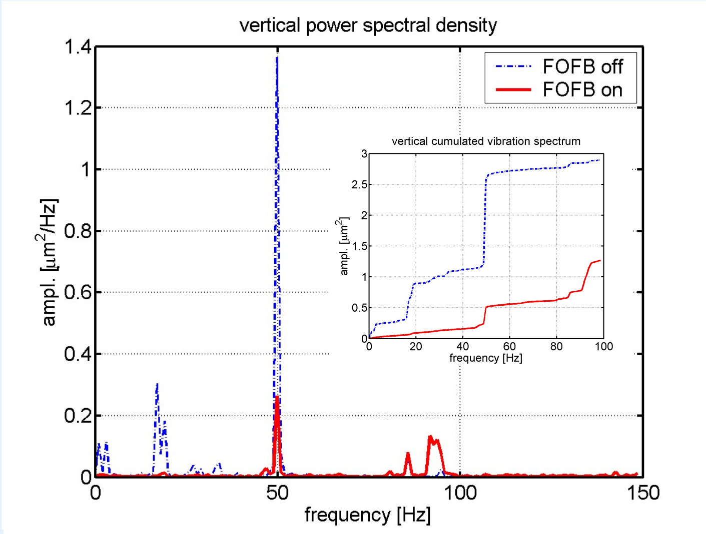


- measured at tune BPM outside of feedback loop (β_x = 11 m, β_y = 18 m)
- no ID-gap changes

BPM Applications VII: Global Fast Orbit Feedback & Short Term Stability

Performance of SLS Global Fast Orbit Feedback





- measured at tune BPM outside of feedback loop (β_x = 11 m, β_y = 18 m)
- no ID-gap changes

FOFB – Accumulated Power Densities (1 – 150 Hz)

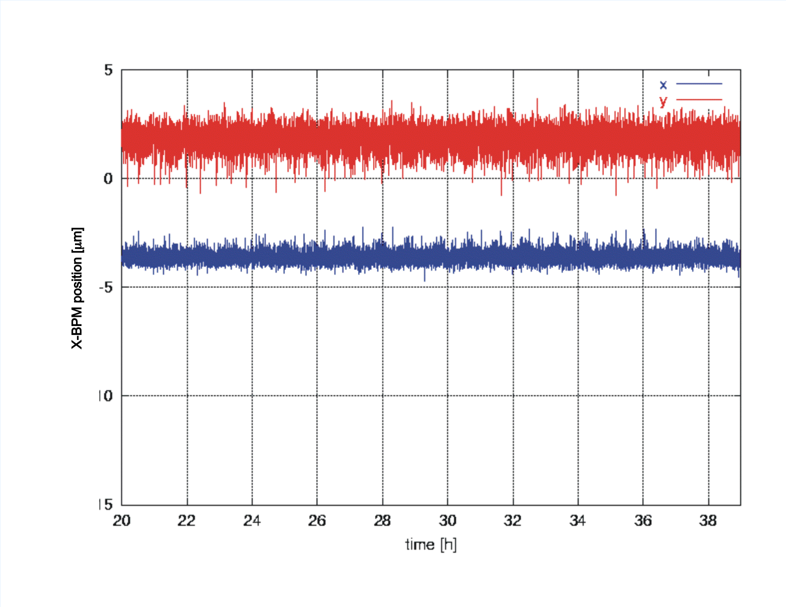
	horizontal		vertical	
FOFB	off	on	off	on
1- 100 Hz	**0.83 µm · $\sqrt{\beta_x}$**	**0.38 µm · $\sqrt{\beta_x}$**	**0.40 µm · $\sqrt{\beta_y}$**	**0.27 µm · $\sqrt{\beta_y}$**
100-150 Hz	0.08 µm · $\sqrt{\beta_x}$	0.17 µm · $\sqrt{\beta_x}$	0.06 µm · $\sqrt{\beta_y}$	0.11 µm · $\sqrt{\beta_y}$
1-150 Hz	0.83 µm · $\sqrt{\beta_x}$	0.41 µm · $\sqrt{\beta_x}$	0.41 µm · $\sqrt{\beta_y}$	0.29 µm · $\sqrt{\beta_y}$

Examples (1 – 150 Hz):

- tune BPM (β_y = 18 m): σ_y = 1.2 µm
- ID 6S (β_y = 0.9 m): σ_y = 0.28 µm

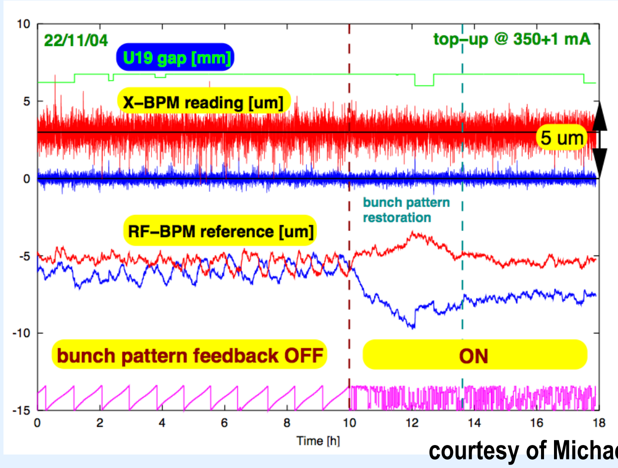
Photon BPMs: FOFB „Watchdog“ Function and Slow ID Feedbacks

Example of Photon Beam Stability at SLS Beamlines



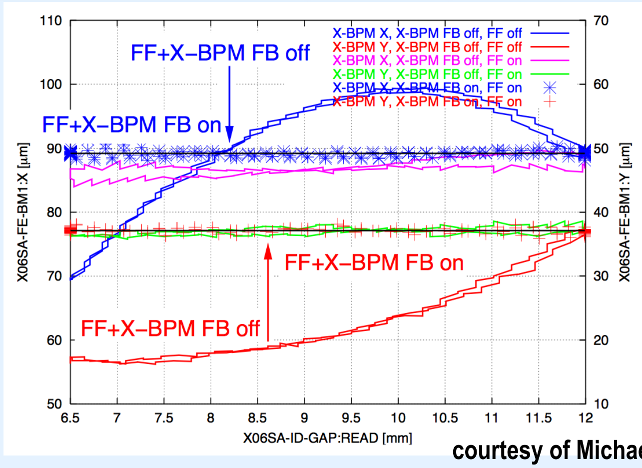
- systematic electron BPM effects are suppressed by slow, high level feedbacks on photon BPM readings
- resulting photon beam stability at the location of first optical elements of beamlines < 1 µm !

Photon BPM Stability vs. E-BPM Systematic Effects



courtesy of Michael Boege, PSI

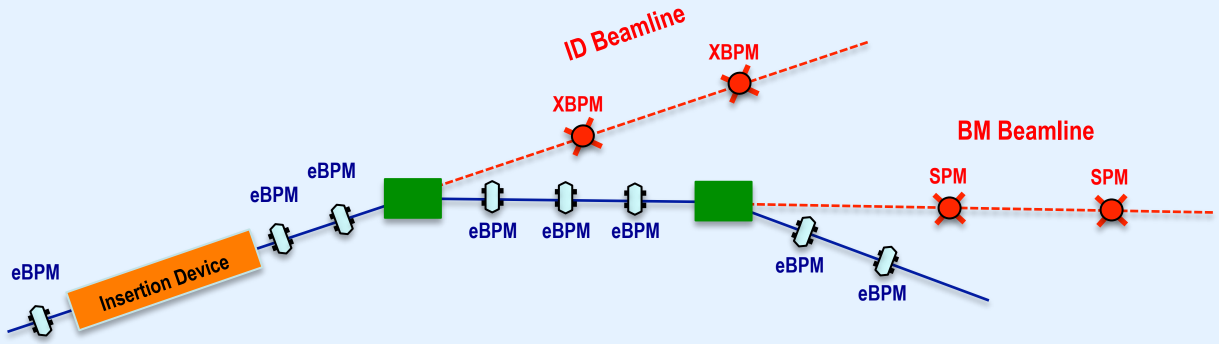
Photon BPM FB and Undulator Gap Variations



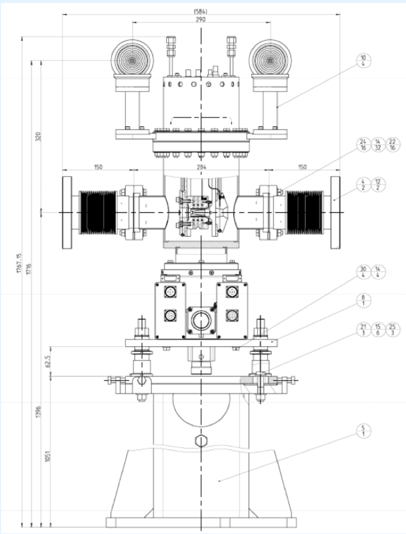
courtesy of Michael Boege, PSI

Photon BPMs: Front End Layout & BESS – FMB Blade Monitor Design

Photon BPM Layout with SPMs and XBPMs in Beamline Front Ends



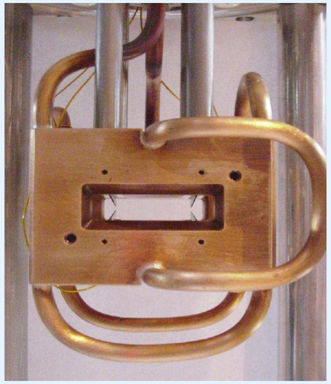
BESSY – FMB-Berlin Photon BPM Design



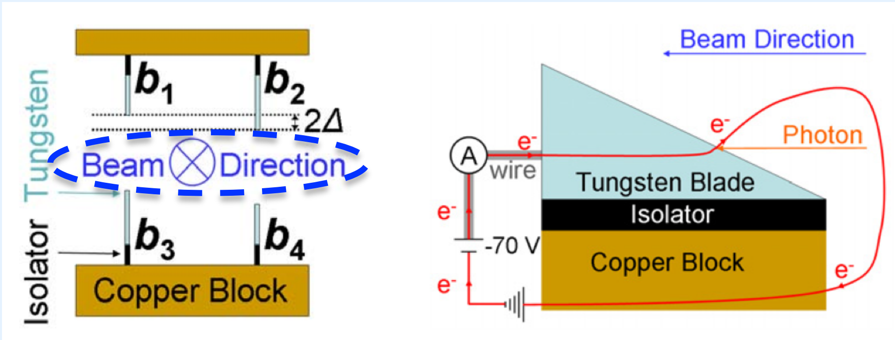
- photon BPMs provide better position resolution than electron BPMs due to larger lever arm
- absolute position reference to photon BPM alignment accuracy
- photon BPM FB compensates electron beam motions due undulator gap variations
- "out-of-loop" reference for global FOFB

Photon BPMs: Principle of SPM & XBPM Blade Monitors

„Staggered Pair“ Blade Monitors for Wiggler & Bending Magnet Beamlines



Schematic of SPM Arrangement for Wiggler & Bending Magnets

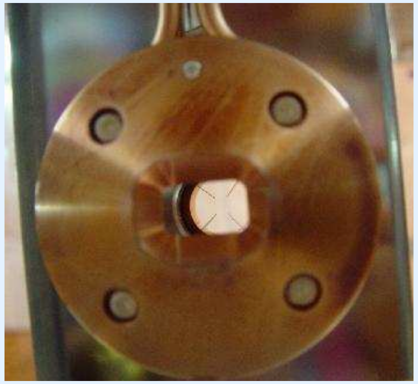


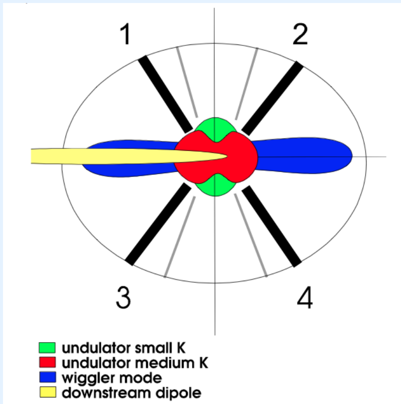
Vertical Photon Beam Position

$$P_v = \frac{\left(\frac{b_1 - b_3}{b_1 + b_3}\right) + \left(\frac{b_2 - b_4}{b_2 + b_4}\right)}{\left(\frac{b_1 - b_3}{b_1 + b_3}\right) - \left(\frac{b_2 - b_4}{b_2 + b_4}\right)} \cdot \Delta$$

with $2 \cdot \Delta$ = blade offset

X-Ray BPM Blade Monitors for Undulator Beamlines





Position Determination (like e-BPMs)

$$X_{pos} = K_x \cdot \frac{(I_1 + I_3) - (I_2 + I_4)}{I_1 + I_2 + I_3 + I_4}$$

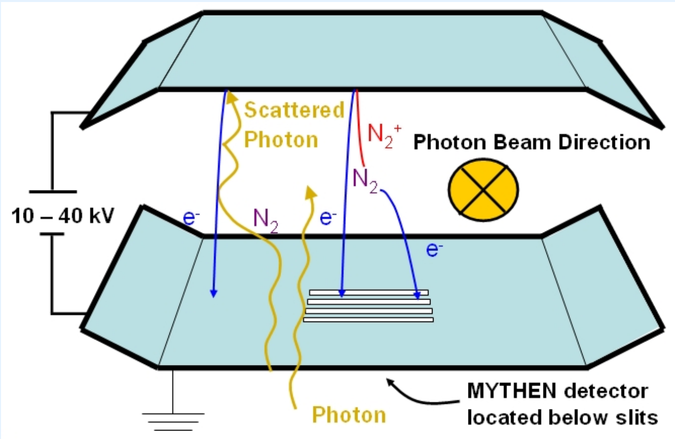
$$Y_{pos} = K_y \cdot \frac{(I_1 + I_2) - (I_3 + I_4)}{I_1 + I_2 + I_3 + I_4}$$

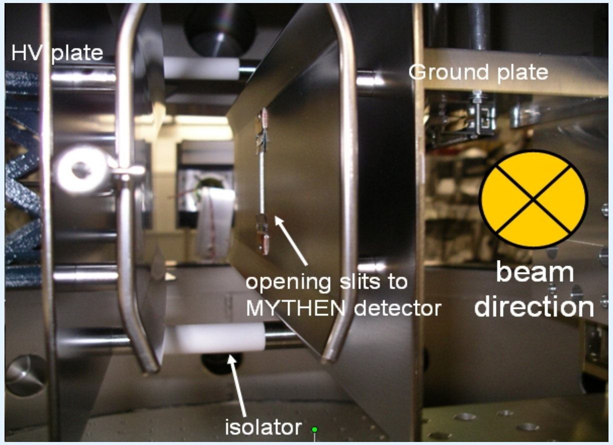
calibration required: SR contaminations from bends
optical mode / gap changes

Photo-induced currents (typ. nA – μA) are read out by low noise current amplifier & digitized for position processing

Gas Monitors – Example of Alternative Photon BPM for Light Sources

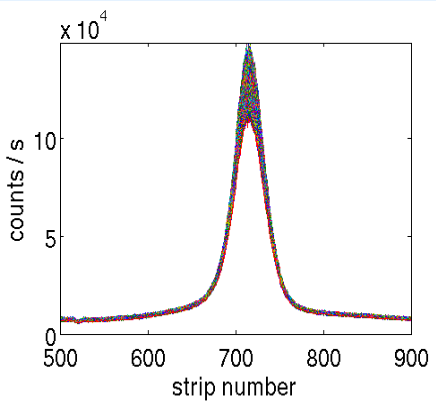
PSI Development of MYTHEN-based Gas Photon Monitor *



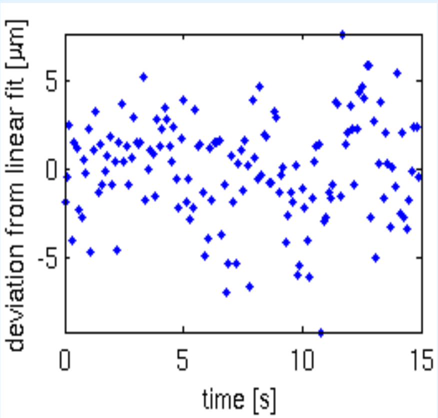


* courtesy of Thomas Wehrli, PSI

Photon Beam Profile °



Photon Beam Position °



Preliminary Results from SLS *

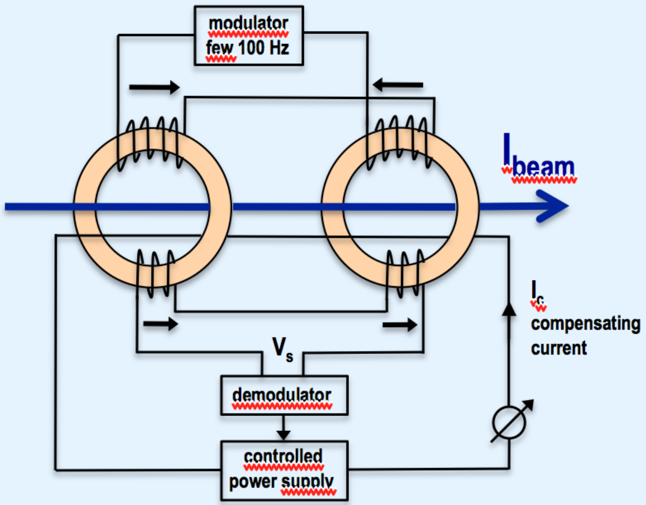
- position resolution: $\Delta x, y_{ph}$ = 2.9 μm (rms)
- profile resolution: σ_{ph} = 4.4 μm
- resolutions are close to statistical limit
- photo-ions promise improvement of profile resolution by $\sqrt{\text{mass}}$
- integrating EIGER detector for SwissFEL

° photo-electrons @ 17 kV, 3.3 10^{-6} mbar N_2, 100 ms integration time

Beam Current Measurement: DC Parametric Current Transformer

Principle of the DC Parameteric Current Transformer (introduced by K. Unser, CERN 1966):

- a modulator sends a current (few 100 Hz) through two coils, which are excited in opposite directions
- the pick-up coils are connected in series so that the resulting voltage (sum signal) V_s is zero
- a beam current I_{beam} induces a bias in the cores, so that V_s becomes non-zero and a 2nd harmonic of the modulator frequency will appear, which is converted to DC by the demodulator
- a compensating current I_c, which cancels the beam current I_{beam} is sent through the windings
- the measurement of I_c which corresponds to the beam current I_{beam} is done with a precision resistor

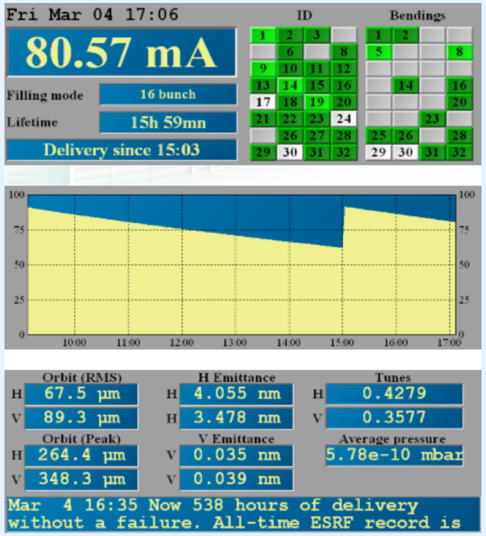


Commercially available NPCT from Bergoz Instrumentation

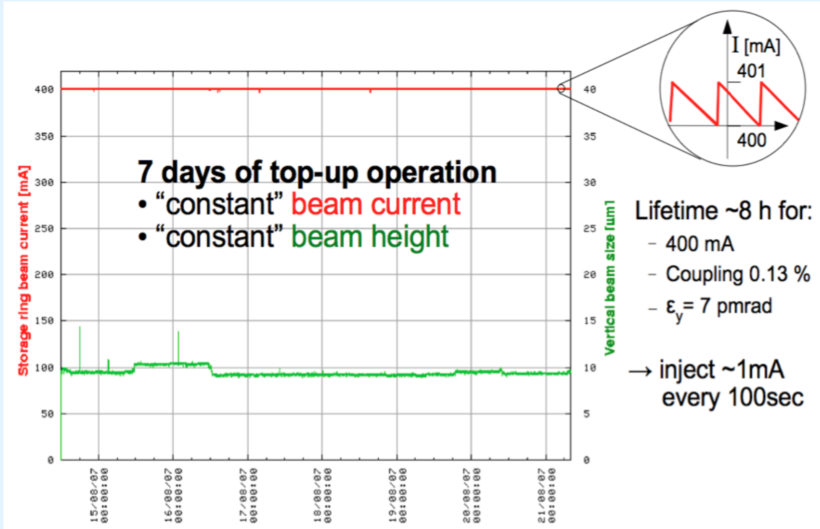
- resolution of 1 μA → 10^{-5} of stored beam currents
- careful magnetic shielding and temperature control necessary

Beam Current Measurement: Injection Rate & Beam Lifetime

ESRF Status – Beam Current



SLS Top-Up Operation



→ **precise beam current measurement provides...:** **... Injection Rate:** $I(t) = I_0 \cdot \dot{I}\, t$

... Beam Lifetime:

$$\frac{1}{\tau} = \frac{1}{\tau_{quantum}} + \frac{1}{\tau_{Touschek}} + \frac{1}{\tau_{elastic}} + \frac{1}{\tau_{inelastic}}$$

$\tau_{quantum}$ particle losses due to quantum emission and radiation damping

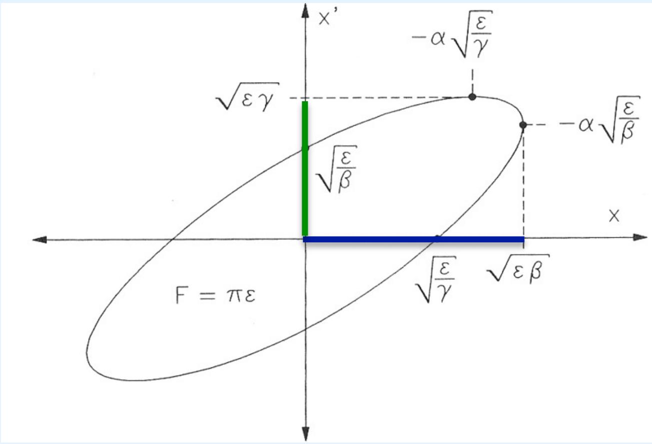
$\tau_{Touschek}$ particle losses due to elastic collisions of electrons in bunch

$\tau_{elastic}$ particle losses due to elastic scattering with residual gas molecules

$\tau_{inelastic}$ particle losses due to inelastic scattering → photo-emission / Bremsstrahlung

Synchrotron Radiation Monitors: Transverse Profiles and Emittance

beam emittance: projected area of transverse phase space volume



in case of a „flat lattice" (low coupling) with $\eta_y \approx 0$

→ horiz. beam size $\sigma_x = \sqrt{\beta_x \varepsilon_x + (\sigma_\delta \eta_x)^2}$

use location with $\eta_x = 0$ for ε_x measurement

→ vertical beam size $\sigma_y = \sqrt{\beta_y \varepsilon_y}$

→ beam divergence $\sigma' = \sqrt{\gamma \varepsilon}$

- β-functions and dispersion are well known in light sources → ε can be determined from beam size σ
- synchrotron radiation from bending magnets (undulators and wigglers) are non-invasive sources
- small opening angle $\Theta \sim 1/\gamma$ (typ. << 1 mrad) of synchrotron radiation limits spatial resolution due to diffraction

→ spatial resolution limit: $\Delta\sigma \approx \lambda / 2\Delta\Theta \approx 250\ \mu m$ for λ = 500 nm and $\Delta\Theta$ = 1 mrad

measurement of small beam sizes...:
→ X-ray pinhole camera
→ interferometeric techniques (UV, visible radiation)
→ X-ray (VUV) imaging

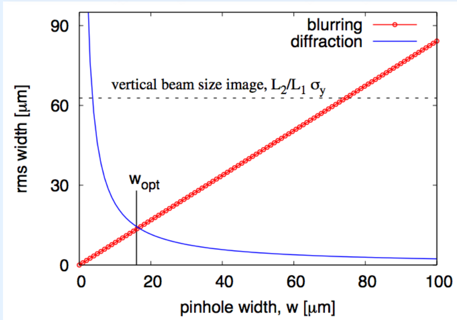
Synchrotron Radiation Monitors: X-Ray Pinhole Camera

X-ray pinhole camera resolution is limited by:

... blurring $$\sigma_{blurr} = \frac{w\left(L_1 + L_2\right)}{\sqrt{12}\cdot L_1}$$

... diffraction $$\sigma_{diff} = \left(\frac{\sqrt{12}}{4\pi}\right)\frac{\lambda L_2}{w}$$

Example from ALBA, U. Iriso et al., EPAC 2006

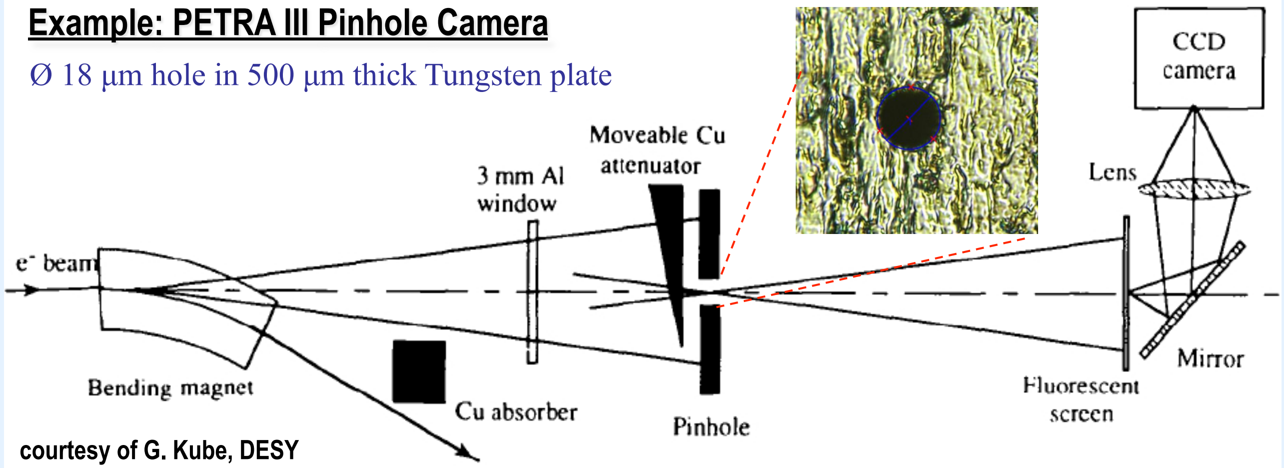


with L_1 = 6 m
L_2 = 12 m
λ = 12 nm (17 keV)
$\rightarrow$ w = 20 µm

typical resolution limitation of x-ray pinhole cameras ~ 10 µm

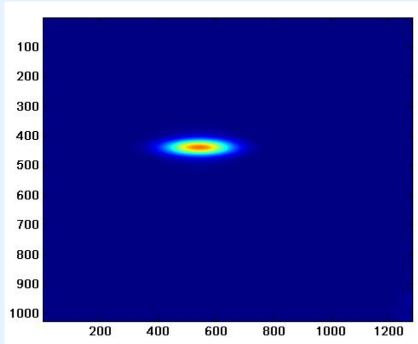
Example: PETRA III Pinhole Camera

Ø 18 µm hole in 500 µm thick Tungsten plate



courtesy of G. Kube, DESY

ESRF ID-25 X-Ray Pinhole Camera

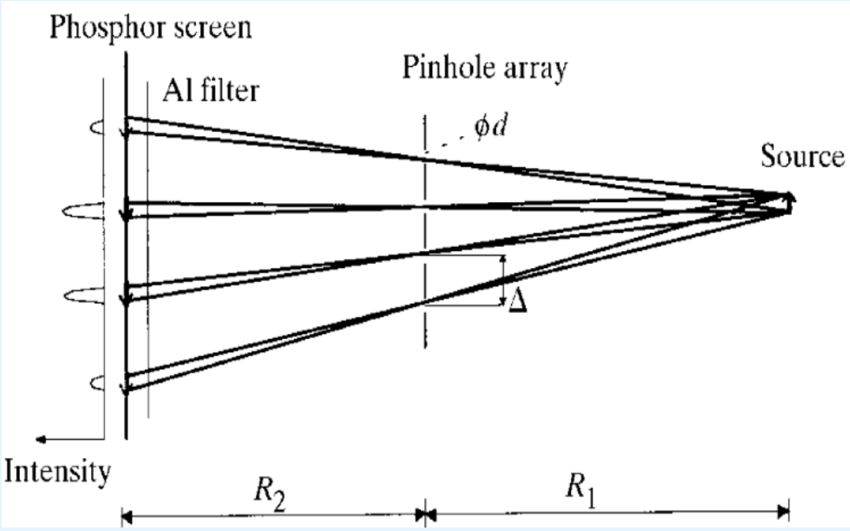


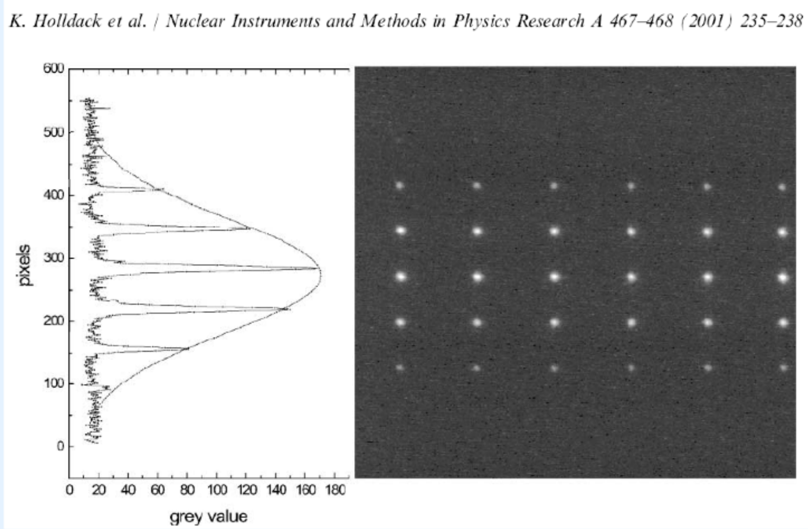
courtesy of K.Scheidt, ESRF

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

Synchrotron Radiation Monitors: X-Ray Pinhole Array

BESSY II X-Ray Pinhole Array





W.B. Peatman, K. Holldack, J.Synchrotron Rad. (1998) 5, 639-641

diffraction limited resolution: ~ 11 μm

simultaneous measurement of...: → beam size through single pinhole image

→ beam divergence through envelope

Synchrotron Radiation Monitors: Principle of Interference Monitors

a two-beam (double-slit) Michelson-type interferometer adapted from stellar interferometry by T. Mitsuhashi

→ beam size is estimated from the visibility of interferogram, indicating the degree of complex coherence

van Citert-Zernike's theorem

relates a transverse distribution $f(y)$ of an object with the degree of spatial coherence $\gamma(y)$ via Fourier Transform:

$$\gamma(\nu) = \int f(y)\exp(-i2\pi\nu y)\,dy \qquad \text{with spatial frequency} \quad \nu = \frac{D}{\lambda R_0}$$

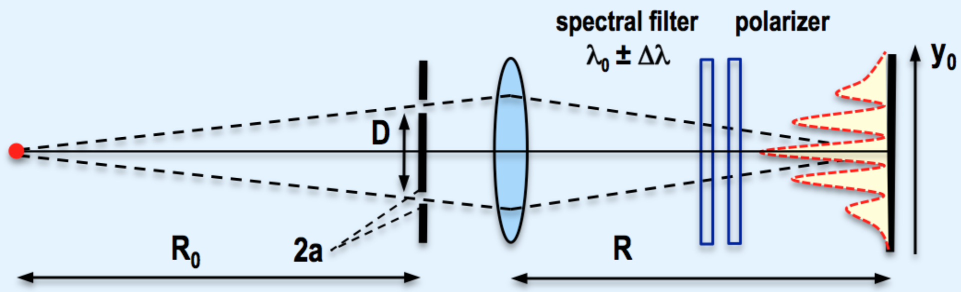
intensity of interference pattern is given by:

$$I(y_0) = I_0\left[\operatorname{sinc}\left(\frac{2\pi a}{\lambda R}y_0\right)\right]\cdot\left[1+|\gamma|\cos\left(\frac{2\pi D}{\lambda R}y_0+\phi\right)\right]$$

and the fringe visibility γ is realted to the rms width of the interference pattern σ_D by: $\gamma = \exp\left(-\frac{D^2}{2\sigma_D^2}\right)$

→ beam size of an object is given by:

$$\sigma_y = \frac{\lambda R}{\pi D}\cdot\sqrt{\frac{1}{2}\ln\left(\frac{1}{\gamma}\right)}$$



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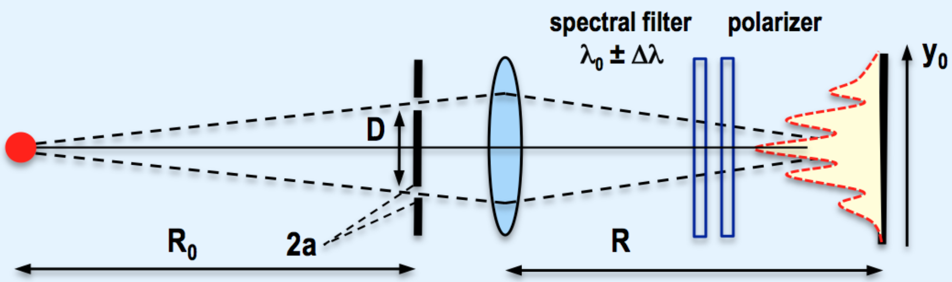
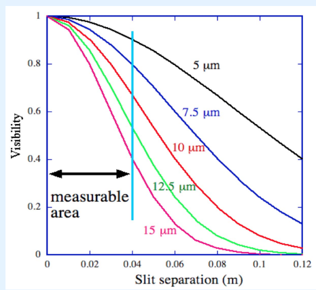
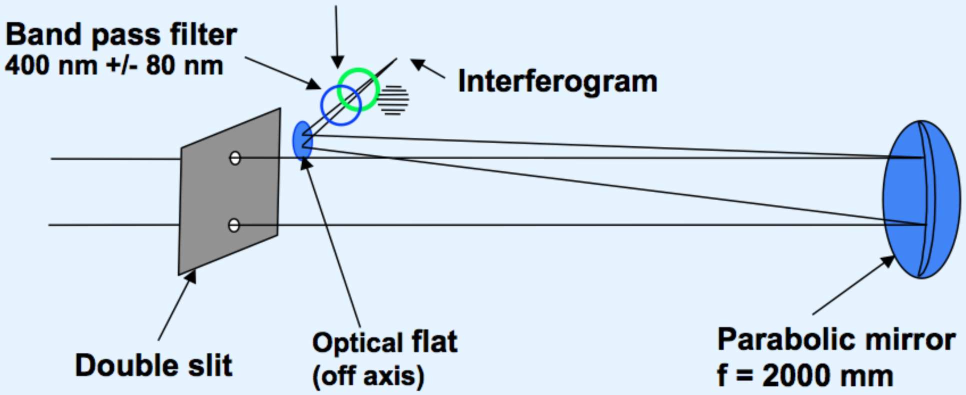




Synchrotron Radiation Monitors: ATF Interference Monitor (with Mirror Optics)

T. Naito and T. Mitsuhashi, Phys. Rev. ST Accel. Beams 9 (2006) 122802

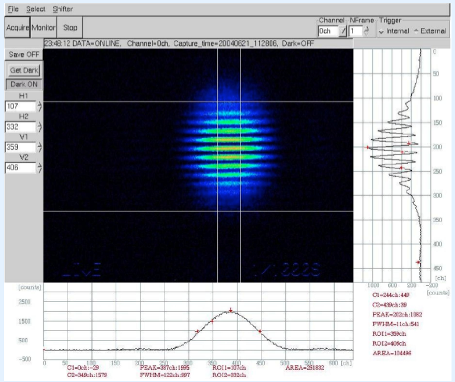
Schematic Set-Up of ATF Interference Beam Size Monitor



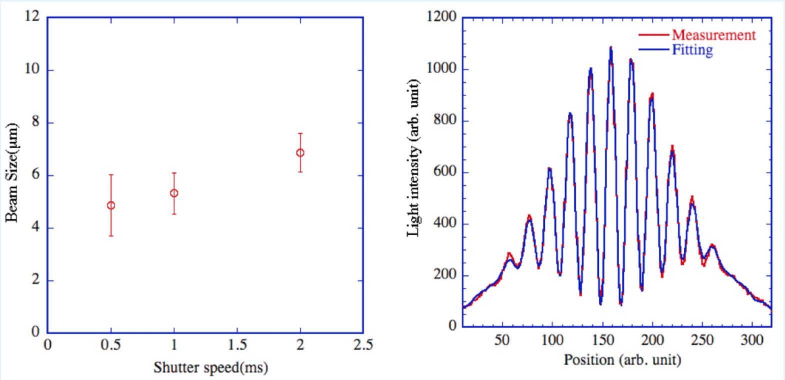
minimal measured beam size:

$$\sigma_y = 4.73 \pm 0.55\ \mu m$$

Example of an Interferogram



Beam Size vs. Shutter Time and Fit of Interferogram



SR Monitors: Imaging of Vertically Polarized Optical Radiation

courtesy of Åke Andersson, MAX-lab

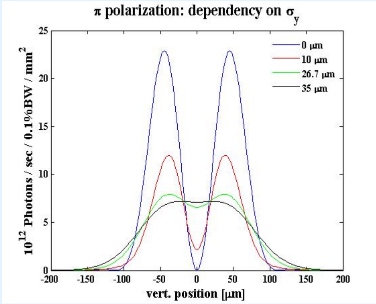
for an ideally "flat beam" ($\sigma_y = 0$) → only horizontal polarization in the midplane
→ vertical polarization only above and below the midplane

for a "real beam" ($\sigma_y > 0$) → some vertical polarization can also be observed in the midplane

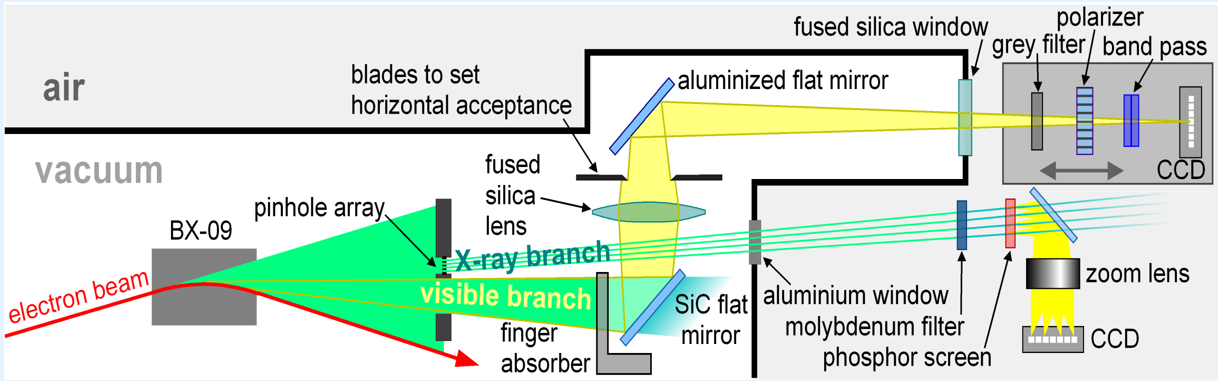
imaging vertically polarized SR in the visible

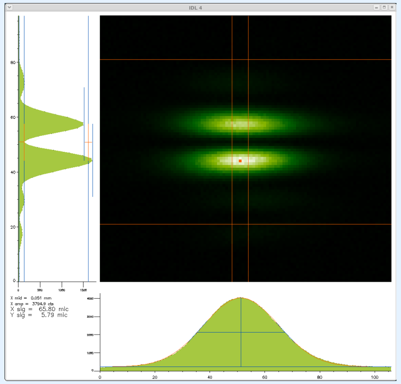
→ two peaked distribution

→ fringe visibility depends on vertical beam size σ_y



Schematic Set-Up of Visible Light SR Monitor at SLS





vertical beam size σ_y = 5.8 µm for β_y = 13.5 m → vertical ε_y = 2.5 pm (natural limit from 1/γ: $\varepsilon_{y,min}$ = 0.2 pm)

SR Monitors: Imaging with X-Ray (Focusing) Optics

Reflective Optics:

→ Kirkpatrick-Baez mirror scheme of grazing incidence ($\theta < 0.5°$) with pair of ellipsoidal / cylindrical curved mirrors

Example: Advanced Light Source Diagnostics Beamline

T.R. Renner, H.A. Padmore, R. Keller, Rev.Sci.Instrum. 67 (1996) 3368

Diffractive Optics:

→ Fresnel Zone Plates: spacing of rings (e.g. Si, Au) result in constructive interference of light waves in focal point

Examples: X-Ray Beam Imager at Spring-8

S. Takano, M. Masaki, H. Ohkuma, Proc. DIPAC05, Lyon, France (2005) 241 and NIM A556 (2006) 357

Fresnel Zone Plate Monitor at ATF (KEK)

K. Ida et al., NIM A506 (2003) 49 and H. Sakai et al., Phys. Rev. ST Accel. Beams 10 (2007) 042801

Refractive Optics:

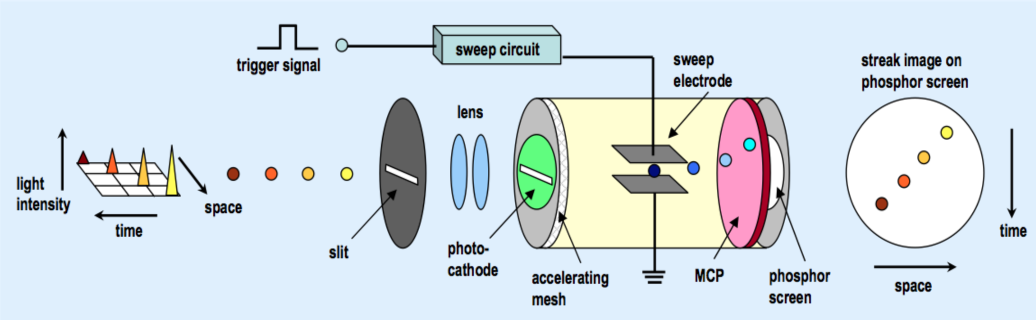
→ many (30 – 100) Compound Refractive Lenses made from Al or Be for focusing hard X-ray radiation (20 keV)

Example: PETRA III Diagnostics Beamline for Emittance Measurements

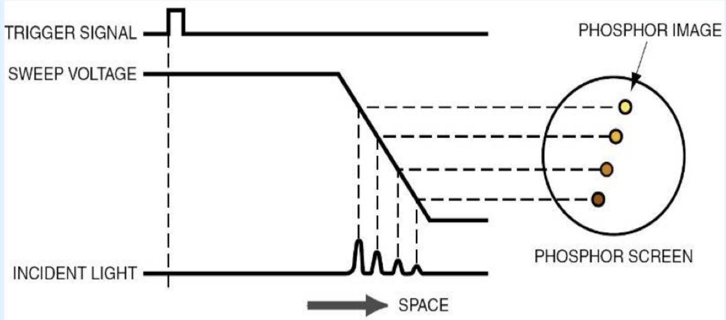
G. Kube et al., Proc. IPAC'10, Kyoto, Japan (2010), MOPD089, 909

Bunch Length Measurement with Visible SR: Streak Camera

Principle of Streak Camera Measurement



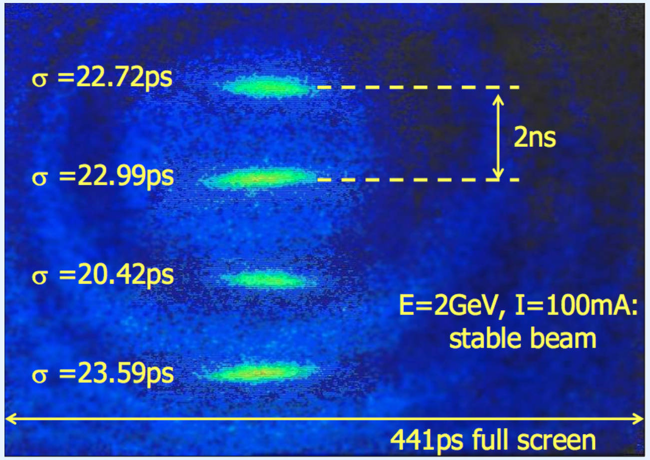
Streak Camera Timing Diagram



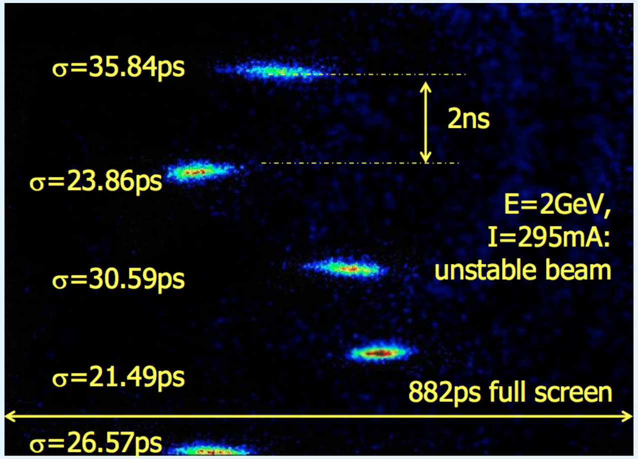
- visible light pulses from synchrotron radiation (bending magnet) are converted on the SC photo-cathode into a number of photo-electrons, which are proportional to the incident light distribution
- the photo-electrons are accelerated along the streak tube, transverse (vertically) swept by deflecting plates to convert the incident time distribution in a spatial distribution on the MCP
- the photo-electrons are amplified by the MCP and converted back to visible light on the phosphor screen
- an initial spatial offset of the light pulses at the entrance slit is preserved on the phosphor screen
- at synchrotron light sources „dual-sweep“ synchroscan streak cameras are typically used to observe electron bunch lengths along the storage ring filling pattern and / or during several turns around the storage ring

Examples of Synchroscan Streak Camera Measurements (by M. Ferianis, ELETTRA)

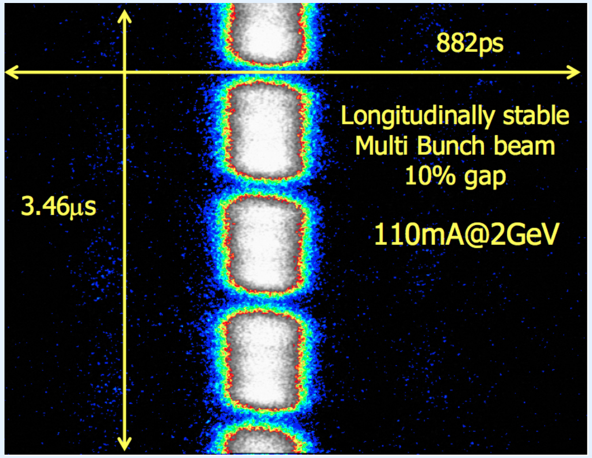
Four Bunch Mode – Stable Beam



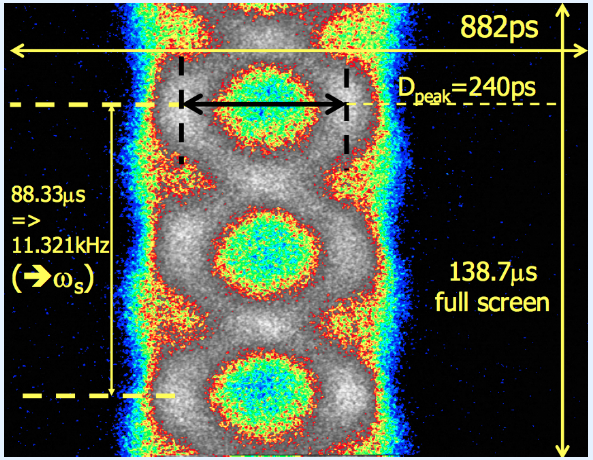
Four Bunch Mode – Unstable Beam



Multi-Bunch Mode – Stable Beam



Multi-Bunch Mode – Unstable Beam



Light Source Diagnostics – Summary (personal opinion…)

various diagnostics devices and measurement examples have been presented…

Electron BPMs…:
→ key diagnostic for synchrotron light source
→ turn-by-turn and high resolution (FOFB) measurement modes provide tunes, chromaticity, β-functions (orbit response) and beam stability

Photon BPMs…:
→ provide higher resolution than electron BPMs but many systematic effects
→ "watch-dog" functionality for electron BPMs
→ slow feedbacks to compensate undulator gap variations and systematic e-BPM effects

Current Monitors…:
→ high resolution DCCT allows current measurement at 10^{-5} level (1 μA)
→ determination of beam lifetime and injection efficiency (important for top-up operation)

SR Monitors…:
→ determine transverse emittances through measurement of (vertical) beam sizes
→ bunch lengths, filling pattern and longitudinal stability with diodes or streak camera
→ application of pinhole camera, interference monitors and X-ray imaging
→ use of visible light for bunch length and filling pattern