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Beam Diagnostics for Ultra-Low Emittance Storage Rings

FLS 2023, Lucerne, Switzerland August 27th – September 1st 2023

Overview

- **Introduction**
- **Beam Diagnostics Requirements**
- **Beam Diagnostics Systems**
  - **… Overview**
  - **… Transverse Profile Monitors → Emittance & Energy Spread**
  - **… Beam Position Monitors**
- **Some Words on Photon BPMs**
  - **… Improved Beam Stability with (FO)FB Integration**
- **Outlook and Conclusions**

Acknowledgements 😀 😘 😀

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… Gero Kube (DESY: PETRA-III, PETRA-IV)

… Claire Houghton, Lorraine Bobb, Chris Bloomer (DIAMOND-I and II)

… Massimo Camarda (SenSiC)

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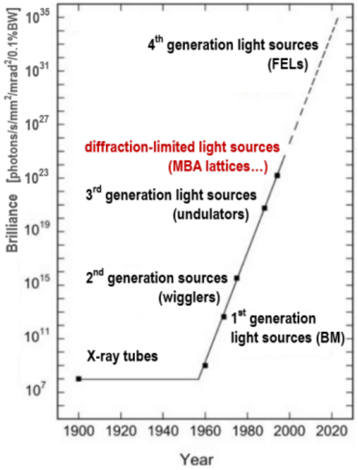
Some General Remarks on LESR and Diagnostics

Light Sources and Storage Rings evolve stepwise in generation

1st GLS	parasitic use of dipole sources (HEP facilities)
2nd GLS	dedicated facilities (BM, wiggler)
3rd GLS	optimized lattices (DBA, TBA) for undulators
4GLS / DLSR	MBA lattices and customized insertion devices

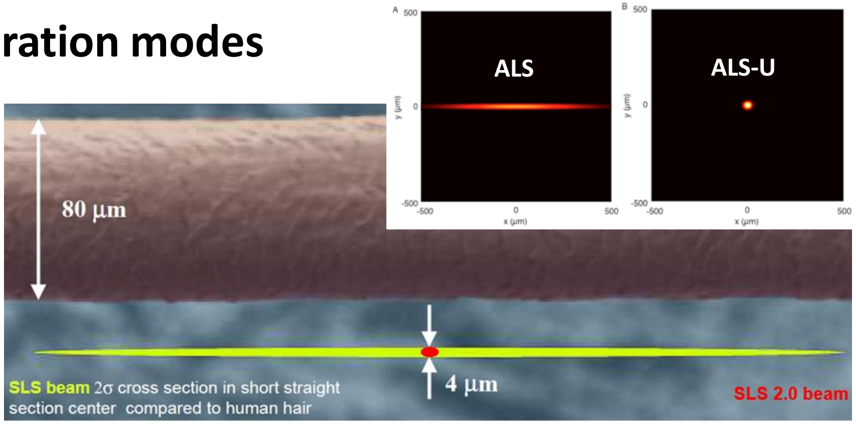


Diagnostic Systems are subject to a more continuous evolution…

… increasing requirements and new operation modes
(e.g. low coupling, top-up, fs-slicing…)

… experience and "lessons-learned"
(e.g. calibration and drift-compensation)

… technological advances
(e.g. low latency digital electronics)



SLS beam 2σ cross section in short straight section center compared to human hair

Requirements for LESR Diagnostics Systems are close to those of 3GLS in the vertical plane ☺

However, some systems need to provide improved performance and advanced functionalities…!!!

Requirements for LESR Diagnostics Systems

- **Commissioning** → **~ 5 – 10 % initial calibration errors** and small mechanical offsets (e.g. ≤ 500 µm for BPMs)
  → **first turn / turn-by-turn operation modes** for BPMs and BLMs (working horse diagnostics)

- **Beam Dynamics** → fast and efficient **beam-based-alignment** (BBA) with high resolution (µm level)
  → indispensable for **optics studies** (orbit response matrix, coupling, LOCO, optics correction…)

- **User Operation** → **very high reliability** of **all** diagnostics systems
  (self-calibration, self diagnosis, negligible current and filling pattern dependency)
  → **high resolution / sensitivity (sub-µm level) at highest possible bandwidth (kHz)**
  → input for any kind of **beam-based feedbacks**
  (FOFB (local, global), top-up and filling pattern control, coupling / lifetime, injection)
  → separate outputs for **interlock and safety systems**, provision of **post-mortem** (beam) data

Beam Parameters	3GLS	4GLS / LESR
Energy	~ 1.5 – 6 GeV	~ 2 – 6 GeV
Current	~ 100 – 500 mA	~ 200 – 400 mA
Horizontal Emittance	~ 1’000 – 10’000 pm rad	20 – 330 pm rad
Vertical Emittance	3 – 10 pm rad @ << 1 % coupling	2 – 10 pm rad @ typically 10 % coupling
RMS Beam Sizes (h/v) (minimum values at source points)	≥ 100 µm / ~ 10 µm	~ 5 – 10 µm / ~ 2 – 10 µm
Short Term Beam Stability - RMS Position / Angle - Range	10 % of beam size ~ 1’000 nm / nrad 0.01 Hz – few 100 Hz	2 – 3 % of beam size ~ 100 nm / nrad 0.01 Hz – 1 kHz
Long Term Beam Stability - RMS Position - Range	~ 1’000 nm day(s)	~ 500 nm / ~1’000 nm day / week

Overview of LESR Diagnostics Systems

Parameter	Measurement System	Status / Remark
Beam Current *	ICT & DCCT	ready for LE rings
Filling Pattern *	**button pick-up**, visible or X-ray **diode**	ready for LE rings
Bunch Purity *	visible or X-ray **APD / TCSPC**	ready for LE rings
Bunch Length *	visible light & **synchro-scan streak camera**	ready for LE rings
Beam Loss *	scintillator & PMT	ready for LE rings
ID & Machine Protection *	scrapers & collimators	ready for LE rings

* These diagnostics systems will not be treated in detail during this presentation.
Remarks and examples may be given in additional slides or references.

Beam Position	button pick-ups & BPM electronics	long-term drifts resolution
Tune and Chromaticity *	pinger or stripline kicker & BPM electronics	ready for LE rings
Emittance & Energy Spread	**x-ray imaging** (pinhole camera) **& diffraction** **visible light interference & pi-polarization**	needs improvement, complex engineering
Beam Stability	**fast orbit feedback** **filling pattern** (top-up) **& coupling feedbacks**	increased BW (1 kHz), include X-BPMs
Instabilities, Emittance Control	multi-bunch feedback	implement ε-FB, injection transients

Quick Summary of “Ready-to-Go” Systems

Beam Current — **lifetime, injection / transmission efficiency and top-up control**

DCCT (commercial devices available, usually analog output)

< 1 µA/√Hz (absolute calibration); up to 10 kHz BW (typ. sampling at 100 Hz)

Filling Pattern — **injection and top-up control, filling pattern feedback**

beam pick-up, visible or X-ray **diode**

≤ 1 ns FW detector response time; low latency GS/s ADC (e.g. 12 bit, > 4 GS/s)

filling pattern FB via event and control system

Bunch Purity — **for time-resolved experiments (single bunch or hybrid modes)**

visible or X-ray **APD** & **TCSPC system** (e.g. PicoHarp)

photon counting up to 10^7 dynamics; milliseconds count rates may allow top-up control

Bunch Length — **bunch length / lengthening as function of bunch charge and RF settings**

synchro-scan streak camera

$\tau \leq 2$ ps FWHM, sweep-rate: 500 (250) MHz; slow time axes at µs to ms

visible light extraction from MBA lattices may become a challenge

Beam Loss — **loss detection, injection / transmission efficiency and aperture optimization**

scintillator & **PMT** or **PIN diodes** / long **Cerenkov fibers (LLM)** & **PMT**

placement in transfer lines, storage ring arcs and around IDs

from single-bunch and turn-by-turn to long-term loss / radiation mapping

primary BLM use for ID protection and machine interlock

BLMs may be most sensitive system for injection monitoring & optimization (commissioning)

Quick Summary of “Ready-to-Go” Systems

Beam Current lifetime, injection / transmission efficiency and top-up control

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F

, > 4 GS/s)

es)

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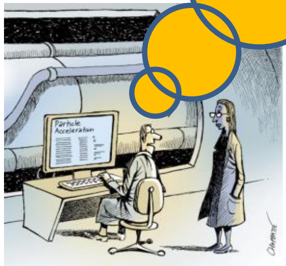
tices may become a challenge

Keep in mind…:

all these systems are indispensable for successful LESR commissioning and stable and reproducible user operation…!!!

However, they have no specific or more stringent requirements for LESR or 4GLS

Beam Los **loss detection, / transmission efficiency and aperture optimization**



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LESR / 4GLS Beam Profile Monitors

- Sources → make use of dipole sources since straight sections are too “valuable” (for users)

→ select two locations with and without dispersion for $\varepsilon_{h/v}$ and relative **ΔE/E**

- Lattice Constraints → out-coupling of synchrotron radiation and placement of first optical elements become difficult due to decreased bending angles, dense magnet structures and small vacuum chambers in low emittance MBA lattices

- Operational Aspects → verification of beam optics and coupling control

→ coupling FBs may require high (up to 100 Hz) update rates

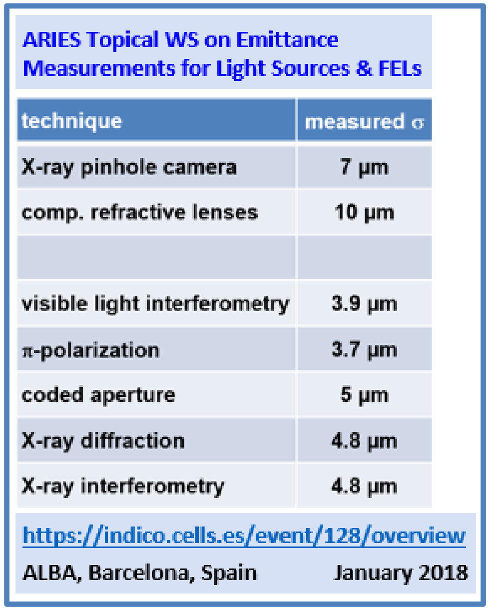
→ observation of beam disturbances (e.g. during top-up) and instabilities

→ minimization of energy spread by RF cavity tuning

Typical LESR / 4GLS Profile Monitor Specifications

Parameter	horizontal	vertical	coupling
Emittance (pm·rad)	**20 – 330**	**2 – 10**	**≤ 10 %**
RMS Beam Size (µm)	**5 – 10**	**2 – 10**	
Emittance Change (pm·rad)	**1 – 5**	**≤ 1**	**≤ 1 %**
RMS Beam Size Change (µm)	**~ 1**	**0.1 – 1**	

LESR / 4GLS Profile Monitors – State-of-the-Art



ARIES Topical WS on Emittance Measurements for Light Sources & FELs

technique	measured σ
X-ray pinhole camera	7 µm
comp. refractive lenses	10 µm
visible light interferometry	3.9 µm
π-polarization	3.7 µm
coded aperture	5 µm
X-ray diffraction	4.8 µm
X-ray interferometry	4.8 µm

https://indico.cells.es/event/128/overview

ALBA, Barcelona, Spain January 2018

X-Ray Pinhole Camera

→ C. Thomas et al., “X-ray Pinhole Camera Resolution and Emittance Measurement”, Phys. Rev. ST Accel. Beams 13, 022805 (2010)

π-Polarization Monitor with Diffraction Obstacle

→ Å. Andersson, J. Breulin et al., “Transverse Beam Diagnostics at MAX-IV”, I.FAST Workshop, KIT, Karlsruhe, Germany, April 2022 (virtual)

Coded Aperture

→ J.W. Flanagan et al., “X-ray Monitor based on Coded-Aperture Imaging for KEKB Upgrade and ILC Damping Ring”, Proc. EPAC 2008, Genoa, Italy, TUOCM02, 1029

Single or Double Slit Interferometry

→ T. Naito, T. Mitsuhashi, “Very Small Beam size measurement by a Reflective Synchrotron Radiation Interferometer”, Phys. Rev. ST Acc. Beams **9**, 122802, December 2006

→ M. Masaki, S. Takano, “Two-Dimensional Visible Synchrotron Light Interferomerty for Transverse Beam Profile Measurement at the Spring-8 Storage Ring”, Journal of Synchrotron Radiation **vol. 10**, **part 4**, July 2003, 295-302

Fresnel Zone Plates

→ H. Sakai et al., “Improvement of Fresnel Zone Plate Beam-Profile Monitor and Application to Ultralow Emittance Beam Profile Measurements”, Phys. Rev. ST Acc. Beams **10**, 042801, April 2007

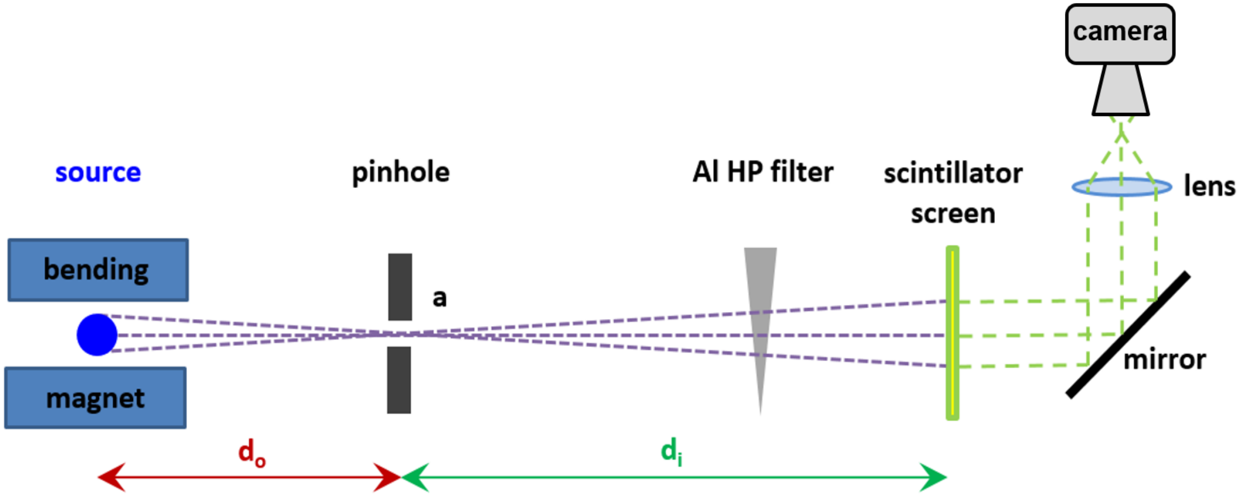
X-Ray Diffraction

→ B. Yang, S. Lee, “Planned X-Ray Diffraction Diagnostics for APS-U Emittance Measurements” ARIES Topical Workshop on Emittance Measurements for Light Sources and FELs, Barcelona, Spain, January 2018

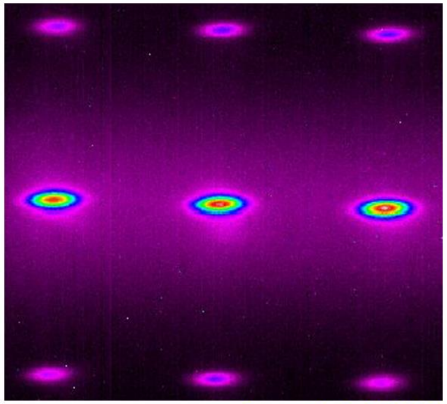
→ N. Samadi et al., “A Spatial Beam Property Analyzer Based on Dispersive Crystal Diffraction for Low Emittance X-Ray Light Sources”, Scientific Reports 12, 18267 (2022)

Profile Monitors: X-Ray Pinhole Camera

Schematic of an X-Ray Pinhole Camera Set-Up



12.5 µm LIGA-fabricated pinhole image at DLS



courtesy of L. Bobb (DLS)

Beam Size Determination

$$\Sigma^2 = (M \cdot \sigma_{source})^2 + \underbrace{\sigma^2_{pinhole} + \sigma^2_{detector}}$$

point spread function $\sigma^2_{PSF} > 0$

image size on detector

source-to-scintillator magnification $M = \frac{d_i}{d_o}$

Profile Monitors: X-Ray Pinhole Camera

Beam Size Determination – the Point Spread Function

$$\Sigma^2 = (M \cdot \sigma_{source})^2 + \underbrace{\sigma^2_{pinhole} + \sigma^2_{detector}}_{\boxed{\sigma^2_{PSF} > 0}}$$

typical PH-camera parameters at 4GLS:

- photon energies: 15 – 30 keV (0.8 – 0.25 Å)
- pinhole apertures: 10 – 20 μm
- source-to-pinhole: 5 – 10 m
- pinhole-to-screen: 10 – 20 m

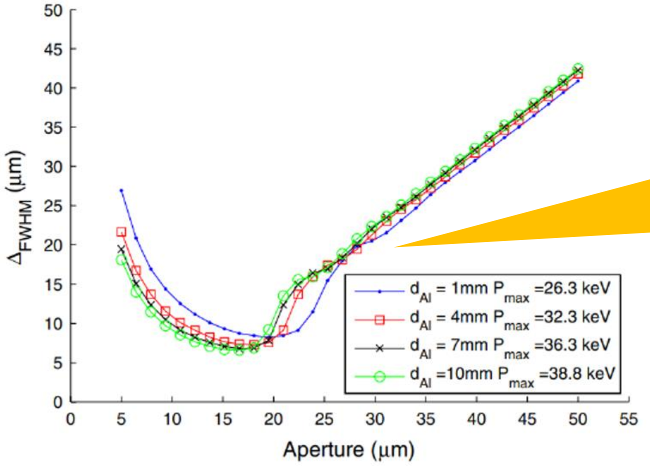
with $\sigma^2_{detector} = \sigma^2_{screen} + \sigma^2_{lens} + \sigma^2_{sensor}$

and $\sigma^2_{pinhole} = \sigma^2_{aperture} + \sigma^2_{diffraction}$

$$\sigma_{aperture} = \frac{a}{2\sqrt{3}} \frac{(d_o + d_i)}{d_o}$$

$$\sigma_{diffraction} = \frac{\sqrt{12}}{4\pi} \frac{\lambda \cdot d_i}{a}$$

FWHM of pinhole camera PSF at DIAMOND



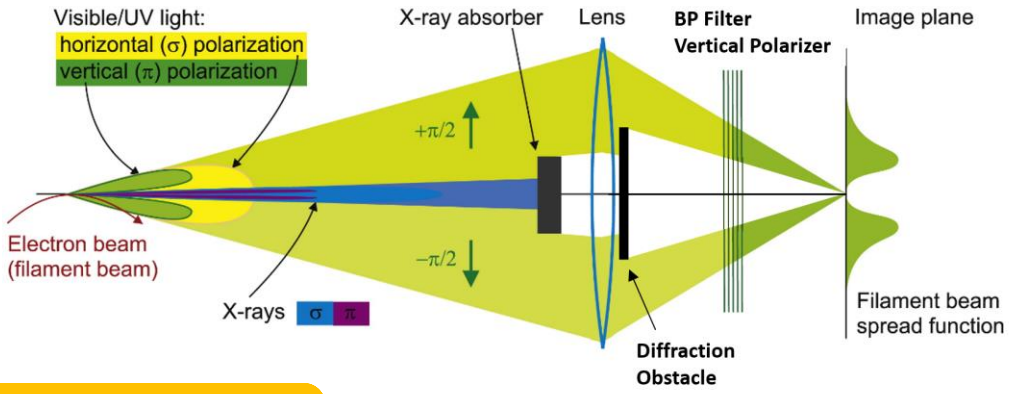
Phys. Rev. ST Accel. Beams 13, 022805 (2010)

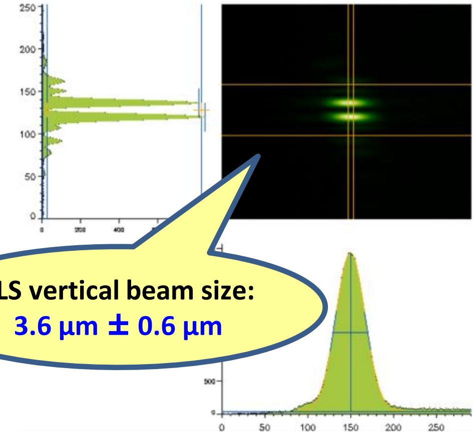
5 μm spatial resolution can be reached at **DLS-2** with thin scintillator & matched pinhole aperture

LESR / 4GLS Profile Monitor Options II

Principle of π-Polarization Beam Size Monitor

Å. Andersson, J. Breulin (MAX-IV)





SLS vertical beam size:
3.6 µm ± 0.6 µm

Å. Andersson et al., NIM-A 592 (2008) 437-446

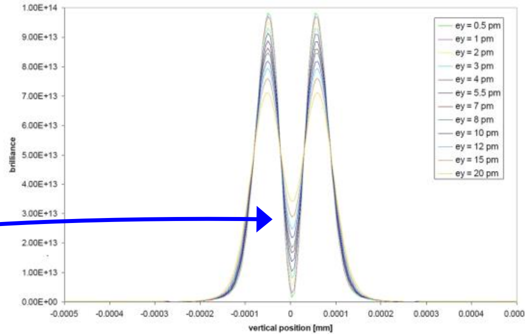
aperture restrictions (< 10 mrad) at LESR / 4GLS prevent out-coupling of visible (UV) light ☹

- **imaging of vertically polarized SR in the visible or UV**
- **phase shift of π between two radiation lobes**
  - → destructive interference in mid plane
  - → $I_{y=0} = 0$ in FBSF (filament beam spread function)
- **for finite vertical beam size → $I_{y=0} > 0$ in FBSF**
- **beamline modelling with SRW***
- **beam size is determined by peak-to-valley modulation**

* O. Chubar & P. Ellaume, *Accurate and Efficient Computation of Synchrotron Radiation in the Near Field Region*, EPAC 1998

2-D intensity distribution in image plane

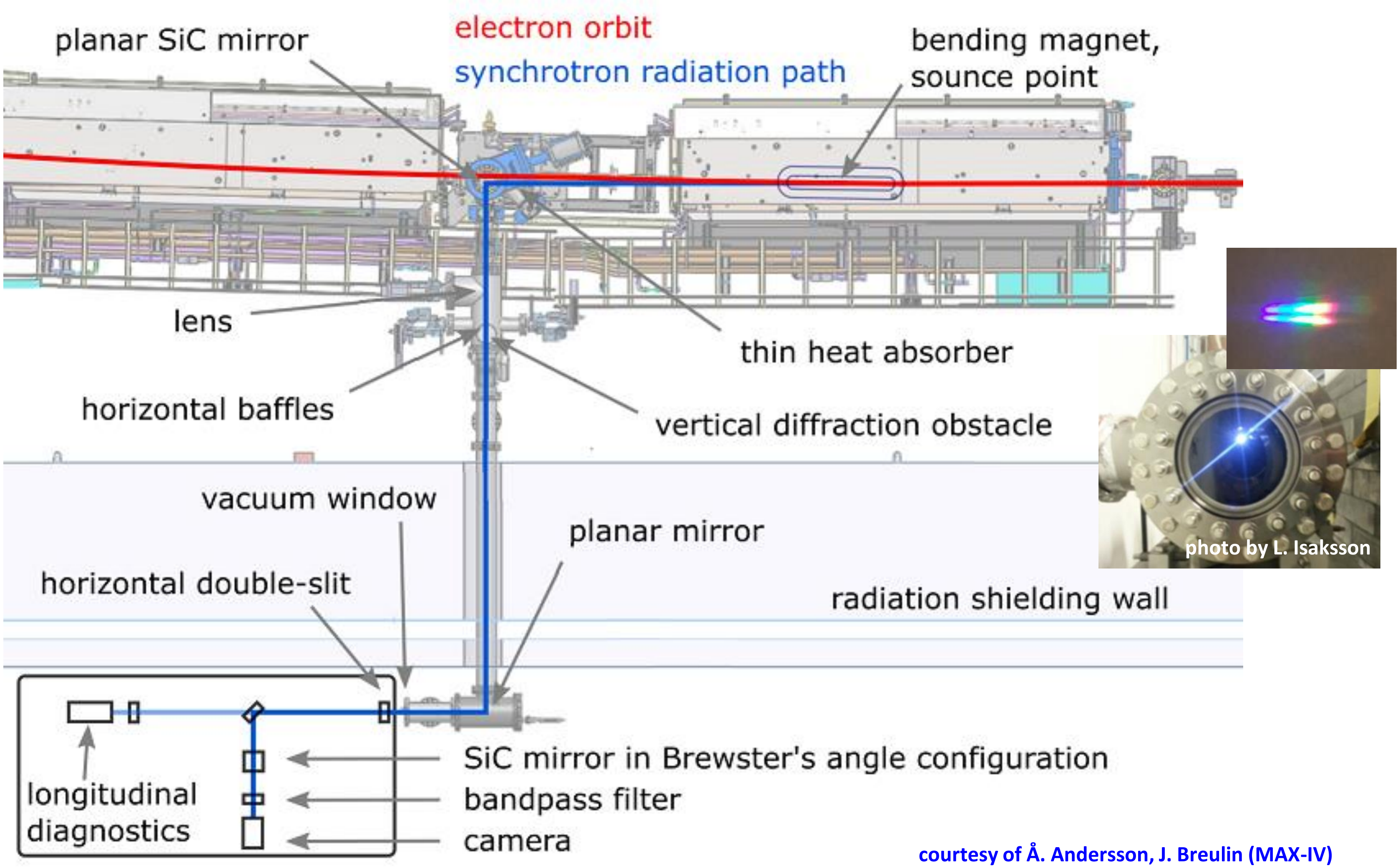
$$I_\pi(x,y) \sim \mathrm{sinc}^2(x) \times \left|\frac{\cos(\psi)-1}{\psi}\right|^2 \quad with\ \psi = \frac{2\pi\,\theta\,y}{\lambda}$$



LESR / 4GLS Profile Monitor – MAX-IV

Schematic of MAX-IV π-Polarization Beam Size Monitor

Å. Andersson, J. Breulin (MAX-IV)



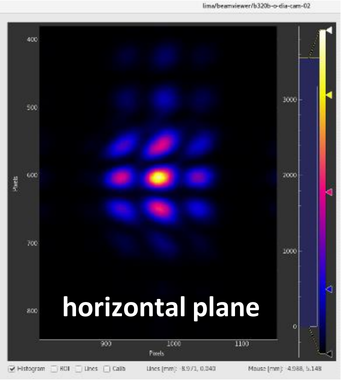
courtesy of Å. Andersson, J. Breulin (MAX-IV)

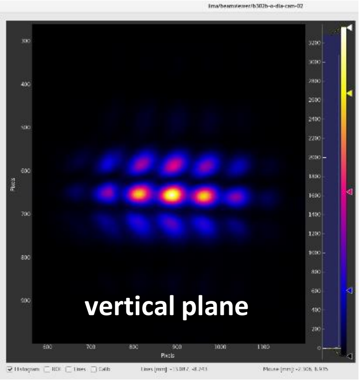
Use of Profile Monitor Data at MAX-IV

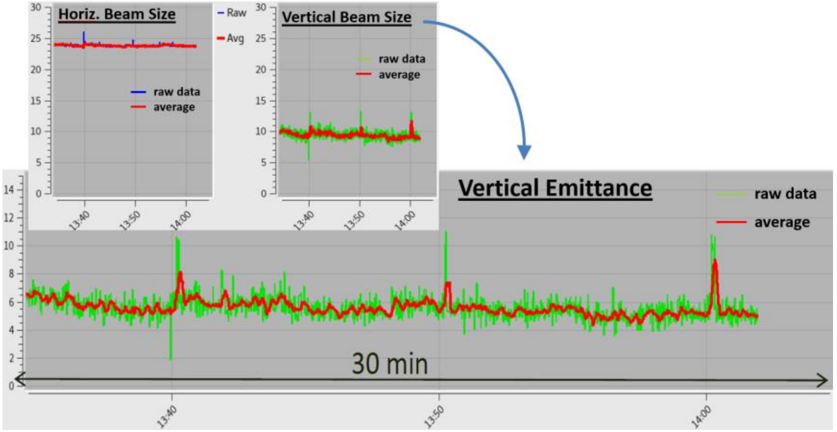
π-pol. with diffraction obstacle (visible light)

Continuous Control Room Display of π-Polarization: Beam Size / Emittance Information

courtesy of Å. Andersson, J. Breulin (MAX-IV)

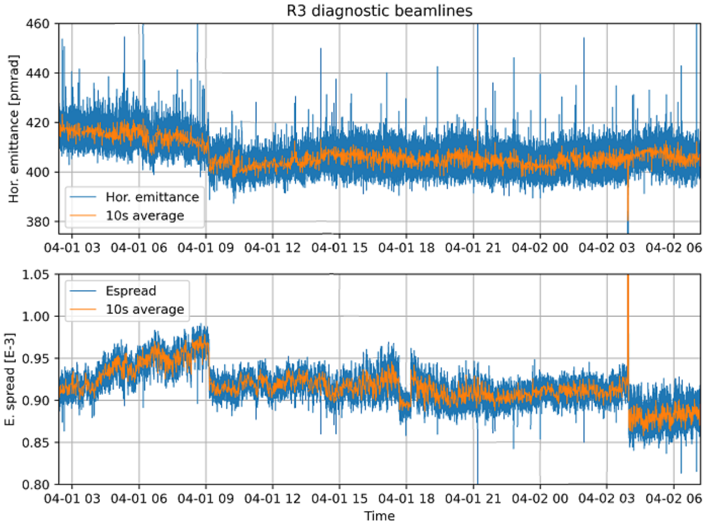






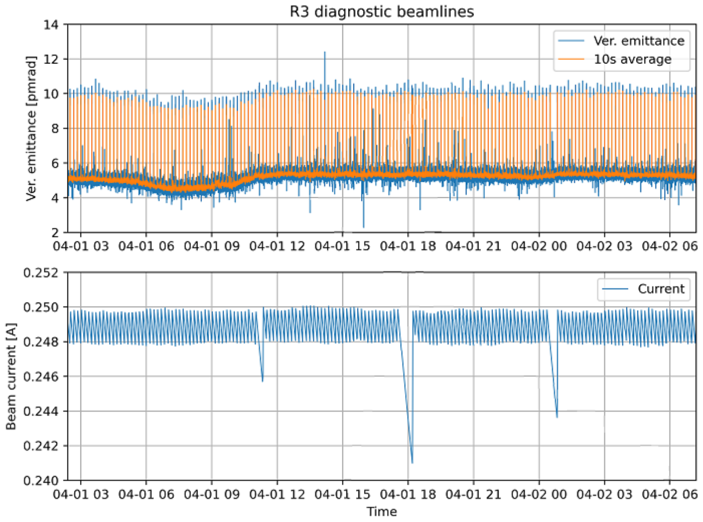
Horizontal Emittance and Energy Spread

courtesy of Å. Andersson, J. Breulin (MAX-IV)



Vertical Emittance and Top-Up Injections

courtesy of Å. Andersson, J. Breulin (MAX-IV)

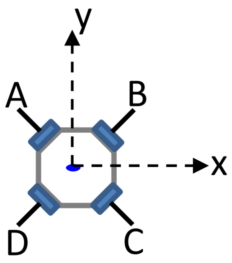


Beam Position Monitors – Specifications

Parameter	Operation Mode	Bandwidth / Time	Specification	Conditions
Position Noise or Resolution	commissioning	~ 100 – 500 kHz	< 50 μm RMS	≤ 1 mA, single bunch
	turn-by-turn	~ 100 – 500 kHz	< 1 μm RMS	nominal beam current and filling pattern
	fast orbit FB	≥ 10 kHz	< 50 nm RMS	nominal beam current and filling pattern
Position Drift (electronics only)	fast orbit FB	hour	< 100 nm	nominal beam current and filling pattern
		week	< 400 nm	nominal beam current and filling pattern
		year	< 1’000 nm	nominal beam current and filling pattern; BBA
Position Drift (mechanics only)	nominal user / top-up operation tunnel temperature stability ≤ 1 °K	hour	< 100 nm	nominal beam current and filling pattern
		week	< 400 nm	nominal beam current and filling pattern
		year	< 1’000 nm	nominal beam current and filling pattern
Beam Current Dependency	SR filling (full range)	minutes	10 μm	nominal beam current and filling pattern
	top-up operation (1%)	seconds	< 100 nm	nominal beam current and filling pattern
Absolute Accuracy	commissioning	initial	< 500 μm	limited beam current dominated by mechanics
	after BBA	week(s)	< 5 μm	nominal beam current and filling pattern

Beam Position Monitors – Principle

Determination of Beam Position



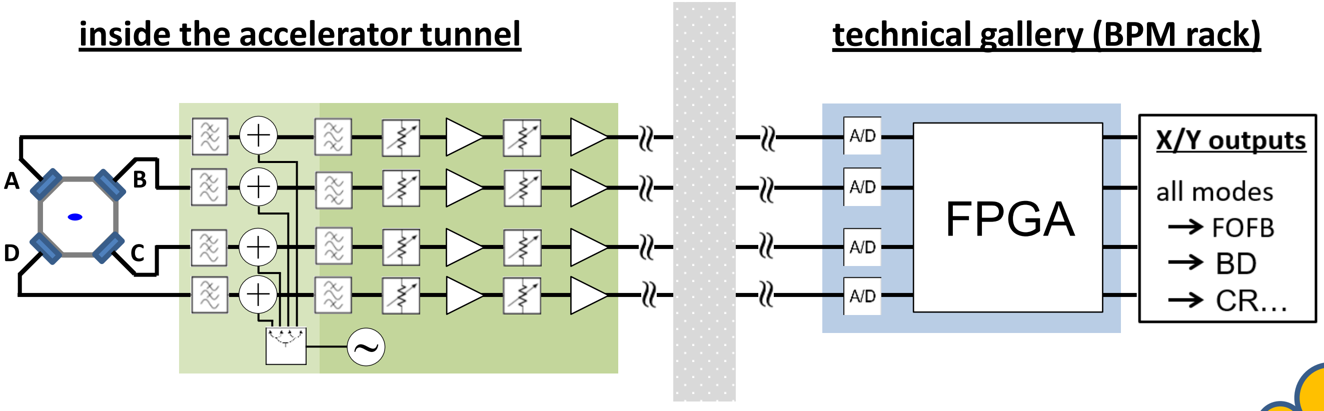
$$X = \frac{\Delta}{\Sigma} = K_x \left(\frac{V_A+V_D-V_B-V_C}{V_A+V_B+V_C+V_D}\right)$$

$$Y = \frac{\Delta}{\Sigma} = K_y \left(\frac{V_A+V_B-V_C-V_D}{V_A+V_B+V_C+V_D}\right)$$

improved resolution due to smaller geometric factor

	BPM Geometric Factor
3GLS	$K_{x,y}$ ~ 10 – 20 mm
LESR	$K_{x,y}$ ~ 5 – 10 mm

Schematic Building Blocks of LESR BPM Systems



Pick-Up **RF-FE with calibration** **Tunnel Wall** **Digital Back End**

- **pilot tone** (shown here)
- **crossbar switch** (proven concept)

calibration removes drifts mainly caused by temperature and humidity changes

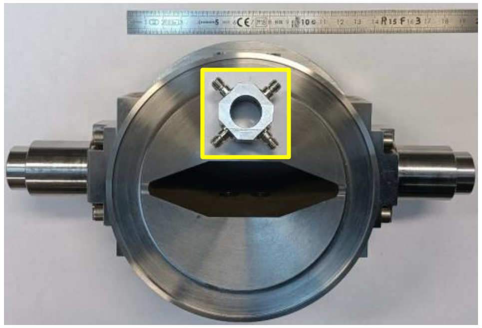
e.g. environment, cables, electronics components…

Beam Position Monitors – Mechanics

Button-type Pick-Up

- small diameter PU (≈ 10 – 25 mm) and buttons (≈ 5 – 10 mm)
- materials: SS (316L) with Cu-coating and NEG layers for pick-up
  Mo or SS (316L) for buttons
  ceramic or borosilicate glass as insulator
- good impedance properties and careful feedthrough design to prevent trapped modes and heating

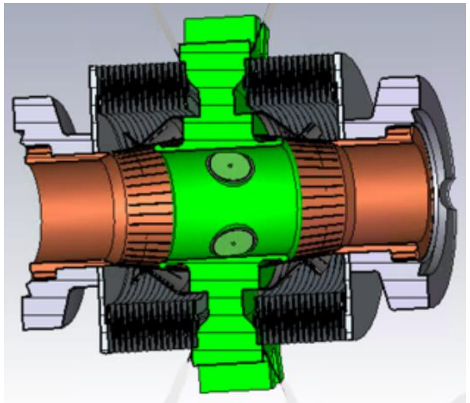
SOLEIL & SOLEIL Upgrade BPM Pick-Ups



courtesy of N. Hubert

- SR shielding by pick-up diameter increase and tapering or set-back of buttons
- water-cooled SS, invar or granite supports for mechanical stability and de-coupling with bellows to prevent mechanical stress
- optional monitoring of mechanical BPM pick-up position (e.g. by using dial gauges)

ALS-U BPM Pick-Up Design

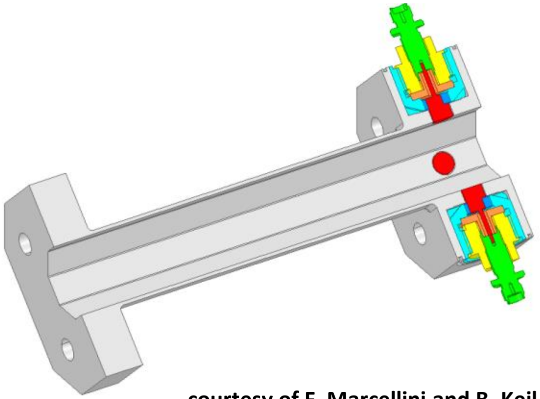


courtesy of S. De Santis and C. Steier

APS-U Prototype BPM Pick-Up

courtesy of N. Sereno

SLS 2.0 BPM PU / Corrector Chamber Design



courtesy of F. Marcellini and B. Keil

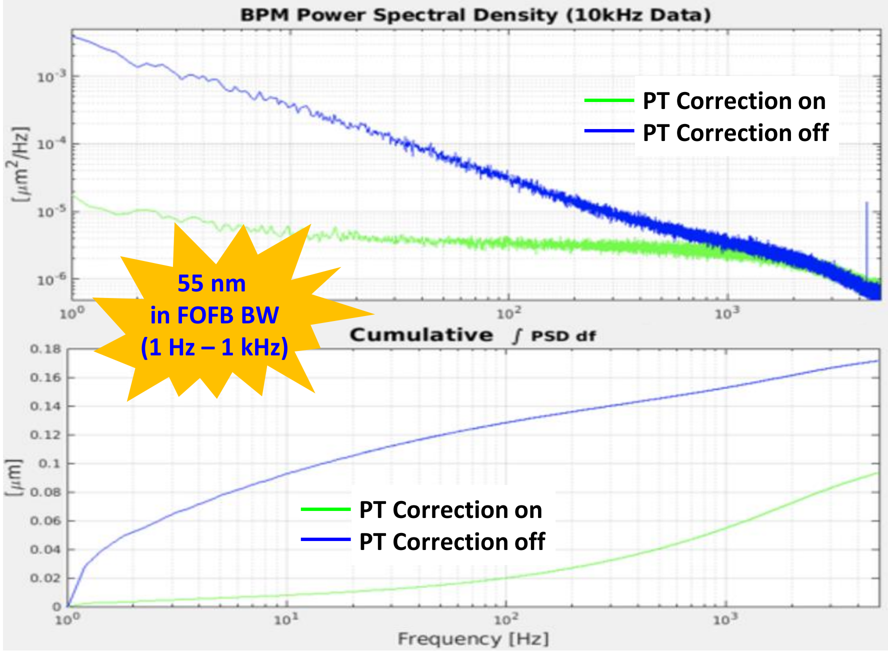
Beam Position Monitors – Electronics

Numerous In-House and Some Commercial BPM Developments for DLLS Projects

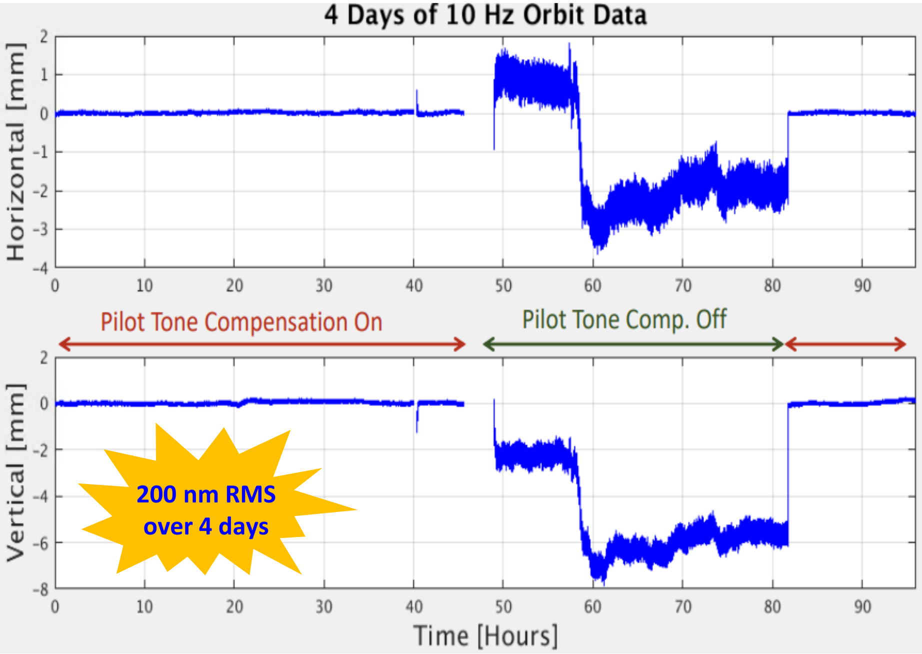
- **drift compensation and calibration by pilot tone or channel switching (cross-bar)**
- radiation safe placement of analog front ends in tunnel
- use of RF cables with low temperature and humidity dependence to avoid drifts
- temperature stabilization of racks and / or temperature regulation of electronics
- digital back-ends provide parallel outputs with different BW (operation modes)

Improved Noise Performance & Drift Compensation by Pilot Tone Correction (ALS BPMs)

G. Portman, E. Norum, M. Chin, J. Weber (ALS-U) presented at IBIC 2020, Santos, Brazil (virtual) FRAO03



55 nm in FOFB BW (1 Hz – 1 kHz)

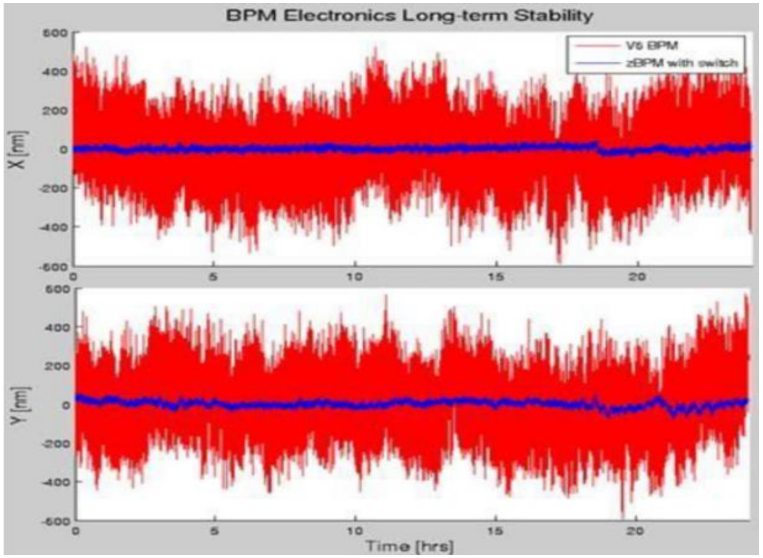


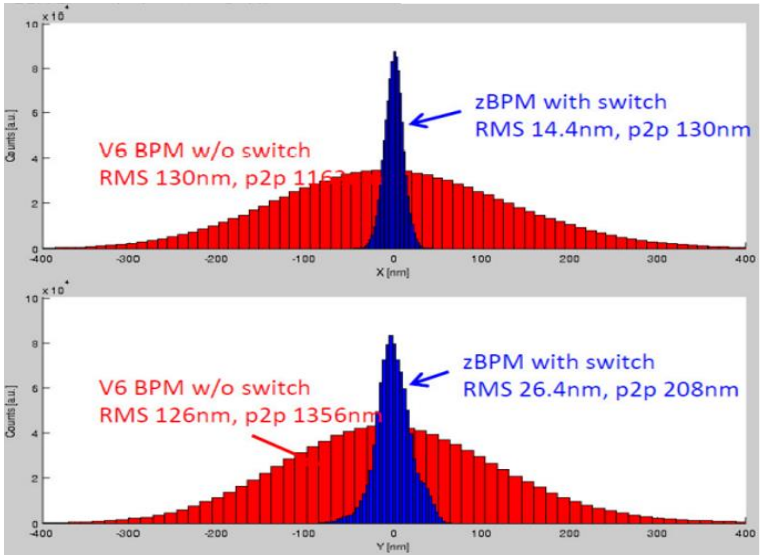
200 nm RMS over 4 days

Beam Position Monitors – Electronics

NSLS-II BPM Tests with Channel Switching

D. Padrazo et al. presented at ARIES Joint WS, Barcelona 2018




zBPM with switch
RMS 14.4nm, p2p 130nm

V6 BPM w/o switch
RMS 130nm, p2p 116

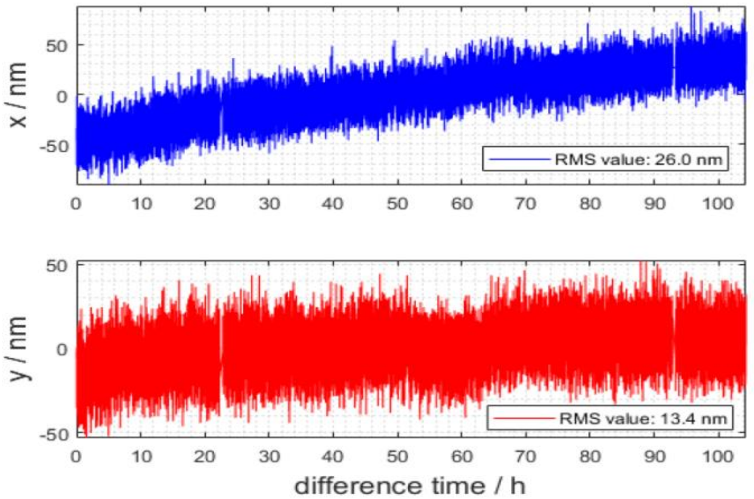
zBPM with switch
RMS 26.4nm, p2p 208nm

V6 BPM w/o switch
RMS 126nm, p2p 1356nm

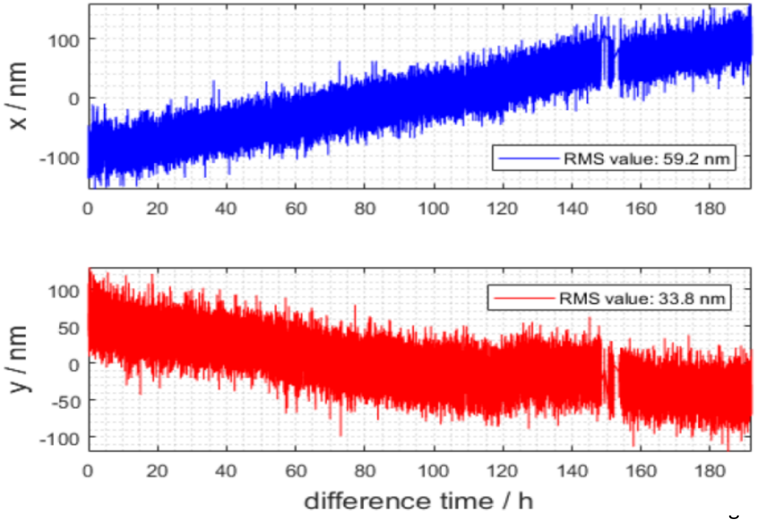
PETRA-IV BPM Prototype Tests with I-Tech

G. Kube et al. / P. Leban et al. presented at IBIC 2022, WEP08 and WEP09

480 bunches of 0.25mA or 1.9nC



40 bunches of 2.5mA or 19nC



Beam Position Monitors – Short Summary

BPM Pick-Ups and Mechanics

- small diameter pick-ups and buttons require profound analysis of impedance and heat load but lead («for free») to resolution improvement due to smaller geometric factors
- active cooling of pick-up and supports, mechanical decoupling with bellows and optional monitoring of pick-up positions avoids temperature and mechanical stress-related movements

BPM Electronics

- drift compensation and resolution improvements by channel switching (crossbar) or pilot tone

  with RF front ends in accelerator tunnel the whole BPM chain including cables can be calibrated
- fast digitizers and SoC technology (System on Chip including FPGAs and ARM processors) allow tens of kHz sampling rates, parallel outputs of operation modes and increased FOFB bandwidths (up to kHz) due to low latency DAQ
- FOFB architecture allows integration of different types of sensors (e.g. electron and photon BPMs) for improved overall stability at future low emittance SR based DLLSs

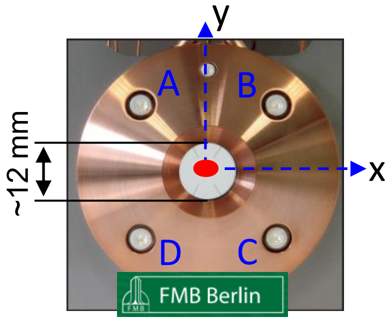
Photon Beam Position Monitors

Different types of photon BPMs have already been successfully used at many 3GLS

→ **ID gap calibration** (with blade monitors and GRID XBPMs in front end)
→ **beamline alignment** (using CVD sc-diamond or SiC quad detectors)
→ **providing mainly slow photon beam position feedbacks** (drift compensation)

Front End – White Beam

ID blade monitor



GRID XBPMs: APS development

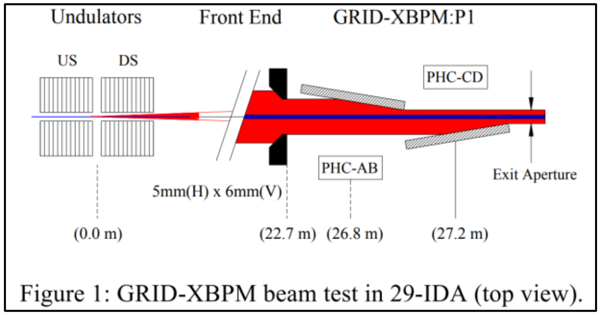
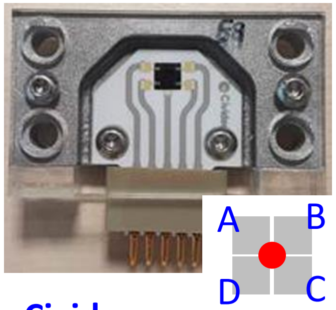


Figure 1: GRID-XBPM beam test in 29-IDA (top view).

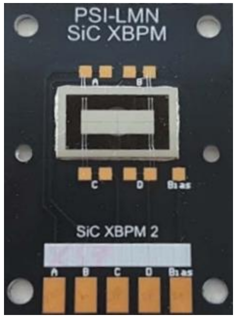
Beamline – Monochromatic Beam

CVD sc diamond



Cividec

Silicon Carbide



SenSiC

FE SiC quad detector

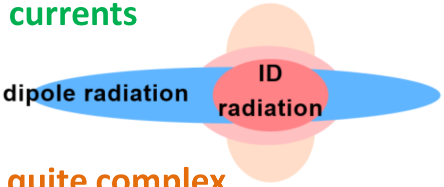
new SenSiC development

Determination of Beam Position

$$X = \frac{\Delta}{\Sigma} = K_x \left(\frac{I_A + I_D - I_B - I_C}{I_A + I_B + I_C + I_D} \right)$$

$$Y = \frac{\Delta}{\Sigma} = K_y \left(\frac{I_A + I_B - I_C - I_D}{I_A + I_B + I_C + I_D} \right)$$

… is similar to electron BPMs using photo currents



but in the FE quite complex due to background radiation pattern

Photon BPMs – FB Integration at 4GLS I

In many 3GLS, Photon BPMs are important devices for beamline stabilization but most of them are not yet part of a fully integrated beam stabilization concept

For 4GLS DLSR, we should use the potential of Photon BPMs even better…

→ **examination and elimination of systematic effects** (e.g. radiation background)

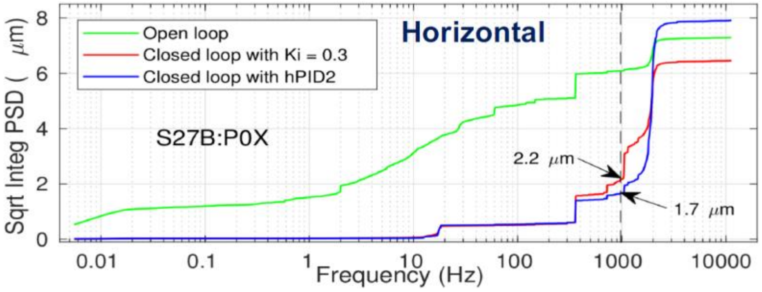
→ **developing and following new monitor and sensor concepts**

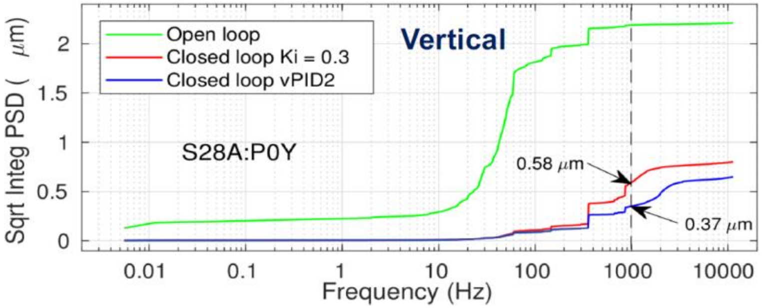
→ **synchronized DAQ and common FB platform with electron BPMs** (FB or watchdog)

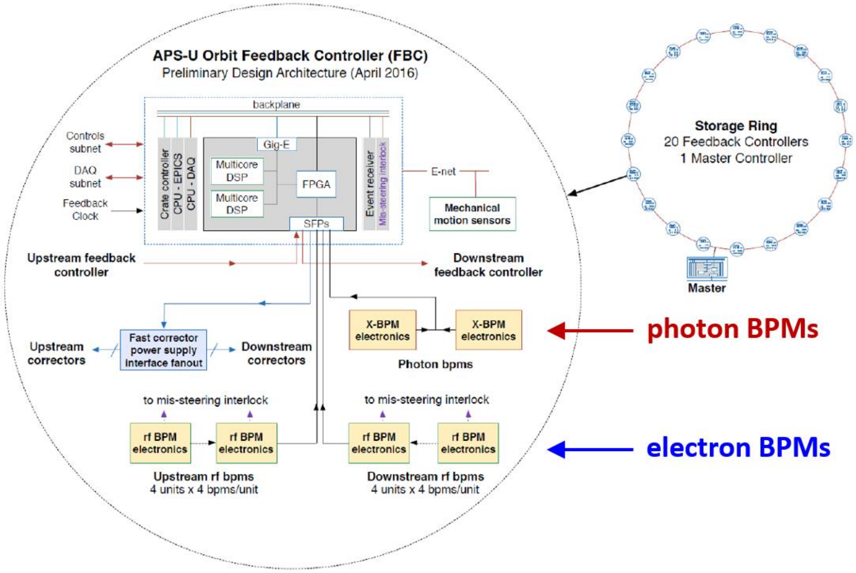
→ **responsibility for electron and photon BPMs in "one hand"…???**

Example 1: Orbit Feedback System for APS-U including Electron and Photon BPMs

N. Sereno et al. IPAC 2015 & IBIC 2016; P. Kallakuri et al. IBIC 2017, J. Carwardine et al. IBIC 2018







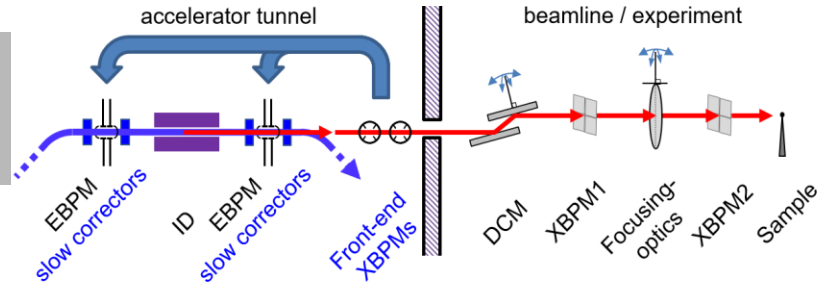
photon BPMs

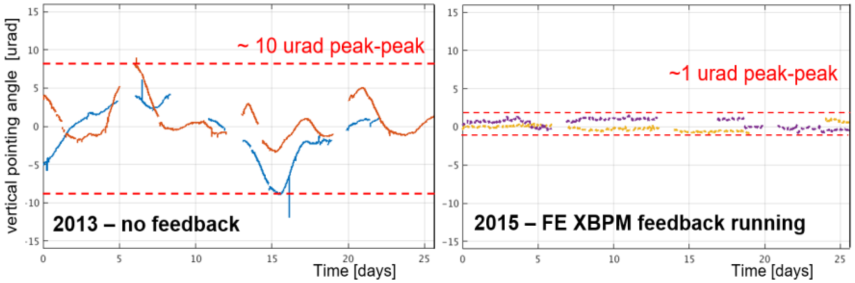
electron BPMs

Photon BPMs – FB Integration at 4GLS II

Example 2: Slow (1 Hz) Feedback using FE XBPM Readings and Electron Beam Steering at DLS

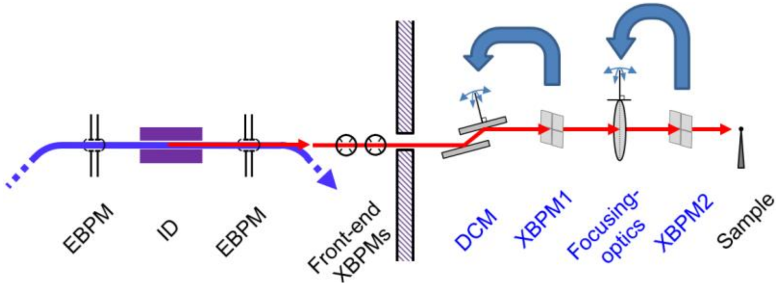
courtesy of C. Bloomer et al., Diamond Light Source

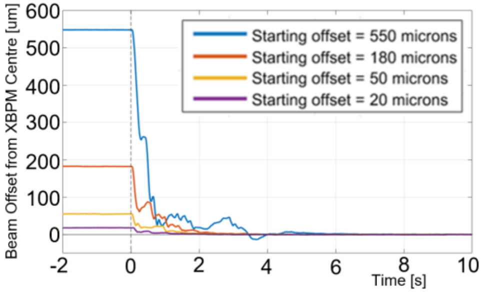




Example 3: Realtime (10Hz) Local FB using BL Photon BPMs and Beamline Optical Elements

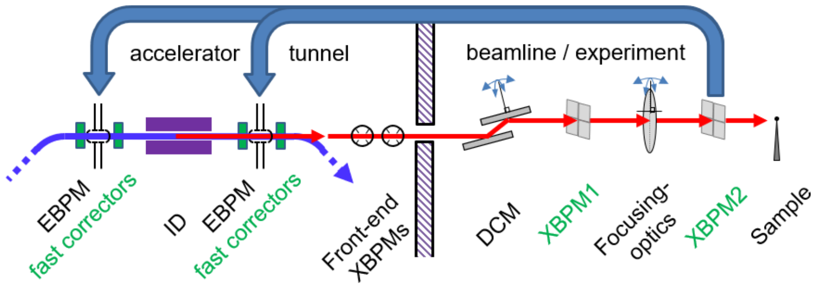
e.g. C. Zhang, Applied Sciences, 2023 (SSRF) or J. Sanchez-Weatherby, J. Sync. Rad. 2019 (DLS) or C. Bloomer, NSS Conf. Record, 2017

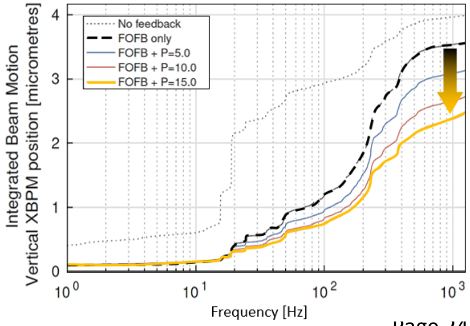




Example 4: Fast (1 kHz) Feedback using BL Photon BPM Readings and Electron Beam Steering at DLS

C. Bloomer, G. Rehm, A. Tipper IBIC 2019





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Closing Remarks and Summary

- Many of state-of-the-art Diagnostics Systems are “ready to go” for ultra-low emittance storage rings (4GLS) – even with sufficient performance ☺☺☺
  - → new BPM developments fulfill already resolution and BW requirements
  - → stringent drift requirements may be achieved by pilot tone calibration
- High resolution Profile Monitors are a challenge
  - → existing designs may work for some “lucky ones”
  - → many have to learn from beamline scientists on X-ray imaging
  - → new ideas are welcome and have already been tested successfully
  - → 100 Hz to kHz update rates will allow for coupling / emittance FBs
- Photon BPMs have great potential for improving source point stability
- Newly designed FB Systems will be open for electron and photon monitors
- FOFBs (electrons and photons) will provide loop BW of up to 1 kHz

Thank You !!!

… for your patience and attention ☺☺☺