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Volker Schlott, Paul Scherrer Institut

Diagnostics Requirements for Ultra-Low Emittance Rings

I.FAST Workshop, Karlsruhe Institute of Technology (virtual) April 25th – 29th 2022

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Acknowledgements 😀 😘 😀

This presentation is based on information from many colleagues working at several light sources!

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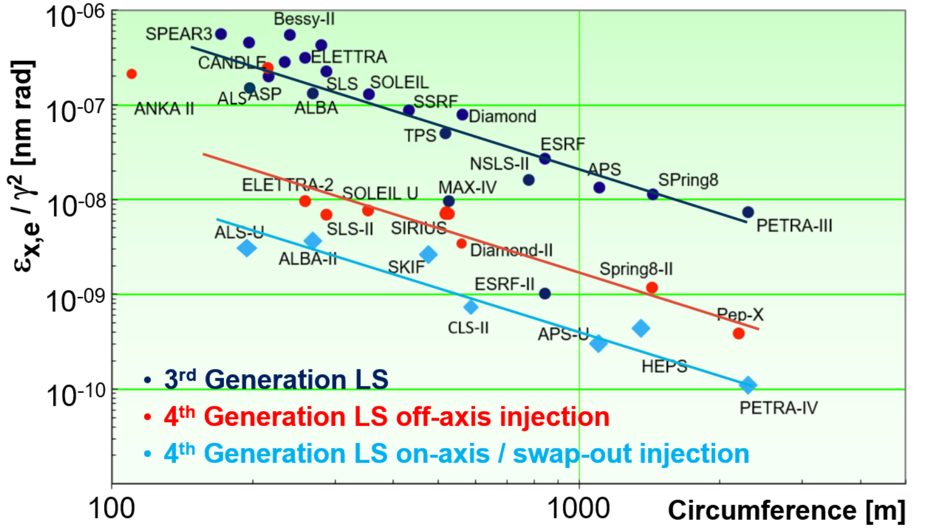
… and especially to Nazanin Samadi for sharing her ideas on the "Dispersive Crystal Diffraction Monitor"

From 3rd to 4th Generation Light Sources

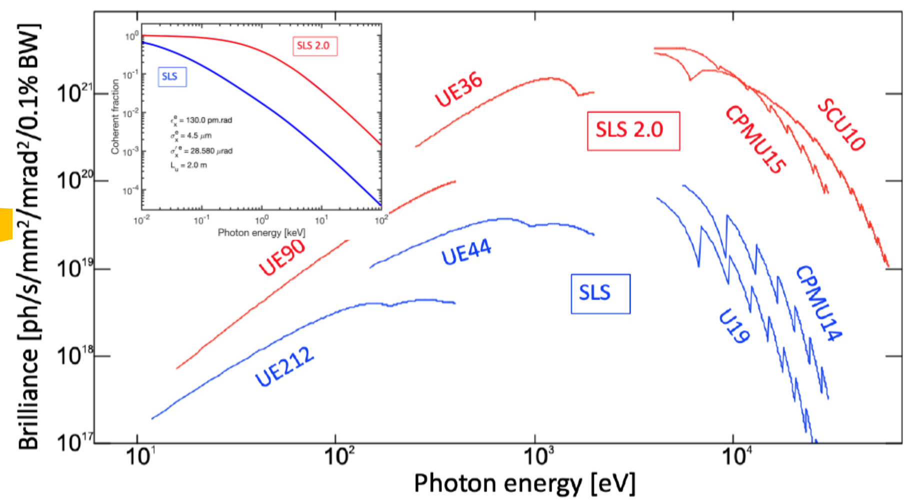
Technological Innovations ➡ > 2 orders of magnitude lower horizontal emittance

- NEG-coated small aperture vacuum chambers
- strong and compact PM magnets
- (ultra) fast injection elements
- advanced insertion devices



Storage Ring Lattice Design

- MBA lattices
- reverse and long. gradient bends
- on-axis / swap-out injection
- phase space matching of electron and photon beams ➡ higher brightness and more coherent photon beams



Beam Diagnostics and Beam Stability have always been pre-requisites for successful LS operation – even more for 4th GLS

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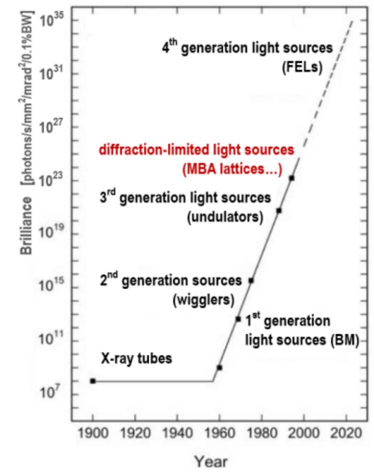
Some Introductory Remarks on Diagnostics

Light Sources and Storage Rings evolve stepwise in generation

1^{st} GLS	parasitic use of dipole sources (HEP facilities)
2^{nd} GLS	dedicated facilities (BM, wiggler)
3^{rd} GLS	optimized lattices for undulators
DLSR	multi-bend achromats and optimized IDs

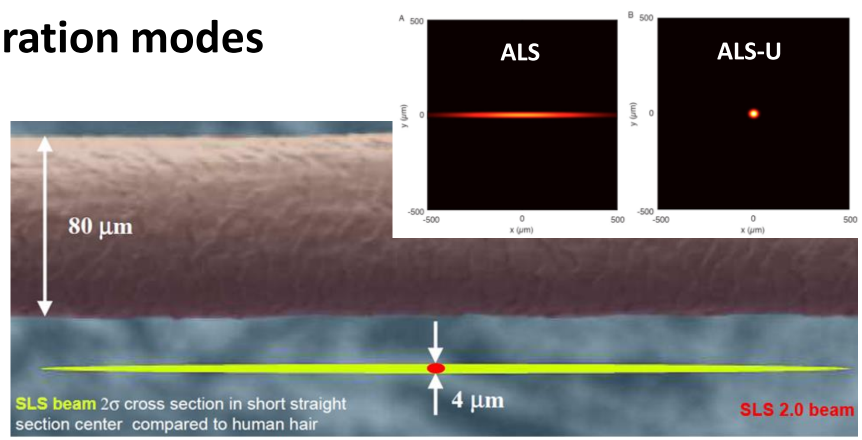


Diagnostic Systems are subject to a more continuous evolution…:

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)



Diagnostics requirements for ultra low emittance rings are close to those of 3GLS in the vertical plane ☺
However, Diagnostics Systems have to provide improved performance and advanced functionalities

Basic Requirements and Functionalities

Pre-Beam Commissioning

- lab-calibration → 5-10% calibration errors (including DAQ systems)
- initial alignment → sufficiently good to find, optimize and accumulate beam
  e.g. BPM offsets ≤ 500 µm, beam line optics pre-adjusted with alignment tools (e.g. laser)
- validity checks → BPM non-linearity correction for large beam offsets and cross sums

Beam Commissioning

- full characterization of injected beam in injector and/or BR transfer line
- first turn / turn-by-turn operation modes for BPMs and BLMs (working horse diagnostics)
- profile measurements should be available after accumulation to allow optic checks

reserve sufficient time for diagnostics commissioning with beam

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…)

reserve sufficient time for diagnostics optimization and implementation of beam-based FBs

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

Overview of 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 measurement 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
Tune *	**pinger or stripline kicker** & **BPM electronics**	ready for LE rings
Emittance & Energy Spread	**visible light interference** & **pi-polarization** **x-ray imaging** (pinhole camera) & **diffraction**	needs improvement, complex engineering
Beam Stability	**fast orbit feedback**	increase BW (1 KHz), include X-BPMs
Instabilities / Emittance FB	**multi-bunch feedback**	implement ε-FB, injection transients

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Requirements for "Ready-to-Go" Systems

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

DCCT (commercial device, analog)

< 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, rep.-rate: 500 (250) MHz; slow time axes at μs to ms

visible light extraction 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

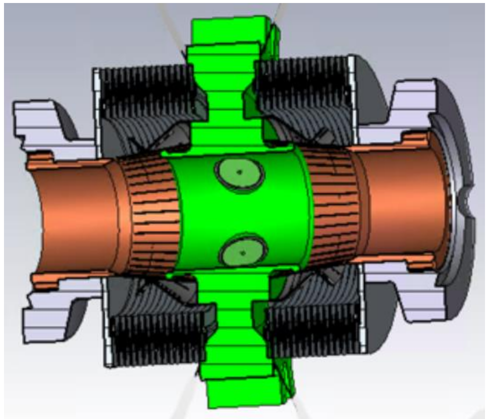
BLMs may be most sensitive system for injection monitoring & optimization (commissioning)

Requirements for Beam Position Monitors I

Mechanics **button-type pick-up**

- small diameter beam pipe (≈ 16 – 25 mm) and button feedthroughs (≈ 5 – 10 mm)
- SS with Cu-coating and NEG layers
- SR shielding by diameter increase of pick-up and tapers or set-back of feedthroughs
- good impedance properties and careful feedthrough design to prevent trapped modes and heating
- mechanical 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

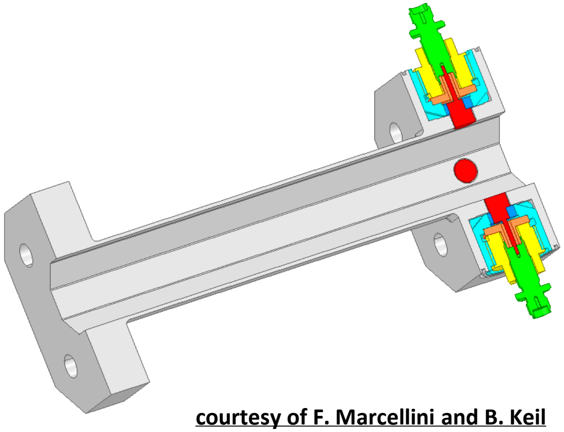


courtesy of S. De Santis and C. Steier

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

Requirements for Beam Position Monitors II

Electronics — **numerous in-house and some commercial developments for DLLS projects**

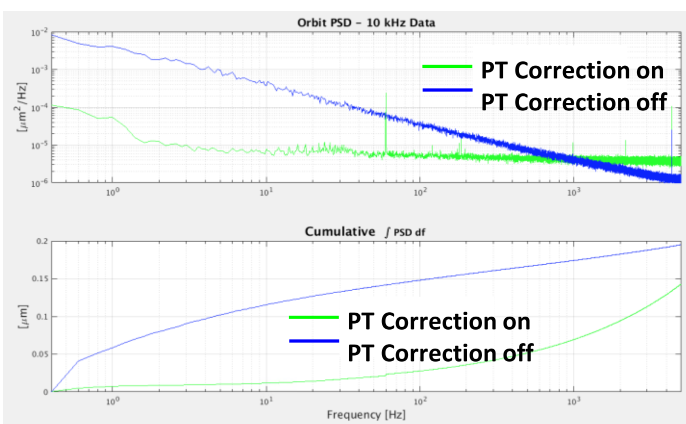
typical specs: commissioning	< 50 µm rms @ low beam currents (1 mA)
turn-by-turn	< 1 µm rms (at nominal beam current)
orbit mode	< 100 nm rms @ 10 kHz sampling rate
drift	< 100 nm / h; < 1 µm / week

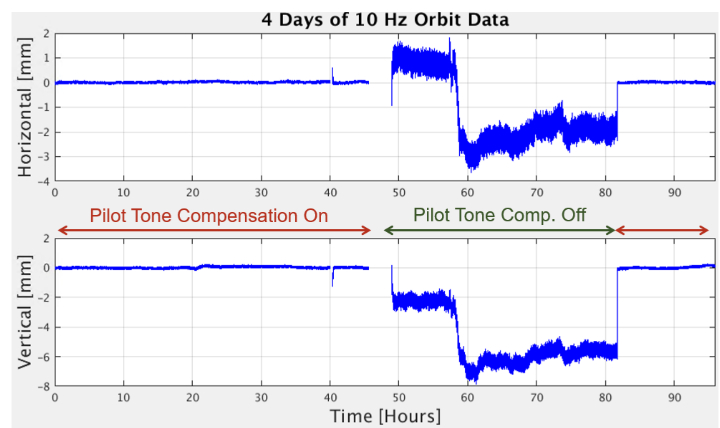
- 4-channel parallel systems
- drift compensation and calibration by channel switching (cross-bar) or pilot tone
- radiation safe placement of analog front ends in tunnel (pilot tone approach)
- use of RF cables with low temperature and humidity dependence to avoid drifts
- temperature stabilization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

BPM requirements are challenging
but advances in technology and proven concepts make improvements feasible

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

G. Portman, E. Norum, M. Chin, J. Weber (ALS-U) presented at ARIES WS on Next Generation BPM and FB Systems, Barcelona, Spain Nov. 2018





Requirements for Beam Profile Monitors

Beam Profile — **emittance, energy spread measurements and coupling control**

typical beam sizes: $\sigma_{h,v} \approx$ 5 - 10 µm (horizontal and vertical)

smallest beam sizes: $\sigma_v \approx$ 1 - 5 µm

beam size changes: $\Delta\sigma_{h,v} \leq$ 100 nm

beam size / coupling monitoring : coupling control → FBs
coupling FBs with update rates of up to 100 Hz

mechanical constraints: limited vertical aperture (<< 10 mrad)
→ difficult out-coupling of visible light
dense lattices and small bending angles
→ large distance to first optical elements

profile monitors are very challenging!!!
"lucky ones" can use proven concepts
a few have to learn about
X-ray optics & develop new ideas

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

State-of-the-Art at 3GLS

imaging-based methods

- X-ray pinhole camera (> 15 keV)
- π-polarization (visible)
- coded aperture (X-rays)

interference-based methods

- double slit interferometry (visible)
- π-pol. with diffraction obstacle (visible)

Proposed Beam Profile Monitors for 4GLS

imaging-based methods

- existing methods and X-ray imaging
- Fresnel zone plates or KB mirrors (X-rays)
- compound refractive lenses (X-rays)

interference-based methods

- X-ray interferometry
- grating interferometry (X-rays)

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Beam Profile Monitors – State-of-the-Art

X-Ray Pinhole Camera

→ see presentation from Friederike Ewald (ESRF-EBS)

π-Polarization Monitor with Diffraction Obstacle

→ see presentation from Åke Andersson (MAX-IV)

Single or Double Slit Interferometry

"working horses" at light sources

→ 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

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

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

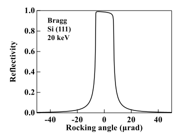
→ B. Yang, S. Lee, "Planned X-Ray Diffraction Diagnostics for APS-U Emittance Measurements" ARIES Topical Workshop on Emittance Measurements for Light Sources and FELs, Barcelona, Spain, January 2018

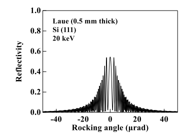
Beam Profile Monitors – New Ideas

X-Ray Beam Property Analyzer Based on Dispersive Crystal Diffraction

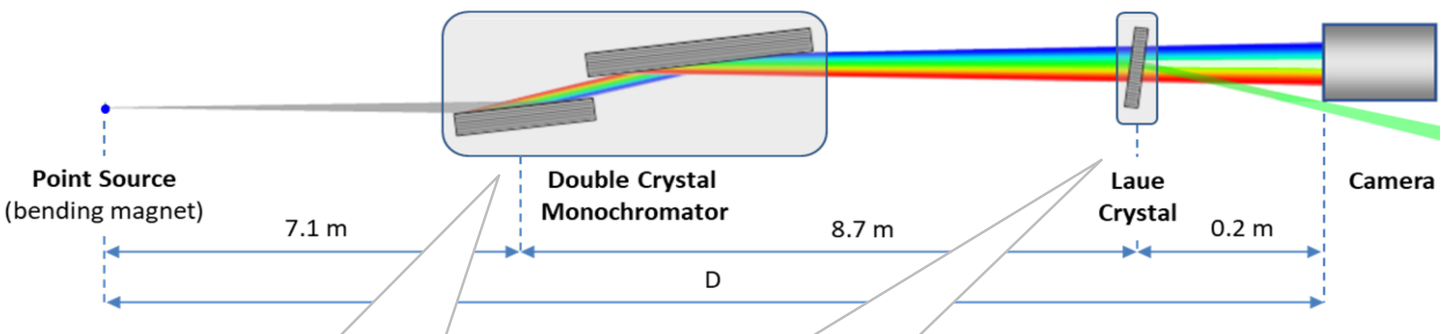
→ **N. Samadi**, X. Shi, C. O. Loch, M. Boege, J. Krempasky, D. Chapman, M. Stampanoni (2021), submitted to JSR

DCM:
e.g. cryogenically cooled channel-cut Si (1,1,1) DCM
→ E_{ph}= 18 keV

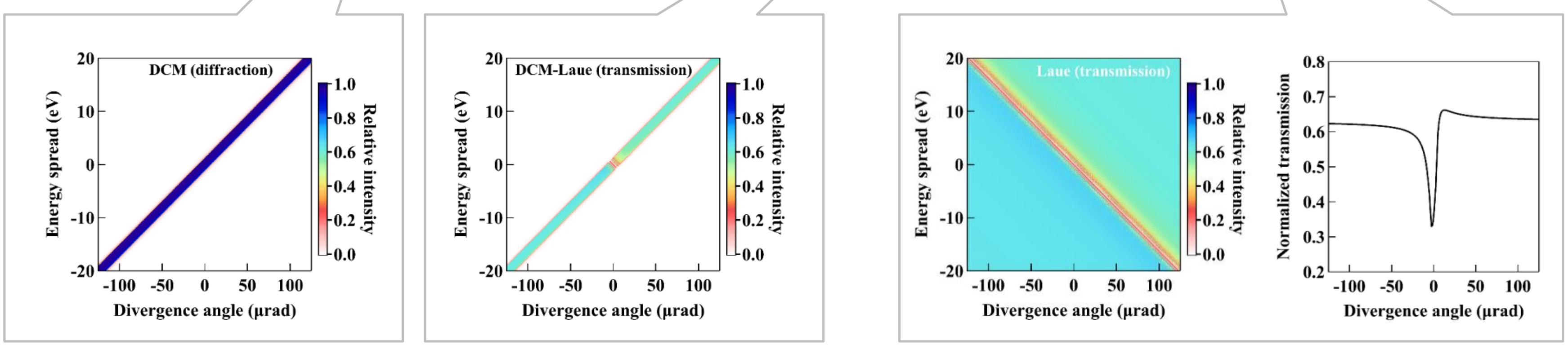




Laue crystal:
0.35 mm Si (1,1,1)
dispersive geometry against the DCM

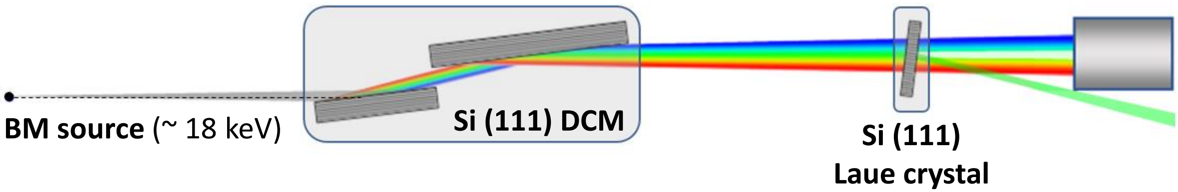


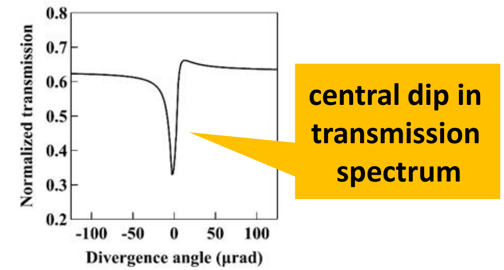
Detector:
sCMOS pco.edge 5.5
2 x objective
100 µm Ce:YAG scintillator
effective pixel size=3.25 µm



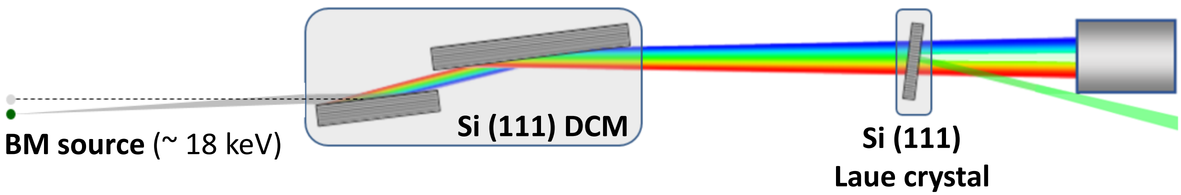
Dispersive Crystal Diffraction Monitor

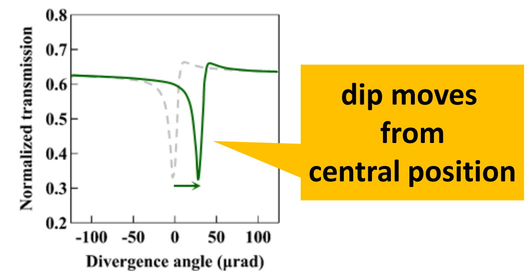
Point Source at Central Position



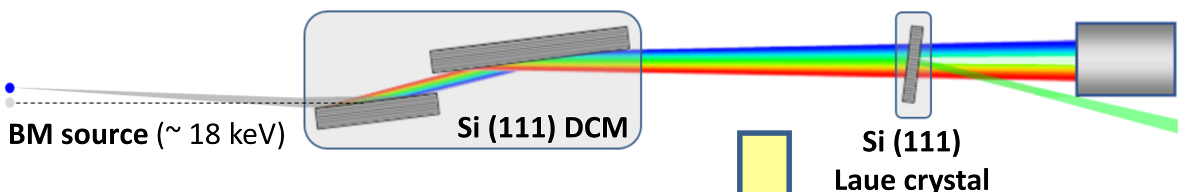


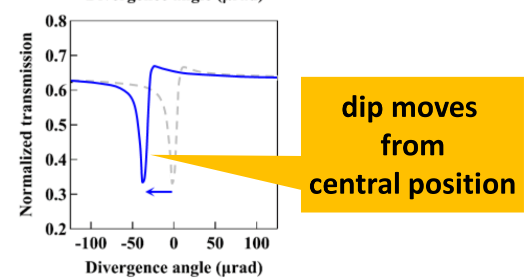
Point Source Downward Moved Beam



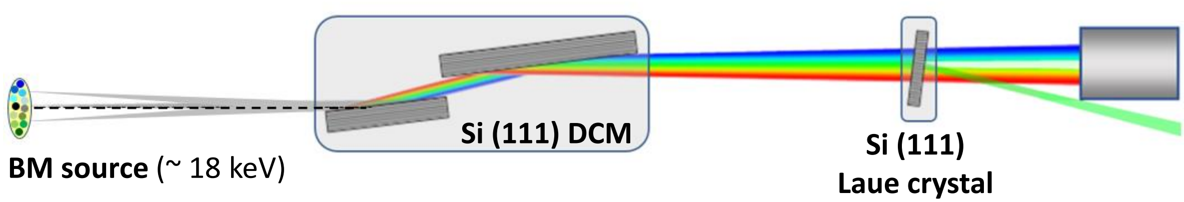


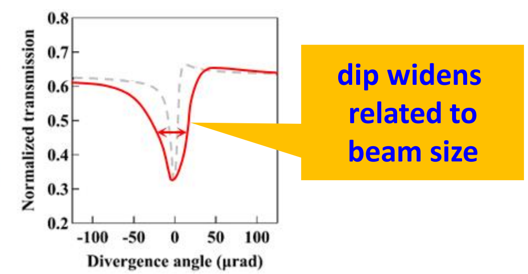
Point Source Upward Moved Beam





Finite Beam Size

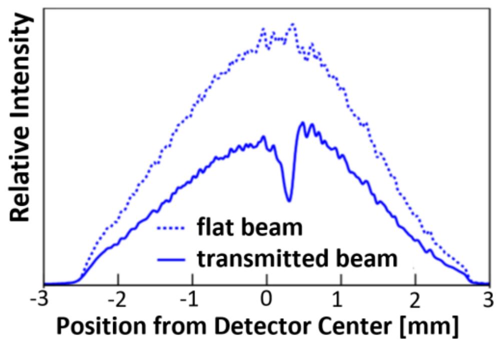




Dispersive Crystal Diffraction Monitor

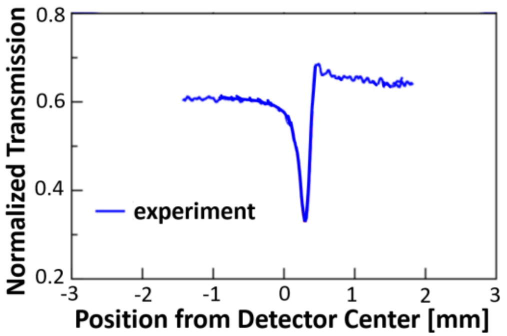
Data Analysis – Extracting the Source Size from the Transmission Spectrum

1st Step: Measurement of "flat beam" (only DCM) **and "transmitted beam"** (DCM & Laue)



normalization

$$I_m(y) = I_{trans}(y) / I_{flat}(y)$$



2nd Step: Fitting process for known source profiles

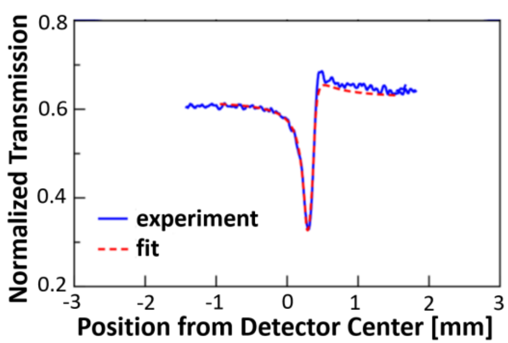
- Normalized transmission function $I_p\,(y_i)$ is known from "dynamical theory"

  see e.g.: Zachariasen, W. H. W. Theory of X-Ray Diffraction in Crystals. (New York: John Wiley, 1945)

- Gaussian beam from bending magnet: $I_s(y) = \exp[-(y - y_s)^2/(2\sigma_y^2)]$

- Minimizing ***err-function*** by deconvolution of $I_p\,(y_i)$ and fitting the beam size σ_y to the measured data $I_m\,(y_i)$

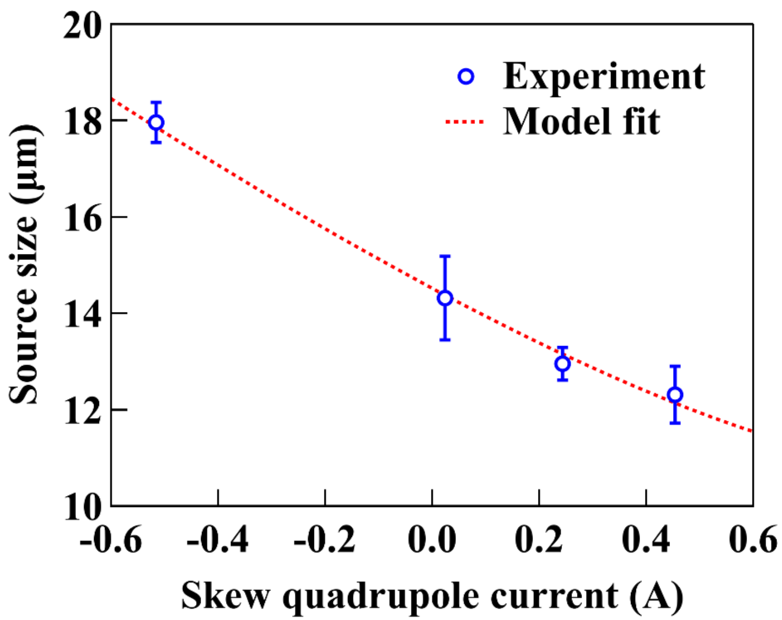
$$err = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[I_p(y_i) * I_s(y_i) - I_m(y_i)\right]^2}$$



Experimental Results – SLS Measurements

- **variation of source size** (vertical beam size) **by changing the horizontal-to-vertical coupling** (changing current in skew quadrupoles)
- **prediction of source size by model fitting using the TRACY-2 accelerator library**
- **excellent agreement of measured data and model fit**
  → **confirms that a "dispersive crystal diffraction monitor" can measure small electron beam sizes with high sensitivity and accuracy** (< 10%) ☺

- **needs a compact and "simple" DCM design for diagnostics purposes**
  (also required for other 4GLS beam size monitors, in preparation e.g. at SLS 2.0)
- **DCM / Laue can be made of polished Si crystals**
  (crystal quality and costs are of no major concern)
- **PD line arrays may speed up sampling time**
  (emittance FBs may profit from high update rates)
- **resolution can be improved for 4GLS beam profile monitor requirements by using Si (3,3,3)**
  (...instead of Si (1,1,1) in SLS experiments)



Beam Stability and Feedback Systems

Intensity: << 1 % of beam current / photon beam intensity through top-up operation

Energy Stability: < 10^{-4} $\Delta E/E$ with digital LLRF

Coupling: keep 10 % coupling in the vertical plane with coupling FB (beam size monitors as sensor)

Position & Angle: Fast Orbit Feedback → sub-µm stability from 0.01 to 1 kHz (a few percent of beam size)
→ drift: < 1 µm / week

1st Step

"Stability Task Force" (MAX-IV approach) implemented a common strategy for passive stability and isolation of vibrational and thermal sources over the whole facility (building, accelerator and beamlines)

stability is a common effort throughout the facility

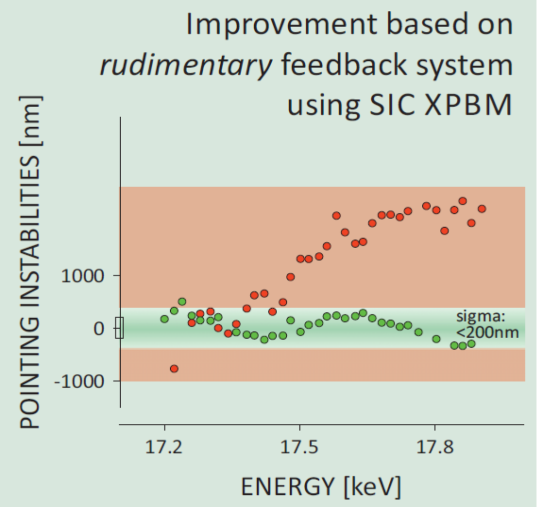
This approach may only work for new facilities!

Upgrading facilities – the majority of 4GLS – may put the responsibility for electron and photon diagnostics in one hand…

2nd Step

Implement a common feedback platform open to connect all electron and photon diagnostics systems and make use of their improved performance

Energy Scan at SLS microXAS Beamline with XBPM FB

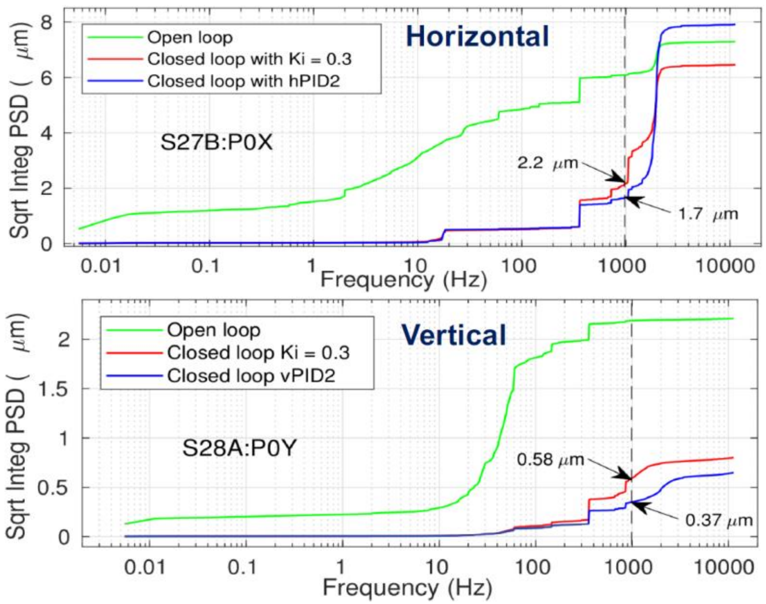


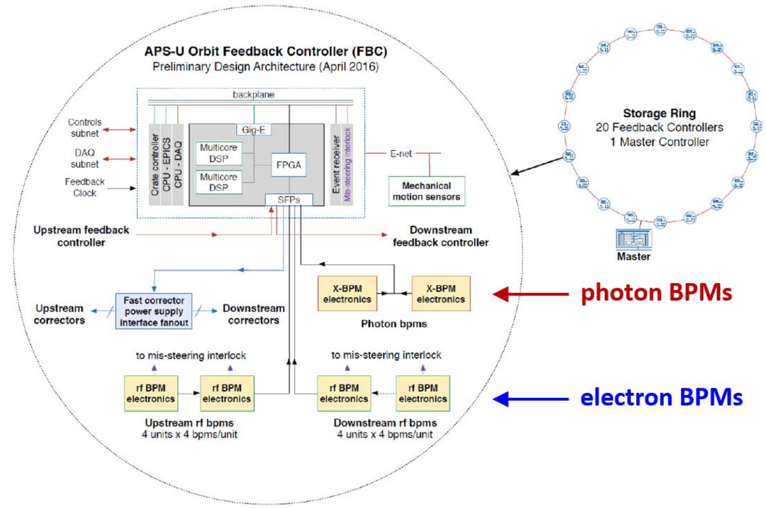
courtesy of D. Grolimund (SLS)

Orbit & Source Point Stabilization

Example 1: Orbit Feedback System for APS-U

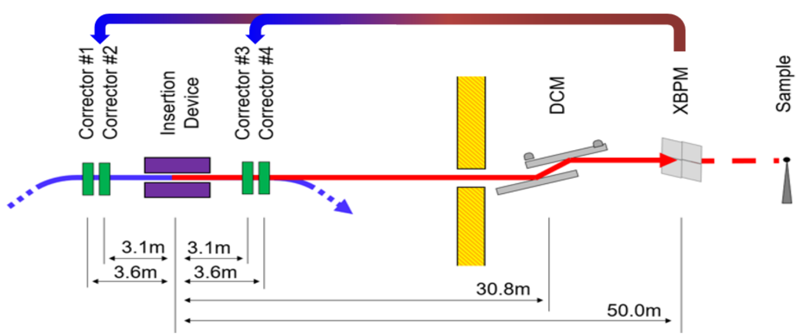
N. Sereno et al. IPAC 2015 & IBIC 2016; P. Kallakuri et al. IBIC 2017, J. Carwardine et al. IBIC 2018

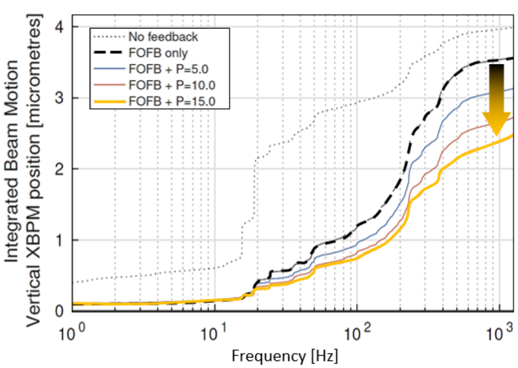




Example 2: Fast (1 kHz) Feedback using XBPM Reading and Electron Beam Steering at DLS

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 ☺ ☺ ☺
  - → BLMs can be important for commissioning and injection optimization
  - → new BPM developments fulfill 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
- Newly designed FB Systems are open for electron and photon diagnostics monitors and improve photon beam stabilization on the sample to closed loop BW of up to 1 kHz
- I'm very excited to learn more about recent results from existing facilities and improvements of diagnostics systems for new (upgrade) projects ☺ ☺ ☺

Thank You

… for your patience and attention ☺☺☺