Diagnostic Requirements for DLSRs
(Diffraction Limited Synchrotron Radiation sources)

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Outline

I. Introduction
II. Beam diagnostics in DLSRs
III. Current diagnostic status in SRs
IV. Challenges for DLSRs
V. Summary

Introduction: SR source development

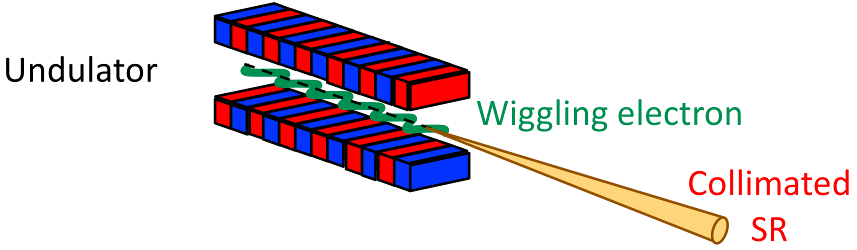
3rd generation synchrotron radiation sources (3GSRs)

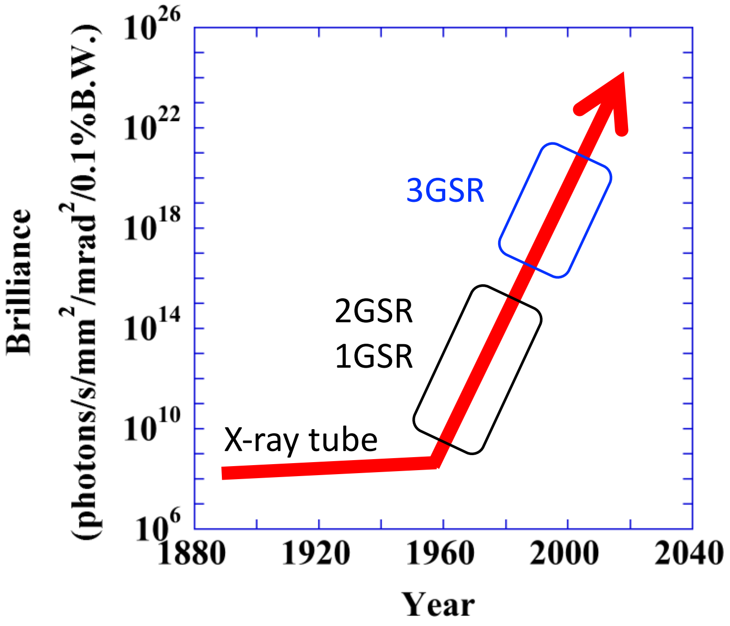
- Brilliant X-ray sources

  $\geq 10^{20}$ photons/s/mm^2/mrad^2/0.1%B.W .

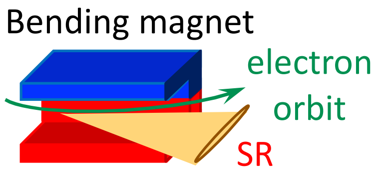
  - Insertion device (undulator)
  - Low-emittance beam ε_x~ 2- 5 nm.rad, $\varepsilon_y \leq$ 10 pm.rad

    vertical emittance in diffraction limited condition



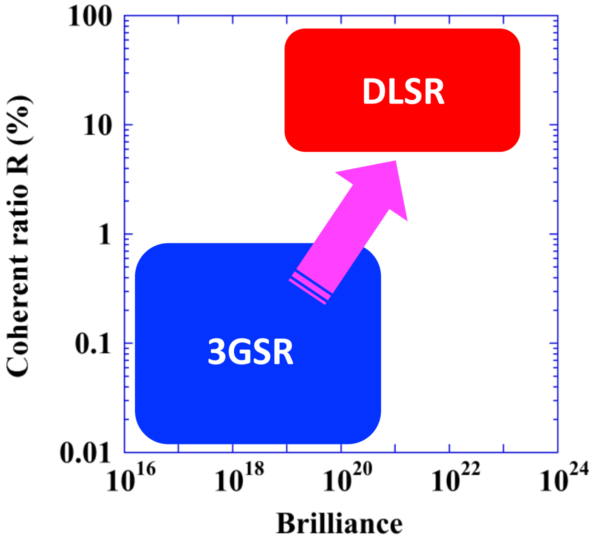


1GSR/2GSR



Jump in the quantity of X-ray photons, brilliance

SR source development (Cont.)



Diffraction Limited Synchrotron Radiation sources (DLSRs)

- Coherent X-ray sources

  coherent ratio > 10% for E_p>10keV

  - Diffraction limited horizontal emittance $\varepsilon_x \leq 10$ pm.rad

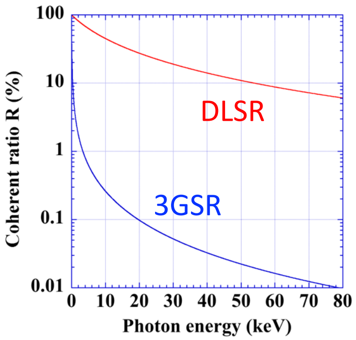
Jump in the quality of X-ray photons, coherence

e Beam	3GSR	DLSR
E_e (GeV)	6	
I (mA)	200	
ε_x (pm.rad)	2500	10
ε_y (pm.rad)	5	1
β_x (m) @ undulator	30	0.8
η_x (m) @ undulator	0.15	0
β_y (m) @ undulator	4	0.8

Example

Undulator	
Total length L_U (m)	5
Period length λ_U (cm)	2

Coherent ratio



Coherent ratio

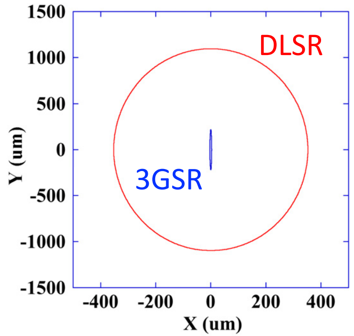
$$R(\%) = \left(\frac{\varepsilon_p}{\varepsilon_x+\varepsilon_p}\right)\left(\frac{\varepsilon_p}{\varepsilon_y+\varepsilon_p}\right)$$

Coherence length

$$L_x = \frac{\lambda R}{4\pi\sigma_x}$$

$$L_y = \frac{\lambda R}{4\pi\sigma_y}$$

Coherence length



R=100m
E_p=10keV

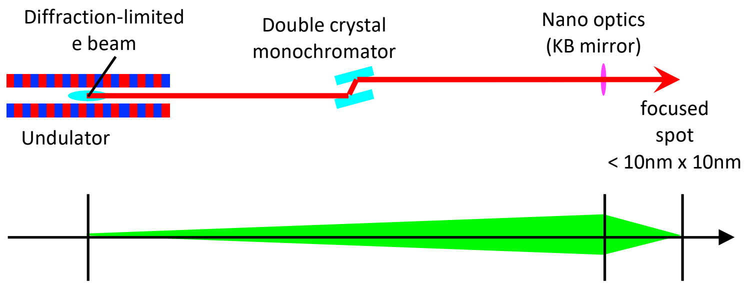
Diffraction Limited Synchrotron Radiation sources (DLSRs)

Opportunities (Example)

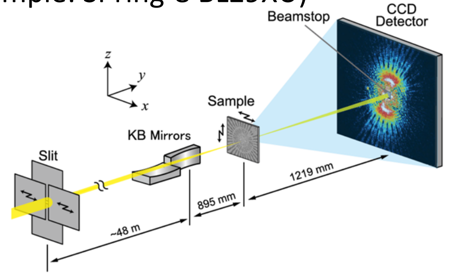
- Direct x-ray nanofocusing
  - Eliminating a virtual source (pinhole or slit) used in 3GSRs
  - Brighter coherent X-ray nano-beam ~ 10^{13} photons/s
- Coherent diffractive imaging (CDI)
  - Lensless imaging based on the iterative phasing of diffraction amplitudes
- X-ray ptychography
  - Overlapped scanning by a focused X-ray beam
  - Image reconstruction by CDI technique
  - Resolution better than the focused x-ray spot size

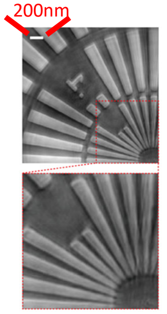
3D microscopy with atomic scale resolution in shortened measuring time, e.g. several minutes

Direct nanofocusing



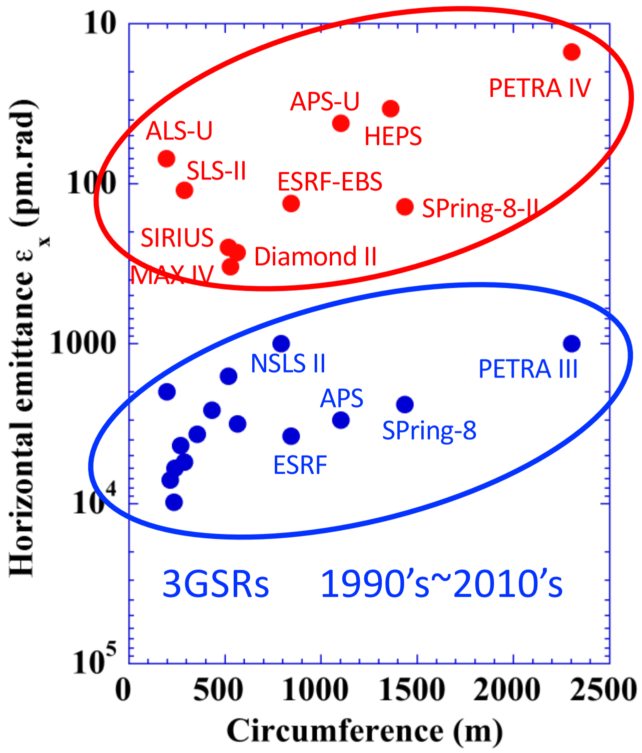
X-ray ptychography
(Example: SPring-8 BL29XU)





N Burdet et al. ,"Efficient use of coherent X-rays in ptychography: Towards high-resolution and high-throughput observation of weak-phase objects", Appl. Phys. Lett. 108, 071103 (2016);

Multi-bend achromat (MBA)-based SRs toward DLSRs



MBA-based SRs

MAX-IV(2015~), SIRIUS(2019~), ESRF-EBS(2019~)

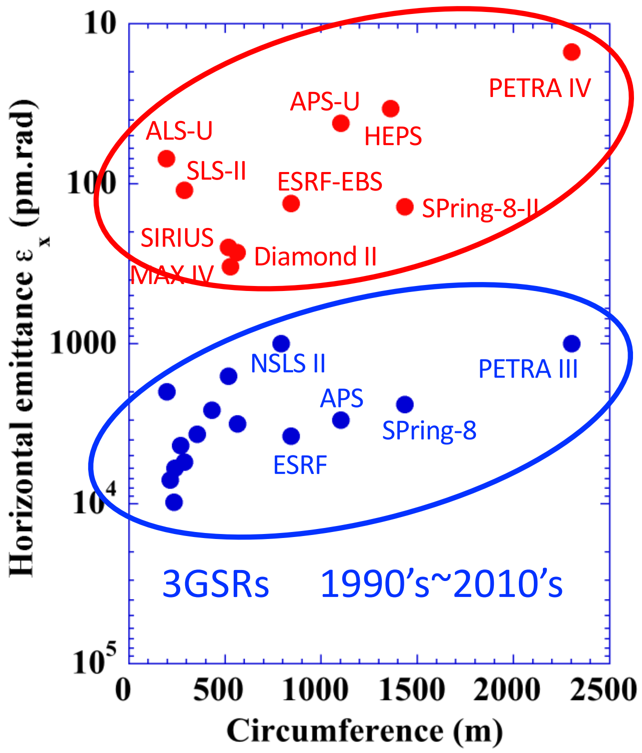
Ongoing MBA projects

APS-U, HEPS, ALS-U, DIAMOND-II, SLS-II, SOLEIL-II, PETRA-IV, SPring-8-II, etc.

Features of SR machines toward DLSRs

- Multi bend lattice of strong focusing magnets with high packing factor
- Narrow vacuum chamber apertures imposed by small magnet bores
- Non-linear beam dynamics with tight stable regions (dynamic and momentum apertures)

Multi-bend achromat (MBA)-based SRs toward DLSRs



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What about the beam diagnostics in DLSRs?

Missions of beam diagnostics in DLSRs

Provide right information for accelerator commissioning to achieve the design emittance

i. Injection tuning to get beam circulation and the first stored beam
ii. Optics tuning and characterization at low stored beam current
    - Beam based optics calibration
    - Emittance measurement
iii. Beam current accumulation
iv. Insertion device commissioning

Support solid operation for photon beam users, keeping the photon beam performance

Against disturbances by
- Environment variations (temperature etc.)
- Vibration from the ground and the cooling system
- Undulators

etc.

Key diagnostic instruments
- Beam size monitor
- Beam position monitor (BPM) and orbit feedback
- Photon BPM
- Instability feedback system

etc.

Beam diagnostics in DLSRs

DLSR beam parameters (example)

- Electron energy: E_e = 6 GeV
- Emittance: ε_x = 10 pm.rad, ε_y = 1 pm.rad
- Dynamic aperture: 1mm
- Undulator:
  - Length L_U = 5 m
  - Photon energy E_p = 10 keV
    - emittance $\varepsilon_p = \lambda/4\pi$=10 pm.rad
  - divergence $\sigma_p' = (\lambda/2L_U)^{1/2}$ = 3.5 urad
- Beam size and divergence at the undulator source:
  - $\beta_x = \beta_y = L_u/2\pi$ = 0.8 m
  - $\Sigma_x = (\varepsilon_x \beta_x)^{1/2}$ = 2.8 um, $\Sigma_y = (\varepsilon_y \beta_y)^{1/2}$ = 0.9 um
  - $\Sigma_x' = (\varepsilon_x/\beta_x + \sigma_p'^2)^{1/2}$ = 5 urad, Σ_y' = 3.7 urad
- Stability tolerance (10 % of size and divergence):
  - Position: 0.1 um, Angle: 0.4 urad

Diagnostic instruments required

- Beam size monitor
  - resolution < 1 um
- Beam position monitor (BPM)
  - turn-by-turn resolution < 10um
  - COD meas. resolution < 0.1 um (1 kHz B.W.)
  - accuracy to Q/S magnet center < 10um
  - stability: offset drift < 1um (in a month)
- Orbit feedback:
  - operating frequency up to about 1kHz
- Photon BPM
  - resolution < 0.1 urad
- Instability feedback system

Beam diagnostics in DLSRs

DLSR beam parameters (example)

- Electron ener
- Emittance: ε_x
- Dynamic aper
- Undulator:

  Length L_U = 5

  Photon energy E_p = 10 keV

  emittance $\varepsilon_p = \lambda/4\pi$=10 pm.rad

  divergence $\sigma_p' = (\lambda/2L_U)^{1/2}$ = 3.5 urad
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Diagnostic instruments required

um

m (1 kHz B.W.)

accuracy to Q/S magnet center < 10um

stability: offset drift < 1um (in a month)

- Orbit feedback:

  operating frequency up to about 1kHz
- Photon beam position monitor

  resolution < 0.1 urad
- Instability feedback system

Deja vu…

✓ The electron beam parameters of DLSRs look like those in the vertical plane of the 3GSRs.

Current diagnostic status in SRs

- The vertical emittance of the 3GSRs reached the diffraction limited condition for hard (>10keV) X-rays. It gave an impact on and boosted developments of beam diagnostic instruments.

- Recent MBA-based SR developments toward the DLSRs are driving improvements of diagnostics instruments. Most of the diagnostics requirements for DSLRs are about to be fulfilled.

Topics presented here:

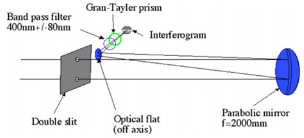
Beam size monitors, BPMs and orbit feedback, BPM alignment, photon BPMs, and instability feedback system.

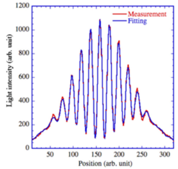
Beam size monitors

The small vertical emittance of 3GSRs, lower than 10 pm.rad, matured a variety of techniques for small beam size measurement.

- Visible light interferometry
  - Double slit interferometer
  - π-polarization method

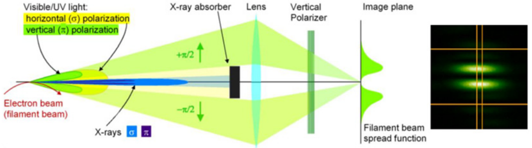
T. Naito and T. Mitsuhashi, Phys. Rev. ST Accel. Beams 9, 122802 (2006)





σ_y=4.7um (KEK-ATF)

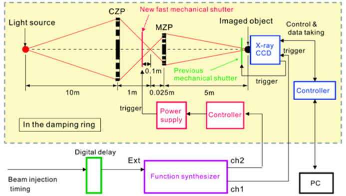
C. O. Lock, DEELS2019

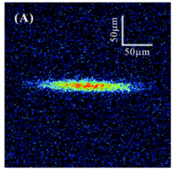


σ_y=3.6um (SLS)

- X-ray imaging
  - Zone plate imaging
  - X-ray pinhole camera
    - source resolution ~ 3 um
    - (C. Thomas, et al., Phys. Rev. ST Accel. Beams 13, 022805 (2010))

H. Sakai et al., Phys. Rev. ST Accel. Beams10,042801 (2007)





σ_y=6um (KEK-ATF)

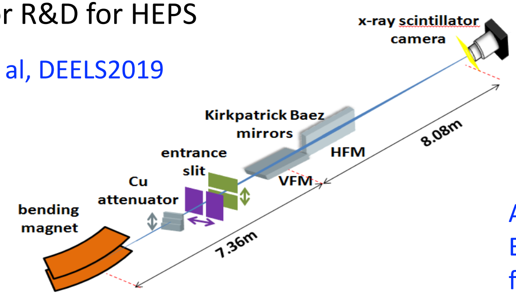
Beam size monitors (Cont.)

Efforts to improve the spatial resolution continuing for the coming MBA-based SRs; ESRF-EBS, APS-U, HEPS, etc.

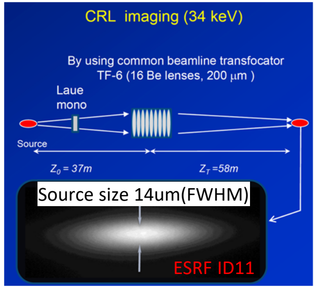
- X-ray techniques
  - X-ray imaging (KB-mirror, X-ray lens)
  - X-ray Fresnel diffractometry
  - X-ray interferometer

KB mirror R&D for HEPS

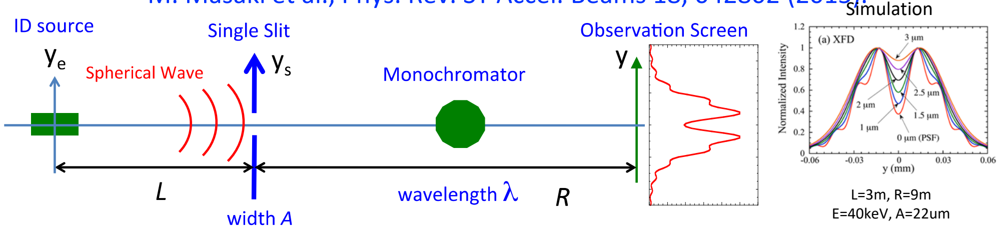
Y Sui et al, DEELS2019



A. Snigirev, Workshop on Emittance Measurements for Light Sources and FELs(2018)



M. Masaki et al., Phys. Rev. ST Accel. Beams 18, 042802 (2015).



Beam size monitors fulfilling the requirements for the DLSRs will be feasible.

Beam Position monitors (BPMs)

Digital BPM reading electronics have developed in 3GSRs, further improving for MBA-based SRs.

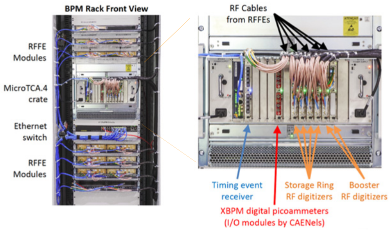
Reading each electrode signal in parallel, with simultaneous turn-by-turn, fast (~10kHz) and slow (~10Hz) samplings

Instrumentation Technologies

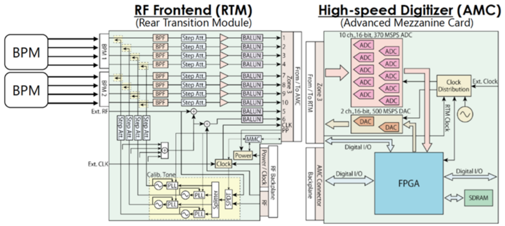
- Libera Brilliance+

MAX-IV, ESRF-EBS, APS-U, etc.

Sirius



SPring-8-II



- Original BPM reading electronics

Sirius (D. Tavares, IBIC2019)

SPring-8-II (H. Maesaka et al., IBIC2019)

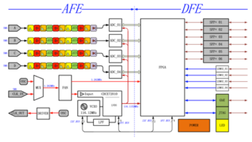
HEPS (S. Wei, et al.#)

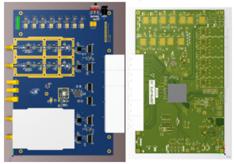
ALS-U (G. Portmann#)

SLS2 (B. Keil#)

etc.

HEPS





The requirements for DLSRs are getting fulfilled in terms of data sampling rate and resolution as well as for application to fast orbit feedback.

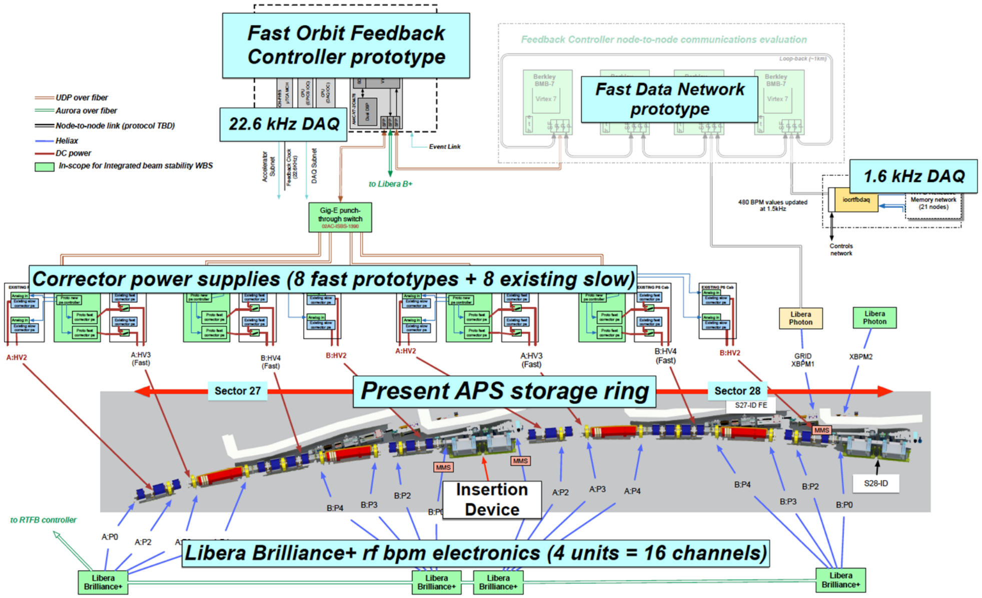
Joint ARIES Workshop on Electron and Hadron Synchrotrons: "Next Generation Beam Position Acquisition and Feedback Systems",2018

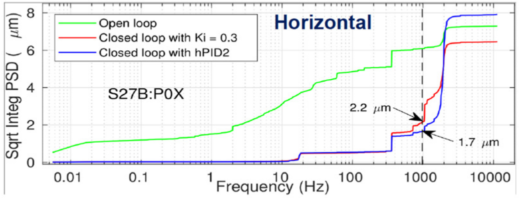
Beam orbit feedback

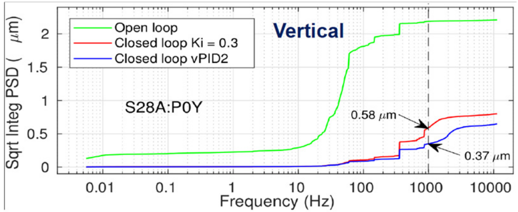
J. Carwardine, et., al. IBIC2018
N. Sereno, DEELS2019

- ➢ R&D for APS-U

APS-U ORBIT FEEDBACK PROTOTYPE







APS-U stability requirements

Plane	AC rms motion (0.01 -1000 Hz)
Horizontal	1.3 um
Vertical	0.4 um

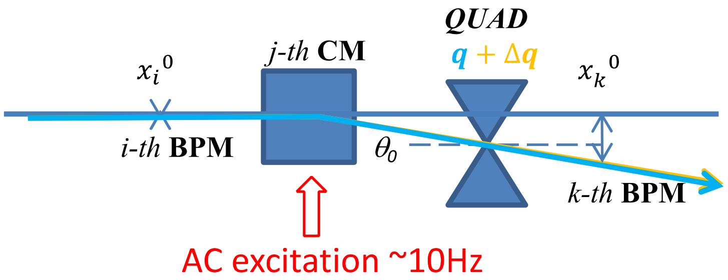
Ability to meet the stability requirements for APS-U successfully demonstrated.

Beam based alignment (BBA) of BPM

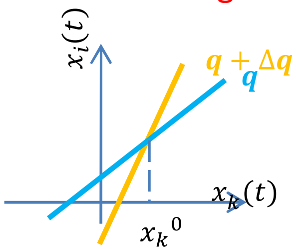
Beam based methods for the BPM alignment and the electron beam optics calibration have developed in 3GSRs, contributed to reaching the diffraction limited vertical emittance.

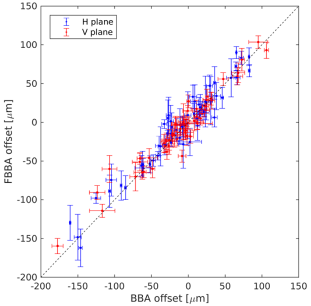
Z.Martí et al., IPAC2018
Z.Martí et al., TW-DUER2018

- Fast BPM BBA to Quadrupoles (ALBA)



Fast (~10kHz)
BPM reading





precision
~10's um

Offsets of 120 BPMs calibrated in only 10 min. successfully

30 times faster than the conventional method based on DC orbit bumps (~5hrs).

Issues for DLSRs: accuracy improvement down to 10 um

BPM alignment to the sextupoles based on tune-shift measurement

Photon BPMs

To stabilize the collimated X-ray photon beam from undulators, photon BPMs have developed in 3GSRs.

- Blade type X-ray BPMs (XBPMs)   Operating in many 3GSRs

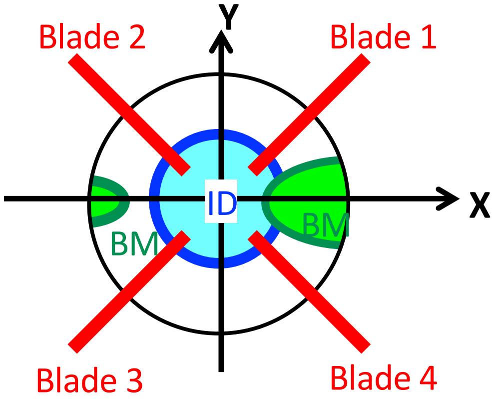
  Tail of undulator radiation hits the blades (tungsten or CVD diamond)

  Photon beam position is calculated form the asymmetry of photoemission current detected

  Drawbacks:

  - Contamination of X-rays from bending magnets (BMs)
  - Position offset of 100's um depending on the undulator gap
  - Remaining error of 10's um after correction, corresponding to 1's urad of photon beam angle

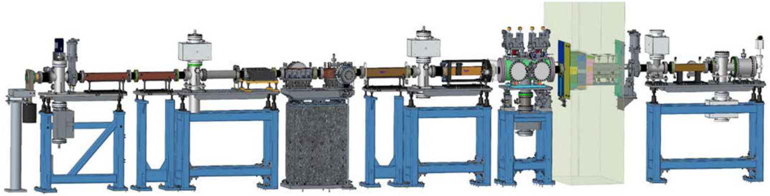
XBPM for Undulator (SLS)
(V. Schlott, DEELS2018)

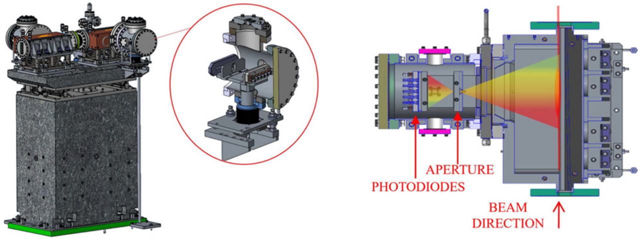


Photon BPMs (cont.)

➢ GRID (GRazing Incidence insertion Device) XBPM for APS-U

Most background X-ray from BMs in the soft X-ray region
Hard X-ray detecting XBPM mitigates the undulator gap dependence





✓ Photon mask of water-cooled GlidCop taking undulator power at 1.0˚ angle

✓ Beam footprint of Cu fluorescent X-ray (9keV) imaged by a pinhole on the PIN diodes array

B. Yang, FLS2018.
S. Oprondek et al, TIPH29, MEDSI2018.

Probing the tail of the power distribution of undulator radiation outside of the core to infer the central core position.

Challenge for DLSRs: Non-destructive in-line probing of the photon beam core

Instability feedback systems

FPGA based digital instability feedback systems have developed in 3GSRs.

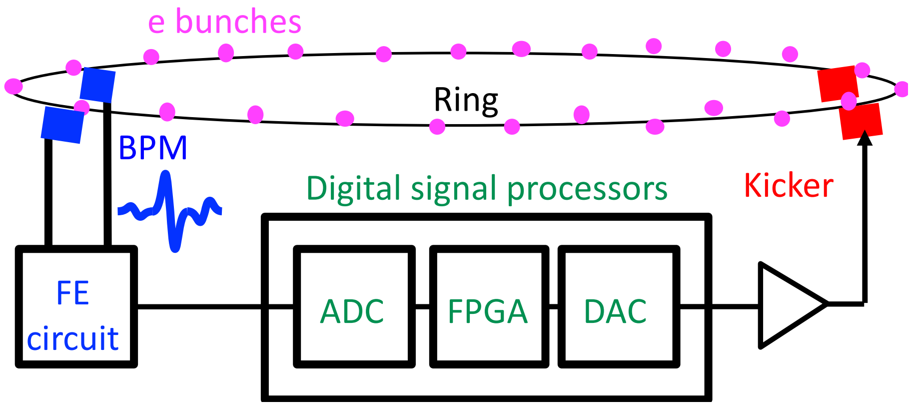
- SPring-8 feedback processor

  (T. Nakamura, IPAC2018)

  SPring-8, SOLEIL, PLS etc.

- iGp12 (Dimtel, Inc.)

  ALS, SPEAR3, BESSY II, NSLS-II, TPS etc.



Issues for DLSRs:

Narrower vacuum chambers and narrower undulator magnet gaps will increase the resistive wall impedance, demanding faster feedback damping time than in 3GSRs.

To operate the system with higher feedback gain without increasing the small beam size, careful design of the high resolution BPM will be crucial.

Diagnostic challenges for DLSRs

- ✓ Beam diagnostic instruments for the electron beam developed in 3GSRs almost fulfills the requirements for DLSRs or can satisfy it with some improvements.
- ✓ However photon BPMs probing the core of collimated undulator X-ray beam, and electron beam orbit control based on photon BPM information are yet to be completed.

- ➢ The most significant jump of the DLSRs from the 3GSRs is the high coherence (> 10 %) of the X-ray photons.
- ➢ Now, the XFELs are delivering highly coherent X-ray laser, demanding X-ray-based control of the XFEL driving linear accelerator.

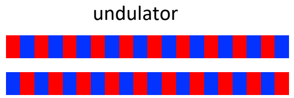
Non-destructive and in-line photon beam diagnostics will be the key to the success of the DLSRs, highly coherent X-ray sources.

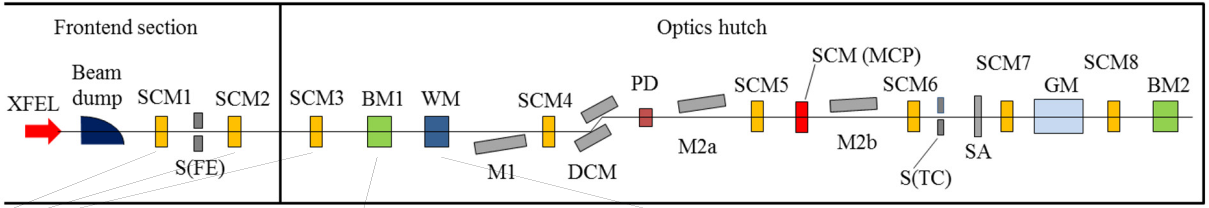
Photon beam diagnostics in XFEL of SACLA

- Photon beam monitors with thin diamond foils with speckle free quality to avoid wavefront distortion of the coherent XFEL beam
- In-line monitoring of the photon beam axis, intensity and lasing wavelength for X-ray based control of the XFEL linac

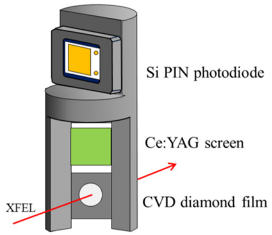
Tono et al, "Beamline, experimental stations and photon beam diagnostics for the hard x-ray free electron laser of SACLA", New J. Phys. 15 (2013) 083035

SACLA BL3
Ep ~ 10keV



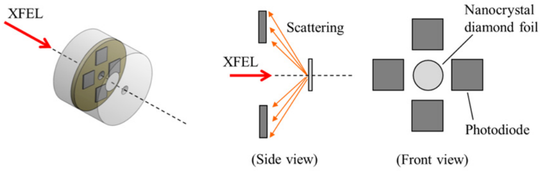


Screen monitor (SCM)



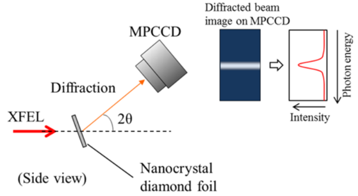
spatial profile,
intensity
non-destructive

Thin-foil beam monitor (BM)



beam center position, intensity
in-line monitoring

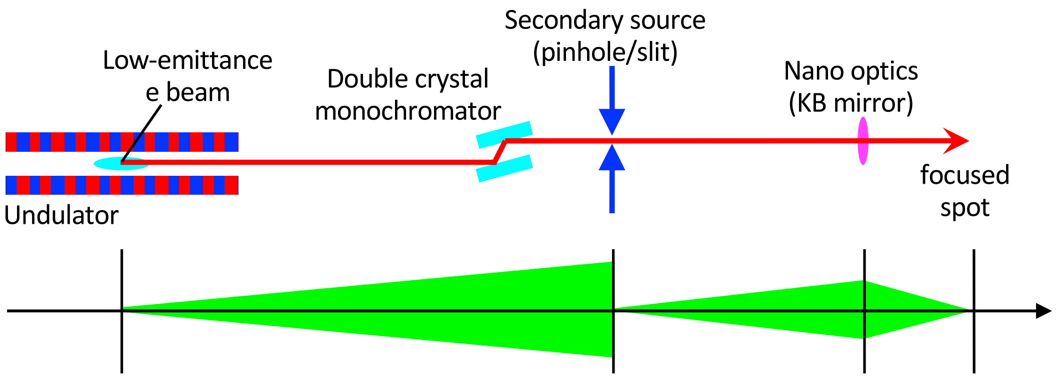
Thin-foil wavelength monitor (WM)



lasing wavelength
in-line monitoring

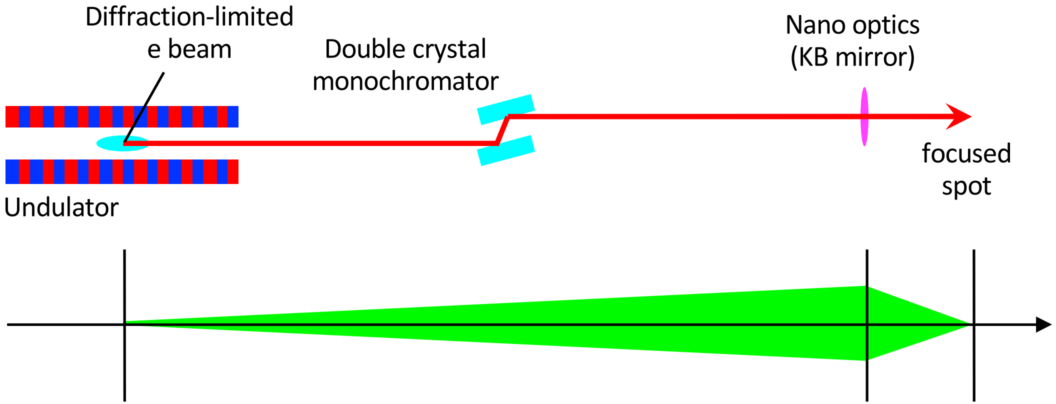
Direct nanofocusing in DLSRs

3GSR



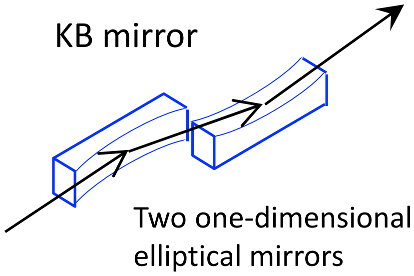
- Secondary source necessary due to large source beam size ~300um
- Significant photon loss by a pinhole/slit ~1/100

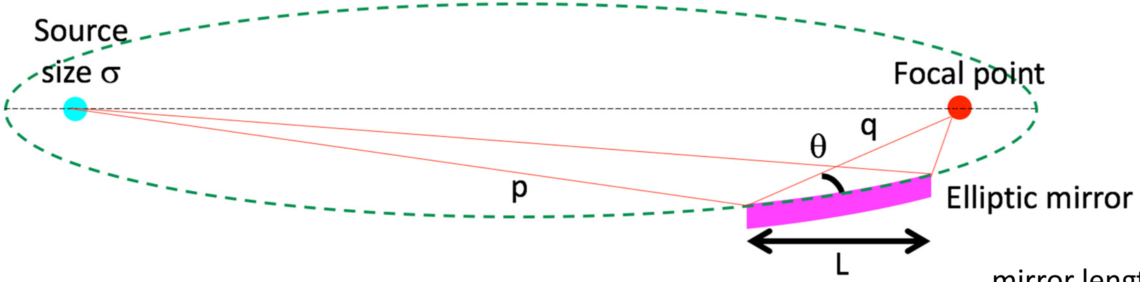
DLSR



- Elimination of secondary source enabled by compact source beam size ~3um
- Bright nano-focused X-ray spot
  - > 10^{13} photons/s
  - < 10 nm x 10nm

Nanofocusing with mirrors





mirror length: L
grazing angle: θ
mirror acceptance: L sin θ

Focused spot size:

$$\Delta = \sqrt{d_G^2 + d_D^2}$$

Geometric optical size (FWHM)

$$d_G = 2.355 \frac{q}{p} \sigma$$

Diffraction-limited size (FWHM)

$$d_D = 0.88 \frac{\lambda q}{L \sin \theta}$$

Example

Mirror p = 100m
Focused spot size Δ = 10nm (FWHM)
$d_D = d_G$ = 7nm

wavelength λ = 0.1nm

source size σ = 3um
photon beam divergence σ' = 5urad

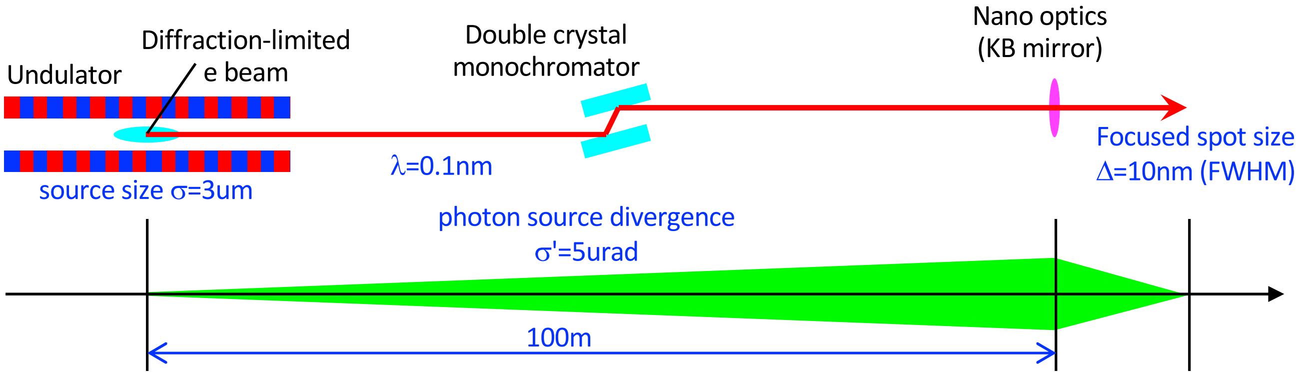
mirror working distance
q=0.1m

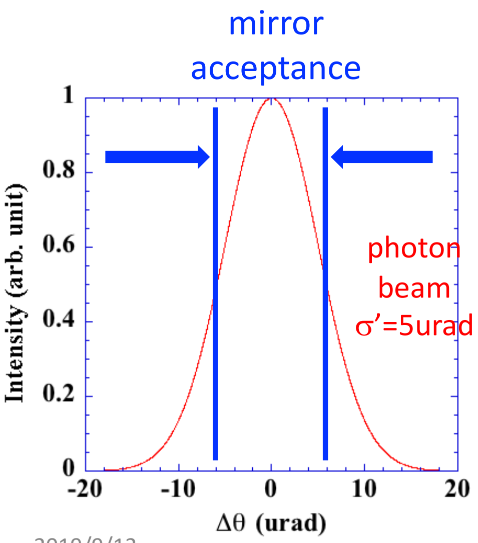
mirror angular acceptance
L sin θ /p = 12 urad

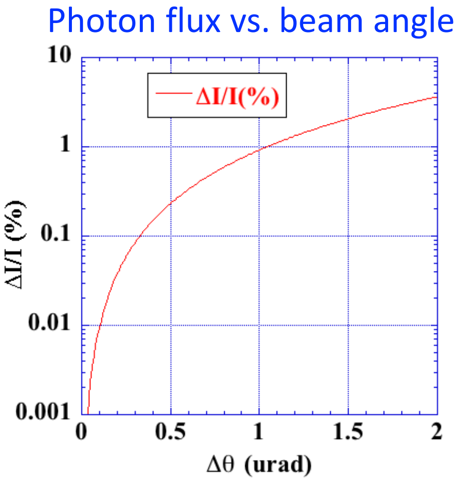
Photon beam stability tolerance for nanofocusing

Example

mirror angular acceptance
$L \sin \theta / p = 12$ urad



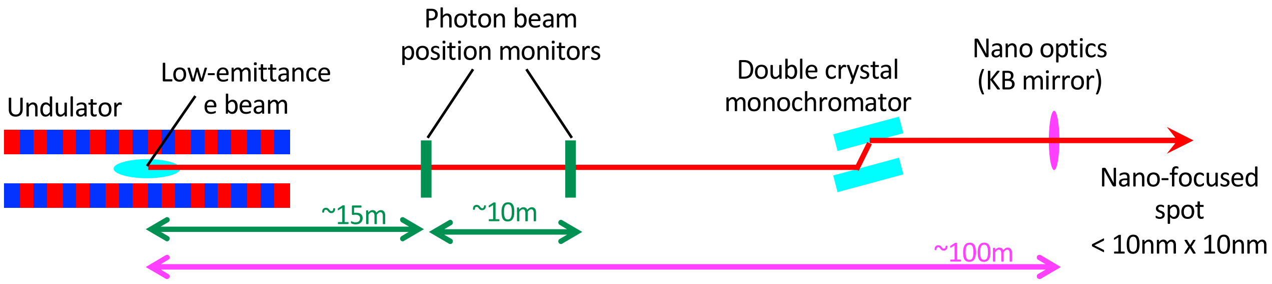




- Photon beam axis deviation of 1urad decreases the intensity by 1 %
- To assure the intensity stability of 0.1%, photon axis to be stabilized within 0.3 urad
- Photon BPM resolving the core center with 0.1 urad resolution necessary

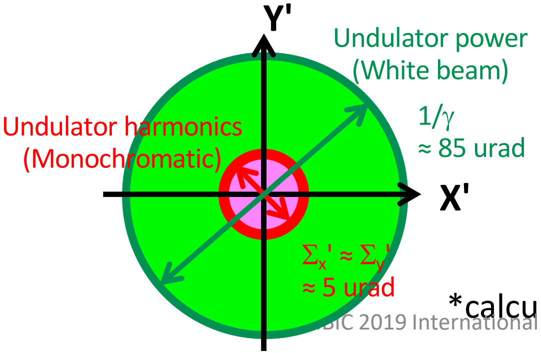
Photon BPMs for DLSRs

- Integration of accurate information on the photon beam-axis into the electron beam orbit control
- Photon BPM resolving the core center with 0.1 urad resolution

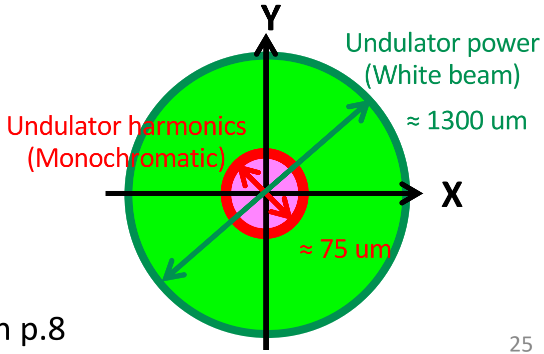


Key is the non-invasive probing of the narrow central cone of undulator harmonics in the wider and more intense undulator power distribution.

Beam divergence*



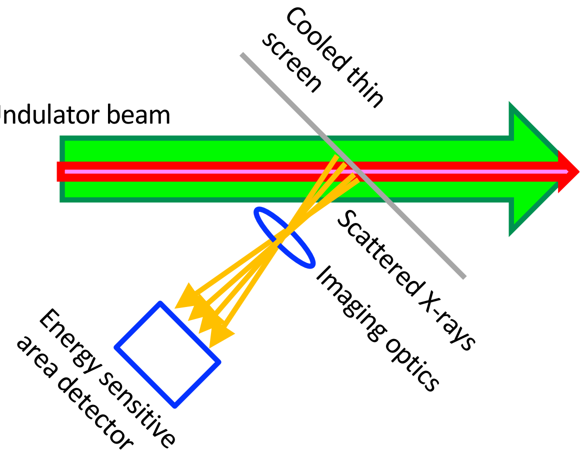
Spot size at 15m from ID*



*calculations with parameters in p.8

Photon BPMs for DLSRs (cont.)

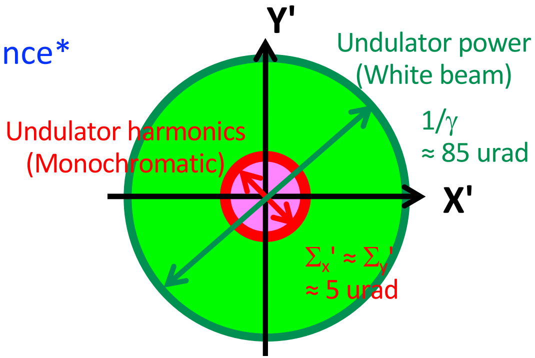
Photon BPM for undulator X-ray beam core



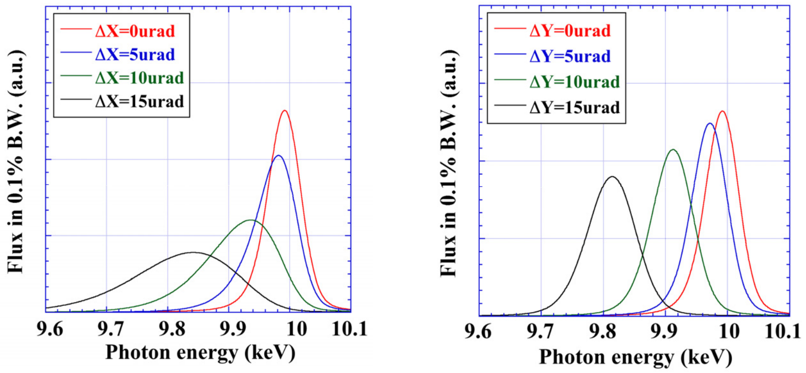
Challenges

- Cooling for heat load from the undulator power
- Transparent and speckle free thin screen
- X-ray imaging optics
- Energy sensitive X-ray area detector

Beam divergence*



Off-axis 1st harmonics spectra*

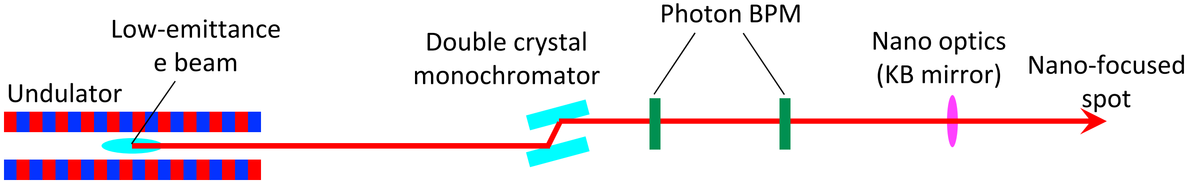


*calculated by SPECTRA with parameters in p.8

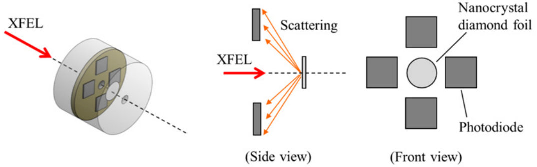
Photon BPMs for DLSRs (cont.)

Alternative approach

- Non-destructive probing of the undulator beam core center before the monochromator should be the best diagnostics for the photon-axis control, but contains tough challenges.
- If the photon beam after the monochromator carries right information on the source electron beam, speckle free diamond thin-foil monitors like those developed at SACLA will be available.
- A challenge in this approach is beamline optics stabilization.



Thin-foil beam monitor (BM) of SACLA



beam center position, intensity

Non-destructive, speckle free

Summary

- The impact of 3GSRs on beam diagnostics was the vertical emittance of the electron beam reaching the diffraction limited condition for hard (>10keV) X-rays.

- The beam diagnostic instruments for the electron beam greatly developed in 3GSRs, are ready to fulfill the DLSR requirements or can satisfy it with some improvements.

- The most significant jump of the DLSRs from the 3GSRs is the higher coherence (> 10 %) of the X-ray beam. It will enable direct nanofocusing and boost coherent diffractive imaging toward the 3D microscopy with atomic scale resolution.

- Diagnostic challenges for the DLSRs are non-destructive in-line diagnostics of the coherent X-ray beam and photon-based control of the accelerator beam to deliver stable high-quality photon beams.

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All specialists and experts on beam diagnostics and related fields from light sources and other accelerators for their excellent work and presentations in;

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- IPAC conference series
- DLSR workshop series

etc.

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