Comparison of Beam Diagnostics for 3rd and 4th Generation Ring-based Light Sources

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Outline

- Introduction:
  Evolution of ring-based light sources

- Innovation of Diagnostic Instruments for 3^{rd} generation light sources (3GLS)

- Diagnostics challenges for 4^{th} generation light sources (4GLS)

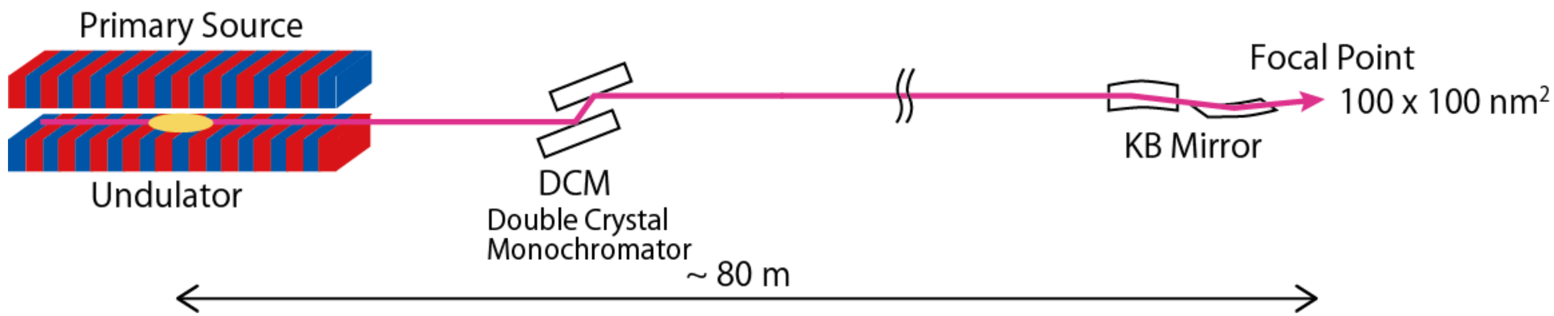
- Summary

Introduction

- Impact of 3GLS is realization of low-emittance beam and in-vacuum undulator
- It has created XFEL by combining advanced linear accelerator technology
  - Excellent transverse coherence and high peak brilliance
- Success of XFEL has stimulated 3GLS to evolve into so-called diffraction limited storage ring (DLSR), i.e. 4GLS.
- Evolution of light source has been closely linked to progress of beam diagnostics

4^{th} Generation Light Source (4GLS)

- Pursuit of Photon Brilliance and Coherence
  - Nano-probing by direct focusing w/o secondary source aperture



- Emittance improvement toward diffraction limit
  - Diffraction-limited hard X-rays (~10 keV): ~ 10 pm rad
  - Typical 3GLS emittance: ~ 3000 pm rad

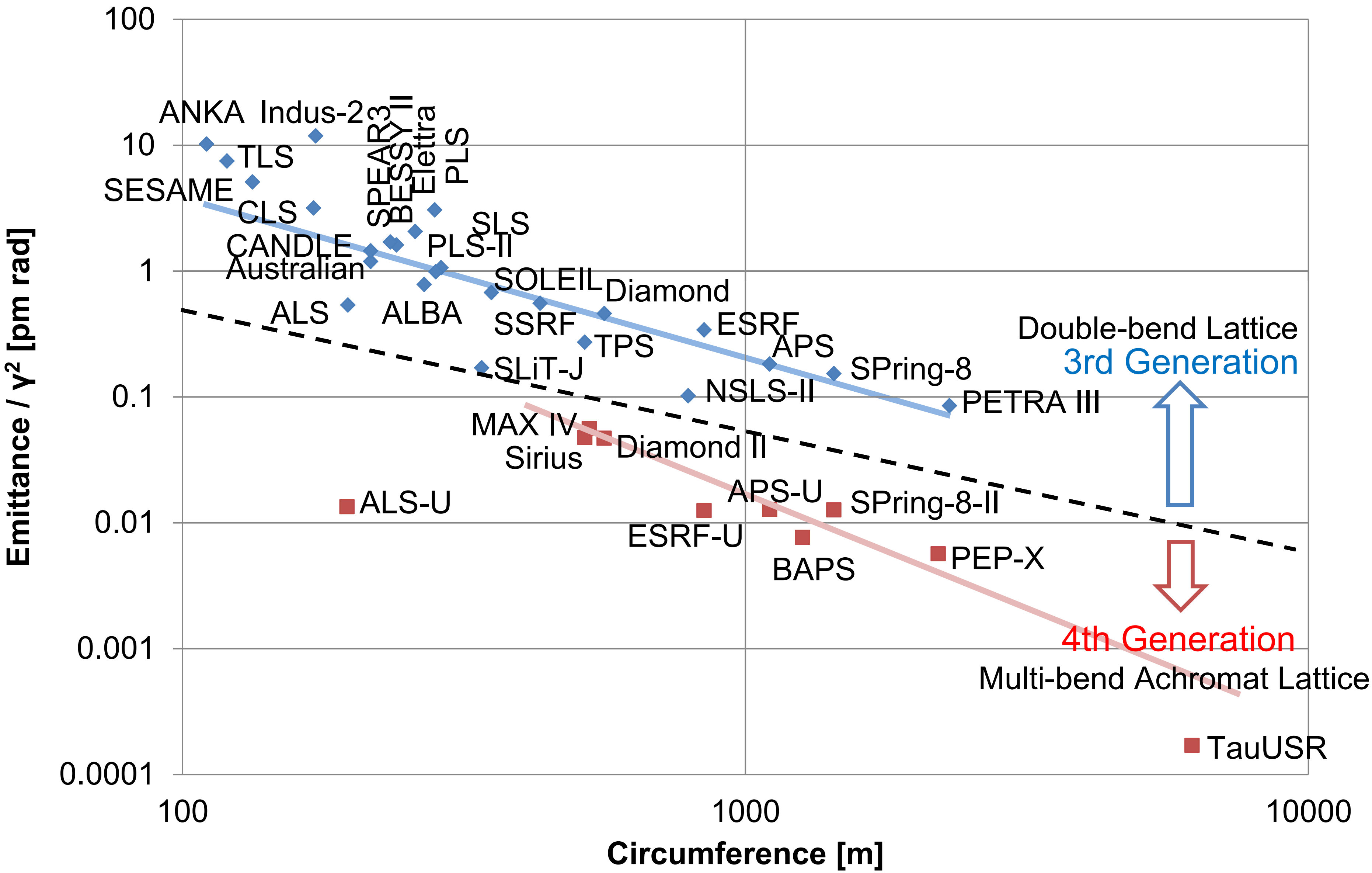
- New trend in lattice design: **Multi-bend Achromat (MBA)**
  - Scaling formula of equilibrium beam emittance of an electron storage ring

H. Wiedemann, Particle Accelerator Physics 3rd edition (2007)

$$\epsilon_0 \propto \gamma^2 \theta^3$$

  - γ: Lorentz factor
  - θ: Bending angle for each dipole magnet
  - More number of dipoles, smaller energy, and longer circumference

3GLS and 4GLS Facilities



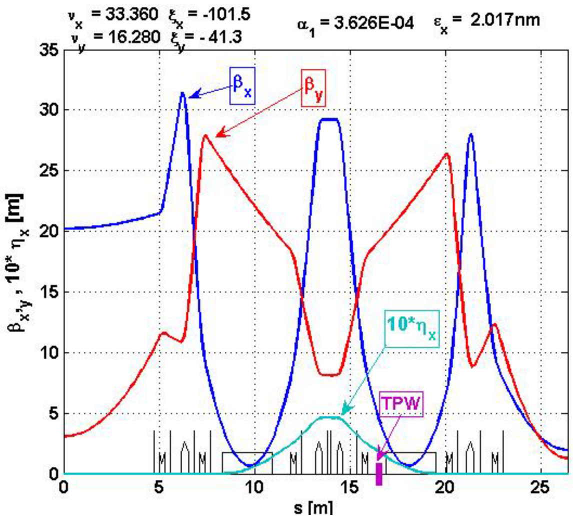
4GLS Examples

Facility	Country	Energy [GeV]	Emittance [pm rad]	Circumference [m]	Lattice	Ref.
MAX IV	Sweden	3.0	330	528	7BA	[1]
Sirius	Brazil	3.0	280	518.4	5BA	[2]
ESRF-U	France	6.0	147	844	7BA	[3]
SPring-8-II	Japan	6.0	149	1435.4	5BA	[4]
APS-U	USA	6.0	150	1104	7BA	[5]
DIAMOND-II	UK	3.0	276	561	DDBA	[6]
ALS-U	USA	1.9	50	196	9BA	[7]
PEP-X	USA	4.5	50	2199	7BA	[8]
BAPS	China	5.0	75	1263	7BA	[9]
TauUSR	USA	9.0	3	6210	7BA	[10]

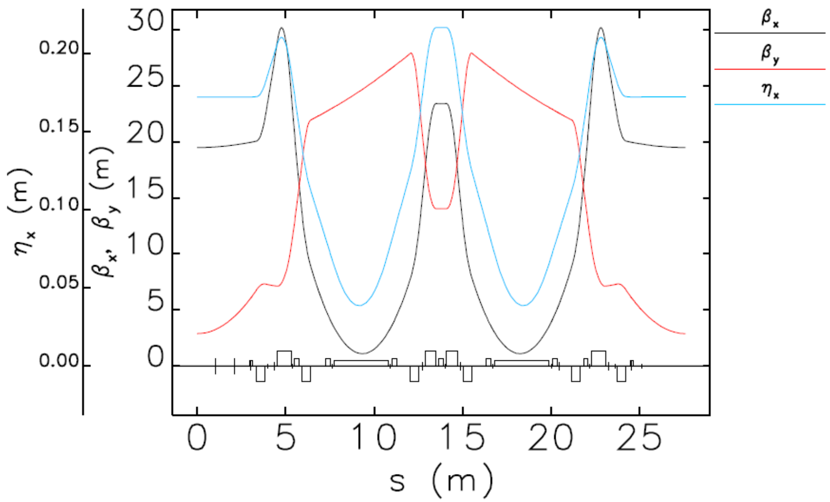
[1] M. Eriksson, et al., Proc. of IPAC’11, pp.3026-3028, THPC058; MAX IV Detailed Design Report (2010).
[2] L. Liu, et al., Proc. of IPAC’14, pp.191-193 , MOPRO048; Sirius Design Report, (2013).
[3] J-L. Revol, et al, Proc. of IPAC’14, pp.209-212, MOPRO055; ESRF Upgrade Program Phase II Technical Design Study (2014).
[4] SPring-8-II Conceptual Design Report (2014).
[5] Y. Sun, et al., Proc. of PAC’13, pp.267-269, MOPHO13.
[6] R. Bartolini, et al., Proc. of PAC’13, pp.24-26, MOOAB2.
[7] C. Steier, et al., Proc. of IPAC’14, pp.567-569, MOPME084.
[8] R. Hettel, et al., Proc. of PAC’11, pp.2336-2338, THP114.
[9] X. Gang, et al., arXiv:1305.0995 [physics.acc-ph] (2013).
[10] M. Borland, Proc. of IPAC’12, pp.1683-1685, TUPPP033.

Double Bend Lattices (3GLS)

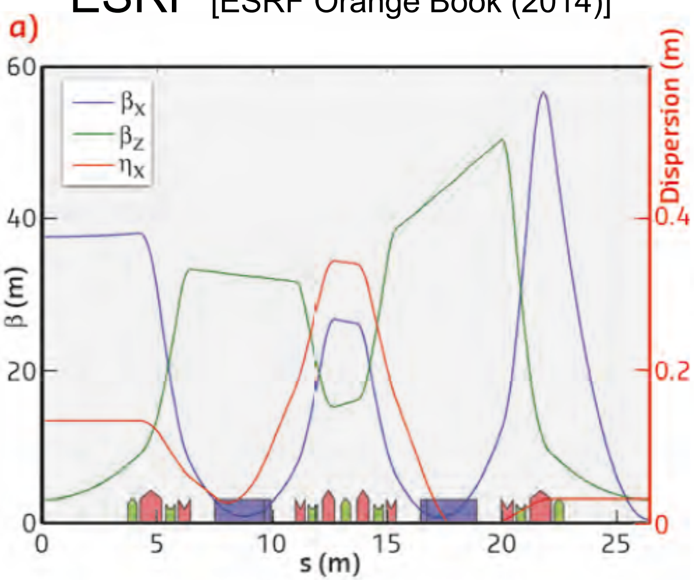
NSLS-II [NSLS-II PDR (2007)]



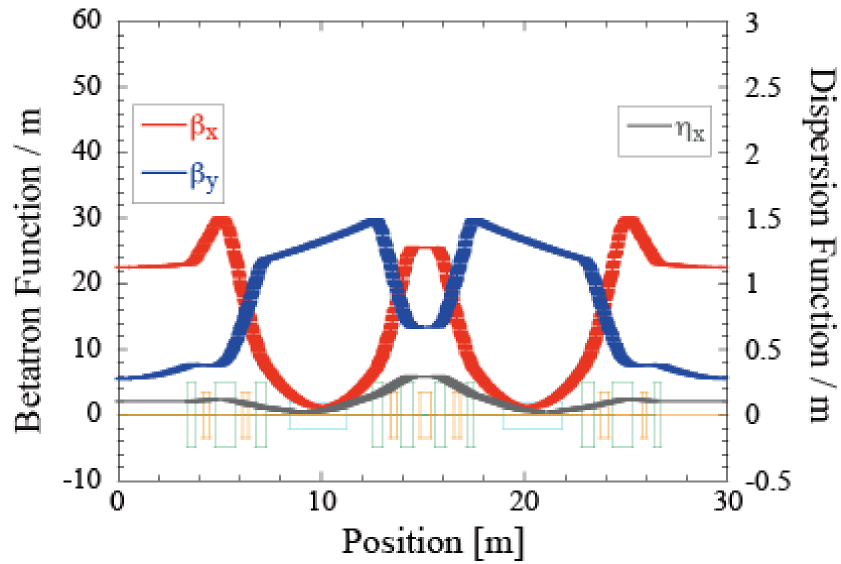
APS [APS-U PDR (2012)]



ESRF [ESRF Orange Book (2014)]

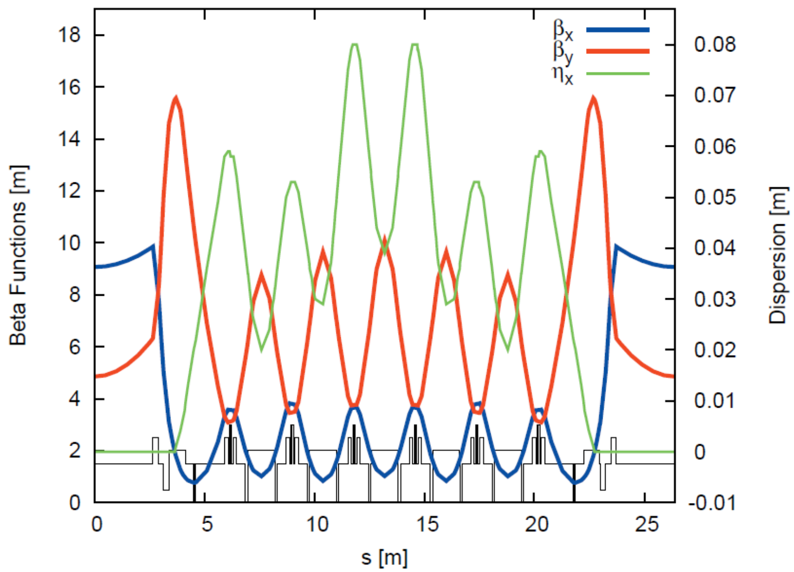


SPring-8

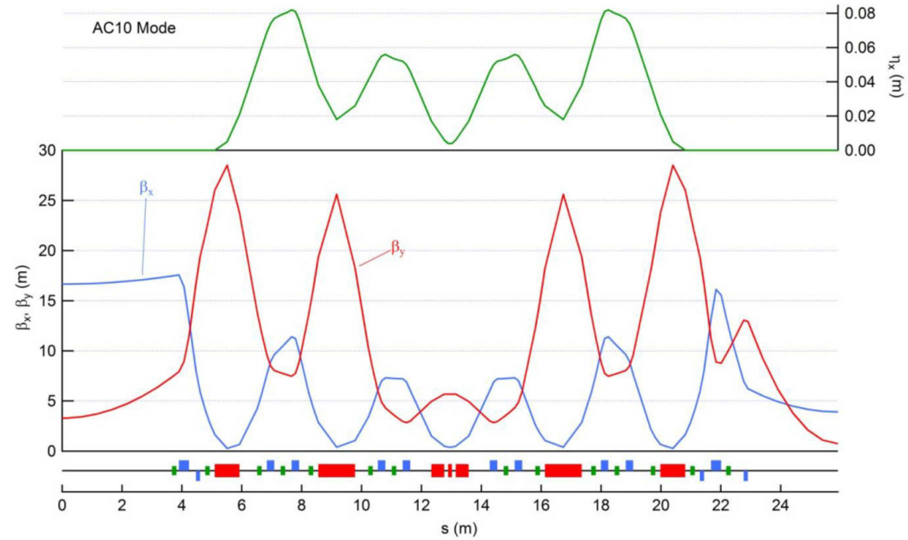


Multi-bend Achromat Lattices (4GLS)

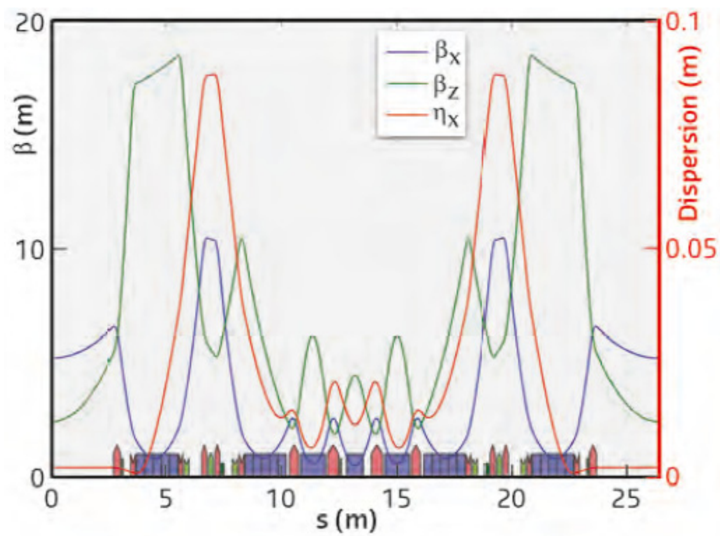
MAX IV (7BA) [MAX IV DDR (2010)]



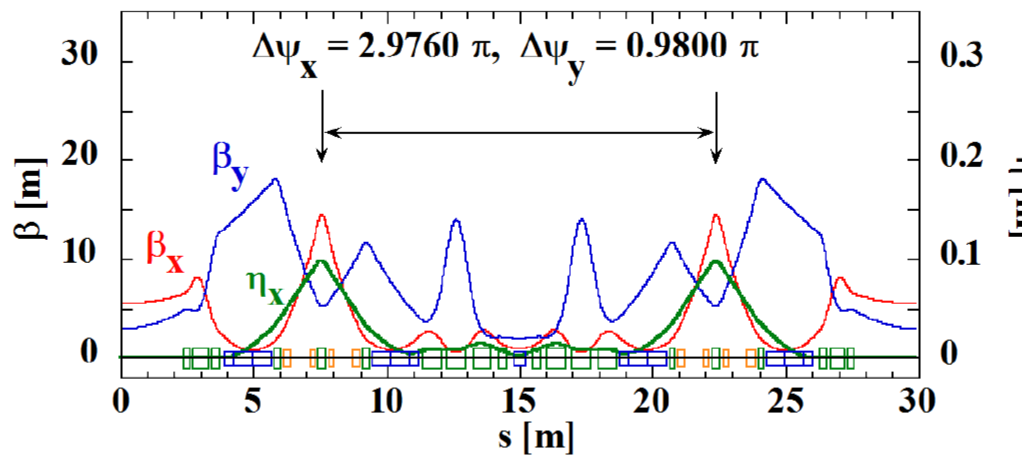
Sirius (5BA) [Sirius DR (2013)]



ESRF-U (7BA) [ESRF Orange Book (2014)]



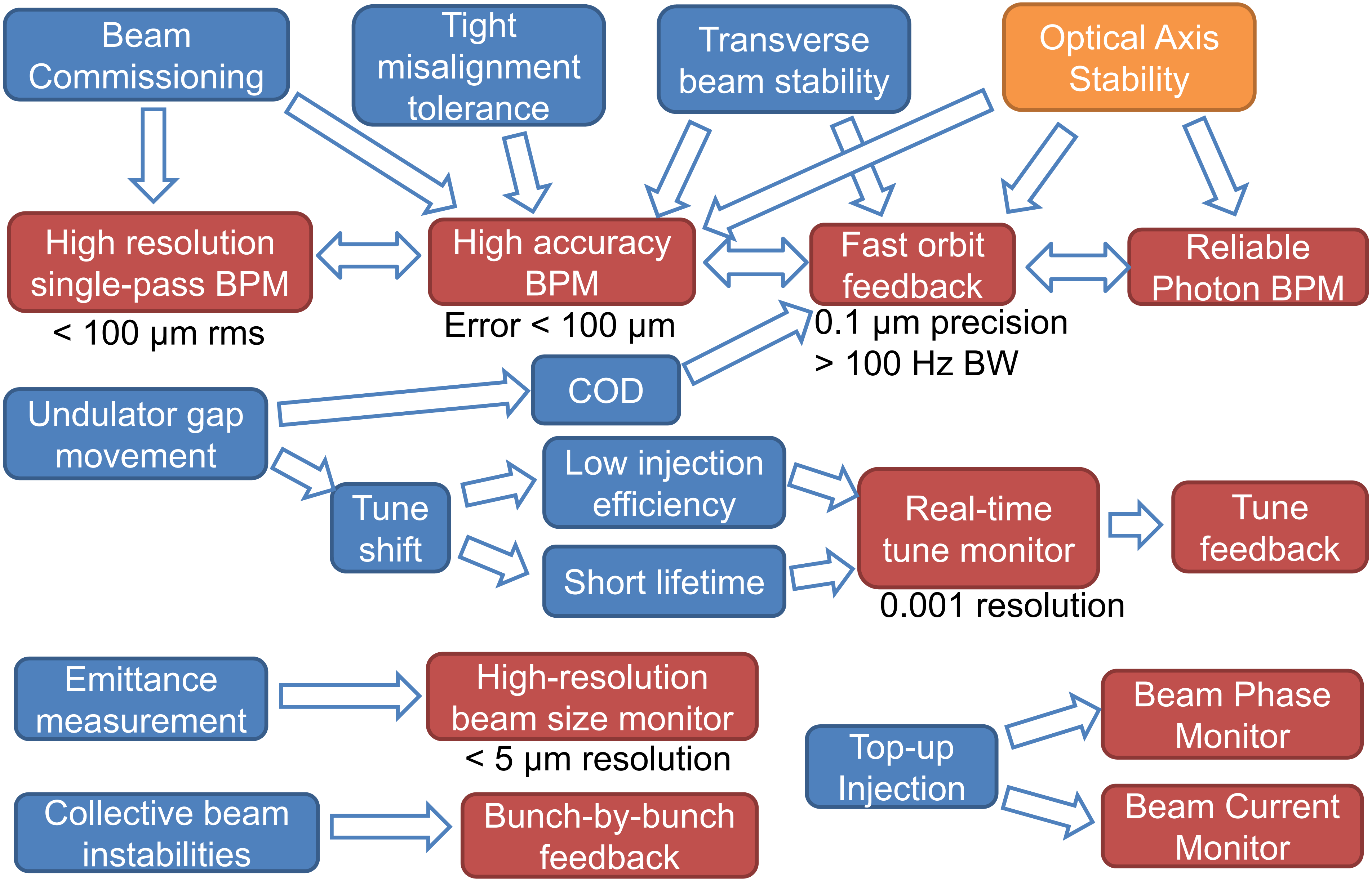
SPring-8-II (5BA) [SPring-8-II CDR (2014)]



Comparison between 4GLS and 3GLS

	4GLS	3GLS
Lattice	Multi-bend acrhomat (MBA)	Double-bend (DB)
Natural emittance	~ 100 pm rad	1 – 10 nm rad
Brilliance [photons/s/mm^2/mrad^2/0.1%BW]	~ 10^{22}	~ 10^{20}
Coherent fraction	~ 10% (H), ~ 20% (V)	< 1% (H), ~ 20% (V)
Beam size	~ 20 x 5 μm^2	~ 100 x 5 μm^2
Multipole B-field gradient	Strong	Moderate
Non-linear effects	Large	Moderate
Dynamic aperture	< 10 mm	> 10 mm
Chamber aperture	~ 30 x 20 mm^2	~ 70 x 40 mm^2
Misalignment tolerance	~ 30 μm	~ 100 μm

Requirements for 4GLS Beam Diagnostics



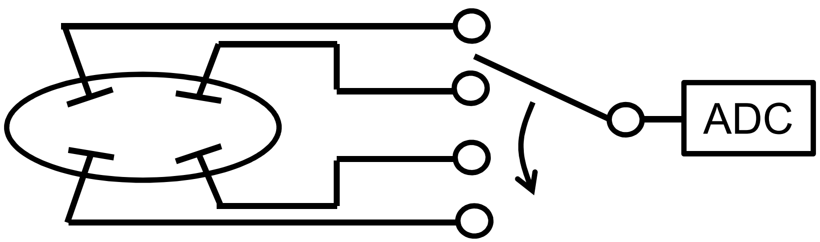
Innovation of Diagnostic Instruments for 3GLS

- *Electron-beam-oriented diagnostics*

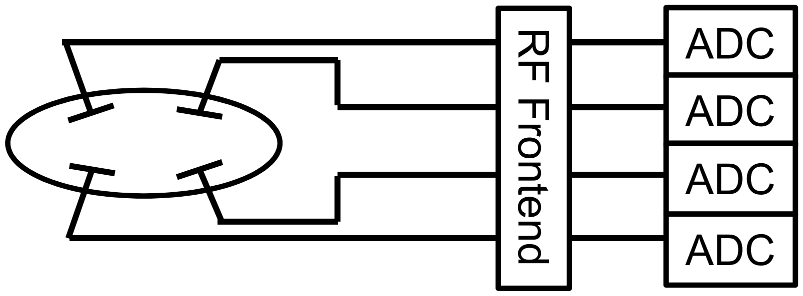
  Motivation: The photon beam performance is guaranteed by the electron beam quality.
- Cutting-edge diagnostic technologies developed
  - Digital BPM Electronics
  - Fast Orbit Feedback (FOFB)
  - High-resolution Beam Size Monitor
  - Bunch-by-bunch Feedback (BBF)
  - Real-time Tune Monitor
- These technologies meet the requirements for 4GLS.

BPM Electronics

- Conventional electronics: multiplexing method
  - Several BPM signals are sequentially read with one ADC by using RF switch.
  - Small gain error
  - Slow data rate < 100 Hz

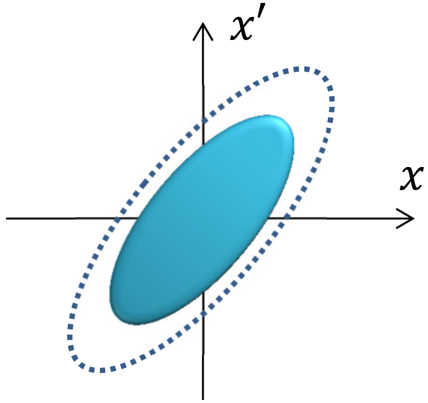


- In recent BPM electronics, the signal from each electrode is read by an individual ADC.
  - APS BPM, SLS BPM, Libera brilliance etc.
  - Single-pass and COD data are obtained at the same time.
  - Fast data rate
    > 1 kHz
  - Fast orbit correction

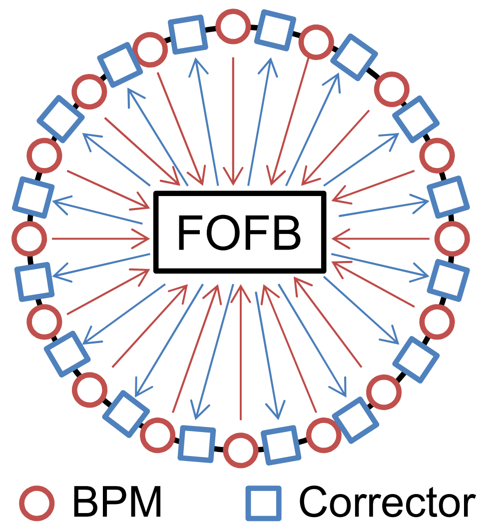


Fast Orbit Feedback (FOFB)

- Fast orbit fluctuation effectively increase the emittance
- Sources of orbit fluctuation
  - Vibrations
    - Ground motion, cooling water, etc.
  - Power supply ripple
  - Undulator gap movement

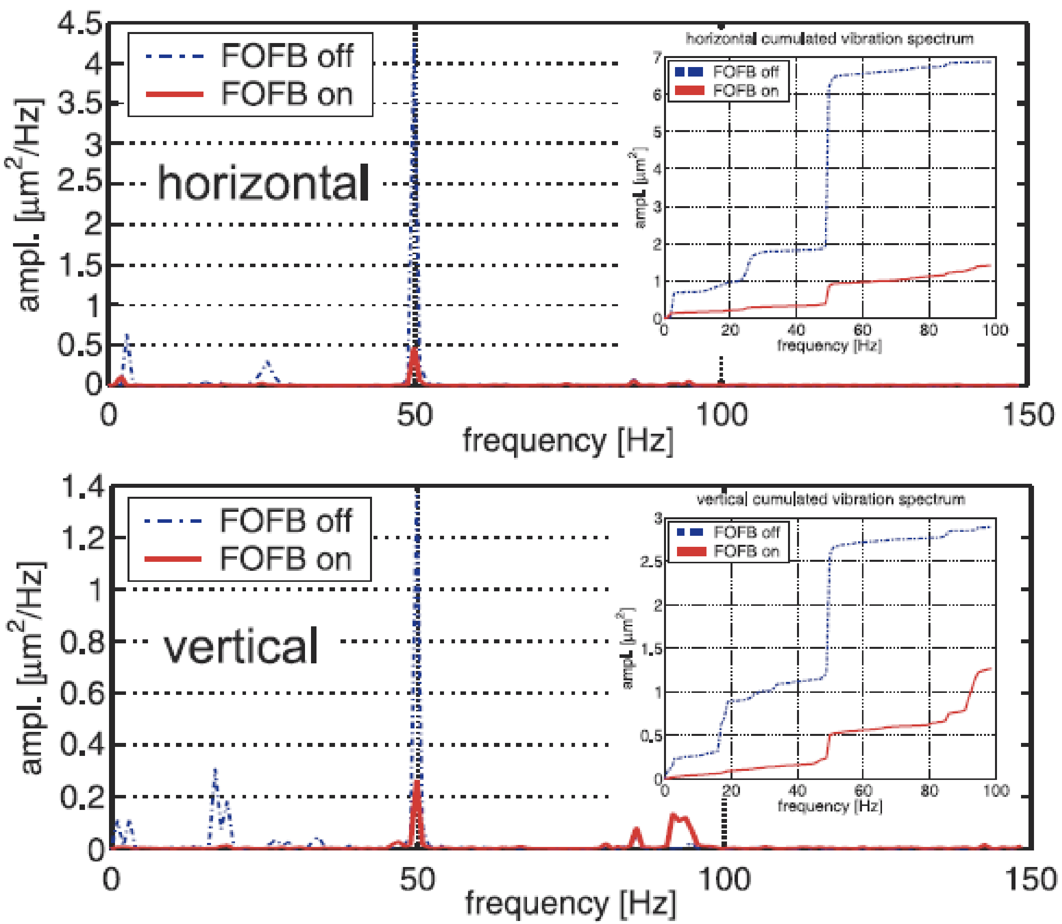


- Total orbit fluctuation > 1 μm rms without stabilization
- Demanded performance for FOFB
  - Feedback bandwidth > 100 Hz
  - ~ 10 kHz data rate from BPM electronics
  - BPM resolution < 0.1 μm at 1 kHz BW
  - Fast corrector > 100 Hz
    - Small magnet inductance, fast power supply, small eddy current in vacuum chambers

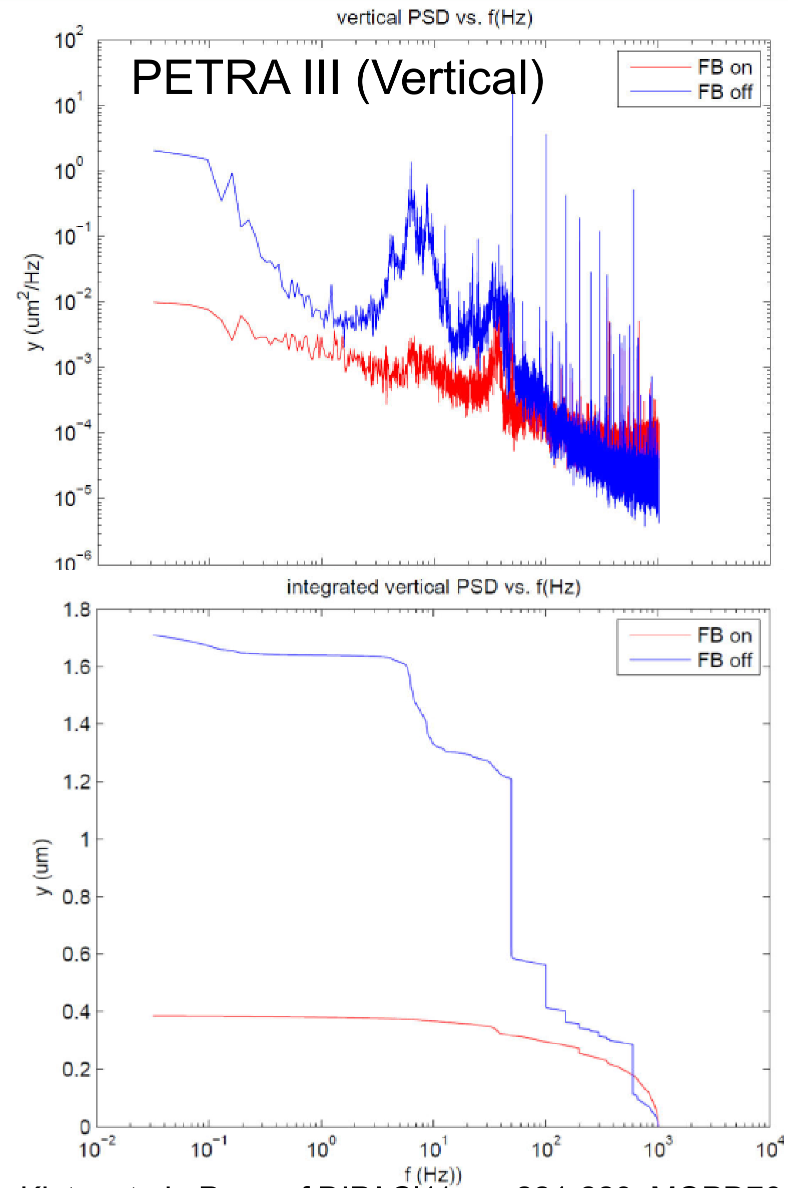


Fast Orbit Feedback Performance

SLS



T. Schilcher, et al., Proc. of EPAC'04, pp.2523-2525, THPLT024.



J. Klute, et al., Proc. of DIPAC'11, pp.221-223, MOPD76.

3GLS Fast Orbit Feedback Examples

Facility	BW	Data Rate	N-BPM	H-Tune	Electronics	Reference
ESRF	150 Hz	10 kHz	224	36.44	Libera B	E. Plouviez, et al., Proc. of DIPAC'11, pp.215-217, MOPD74. E. Plouviez, et al., Proc. of IPAC'11, pp.478-480, MOPO002.
ALS	50 Hz	1 kHz	40	~14	Unique	C. Steier, et al., Proc. of PAC'03, pp.3374-3376, FPAB037.
Elettra	70 Hz	10 kHz	96	14.3	Libera E	G. Gaio, et al., Proc. of IPAC'14, pp.1742-1744, TUPRI075. M. Lonza, et al., Proc. of PAC'07, pp.203-205, MOPAN024.
APS	100 Hz	1.5 kHz	160	36.2	Unique	W.E. Norum, et al., Proc. of PAC'09, pp.3441-3443, TH5RFP004. S. Xu, et al., Proc. of IPAC'12, pp.2870-2872, WEPPP070.
SLS	100 Hz	4 kHz	72	20.38	Unique	T. Schilcher, et al., Proc. of EPAC'04, pp.2523-2525, THPLT024. T. Schilcher, et al., Proc. of PAC'03, pp.3386-3388, FPAB041.
SPEAR3	100 Hz	4 kHz	54	14.19	Unique	A. Terebilo, et al., Proc. of EPAC'06, pp.3035-3037, THPCH102.
SOLEIL	100 Hz	10 kHz	120	18.2	Libera E	N. Hubert, et al., Proc. of DIPAC'07, pp.189-191, TUPC20.
Diamond	100 Hz	10 kHz	168	27.23	Libera E	M.G. Abbott, et al., Proc. of EPAC'08, pp.3257-3259, THPC118. R. Bartolini, Proc. of PAC'07, pp.1109-1111, TUPMN085.
Australian	100 Hz	10 kHz	98	13.3	Libera E	Y-R.R. Tan, et al., Proc. of IBIC'12, pp.437-440, TUPA37.
SSRF	100 Hz	10 kHz	40	22.22	Libera E	C.X. Yin, et al., Proc. of IPAC'13, pp.2995-2997, WEPME033. S.Q. Tian, et al., Proc. of IPAC'12, pp.1647-1649, TUPPP018.
PETRA III	200 Hz	39 kHz BW	226	37.26	Libera B	J. Klute, et al., Proc. of DIPAC'11, pp.221-223, MOPD76.
ALBA	200 Hz	10 kHz	104	18.15	Libera B	X. Serra-Gallifa, et al., Proc. of ICALEPCS'13, pp.1328-1330, THPPC115. M. Pont, Proc. of IPAC'12, pp.1659-1661 , TUPPP023.
TPS	300 Hz	10 kHz	228	14.37	Libera B+	P.C. Chiu, et al., Proc. of IPAC'13, pp.1146-1148, TUOCB202. C.H. Kuo, et al., Proc. of ICALEPCS'13, pp.158-161, MOPPC036.
NSLS-II	~300 Hz	10 kHz	180	32.35	Unique	O. Singh, et al., Proc. of IBIC'13, pp.316-322, TUBL1. NSLS-II PDR (2007).

Elettra, PETRA III etc. have harmonics suppressor of line frequency.
SOLEIL has system band width > 2.5 kHz.

4GLS Fast Orbit Feedback Examples

Facility	BW	Data Rate	N-BPM	H-Tune	Electronics	Reference
MAX IV	~300 Hz	10 kHz	200	42.20	Libera B+	[1]
Sirius	> 1 kHz	50 kHz	180	44.6	Unique	[2]
ESRF-U	> 120 Hz	10 kHz	288	75.6	Libera B	[3]
SPring-8-II	> 100 Hz	~10 kHz	288	109.14	TBD	[4]
APS-U	> 200 Hz	22.6 kHz	420	~84	TBD	[5]

[1] P. Leban, et al., Proc. of IPAC'14, pp.1748-1750, TUPRI078.
[2] Sirius Design Report (2013).
[3] ESRF Upgrade Program Phase II Technical Design Study (2014).
[4] SPring-8-II CDR (2014).
[5] H. Shang, et al., Proc. of ICALEPCS'13, pp.1373-1375, THPPC137; Y. Sun, et al., Proc. of NA-PAC'13, pp.267-269, MOPHO13.

Beam Size Monitor

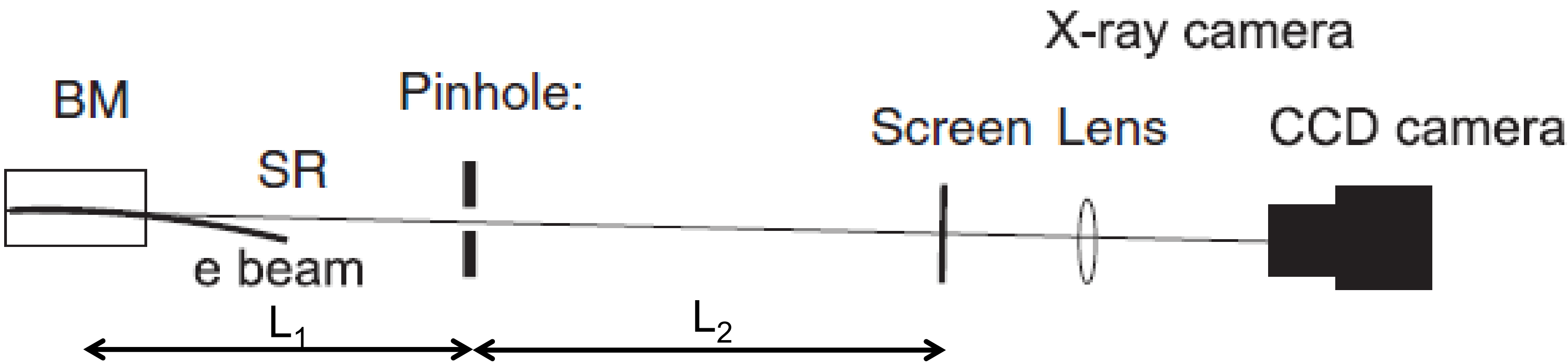
- Visible light
  - Optical Interferometer methods have been developed.
  - KEK-ATF: T. Naito and T. Mitsuhashi, Phys. Rev. ST Accel. Beams 9, 122802 (2006)
  - SPring-8: M. Masaki et al, J. Synchrotron Rad., 10, pp.295-302 (2003).
  - SLS: Nucl. Instrum. Meth. A 591, pp.437-446 (2008)

- X-rays
  - Pinhole camera
    - Diamond: C. Thomas, et al., Phys. Rev. ST Accel. Beams 13, 022805 (2010)
  - Zone plates
    - KEK-ATF: H. Sakai, et al., Phys. Rev. ST Accel. Beams 10, 042801 (2007)
  - Vertical undulator method
    - Australian Synchrotron: Phys. Rev. Lett 109,194801 (2012)
  - X-ray Fresnel diffractometry
    - SPring-8: M. Masaki, et al., Phys. Rev. ST Accel. Beams 18, 042802 (2015).

- Visible light monitors require larger acceptance angle (~ 10 mrad) than X-ray monitors to achieve μm resolution, less feasible for 4GLS.

Pinhole Camera

C. Thomas, et al., Phys. Rev. ST Accel. Beams 13, 022805 (2010)

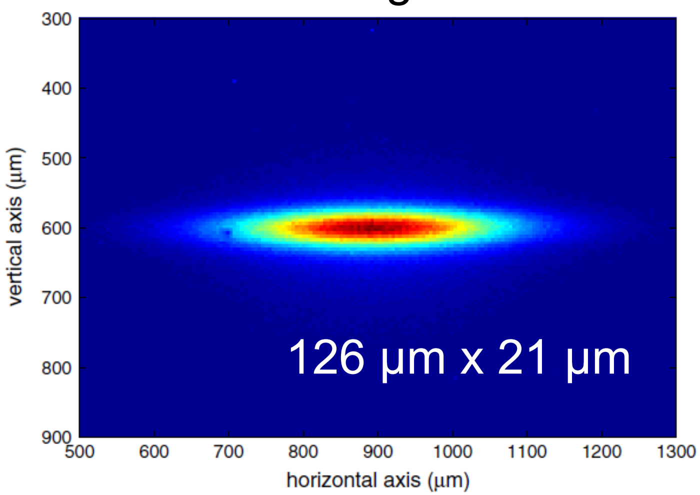


- Pinhole imaging by white X-ray beam
  - Monochromator is not needed
- Magnification: > 2

$$M = \frac{L_1}{L_2}$$

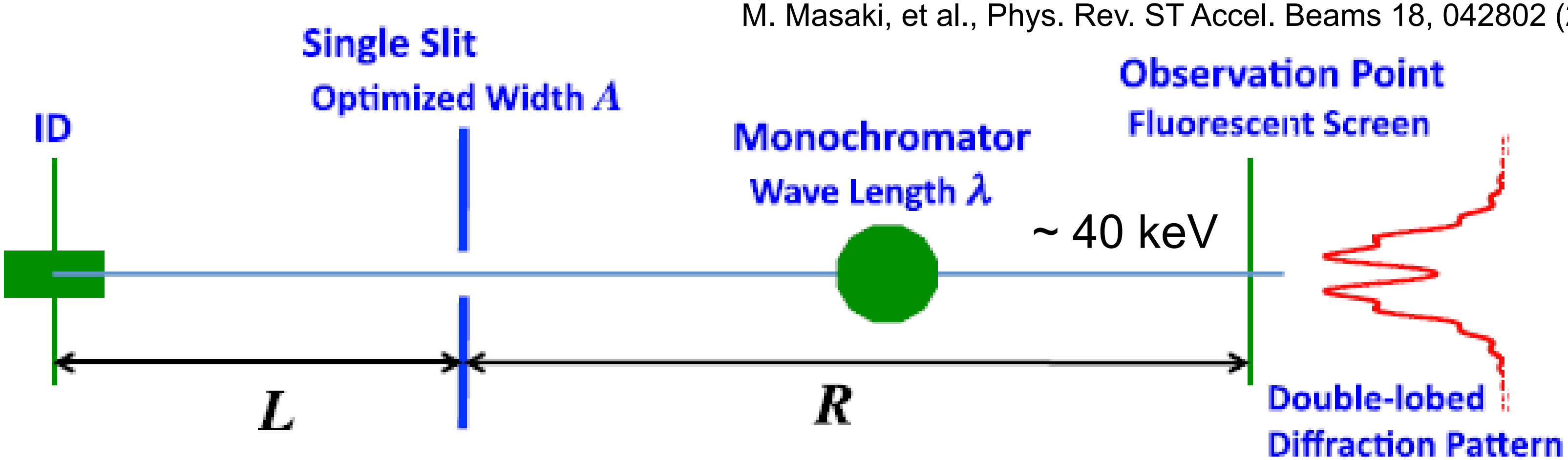
- Photon energy: ~ 50 keV
- Typical pinhole size: 20 μm
- Fresnel diffraction at the pinhole limits the resolution
- Resolution betther than 5 μm is feasible

Diamond light source

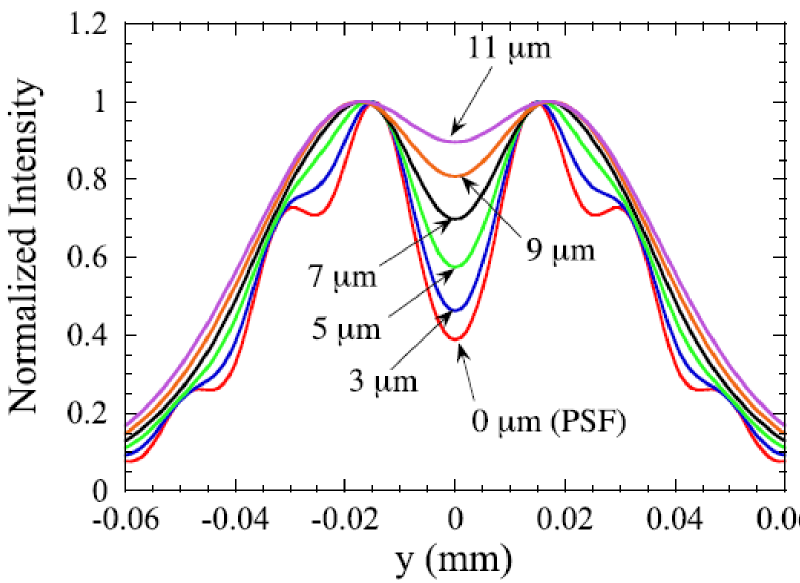


X-ray Fresnel Diffractometry Monitor

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



- When monochromatic X-rays are cut out by a certain slit, a double-lobed diffraction pattern is generated
- The beam size is estimated from the depth of the central dip.
- Resolving beam size less than 5 μm is feasible
  - $L = R = 25$ [m]
  - Slit width: 52 μm
  - 40 keV X-rays



Collective Beam Instabilities

- Collective beam instabilities due to beam impedance
  - Coupled-bunch instability (CBI) for high storage current
  - Transverse mode coupling instability (TMCI) for a high current bunch
    - So called single-bunch instability

- Narrow vacuum chamber and undulator gap for 4GLS causes larger resistive wall impedance than 3GLS
- Transverse resistive wall impedance for a round pipe

$$Z_T(\omega) \propto \frac{1}{b^3\sqrt{\omega}}$$

b: pipe radius

- Growth rate of the instability

$$\frac{1}{\tau} \propto \int \beta Z_T \, ds$$

β: beta function

- Instability growth rate of 4GLS is roughly 4 times larger

$$b_{4GLS} \sim \frac{b_{3GLS}}{2}, \qquad \beta_{4GLS} \sim \frac{\beta_{3GLS}}{2}$$

$$\therefore \frac{1}{\tau_{4GLS}} \sim \frac{4}{\tau_{3GLS}}$$

Vacuum Chambers

- ~ 70 x 40 mm^2 → ~ 30 x 20 mm^2

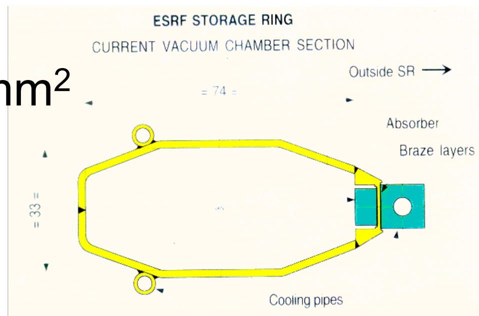
ESRF

3GLS

SPring-8

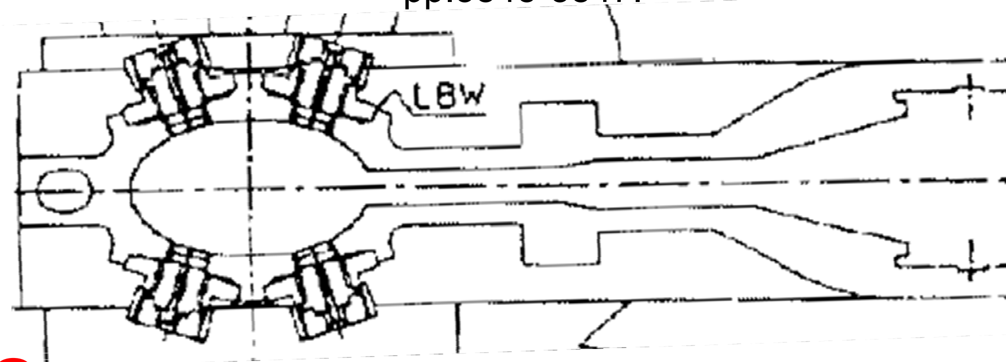
R. Kersevan, Proc. of EPAC98, pp.2178-2180, TUP03C.

74 x 33 mm^2



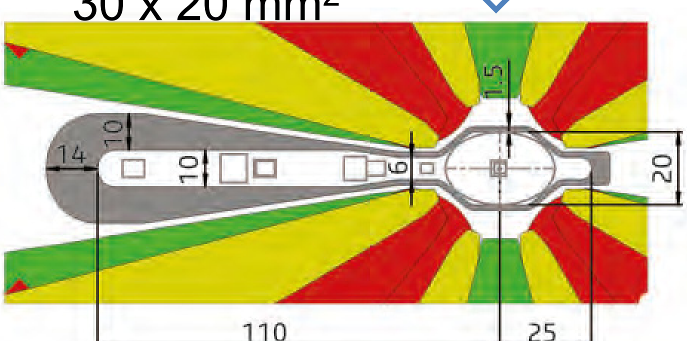
K. Watanabe, et al., Proc. of PAC'93, pp.3845-3847.

70 x 40 mm^2



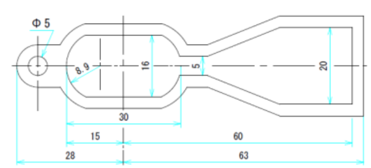
4GLS

30 x 20 mm^2



ESRF Upgrade Phase II Orange Book (2014).

30 x 16 mm^2

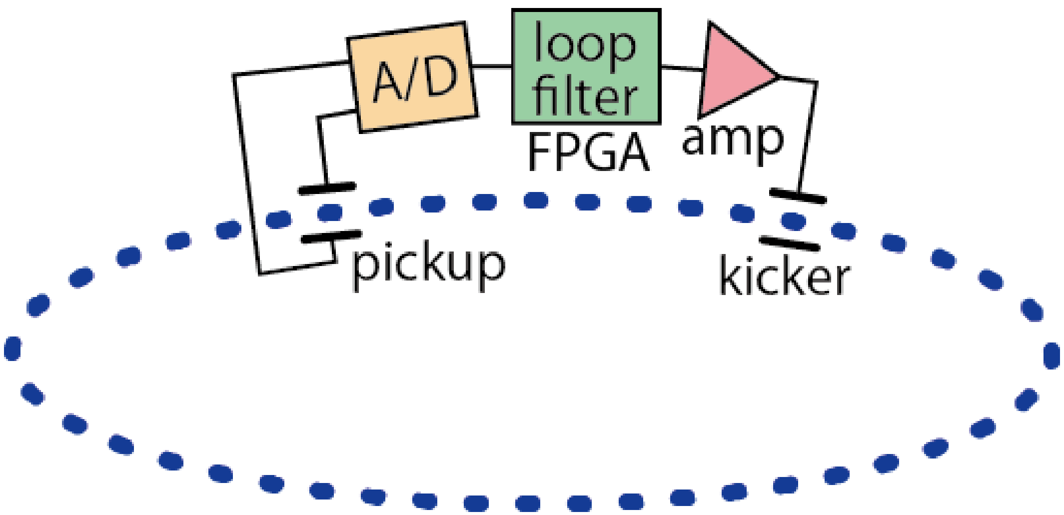


SPring-8-II CDR (2014)

Scale adjusted

Bunch-by-bunch Feedback (BBF)

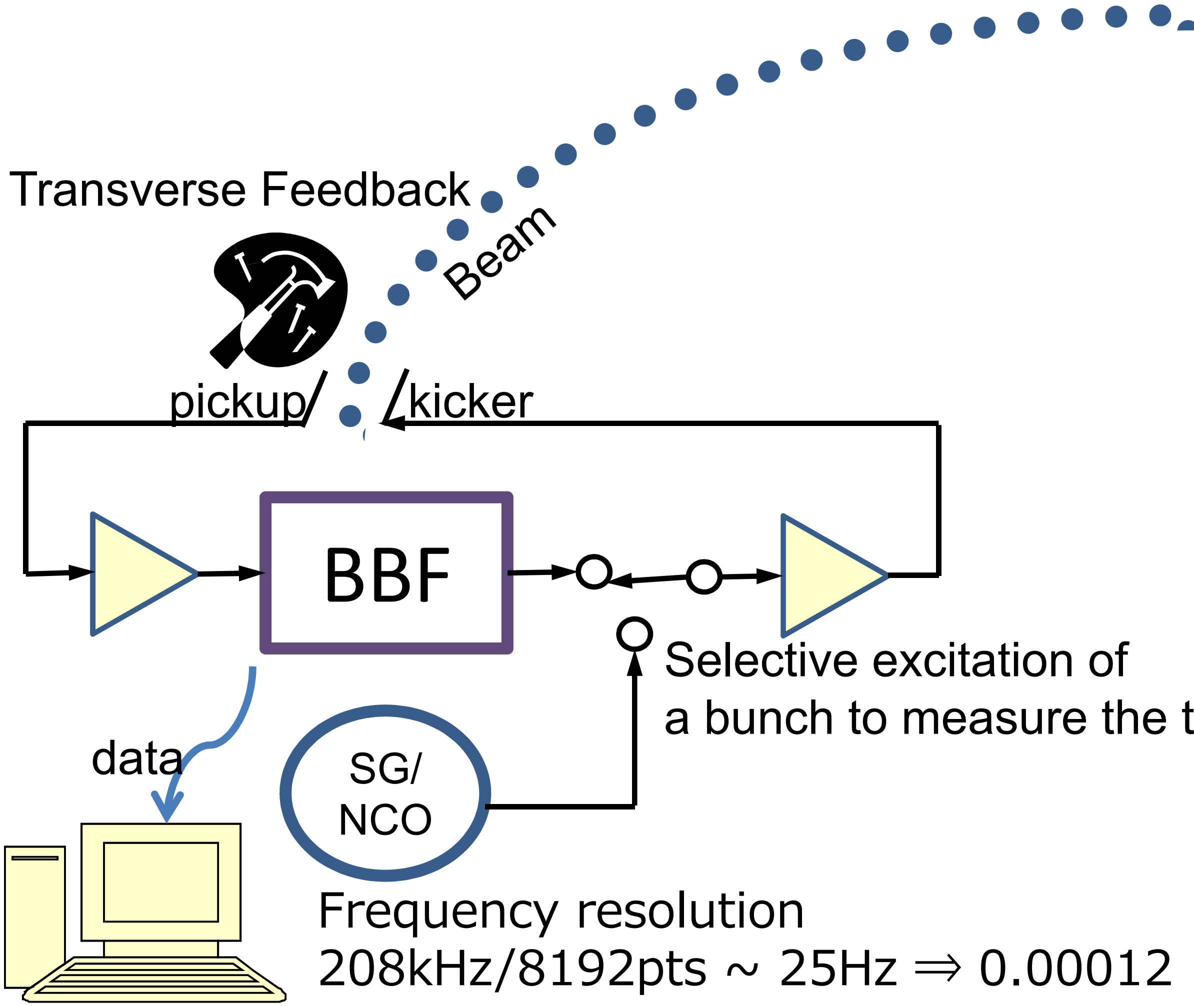
- 4GLS Instability Threshold beam current
  - < 100 mA for CBI
  - < 1 mA / bunch for TMCI
- 4GLS operation needs effective bunch-by-bunch feedback (BBF) system
- BBF systems recently implemented to 3GLS for e.g. large bunch-current operation
  - They are applicable to 4GLS.

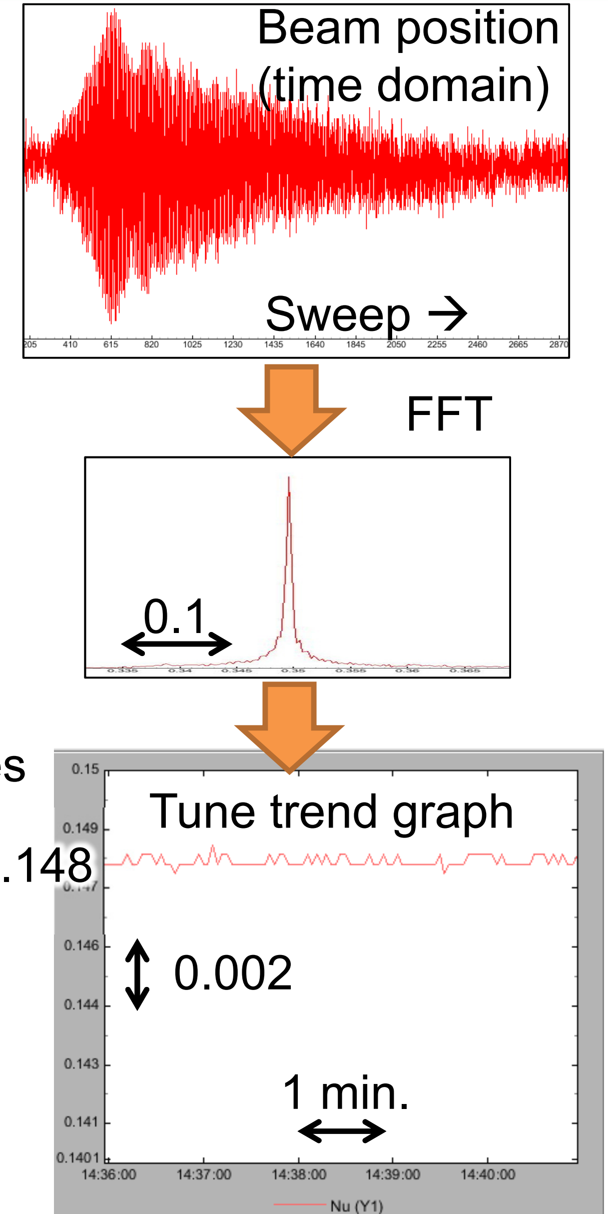


Real-time Tune Monitor

- To correct the betatron tune shift due to undulator gap change.
  - Tune shift may cause lower lifetime and/or injection efficiency
- Conventional excitation method disturbs the user operation of 4GLS
- Real-time tune monitoring by BBF system
  - A dedicated bunch is excluded from the feedback loop, transversally perturbed for tune observation.
- Available systems in 3GLS
  - Elettra: G. Gaio, et al., Proc. of IPAC'14, pp.1742-1744, TUPRI075.
  - SLS: D. Bulfone, et al., Proc. of EPAC'02, pp.2061-2063.
  - SPring-8: K. Kobayashi, private communication.
  - TLS: C.H. Kuo, et al., Proc. of DIPAC'11, pp.491-493, TUPD79.
  - PETRA III: K. Blewski, et al., Proc. of BIW'08, pp.50-54, MOVTC06.

Real-time Tune Monitor at SPring-8





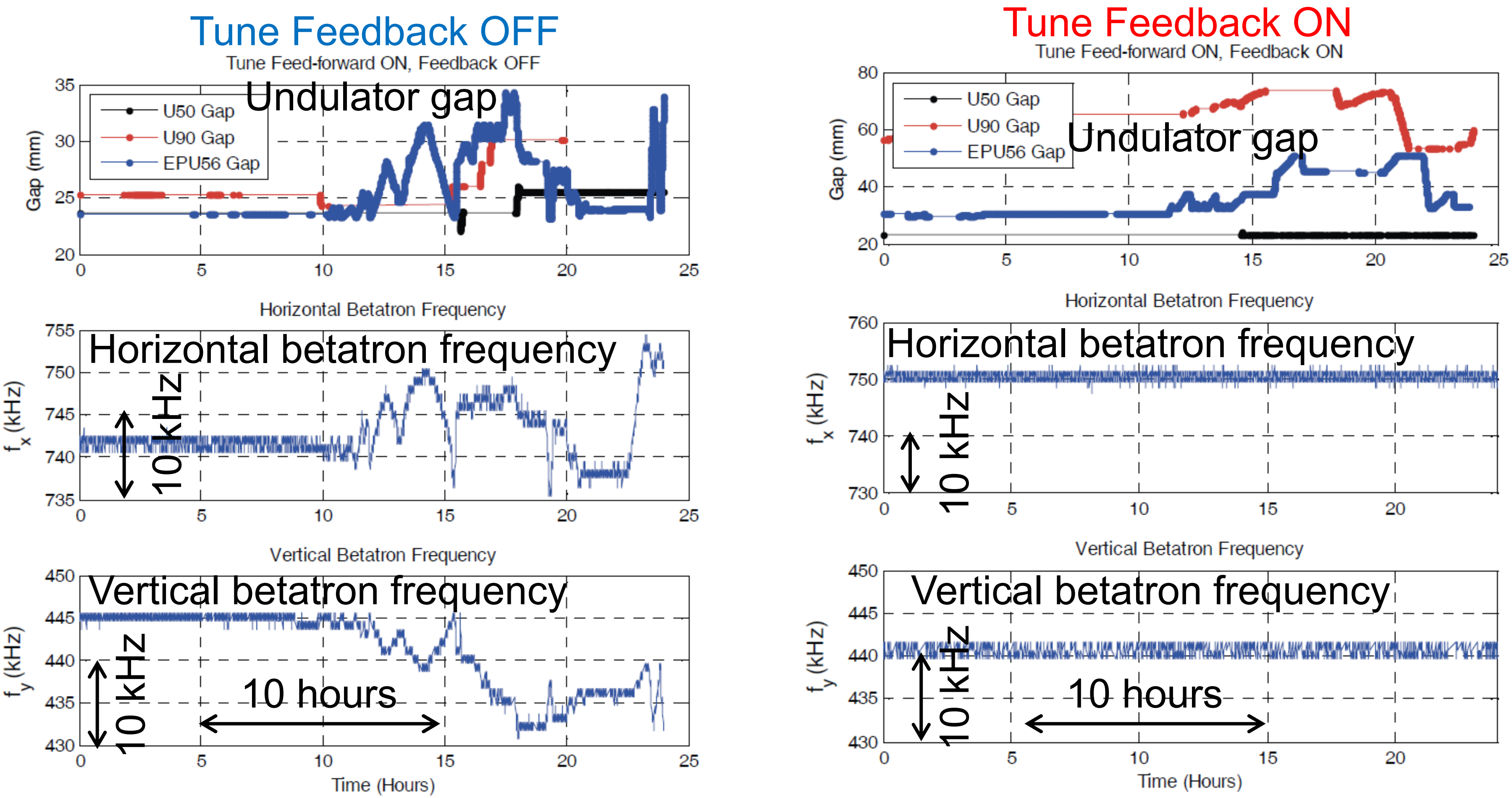
Frequency resolution
208kHz/8192pts ~ 25Hz ⇒ 0.00012

Courtesy of K. Kobayashi

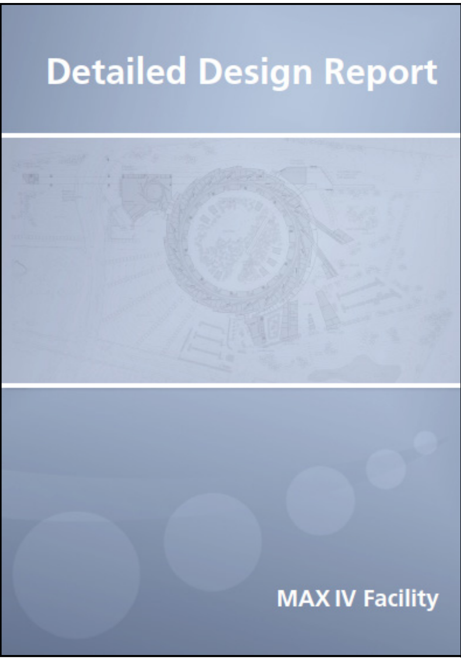
Tune Feedback Test at TLS

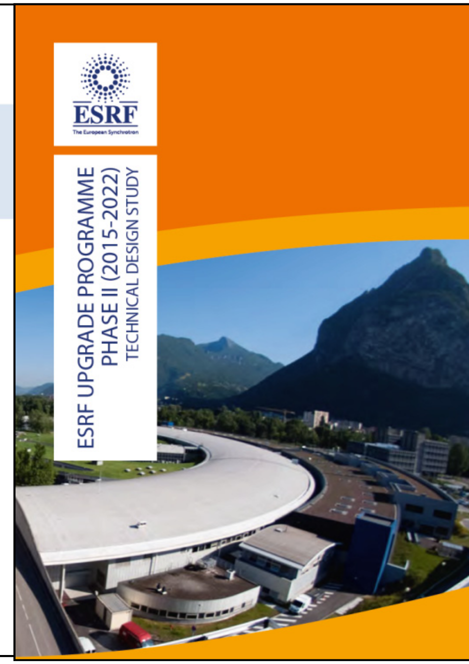
- Tune data from the BBF system is fed back to some quadrupole magnets.

C.H. Kuo, et al., Proc. of DIPAC'11, pp.491-493, TUPD79.



What else for 4GLS ?





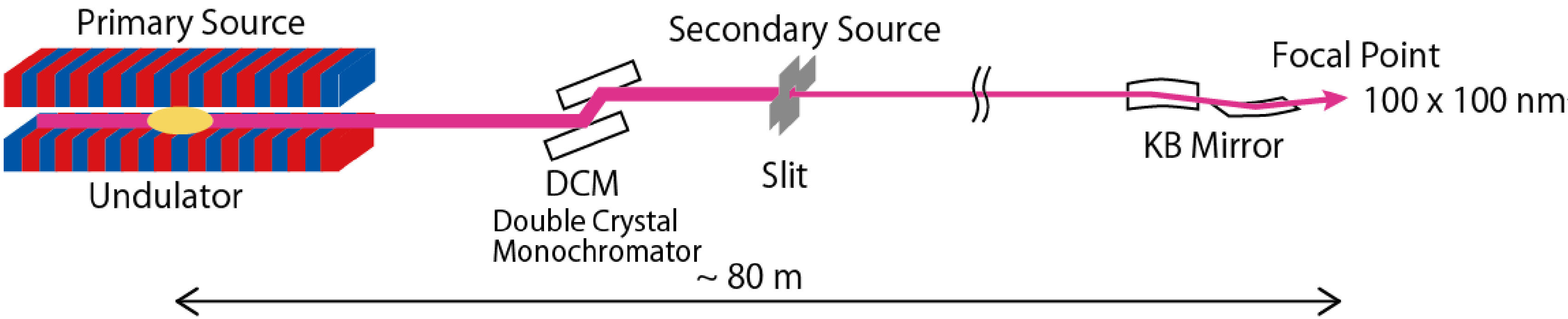
- Is “electron-beam-oriented diagnostics” all for 4GLS ?

Diagnostics Challenges for 4GLS

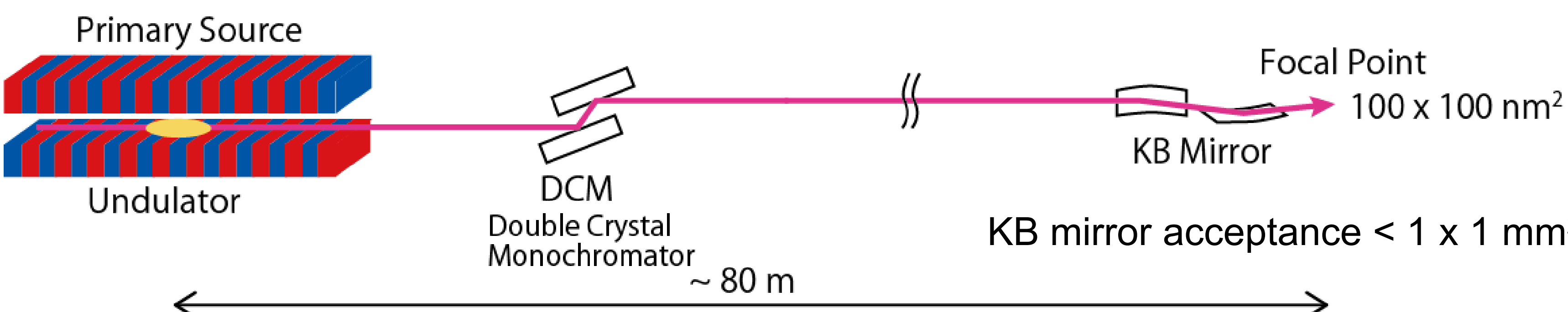
- ***"Photon-beam-oriented diagnostics"*** is crucial
  - Stabilize the optical axis
  - Maximize the brightness and coherence on the sample
- Direct nano-focusing, for example, requires tight optical axis stability.
  - 1/10 of beam size and beam divergence
  - Position: 2 x 0.5 μm^2, Angle: 0.5 x 0.5 μrad^2

Nano-focusing (3GLS vs. 4GLS)

- 3GLS: Need secondary source aperture
  - Flux: ~ 10^{10} photons/sec
  - Significant loss of brightness by the aperture (~ 10 x 10 μm^2)
  - Secondary source relaxes the primary source fluctuation



- 4GLS: Direct nano-focusing
  - Flux: ~ 10^{13} photons/sec (x 10^3 increase!)
  - Primary source fluctuation spoils the beamline performance



Diagnostics Challenges for 4GLS

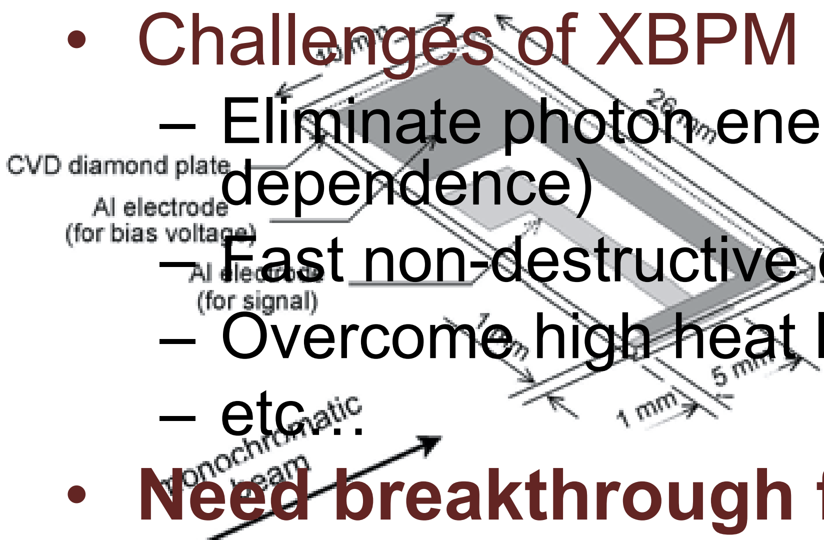
- ***"Photon-beam-oriented diagnostics"*** is crucial
  - Stabilize the optical axis
  - Maximize the brightness and coherence on the sample
- Direct nano-focusing, for example, requires tight optical axis stability.
  - 1/10 of beam size and beam divergence
  - Position: 2 x 0.5 μm^2, Angle: 0.5 x 0.5 μrad^2
- Challenges
  - Long-term stability of BPM heads and electronics
  - Reliable X-ray photon BPMs (XBPM) for orbit feedback loop

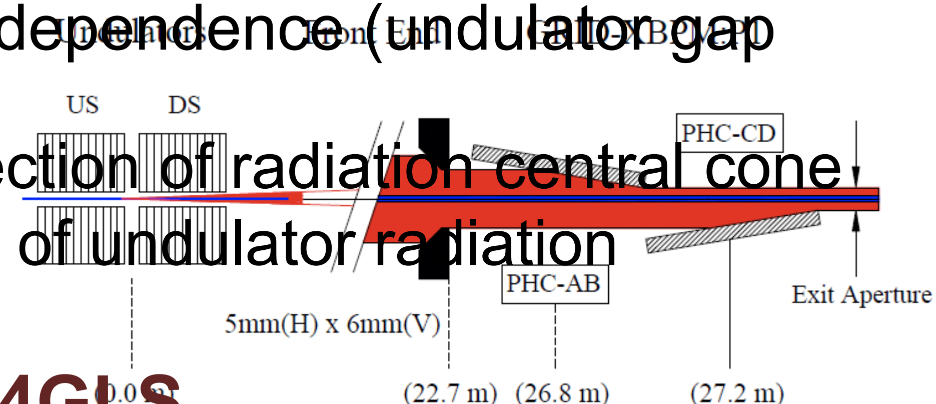
Toward Long-Term Stable BPM

- FOFB works well for the fast orbit fluctuation.
- Concern for slow orbit drift is remaining for optical axis stability of 4GLS
- Sources of slow drift
  - Ground motion
  - Thermal expansion of girder, chamber etc.
    - Monitor the BPM head position and correct the BPM data?
  - Electronics gain
    - 10^{-4} gain error corresponds to ~ 1 μm
  - Beam current dependency
  - etc…
- Need further R&D efforts for stable BPM.

X-ray Photon BPM (XBPM)

- Indispensable for ultimate optical-axis stability.
  - Mechanical stability of electron BPMs is limited.
  - Optical axis information is needed for precise orbit feedback loop.
- XBPM examples
  - Tungsten blade: E. D. Johnson, et al., Rev. Sci. Instrum. 60, 1947 (1989).
  - Diamond blade: H. Aoyagi, et al., Nucl. Instrum. Meth. A 467-468, pp.252-255 (2001).
  - GRID-XBPM: B.X. Yang, et al., Proc. of BIW'12, pp.235-237, WECP01.
- Challenges of XBPM
  - Eliminate photon energy dependence (undulator gap dependence)
  - Fast non-destructive detection of radiation central cone
  - Overcome high heat load of undulator radiation
  - etc...
- **Need breakthrough for 4GLS**





Summary

- Cutting-edge diagnostic technologies developed for 3GLS meet the requirement for 4GLS
  - Digital beam position monitor (BPM) electronics
  - Fast orbit feedback (FOFB)
  - High resolution beam size monitor
  - Bunch-by-bunch feedback (BBF)
  - Real-time tune monitor
- Based on "electron-beam-oriented diagnostics"
- ***"Photon-beam-oriented diagnostics"*** is crucial for 4GLS
  - Optical axis stability is critical for e.g. direct nano-focusing.
    - Position: 2 x 0.5 μm^2, Angle: 0.5 x 0.5 μrad^2
  - Developments of long-term stable BPM and reliable XBPM are urgently needed.

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Thank you for your attention!