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

May 7th, 2015
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RIKEN SPring-8 Center
Outline

• Introduction:
  Evolution of ring-based light sources

• Innovation of Diagnostic Instruments for 3rd generation light sources (3GLS)

• Diagnostics challenges for 4th generation light sources (4GLS)

• Summary
• 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
4th 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
    \[ \varepsilon_0 \propto \gamma^2 \theta^3 \]
  - \( \gamma \): Lorentz factor
  - \( \theta \): Bending angle for each dipole magnet
  - More number of dipoles, smaller energy, and longer circumference

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H. Wiedemann, Particle Accelerator Physics 3rd edition (2007)
3GLS and 4GLS Facilities

Emittance / $\gamma^2$ [pm rad]

Circumference [m]

- ANKA
- Indus-II
- TLS
- CLS
- CANDLE
- Australian
- ALS
- ALBA
- SLS
- SOLEIL
- Diamond
- MAX IV
- Sirius
- APS
- SPring-8
- PETRA III
- ESRF-U
- SLiT-J
- NSLS-II
- PEP-X
- TauUSR

3rd Generation
Double-bend Lattice

4th Generation
Multi-bend Achromat Lattice
## 4GLS Examples

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX IV</td>
<td>Sweden</td>
<td>3.0</td>
<td>330</td>
<td>528</td>
<td>7BA</td>
<td>[1]</td>
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<tr>
<td>Sirius</td>
<td>Brazil</td>
<td>3.0</td>
<td>280</td>
<td>518.4</td>
<td>5BA</td>
<td>[2]</td>
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<tr>
<td>ESRF-U</td>
<td>France</td>
<td>6.0</td>
<td>147</td>
<td>844</td>
<td>7BA</td>
<td>[3]</td>
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<td>SPring-8-II</td>
<td>Japan</td>
<td>6.0</td>
<td>149</td>
<td>1435.4</td>
<td>5BA</td>
<td>[4]</td>
</tr>
<tr>
<td>APS-U</td>
<td>USA</td>
<td>6.0</td>
<td>150</td>
<td>1104</td>
<td>7BA</td>
<td>[5]</td>
</tr>
<tr>
<td>DIAMOND-II</td>
<td>UK</td>
<td>3.0</td>
<td>276</td>
<td>561</td>
<td>DDBA</td>
<td>[6]</td>
</tr>
<tr>
<td>ALS-U</td>
<td>USA</td>
<td>1.9</td>
<td>50</td>
<td>196</td>
<td>9BA</td>
<td>[7]</td>
</tr>
<tr>
<td>PEP-X</td>
<td>USA</td>
<td>4.5</td>
<td>50</td>
<td>2199</td>
<td>7BA</td>
<td>[8]</td>
</tr>
<tr>
<td>BAPS</td>
<td>China</td>
<td>5.0</td>
<td>75</td>
<td>1263</td>
<td>7BA</td>
<td>[9]</td>
</tr>
<tr>
<td>TauUSR</td>
<td>USA</td>
<td>9.0</td>
<td>3</td>
<td>6210</td>
<td>7BA</td>
<td>[10]</td>
</tr>
</tbody>
</table>

Double Bend Lattices (3GLS)

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

\[ \gamma_y = 33.360 \quad \gamma_x = -101.5 \quad \alpha_y = -16.280 \quad \alpha_x = 41.3 \quad c_x = 2.017 \text{nm} \]

\[ \beta_x, 10^1 \gamma_x, \eta_x \text{ vs. } s (\text{m}) \]

ESRF [ESRF Orange Book (2014)]

\[ \beta_x, \eta_x \text{ vs. } s (\text{m}) \]

APS [APS-U PDR (2012)]

\[ \beta_x, \beta_y, \eta_x \text{ vs. } s (\text{m}) \]

SPring-8

\[ \beta_x, \beta_y \text{ vs. Position [m]} \]

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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)]**

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## Comparison between 4GLS and 3GLS

<table>
<thead>
<tr>
<th>Feature</th>
<th>4GLS</th>
<th>3GLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice</td>
<td>Multi-bend acrhomat (MBA)</td>
<td>Double-bend (DB)</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>~ 100 pm rad</td>
<td>1 – 10 nm rad</td>
</tr>
<tr>
<td>Brilliance [photons/s/mm²/mrad²/0.1%BW]</td>
<td>~ 10&lt;sup&gt;22&lt;/sup&gt;</td>
<td>~ 10&lt;sup&gt;20&lt;/sup&gt;</td>
</tr>
<tr>
<td>Coherent fraction</td>
<td>~ 10% (H), ~ 20% (V)</td>
<td>&lt; 1% (H), ~ 20% (V)</td>
</tr>
<tr>
<td>Beam size</td>
<td>~ 20 x 5 µm²</td>
<td>~ 100 x 5 µm²</td>
</tr>
<tr>
<td>Multipole B-field gradient</td>
<td>Strong</td>
<td>Moderate</td>
</tr>
<tr>
<td>Non-linear effects</td>
<td>Large</td>
<td>Moderate</td>
</tr>
<tr>
<td>Dynamic aperture</td>
<td>&lt; 10 mm</td>
<td>&gt; 10 mm</td>
</tr>
<tr>
<td>Chamber aperture</td>
<td>~ 30 x 20 mm²</td>
<td>~ 70 x 40 mm²</td>
</tr>
<tr>
<td>Misalignment tolerance</td>
<td>~ 30 µm</td>
<td>~ 100 µm</td>
</tr>
</tbody>
</table>
Requirements for 4GLS Beam Diagnostics

Beam Commissioning
- High resolution single-pass BPM
  - Error < 100 μm
- Undulator gap movement

Tight misalignment tolerance
- High accuracy BPM
  - Error < 100 μm

Transverse beam stability
- Fast orbit feedback
  - 0.1 μm precision
  - > 100 Hz BW
- Reliable Photon BPM

Optical Axis Stability

Collective beam instabilities
- High-resolution beam size monitor
  - < 5 μm resolution

Emittance measurement
- Low injection efficiency
- Short lifetime
- Real-time tune monitor
  - 0.001 resolution

Beam Phase Monitor
- Top-up Injection
- Beam Current Monitor
- Tune feedback

Bunch-by-bunch feedback
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

PETRA III (Vertical)


### 3GLS Fast Orbit Feedback Examples

<table>
<thead>
<tr>
<th>Facility</th>
<th>BW</th>
<th>Data Rate</th>
<th>N-BPM</th>
<th>H-Tune</th>
<th>Electronics</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALS</td>
<td>50 Hz</td>
<td>1 kHz</td>
<td>40</td>
<td>~14</td>
<td>Unique</td>
<td>C. Steier, et al., Proc. of PAC'03, pp.3374-3376, FPAB037.</td>
</tr>
<tr>
<td>APS</td>
<td>100 Hz</td>
<td>1.5 kHz</td>
<td>160</td>
<td>36.2</td>
<td>Unique</td>
<td>W.E. Norum, et al., Proc. of PAC'09, pp.3441-3443, TH5RFP024.</td>
</tr>
<tr>
<td>SOLEIL</td>
<td>100 Hz</td>
<td>10 kHz</td>
<td>120</td>
<td>18.2</td>
<td>Libera E</td>
<td>M.G. Abbott, et al., Proc. of EPAC'08, pp.3257-3259, THPC118.</td>
</tr>
<tr>
<td>Diamond</td>
<td>100 Hz</td>
<td>10 kHz</td>
<td>168</td>
<td>27.23</td>
<td>Libera E</td>
<td>R. Bartolini, Proc. of PAC'07, pp.1109-1111, TUPMN085.</td>
</tr>
</tbody>
</table>

Eletta, PETRA III etc. have harmonics suppressor of line frequency. 
SOLEIL has system band width > 2.5 kHz.
<table>
<thead>
<tr>
<th>Facility</th>
<th>BW</th>
<th>Data Rate</th>
<th>N-BPM</th>
<th>H-Tune</th>
<th>Electronics</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX IV</td>
<td>~300 Hz</td>
<td>10 kHz</td>
<td>200</td>
<td>42.20</td>
<td>Libera B+</td>
<td>[1]</td>
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<tr>
<td>Sirius</td>
<td>&gt; 1 kHz</td>
<td>50 kHz</td>
<td>180</td>
<td>44.6</td>
<td>Unique</td>
<td>[2]</td>
</tr>
<tr>
<td>ESRF-U</td>
<td>&gt; 120 Hz</td>
<td>10 kHz</td>
<td>288</td>
<td>75.6</td>
<td>Libera B</td>
<td>[3]</td>
</tr>
<tr>
<td>SPring-8-II</td>
<td>&gt; 100 Hz</td>
<td>~10 kHz</td>
<td>288</td>
<td>109.14</td>
<td>TBD</td>
<td>[4]</td>
</tr>
<tr>
<td>APS-U</td>
<td>&gt; 200 Hz</td>
<td>22.6 kHz</td>
<td>420</td>
<td>~84</td>
<td>TBD</td>
<td>[5]</td>
</tr>
</tbody>
</table>

Beam Size Monitor

- **Visible light**
  - Optical Interferometer methods have been developed.

- **X-rays**
  - Pinhole camera
  - Zone plates
  - Vertical undulator method
  - X-ray Fresnel diffractometry

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

• Pinhole imaging by white X-ray beam
  – Monochromator is not needed
• Magnification: > 2
  \[ M = \frac{L_1}{L_2} \]
• Photon energy: \( \sim 50 \) keV
• Typical pinhole size: 20 \( \mu \text{m} \)
• Fresnel diffraction at the pinhole limits the resolution
• Resolution better than 5 \( \mu \text{m} \) is feasible

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 \( \mu m \) is feasible:

- \( L = R = 25 \) [m]
- Slit width: 52 \( \mu m \)
- 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 (TMCl) 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
  \[ \frac{1}{\tau} \propto \int \beta Z_T \, ds \]
  \( \beta \): beta function

- Instability growth rate of 4GLS is roughly 4 times larger
  \[ b_{4GLS} \sim \frac{b_{3GLS}}{2}, \quad \beta_{4GLS} \sim \frac{\beta_{3GLS}}{2} \]

  \[
  \therefore \quad \frac{1}{\tau_{4GLS}} \sim \frac{4}{\tau_{3GLS}}
  \]
Vacuum Chambers

• ~ 70 x 40 mm² \(\rightarrow\) ~ 30 x 20 mm²

ESRF

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

74 x 33 mm²

ESRF Upgrade Phase II Orange Book (2014).

3GLS


70 x 40 mm²

SPring-8

SPring-8-II CDR (2014)

4GLS

30 x 20 mm²

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
  – SPring-8: K. Kobayashi, private communication.
Real-time Tune Monitor at SPring-8

May 7th, 2015 24H. Maesaka, RIKEN SPring-8 Center

Transverse Feedback

Beam

pickup/kicker

BBF

Selective excitation of a bunch to measure the tunes

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

Tune trend graph

Courtesy of K. Kobayashi

Beam position (time domain)

Sweep ⇒

FFT

data

SG/NCO

0.1

0.148

0.002

1 min.

14:36:00 14:37:00 14:38:00 14:39:00 14:40:00

Nu (Y1)
Tune Feedback Test at TLS

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


**Tune Feedback OFF**

- Undulator gap
- Horizontal betatron frequency
- Vertical betatron frequency

**Tune Feedback ON**

- Undulator gap
- Horizontal betatron frequency
- Vertical betatron frequency

May 7th, 2015

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• Is “electron-beam-oriented diagnostics” all 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 μm², Angle: 0.5 x 0.5 μrad²
Nano-focusing (3GLS vs. 4GLS)

- **3GLS:** Need secondary source aperture
  - Flux: $\sim 10^{10}$ photons/sec
  - Significant loss of brightness by the aperture ($\sim 10 \times 10 \mu m^2$)
  - Secondary source relaxes the primary source fluctuation

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

KB mirror acceptance $< 1 \times 1 \ mm^2$
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: $2 \times 0.5 \, \mu m^2$, Angle: $0.5 \times 0.5 \, \mu rad^2$

• 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 $\sim 1 \mu m$
  – 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**

- **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**
• 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 μm², Angle: 0.5 x 0.5 μrad²
  – Developments of long-term stable BPM and reliable XBPM are urgently needed.
Acknowledgments

• Special thanks to
  – H. Tanaka
  – S. Goto
  – S. Takano
  – T. Fujita
  – M. Masaki

for fruitful discussions about beam instrumentations for 4GLS
Thank you for your attention!