Performance and Trends of Storage Ring Light Sources

R. Bartolini

Diamond Light Source Ltd
and
John Adams Institute, University of Oxford

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Outline

• Introduction
  user’s requirements and accelerator physics challenges

• Overview of the performance of 3rd generation light sources
  comparison of design with achieved parameters
  brightness, stability and time structure

• Trends and Improvements
  review of the upgrades of existing facilities
  technological developments

• Conclusions
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<thead>
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<th>Year</th>
<th>Source</th>
<th>Country</th>
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<td>2004</td>
<td>SPEAR3</td>
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<td>Australia</td>
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<td>MAX III</td>
<td>Sweden</td>
<td>700 MeV</td>
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<td>India</td>
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<td>2008</td>
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# 3rd generation storage ring light sources

under construction or planned

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Country</th>
<th>Energy</th>
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<tr>
<td>2009</td>
<td>ALBA, Spain</td>
<td>Spain</td>
<td>3 GeV</td>
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<tr>
<td></td>
<td>Petra-III, Germany</td>
<td>Germany</td>
<td>6 GeV</td>
</tr>
<tr>
<td>&gt; 2009</td>
<td>NSLS-II, US</td>
<td>US</td>
<td>3 GeV</td>
</tr>
<tr>
<td></td>
<td>SESAME, Jordan</td>
<td>Jordan</td>
<td>2.5 GeV</td>
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<tr>
<td></td>
<td>MAX-IV, Sweden</td>
<td>Sweden</td>
<td>1.5-3 GeV</td>
</tr>
<tr>
<td></td>
<td>TPS, Taiwan</td>
<td>Taiwan</td>
<td>3 GeV</td>
</tr>
<tr>
<td></td>
<td>CANDLE, Armenia</td>
<td>Armenia</td>
<td>3 GeV</td>
</tr>
</tbody>
</table>
Synchrotron radiation sources properties

Broad Spectrum which covers from microwaves to hard X-rays

High Flux: high intensity photon beam

\[
\text{Flux} = \frac{\text{Photons}}{(s \cdot BW)}
\]

High Brilliance (Spectral Brightness): highly collimated photon beam generated by a small divergence and small size source (partial coherence)

\[
\text{Brilliance} = \frac{\text{Photons}}{(s \cdot \text{mm}^2 \cdot \text{mrad}^2 \cdot BW)}
\]

High Stability: submicron source stability

Polarisation: both linear and circular (with IDs)

Pulsed Time Structure: pulsed length down to tens of picoseconds
Accelerator Physics challenges

Photon energy

Brilliance

Flux

Stability

Polarisation

Time structure

Ring energy

Small Emittance

Insertion Devices

High Current; Feedbacks

Vibrations; Orbit Feedbacks; Top-Up

Short bunches; Short pulses
Brilliance and low emittance

The brilliance of the photon beam is determined (mostly) by the electron beam emittance that defines the source size and divergence.

$$\text{brilliance} = \frac{\text{flux}}{4\pi^2 \Sigma_x \sum_x \sum_y \sum_y'}$$

$$\Sigma_x = \sqrt{\sigma_{x,e}^2 + \sigma_{ph,e}^2}$$

$$\Sigma_{x'} = \sqrt{\sigma_{x',e}^2 + \sigma_{ph,e}^2}$$

$$\sigma_x = \sqrt{\varepsilon_x \beta_x + (D_x \sigma_\varepsilon)^2}$$

$$\sigma_{x'} = \sqrt{\varepsilon_{x'} \beta_x + (D' \sigma_{\varepsilon})^2}$$
Brilliance with IDs

Thanks to the progress with IDs technology storage ring light sources can cover a photon range from few tens of eV to tens 10 keV or more with high brilliance.

Medium energy storage rings with In-vacuum undulators operated at low gaps (e.g. 5-7 mm) can reach 10 keV with a brilliance of $10^{20}$ ph/s/0.1%BW/mm$^2$/mrad$^2$.

Courtesy M.E. Couprie (SOLEIL)
Low emittance and adequate space in straight sections to accommodate long Insertion Devices are obtained in

Double Bend Achromat (DBA)

Triple Bend Achromat (TBA)

DBA used at: ESRF, ELETTRA, APS, SPring8, Bessy-II, Diamond, SOLEIL, SPEAR3...

TBA used at: ALS, SLS, PLS, TLS ...

\[ \varepsilon_x = F \frac{C_q \gamma^2 \theta_b^3}{J_x} \propto \frac{1}{N_b^3} \]

\[ F_{MEDBA} = \frac{1}{4\sqrt{15}} \quad F_{MEDBA-disp} = \frac{1}{12\sqrt{15}} \]
The original achromat design can be broken, leaking dispersion in the straight section:

- ESRF: 7 nm → 3.8 nm
- APS: 7.5 nm → 2.5 nm
- SPring8: 4.8 nm → 3.0 nm
- SPEAR3: 18.0 nm → 9.8 nm
- ALS (SB): 10.5 nm → 6.7 nm

New designs envisaged to achieve sub-nm emittance involve:

- MBA
- MAX-IV (7-BA): S. Leemann WEPC011
- Damping Wigglers
- NSLS-II: J. Bengtsson this session
- Petra-III: K. Balewski WEPC001
Linear optics modelling: Diamond

Modified version of LOCO with constraints on gradient variations (see ICFA newsletter, Dec’07)

- Beta beating reduced to 0.4% rms
- Quadrupole variation reduced to 2%
- Results compatible with mag. meas.
Linear optics modelling: SOLEIL

Modified version of LOCO with constraints on gradient variations

$\beta$ - beating reduced to 0.3% rms

Results compatible with mag. meas. (10^{-3} gradient identity, Brunelle et al., EPAC’06) and internal DCCT calibration of individual power supply

Hor. dispersion

Quadrupole gradient variation

Courtesy A. Nadji (SOLEIL)
MATLAB LOCO and Middlelayer

LOCO: Linear Optics from Closed Orbit

- Calibrate/control optics using orbit response matrix
- Determine quadrupole gradients
- Correct coupling
- Calibrate BPM gains, steering magnets

High Level Matlab Applications (scripts and functions)

Matlab Middle Layer

Matlab to EPICS (MCA, LabCA) Accelerator Toolbox (AT - Model)

Accelerator Hardware

LOCO and Middlelayer are used at

ALS Diamond
Spear3 ASP
CLS SSRF
PLS ALBA
SOLEIL NSLS-II

Courtesy J. Safranek (SSRL), G. Portmann (ALS)
## Summary of comparison model/machine for linear optics

<table>
<thead>
<tr>
<th>Model</th>
<th>Model emittance</th>
<th>Measured emittance</th>
<th>β-beating (rms)</th>
<th>Coupling* ((\varepsilon_y/\varepsilon_x))</th>
<th>Vertical emittance</th>
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<tbody>
<tr>
<td>ALS</td>
<td>6.7 nm</td>
<td>6.7 nm</td>
<td>0.5 %</td>
<td>0.1%</td>
<td>4-7 pm</td>
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<tr>
<td>APS</td>
<td>2.5 nm</td>
<td>2.5 nm</td>
<td>1 %</td>
<td>0.8%</td>
<td>20 pm</td>
</tr>
<tr>
<td>CLS</td>
<td>18 nm</td>
<td>17-19 nm</td>
<td>4.2%</td>
<td>0.2%</td>
<td>36 pm</td>
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<tr>
<td>Diamond</td>
<td>2.74 nm</td>
<td>2.6-2.9 nm</td>
<td>0.4 %</td>
<td>0.15%</td>
<td>4 pm</td>
</tr>
<tr>
<td>ESRF</td>
<td>4 nm</td>
<td>4 nm</td>
<td>1%</td>
<td>0.25%</td>
<td>10 pm</td>
</tr>
<tr>
<td>SLS</td>
<td>5.6 nm</td>
<td>5.4-7 nm</td>
<td>4.5% H; 1.3% V</td>
<td>0.05%</td>
<td>3.2 pm</td>
</tr>
<tr>
<td>SOLEIL</td>
<td>3.73 nm</td>
<td>3.70-3.75 nm</td>
<td>0.3 %</td>
<td>0.1%</td>
<td>4 pm</td>
</tr>
<tr>
<td>SPEAR3</td>
<td>9.8 nm</td>
<td>9.8 nm</td>
<td>&lt; 1%</td>
<td>0.05%</td>
<td>5 pm</td>
</tr>
<tr>
<td>SPring8</td>
<td>3.4 nm</td>
<td>3.2-3.6 nm</td>
<td>1.9% H; 1.5% V</td>
<td>0.2%</td>
<td>6.4 pm</td>
</tr>
</tbody>
</table>

* best achieved

M. Boge: WEPC003  Coupling Control at the SLS
Dynamic Aperture

SOLEIL bare lattice at zero chromaticity

Tracking includes

Systematic multipole errors
- Dipole: up to 14-poles
- Quadrupoles: up to 28-poles
- Sextupoles: up to 54-poles
- Correctors (steerers): up to 22-poles
- Secondary coils in sext. \( \rightarrow \) strong 10-pole term

From magnetic measurements:
- Dipole: fringe field, gradient error, edge tilt errors
- Coupling errors (random rotation of quadrupoles)
- No quadrupole fringe fields

Courtesy A. Nadji (SOLEIL)
A very accurate description of machine model is mandatory

- fringe fields: dipole, quadrupole (and sextupole) magnets
- systematic octupole components in quadrupole magnets
- decapoles, skew decapoles and octupoles in sextupole magnets

 Courtesy C. Steier (ALS) P. Kuske (BESSY-II)
Orbit stability: disturbances and requirements

Beam stability should be better than

10% of the beam size

10% of the beam divergence

up to 100 Hz

but IR beamlines will have tighter requirements

for 3rd generation light sources this implies sub-μm stability

- identification of sources of orbit movement
- passive damping measures
- orbit feedback systems
Ground vibrations to beam vibrations: Diamond

Amplification factor girders to beam: H 31 (theory 35); V 12 (theory 8);

<table>
<thead>
<tr>
<th>1-100 Hz</th>
<th>Horizontal</th>
<th></th>
<th>Vertical</th>
<th></th>
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<tr>
<td></td>
<td>Long Straight</td>
<td>Standard Straight</td>
<td>Long Straight</td>
<td>Standard Straight</td>
</tr>
<tr>
<td>Position (μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Target</td>
<td>17.8</td>
<td>12.3</td>
<td>1.26</td>
<td>0.64</td>
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<tr>
<td>Measured</td>
<td>3.95 (2.2%)</td>
<td>2.53 (2.1%)</td>
<td>0.70 (5.5%)</td>
<td>0.37 (5.8%)</td>
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<tr>
<td>Angle (μrad)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>1.65</td>
<td>2.42</td>
<td>0.22</td>
<td>0.42</td>
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<tr>
<td>measured</td>
<td>0.38 (2.3%)</td>
<td>0.53 (2.2%)</td>
<td>0.14 (6.3%)</td>
<td>0.26 (6.2%)</td>
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Global fast orbit feedback: Diamond

Significant reduction of the rms beam motion up to 100 Hz;

Higher frequencies performance limited mainly by the correctors power supply bandwidth

M. Heron (DLS): THPC118

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<th>1-100 Hz</th>
<th>Standard Straight H</th>
<th>Standard Straight V</th>
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<tr>
<td><strong>Position (μm)</strong></td>
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<tr>
<td>Target</td>
<td>12.3</td>
<td>0.64</td>
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<tr>
<td>No FOFB</td>
<td>2.53 (2.1%)</td>
<td>0.37 (5.8%)</td>
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<tr>
<td>FOFB On</td>
<td>0.86 (0.7%)</td>
<td>0.15 (2.3%)</td>
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<tr>
<td><strong>Angle (μrad)</strong></td>
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<tr>
<td>Target</td>
<td>2.42</td>
<td>0.42</td>
</tr>
<tr>
<td>No FOFB</td>
<td>0.53 (2.2%)</td>
<td>0.26 (6.2%)</td>
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<tr>
<td>FOFB On</td>
<td>0.16 (0.7%)</td>
<td>0.09 (2.1%)</td>
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**Overview of fast orbit feedback performance**

Summary of integrated rms beam motion (1-100 Hz) with FOFB and comparison with 10% beam stability target

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<td><strong>ALS</strong></td>
<td>40 Hz</td>
<td>&lt; 2 μm in H (30 μm)*</td>
<td>&lt; 1 μm in V (2.3 μm)*</td>
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<td><strong>APS</strong></td>
<td>60 Hz</td>
<td>&lt; 3.2 μm in H (6 μm)**</td>
<td>&lt; 1.8 μm in V (0.8 μm)**</td>
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<tr>
<td><strong>Diamond</strong></td>
<td>100 Hz</td>
<td>&lt; 0.9 μm in H (12 μm)</td>
<td>&lt; 0.1 μm in V (0.6 μm)</td>
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<tr>
<td><strong>ESRF</strong></td>
<td>100 Hz</td>
<td>&lt; 1.5 μm in H (40 μm)</td>
<td>~ 0.7 μm in V (0.8 μm)</td>
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<tr>
<td><strong>ELETTRA</strong></td>
<td>100 Hz</td>
<td>&lt; 1.1 μm in H (24 μm)</td>
<td>&lt; 0.7 μm in V (1.5 μm)</td>
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<tr>
<td><strong>SLS</strong></td>
<td>100 Hz</td>
<td>&lt; 0.5 μm in H (9.7 μm)</td>
<td>&lt; 0.25 μm in V (0.3 μm)</td>
</tr>
<tr>
<td><strong>SPEAR3</strong></td>
<td>60Hz</td>
<td>~ 1 μm in H (30 μm)</td>
<td>~ 1 μm in V (0.8 μm)</td>
</tr>
</tbody>
</table>

*Trends on Orbit Feedback*

- restriction of tolerances w.r.t. to beam size and divergence
- higher frequencies ranges
- integration of XBPMs
- feedback on beamlines components

* up to 500 Hz  
** up to 200 Hz
Top-Up Operation

Top-Up operation consists in the continuous (very frequent) injection to keep the stored current constant

\[ \Delta I/I \sim 10^{-3} \]

Already in operation at APS, SLS, SPring8, TLS

New commissioned machines Diamond, SOLEIL are undergoing tests and will operate Top-Up soon

Retrofitted in ALS, SPEAR3, ELETTRA, BESSY-II, ESRF (few bunches mode)

Operating modes are machine specific (frequency of injection, # of shots, charge)
Advantages of Top-Up Operation: stability

Top-Up improves stability:
- constant photon flux for the users
- higher average current
- constant thermal load on components

BPMs block stability
- without Top-Up $\sim 10 \, \mu m$
- with Top-Up $< 1 \, \mu m$

**Crucial for long term sub- $\mu m$ stability**

Courtesy M. Boge (SLS)
Time resolved science requires operating modes with single bunch or hybrid fills to exploit the short radiation pulses of a single isolated bunch.

The rms bunch length increases with the stored charge per bunch (PWD and MI).

Modern light sources can operate a wide variety of fill patterns (few bunches, camshaft).
There are three main approaches to generate short radiation pulses in storage rings:

1) Shorten the e-bunch

2) Chirp the e-bunch + slit or optical compression

3) Laser induced local energy-density modulation
The equilibrium bunch length is due to the quantum nature of the emission of synchrotron radiation and is the result of the competition between quantum excitation and radiation damping. If high current effects are negligible the bunch length is

$$\sigma_z = \frac{\alpha c}{2\pi f_s \sigma_e} \propto \sqrt{\frac{\alpha \gamma^3}{d V_{RF} / dz}}$$

We can modify the electron optics to reduce $\alpha$

$$\alpha \approx \frac{1}{L} \int \frac{D_x}{\rho} ds \approx 10^{-6}$$

$\alpha_{(low\_alpha\_optics)} \approx \alpha_{(nominal)}/100 \rightarrow \sigma_z_{(low\_alpha\_optics)} \approx \sigma_z_{(nominal)}/10$

Bessy-II, ANKA, ELETTRA and SPEAR3 have successfully demonstrated low-alpha operation with few ps bunches for Coherent THz radiation or short X-ray pulses.

G. Wuestefeld: MOZAG02 Coherent Synchrotron Radiation and Short Bunches in Electron Storage Rings
S.A. Muller: WEPC046 Characterising THz Coherent Synchrotron Radiation at the ANKA Storage Ring
E. Karantzoulis: WEPC027 Coherent THz Radiation at ELETTRA
Low alpha optics: BESSY-II

When the bunch is too short CSR generates chaotic bursts of THZ radiation

Microbunch instability (Stupakov-Heifets)

\[ \alpha = 7 \cdot 10^{-4} \rightarrow 10^{-6} \]

\[ \sigma_z = 12 \text{ ps (rms)} \rightarrow 0.7 \text{ ps} \]

\[ \varepsilon_x = 6 \text{ nm} \rightarrow 30 \text{ nm} \]

\[ l_{\text{th}} \propto \sigma_z^a \frac{dV_{\text{RF}}}{dz} \]

\[ a = 7/3 \text{ theory} \]

\[ a = 8/3 \text{ experiment} \]
Performance and possible upgrades

At BESSY-II coherent radiation is offered to user 4 times a year in dedicated shifts of 3 days

\[ \sigma_z = 3 \text{ ps rms} \]

15 mA in 400 bunches (37.5 \( \mu \text{A per bunch} \))

stable emission: \( \frac{P \text{ (coherent)}}{P \text{ (incoherent)}} \sim 10^7 \)

Possible upgrade based on the combination of low-alpha with a 3HC SC cavity in bunch shortening mode

50 MV - 1.5 GHz giving 100 higher RF gradient can allow

1.3 ps, 0.5 mA per bunch in nominal optics

300 fs, 17 \( \mu \text{A per bunch} \) in the low-alpha optics
Femtosecond slicing

BESSY-II, ALS and SLS have successfully demonstrated the generation of X-ray pulses with few 100 fs pulse length, tunable and synchronised to an external laser for pump-probe experiments.
# Femto-slicing summary

<table>
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<tr>
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<th>ALS</th>
<th>ALS upgrade</th>
<th>BESSY-II</th>
<th>SLS</th>
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<tbody>
<tr>
<td>Ph. energy</td>
<td>0.5 – 7 keV</td>
<td>0.2 – 10 keV</td>
<td>0.4-1.4 keV</td>
<td>5-8 keV</td>
</tr>
<tr>
<td>Ph/sec/0.1% BW</td>
<td>$3 \cdot 10^4$</td>
<td>$2 \cdot 10^6$</td>
<td>$10^6$</td>
<td>$4 \cdot 10^5$</td>
</tr>
<tr>
<td>Pulse length (fwhm)</td>
<td>140 fs</td>
<td>200 fs</td>
<td>100-150 fs</td>
<td>110-170 fs</td>
</tr>
<tr>
<td>Rep rate</td>
<td>1 kHz</td>
<td>20 kHz</td>
<td>1-2 kHz</td>
<td>2 kHz</td>
</tr>
<tr>
<td>Modulator</td>
<td>wiggler 16 cm</td>
<td>wiggler 11.4 cm</td>
<td>planar 13.9 cm</td>
<td>wiggler 13.8 cm</td>
</tr>
<tr>
<td>Radiator</td>
<td>Bending</td>
<td>In-vac U30; 5.5 mm gap</td>
<td>UE56;</td>
<td>In-vac U19; 5 mm gap</td>
</tr>
<tr>
<td>Laser</td>
<td>0.7 mJ; 50 fs</td>
<td>1.5 mJ; 100 fs</td>
<td>5 mJ; 70 fs;</td>
<td>5 mJ; 70 fs;</td>
</tr>
<tr>
<td>separation</td>
<td>H spatial</td>
<td>V spatial</td>
<td>angular</td>
<td>angular</td>
</tr>
</tbody>
</table>

Adapted from S. Khan (U. Hamburg)
**Crab Cavities for optical pulse shortening**


Cavity frequency is harmonic $h$ of ring rf frequency

*Ideally*, second cavity exactly cancels effect of first if phase advance is $n \times 180$ degrees

Pulse can be sliced or compressed with asymmetric cut crystal

Courtesy M. Borland (APS)
Several schemes based on Superconducting RF or Pulsed Normal conducting RF were investigated.

The presently proposed scheme is based on a Superconducting RF option with 2815 Hz (8th harmonic of the main RF) 4 MV.

The system delivers:
- x-ray pulses with lengths 1-2 ps FWHM
- Photon energies of 4 keV or greater
- Photon energy tunability
- \(10^4 \text{ – } 10^6\) photon per pulse
- 1\% of nominal intensity
- High repetition rate (many MHz)
- Acceptable vertical emittance growth (20 > 40 pm)

R&D required to damp LOM and HOM in SC RF structures.

Courtesy A. Nassiri (APS)
# Comparison of options for short radiation pulses

<table>
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<tr>
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<th>Low-alpha</th>
<th>Crab cavity</th>
<th>femtoslicing</th>
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<tr>
<td><strong>Pulse length</strong></td>
<td>~1 ps</td>
<td>~1 ps</td>
<td>~100 fs</td>
</tr>
<tr>
<td><strong>Photon flux</strong></td>
<td>poor</td>
<td>good</td>
<td>very poor</td>
</tr>
<tr>
<td><strong>synchronisation</strong></td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Hardware upgrade</strong></td>
<td>easy</td>
<td>difficult</td>
<td>manageable</td>
</tr>
<tr>
<td><strong>Compatibility with normal users operation</strong></td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Rep rate</strong></td>
<td>MHz</td>
<td>MHz</td>
<td>KHz</td>
</tr>
</tbody>
</table>
ESRF has already undergone a number of machine performance improvements since commissioning in 1992 with an emittance of 7 nm at 6 GeV

- Distributed dispersion → Emittance of 3.8 nm
- higher current (100 mA to 200 mA)
- Vertical beta tuned to 2.5 m in all ID straight to allow for small ID gap.
- One more family of chromatic sextupoles
- global FOFOB

A new upgrade program is proposed for funding (“The purple Book”)

- Lower vertical emittance (lower coupling)
- Longer straight sections (longer IDs or canted Ids)
- Higher current (from 200 mA to 300 mA)
- Top Up for 16 and 4 bunches modes
- Cryogenic Permanent Magnet undulators

New technology: BPMs, RF NC HOM free cavities.

P.Elleaume WEPC010: Upgrade of the ESRF Accelerator Complex
Trends and upgrades: ESRF

Longer straight section allow for longer IDs or canted schemes serving more beamlines
ESRF Increased brightness with longer IDs, lower coupling, higher current
APS upgrade since commissioning in 1995 with an emittance of 7.5 nm at 7 GeV

- Distributed dispersion → effective emittance of 3.1 nm (natural emittance 2.5 nm)
- FOFB (60 Hz BW)
- Top-Up
- Canted undulators

The current upgrade concepts include an ERL upgrade option

Intermediate upgrades options have been explored (not precluding the ERL option):

- Longer straight sections (longer IDs, customized optics, canted IDs)
- Higher current (from 100 mA to 200 mA)
- Short pulses programme with crab cavities,
- Increase BW of orbit feedback system to achieve sub-μm stability up to 200 Hz

Courtesy M. Borland, G. Decker (APS)
Trends and upgrades: Diamond and Soleil

Diamond since the start of user operation:

- FOFB run in user operation
- TMBF under commissioning
- Top-Up
- 300 mA for users
- low-alpha
- canted undulators, customised optics
- CPMU

Soleil since the start of user operation:

- TMBF run in user operation
- FOFB under commissioning
- Top-Up
- 500 mA for users; 100 mA in 8 bunches
- low-alpha first test started; femtoslicing considered
- new IDs, CPMU

J. M Filhol (SOLEIL): WEPC016
Technological developments

Insertion Devices

- EPU and APPLE-II
- Small gap in-vacuum ~5 mm
- Superconducting wigglers
- Cryogenic Permanent Magnets Undulator (ESRF, SOLEIL, Diamond)
- Superconducting undulators (ANKA)

Higher field allows higher flux on harmonics
Shorter undulators allow canted beamlines from the same straight
Better resistance to radiation

CMPU: J. Chavanne (ESRF): WEPC105, C. Benabderrahmane (SOLEIL) WEPC098
SC undulators: Rossmanith (ANKA) WEPC125
Technological developments

RF systems:

- Superconducting RF-system (CLS, TLS, SOLEIL, Diamond, …)
- Normal Conducting HOM damped structures (BESSY-II, ALBA, ESRF)
- HHC: SC @ Elettra, SLS, TLS; NC @ ALS, BESSY-II
- IOTs (Diamond, ALBA, Elettra), Solid State Amplifiers (Soleil)

BPMs:

- Digital BPM electronics: simultaneous t-b-t, fast orbit feedback data, slow orbit data (Diamond, SOLEIL, ELETTRA, ASP, ALBA, …)
- sub-μm resolution (few μm in turn-by-turn mode)

Power Supplies:

- Digital Power Supply controllers (SLS, Diamond, SSRF, Elettra, PLS)
Conclusions

Third generation light sources provide a very reliable source of high brightness, very stable X-rays

No evidence of under subscription: user's community and the number of beamlines per facility is increasing;

The agreement with model is excellent for the linear optics and improvements can be foreseen for the nonlinear optics

Future developments will target

- higher brightness
- even lower emittance < 1 nm, lower coupling
- higher stability
- Top-Up, sub-\(\mu\)m over few hundreds Hz
- short pulses
- < 1 ps
- higher current
- \(~ 500 \text{ mA}\)
- larger capacity
- more undulator per straights (canted undulators)

Technological progress is expected to further improve brightness and stability (IDs, RF, BPMs, DPS, …)
Thanks to many colleagues which have provided the material for this talk and thank you for your attention.