X-Ray sources

Lenny Rivkin, PSI & EPFL
Curved orbit of electrons in magnetic field

Accelerated charge → Electromagnetic radiation
Wavelength continuously tunable!
60‘000 users world-wide
A larger view
The “brightness” of a light source:

\[ \text{Brightness} = \text{constant} \times \frac{F}{S \times \Omega} \]
Steep rise in brightness

10^{21} 10^{15} 10^9

1900 1950 2000

Undulators
Wigglers
Bending magnets
Rotating anode

Bertha Roentgen’s hand (exposure: 20 min)

Moore’s Law for semiconductors

the second wave

SLS
SOLEIL (F)
DIAMOND (UK)

XFEL

ESRF
SPRING8
APS

X-ray sources, ICFA Seminar, SNAL, October 2008, L. Rivkin, PSI & EPFL
Higher brightness: more photons on small sample or through a pinhole of ~ $\lambda$: coherence

- measurements on very small probes (few $\mu$m crystals)
- small divergence:
  - compact mirrors, optics elements
  - minimized aberrations
- short measurement times
- high transverse coherence
  - phase contrast imaging
Microtomography

Brain blood vessels in a mouse with Alzheimer
Demand for beam time remains high

Industrial use is growing

Overbooking of SLS beamlines

- Lucia
- MS
- PX
- SIM
- SIS

Demand for beam time remains high
Industrial use is growing

Overbooking of SLS beamlines

- Lucia
- MS
- PX
- SIM
- SIS

Graph showing overbooking of SLS beamlines from 2003 to 2006.
Undulators

\[ T_{\text{obs}} = T_{\text{emit}} (1 - \beta) \]

\[ \lambda_{\text{light}} \approx \frac{\lambda_u}{2\gamma^2} \]

X-ray sources, ICFA Seminar, SNAL, October 2008, L. Rivkin, PSI & EPFL
Undulator radiation

\[ \lambda = \frac{\lambda_u}{2n\gamma^2} \left( 1 + \frac{K^2}{2} + \gamma^2 \Theta^2 \right) \]

\[
\lambda^* = 2'500 \text{ mm}
\]

\[
\lambda^* = 1.5 \text{ mm}
\]

Medium energy rings

ESRF, APS

K-edges

Visible light

Water window
Main R&D directions

- Short period (small gap) undulator developments
- Approaching diffraction limit: very small equilibrium emittance with large rings and damping wigglers
- Detector development complementing source improvements
- Linac based light sources development: ERLs
- Free electron lasers developments
In-vacuum undulators / s.c. undulators

Gaps down to 3 mm
Cryo–cooled undulators

H. Kitamura, SPring-8

X-ray sources, ICFA Seminar, SNAL, October 2008, L. Rivkin, PSI & EPFL
Third Generation Light Sources in Operation
## Third Generation Light Sources in Operation

<table>
<thead>
<tr>
<th>Light Source</th>
<th>Energy (GeV)</th>
<th>Circumference (m)</th>
<th>Emittance (nm.rad)</th>
<th>Current (mA)</th>
<th>Straight Section</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESRF</td>
<td>6.0</td>
<td>844.4</td>
<td>3.7</td>
<td>200</td>
<td>32×6.3m</td>
<td>Operational (1993)</td>
</tr>
<tr>
<td>APS</td>
<td>7.0</td>
<td>1104</td>
<td>3.0</td>
<td>100</td>
<td>40×6.7m</td>
<td>Operational (1996)</td>
</tr>
<tr>
<td>SPring-8</td>
<td>8.0</td>
<td>1436</td>
<td>2.8</td>
<td>100</td>
<td>44×6.6m, 4×30m</td>
<td>Operational (1997)</td>
</tr>
<tr>
<td>ALS</td>
<td>1.9</td>
<td>196.8</td>
<td>6.3</td>
<td>400</td>
<td>12×6.7m</td>
<td>Operational (1993)</td>
</tr>
<tr>
<td>TLS</td>
<td>1.5</td>
<td>120</td>
<td>25</td>
<td>240</td>
<td>6×6m</td>
<td>Operational (1993)</td>
</tr>
<tr>
<td>ELETTRA</td>
<td>2.0/2.4</td>
<td>259</td>
<td>7</td>
<td>300</td>
<td>12×6.1m</td>
<td>Operational (1994)</td>
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<tr>
<td>PLS</td>
<td>2.5</td>
<td>280.56</td>
<td>10.3</td>
<td>200</td>
<td>12×6.8m</td>
<td>Operational (1995)</td>
</tr>
<tr>
<td>LNLS</td>
<td>1.37</td>
<td>93.2</td>
<td>70</td>
<td>250</td>
<td>6×3m</td>
<td>Operational (1997)</td>
</tr>
<tr>
<td>MAX-II</td>
<td>1.5</td>
<td>90</td>
<td>9.0</td>
<td>200</td>
<td>10×3.2m</td>
<td>Operational (1997)</td>
</tr>
<tr>
<td>BESSY-II</td>
<td>1.7</td>
<td>240</td>
<td>6.1</td>
<td>200</td>
<td>8×5.7m, 8×4.9m</td>
<td>Operational (1999)</td>
</tr>
<tr>
<td>Siberia-II</td>
<td>2.5</td>
<td>124</td>
<td>65</td>
<td>200</td>
<td>12×3m</td>
<td>Operational (1999)</td>
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<tr>
<td>NewSUBARU</td>
<td>1.5</td>
<td>118.7</td>
<td>38</td>
<td>500</td>
<td>2×14m, 4×4m</td>
<td>Operational (2000)</td>
</tr>
<tr>
<td>SLS</td>
<td>2.4-2.7</td>
<td>288</td>
<td>5</td>
<td>400</td>
<td>3×11.7m, 3×7m, 6×4m</td>
<td>Operational (2001)</td>
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<tr>
<td>ANKA</td>
<td>2.5</td>
<td>110.4</td>
<td>50</td>
<td>200</td>
<td>4×5.6m, 4×2.2m</td>
<td>Operational (2002)</td>
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<tr>
<td>CLS</td>
<td>2.9</td>
<td>170.88</td>
<td>18.1</td>
<td>500</td>
<td>12×5.2m</td>
<td>Operational (2003)</td>
</tr>
<tr>
<td>SPEAR-3</td>
<td>3.0</td>
<td>234</td>
<td>12</td>
<td>500</td>
<td>2×7.6m, 4×4.8m, 12×3.1m</td>
<td>Operational (2004)</td>
</tr>
<tr>
<td>SAGA-LS</td>
<td>1.4</td>
<td>75.6</td>
<td>7.5</td>
<td>300</td>
<td>8×2.93m</td>
<td>Operational (2005)</td>
</tr>
</tbody>
</table>
Main R&D directions

- Short period (small gap) undulator developments
- Approaching diffraction limit: very small equilibrium emittance with large rings and damping wigglers
- Detector development complementing source improvements
- Linac based light sources development: ERLs
- Free electron lasers developments
The electron beam "emittance":

\[ \text{Emittance} = S \times \Omega \]

Source area, $S$

Angular divergence, $\Omega$

The brightness depends on the geometry of the source, i.e., on the electron beam emittance.
Ring equilibrium emittance

\[ \sigma'_0 = \sqrt{\sigma'_0^2 + \sigma'_{MS}^2} \]

\[ \sigma'_0 \gg \sigma'_{MS} \]

to minimize the blow up due to multiple scattering in the absorber we can focus the beam

Theoretical Minimum Emittance lattice

\[ \varepsilon_{x0} = \frac{C_q E^2}{J_x} \cdot \theta^3 \cdot F_{latt} \]

\[ F_{\text{min}} = \frac{1}{12\sqrt{15}} \]
Third Generation Light Sources

![Graph showing energy (GeV) vs. emittance (nm.rad) for various third generation light sources, including operational, commissioning, construction, and planned categories.](image-url)
New Synchrotron Radiation Facilities
New Synchrotron Radiation Facilities

NSLS-II

CANDLE

TPS

MAX-IV

Zhentang Zhao

PAC07, Albuquerque, New Mexico, June 25, 2007
New Synchrotron Radiation Facilities

SSRF

SESAME

PETRA-III

ALBA
From PEP–II to PEP–X

Use of damping wigglers as in PETRA III to reach 0.1 nm.rad
Third Generation Light Sources

- ELETTRA
- SLS
- Bessy II
- TSRF
- ALS
- Indus II
- CLS
- Kazakhstan
- TLS
- NewSUBARU
- LNLS
- MAX II
- SAGA LS
- PETRA III
- SPring8
- NSLS II
- ESRF
- APS
- SPEAR3
- ASP, CANDLE
- ALBA
- MAX IV
- ANKA
- SESAME
- Siberia II
- ANKA
- TPS
- Soleil
- Diamond
- PETRA III
- SPring8
- NSLS II
- ESRF
- APS
- SPEAR3
- ASP, CANDLE
- ALBA
- MAX IV
- ANKA
- SESAME
- Siberia II
- ANKA
- TPS
- Soleil
- Diamond

Circumference (m) vs. Energy (GeV)
CERN’s 27 km ‘tunnel with a future’
Top-up injection: key to stability

also Trickle Charge cont. Injection at PEP-II, KEKB
Top-up is key to the source stability

Constant thermal load on:

- Beam line optics
- Accelerator components (BPMs, vacuum chamber…)

Beam lifetime ~7h, not relevant! Injection every 1.5 min

Tunnel Temperature [$^\circ$C] 25 ± 0.03

Beamsizes $\sigma_x \sigma_y$ [$\mu$m]

Vertical emittance $\varepsilon_y \rightarrow 4$ pm-rad; coupling $\varepsilon_y/\varepsilon_x \sim 0.08\%$

Diffraction limit @ 1 Å
Damping Rings beam emittances

![Graph showing emittance measurements for different experiments and designs, including CLIC, ATF, SLC, NSLS II, and ILC. The graph plots horizontal and vertical emittances in micro-radians meters (μrad-m).]
## Top-up Status at routinely operated sources

<table>
<thead>
<tr>
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<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>APS</td>
<td>7</td>
<td>102</td>
<td>3</td>
<td>7GeV Boost.</td>
<td>80 - 100%</td>
<td>±0.4%</td>
<td>Oper. (1996)</td>
<td>Oper. (2001)</td>
</tr>
<tr>
<td>SLS</td>
<td>2.4 (2.7)</td>
<td>400</td>
<td>5</td>
<td>2.7GeV Boost.</td>
<td>90 - 100%</td>
<td>0.3%</td>
<td>Oper. (2001)</td>
<td>Oper. (2001)</td>
</tr>
<tr>
<td>New SUBARU</td>
<td>1 (1.5)</td>
<td>220 (350)</td>
<td>67</td>
<td>1GeV Li.</td>
<td>~80%</td>
<td>0.6%</td>
<td>Oper. (2000)</td>
<td>Oper. (2003)</td>
</tr>
<tr>
<td>SPring-8</td>
<td>8</td>
<td>99.8</td>
<td>3.2</td>
<td>8GeV Boost.</td>
<td>&gt;80%</td>
<td>0.03%</td>
<td>Oper. (1997)</td>
<td>Oper. (2004)</td>
</tr>
<tr>
<td>TLS</td>
<td>1.5</td>
<td>300 (360)</td>
<td>25</td>
<td>1.5GeV Boost.</td>
<td>&gt;70%</td>
<td>±0.2%</td>
<td>Oper. (1993)</td>
<td>Oper. (2005)</td>
</tr>
</tbody>
</table>

H. Ohkuma, JASRI/SPring-8, EPAC08
Top up vs. top off

Which definition?

**top up** *vb.* *(tr., adv.) Brit.*

1. to raise the level of (a liquid, powder, etc.) in (a container), usually bringing it to the brim of the container:
   
   *top up the sugar in those bowls.*

**top off** *vb.*

*(tr., adv.)* to finish or complete, esp. with some decisive action:

*he topped off the affair by committing suicide.*
Protein structure

Part of a Ribosome

Diffraction pattern

N. Ban et al.
Spectacular growth of structural biology

Advent of X-ray SR sources
ESRF, APS, SPring8, etc.
Nobel Prizes in Chemistry to Synchrotron Radiation Work in Protein Crystallography

1997 John E. Walker
Structure of F1-ATPase

2003 Roderick McKinnon
Structure of Cellular Ion Channels

2006 Roger D. Kronberg
Structure of RNA polimerase
Transverse coherence

- High brightness gives coherence
- Wave optics methods for X-rays (all chapters in Born & Wolf)
- Holography

The knee of a spider
Lithographic Performance

- Worldwide highest resolution in photon-based lithography
- Field size: up to 2x2 mm² (Achromatic Talbot)
- High throughput: ~10’000x e-beam
- Quality, reproducibility: enabling industrial operation

**Fundamentals:**
- Stable, coherent source
- Short wavelength (13.5 nm)
- No proximity effect (electron mean free path <1 nm)
Main R&D directions

- Approaching diffraction limit: very small equilibrium emittance with large rings and damping wigglers
- Short period (small gap) undulator developments
- Detector development complementing source improvements
- Linac based light sources development: ERLs
- Free electron lasers developments
X-ray phase contrast imaging

C. David, T. Weitkamp

using a shearing interferometer based on microfabricated silicon diffraction gratings

F. Pfeiffer et al., PRL 94, April 2005

Advantages:
- significantly enhanced contrast compared to conventional "absorption-mode" for light materials
- High potential in medical diagnosis and research

Phase-object example:
100µm and 200µm styrene beads

Tomographic phase reconstruction of a spider

X-ray sources, ICFA Seminar, SNAL, October 2008, L. Rivkin, PSI & EPFL
X-ray Radiography of a fish

conventional Absorption a (+ details c, e, g)

Phase contrast Microscopy b (+ details d, f, h) (F.Pfeiffer)
Into the hospital?
Lensless coherent Scanning Microscopy with hard X-rays

x-ray source

pinhole aperture

sample

Fraunhofer plane

5 µm
Ultrafast X–ray science

„If you want to understand function, study structure“

Francis Crick

- X–ray Free Electron Lasers extend the ultrafast laser techniques to the X–ray domain
- „Seeing“ structures evolving with time as phenomena take place
- FEMTO: Slicing technique at synchrotrons
- Similar technique to reach < 1 fs with XFELs
Ultrafast Sources and Science

X-ray sources:

Current lasers:

Science:

Ultrafast lasers

XFEL’s

Synchrotrons

Laser plasmas

Acoustic phonons

Vibrations (Optical phonons)

Chemistry and Biochem

Electron dynamics

Strings, Cosmology

Particle Collisions

harpo $10^{-27}$

yocto $10^{-24}$

zepto $10^{-21}$

atto $10^{-18}$

femto $10^{-15}$

pico $10^{-12}$
nano $10^{-9}$

micro $10^{-6}$

milli $10^{-3}$

J. Hastings

X-ray sources, ICFA Seminar, SNAL, October 2008, L. Rivkin, PSI & EPFL
Laser slicing
Pioneering ideas and experiments at ALS
Facilities at ALS, BESSYII, SLS
Dynamics on atomic scale visible with ultra-short X-ray pulses

FEMTO

First optical experiment with atomic resolution:

Amplification and damping of lattice vibrations

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Energy Recovery Linac Schematic

Single pass: emittance and energy spread are determined by injector, can be much smaller than in storage ring.

Ch. Sinclair, Cornell
Main R&D directions

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COHERENT EMISSION BY THE ELECTRONS

Intensity $\propto N$

Intensity $\propto N^2$

INCOHERENT EMISSION

COHERENT EMISSION
MUCH HIGHER BRIGHTNESS CAN BE REACHED WHEN THE ELECTRONS COOPERATE

INCOHERENT EMISSION

COHERENT EMISSION
From rings to linear accelerators

- The number of beamlines served simultaneously
- The stability of the rings based sources
- High average brightness
  - Fewer beamlines
  - Very short pulses, single shot measurements
  - High peak brightness
X-FEL facilities

USA
LCLS – SLAC 2009

Japan
SCSS – SPring8 2010

European XFEL
DESY 2013
# Expected Fluctuations of LCLS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Origin*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse intensity fluctuation</td>
<td>~ 30 %</td>
<td>Varying # of FEL producing SASE spikes; 100% intensity fluctuation/per-spke; etc.</td>
</tr>
<tr>
<td>Position &amp; pointing jitter (x, y, α, β)</td>
<td>~ 25 % of beam diameter&lt;br&gt;~ 25 % of beam divergence</td>
<td>Varying trajectory per pulse; Saturation at different locations of β-tron curvature</td>
</tr>
<tr>
<td>Source point jitter (z)</td>
<td>~ 5 m</td>
<td>SASE process reaching saturation at different z-points in undulator</td>
</tr>
<tr>
<td>X-ray pulse timing (arrival time) jitter</td>
<td>~ 1 ps FWHM</td>
<td>Timing jitter btw injection laser and RF; Varying e-energy per-pulse</td>
</tr>
<tr>
<td>X-ray pulse width variation</td>
<td>~ 15 %</td>
<td>Varying e-energy leading to varying path (compression) in bunch compressors</td>
</tr>
<tr>
<td>Center wavelength variation</td>
<td>~ 0.2 % (comparable to FEL bandwidth)</td>
<td>Varying e-energy leading to varying FEL fundamental wavelength and higher order</td>
</tr>
</tbody>
</table>
FELs and ERLs COMPLEMENT the Ring sources

Peak Brightness

$10^{15}$

$10^{25}$

$10^{35}$

Pulse duration

10 ps

100 fs

1 fs

X-ray FELs

3G rings

2G rings

Slicing

ERLs

After H.-D. Nuhn, H. Winick
Structure determination of single molecules before the Coulomb explosion

Peak brightness of the FELs

photons per phase-space volume per bandwidth

~10⁹ photons per phase-space volume per band-width

10⁶ by FEL gain

10³ by e⁻ quality, long undulators

courtesy T. Shintake
Main R&D directions

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Hybrid-Pixel Technology

Si-sensor with pixelated pn-diode structure

Indium bump-bonding technology
18um bumps

CMOS chip technology,

Direct Detection of X-rays
Single Photon Counting
Frame rate ~ 1 kHz

X-rays

X-ray sources, ICFA Seminar, SNAL, October 2008, L. Rivkin, PSI & EPFL
Cutting-edge 2D pixel detectors

Spin-off company from PSI
C. Brönnimann, et al
Further reading
Summary

- Strong growth in ring based supply continues
- Complementary laser–like X–ray sources for atomic resolution studies: lots of learning to do
- Linac based sources for ultra–fast X–ray science
- Detector development is crucial
- Sample damage: a problem looking for a solution