X-RAY SOURCES

Lenny Rivkin
Ecole Polytechnique Federale de Lausanne (EPFL)
and Paul Scherrer Institute (PSI), Switzerland

Introduction to Accelerator Physics Course
CERN Accelerator School, Frascati, Italy
2 – 14 November 2008
Curved orbit of electrons in magnetic field

Accelerated charge → Electromagnetic radiation
Wavelength continuously tunable!
The Scale of Things – Nanometers and More

**Things Natural**

- **Ant** ~ 5 mm
- **Dust mite** ~ 200 μm
- **Human hair** ~ 60-120 μm wide
- **Red blood cells** (~7-8 μm)
- **DNA** ~ 2-1/2 nm diameter
- **Atoms of silicon** spacing ~tenths of nm
- **ATP synthase** ~10 nm diameter
- **Quantum corral of 48 iron atoms on copper surface** positioned one at a time with an STM tip

**Microworld**

- **10^{-2} m**
- **10^{-3} m**
- **10^{-4} m**
- **10^{-5} m**
- **10^{-6} m**
- **10^{-7} m**
- **10^{-8} m**
- **10^{-9} m**
- **10^{-10} m**

**Nanoworld**

- **10^{-10} m**
- **10^{-11} m**
- **10^{-12} m**
- **10^{-13} m**
- **10^{-14} m**

**The Challenge**

Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.

**Things Manmade**

- **Head of a pin** 1-2 mm
- **MicroElectroMechanical (MEMS) devices** 10 -100 μm wide
- **Zone plate x-ray “lens”** Outer ring spacing ~35 nm
- **Self-assembled, Nature-inspired structure** Many 10s of nm
- **Nanotube electrode**
- **Carbon buckyball** ~1 nm diameter
- **Carbon nanotube** ~1.3 nm diameter

**Micrometer (μm)**

- **1000 nanometers = 1 millimeter (mm)**
- **10 μm = 0.1 mm**
- **100 μm = 0.1 mm**
- **1 μm = 0.001 mm**
- **100 nm = 0.1 μm**
- **1 nm = 0.001 μm**

**Nanometers**

- **100,000,000 nanometers = 1 kilometer (km)**
- **1000 nanometers = 1 millimeter (mm)**
- **100 nm = 0.1 μm**
- **10 μm = 0.1 mm**
- **1 μm = 0.001 mm**
- **100 nm = 0.001 μm**
- **1 nm = 0.000001 μm**
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

Bertha Roentgen’s hand
(exposure: 20 min)

1900       1950        2000

Unfolding X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008
Higher brightness: more photons on small sample or through a pinhole of $\sim \lambda$: 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
3 types of storage ring sources:

1. Bending magnets: \( B \sim N_e \)

- Short signal pulse
- Broad hv-band

Diagram showing the time and frequency aspects with a detector.
3 types of storage ring sources:

2. Wigglers: 

- Large undulations

\[ B \sim N_e N_w \times 10 \]

Series of short pulses

Broad hv-band

Time

Frequency
3 types of storage ring sources:

3. Undulators:

- Small undulations
- Detector continuously illuminated

\[ B \sim N_e N^2 u \times 10^3 \]

- Long signal pulse
- Narrow hv-band

\[ \frac{h\nu}{\Delta h\nu} \approx N \]
Anatomy of a light source

Linac 100 MeV

Booster 2.7 GeV

Storage Ring

Undulators

Beam lines
About 60 ring sources world-wide
Microtomography

Brain blood vessels in a mouse with Alzheimer

X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008
Undulators

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

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

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

\[ \lambda^* = \frac{1}{2} \frac{K^2}{\lambda_u} \lambda \]

Medium energy rings

ESRF, APS

IR-FEL

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

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

Permanent magnet materials: SmCo$_5$, NdFeB

e.g. a pencil made of such material corresponds to 15‘000 A-turns!

Hybrid undulator:
permanent magnets and iron
Field tuning with gap

\[
B \approx 1.8 \cdot B_r \cdot e^{-\pi \cdot \frac{\text{gap}}{\lambda_u}}
\]

<table>
<thead>
<tr>
<th>Permanent magnet material</th>
<th>Remanent field [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SmCo₅</td>
<td>0.9 – 1.0</td>
</tr>
<tr>
<td>Sm₂Co₁₇</td>
<td>1.0 – 1.1</td>
</tr>
<tr>
<td>NdFeB</td>
<td>1.0 – 1.4</td>
</tr>
</tbody>
</table>

X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008
In-vacuum undulators / s.c. undulators

Gaps down to 3 mm
Selection of wavelength in an undulator

In an undulator an electron (on a slalom) races an emitted photon at A an electron emits a photon with wavelength $\lambda$ and flies one period $\lambda_u$ ahead to B with velocity $v = \beta c$. There it emits another photon with the same wavelength $\lambda$. At this moment the first photon is already at C. If the path difference $\delta L$ corresponds to $n$ wavelengths, then we have a positive interference between the two photons. This enhances the intensity at this wavelength.

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X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008
Selection of wavelength in an undulator II

<table>
<thead>
<tr>
<th>N</th>
<th>S</th>
<th>N(orth)</th>
<th>S(outh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>

period $\lambda_u$

$\delta L = n \lambda$

electron $v \equiv \beta c$

photon $c$

The path difference $\delta L \equiv n \lambda \approx (1 - \beta) \lambda_u$, $1 - \beta \approx \frac{1}{2 \gamma^2}$

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

detour through slalom

$K = 0.0934 \cdot \lambda_u \ [mm] \cdot B \ [T]$

X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008
Undulator of infinite length

Finite length undulator

- radiation pulse has as many periods as the undulator
- the line width is

Due to the electron energy spread

\[ N_u = \infty \Rightarrow \frac{\Delta \lambda}{\lambda} = 0 \]

\[ \frac{\Delta \lambda}{\lambda} \sim \frac{1}{N_u} \]

\[ \frac{\Delta \lambda}{\lambda} = 2\frac{\sigma_E}{E} \]
Undulator based sources

**Brightness**

\[ B = \frac{N_{ph}}{\Delta t} \cdot \frac{1}{\Delta S \cdot \Delta \Omega} \cdot \frac{1}{\Delta \nu_{\lambda}} \]

**Flux** \[ N_{ph} \propto N_u \] (periods)

The line width \[ \frac{\Delta \lambda}{\lambda} \sim \frac{1}{N_u} \] if \[ \frac{1}{N_u} > 2\pi \cdot \frac{\sigma_E}{E} \]

If energy spread is small enough \[ B \sim N_u^2 \]
Radiation cone of an undulator

Undulator radiates from the whole length $L$ into a narrow cone.

Propagation of the wave front $BC$ is suppressed under an angle $\theta_0$, if the path length $AC$ is just shorter by a half wavelength compared to $AB$ (negative interference). This defines the central cone.

$$\Delta L = AB - AC = \frac{1}{2}L(1 - \cos \theta_0) \approx \frac{1}{4}L\theta_0^2$$

$$\theta_0 = \sqrt{\frac{2\lambda}{L}} \quad \text{and} \quad R_0 = \sqrt{\frac{\lambda \cdot L}{2}}$$

$$\epsilon_0 = \theta_0 R_0 = \lambda$$

Negative interference for $\Delta L = \frac{\lambda}{2}$

X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008
WHAT DO USERS EXPECT FROM A HIGH PERFORMANCE LIGHT SOURCE?

- PROPER PHOTON ENERGY FOR THEIR EXPERIMENTS
- BRILLIANCE
- STABILITY

\[ Σ^2 = σ_e^2 + σ_γ^2 \]

\[ Σ_x Σ_{x'} ≈ σ_x σ'_x ∼ ε_x \]

\[ σ_γ = \frac{\lambda}{\sqrt{L}} \]

\[ Φ = \frac{B}{(2π)^2 Σ_x Σ_{x'} Σ_y Σ_{y'}} \]

**FIGURE OF MERIT**

**Photon beam size (U):**
Undulator radiation from 6 GeV beam with zero emittance, energy spread (example ESRF)

Emittance 4 nm·rad, 1% coupling, finite energy spread
Third Generation Light Sources in Operation

Zhentang Zhao

PAC07, Albuquerque, New Mexico, June 25, 2007
### 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>
</tr>
<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>
</tr>
<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>
</tr>
<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>
</tr>
<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>
The electron beam “emittance”:

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

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

Betatron oscillations

- Particles in the beam execute betatron oscillations with different amplitudes.

Transverse beam distribution

- Gaussian (electrons)
- “Typical” particle: $1 - \sigma$ ellipse
  (in a place where $\alpha = \beta' = 0$)

Emittance $\equiv \frac{\sigma_x^2}{\beta}$

Area $= \pi \cdot \varepsilon$

Units of $\varepsilon$ [m \cdot rad]

$\varepsilon = \sigma_x \cdot \sigma_{x'}$

$\sigma_x = \sqrt{\varepsilon} \beta$

$\sigma_{x'} = \sqrt{\varepsilon} / \beta$

$\beta = \frac{\sigma_x}{\sigma_{x'}}$
FODO Lattice emittance

\[ \varepsilon \propto \frac{1}{Q^3} \]

\[
\varepsilon \propto \frac{E^2}{J_x} \theta^3 F_{FODO}(\mu)
\]

Emittance

Phase advance per cell [degrees]
Small emittance lattices

Equilibrium horizontal emittance

\[ \varepsilon_{x0} \equiv \frac{\sigma_{x\beta}^2}{\beta} = \frac{C q E^2}{J_x} \cdot \langle \mathcal{H} \rangle_{\text{mag}} \rho \]

- one tries to optimize the \( \mathcal{H} \) function in bending magnets

\[ \mathcal{H} = \gamma D^2 + 2\alpha DD' + \beta D'^2 \]

- the equilibrium emittance can be written as:

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

\[ F_{\text{min}} = \frac{1}{12\sqrt{15}} \]

there exists a minimum

\[ \beta^* = \frac{L}{2\sqrt{15}}, \quad D^* = \frac{L \theta}{24} \]

\[ \alpha = D' = 0 \]

\[ \beta \]

\[ \alpha = D' = 0 \]

\[ \beta \]

\[ \alpha = D' = 0 \]

\[ \beta \]
Theoretical minimum emittance
Ring equilibrium emittance

\[ \sigma_0 \]
\[ \sigma'_0 \]
\[ \sigma' = \sqrt{\sigma'_0^2 + \sigma'_{\text{MS}}^2} \]
\[ \sigma'_0 >> \sigma'_{\text{MS}} \]

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

Theoretical Minimum Emittance lattice

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

\[ F_{\text{min}} = \frac{1}{12\sqrt{15}} \]
Low emittance lattice examples

Double Bend TME

Triple Bend TME
Third Generation Light Sources

Zhentang Zhao

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

Diamond

Indus-2

SOLEIL

ASP

Zhentang Zhao

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

NSLS-II

CANDLE

TPS

MAX-IV

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

SSRF

SESAME

PETRA-III

ALBA

Zhentang Zhao

PAC07, Albuquerque, New Mexico, June 25, 2007
From PEP–II to PEP–X

Use of damping wigglers as in PETRA III to reach 0.1 nm.rad
CERN’s 27 km ‘tunnel with a future’
Top-up injection: key to stability

also Trickle Charge cont. Injection at PEP-II, KEKB

X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008
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 [°C] 25 ± 0.03

Beamsizes $\sigma_x \, \sigma_y$ [µm]

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

Diffraction limit @ 1 Å

X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008
Damping Rings beam emittances

Horizontal Emittance ($\mu$rad-m)

Vertical Emittance ($\mu$rad-m)
APPLICATIONS

e.g. Protein Crystallography
Protein structure

Diffraction pattern

Part of a Ribosome

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Spectacular growth of structural biology

Advent of X-ray SR sources
ESRF, APS, SPring8, etc.

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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

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Transverse coherence

- High brightness gives coherence

- Wave optics methods for X-rays (all chapters in Born & Wolf)

- Holography
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)

J. Gobrecht, SLS-SAC Meeting, 11 July 07
**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

*Tomographic phase reconstruction of a spider*

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

*X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008*
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?

absorption

17.5 keV, synchrotron results

phase contrast

(C. David, F. Pfeiffer)
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:
- Synchrotrons
- Laser plasmas
- XFEL’s

Current lasers:
- Ultrafast lasers

Science:
- Electron dynamics
- Acoustic phonons
- Vibrations (Optical phonons)
- Chemistry and Biochem
- Strings, Cosmology
- Particle Collisions

Time scales:
- 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

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Muybridge and Stanford disagree whether all feet leave the ground at one time during the gallop…

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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Fast processes and short pulses

Laser pump / X-ray probe
Energy Recovery Linac Schematic

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

M Tigner, Cornell
FREE ELECTRON LASERS
Take a standard photon source with limited brightness and no lateral coherence …

… with a pinhole (size $\xi$), we can extract coherent light with good geometrical characteristics (at the cost of losing most of the emission)

However, if the pinhole size is too small, diffraction effects increase the beam divergence so that:

$$\xi \cdot \theta > \lambda$$

No source geometry beats this diffraction limit
PERFORMANCE OF 3rd GENERATION LIGHT SOURCES

BRIGHTNESS:

PHOTON ENERGY [eV]
## BRIGHTNESS OF SYNCHROTRON RADIATION

<table>
<thead>
<tr>
<th>Device</th>
<th>Electrons</th>
<th>Periods</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending magnet</td>
<td>$\sim N_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wiggler</td>
<td>$\sim N_e$</td>
<td>$\sim N$</td>
<td>10</td>
</tr>
<tr>
<td>Undulator</td>
<td>$\sim N_e$</td>
<td>$\sim N^2$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>FEL</td>
<td>$\sim N_{\mu-b}^2$</td>
<td>$\sim N^2$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>Superradiance</td>
<td>$\sim N_e^2$</td>
<td>$\sim N^2$</td>
<td>$10^{12}$</td>
</tr>
</tbody>
</table>
COHERENT EMISSION BY THE ELECTRONS

Intensity ∝ N

Intensity ∝ N^2

INCOHERENT EMISSION

COHERENT EMISSION
FIRST DEMONSTRATIONS OF COHERENT EMISSION (1989-1990)

T. Nakazato et al., Tohoku University, Japan
J. Ohkuma et al., Osaka University, Japan

180 MeV electrons
T. Nakazato et al., Tohoku University, Japan

30 MeV electrons
J. Ohkuma et al., Osaka University, Japan

Fig. 4. Dependence of SR intensity on the beam current at \( \lambda = 400 \, \mu \text{m} \) and \( \lambda = 520 \, \text{nm} \) for the long pulse/short bunch beam. The ordinate is given on the left-hand side for \( \lambda = 400 \, \mu \text{m} \) and on the right for \( \lambda = 520 \, \text{nm} \). The two lines show the linear and quadratic relations to the beam current. The beam current is converted to the average number of electrons in a bunch on the upper side.

FIG. 3. The intensity of the CR measured for the bandwidths indicated with horizontal bars, the spectrum calculated according to Eq. (1) for 10% bandwidth (solid line), and the intensity expected for the complete coherence over the bunch for 10% bandwidth (open circle).
MUCH HIGHER BRIGHTNESS CAN BE REACHED WHEN THE ELECTRONS COOPERATE

INCOHERENT EMISSION

COHERENT EMISSION

WAVELENGTH
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
Free Electron Laser Keywords:

- Linac driven, single-pass
  (no optics for cavity mirrors)

SASE
(Self Amplified Spontaneous Emission)
i.e., startup from noise

R. Bakker
THE ELECTRON BEAM SHOULD BE ~ 1 Å AS SMALL AS THE X-RAY WAVELENGTH!
X-FEL facilities

European XFEL
DESY 2013

Japan
SCSS – SPring8 2010

USA
LCLS – SLAC 2009

X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008
Microbunching through SASE Process

**GENESIS** - simulation for TTF parameters

Courtesy - Sven Reiche (PSI)
FLASH: Free Electron LASer in Hamburg

4 MeV 130 MeV 380 MeV 450…800 MeV

250 m

X-Ray Sources, L. Rivkin, EPFL & PSI, Frascati, November 2008
FELs and ERLs COMPLEMENT the Ring sources

X-ray FELs

H.-D. Nuhn, H. Winick

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

Peak brightness of the FELs

- Peak brightness is a measure of the number of photons emitted per unit phase-space volume per bandwidth.
- At 1 Å, the peak brightness is approximately $10^9$ photons per $10^3$ electrons, due to FEL gain and long undulators.
- Courtesy T. Shintake.
END