Spatial and Temporal Coherence; Coherent Undulator Radiation

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(http://www.coe.berkeley.edu/AST/srms)
\[ l_{\text{coh}} = \frac{\lambda^2}{2\Delta\lambda} \{\text{temporal (longitudinal) coherence}\} \quad (8.3) \]

\[ d \cdot \theta = \frac{\lambda}{2\pi} \{\text{spatial (transverse) coherence}\} \quad (8.5) \]

or \[ d \cdot 2\theta|_{\text{FWHM}} = 0.44 \lambda \quad (8.5^*) \]

\[ P_{\text{coh}} = \frac{\lambda^2}{2\pi^2} \left(\frac{\lambda}{d_{x}\theta_{x}}\right)^2 \left(\frac{\lambda}{d_{y}\theta_{y}}\right)^2 P_{\text{laser}} \quad (8.11) \]
Young’s Double Slit Experiment: Spatial Coherence and the Persistence of Fringes

Persistence of fringes as the source grows from a point source to finite size.

\[ \lambda_{\text{coh}} = \frac{\lambda^2}{2\Delta\lambda} = \frac{1}{2} N_{\text{coh}}\lambda \]

\[ d \cdot 2\theta_{\text{FWHM}} \approx \frac{\lambda}{2} \]
Spatial and Spectral Filtering to Produce Coherent Radiation

Courtesy of A. Schawlow, Stanford.
Coherence, Partial Coherence, and Incoherence

Point source oscillator
\(-\infty < t < \infty\)

Source of finite size, divergence, and duration
Mutual coherence factor

\[ \Gamma_{12}(\tau) \equiv \langle E_1(t + \tau)E_2^*(t) \rangle \]  

(8.1)

Normalize degree of spatial coherence (complex coherence factor)

\[ \mu_{12} = \frac{\langle E_1(t)E_2^*(t) \rangle}{\sqrt{\langle |E_1|^2 \rangle \langle |E_2|^2 \rangle}} \]  

(8.12)

A high degree of coherence (\( \mu \to 1 \)) implies an ability to form a high contrast interference (fringe) pattern. A low degree of coherence (\( \mu \to 0 \)) implies an absence of interference, except with great care. In general radiation is partially coherent.

Longitudinal (temporal) coherence length

\[ \ell_{\text{coh}} = \frac{\lambda^2}{2 \Delta \lambda} \]  

(8.3)

Full spatial (transverse) coherence

\[ d \cdot \theta = \frac{\lambda}{2\pi} \]  

(8.5)
Define a coherence length $\ell_{\text{coh}}$ as the distance of propagation over which radiation of spectral width $\Delta\lambda$ becomes $180^\circ$ out of phase. For a wavelength $\lambda$ propagating through $N$ cycles

$$\ell_{\text{coh}} = N\lambda$$

and for a wavelength $\lambda + \Delta\lambda$, a half cycle less $(N - \frac{1}{2})$

$$\ell_{\text{coh}} = (N - \frac{1}{2})(\lambda + \Delta\lambda)$$

Equating the two

$$N = \frac{\lambda}{2\Delta\lambda}$$

so that

$$\ell_{\text{coh}} = \frac{\lambda^2}{2\Delta\lambda}$$

(8.3)
• Associate spatial coherence with a spherical wavefront.
• A spherical wavefront implies a point source.
• How small is a “point source”?

From Heisenberg’s Uncertainty Principle ($\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$), the smallest source size “$d$” you can resolve, with wavelength $\lambda$ and half angle $\theta$, is

$$d \cdot \theta = \frac{\lambda}{2\pi}$$
Partially Coherent Radiation Approaches
Uncertainty Principle Limits

\[ \Delta x \cdot \Delta p \geq \hbar / 2 \quad (8.4) \]

\[ \Delta x \cdot \hbar \Delta k \geq \hbar / 2 \]

\[ \Delta x \cdot k \Delta \theta \geq 1/2 \]

\[ 2\Delta x \cdot \Delta \theta \geq \lambda / 2\pi \]

\[ d = 2\Delta x \]

Spherical wavefronts occur in the limiting case

\[ d \cdot \theta = \lambda / 2\pi \]

(spatially coherent)

or

\[ (d \cdot 2\theta)_{\text{FWHM}} \approx \lambda / 2 \]

FWHM quantities

Note:

\[ \Delta p = \hbar \Delta k \]

\[ \Delta k = k \Delta \theta \]

Standard deviations of Gaussian distributed functions

(Tipler, 1978, pp. 174-189)

Professor David Attwood
Univ. California, Berkeley
Propagation of a Gaussian Beam

For a spherical wave propagating with a Gaussian intensity distribution, \( I/I_0 = \exp(-r^2/2r_0) \), where \( r_0 \) is the \( 1/\sqrt{e} \) waist radius at the origin (\( z = 0 \)), the intensity distribution grows with a \( 1/\sqrt{e} \) radius given by (Siegman, Lasers)

\[
r(z) = r_0 \sqrt{1 + \left( \frac{\lambda z}{4\pi r_0^2} \right)^2}
\]

In the far field, where \( z \gg 4\pi r_0^2/\lambda \), the \( 1/\sqrt{e} \) divergence half angle is

\[
\theta \equiv \frac{r(z)}{z} = \frac{\lambda}{4\pi r_0}
\]

with waist diameter \( d = 2r_0 \), we have TEM\(_{00}\) radiation with \( d \cdot \theta = \lambda/2\pi \).
Spatially Coherent Undulator Radiation

\[ \lambda = 11.2 \text{ nm} \]

\[ \lambda = 13.4 \text{ nm} \]

1 \( \mu \text{m} \) pinhole

25 mm wide CCD at 410 mm

Courtesy of Patrick Naulleau, LBNL.
Spatial Filtering of Undulator Radiation

Undulator central radiation cone \( \left( \frac{\lambda}{\Delta \lambda} = N ; \theta = \frac{1}{\gamma^*/N} \right) \):

\[
\bar{P}_{\text{cen}} = \frac{\pi e \gamma^2 I}{\epsilon_0 \lambda_u} \frac{K^2}{(1 + K^2/2)^2} f(K) \quad (5.41a)
\]

With spatial filtering (a pinhole and an angular aperture):

\[
\bar{P}_{\text{coh},N} = \left( \frac{\lambda/2\pi}{d_x \theta_x} \right) \left( \frac{\lambda/2\pi}{d_y \theta_y} \right) \bar{P}_{\text{cen}} \quad (8.6)
\]

With eq.(5.28), \( \lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right) \). Convert to photon energies where for \( \theta = 0 \), \( \hbar \omega = \frac{\hbar \omega_0}{1 + K^2/2} \), and where \( \hbar \omega_0 \equiv 4\pi \hbar c \gamma^2 / \lambda_u \) corresponds to \( K = 0 \). For small electron beam divergence, \( \sigma_{x,y}^2 \ll \theta_{\text{cen}}^2 \), the spatially coherent power is

\[
\bar{P}_{\text{coh},N} = \frac{e \lambda_u I N}{8\pi \epsilon_0 d_x d_y} \left( 1 - \frac{\hbar \omega}{\hbar \omega_0} \right) f(\hbar \omega / \hbar \omega_0) \quad (8.9)
\]
Using a pinhole-aperture spatial filter, passing only radiation that satisfies \( d \cdot \theta = \lambda/2\pi \)

\[
\bar{P}_{\text{coh},N} = \left(\frac{\lambda/2\pi}{d_x\theta_x}\right) \left(\frac{\lambda/2\pi}{d_y\theta_y}\right) \bar{P}_{\text{cen}}
\]  

(8.6)

\[
\bar{P}_{\text{coh},N} = \frac{e\lambda_u I N}{8\pi \epsilon_0 d_x d_y} \left(1 - \frac{\hbar \omega}{\hbar \omega_0}\right) f(\hbar \omega/\hbar \omega_0)
\]  

(8.9)

for \( d_x = 2\sigma_X, d_y = 2\sigma_Y, \theta_{TX} \rightarrow \theta_X, \theta_{TY} \rightarrow \theta_Y \), and \( \sigma'^2 \ll \theta_{\text{cen}}^2 \).
Spatial and Spectral Filtering of Undulator Radiation

In addition to the pinhole – angular aperture for spatial filtering and spatial coherence, add a monochromator for narrowed bandwidth and increased temporal coherence:

\[
\bar{P}_{\text{coh},\lambda/\Delta \lambda} = \frac{\eta}{N} \left( \frac{\lambda}{2\pi} \right)^2 \frac{\Delta \lambda}{\lambda} \cdot \bar{P}_{\text{cen}} \tag{8.10a}
\]

which for \( \sigma'_{x,y}^2 \ll \theta_{\text{cen}}^2 \) (the undulator condition) gives the spatially and temporally coherent power \( (d \cdot \theta = \lambda/2\pi ; \ l_{\text{coh}} = \frac{\lambda^2}{2 \Delta \lambda}) \)

\[
\bar{P}_{\text{coh},\lambda/\Delta \lambda} = \frac{e \lambda_u I \eta \left( \frac{\Delta \lambda}{\lambda} \right) N^2}{8\pi \epsilon_0 d_x d_y} \cdot \left( 1 - \frac{\hbar \omega}{\hbar \omega_0} \right) f(\hbar \omega / \hbar \omega_0) \tag{8.10c}
\]

which we note scales as \( N^2 \).
• Pinhole filtering for full spatial coherence
• Monochromator for spectral filtering to $\lambda/\Delta\lambda > N$

$$P_{\text{coh, } \lambda/\Delta\lambda} = \frac{\eta}{(d_x \theta_x)(d_y \theta_y)} \cdot \frac{N \Delta\lambda}{\lambda} \cdot \bar{P}_{\text{cen}}$$ (8.10a)

$$P_{\text{coh, } \lambda/\Delta\lambda} = \frac{e \lambda_n I \eta (\Delta\lambda/\lambda) N^2}{8\pi \varepsilon_0 d_x d_y} \cdot \left(1 - \frac{\hbar \omega}{\hbar \omega_0} \right) f(\hbar \omega/\hbar \omega_0)$$ (8.10c)
Coherent Soft X-Ray Beamline: Use of a Higher Harmonic (n = 3) to Access Shorter Wavelengths

8.0 cm period, N = 55
1.9 GeV, 400 mA
d \cdot \theta = \lambda/2\pi
\ell_{coh} = 1000 \lambda/2
\eta_{euv} = 10\%, \eta_{sxr} = 10\%

Coherent Power with a Monochromator

\[ \frac{\lambda}{\Delta\lambda} = 10^3 \]

Tuning curves

Coherent Soft X-ray End Station
Coherent Power at the ALS

**U8**

1.9 GeV, 400 mA

\[ \lambda_u = 80 \text{ mm}, \ N = 55 \]

\[ 0.5 \leq K \leq 4.0 \]

\[ \sigma_x = 260 \mu\text{m}, \ \sigma_x' = 23 \mu\text{r} \]

\[ \sigma_y = 16 \mu\text{m}, \ \sigma_y' = 3.9 \mu\text{r} \]
1.9 GeV, 400 mA
\[ \lambda_u = 50 \text{ mm}, \quad N = 89 \]
\[ 0.5 \leq K \leq 4.0 \]
\[ \sigma_x = 260 \mu\text{m}, \quad \sigma_x' = 23 \mu\text{r} \]
\[ \sigma_y = 16 \mu\text{m}, \quad \sigma_y' = 3.9 \mu\text{r} \]
\[ \eta = 10\% \]
Coherent Power for an EPU at the ALS

U5 EPU

1.9 GeV, 400 mA

$\lambda_u = 50$ mm, $N = 27$

$0.5 \leq K \leq 4.0$

$\sigma_x = 260$ µm, $\sigma_x' = 23$ µr

$\sigma_y = 16$ µm, $\sigma_y' = 3.9$ µr

$\theta_{cen} = 61$ µr @ $K = 0.87$ (500 eV)
3.0 GeV, 500 mA
$\lambda_u = 3.3 \text{ cm}, N = 105$
$0 \leq K \leq 2.2$
$\sigma_x = 436 \mu\text{m}, \sigma_x' = 43 \mu\text{rad}$
$\sigma_y = 30 \mu\text{m}, \sigma_y' = 6.3 \mu\text{rad}$
$\theta_{cen} = 17 \mu\text{rad} @ K = 1$
$\eta = 10\%$
Coherent Power at the Australian Synchrotron

3.0 GeV, 200 mA
\( \lambda_u = 22 \text{ mm}, N = 80 \)
\( 0 \leq K \leq 1.8 \)
\( \sigma_x = 320 \text{ µm}, \sigma_x' = 34 \text{ µrad} \)
\( \sigma_y = 16 \text{ µm}, \sigma_y' = 6 \text{ µrad} \)
\( \theta_{cen} = 23 \text{ µrad} @ K = 1 \)
\( \eta = 10\% \)
Coherent Power at the UK’s Diamond Synchrotron Facility

3.0 GeV, 300 mA
\( \lambda_u = 2.4 \, \text{cm}, \, N = 82 \)
\( 0 \leq K \leq 1.4 \)
\( \sigma_x = 123 \, \mu\text{m}, \, \sigma_x' = 24 \, \mu\text{r} \)
\( \sigma_y = 6.4 \, \mu\text{m}, \, \sigma_y' = 4.2 \, \mu\text{r} \)
\( \theta_{\text{cen}} = 23 \, \mu\text{r} \, @ \, K = 1 \)
\( \eta = 10\% \)

Courtesy of Brian Kennedy (King’s College London), Susan Smith (Daresbury), and Yanwei Liu (LBNL)
Coherent Power at the APS

**APS**

- Photon Energy (eV) vs. $P_{\text{cen}}$ (W)
  - $P_{\text{cen}}$ vs. Photon Energy (eV) for $n = 1$ and $n = 3$
  - $P_{\text{coh, N}}$ (mW) vs. Photon Energy (eV) for $n = 1$ and $n = 3$
  - $\frac{\lambda}{\Delta \lambda} = 72$
  - $\frac{\lambda}{\Delta \lambda} = 10^3$

- 7.00 GeV, 100 mA
- $\lambda_u = 33$ mm, $N = 72$
- $0.5 \leq K \leq 3.0$
- $\sigma_x = 320$ µm, $\sigma_x' = 23$ µm
- $\sigma_y = 50$ µm, $\sigma_y' = 7$ µm
- $\eta = 10\%$
Coherent Power at SPring-8

8 GeV, 100 mA
\( \lambda_u = 32 \text{ mm}, N = 140 \)
\( 0 \leq K \leq 2.46 \)
\( \sigma_x = 393 \mu \text{m}, \sigma_x' = 15.7 \mu \text{r} \)
\( \sigma_y = 4.98 \mu \text{m}, \sigma_y' = 1.24 \mu \text{r} \)
\( \eta = 10\% \)
Spatially Coherent Undulator Radiation

\[ \lambda = 11.2 \text{ nm} \]

\[ \lambda = 13.4 \text{ nm} \]

1 \( \mu \text{m} \) pinhole

25 mm wide CCD at 410 mm

Courtesy of Patrick Naulleau, LBNL.
Undulator Beamline for High Spatial Coherence Measurements

C. Chang

CCD

Two pinhole mask

Professor David Attwood
Univ. California, Berkeley
Spatial Coherence Measurements of Undulator Radiation Using the Classic 2-Pinhole Technique

Courtesy of Chang Chang, UC Berkeley and LBNL.

$\lambda = 13.4$ nm, 450 nm diameter pinholes, 1024 x 1024 EUV/CCD at 26 cm ALS, 1.9 GeV, $\lambda_u = 8$ cm, $N = 55$
\( \lambda = 13.4 \text{ nm}, 450 \text{ nm diameter pinholes, } 1024 \times 1024 \text{ EUV/CCD at } 26 \text{ cm ALS, } 1.9 \text{ GeV, } \lambda_u = 8 \text{ cm, } N = 55 \)
Spatial Coherence Measurements in the Vertical Plane

\[ \lambda = 13.4 \text{ nm}, \ 450 \text{ nm diameter pinholes, } 1024 \times 1024 \text{ EUV/CCD at } 26 \text{ cm ALS, } 1.9 \text{ GeV, } \lambda_u = 8 \text{ cm, } N = 55 \]

Courtesy of Chang Chang, UC Berkeley and LBNL.
Coherent Undulator Radiation is Used for Interferometric Testing of Multilayer Coated Optics for EUV Lithography

Null test interferogram

σ = 0.044 nm rms = χ_{euv}/300

Interferogram

Wavefront

σ = 0.52 nm rms = χ_{euv}/26

Reference wavefront

−0.25 nm

1.39 nm

−2.82 nm

Courtesy of K. Goldberg, P. Naulleau, J. Bokor, et al., LBNL.
EUV Interferometry of Projection Optics

From undulator beamline
K-B pre-focusing mirrors
Turning mirror
Object stage pinhole array
Grating beam splitter
Spatially coherent EUV radiation
Planar Bearing stage
Image stage pinhole array
EUV CCD

Courtesy of K. Goldberg, P. Naulleau and P. Batson (LBNL) and J. Bokor (UCB/LBL).
A 0.30 NA Micro-Exposure Tool (MET) for Testing EUV Resist Patterns to 12 nm Feature Size

MET
NA = 0.30
13.4 nm
5X
200 X 600 µm field

(Courtesy of J. Taylor, LLNL)
25 nm Pinhole Fabrication

SiN
Cr 5nm/Au 12 nm
Plating Base

HSQ Resist

Expose &
develop
HSQ
Ni Plate

HSQ
strip in
HF
Dry Etch SiN

SEM of
coded 50 nm
pinhole with
HSQ mold
inside

50 nm

TEM of
coded 25 nm
pinholes
on 500 nm
pitch

300 nm

50 nm

(Courtesy of J. Alex Liddle, Deirdre Olynick and Erik Anderson, LBNL)
MET At-Wavelength Interferometry and Alignment Preparation for Static Microfield Imaging

Alignment in progress
September 3, 2003

central field point
astig 0.1 nm
coma 0.3 nm
sph ab 0.4 nm
trifoil 0.2 nm
h-o s. 0.4 nm
RMS 0.8 nm
λ/17

Aberrations may be reduced in final alignment

2 mirrors
0.3 NA, 5x
13.5 nm

200 x 600 μm field of view

- Visible-light alignment at Livermore
- EUV interferometry at Berkeley includes PS/PDI and shearing at 9 points across the field of view and in z.
- Higher-order spherical aberration dominates the wavefront
- A large part of the higher-order spherical is contained in Z35 and Z36. Higher-order spherical magnitude depends strongly on NA.

(Courtesy of K. Goldberg and P. Naulleau, LBNL)
Static Exposures with an Active Coherence Controlling Illuminator

For Interferometry

Partial coherence set by focal spot and angular scan

(Courtesy of P. Naulleau and P. Denham, LBNL)
Addressing critical EUV lithography issues for Sematech at the ALS: testing state-of-the-art EUV resists

Two-bounce, 0.3 NA, MET at ALS Beamline 12.0

Programmable illumination

Annular

45 nm  40 nm  35 nm

35 nm

22 nm lines and spaces

10 mJ/cm²

Major support and collaborators include Sematech, Intel, AMD, IBM, Samsung and others.

Courtesy of Patrick Naulleau, CXRO/LBNL.
Coherent Soft X-Ray Science Beamline

**Energy range** 200-1000eV

- Coherent flux at 600 eV: \(2 \times 10^{11}\) ph/sec/0.1%BW
- \(\lambda = 2.07\text{ nm (600 eV)}\)


- Wavefront interferomery to measure aberrations in zone plate lenses
- Measure material properties \((f_1 & f_2)\)
- Develop new coherent soft x-ray optical techniques (Fourier Optics)
- Coherent scattering from magnetic nanostructures
Coherent Soft X-Ray Beamline: Use of a Higher Harmonic (n = 3) to Access Shorter Wavelengths

Coherent Power with a Monochromator

8.0 cm period, N = 55
1.9 GeV, 400 mA
d \cdot \theta = \lambda/2\pi
\ell_{coh} = 1000 \lambda/2
\eta_{euv} = 10\%, \eta_{sxr} = 10\%
Coherent Soft X-Rays

\[ \lambda = 2.48 \text{ nm} \]
\[ (500 \text{ eV}) \]
\[ d = 2.6 \mu \text{m} \]
\[ t = 40 \text{ msec} \]

ALS beamline 12.0.2

Courtesy of Kris Rosfjord, CXRO/LBNL
Beam Characterization: Double Pinhole Experimental Results

2 μm vertical separation
|μ| = 1.00

6 μm vertical separation
|μ| = .57

d = 500nm diameter individual pinholes at 500eV
Focal spot size of 60μm X 9.4μm FWHM

Courtesy of Kris Rosfjord, CXRO/LBNL
Interferometry of Material Properties ($f_1$ and $f_2$) Using the New XOR Fourier Optic

\[ \delta = \frac{\text{Na re } \lambda^2}{2\pi} f_1^0(w) \]
\[ \beta = \frac{\text{Na re } \lambda^2}{2\pi} f_2^0(w) \]

Coherent Soft X-Ray Science Beamline

- Wavefront interferometry to measure aberrations in zone plate lenses
- Measure material properties ($f_1$ & $f_2$)
- Develop new coherent soft x-ray optical techniques (Fourier Optics)
- Coherent scattering from magnetic nanostructures

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Energy range 200-1000eV
Coherent flux at 600 eV:
\[ 2 \times 10^{11} \text{ ph/sec/0.1\%BW} \]
\[ \lambda = 2.07 \text{ nm (600 eV)} \]

---

Coherent Soft X-Ray Scattering

|ks| = 2π/d represents a spatial non-uniformity in the medium, such as atoms of periodicity d, a grating, or a density distribution due to a wave motion.

If the density distribution is stationary, or near stationary, the scattering diagram is isosceles.

- At a given angle one detects scattering from fluctuations of a specific spatial scale
- At that angle, the frequency content tells you the time structure of those fluctuations

(Soft x-ray speckle pattern: diffraction pattern of the magnetic domain structure)

(Courtesy of Steve Kevan, University of Oregon)
Coherent Soft X-Ray Magnetic Scattering Endstation

Flangosaurus

Scattering in Transmission

Sample location

X rays

Courtesy of K. Chesnel, S. Kevan, U. Oregon
Example of Experiment in Transmission: Coherent Scattering from Nanoparticles

X-ray beam tuned to Co L3 resonant edge

Pinhole (coherence)

Co Nanoparticles assembly precipitated on TEM grid

Diffuse scattering

Scattering ring related to interparticle distance ~12nm

Courtesy of K. Chesnel, S. Kevan, U. Oregon
The Scanning Soft X-Ray Microscope Requires Spatially Coherent Illumination
An Undulator Beamline for Scanning X-Ray Microscopy

Water-cooled beam defining apertures

5.0 cm period elliptically polarizing undulator

M₀ retractable plane

M₂ spherical

Grating

M₃ bendable

M₄ bendable

K-B focus system

Exit slit

Entrance pinhole

Coherent Soft X-ray Scanning Microscope ("STXM")

Professor David Attwood
Univ. California, Berkeley
1.9 GeV, 400 mA

\( \lambda_u = 50 \text{ mm}, N = 27 \)

\( 0.5 \leq K \leq 4.0 \)

\( \sigma_x = 260 \mu\text{m}, \sigma_x' = 23 \mu\text{r} \)

\( \sigma_y = 16 \mu\text{m}, \sigma_y' = 3.9 \mu\text{r} \)

\( \theta_{\text{cen}} = 61\mu\text{r} @ K = 0.87 \) (500 eV)
Biofilm from Saskatoon River

RESULTS
• Ni, Fe, Mn, Ca, K, O, C elemental map,
  (there was no sign of Cr.)
• Different oxidation states for Fe and Ni

Protein (gray), Ca, K

Different oxidation states (minerals) found for Fe & Ni

Tohru Araki, Adam Hitchcock (McMaster University)
Tolek Tyliszczak, LBNL
Sample from: John Lawrence, George Swerhone (NWRI-Saskatoon), Gary Leppard (NWRI-CCIW)
Map chemical spectra taken of pure samples 
Onto a sample containing both components

Exposure to UV light results in loss of carbonyl peak

280 eV  290 eV

Courtesy of Mary Gilles, LBNL

Patterned Polymer Photoresists

M.K. Gilles, R. Planques, S.R. Leone
LBNL
Samples from B. Hinsberg, F. Huele
IBM Almaden
X-ray holography
Lensless imaging at the nanoscale

The ‘Halloween storm’
How the Sun plays its tricks

Protein transport
Escape from the nucleus

Duck-billed platypus
Curiouser and curiouser

Locusts over Africa
Time for biological control?
Coherent Power at BESSY II

1.7 GeV, 200 mA
λ_u = 49 mm, N = 84
0 ≤ K ≤ 2.5
σ_x = 314 µm, σ_x' = 18 µm
σ_y = 24 µm, σ_y' = 2 µm
η_{euv} = 10% ; η_{sxr} = 10%

\[ \frac{\lambda}{\Delta \lambda} = 84 \]

\[ \frac{\lambda}{\Delta \lambda} = 10^3 \]

\[ \frac{\lambda}{\Delta \lambda} = 10^3 \]
Lensless Imaging of Magnetic Nanostructures by X-Ray Spectro-Holography

X-Ray Hologram at 1.59 nm Wavelength Using Undulator Radiation at BESSY

Recorded Pattern of Magnetic Nanostructures and Comparison to Scanning X-Ray Microscope

- Spatial coherence
- Temporal coherence
- Partial coherence
- Full coherence
- Spatial filtering
- Uncorrelated emitters
- Correlated emitters
- True phase coherence and mode control
- Lasers, amplified spontaneous emission (ASE) and mode control
- Undulator radiation
- SASE FEL 100+ fs soft/hard x-rays
- Seeded FEL true phase coherent x-rays
- High harmonic generation (HHG) compact fs/asec EUV
- EUV lasers and laser seeded HHG
- Applications with uncorrelated emitters
- Applications with correlated emitters
Young’s Double Slit Experiment: Spatial Coherence and the Persistence of Fringes
Persistence of fringes as the source grows from a point source to finite size.

\[ d \cdot 2\theta_{\text{FWHM}} \approx \frac{\lambda}{2} \]

\[ \lambda_{\text{coh}} = \frac{\lambda^2}{2\Delta\lambda} = \frac{1}{2} N_{\text{coh}} \lambda \]
Young’s Double Slit Experiment with Random Emitters: Young did not have a laser

- $d \cdot 2\theta_{\text{FWHM}} \approx \frac{\lambda}{2}$
- $\lambda_{\text{coh}} = \frac{\lambda^2}{2\Delta\lambda} = \frac{1}{2} N_{\text{coh}} \lambda$

N uncorrelated emitters

- Self-interference only
- Electric fields chaotic
- Intensities add
- Radiated power $\sim N$
Young’s Double Slit Experiment with Phase Coherent Emitters (some lasers, or properly seeded FELs)

- Phase coherent electric fields
- Electric fields from all particles interfere constructively
- Radiated power $\sim N^2$
- New phase sensitive probing of matter possible

$$d \cdot 2\theta_{\text{FWHM}} \approx \lambda/2$$

$$\lambda_{\text{coh}} = \frac{\lambda^2}{2\Delta\lambda} = \frac{1}{2} N_{\text{coh}}\lambda$$
The Lasing Process Begins with Amplified Spontaneous Emission (ASE)

Gain medium of inverted population density (Both directions equally likely)

but with spatial and temporal filtering, true phase coherence and mode control can be achieved.
Undulators and FELs

**Undulator** – uncorrelated electron positions, radiated fields uncorrelated, intensities add, limited coherence, power $\sim N$.

\[
\frac{dp}{dt} = -e(E + v \times B)
\]
Undulators and FELs

Undulator – uncorrelated electron positions, radiated fields uncorrelated, intensities add, limited coherence, power $\sim N$.

Free Electron Laser (FEL) – very long undulator, electrons are “microbunched” by their own radiated fields into strongly correlated waves of electrons, all radiated electric fields now add, spatially coherent, power $\sim N^2$.
Undulators and FELs

**Undulator** – uncorrelated electron positions, radiated fields uncorrelated, intensities add, limited coherence, power $\sim N$.

\[
\frac{dp}{dt} = -e(E + v \times B)
\]

**Free Electron Laser (FEL)** – very long undulator, electrons are “microbunched” by their own radiated fields into strongly correlated waves of electrons, all radiated electric fields now add, spatially coherent, power $\sim N^2$.
Gain and Saturation in an FEL

Courtesy of K-J. Kim
FEL Microbunching

Courtesy of Sven Reiche, UCLA.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Flash FEL (Hamburg)</th>
<th>LCLS (Stanford, 2010)</th>
<th>European XFEL (Hamburg, Schenefeld; 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_e)</td>
<td>230/1000 MeV</td>
<td>13.6 GeV</td>
<td>17.5 GeV</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>450/2000</td>
<td>26,600</td>
<td>35,000</td>
</tr>
<tr>
<td>(\lambda_u)</td>
<td>2.73 cm</td>
<td>3 cm</td>
<td>5 cm</td>
</tr>
<tr>
<td>(N)</td>
<td>500/1100</td>
<td>3700</td>
<td>4000</td>
</tr>
<tr>
<td>(L_u)</td>
<td>30 m</td>
<td>112 m</td>
<td>200 m</td>
</tr>
<tr>
<td>(\hbar\omega)</td>
<td>50-200 eV</td>
<td>1-10 keV</td>
<td>4-12 keV</td>
</tr>
<tr>
<td>(\lambda/\Delta\lambda)</td>
<td>100</td>
<td>350</td>
<td>1000</td>
</tr>
<tr>
<td>(e^-/\text{bunch})</td>
<td>10^9</td>
<td>(6 \times 10^9) (1 nC)</td>
<td>(6 \times 10^9)</td>
</tr>
<tr>
<td>(\Delta\tau)</td>
<td>25 fsec</td>
<td>160 fsec</td>
<td>100 fsec</td>
</tr>
<tr>
<td>(\mathcal{F})</td>
<td>(3 \times 10^{12}) ph/pulse</td>
<td>(2 \times 10^{12}) ph/pulse</td>
<td>(10^{12} - 10^{14}) ph/pulse</td>
</tr>
<tr>
<td>(\text{rep rate})</td>
<td>1 Hz</td>
<td>120 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>(I)</td>
<td>1.3 kA</td>
<td>3.4 kA</td>
<td></td>
</tr>
<tr>
<td>(\hat{P})</td>
<td>0.3 GW</td>
<td>8 GW</td>
<td>20-100 GW</td>
</tr>
<tr>
<td>(\hat{B})</td>
<td>(1 \times 10^{28})</td>
<td>(1 \times 10^{33})</td>
<td>(5 \times 10^{33})</td>
</tr>
<tr>
<td>(L)</td>
<td>260 m</td>
<td>5 km</td>
<td>3.4 km</td>
</tr>
</tbody>
</table>
FLASH EUV/soft x-ray FEL at DESY Lab, Hamburg

6.5-32 nm wavelength in 1st harmonic
20 fsec, $10^{12}$ photons per pulse

Courtesy of Henry Chapman (LLNL, now Hamburg) and Stefano Marchesini (LLNL, now LBL).
Coherent X-ray Diffractive Imaging with the FLASH free-electron laser (FEL) in Hamburg, Germany

25 fs diffraction pattern