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Advanced School on Synchrotron and Free Electron Laser Sources and their Multidisciplinary Applications

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Spatial and Temporal Coherence, Coherent Undulator Radiation

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Spatial and Temporal Coherence, Coherent Undulator Radiation

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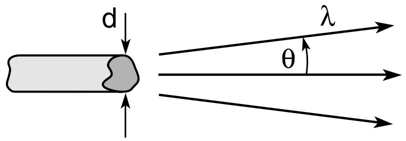
Topics for Today

- 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
- Seeded FEL
- High harmonic generation (HHG)
- EUV lasers and laser seeded HHG
- Applications with uncorrelated emitters
- Applications with correlated emitters

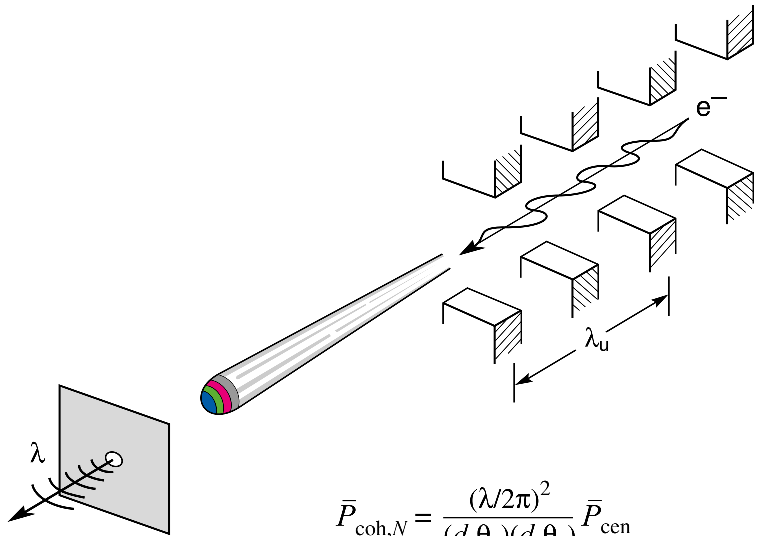
COHERENCE AT SHORT WAVELENGTHS

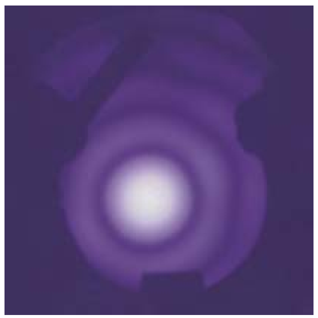


$$l_{coh} = \lambda^2/2\Delta\lambda \text{ \{temporal (longitudinal) coherence\}} \quad (8.3)$$

$$d \cdot \theta = \lambda/2\pi \text{ \{spatial (transverse) coherence\}} \quad (8.5)$$

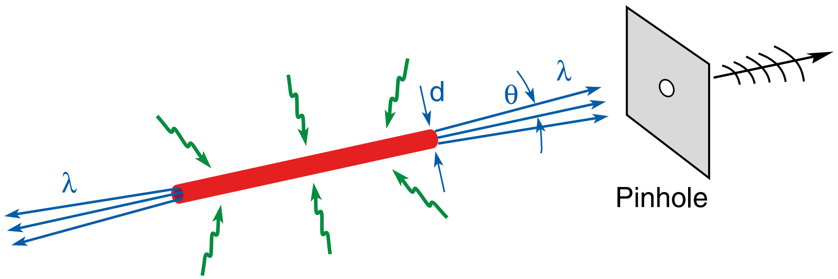
$$\text{or } d \cdot 2\theta|_{FWHM} = 0.44\,\lambda \quad (8.5^*)$$





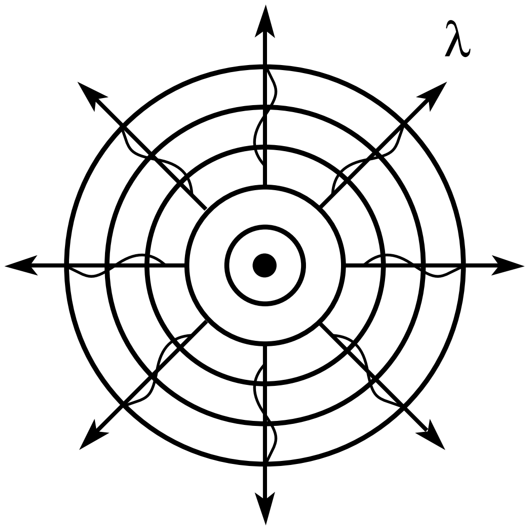
$$\bar{P}_{coh,N} = \frac{(\lambda/2\pi)^2}{(d_x\theta_x)(d_y\theta_y)}\bar{P}_{cen} \quad (8.6)$$

$$\bar{P}_{coh,\lambda/\Delta\lambda} = \frac{e\lambda_u I\eta(\Delta\lambda/\lambda)N^2}{8\pi\epsilon_0 d_x d_y} \cdot \left[1 - \frac{\hbar\omega}{\hbar\omega_0}\right] f(K) \quad (8.9)$$

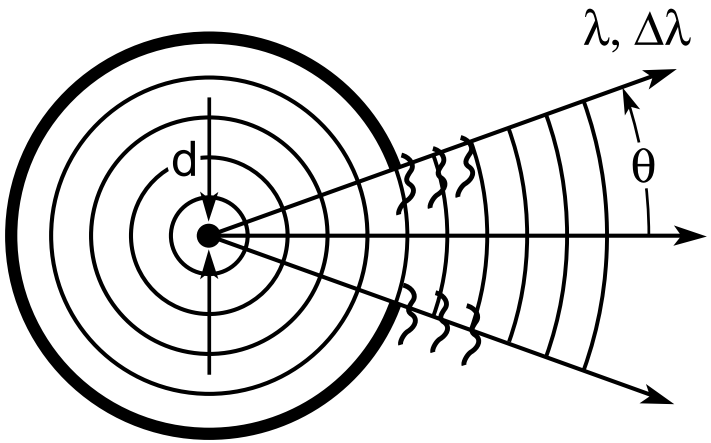


$$P_{coh} = \frac{(\lambda/2\pi)^2}{(d_x\theta_x)(d_y\theta_y)} P_{laser} \quad (8.11)$$

Coherence, Partial Coherence, and Incoherence



Point source oscillator
$-\infty < t < \infty$



Source of finite size,
divergence, and duration

Spatial and Temporal Coherence

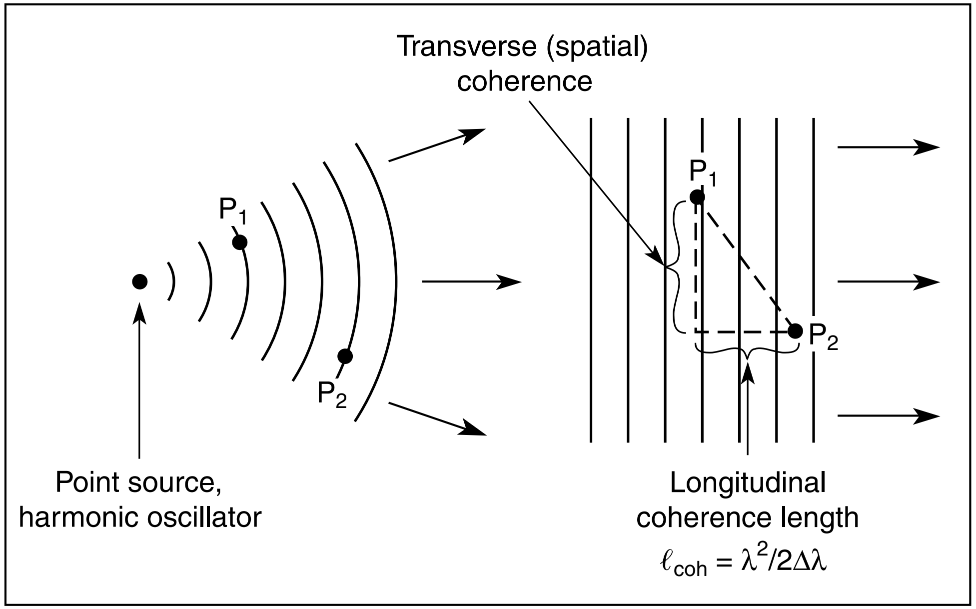
Mutual coherence factor

$$\Gamma_{12}(\tau) \equiv \langle E_1(t+\tau)E_2^*(t)\rangle \qquad (8.1)$$

Normalize degree of spatial coherence (complex coherence factor)

$$\mu_{12} = \frac{\langle E_1(t)E_2^*(t)\rangle}{\sqrt{\langle|E_1|^2\rangle}\sqrt{\langle|E_2|^2\rangle}} \qquad (8.12)$$

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.



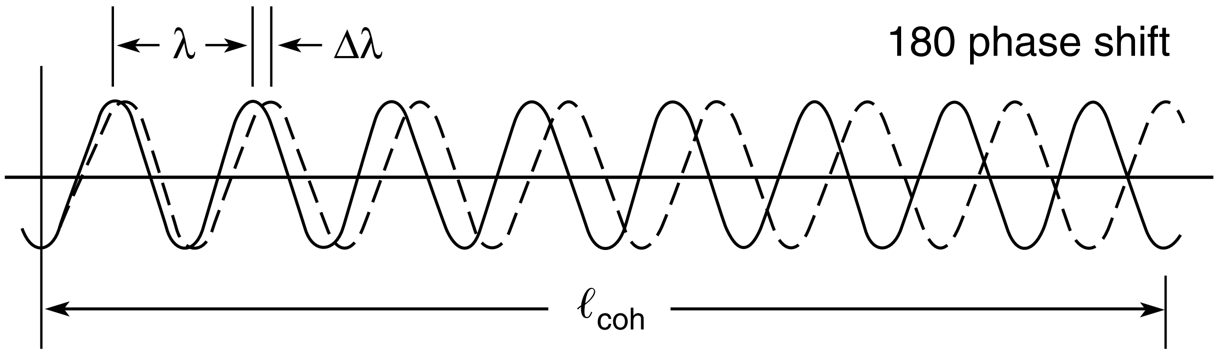
Longitudinal (temporal) coherence length

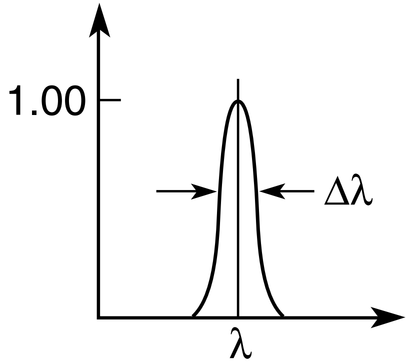
$$\ell_{coh} = \frac{\lambda^2}{2\,\Delta\lambda} \qquad (8.3)$$

Full spatial (transverse) coherence

$$d \cdot \theta = \lambda/2\pi \qquad (8.5)$$

Spectral Bandwidth and Longitudinal Coherence Length





Define a coherence length ℓ_{coh} as the distance of propagation over which radiation of spectral width $\Delta\lambda$ becomes 180° out of phase. For a wavelength λ propagating through N cycles

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

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

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

Equating the two

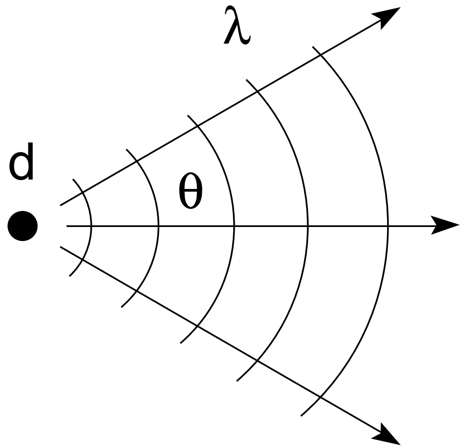
$$N = \lambda/2\Delta\lambda$$

so that

$$\boxed{\ell_{coh} = \frac{\lambda^2}{2\,\Delta\lambda}} \qquad (8.3)$$

A Practical Interpretation of Spatial Coherence

- **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 λ and half angle θ, is

$$d \cdot \theta = \frac{\lambda}{2\pi}$$

Partially Coherent Radiation Approaches Uncertainty Principle Limits

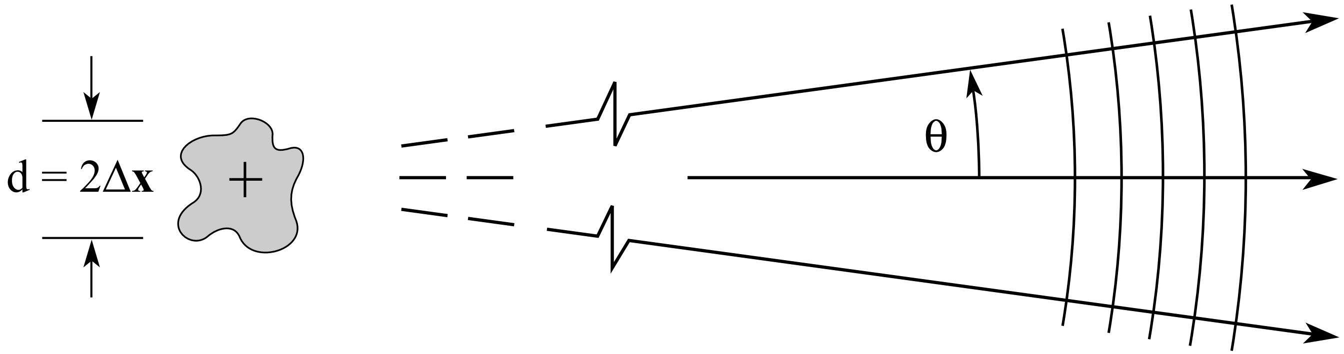
$$\Delta \mathbf{x} \cdot \Delta \mathbf{p} \geq \hbar/2 \qquad (8.4)$$

$$\Delta \mathbf{x} \cdot \hbar \Delta \mathbf{k} \geq \hbar/2$$

$$\Delta \mathbf{x} \cdot \mathbf{k} \Delta \theta \geq 1/2$$

$$2\Delta \mathbf{x} \cdot \Delta \theta \geq \lambda/2\pi$$

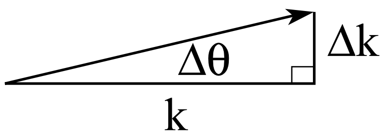
Standard deviations of Gaussian distributed functions (Tipler, 1978, pp. 174-189)



Note:

$$\Delta \mathbf{p} = \hbar \Delta k$$

$$\Delta k = k \Delta \theta$$



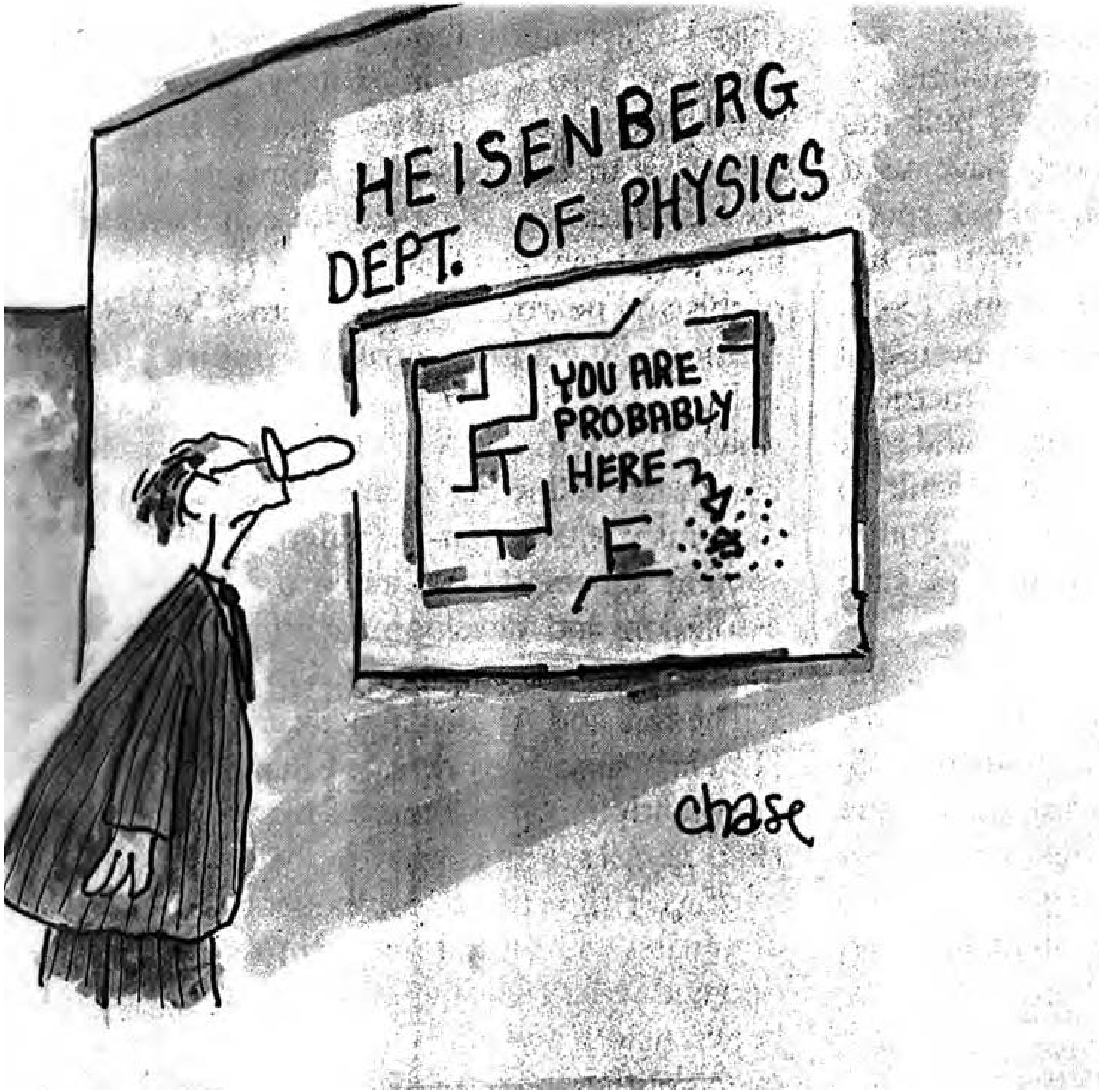
Spherical wavefronts occur in the limiting case

$$\boxed{d \cdot \theta = \lambda/2\pi}$$

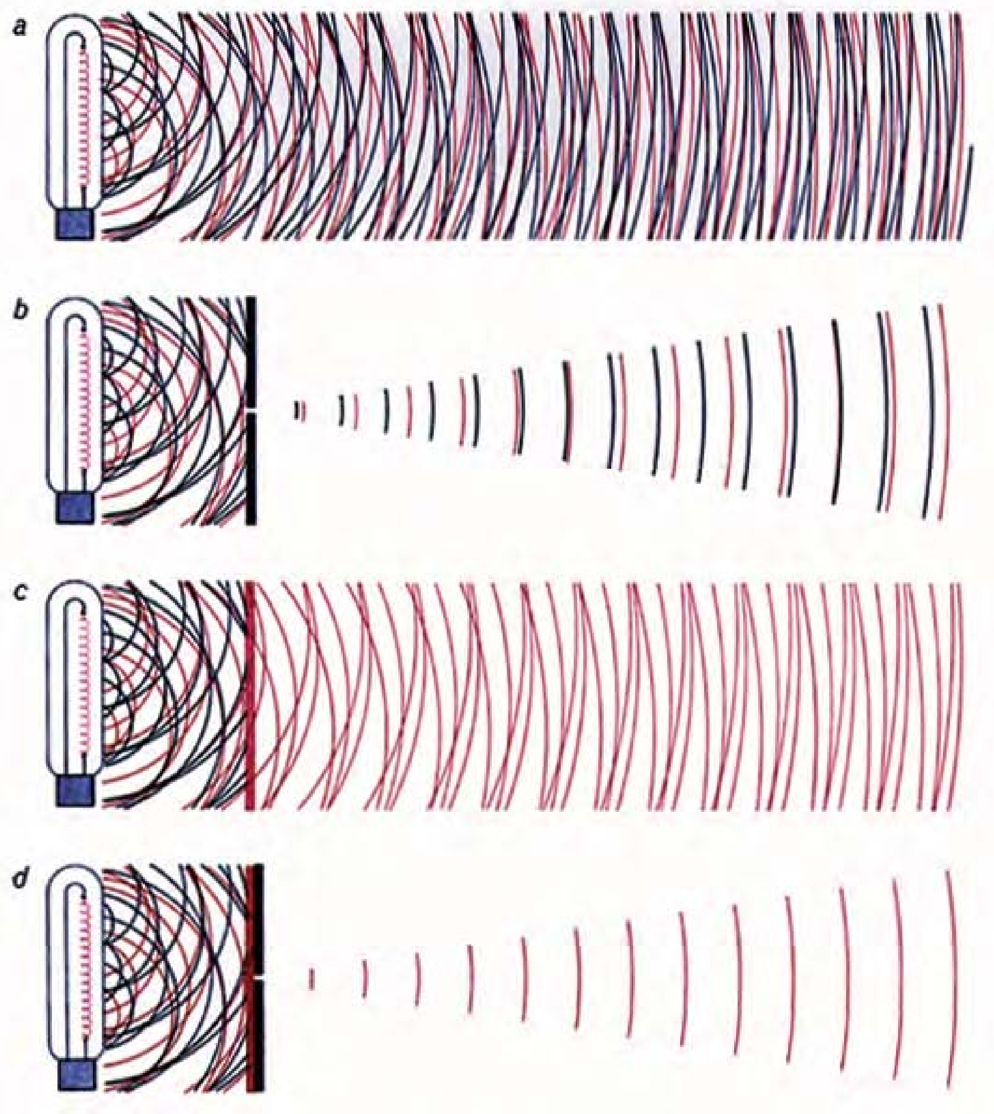
(spatially coherent) $\Big\}$ $\frac{1}{\sqrt{e}}$ quantities

or

$$(d \cdot 2\theta)_{FWHM} \simeq \lambda/2 \; \Big\} \text{ FWHM quantities}$$

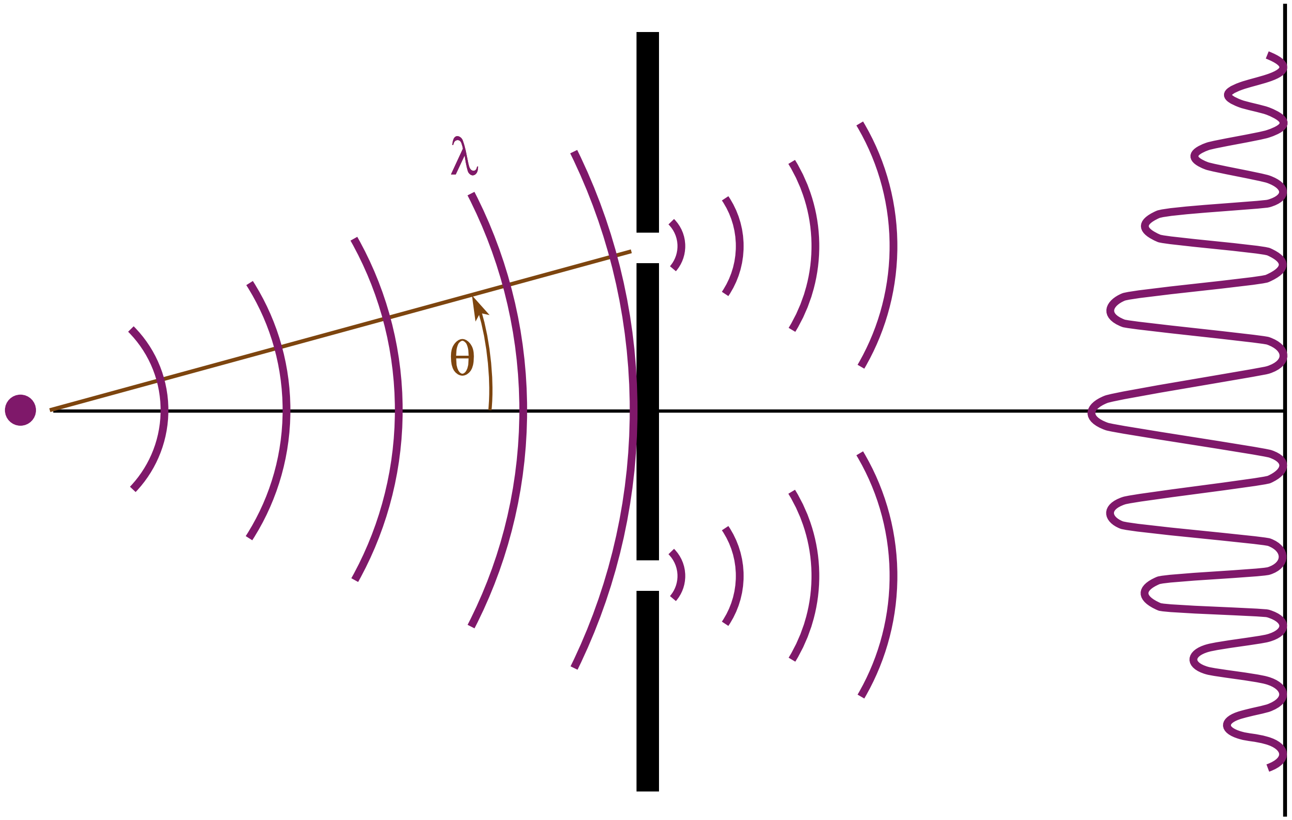

HEISENBERG
DEPT. OF PHYSICS
YOU ARE
PROBABLY
HERE
chase

Spatial and Spectral Filtering to Produce Coherent Radiation



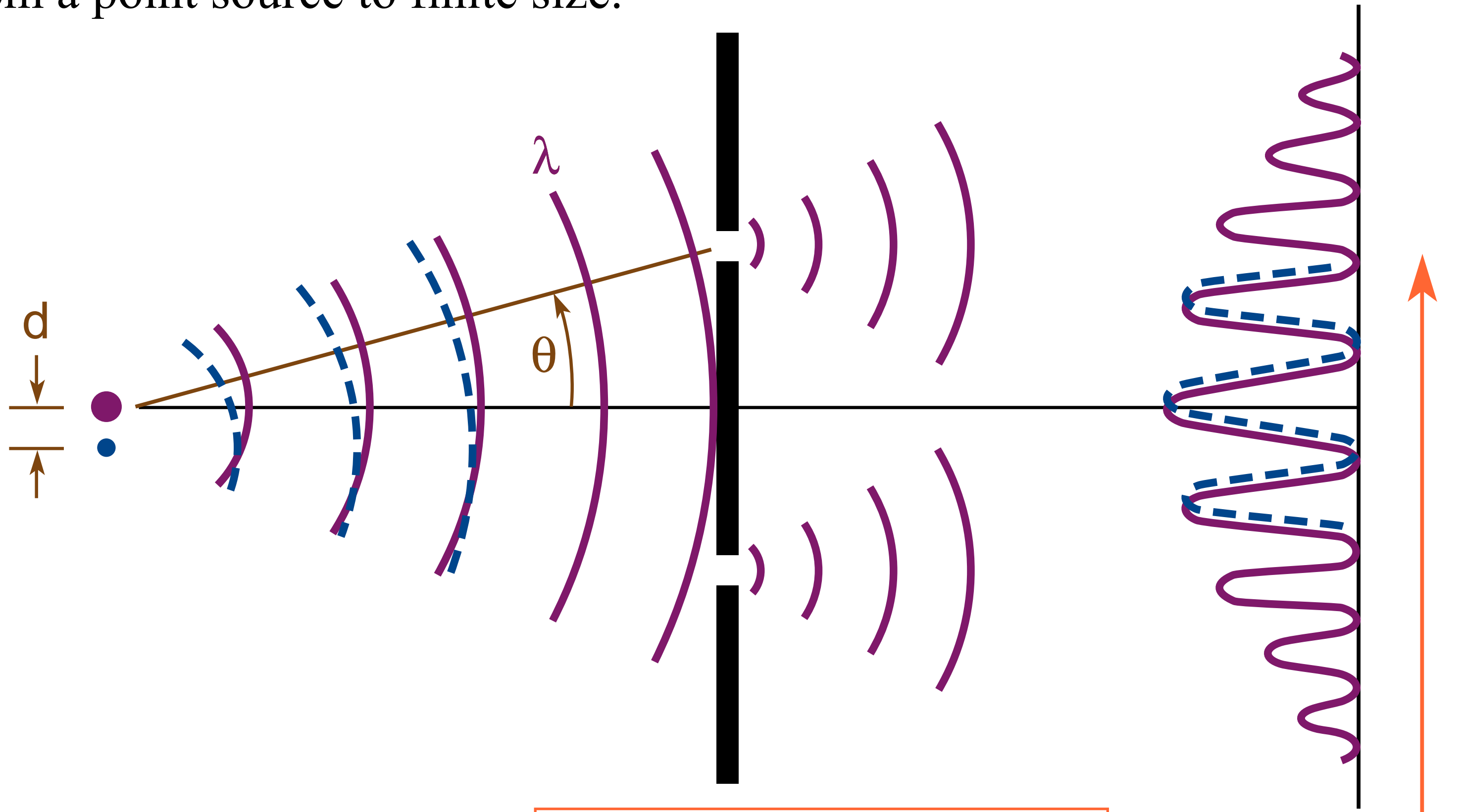
Courtesy of A. Schawlow, Stanford.

Young's Double Slit Experiment: Spatial Coherence and the Persistence of Fringes



Young's Double Slit Experiment: Spatial Coherence and the Persistence of Fringes

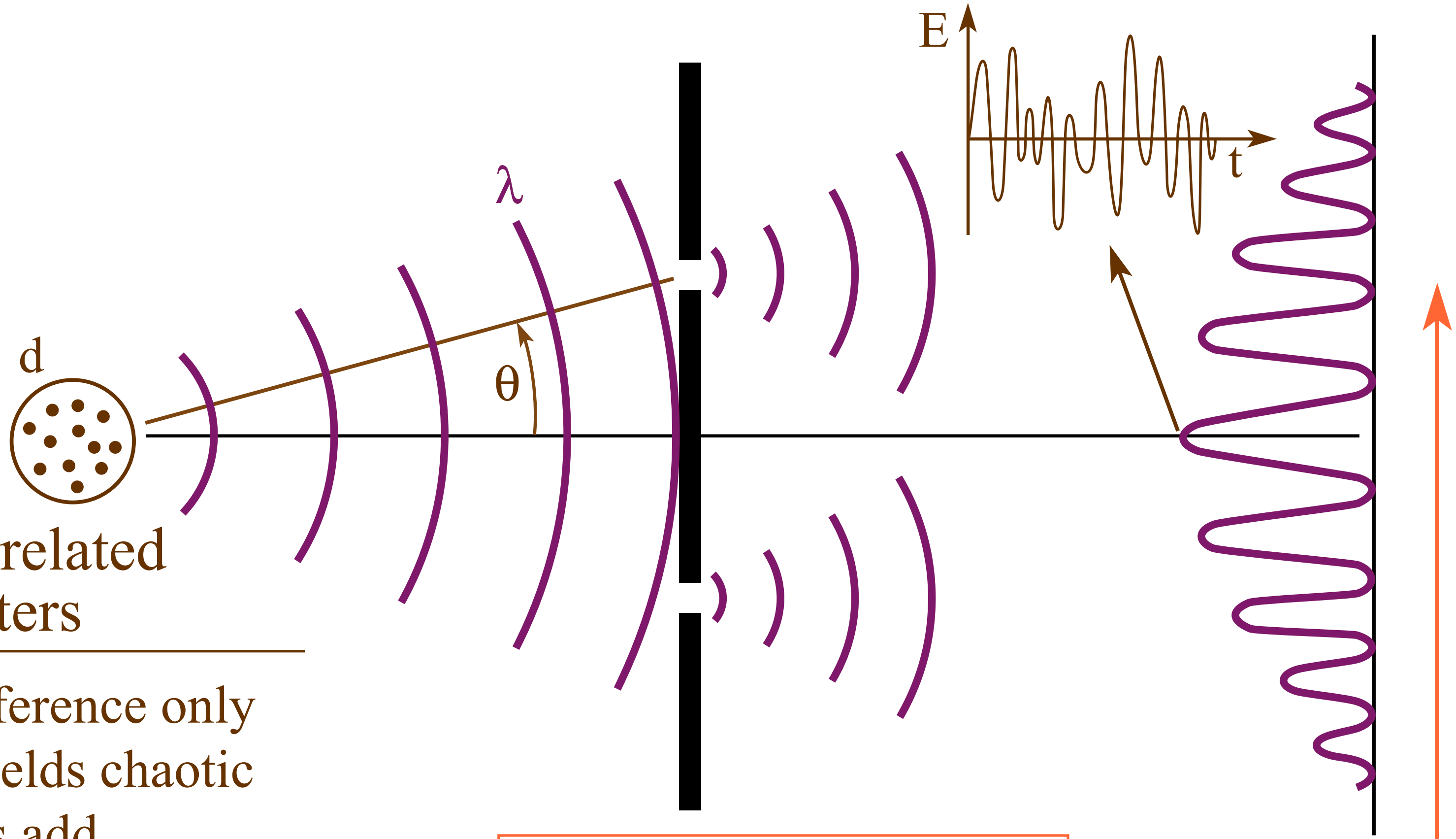
Persistence of fringes as the source grows from a point source to finite size.



$$d \cdot 2\theta|_{FWHM} \simeq \lambda/2$$

$$\lambda_{coh} = \lambda^2/2\Delta\lambda = \frac{1}{2} N_{coh}\lambda$$

Young's Double Slit Experiment with Random Emitters: Young did not have a laser



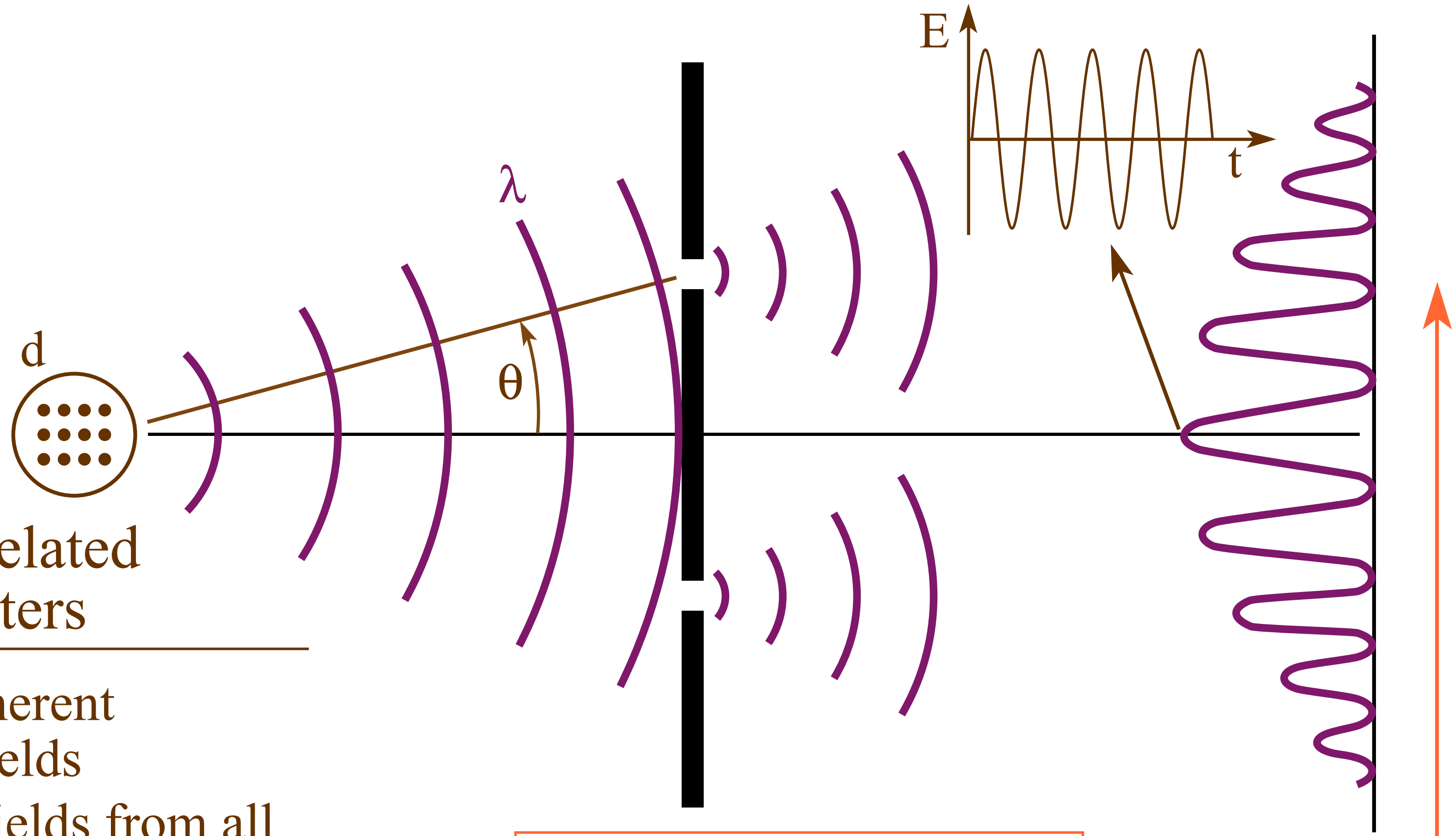
N uncorrelated emitters

- Self-interference only
- Electric fields chaotic
- Intensities add
- Radiated power ~ N

$$d \cdot 2\theta|_{FWHM} \simeq \lambda/2$$

$$\lambda_{coh} = \lambda^2/2\Delta\lambda = \frac{1}{2} N_{coh}\lambda$$

Young's Double Slit Experiment with Phase Coherent Emitters (some lasers, or properly seeded FELs)



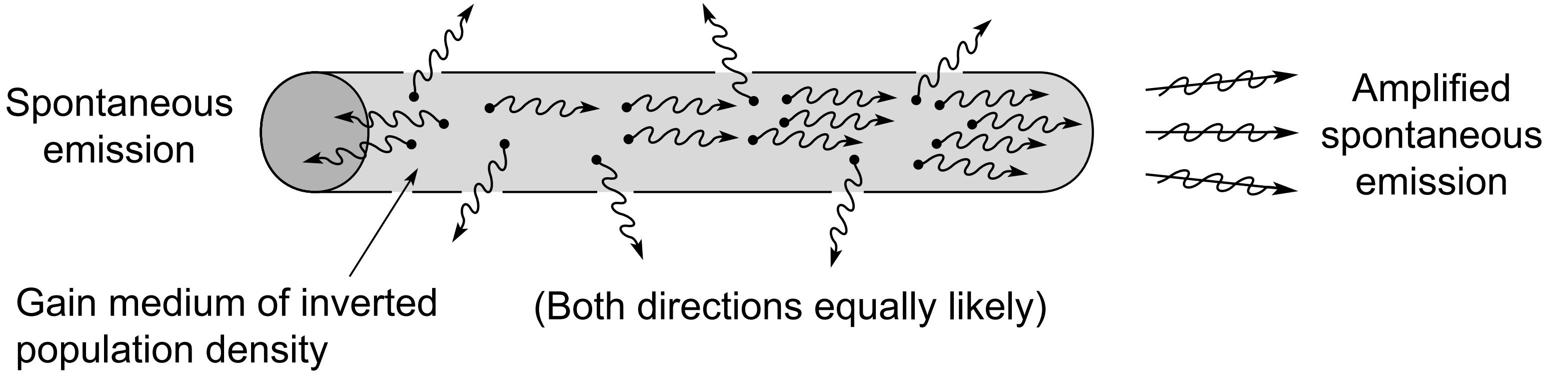
N correlated emitters

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

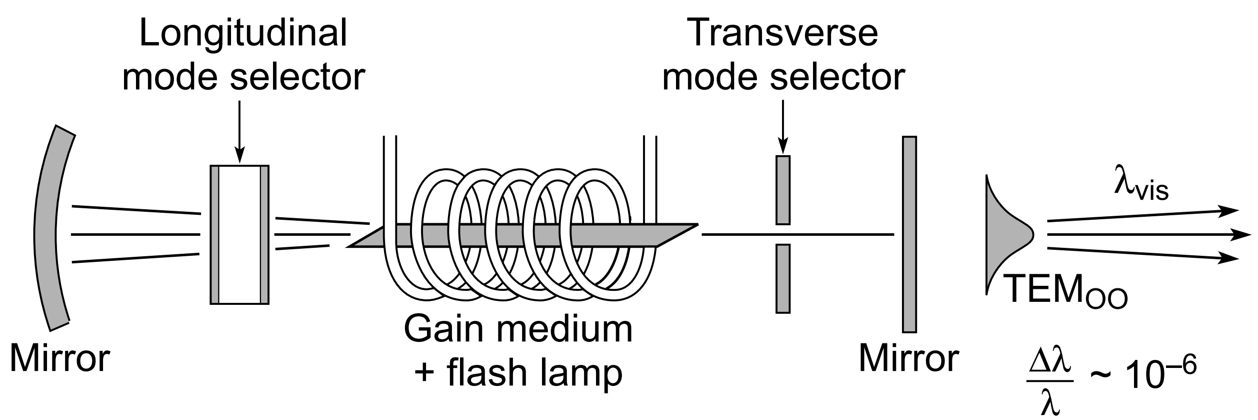
$$d \cdot 2\theta|_{FWHM} \simeq \lambda/2$$

$$\lambda_{coh} = \lambda^2/2\Delta\lambda = \frac{1}{2} N_{coh}\lambda$$

The Lasing Process Begins with Amplified Spontaneous Emission (ASE)



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



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Some Useful Formulas for Synchrotron Radiation

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\beta^2}} \; ; \quad \beta = \frac{v}{c}$$

$$E_e = \gamma mc^2, \quad \boldsymbol{p} = \gamma m\mathbf{v}$$

$$\gamma = \frac{E_e}{mc^2} = 1957\, E_e(\mathrm{GeV})$$

$$\hbar\omega \cdot \lambda = 1239.842 \text{ eV} \cdot \text{nm}$$

$$1 \text{ watt} \Rightarrow 5.034 \times 10^{15} \lambda[\text{nm}] \frac{\text{photons}}{\text{s}}$$

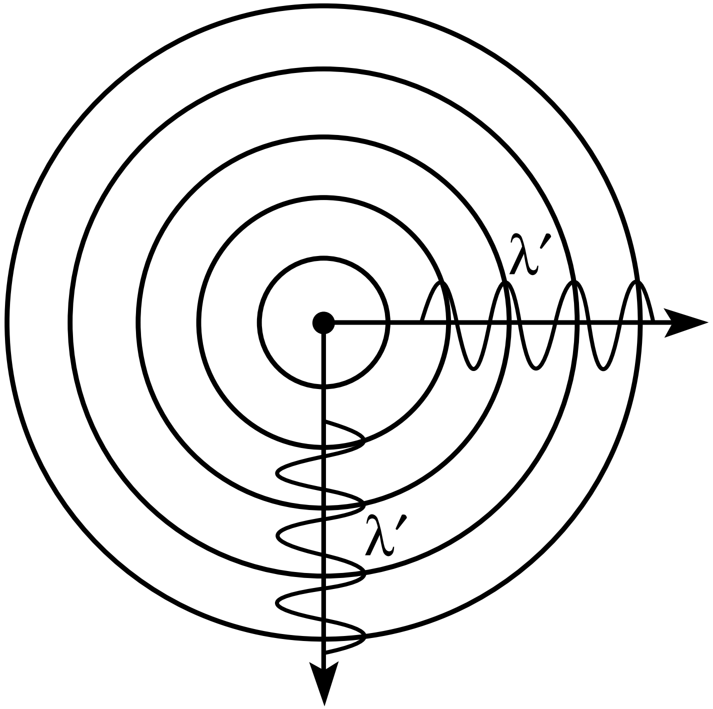
Bending Magnet: $E_c = \dfrac{3e\hbar B\gamma^2}{2m}$, $E_c(\mathrm{keV}) = 0.6650 E_e^2(\mathrm{GeV}) B(\mathrm{T})$

Undulator: $\lambda = \dfrac{\lambda_u}{2\gamma^2}\left(1 + \dfrac{K^2}{2} + \gamma^2\theta^2\right)$; $E(\mathrm{keV}) = \dfrac{0.9496 E_e^2(\mathrm{GeV})}{\lambda_u(\mathrm{cm})\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)}$

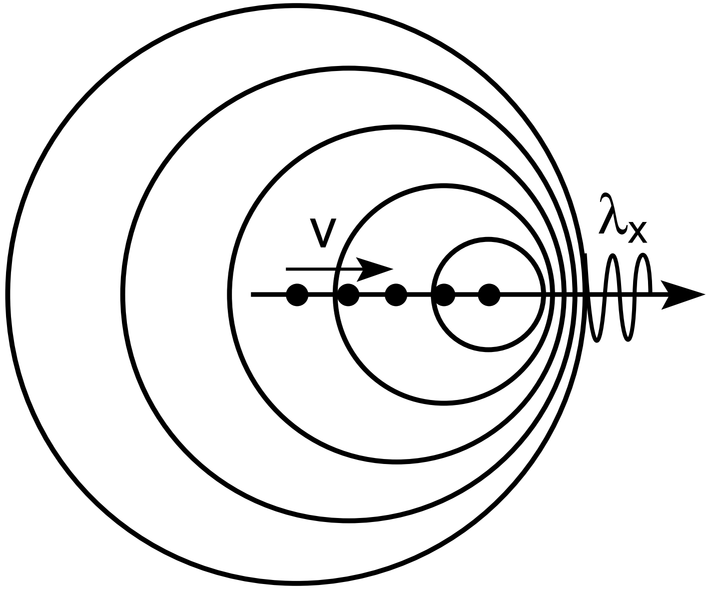
where $K \equiv \dfrac{eB_0\lambda_u}{2\pi mc} = 0.9337 B_0(\mathrm{T})\lambda_u(\mathrm{cm})$

Synchrotron Radiation from Relativistic Electrons

$v \ll c$



$v \lesssim c$



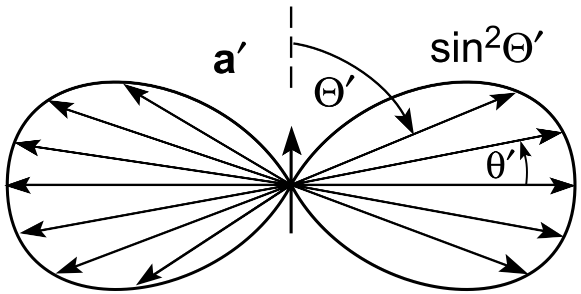
Note: Angle-dependent doppler shift

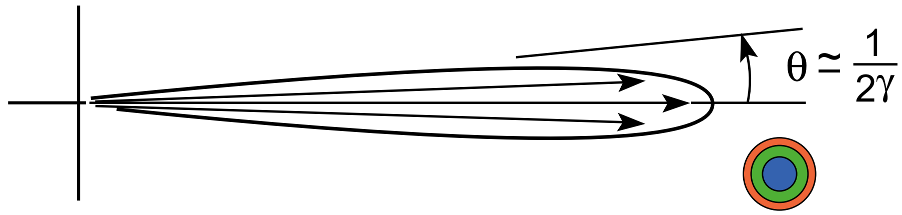
$$\lambda = \lambda' \left(1 - \frac{v}{c}\cos\theta\right) \qquad \lambda = \lambda' \gamma \left(1 - \frac{v}{c}\cos\theta\right)$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Synchrotron Radiation in a Narrow Forward Cone

Frame moving with electron | **Laboratory frame of reference**

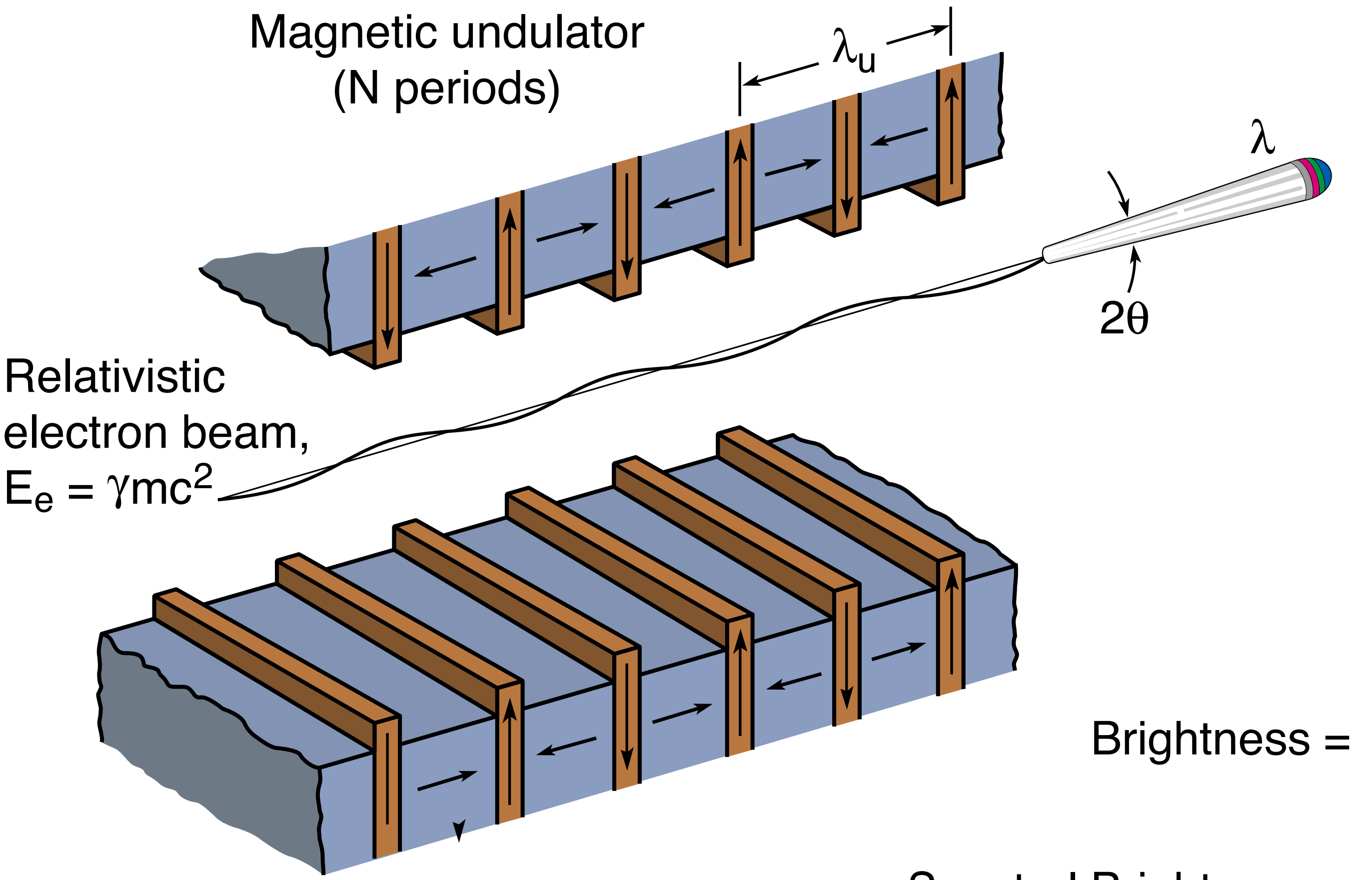




$$\tan\theta = \frac{\sin\theta'}{\gamma(\beta + \cos\theta')} \quad (5.1)$$

$$\theta \simeq \frac{1}{2\gamma} \quad (5.2)$$

Undulator Radiation from a Small Electron Beam Radiating into a Narrow Forward Cone, is Very Bright



$$\lambda \simeq \frac{\lambda_u}{2\gamma^2}$$

$$\theta_{cen} \simeq \frac{1}{\gamma\sqrt{N}}$$

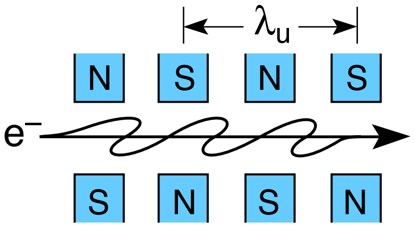
$$\left[\frac{\Delta\lambda}{\lambda}\right]_{cen} = \frac{1}{N}$$

$$\text{Brightness} = \frac{\text{photon flux}}{(\Delta A)\,(\Delta\Omega)}$$

$$\text{Spectral Brightness} = \frac{\text{photon flux}}{(\Delta A)\,(\Delta\Omega)\,(\Delta\lambda/\lambda)}$$

Undulator Radiation

Laboratory Frame of Reference

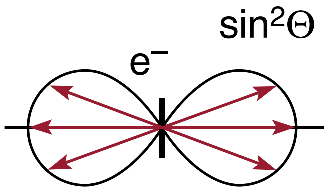


$E = \gamma mc^2$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

N = # periods

Frame of Moving e^-



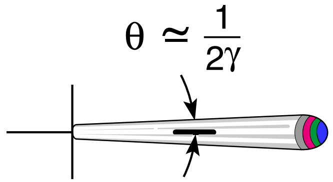
e^- radiates at the Lorentz contracted wavelength:

$$\lambda' = \frac{\lambda_u}{\gamma}$$

Bandwidth:

$$\frac{\lambda'}{\Delta\lambda'} \simeq N$$

Frame of Observer



Doppler shortened wavelength on axis:

$$\lambda = \lambda'\gamma(1 - \beta\cos\theta)$$

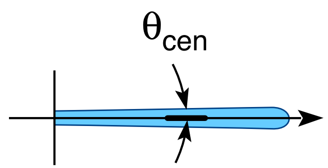
$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + \gamma^2\theta^2)$$

Accounting for transverse motion due to the periodic magnetic field:

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

where $K = eB_0\lambda_u / 2\pi mc$

Following Monochromator



For $\frac{\Delta\lambda}{\lambda} \simeq \frac{1}{N}$

$$\theta_{cen} \simeq \frac{1}{\gamma\sqrt{N}}$$

typically

$$\theta_{cen} \simeq 40 \text{ rad}$$

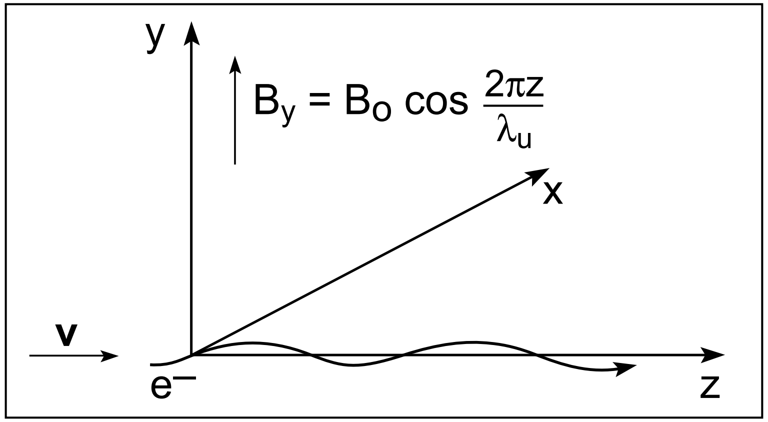
The Equation of Motion in an Undulator

Magnetic fields in the periodic undulator cause the electrons to oscillate and thus radiate. These magnetic fields also slow the electrons axial (z) velocity somewhat, reducing both the Lorentz contraction and the Doppler shift, so that the observed radiation wavelength is not quite so short. The force equation for an electron is

$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad (5.16)$$

where $\mathbf{p} = \gamma m\mathbf{v}$ is the momentum. The radiated fields are relatively weak so that

$$\frac{d\mathbf{p}}{dt} \simeq -e(\mathbf{v} \times \mathbf{B})$$



Taking to first order $v \simeq v_z$, motion in the x-direction is

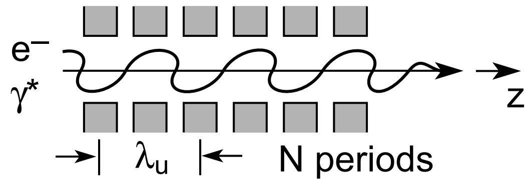
$$m\gamma \frac{dv_x}{dt} = +ev_z B_y$$

$$v_x = \frac{Kc}{\gamma} \sin\left(\frac{2\pi z}{\lambda_u}\right) \qquad (5.19)$$

$$K \equiv \frac{eB_0\lambda_u}{2\pi mc} = 0.9337\, B_0(\mathrm{T})\lambda_u(\mathrm{cm}) \qquad (5.18)$$

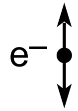
Calculating Power in the Central Radiation Cone: Using the well known "dipole radiation" formula by transforming to the frame of reference moving with the electrons

x, z, t laboratory frame of reference



Lorentz transformation

x′, z′, t′ frame of reference moving with the average velocity of the electron



$$\lambda_u' = \frac{\lambda_u}{\gamma^*}$$

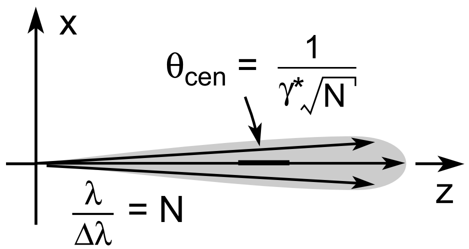
x′, z′, t′ motion

$a'(t')$ acceleration

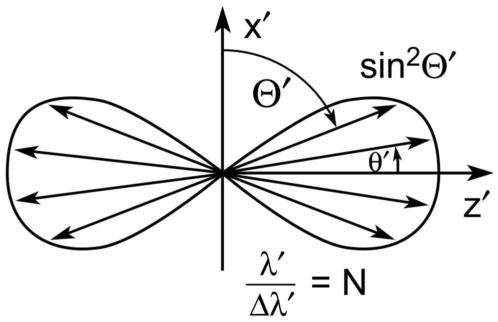
$$\frac{d\mathbf{p}}{dt} = -e\,(\mathbf{E} + \mathbf{v}\times\mathbf{B})$$

Dipole radiation:

$$\frac{dP'}{d\Omega'} = \frac{e^2\,a'^2\sin^2\Theta'}{16\pi^2\epsilon_0 c^3}$$



Lorentz transformation



$$\bar{P}_{cen} = \frac{\pi e\gamma^2 I}{\epsilon_0\lambda_u}\,\frac{K^2}{(1+K^2/2)^2}$$

Undulator Radiated Power in the Central Cone

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

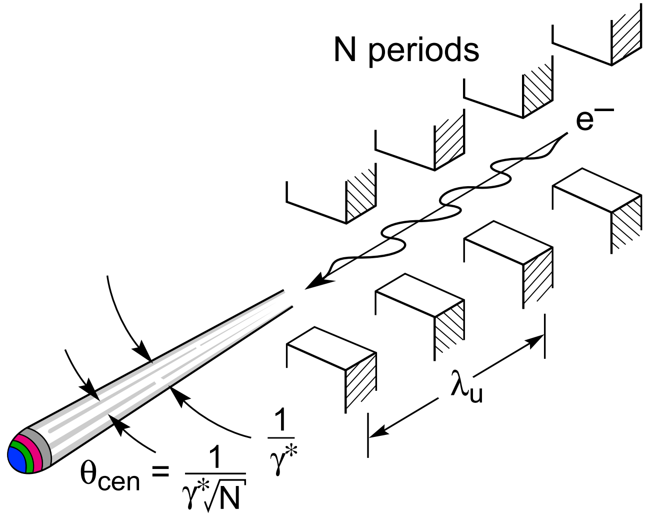
$$\bar{P}_{cen} = \frac{\pi e \gamma^2 I}{\epsilon_0 \lambda_u} \frac{K^2}{(1 + \frac{K^2}{2})^2} f(K)$$

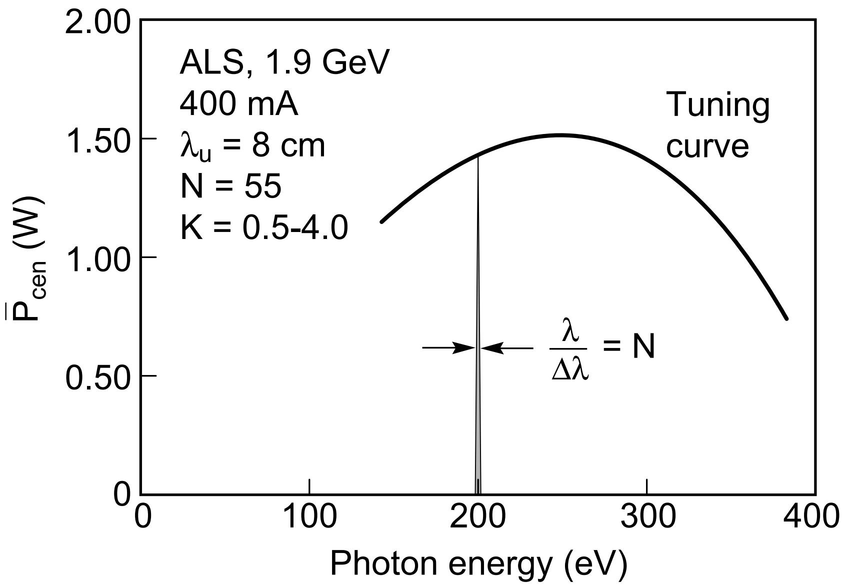
$$\theta_{cen} = \frac{1}{\gamma^* \sqrt{N}}$$

$$\left(\frac{\Delta\lambda}{\lambda}\right)_{cen} = \frac{1}{N}$$

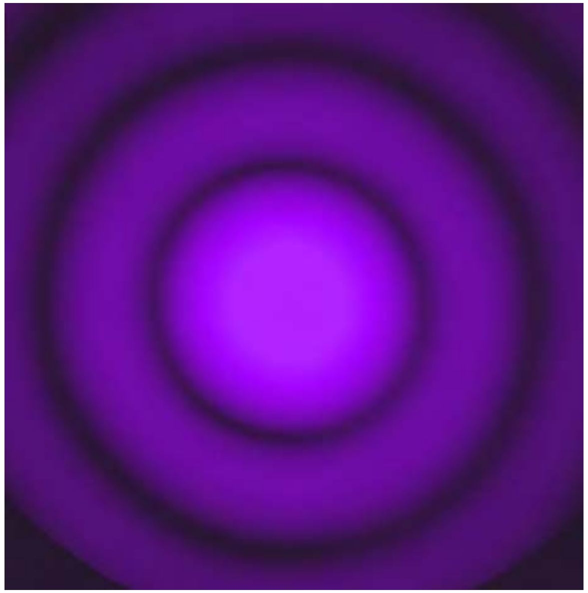
$$K = \frac{e B_0 \lambda_u}{2\pi m_0 c}$$

$$\gamma^* = \gamma \Big/ \sqrt{1 + \frac{K^2}{2}}$$

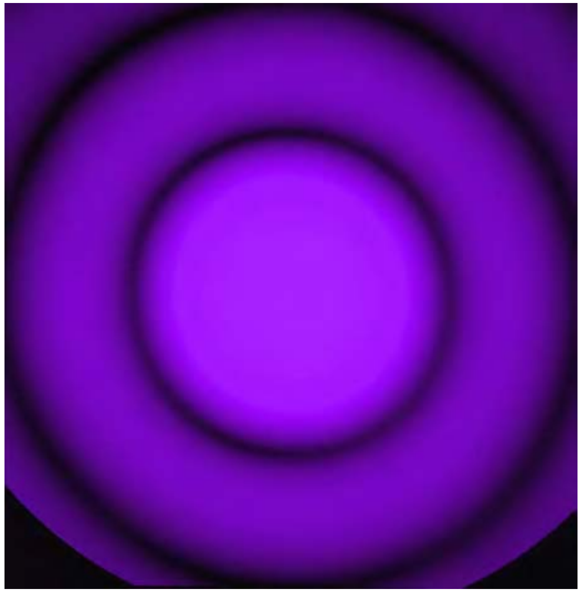




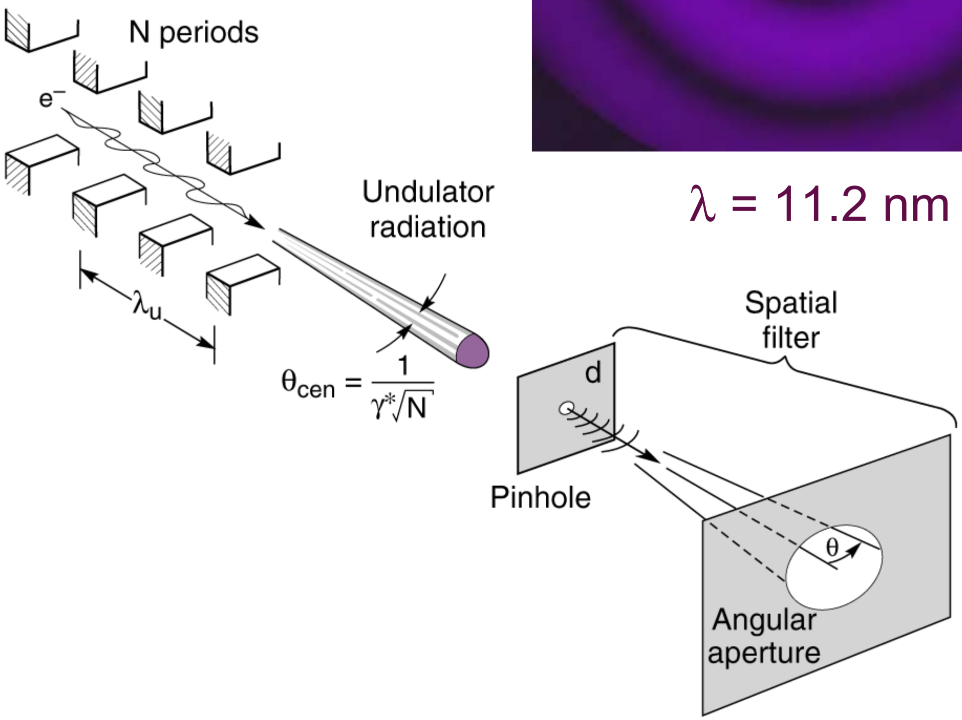
Spatially Coherent Undulator Radiation



λ = 11.2 nm



λ = 13.4 nm



1 μm^D pinhole

25 mm wide CCD at 410 mm

Courtesy of Patrick Naulleau, LBNL.

Spatial and Spectral Filtering of Undulater Radiation

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

$$\bar{P}_{\mathrm{coh},\lambda/\Delta\lambda} = \underbrace{\eta}_{\text{beamline efficiency}} \underbrace{\frac{(\lambda/2\pi)^2}{(d_x\theta_x)(d_y,\theta_y)}}_{\text{spatial filtering}} \cdot \underbrace{N\frac{\Delta\lambda}{\lambda}}_{\text{spectral filtering}} \cdot \bar{P}_{\mathrm{cen}} \qquad (8.10a)$$

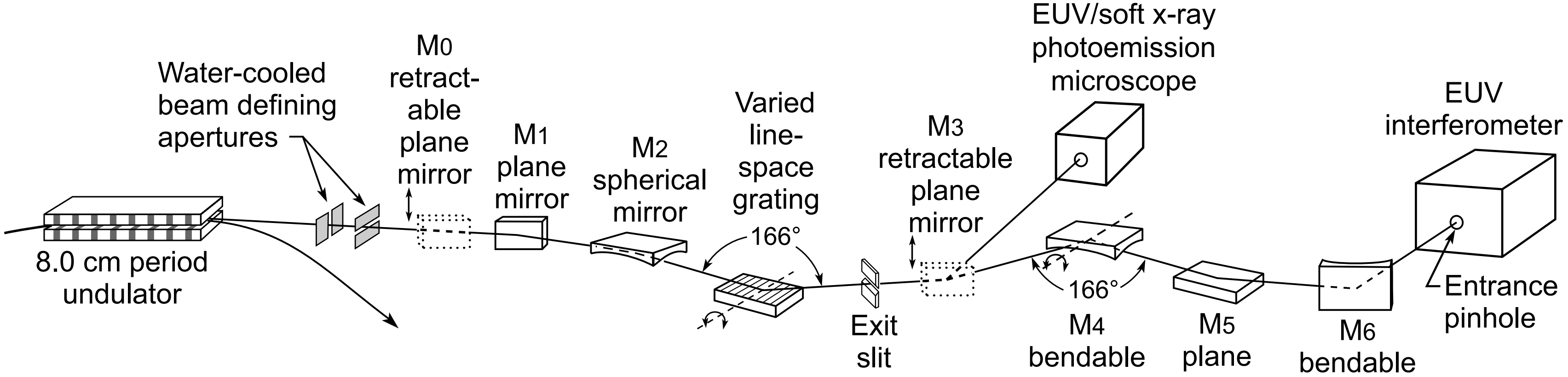
which for $\sigma'^{2}_{x,y} << \theta^2_{cen}$ (the undulator condition) gives the spatially and temporally coherent power ($d \cdot \theta = \lambda/2\pi$; $l_{\mathrm{coh}} = \frac{\lambda^2}{2\,\Delta\lambda}$)

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

which we note scales as N^2.

Spatially and Spectrally Filtered Undulator Radiation

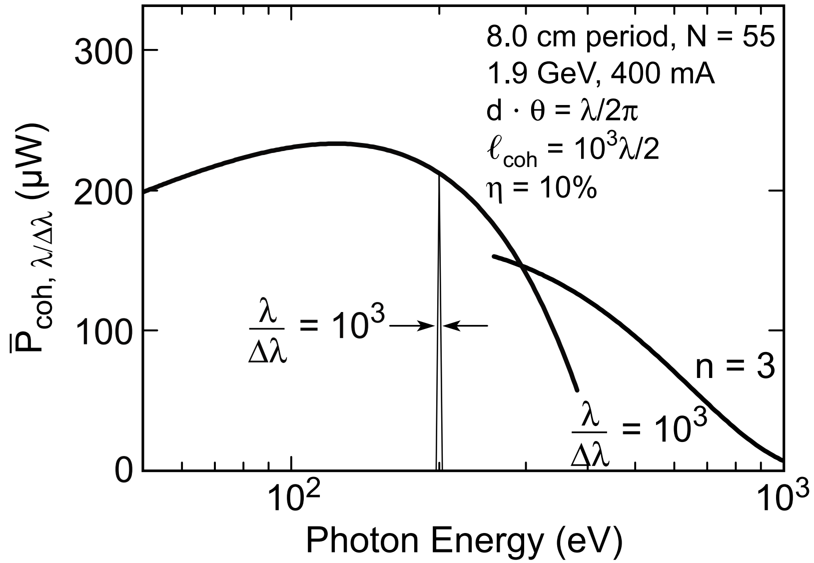
- Pinhole filtering for full spatial coherence
- Monochromator for spectral filtering to $\lambda/\Delta\lambda > N$



$$\bar{P}_{coh,\lambda/\Delta\lambda} = \underbrace{\eta}_{\text{beamline efficiency}} \underbrace{\frac{(\lambda/2\pi)^2}{(d_x\theta_x)(d_y\theta_y)}}_{\text{spatial filtering}} \cdot \underbrace{N\frac{\Delta\lambda}{\lambda}}_{\text{spectral filtering}} \cdot \bar{P}_{cen} \qquad (8.10a)$$

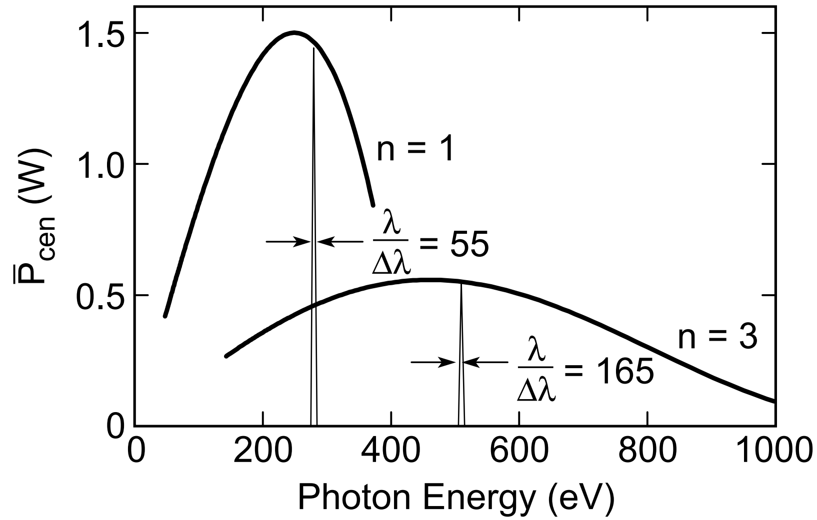
$$\bar{P}_{coh,\lambda/\Delta\lambda} = \frac{e\lambda_u I\eta(\Delta\lambda/\lambda)N^2}{8\pi\epsilon_0 d_x d_y} \cdot \left(1 - \frac{\hbar\omega}{\hbar\omega_0}\right) f(\hbar\omega/\hbar\omega_0)$$

$$(\sigma'^2 \ll \theta^2_{cen}) \qquad (8.10c)$$



Coherent Power at the ALS

U8



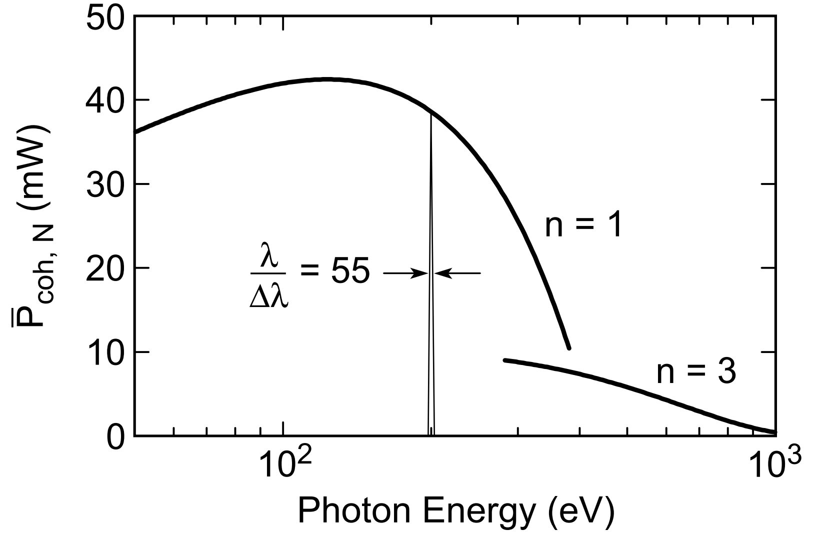
1.9 GeV, 400 mA

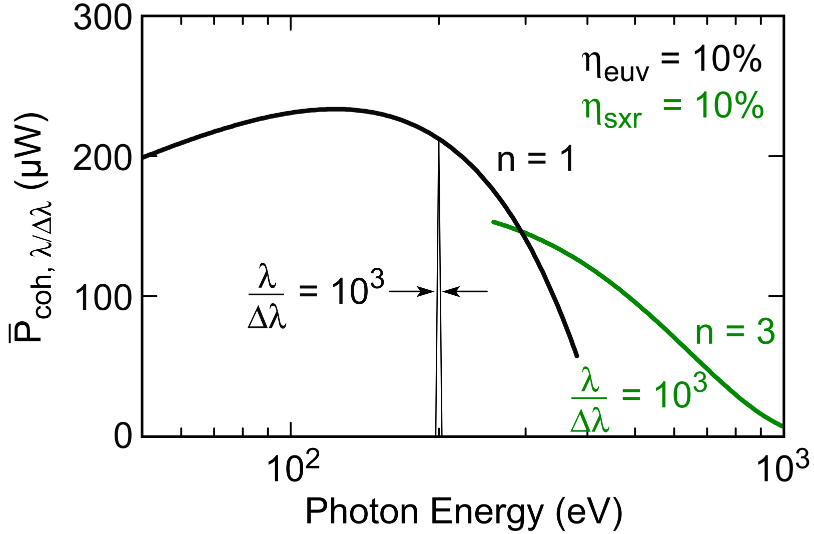
λ_u = 80 mm, N = 55

$0.5 \leq K \leq 4.0$

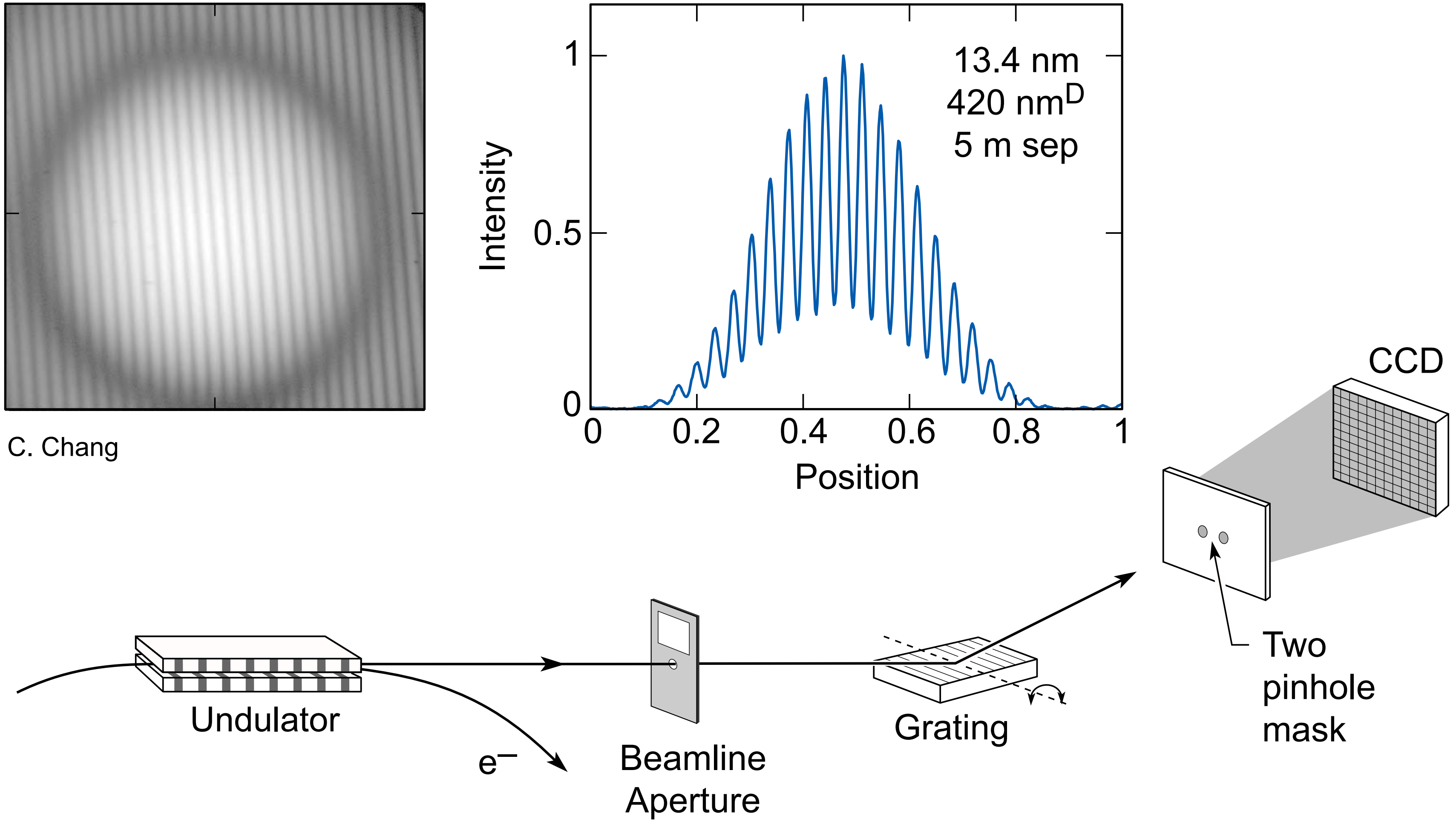
σ_x = 260 μm, σ_x' = 23 μr

σ_y = 16 μm, σ_y' = 3.9 μr



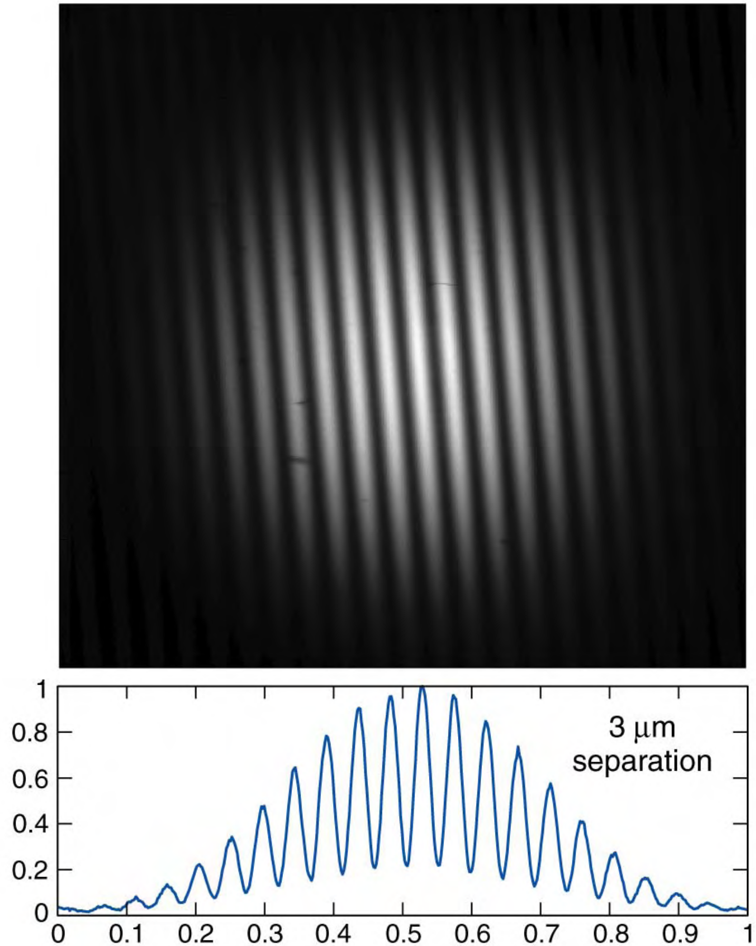


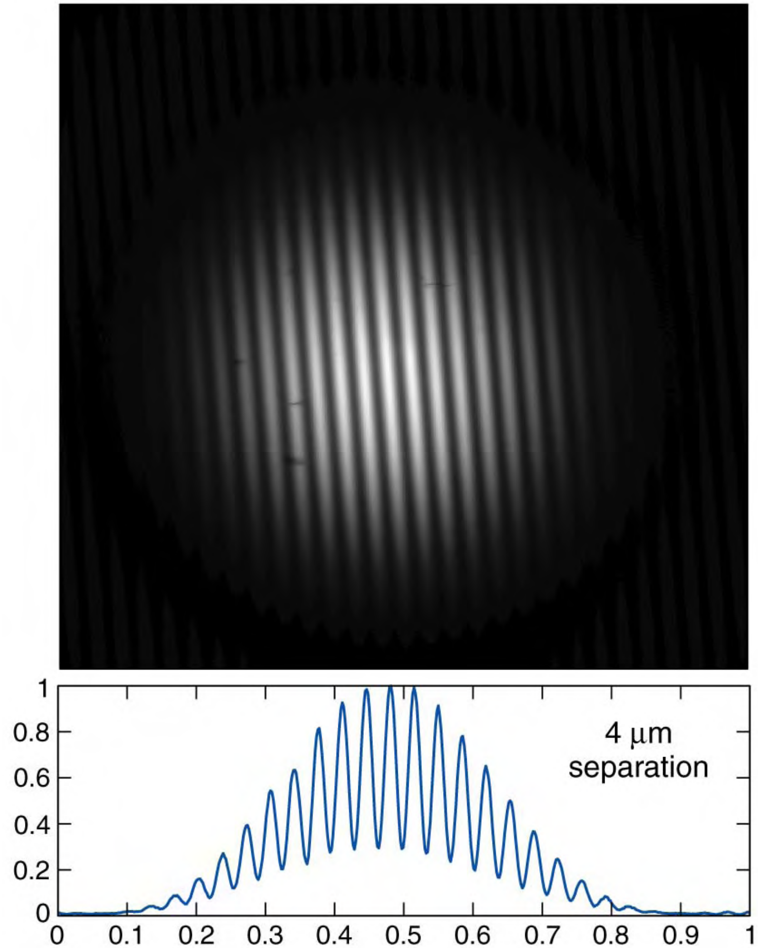
Measurement of Undulator Spatial Coherence



Courtesy of Chang Chang, UC Berkeley and LBNL.

Spatial Coherence Measurements of Undulator Radiation Using the Classic 2-Pinhole Technique

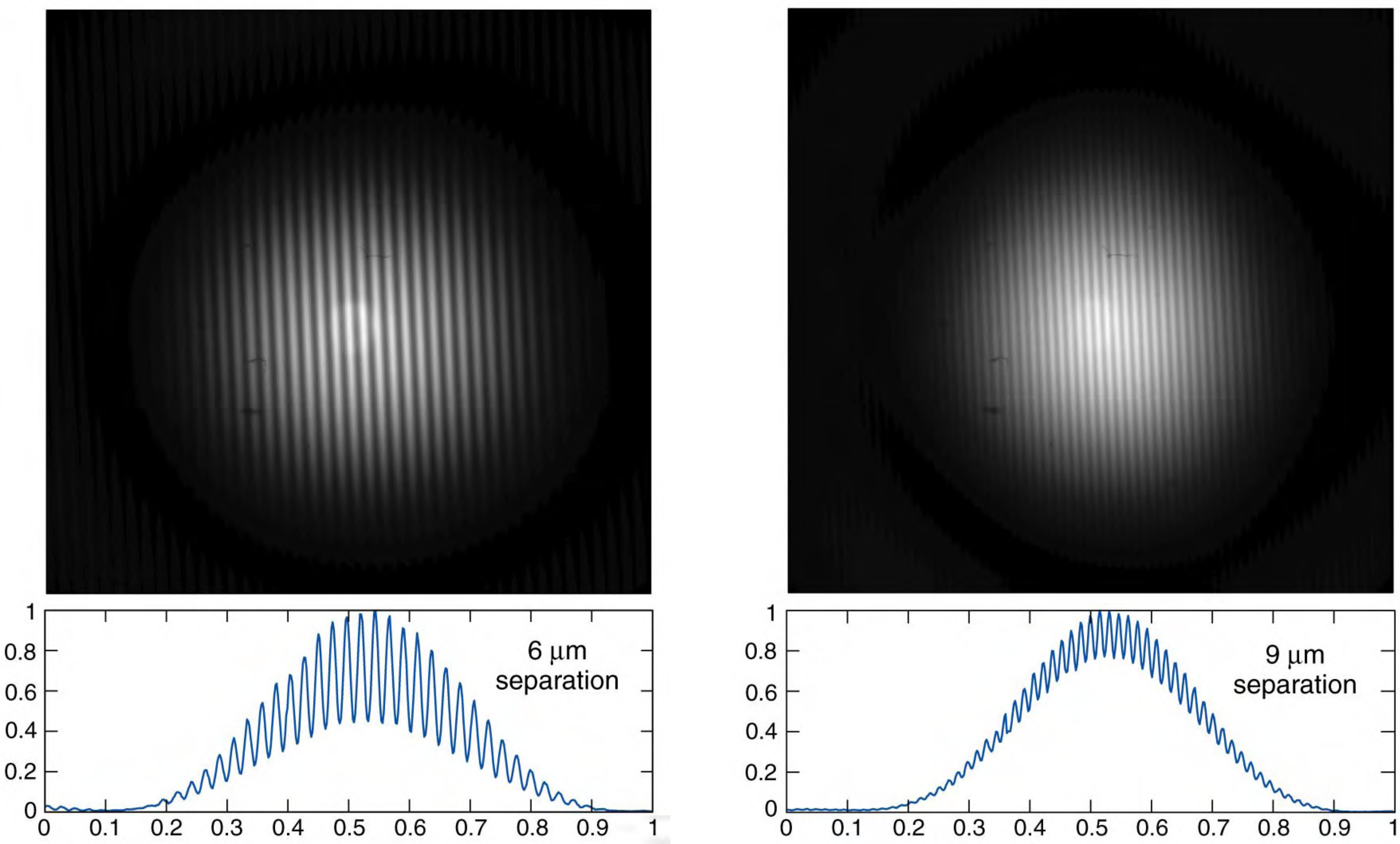




Courtesy of Chang Chang, UC Berkeley and LBNL.

λ = 13.4 nm, 450 nm diameter pinholes, 1024 x 1024 EUV/CCD at 26 cm
ALS, 1.9 GeV, λ_u = 8 cm, N = 55

Spatial Coherence Measurements of Undulator Radiation Using the Classic 2-Pinhole Technique

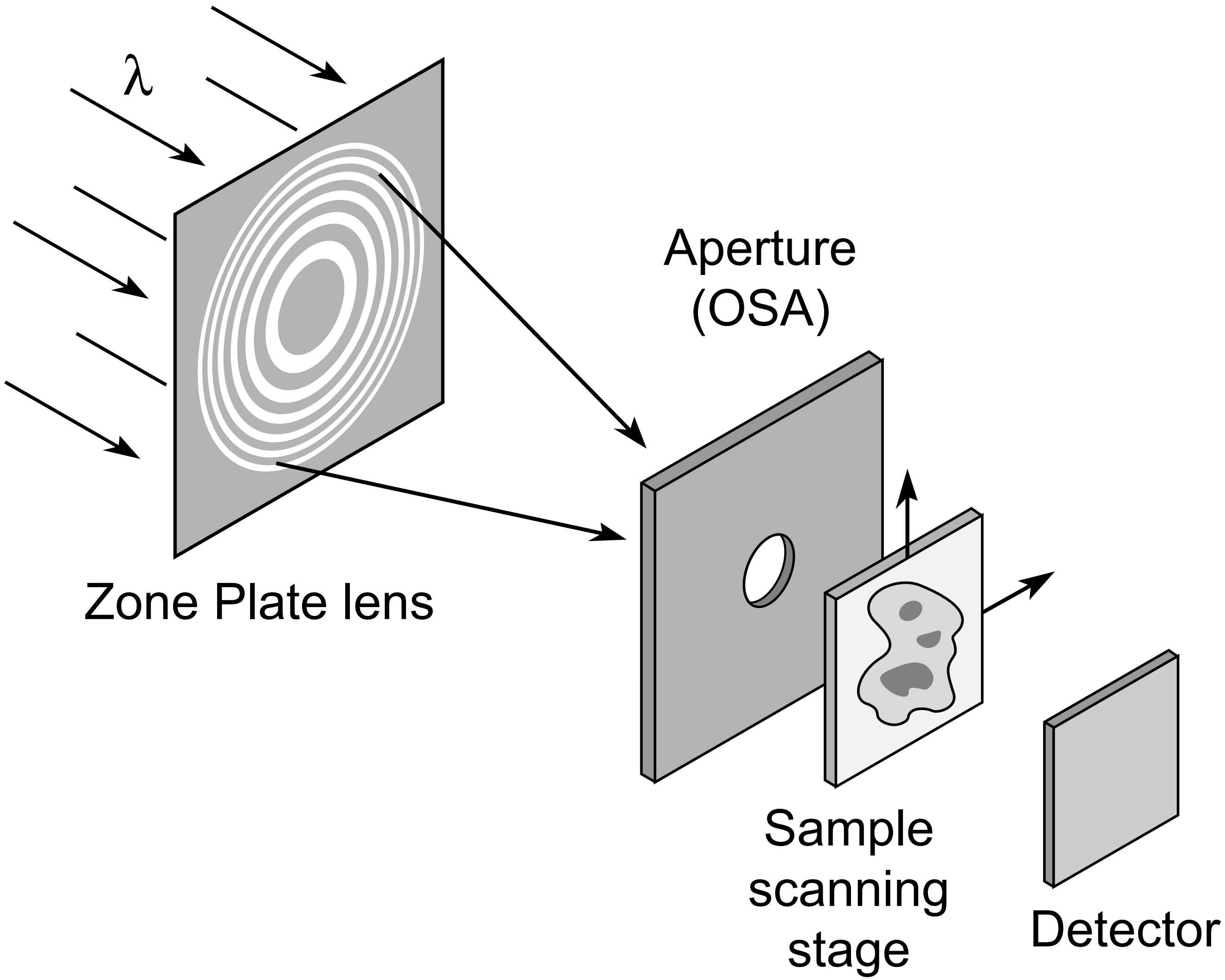


Courtesy of Chang Chang, UC Berkeley and LBNL.

λ = 13.4 nm, 450 nm diameter pinholes, 1024 x 1024 EUV/CCD at 26 cm

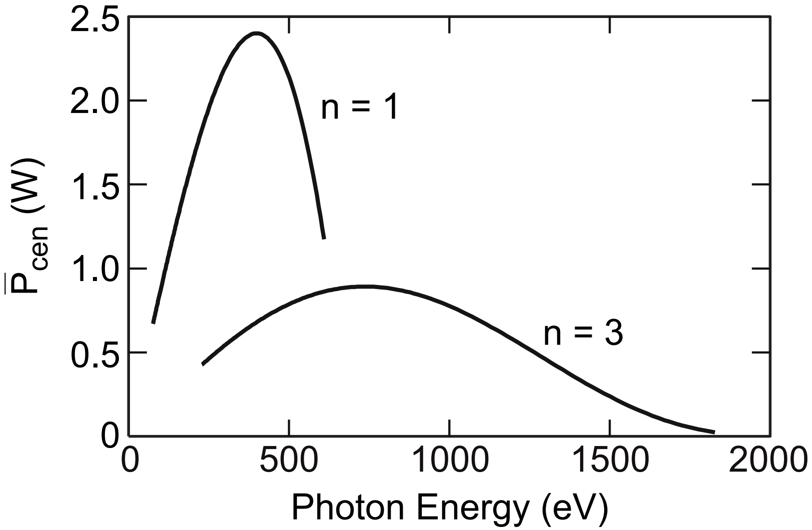
ALS, 1.9 GeV, λ_u = 8 cm, N = 55

The Scanning Soft X-Ray Microscope Requires Spatially Coherent Illumination

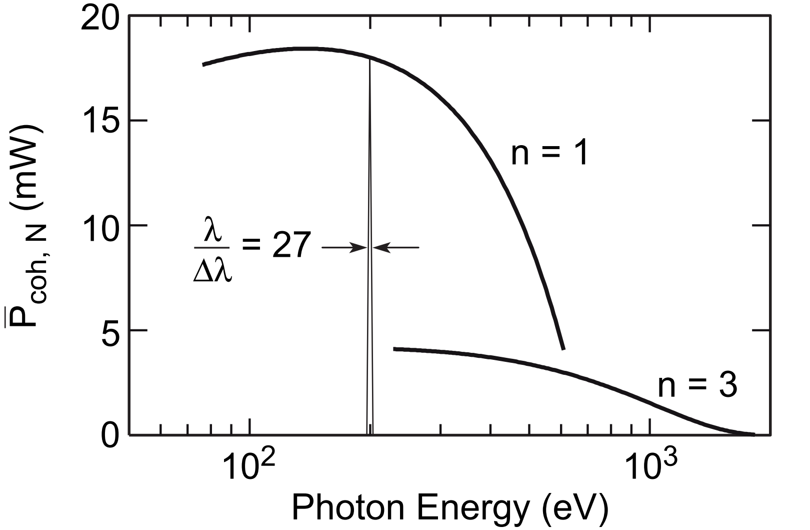


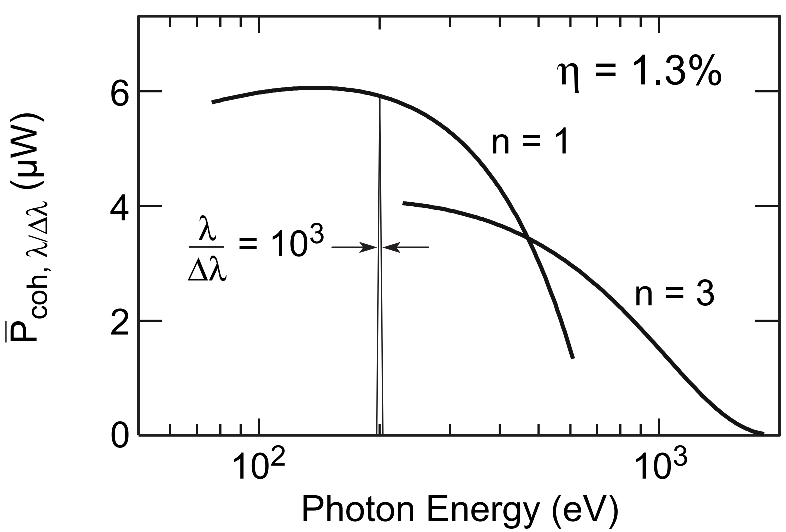
Coherent Power for an EPU at the ALS

U5 EPU

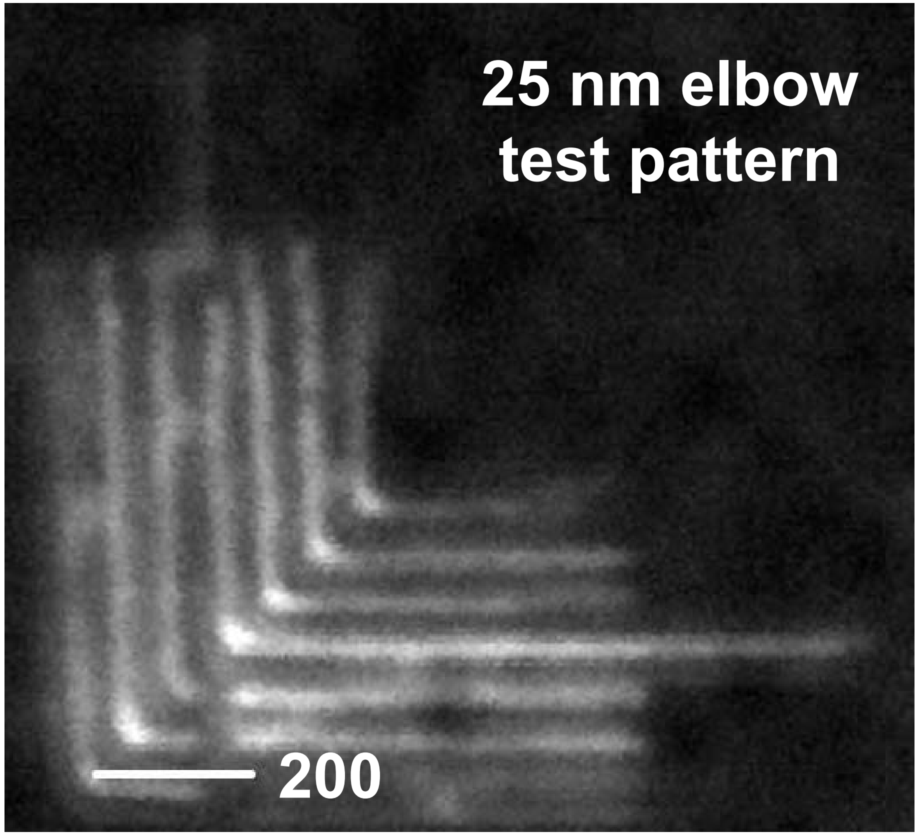


1.9 GeV, 400 mA
λ_u = 50 mm, N = 27
$0.5 \le K \le 4.0$
σ_x = 260 μm, σ_x' = 23 μr
σ_y = 16 μm, σ_y' = 3.9 μr
θ_{cen} = 61μr @ K = 0.87 (500 eV)





Spectromicroscopy: High Spatial and High Spectral Resolution Studies of Surfaces and Thin Films



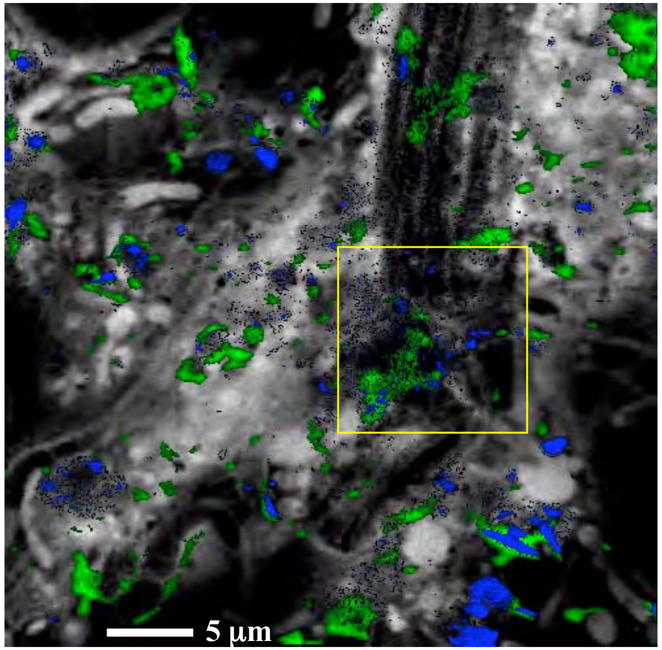
Scanning Soft X-Ray Microscope

ALS beamline 11.0.2
395 eV; $\lambda/\Delta\lambda \simeq 6000$
240×240 pixels
1.2 μm × 1.2 μm
2 ms dwell time

Courtesy of Tolek Tyliszczak (Dec. 2003)

Biofilm from Saskatoon River

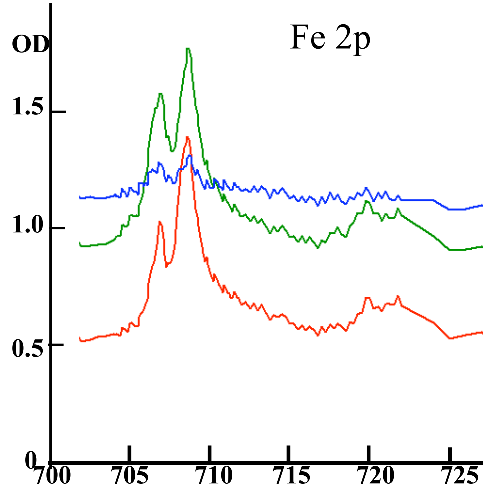
ALS-MES 11.0.2

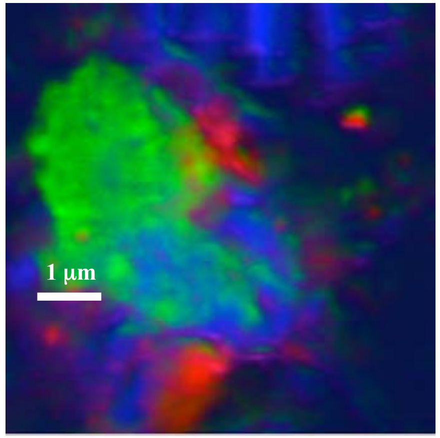


Protein (gray), Ca, K

RESULTS

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





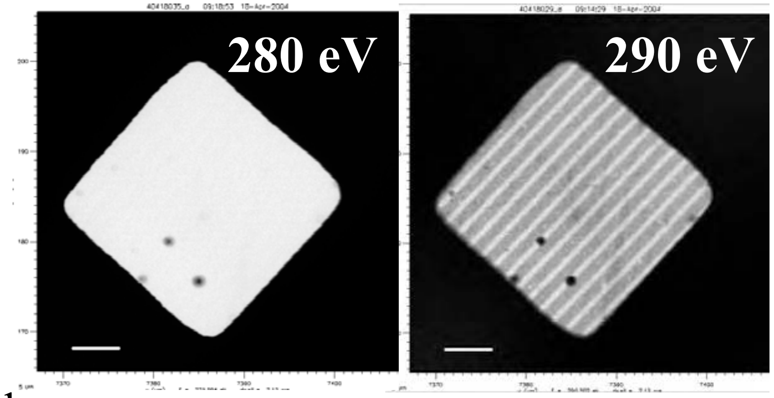
Different oxidation states (minerals) found for Fe & Ni

Tohru Araki, Adam Hitchcock (McMaster University)
Tolek Tyliszczak, LBNL
Sample from: John Lawrence, George Swerhone (NWRI-Saskatoon), *Gary Leppard* (NWRI-CCIW)

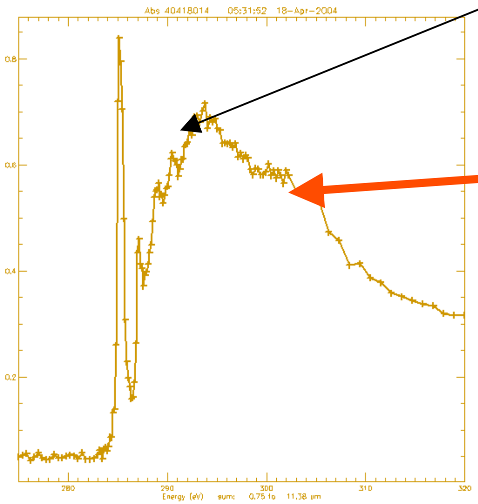
Patterned Polymer Photoresists

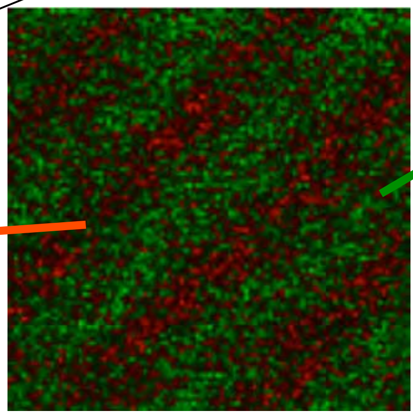
ALS-MES 11.0.2

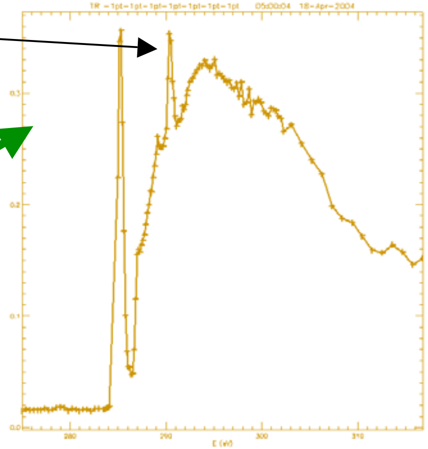
M.K. Gilles, R. Planques, S.R. Leone
LBNL
Samples from B. Hinsberg, F. Huele
IBM Almaden



Exposure to UV light results in loss of carbonyl peak







Map chemical spectra taken of pure samples
Onto a sample containing both components

Courtesy of Mary Gilles, LBNL

16 December 2004

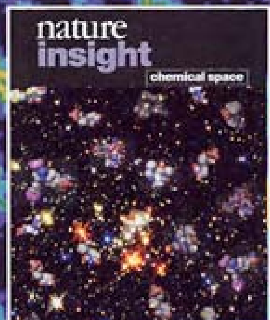
International weekly journal of science

nature

$10.00

www.nature.com/nature

Inside this week



X-ray holography

Lensless imaging at the nanoscale

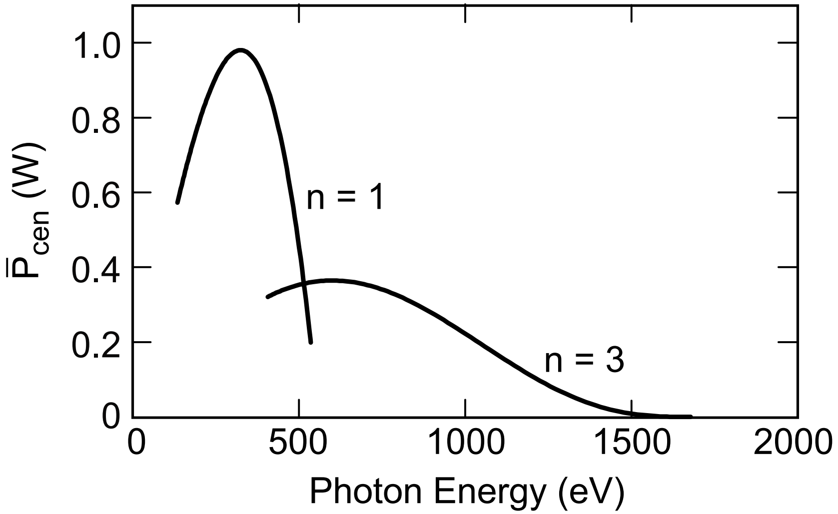
The 'Halloween storm'
How the Sun plays its tricks

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

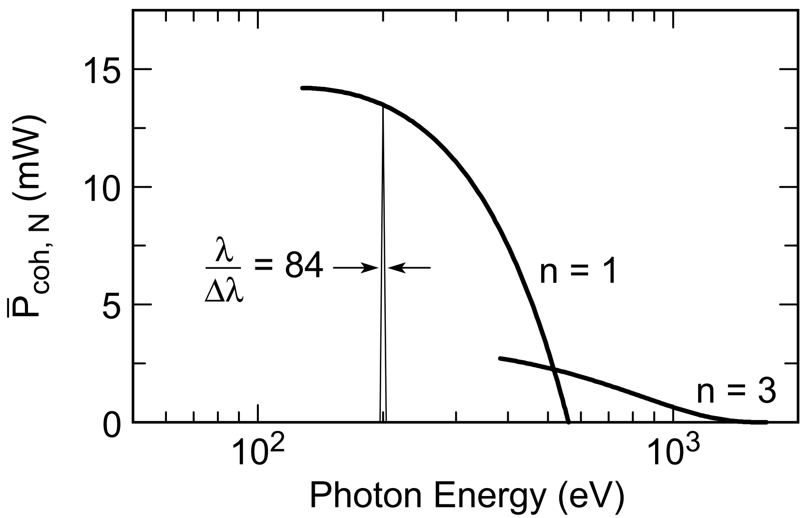
λ_u = 49 mm, N = 84

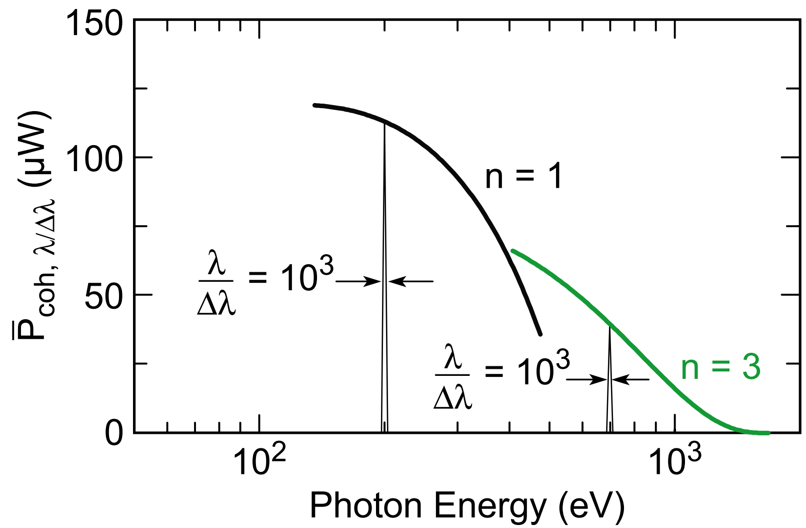
$0 \leq K \leq 2.5$

σ_x = 314 μm, σ_x' = 18 μr

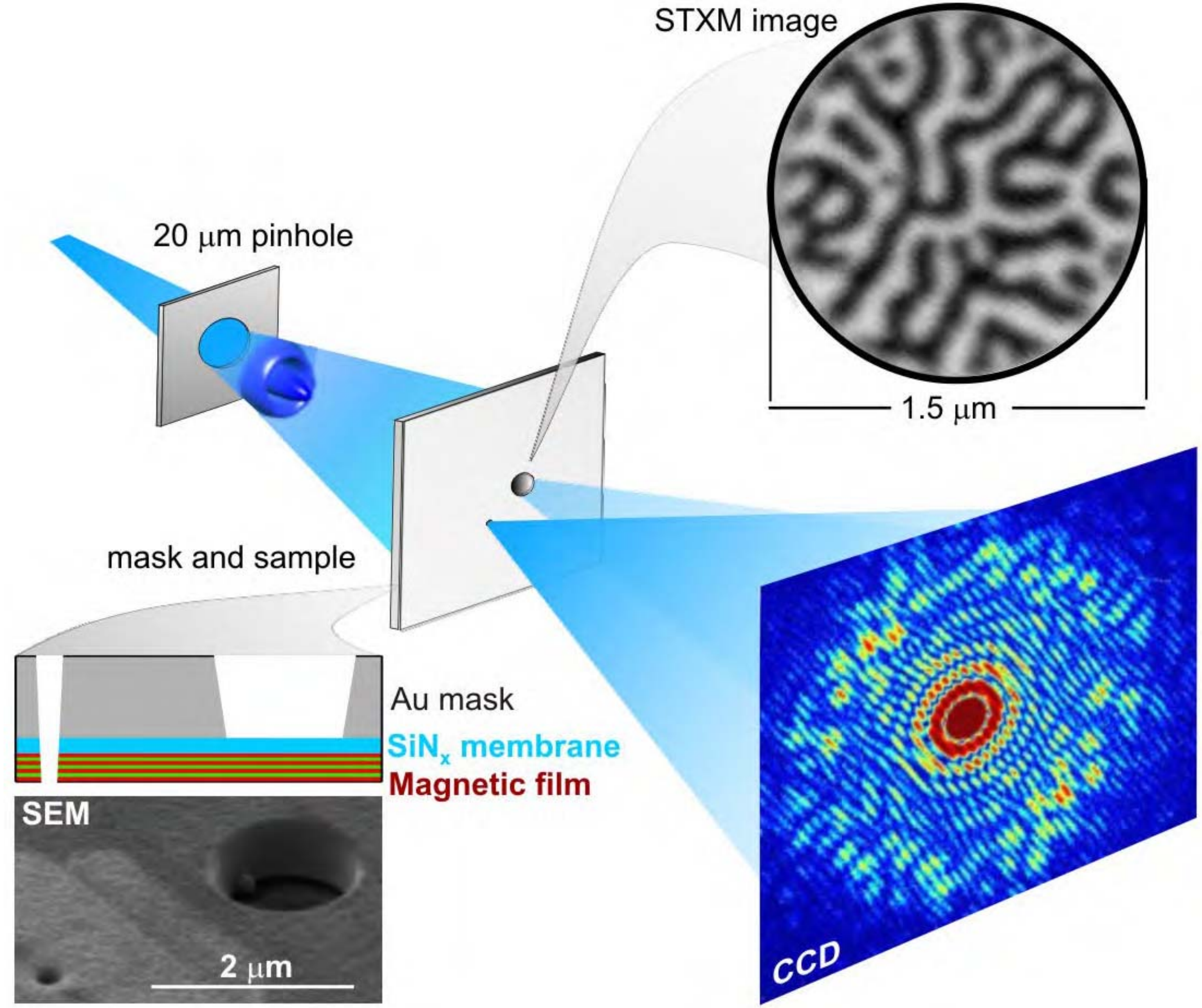
σ_y = 24 μm, σ_y' = 2 μr

η_{euv} = 10% ; η_{sxr} = 10%



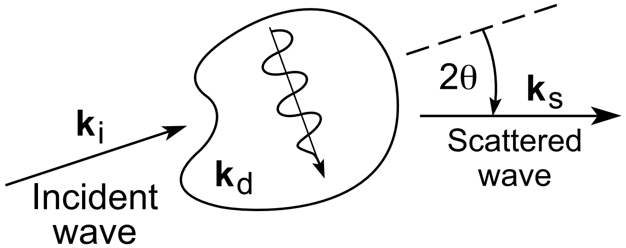


Lensless Imaging of Magnetic Nanostructures by X-Ray Spectro-Holography



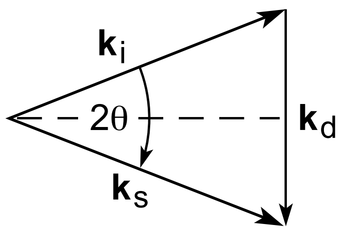
S. Eisebitt, J. Lüning, W.F. Schlotter, M. Lörgen, O. Hellwig,
W. Eberhardt & J. Stöhr / *Nature*, 16 Dec 2004

Coherent Soft X-Ray Scattering



$|\mathbf{k}_d| = 2\pi/d$ 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.

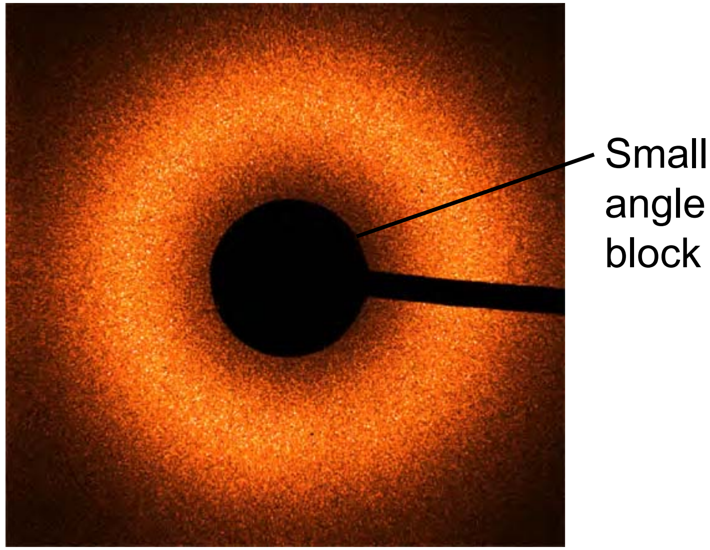
If the density distribution is stationary, or near stationary, the scattering diagram is isosceles.



$$\hbar\omega_s = \hbar\omega_i + \hbar\omega_d$$
$$\hbar\mathbf{k}_s = \hbar\mathbf{k}_i + \hbar\mathbf{k}_d$$

- 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

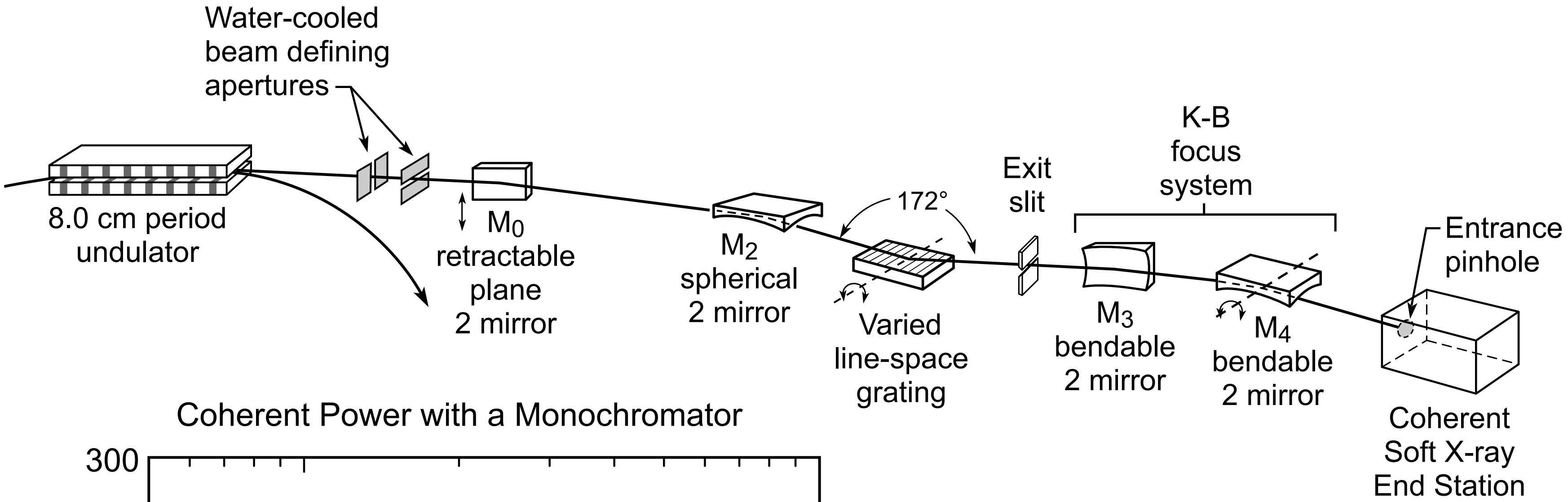
Coherent Scattering from a Pt:Co Multilayer



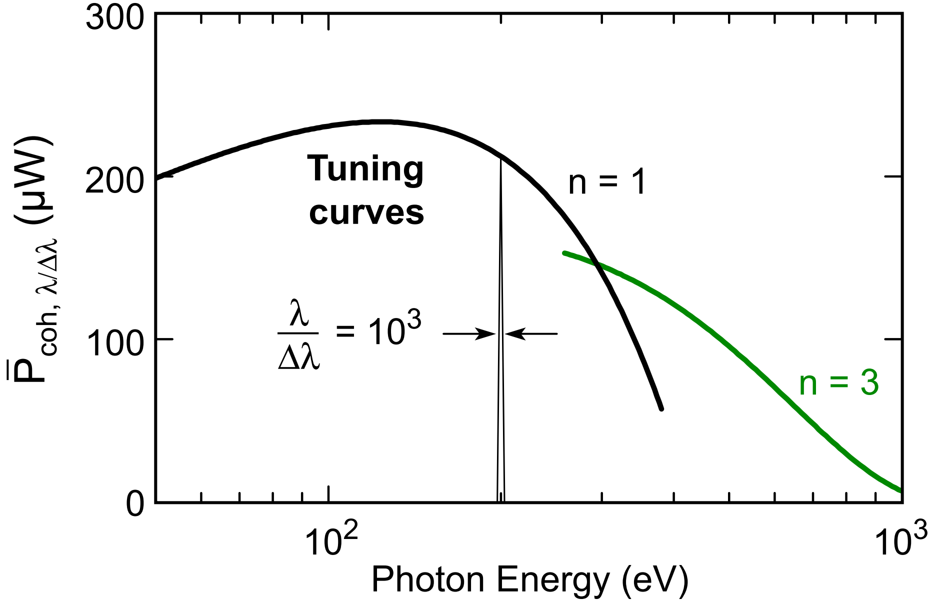
Soft x-ray speckle pattern: diffraction pattern of the magnetic domain structure

(Courtesy of Steve Kevan, University of Oregan)

Coherent Soft X-Ray Beamline: Use of a Higher Harmonic (n = 3) to AccessShorter Wavelengths



Coherent Power with a Monochromator



8.0 cm period, N = 55

1.9 GeV, 400 mA

$d \cdot \theta = \lambda/2\pi$

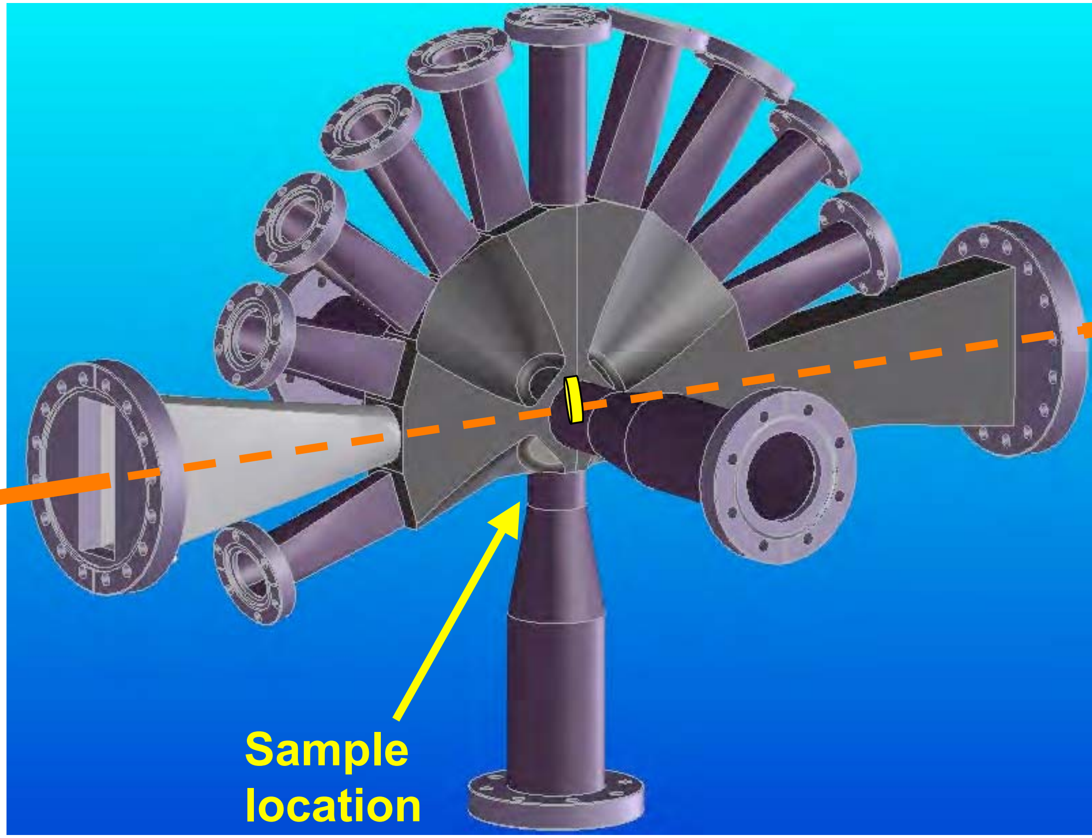
$\ell_{coh} = 1000\ \lambda/2$

$\eta_{euv} = 10\%$, $\eta_{sxr} = 10\%$

Coherent Soft X-Ray Magnetic Scattering Endstation

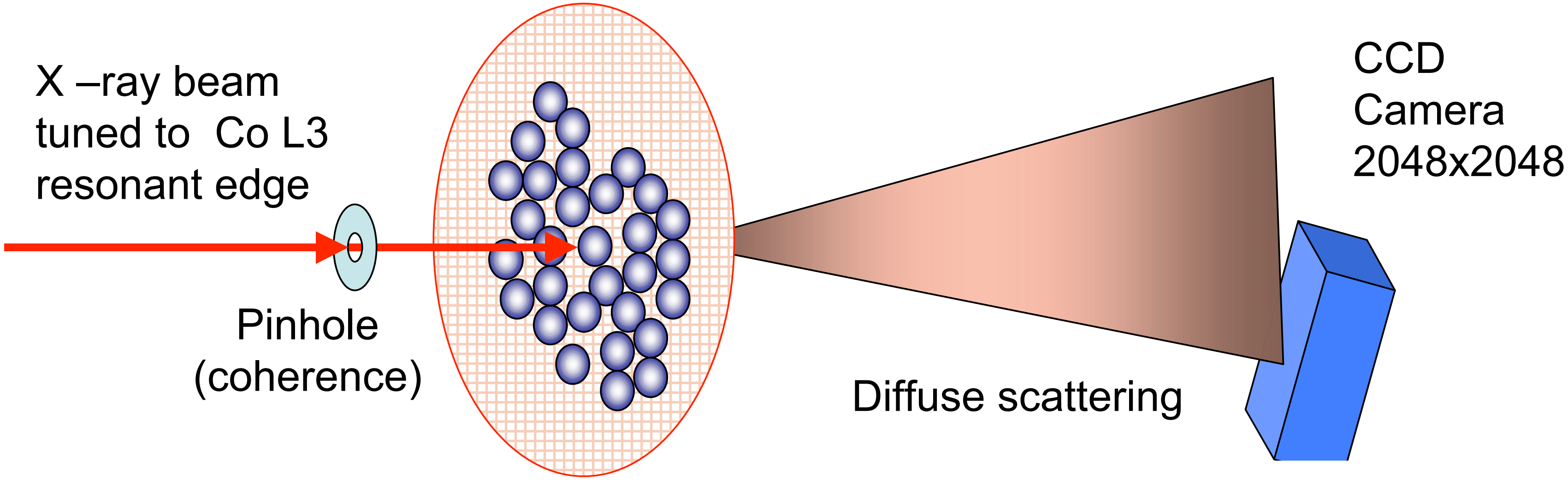
Flangosaurus

Scattering in Transmission



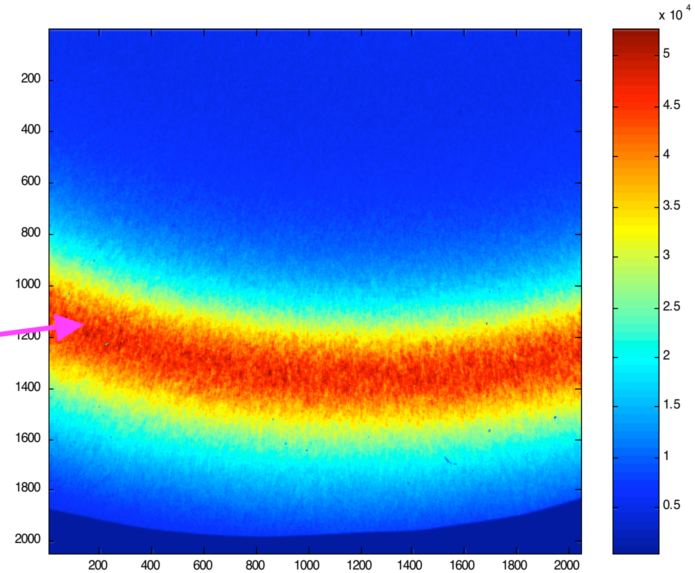
Courtesy of K.Chesnel, S. Kevan, U. Oregon

Example of Experiment in Transmission: Coherent Scattering from Nanoparticles



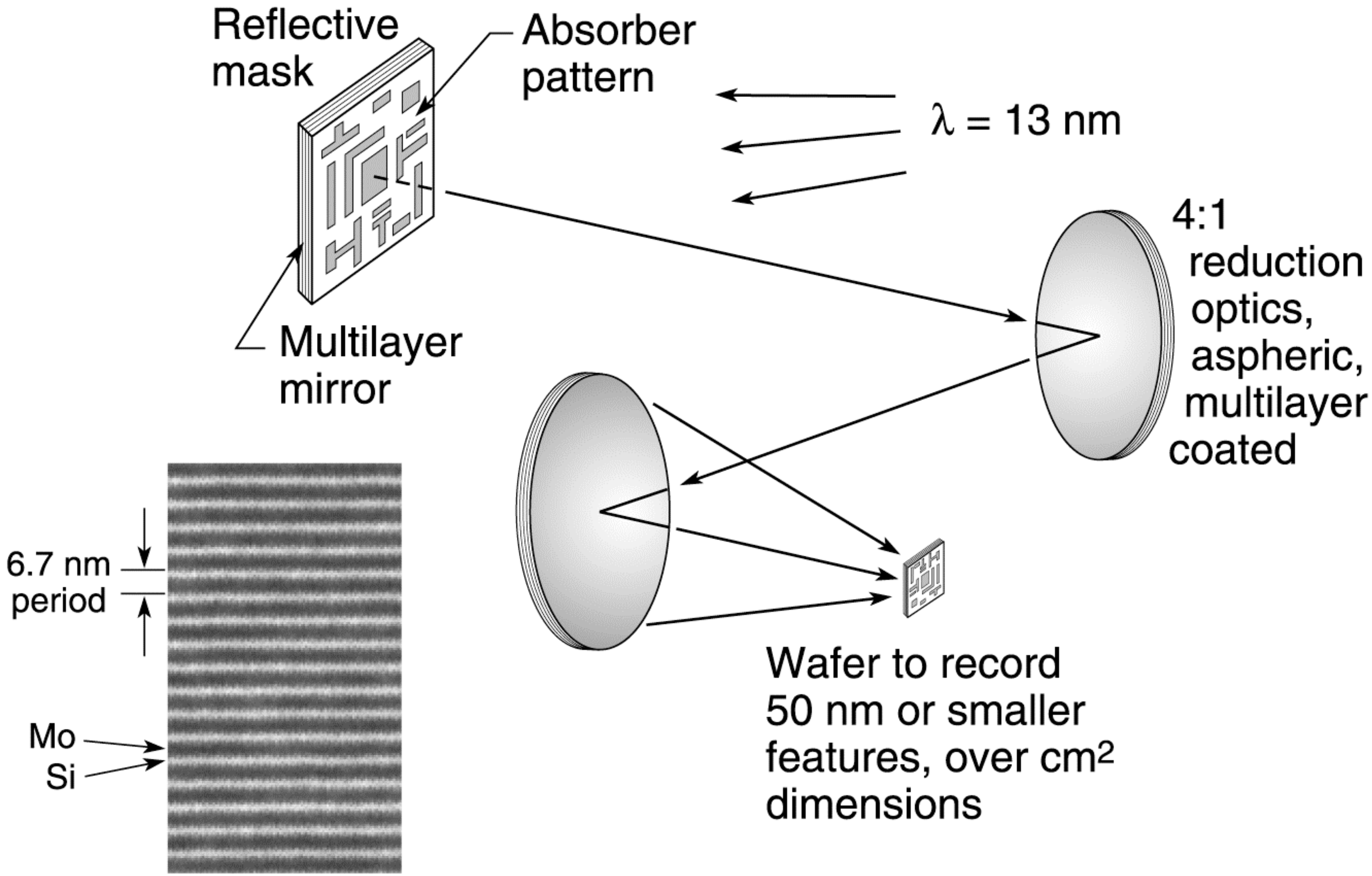
Co Nanoparticles assembly
precipitated on TEM grid

Scattering ring
related to
interparticle distance
~12nm



Courtesy of K.Chesnel, S. Kevan, U. Oregon

Extreme ultraviolet (EUV) lithography based on multilayer coated optics



International Technology Roadmap for Semiconductors†

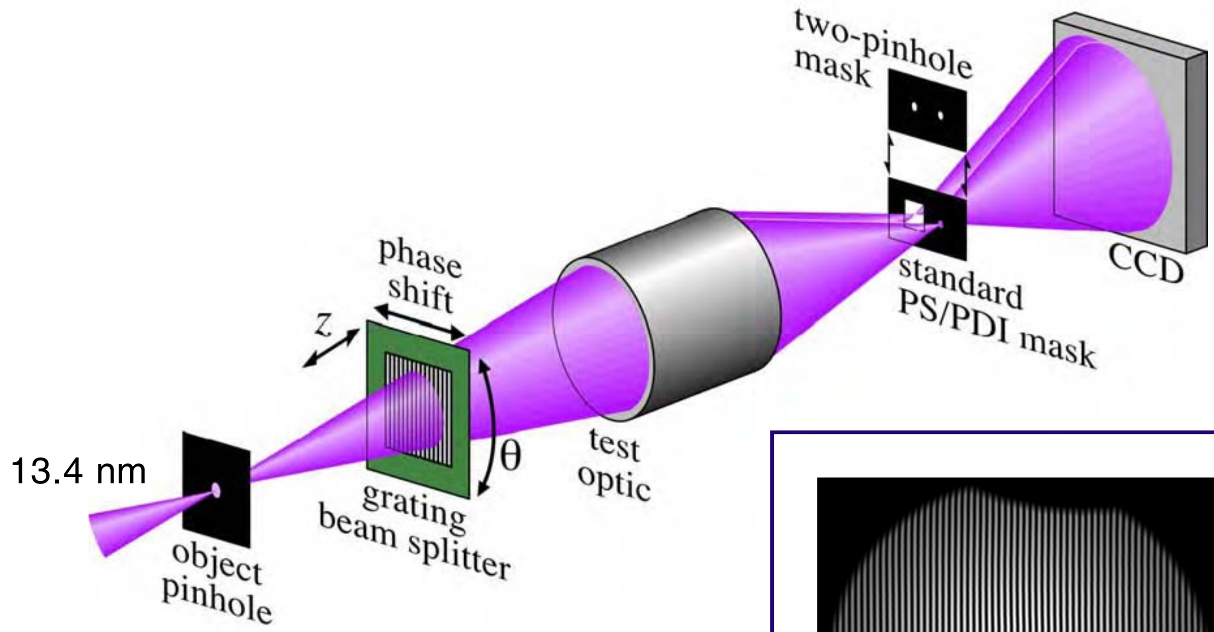
First year of volume production	2003* ~~2004~~	2005* ~~2007~~	2008* ~~2010~~	2010* ~~2013~~	2012* ~~2016~~
Technology Generation (half pitch, 1:1, printed in resist)	90 nm	65 nm	45 nm	32 nm	22 nm
Isolated Lines (in resist) [Physical gate, metalized]	53 nm [37 nm]	35 nm [25 nm]	25 nm [18 nm]	18 nm [13 nm]	13 nm [9 nm]
Chip Frequency	2.5 GHz	4.9 GHz	9.5 GHz	19 GHz	36 GHz
Transistors per chip (HV) (3 × for HP ; 5 × for ASICs)	190 M	390 M	770 M	1.5 B	3.1 B
DRAM Memory (bits per chip)	1.1 G	2.2 G	4.3 G	8.6 G	34 G
Field Size (mm × mm)	22 × 32	22 × 32	22 × 32	22 × 32	22 × 32
Wafer Size (diameter)	300 mm	300 mm	300 mm	450 mm	450 mm

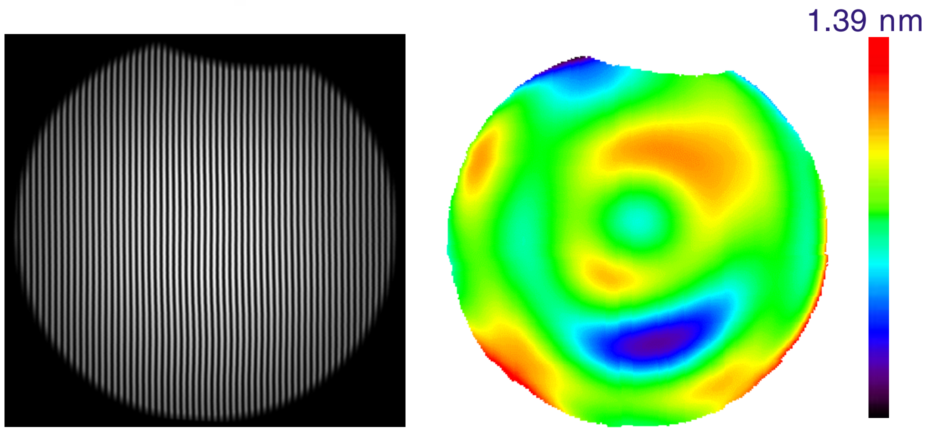
†Semiconductor Industry Association (SIA), December 2004 update.

***Possible 2-year cycle for leading edge companies.**

SIA_Rdmp_2008.ai

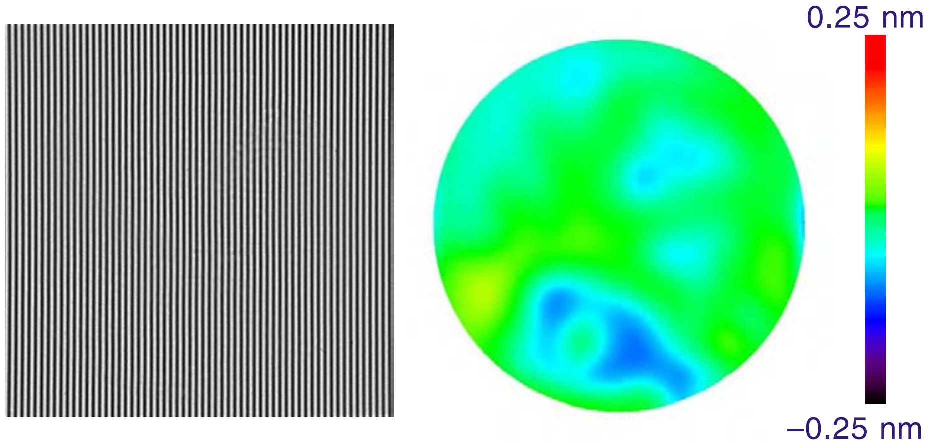
Coherent Undulator Radiation Used for Interferometry Testing Multilayer Coated Optics for EUV Lithography





Interferogram

Wavefront
σ = 0.52 nm rms = $\lambda_{euv}/26$

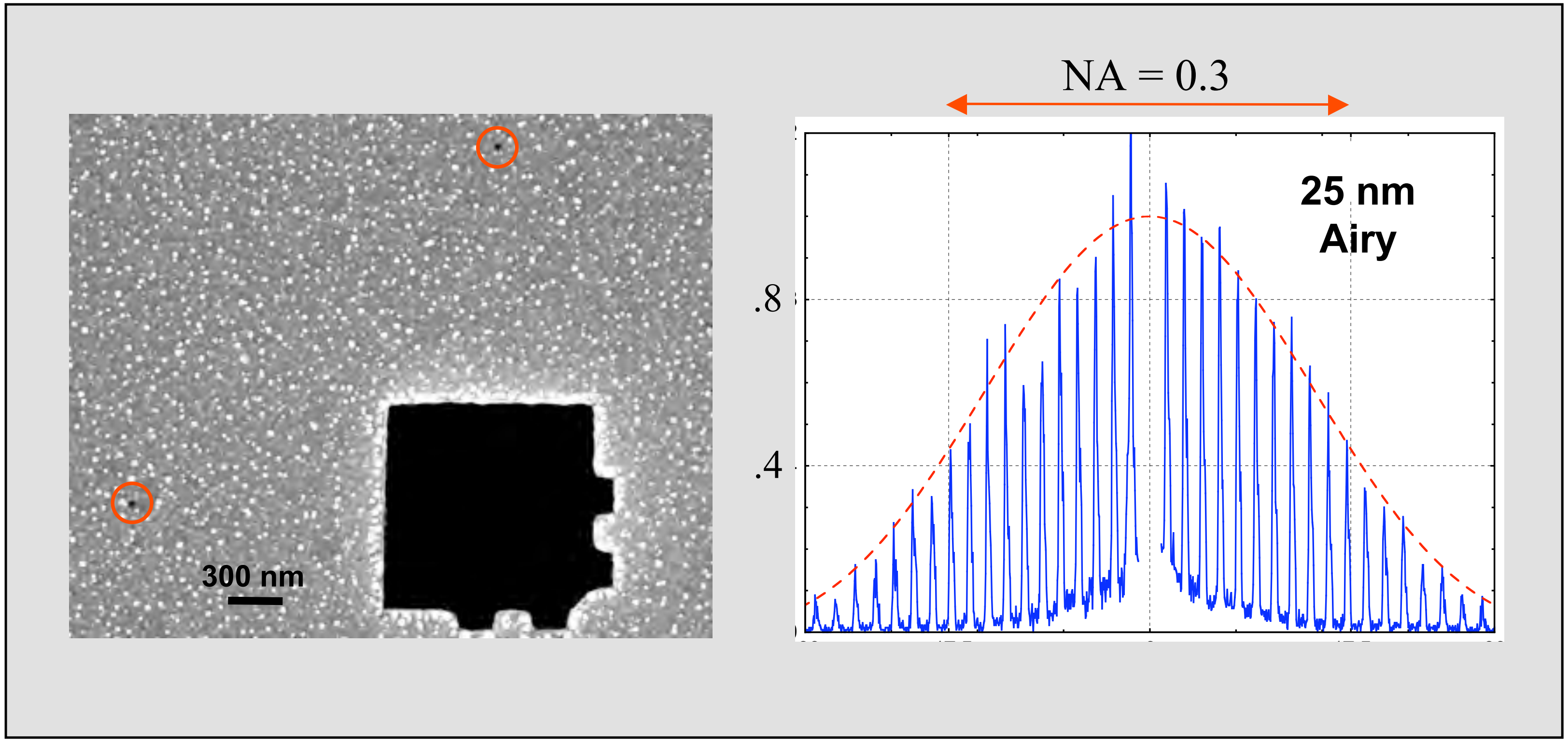


Null test interferogram

Reference wavefront
σ = 0.044 nm rms = $\lambda_{euv}/300$

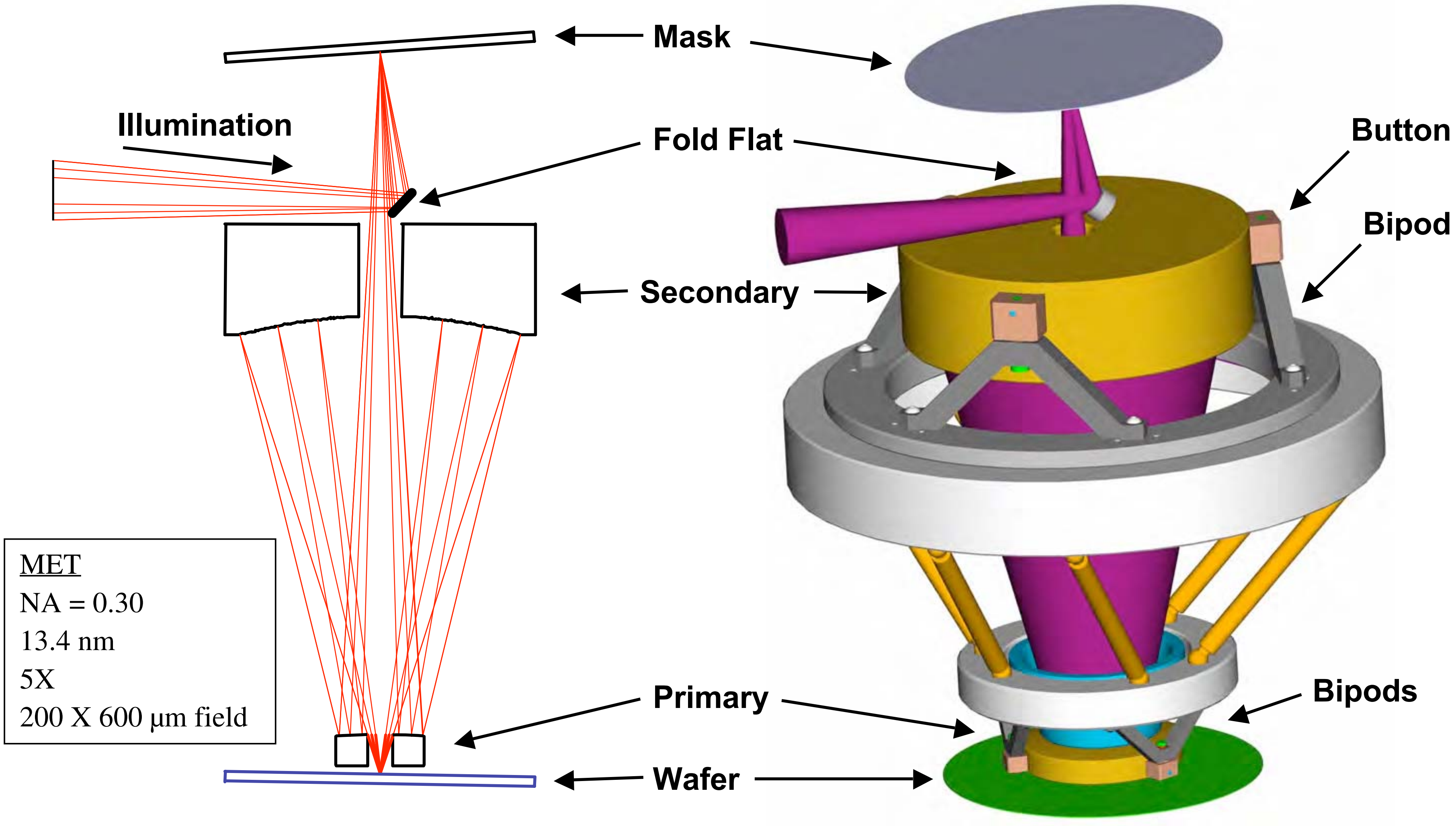
Courtesy of K. Goldberg, P. Naulleau, J. Bokor, et al., LBNL.

25 nm Pinholes for 0.3 NA EUV Interferometry



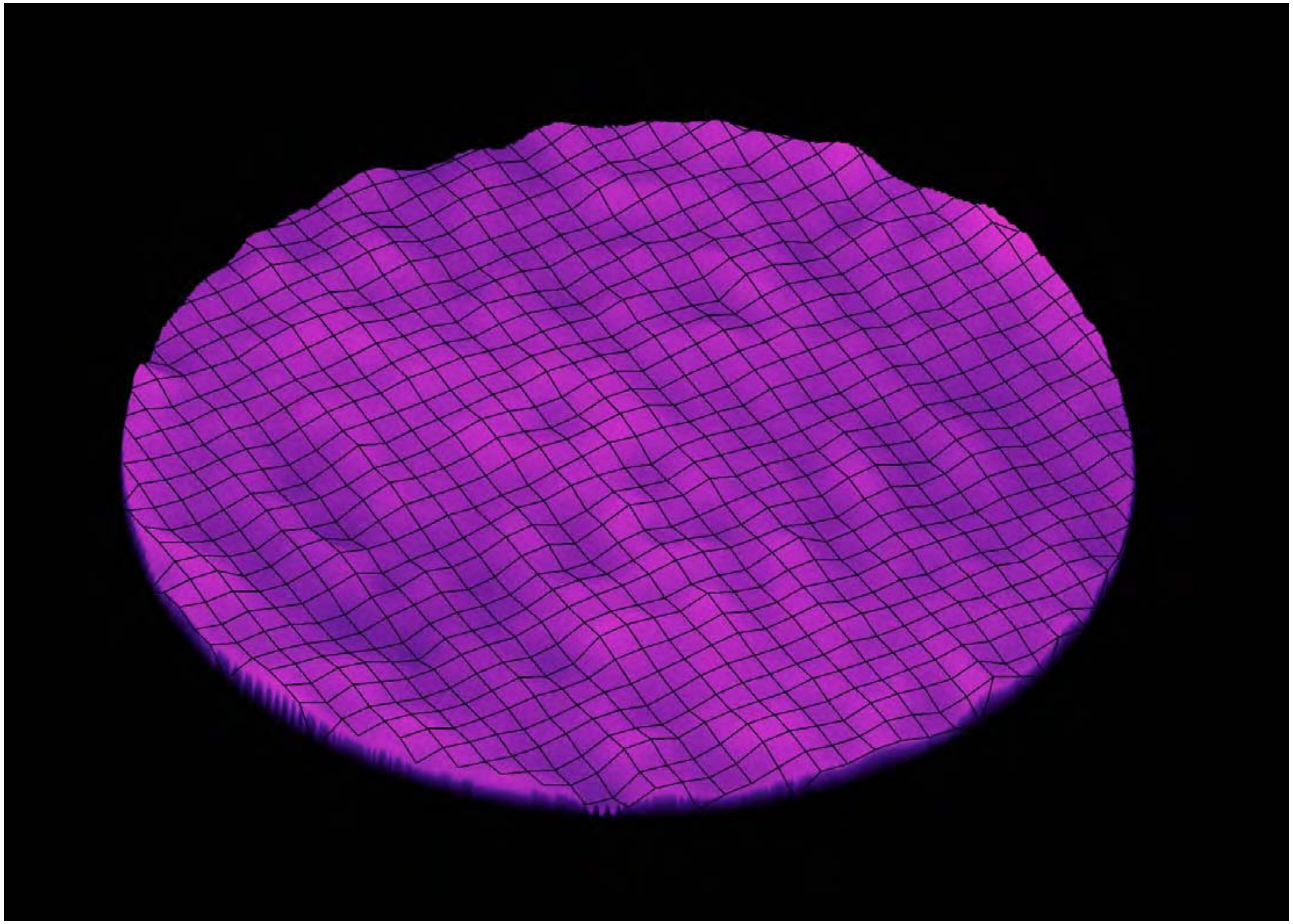
Courtesy of E. Gullikson, E. Anderson and K. Goldberg, LBNL.

A 0.30 NA Micro-Exposure Tool (MET) for Testing EUV Resist Patterns to 12 nm Feature Size



(Courtesy of J. Taylor, LLNL)

EUV wavefront measurements to $\lambda_{euv}/300$



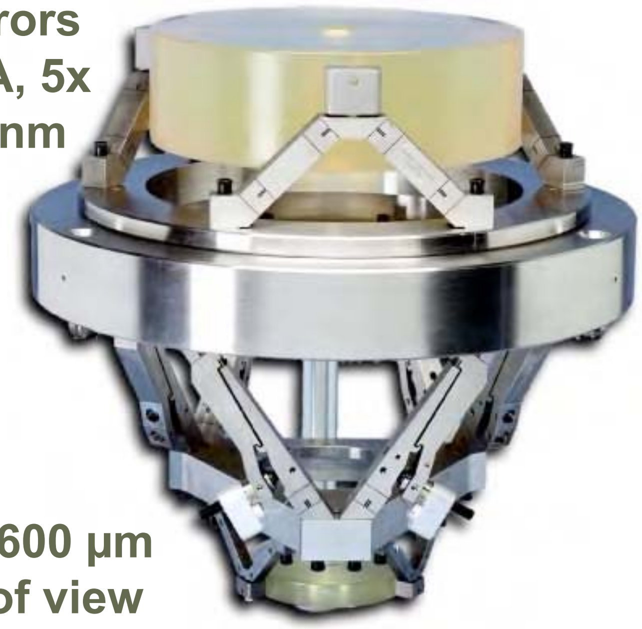
Courtesy of K. Goldberg, LBNL.

MET At-Wavelength Interferometry and Alignment Preparation for Static Microfield Imaging

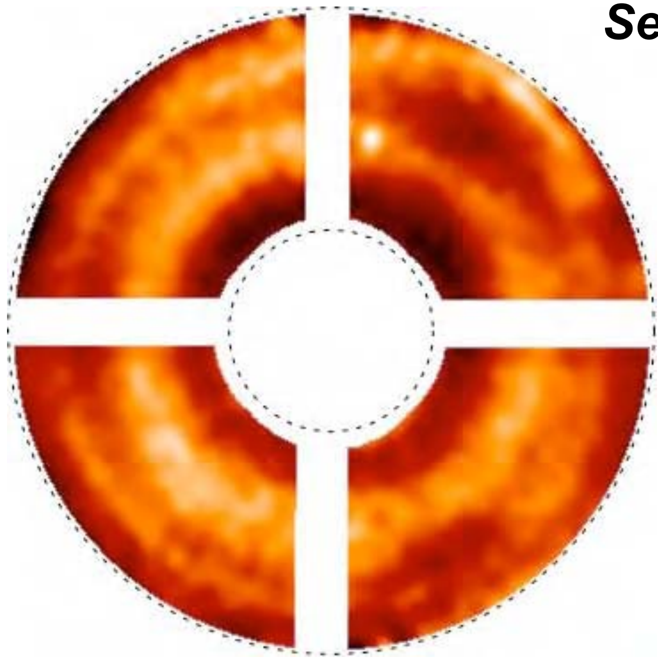
BERKELEY LAB

MET
Micro-Exposure Tool

2 mirrors
0.3 NA, 5x
13.5 nm



200 x 600 µm
field of view



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
	$\lambda/17$

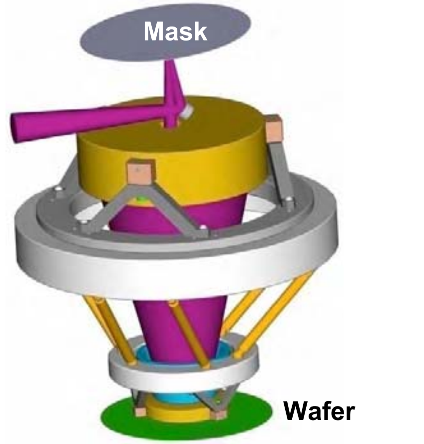
aberrations
may be reduced
in final alignment

- 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.

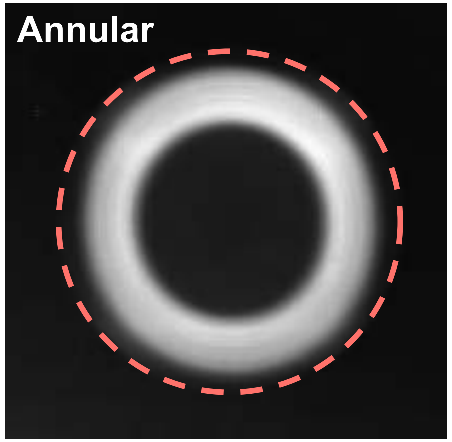
(Courtesy of K. Goldberg and P. Naulleau, LBNL)

Addressing critical EUV lithography issues for Sematech at the ALS: testing state-of-the-art EUV resists

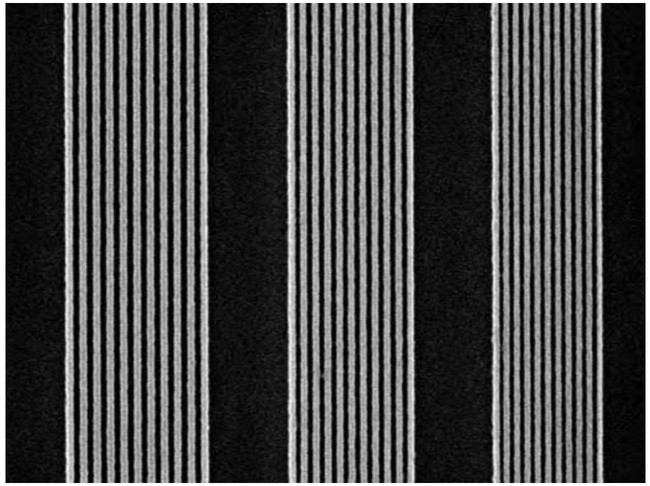
Two-bounce, 0.3 NA, MET at ALS Beamline 12.0



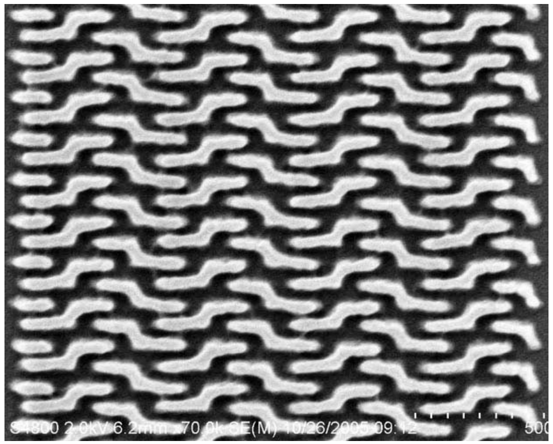
Programmable illumination



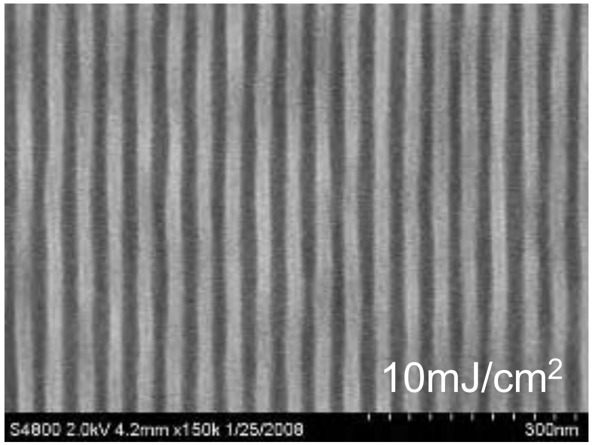
45 nm 40 nm 35 nm



35 nm



22 nm lines and spaces

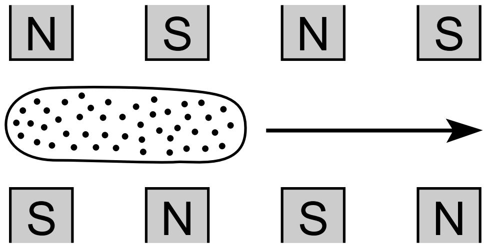


Significant issue for EUV lithography

When will EUV resists be available with combined high spatial resolution (20 nm), high sensitivity (10 mj/cm^2), and low line edge roughness (LER, 1.2 nm)?

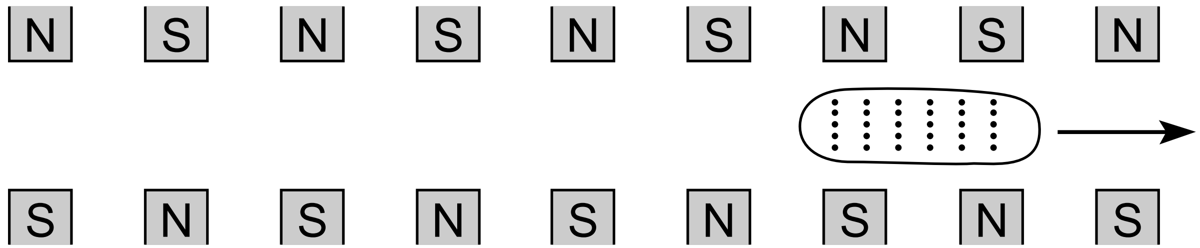
Major support and collaborators include Sematech, Intel, AMD, IBM, Samsung and others.
Courtesy of Patrick Naulleau, CXRO/LBNL.

Undulators and FELs



$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

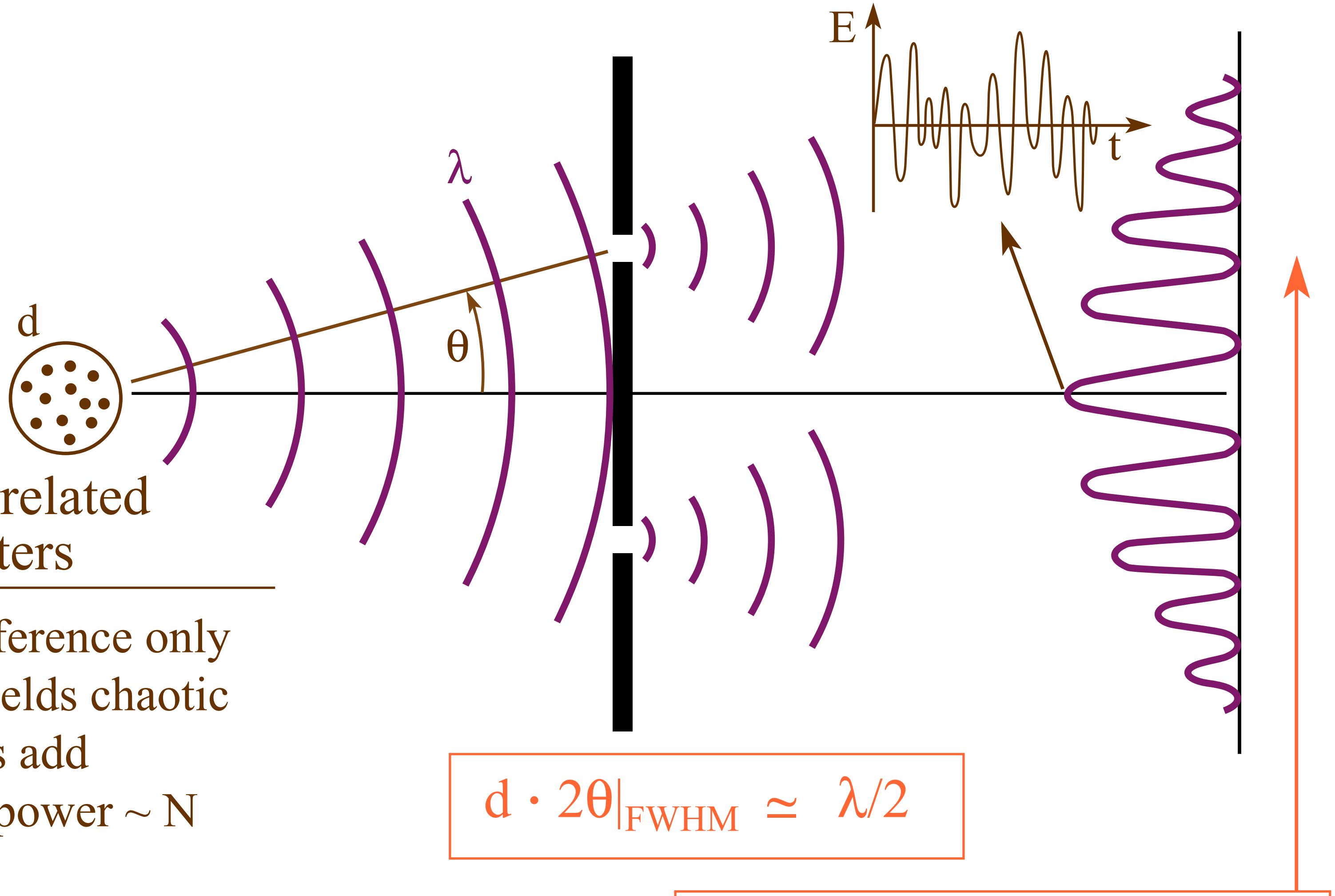
Undulator – uncorrelated electron positions, radiated fields uncorrelated, intensities add, limited coherence, power ~ N.



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 ~ N^2

$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Young's Double Slit Experiment with Random Emitters: Young did not have a laser



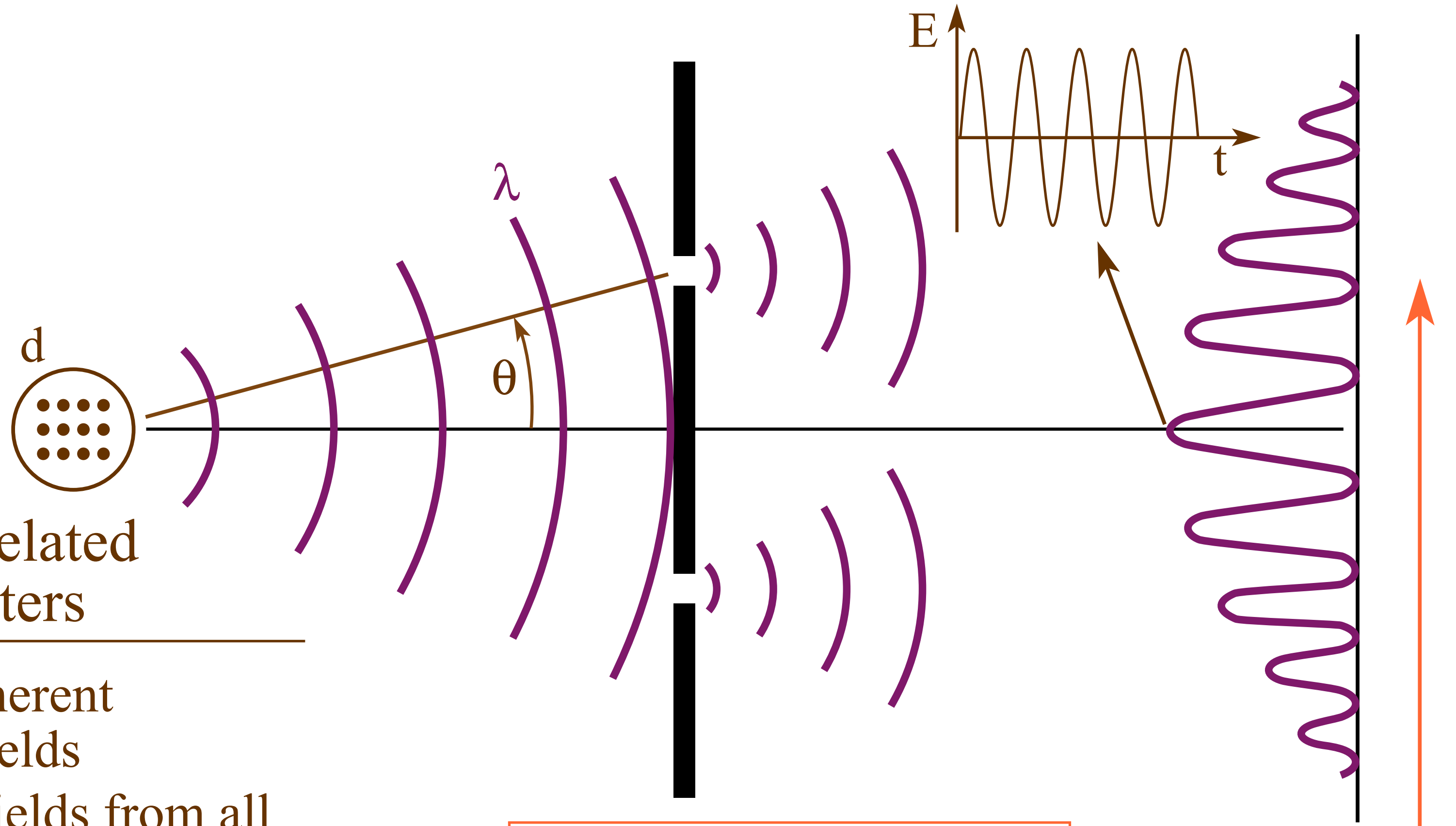
N uncorrelated emitters

- Self-interference only
- Electric fields chaotic
- Intensities add
- Radiated power ~ N

$$d \cdot 2\theta|_{FWHM} \simeq \lambda/2$$

$$\lambda_{coh} = \lambda^2/2\Delta\lambda = \frac{1}{2} N_{coh}\lambda$$

Young's Double Slit Experiment with Phase Coherent Emitters (some lasers, or properly seeded FELs)



N correlated emitters

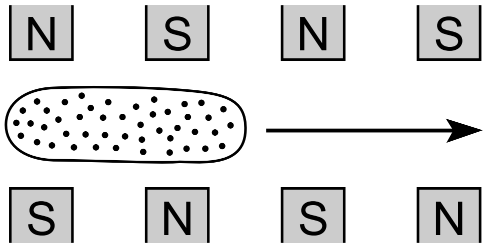
- Phase coherent electric fields
- Electric fields from all particles interfere constructively
- Radiated power ~ N^2
- New phase sensitive probing of matter possible

$$d \cdot 2\theta|_{FWHM} \simeq \lambda/2$$

$$\lambda_{coh} = \lambda^2/2\Delta\lambda = \frac{1}{2} N_{coh}\lambda$$

Professor David Attwood
Univ. California, Berkeley

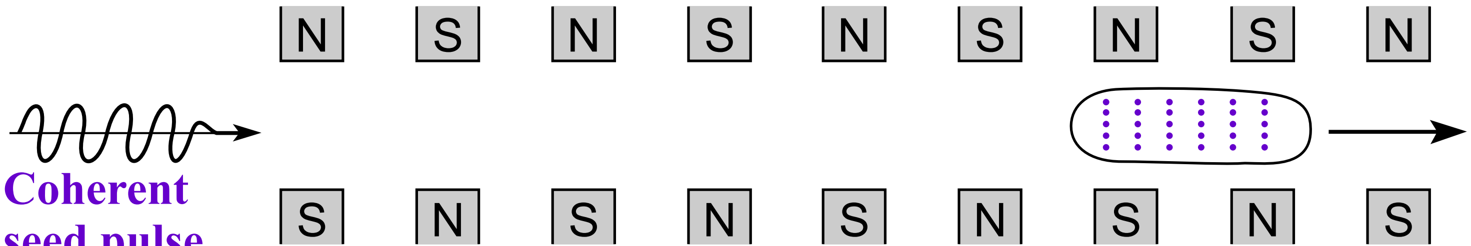
Seeded FEL



$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Undulator – uncorrelated electron positions, radiated fields uncorrelated, intensities add, limited coherence, power ~ N.

Better electron distribution throughout bunch, resulting in better coherence properties.



Coherent seed pulse

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 ~ N^2

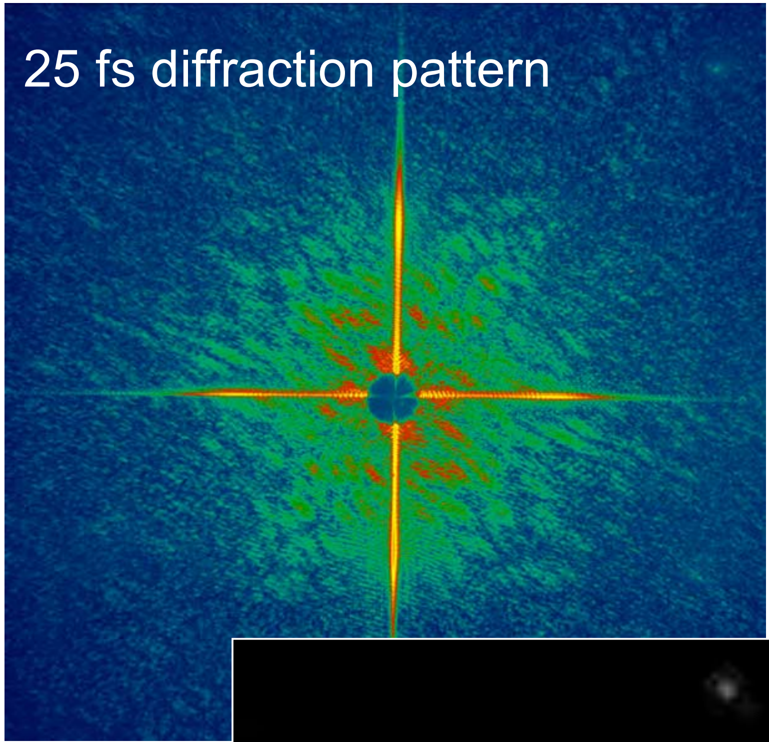
$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

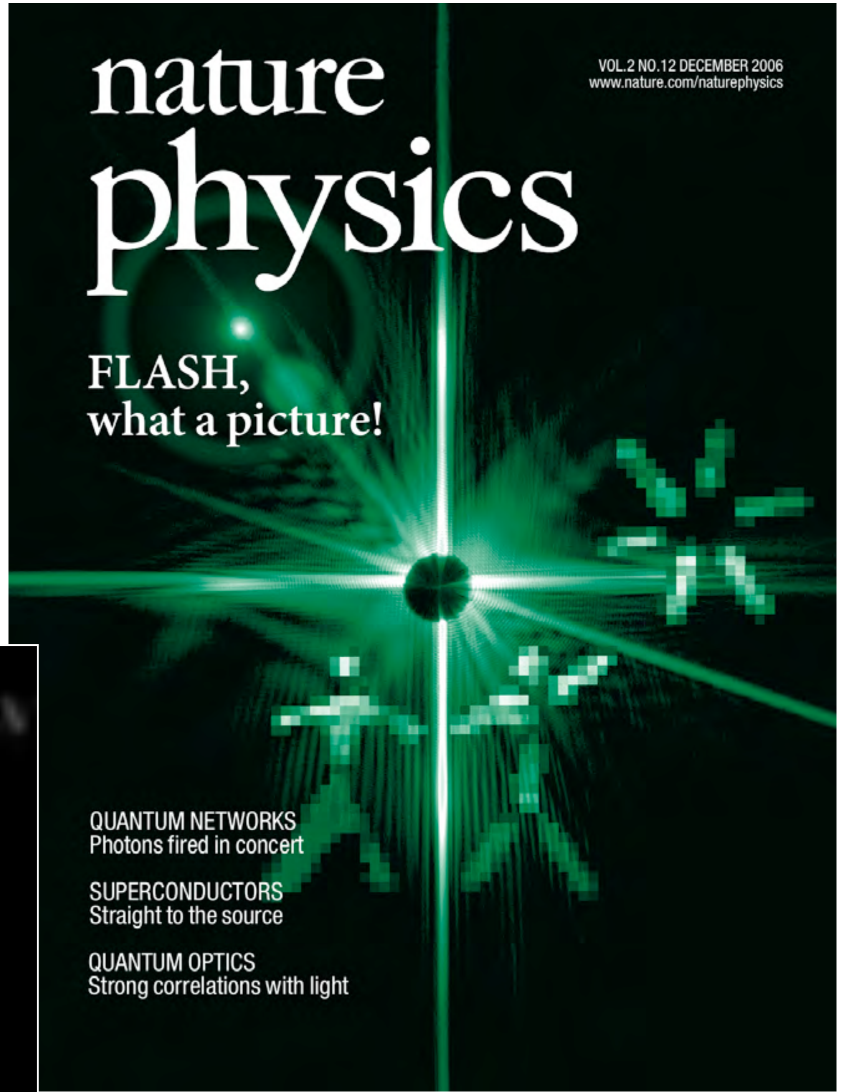
FLASH EUV/soft x-ray FEL at DESY Lab, Hamburg

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





Chapman et al, *Nature Phys* **2** 839 (2006)

Lectures online at www.youtube.com

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