Coherence, Brightness and Time Structure: from Synchrotrons to FELs

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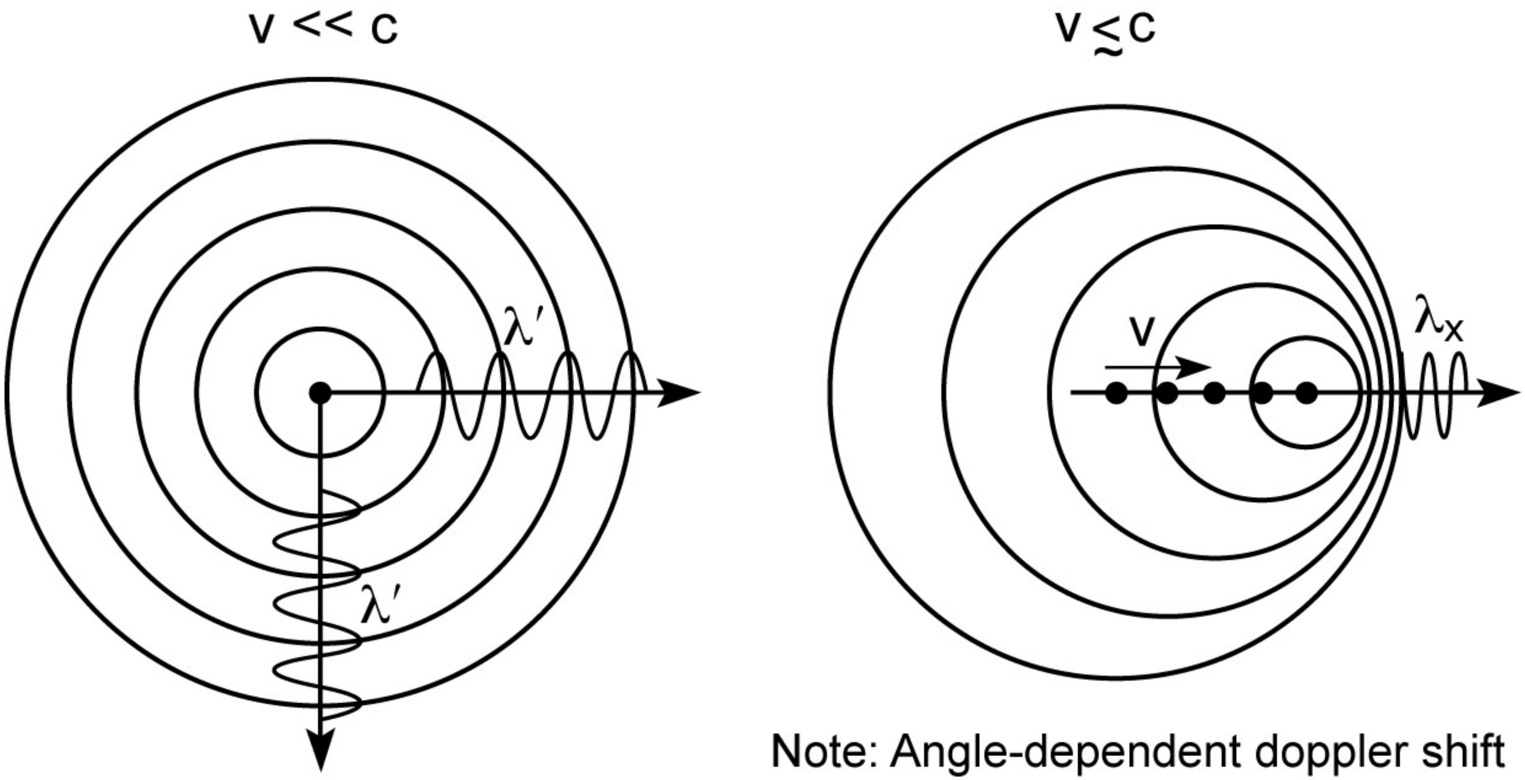
University of California, Berkeley

Synchrotron radiation from relativistic electrons



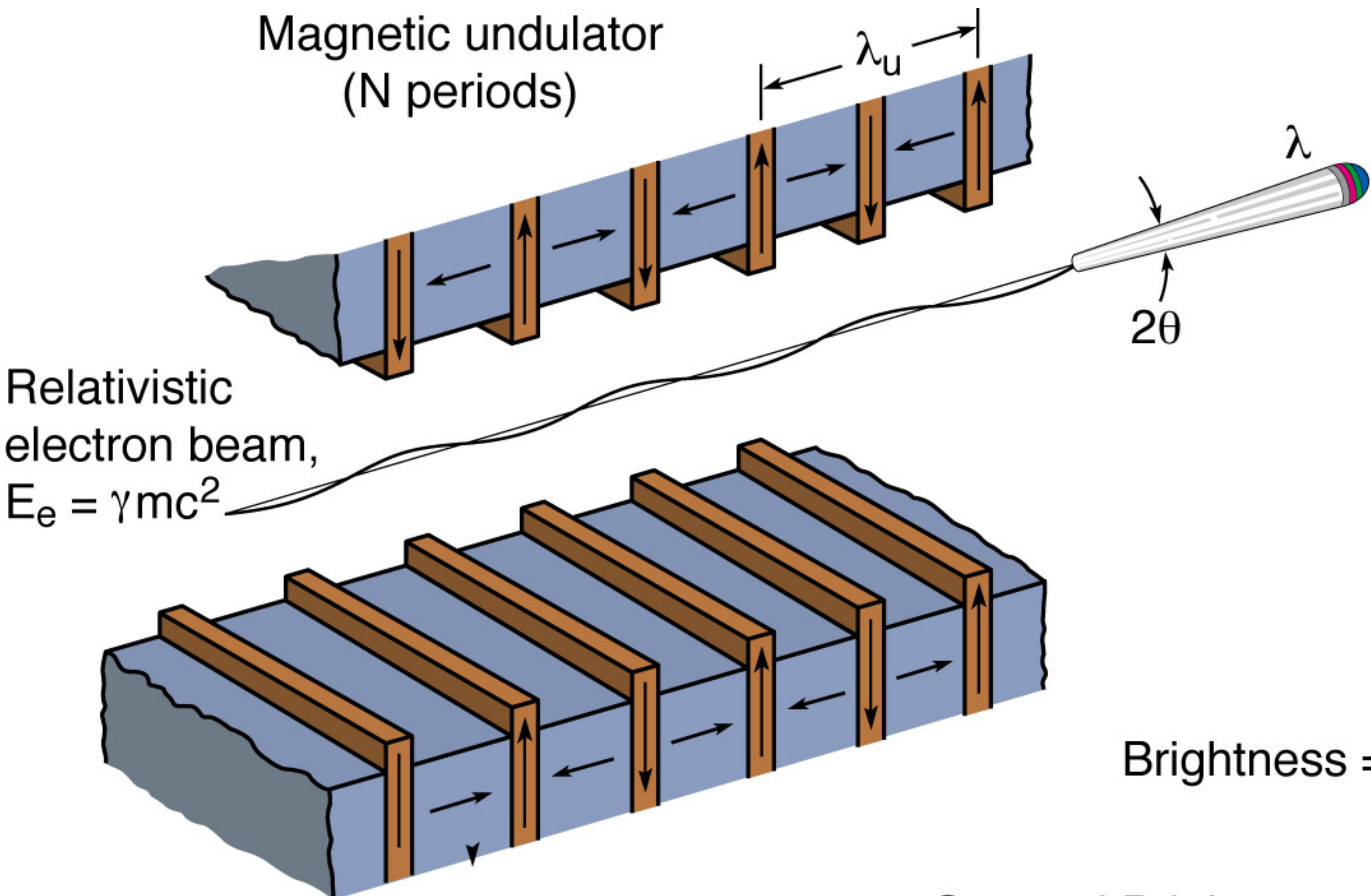
Note: Angle-dependent doppler shift

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

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

Ch05_F09_Apr2008.ai

Undulator radiation from a small electron beam radiating into a narrow forward cone, is very bright



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

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

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

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

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

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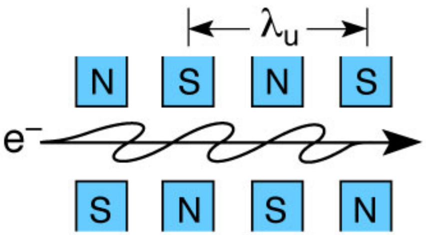
Undulator radiation

Laboratory Frame of Reference

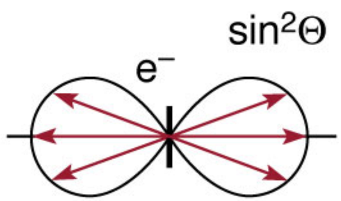


$E = \gamma mc^2$

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

N = # periods

Frame of Moving e⁻



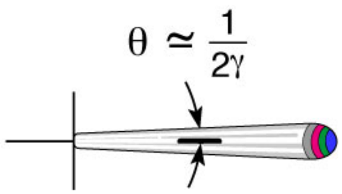
e⁻ radiates at the Lorentz contracted wavelength:

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

Bandwidth:

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

Frame of Observer



Doppler shortened wavelength on axis:

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

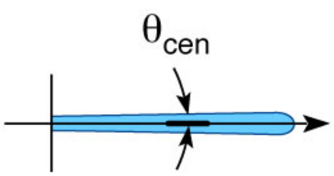
$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + \gamma^2\theta^2)$$

Accounting for transverse motion due to the periodic magnetic field:

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

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

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

Ch05_LG186_Apr2010.ai

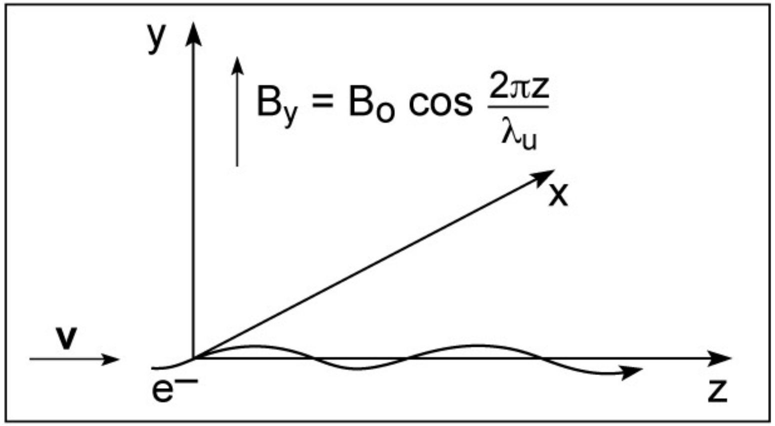
Determining the power radiated: the equation of motion of an electron in an undulator

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

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

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

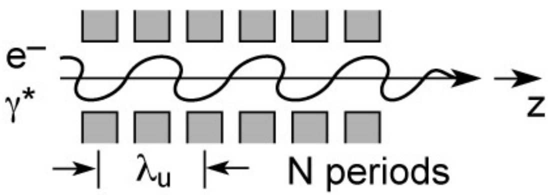
$$K \equiv \frac{eB_0\lambda_u}{2\pi mc} = 0.9337\, B_0(\mathrm{T})\lambda_u(\mathrm{cm}) \qquad (5.18)$$

Ch05_F15_Eq16_19_Mar08.ai

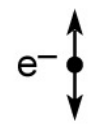
Calculating power in the central radiation cone: using the well known "dipole radiation" formula by transforming to the frame of reference moving with the electrons

x, z, t laboratory frame of reference

x', z', t' frame of reference moving with the average velocity of the electron



Lorentz transformation



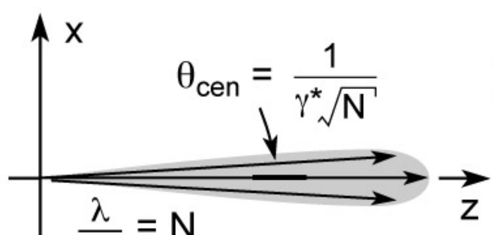
$$\lambda_u' = \frac{\lambda_u}{\gamma^*}$$

x', z', t' motion
$a'(t')$ acceleration

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

Dipole radiation:

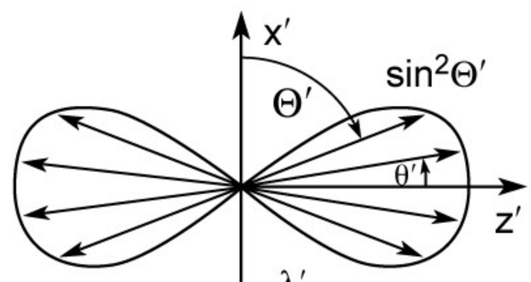
$$\frac{dP'}{d\Omega'} = \frac{e^2\, a'^2 \sin^2 \Theta'}{16\pi^2 \varepsilon_0 c^3}$$



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

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

Lorentz transformation



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

$$\bar{P}_{cen} = \frac{\pi e \gamma^2 I}{\varepsilon_0 \lambda_u} \frac{K^2}{(1 + K^2/2)^2}$$

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Undulator radiated power in the central cone

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

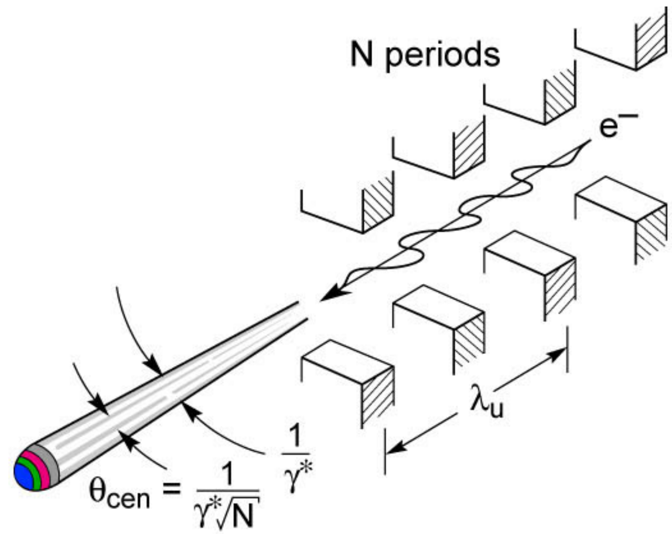
$$\bar{P}_{cen} = \frac{\pi e \gamma^2 I}{\epsilon_0 \lambda_u} \frac{K^2}{\left(1 + \frac{K^2}{2}\right)^2} f(K)$$

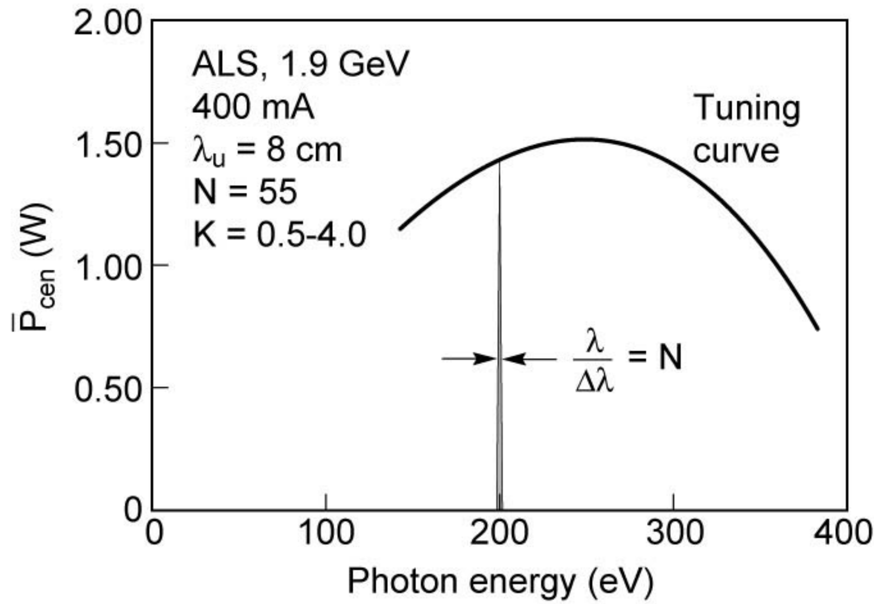
$$\theta_{cen} = \frac{1}{\gamma^* \sqrt{N}}$$

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

$$K = \frac{eB_0\lambda_u}{2\pi m_0 c}$$

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





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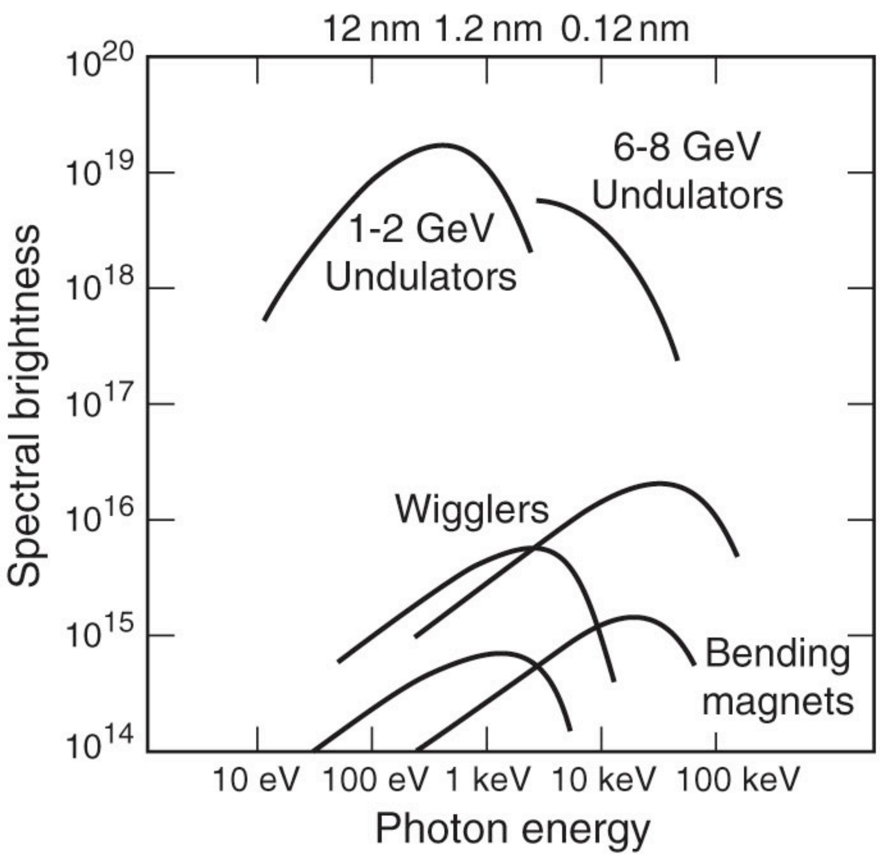
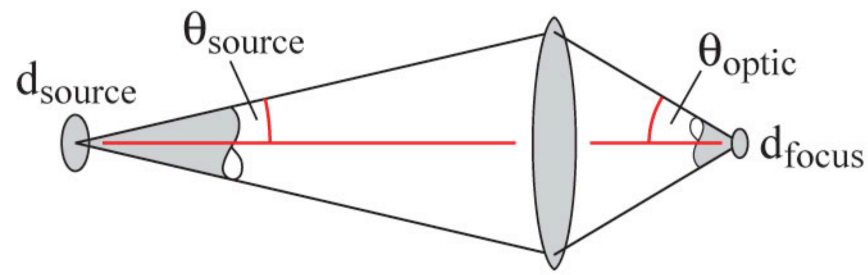
Spectral brightness is useful for experiments that involve spatially resolved studies



- Brightness is conserved (in lossless optical systems)



$$d_{source} \cdot \theta_{source} = d_{focus} \cdot \theta_{optic}$$

Smaller after focus

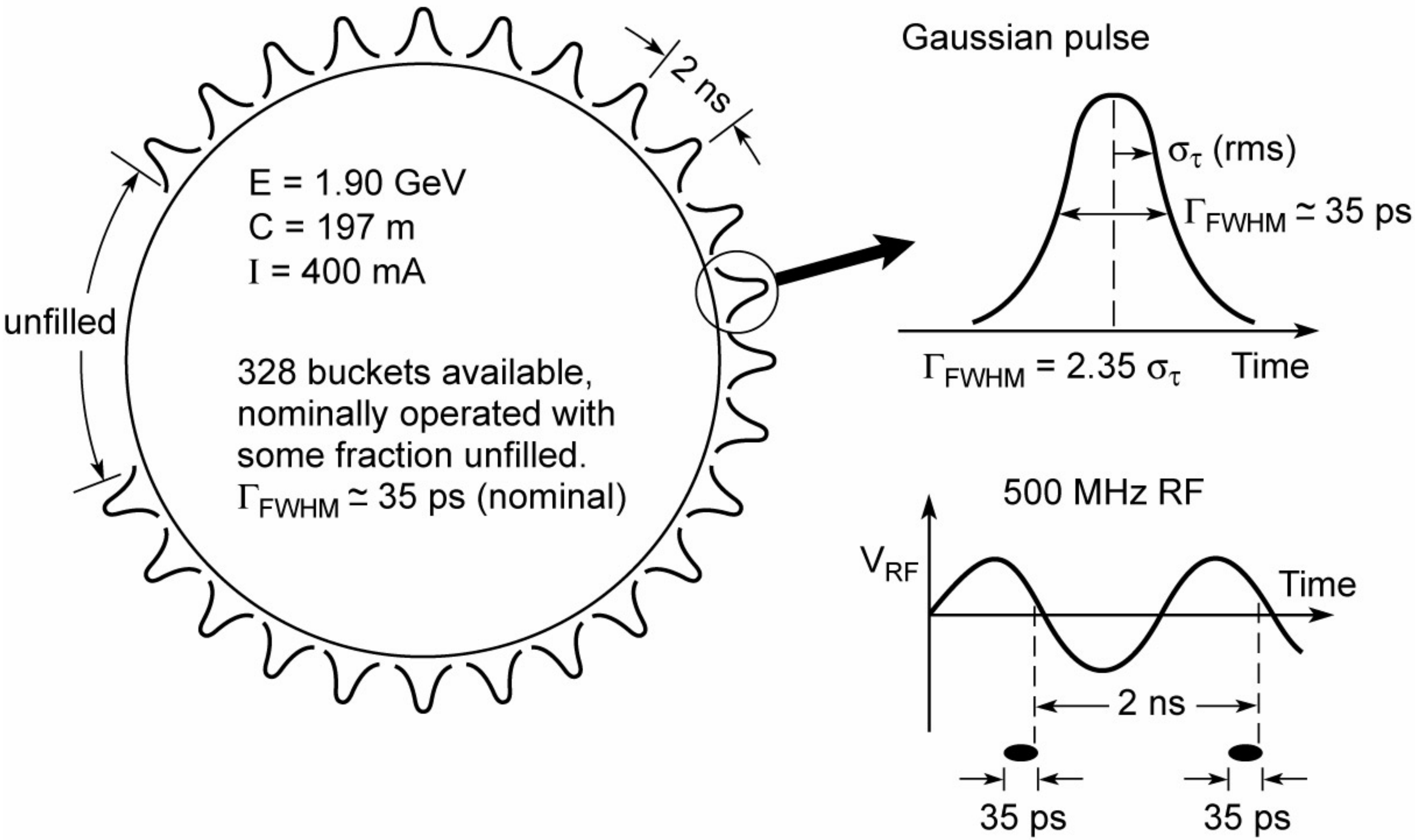
Large in a focusing optic

- Starting with many photons in a small source area and solid angle, permits high photon flux in an even smaller area

Ch05_F24VG_2.04.ai

Time structure of synchrotron radiation

The axial electric field within the RF cavity, used to replenish lost (radiated) energy, forms a potential well “bucket” system that forces electrons into axial electron “bunches”. This leads to a time structure in the emitted radiation.



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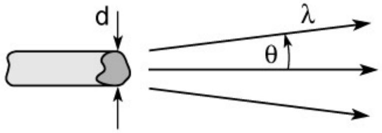
Coherence at short wavelengths

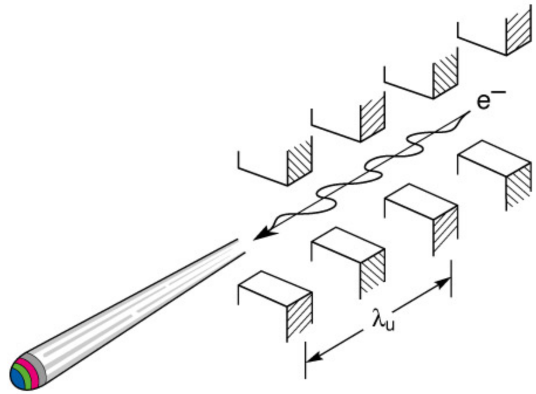
Chapter 8

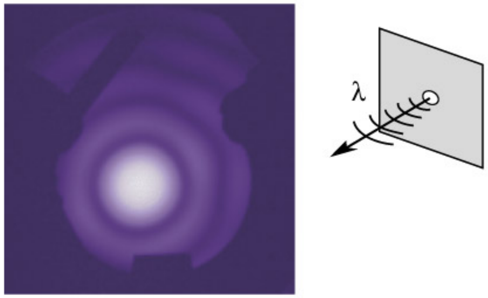


$$l_{coh} = \lambda^2/2\Delta\lambda \ \{\text{temporal (longitudinal) coherence}\} \tag{8.3}$$

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

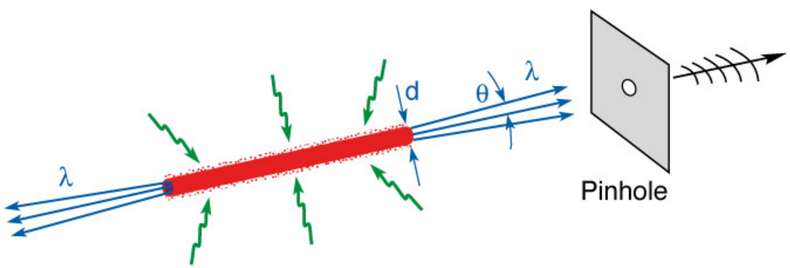
$$\text{or } \ d \cdot 2\theta|_{FWHM} = 0.44\,\lambda \tag{8.5*}$$





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

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



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

Ch08_F00.ai

Coherence

co·here \kō-ˈhi(ə)r\ *vi* [L *cohaerēre*, fr. *co-* + *haerēre* to stick] **1 a :** to hold together firmly as parts of the same mass **b :** ADHERE **c :** to display cohesion **2 :** to consist of parts that cohere **3 a :** to become united in principles, relationships, or interests **b :** to be logically or aesthetically consistent **syn** see STICK
co·her·ence \kō-ˈhir-ən(t)s, -ˈher-\ *n* **:** the quality or state of cohering; *esp* **:** systematic connection esp. in logical discourse
co·her·en·cy \-ən-sē\ *n* **:** COHERENCE
co·her·ent \kō-ˈhir-ənt, -ˈher-\ *adj* [MF or L; MF *cohérent*, fr. L *cohaerent-*, *cohaerens*, prp. of *cohaerēre*] **1 :** having the quality of cohering **2 :** logically consistent **3 :** having waves in phase and of one wavelength ⟨~ light⟩ — **co·her·ent·ly** *adv*

Webster's 7th Collegiate Dictionary (1971)

co·her·ence (kō-hîrʹəns, -hĕrʹ-) also **co·her·en·cy** (-ən-sē) *n.* The quality or state of cohering, esp. logical or orderly relationship of parts.
co·her·ent (kō-hîrʹənt, -hĕrʹ-) *adj.* **1.** Sticking together; cohering. **2.** Marked by an orderly or logical relation of parts that affords comprehension or recognition: *coherent speech.* **3.** *Physics.* Of or pertaining to waves with a continuous relationship among phases. **4.** Of or pertaining to a system of units of measurement in which a small number of basic

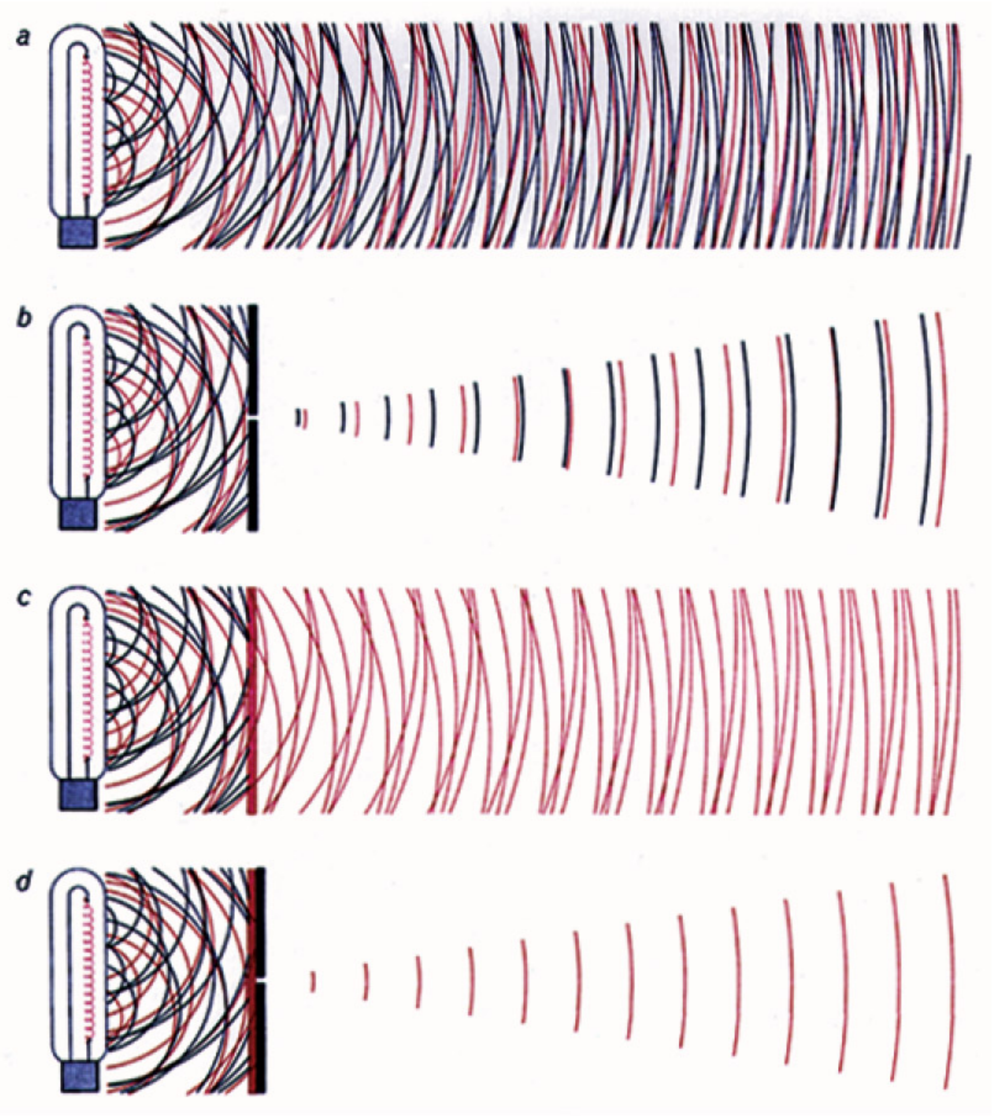
American Heritage 2nd College Edition Dictionary (1985)

- Coherence (physics), an ideal property of waves that enables stationary (i.e. temporally and spatially constant) interference
- Coherence time, the time over which a propagating wave (especially a laser or maser beam) may be considered coherent; the time interval within which its phase is, on average, predictable

Wikipedia, the free encyclopedia

Marching band and coherence lengths

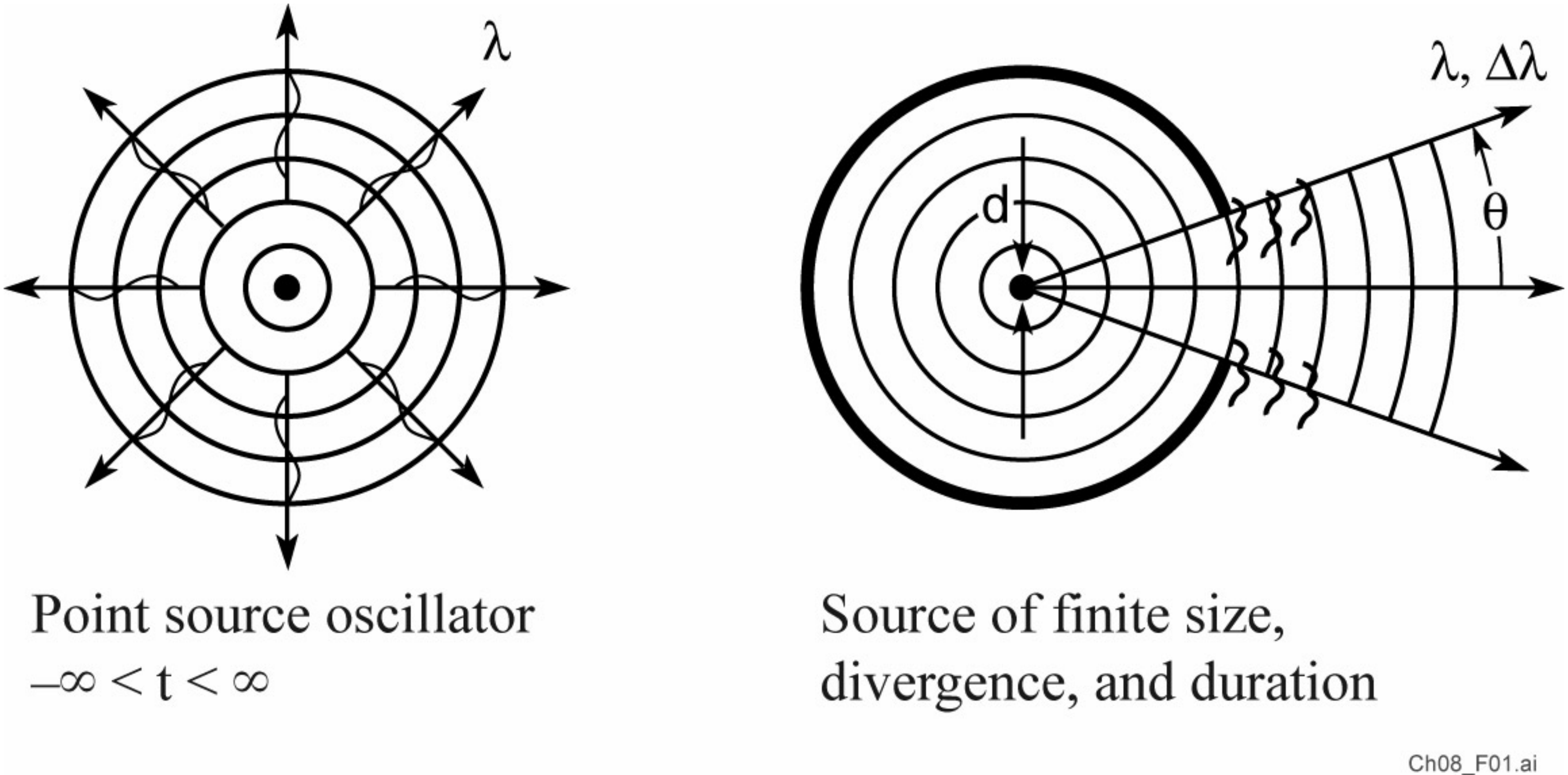
Spatial and spectral filtering to produce coherent radiation



Courtesy of A. Schawlow, Stanford.

Ch08_F08.ai

Coherence, partial coherence and incoherence



Spatial and temporal coherence

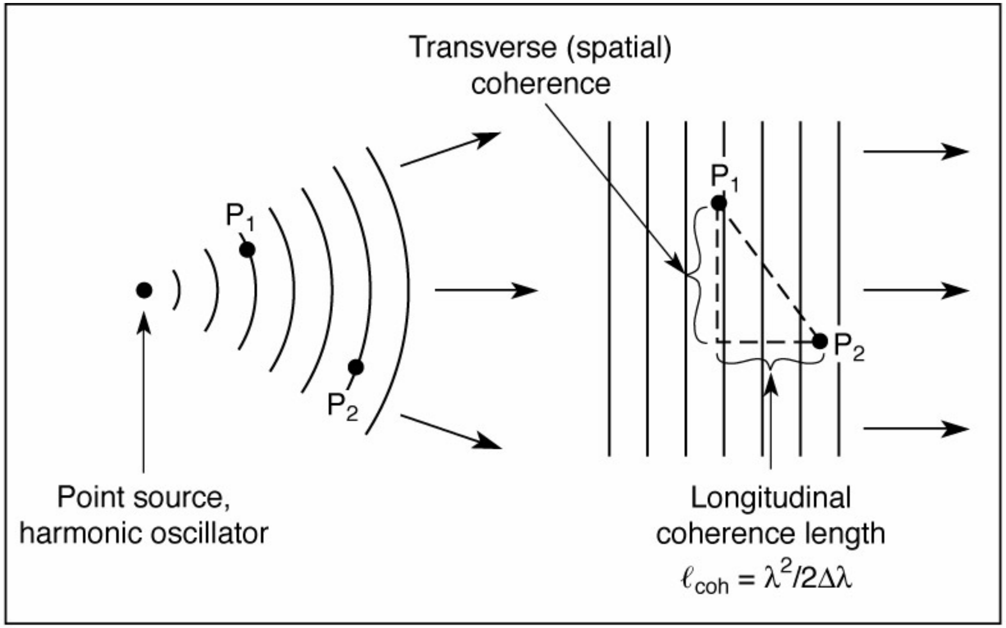
Mutual coherence factor

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

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

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

Full spatial (transverse) coherence

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

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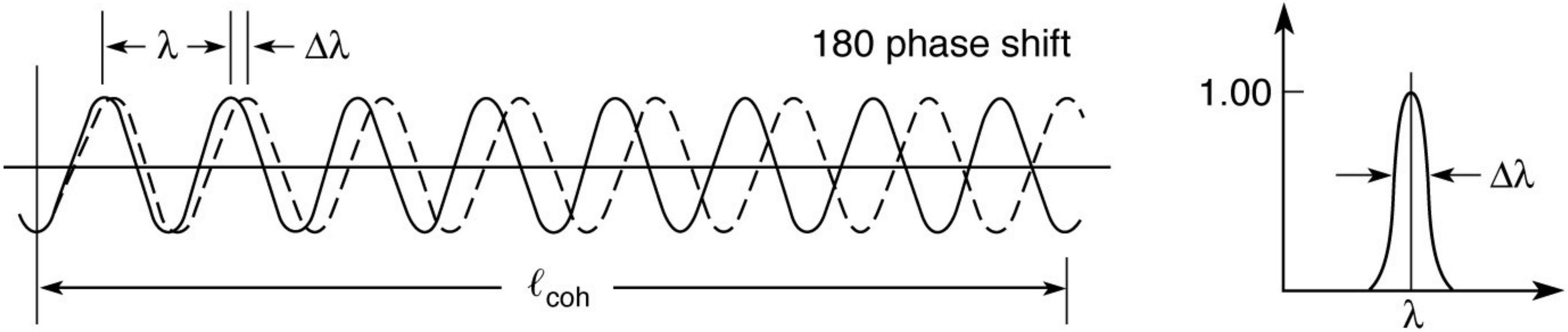
Spectral bandwidth and longitudinal coherence length



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

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

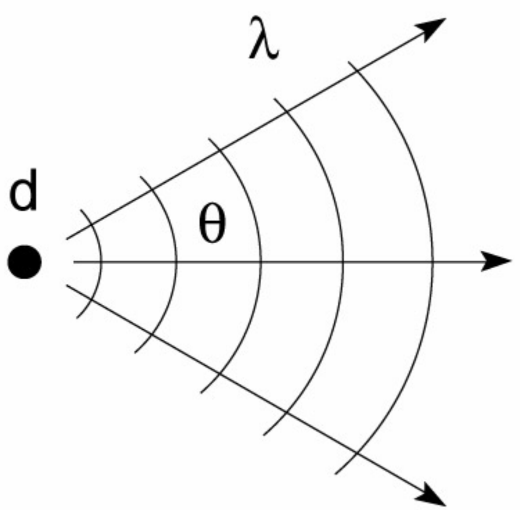
so that

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

Ch08_F03.ai

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

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

Ch08_XBL 915-6740A.ai

Partially coherent radiation approaches uncertainty principle limits

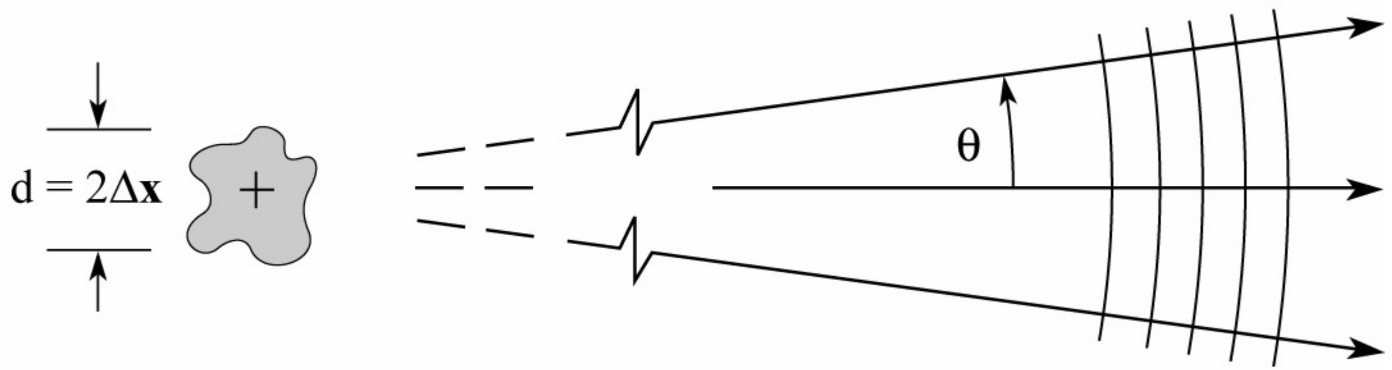
$$\Delta \mathbf{x} \cdot \Delta \mathbf{p} \geq \hbar/2 \qquad (8.4)$$

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

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

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

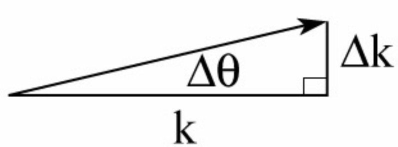
$$2\Delta \mathbf{x} \cdot \Delta\theta \geq \lambda/2\pi$$



Spherical wavefronts occur in the limiting case

Note:

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



$$\left.\begin{array}{c}\boxed{d \cdot \theta = \lambda/2\pi} \\ \text{(spatially coherent)}\end{array}\right\} \frac{1}{\sqrt{e}} \text{ quantities}$$

or

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

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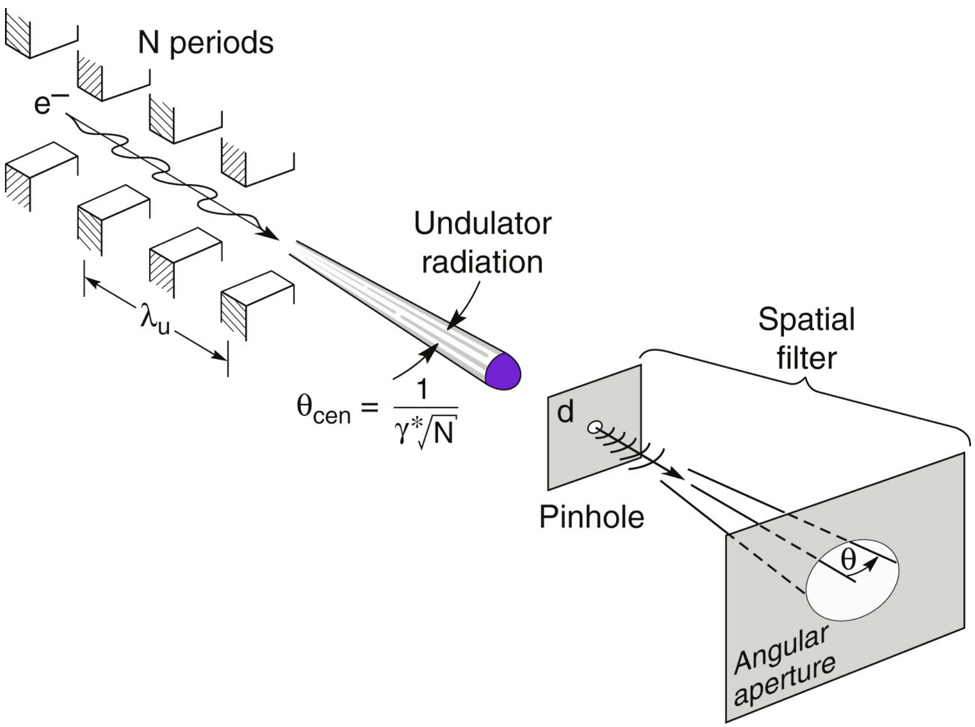
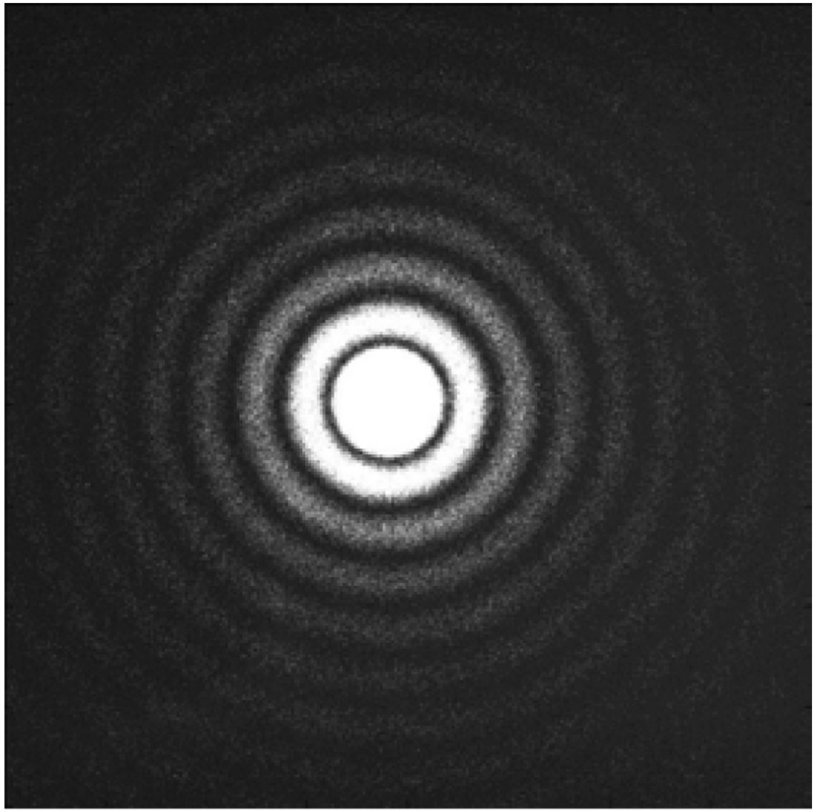
Spatially coherent undulator radiation

λ = 2.48 nm (600 eV)
d = 2.5 μm
t = 200 msec
ALS beamline 12.0.2
λ_u = 80 mm, N = 55, n = 3
25 mm wide CCD at 410 mm





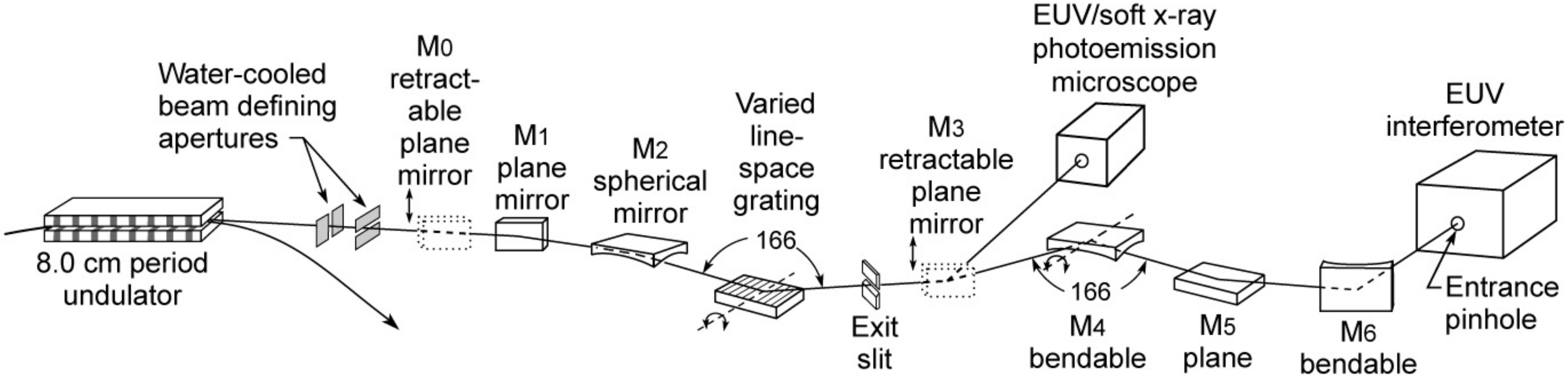
AiryPattrn600eV_Feb2013.ai

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

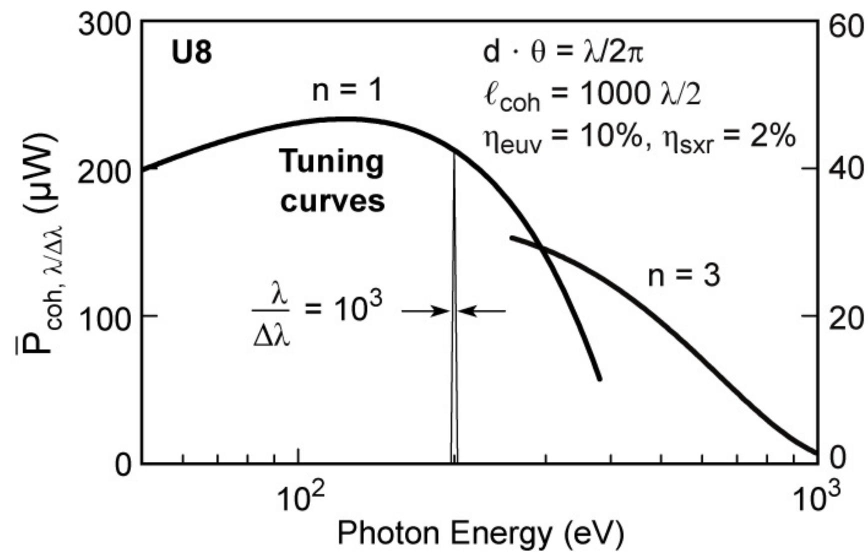
Courtesy of Patrick Naulleau, LBNL / Kris Rosfjord, UCB and LBNL

Spatial and spectral filtering of undulator radiation

- Pinhole filtering for full spatial coherence
- Monochromator for spectral filtering to λ/Δλ > N



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



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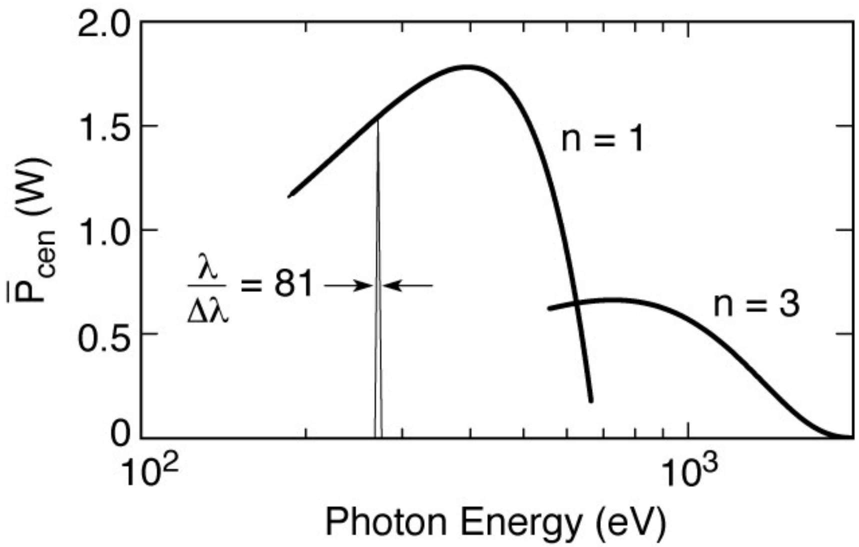
Coherent power at Elettra



2.0 GeV, 300 mA

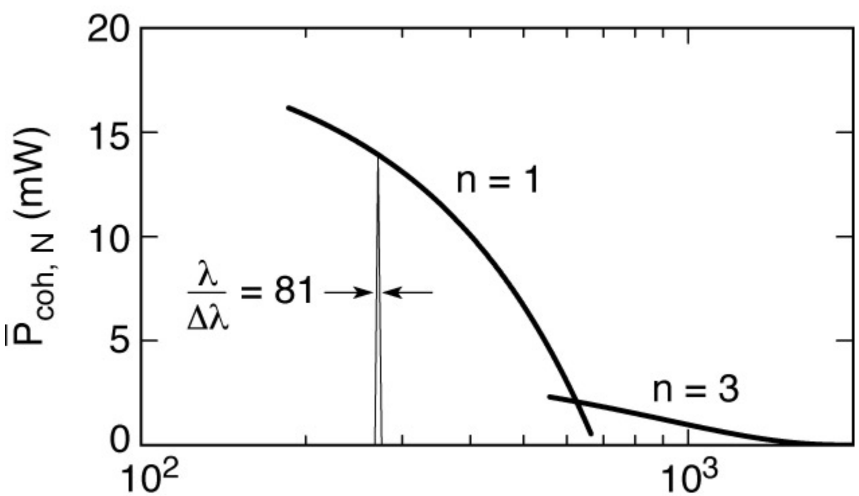
λ_u = 56 mm, N = 81

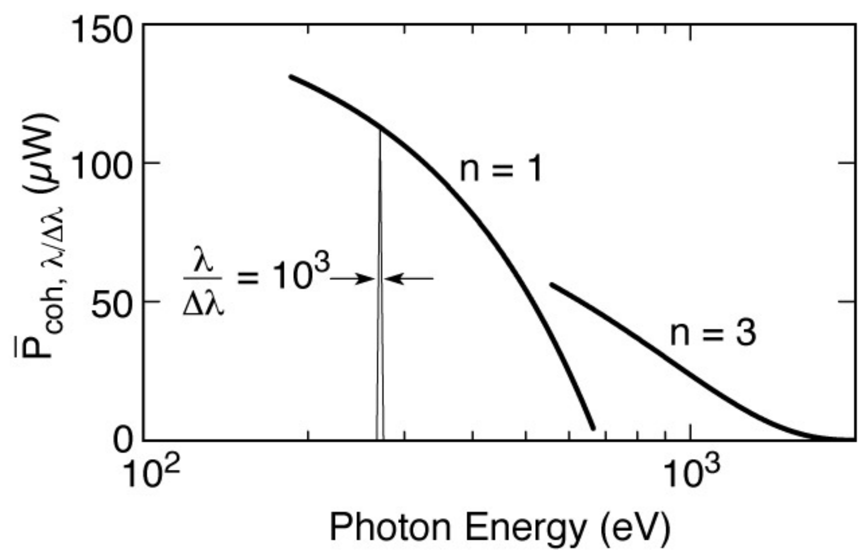
$0.5 \leq K \leq 2.3$

σ_x = 255 μm, σ_x' = 23 μr

σ_y = 31 μm, σ_y' = 9 μr

η = 10%





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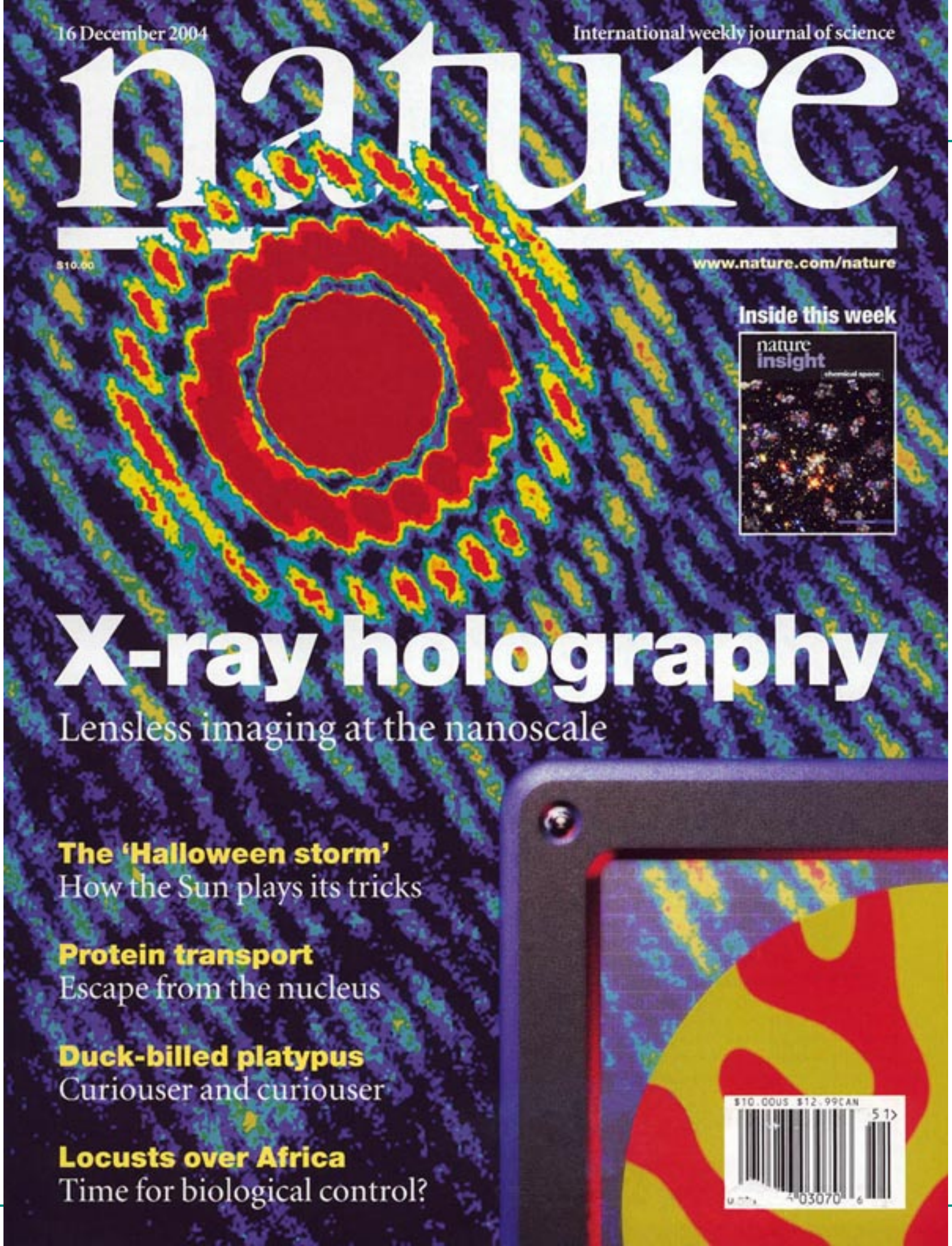
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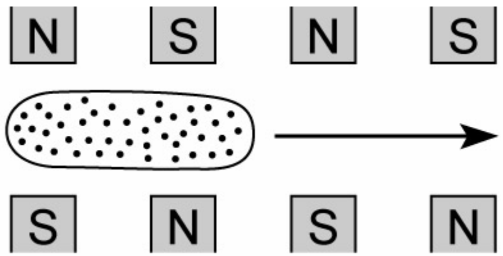
Undulators, FELs and coherence

- 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 fsec and asec x-rays
- Seeded FEL true phase coherent x-rays

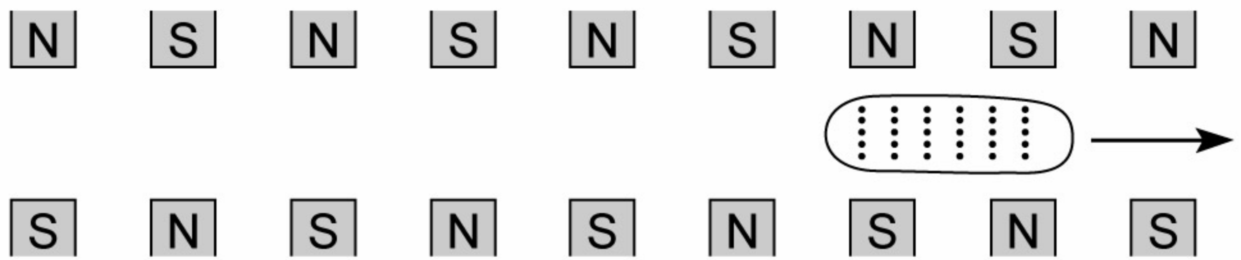
Marching band and coherence lengths

Undulators and FELs



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

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



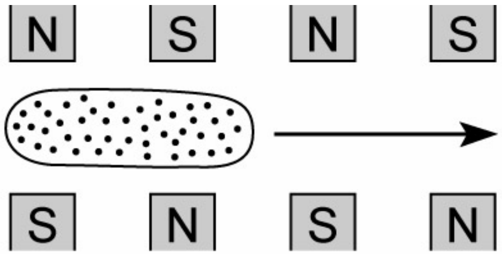
<u>Free Electron Laser</u> (FEL) – very long undulator, electrons are "microbunched" by their own radiated fields into strongly correlated waves of electrons, all radiated electric fields now add, spatially coherent, power ~ N^2

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

"SASE" FEL – no seed (several separate "waves" of electrons possible with uncorrelated phase.) Less peak power, broader spectrum.

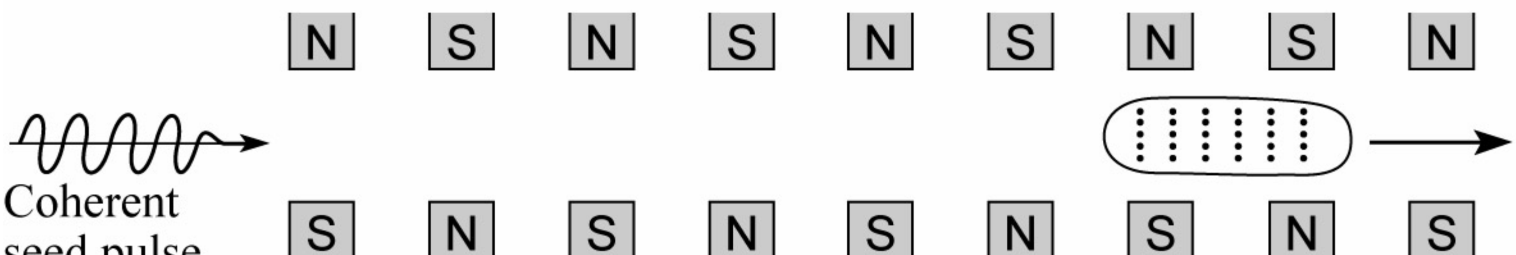
UndulatorsAndFELs2.ai

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.



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

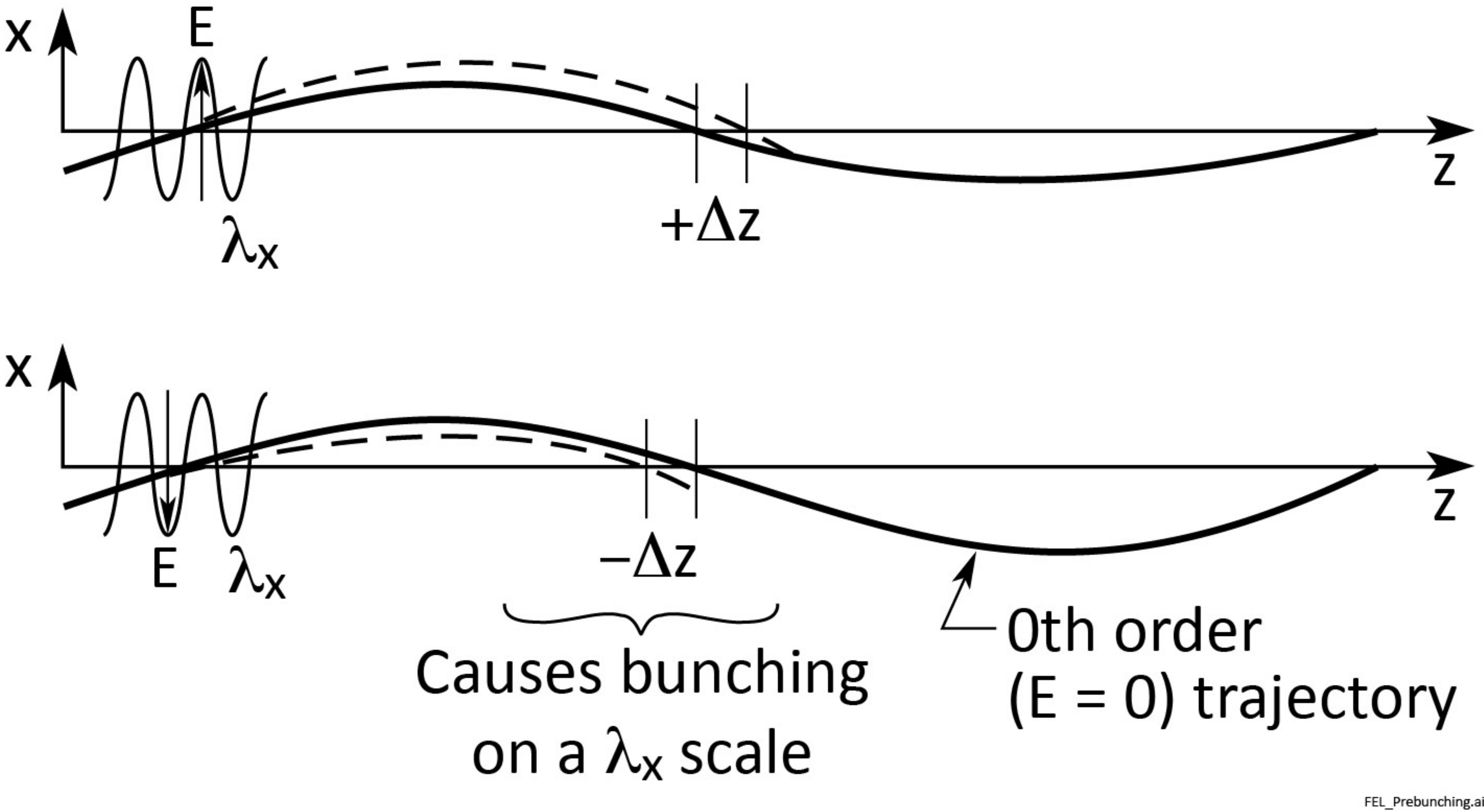
$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Second generation x-ray FELs.
(Fermi in Trieste)

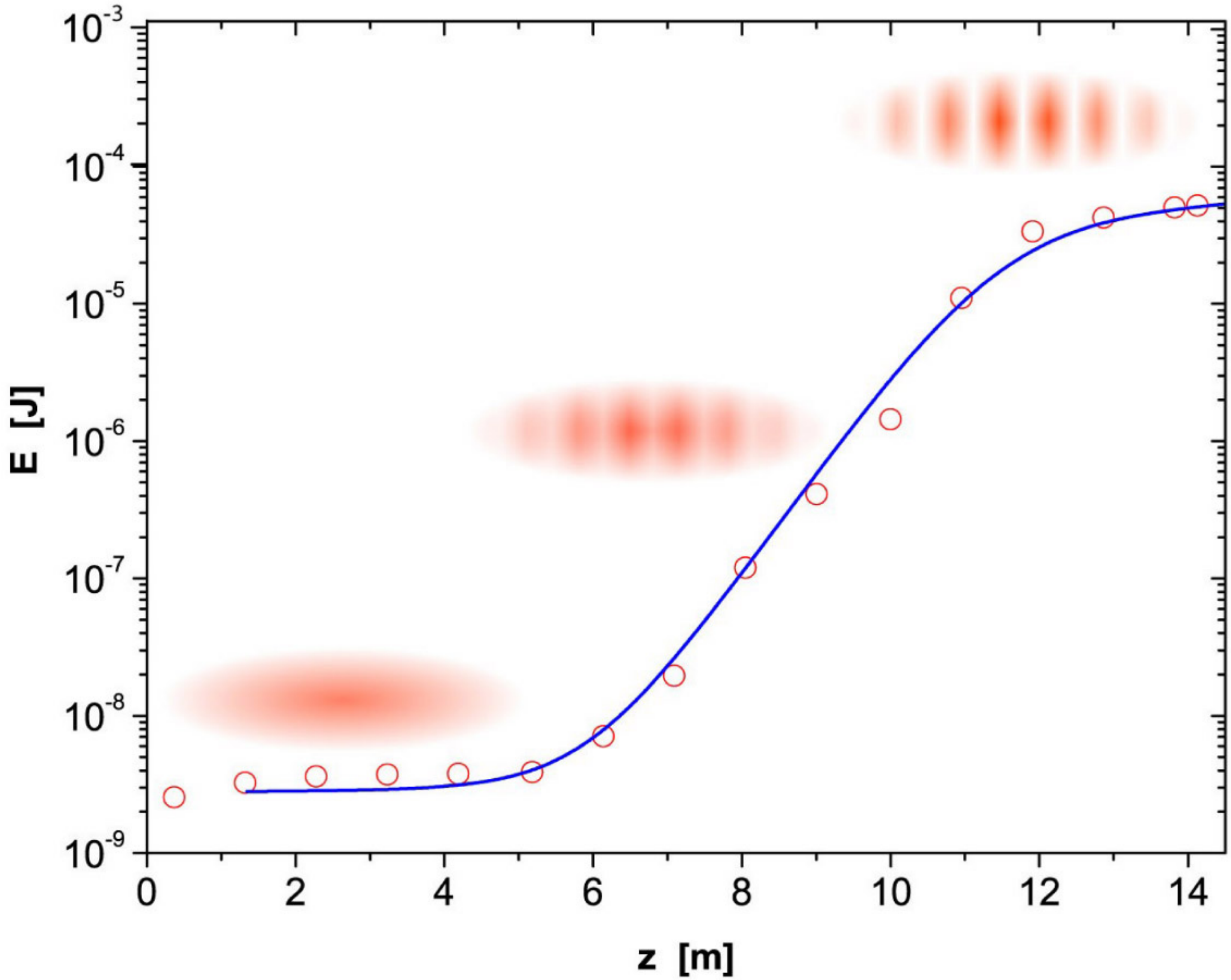
UndulatorsAndFELs3.ai

The evolution of incoherent clapping (applauding) to coherent clapping

Electron energies and subsequent axis crossings are affected by the amplitude and relative phase of the co-propagating field



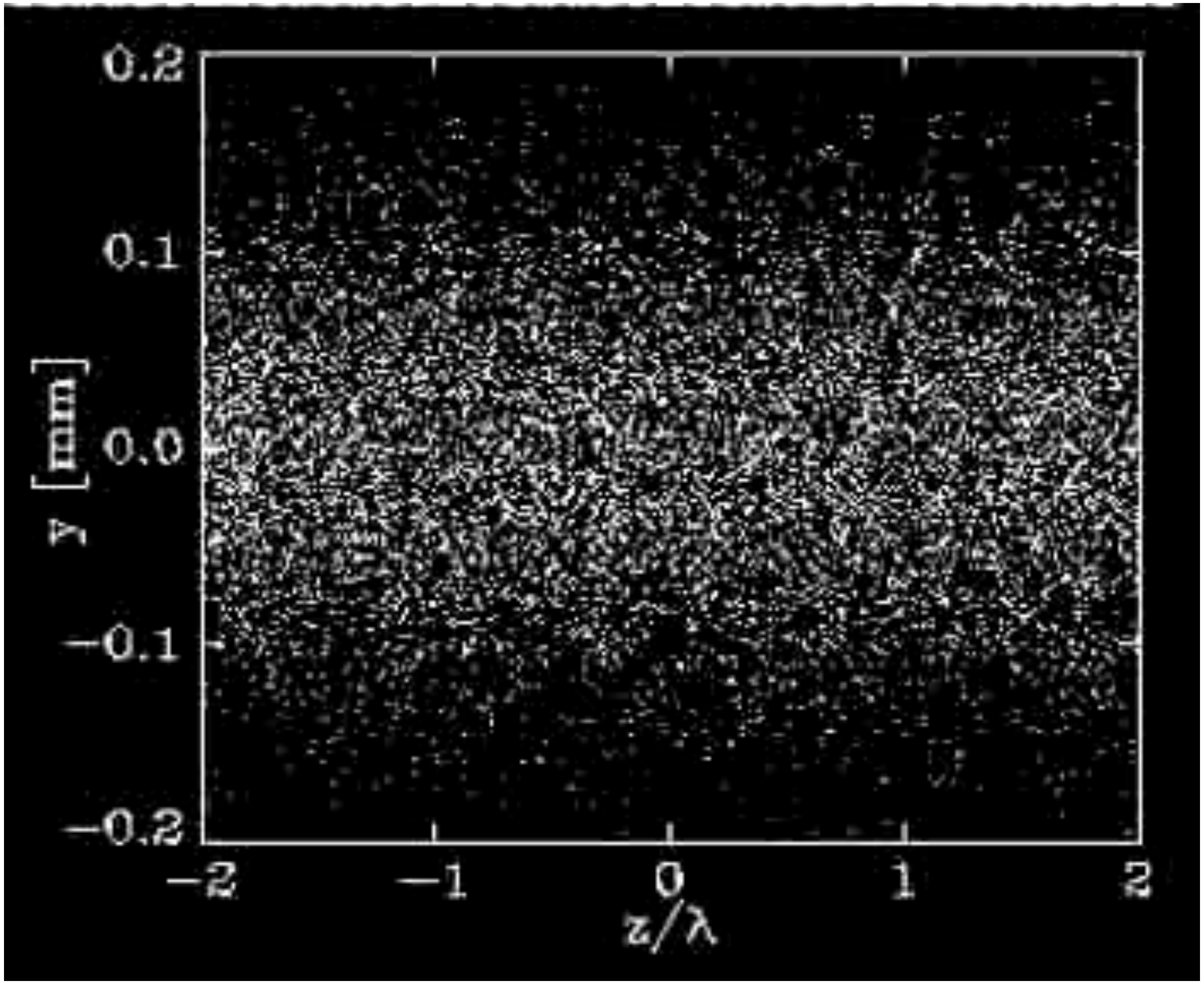
Gain and saturation in an FEL



Courtesy of K-J. Kim

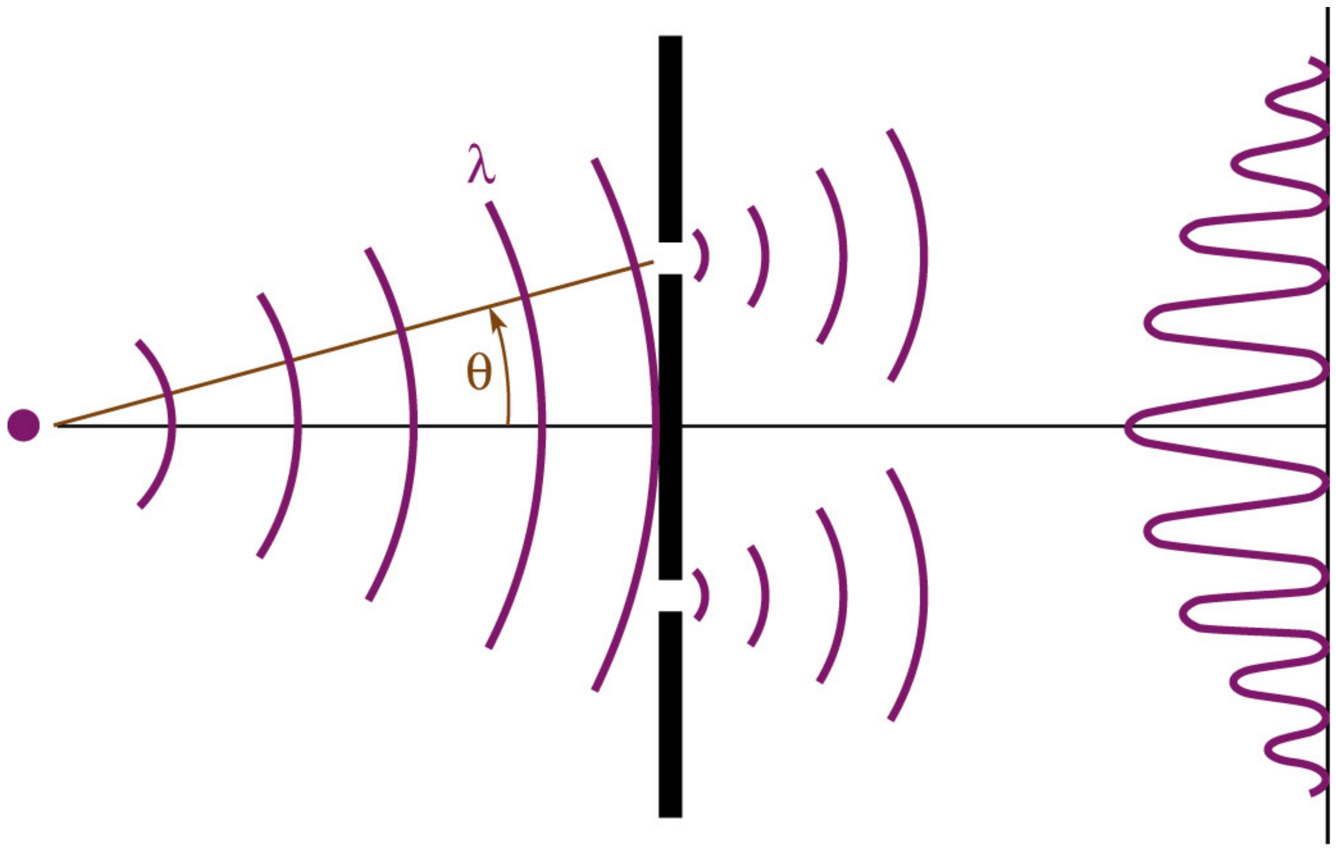
Gain_Saturation_FEL_graph.ai

FEL Microbunching



Courtesy of Sven Reiche, UCLA, now SLS

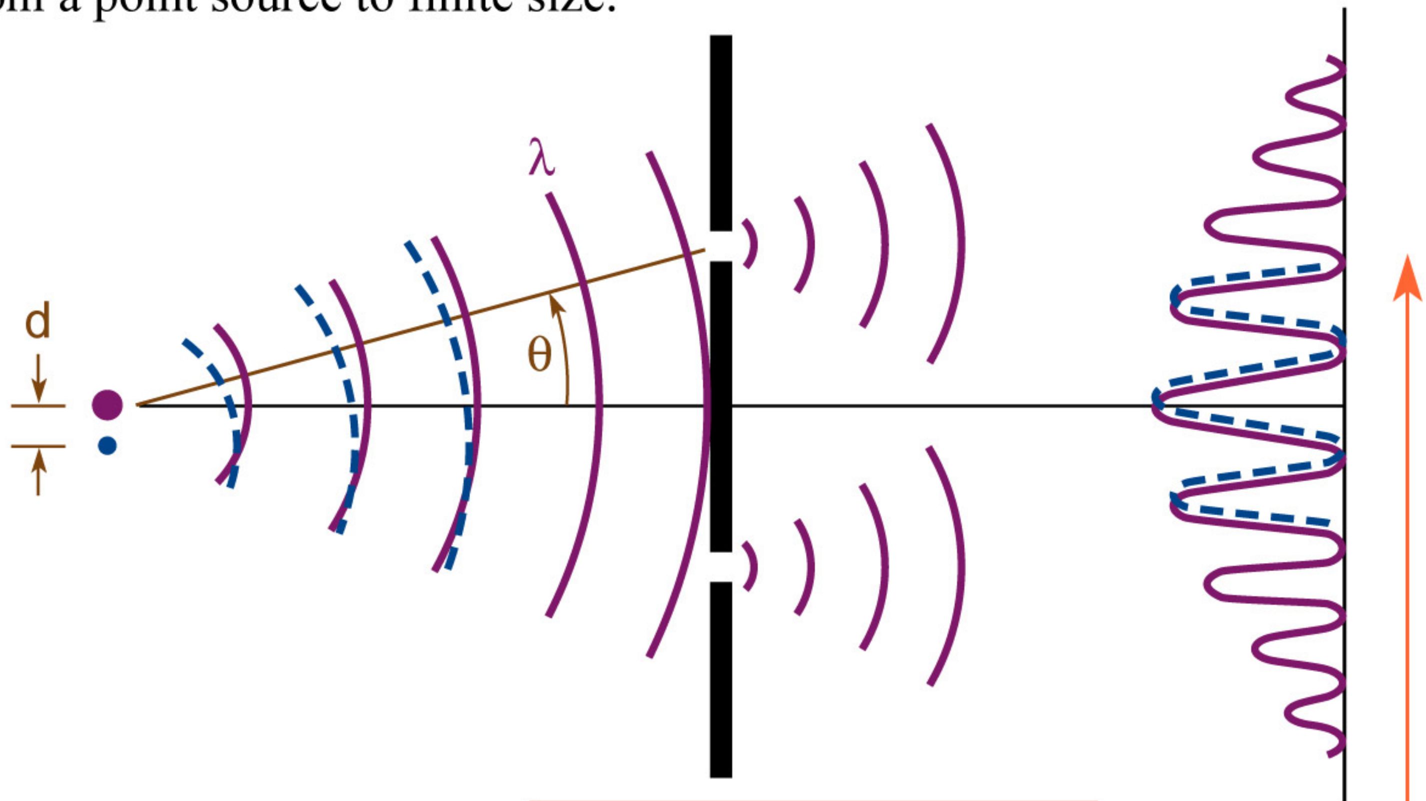
Young's double slit experiment: spatial coherence and the persistence of fringes



YoungsExprmt.ai

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.

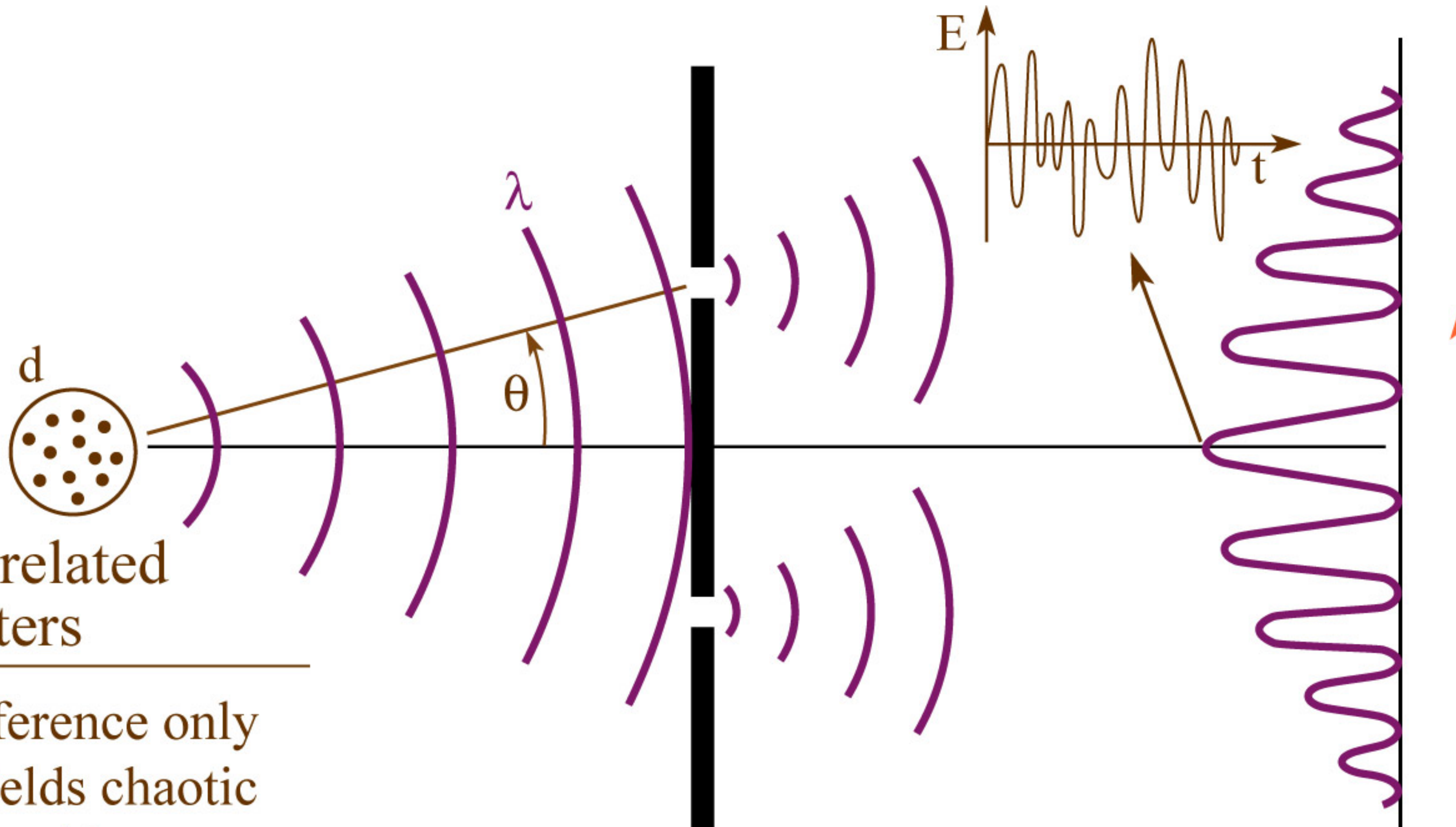


$$d \cdot 2\theta|_{FWHM} \simeq \lambda/2$$

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

CH08_YoungsExprmt_v3.ai

Young's double slit experiment with random emitters: Young did not have a laser



N uncorrelated emitters

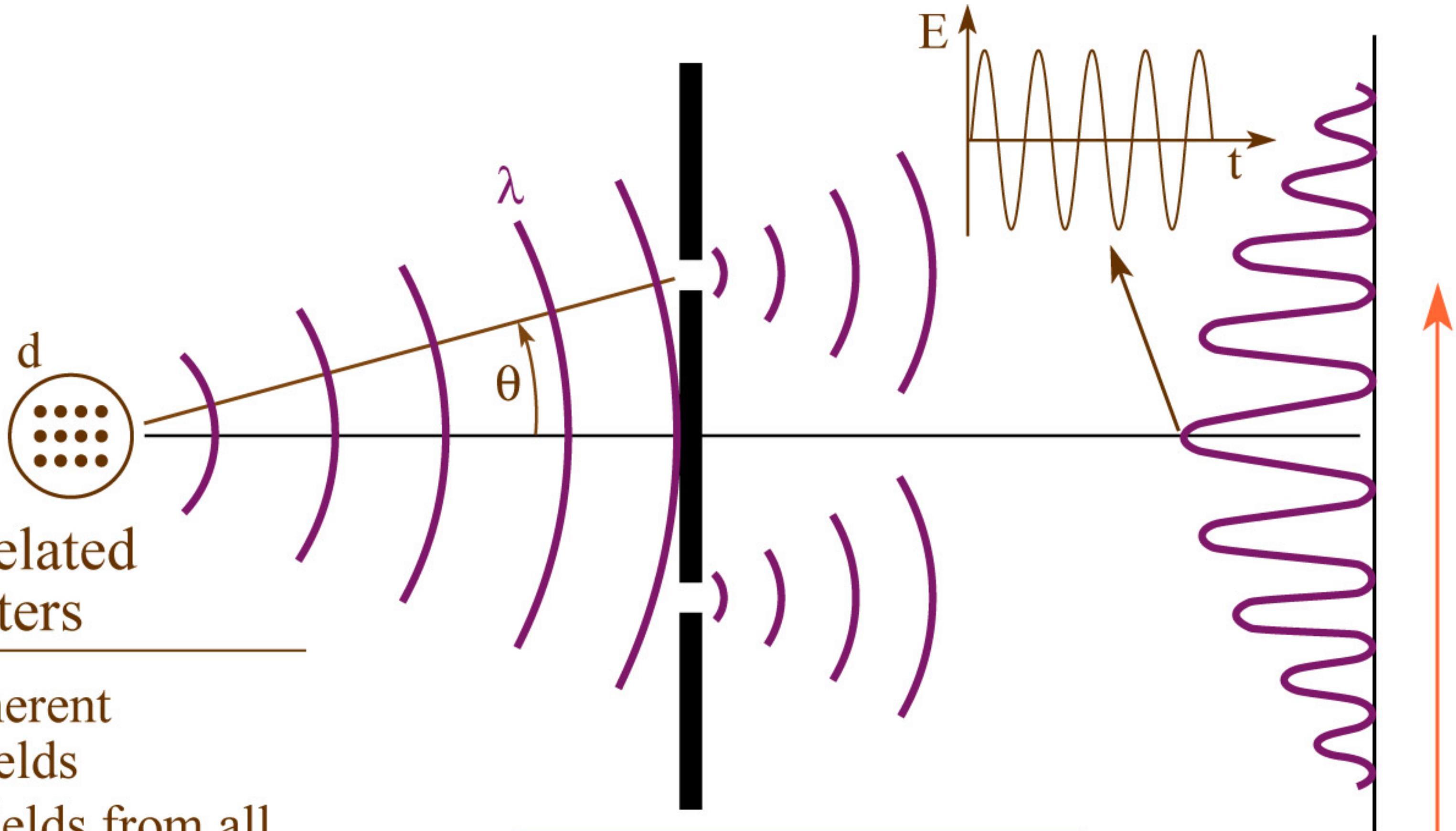
- Self-interference only
- Electric fields chaotic
- Intensities add
- Radiated power ~ N

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

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

YoungsExprmt_Random_March08.ai

Young's double slit experiment with phase coherent emitters (some lasers, or properly seeded FELs)



N correlated emitters

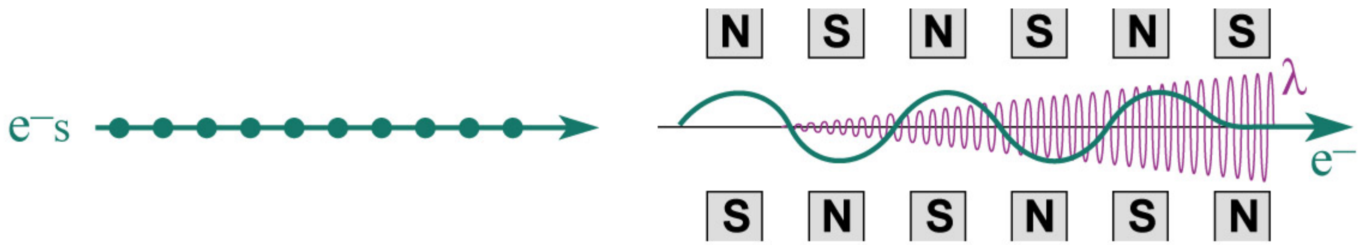
- Phase coherent electric fields
- Electric fields from all particles interfere constructively
- Radiated power ~ N^2
- New phase sensitive probing of matter possible

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

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

YoungsExprmt_PhaseCoh_March08.ai

FEL physics



- Uniformly distributed particles (beam) into undulator.
- Emission of radiation ("spontaneous" emission).
- Wave grows enough (undulator radiation) to begin affecting. particle dynamics through $m\mathbf{a} = -e\mathbf{E}$ radiation.
- Transverse coupling between $\mathbf{E}_{rad}$ and transverse velocity $\mathbf{v}_x$ (in undulator) leads to energy exchange between fields and particle (zero net at first) $\frac{dE_e}{dt} = mc^2\frac{d\gamma}{dt} = \mathbf{F}\cdot\mathbf{v} = -e\,\mathrm{E}\cdot\mathbf{v}_x$.
- Modulated velocities with increments in $\mathbf{v}_x$ lead to bunching on axis.
- Electron density modulation leads to stronger radiation, $P_{Tot} \propto \frac{Q^4}{M^2} \sim N^2\frac{e^4}{m^2}$.
- Stronger fields (wave) drive stronger transverse velocity.
- Stronger $\mathbf{v}_x$ drives stronger bunching, . . . stronger fields, . . . FEL action.

FEL_physics.ai

Free Electron Lasers

Parameters	FLASH FEL (Hamburg 2005)	Fermi (Trieste, 2010)	LCLS (Stanford, 2009)	SACLA (Hyogo, 2011)	Swiss FEL (PSI, 2016)	PAL (Pohang, 2016)	EU XFEL (Hamburg, 2016)
E_e	1.25 GeV	1.5 GeV	13.6 GeV	8 GeV	5.8 GeV	10 GeV	17.5 GeV
γ	2,450	2,900	26,600	15,700	11,300	19,600	35,000
$\hat{I}$	1.3 kA	300 A	3.4 kA	9 kA	3 kA	3 kA	5 kA
λ_u	27.3 mm	55 mm	30 mm	18 mm	15 mm	26 mm	40 mm
N	989	216	3733	4986	3200	3456	4375
L_u	27 m	14 m	112 m	90 m	48 m	90 m	175 m
$\hbar\omega$	30-300 eV (4-40 nm)	20-300 eV (4-60 nm)	250 eV-10 keV (1.2-50 Å)	4.5-15 keV (0.8-2.8 Å)	2-12 keV (1-6 Å)	2-12 keV (1-6Å)	3-25 keV (0.05-4Å)
$\lambda/\Delta\lambda_{FWHM}$	100	1000	200-500	200-400	200-500	200-500	1000
$\Delta\tau_{FWHM}$	50 fsec	85 fsec	<10-70 fsec	<10 fsec	2-20 fsec	5-60 fsec	100 fsec
$\dot{\mathcal{F}}$ (ph/pulse)	3×10^{12}	5×10^{12}	2×10^{12}	4×10^{11}	10^{11}	5×10^{11}	10^{12}
rep rate	1 MHz @ 10 Hz	10 Hz	120 Hz	60 Hz	100 Hz	60 Hz	2.7 kHz @ 5 Hz
$\hat{P}$	1 GW	1 GW	30-60 GW	60 GW	3 GW	15 GW	20 GW
L	260 m	200 m	2 km	710 m	730 m	1.1 km	3.4 km
Polarization	linear	variable	linear	linear	Linear	Linear	Linear
Mode	SASE (3ω Ti: saphire)	Seeded	SASE & self-seeded	SASE	SASE & self-seeded	SASE & self-seeded	SASE

FreeElectronLasersChart_July2015.ai

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- J. Als-Nielsen and D. McMorrow, *Elements of Modern X-ray Physics* (Wiley, New York, 2009), Second edition.
- J.D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1999), Third edition.
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- J. Samson and D. Ederer, *Vacuum Ultraviolet Spectroscopy I and II* (Academic Press, San Diego, 1998). Paperback available.

FEL References

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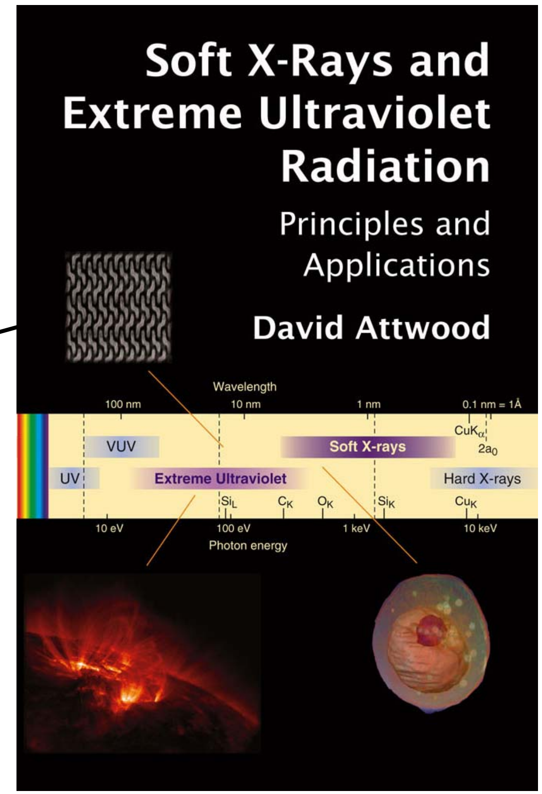
- K.-J. Kim, Z. Huang and R. Lindberg, “Synchrotron Radiation and Free Electron Lasers: Principles of Coherent X-Ray Generation (Cambridge, Fall 2016).
- Chapter 6, “X-ray and EUV Free Electron Lasers” in Attwood & Sakdinawat (Cambridge, Fall 2016).

2nd Edition in progress: new FEL, HHG, Coherence, and X-ray Imaging chapters



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www.coe.AST.berkeley.edu/sxr2009

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