IPAC13
The 4th International Particle Accelerator Conference
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Shanghai International Convention Center

Brightness and Coherence of Synchrotron Radiation and Free Electron Lasers

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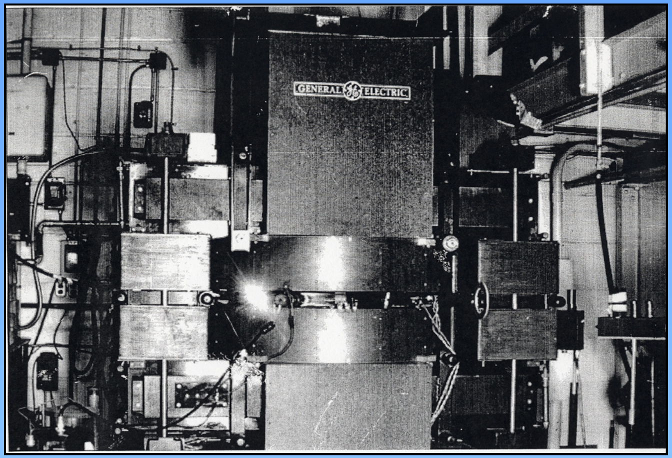
May 13, 2013

SLAC NATIONAL ACCELERATOR LABORATORY
IPAC13

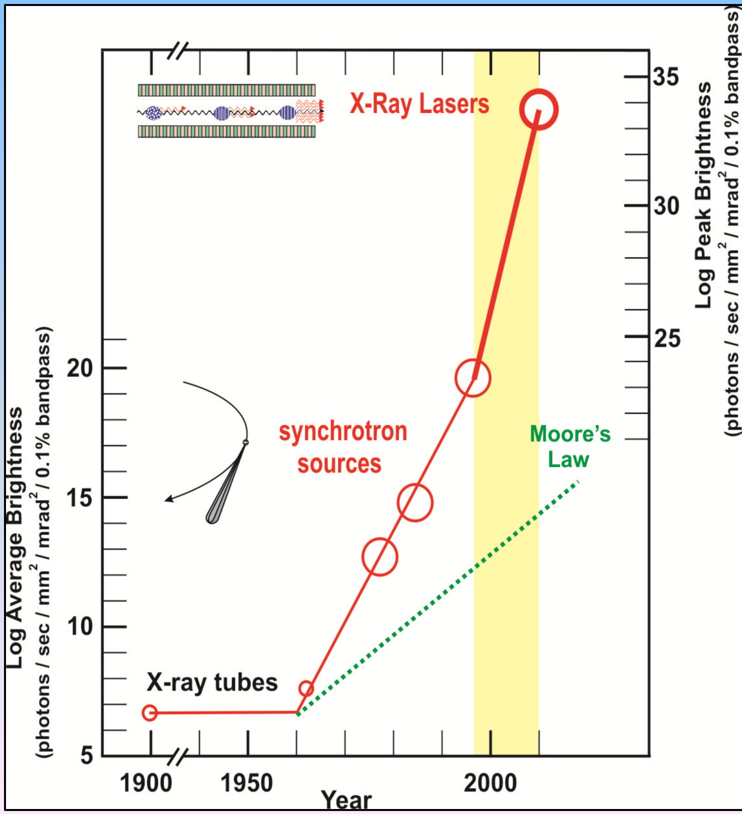
Introduction

- GE synchrotron (1946) opened a new era of accelerator-based light sources.

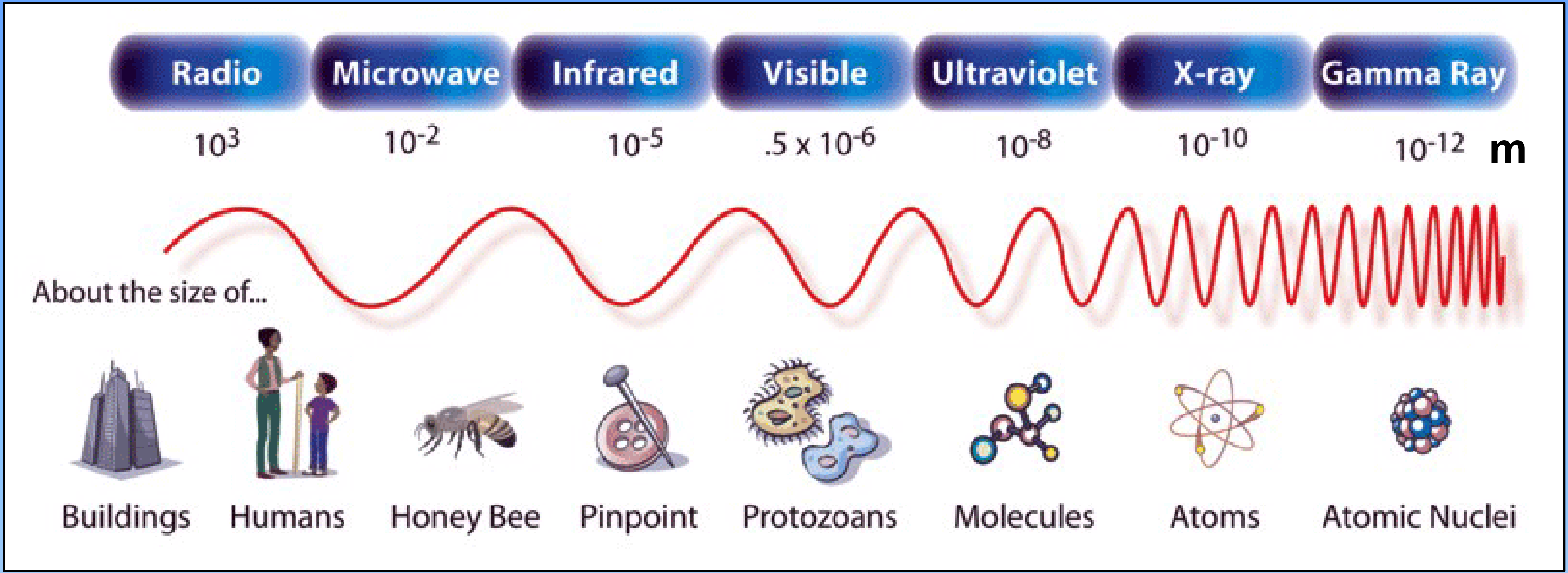


- These light sources have evolved rapidly over four generations.
  - The first three-generations are based on synchrotron radiation.
  - The forth-generation light source is a game-changer based on FELs.

- The dramatic improvement of brightness and coherence over 60 years easily outran Moore's law.



Bright X-ray Vision



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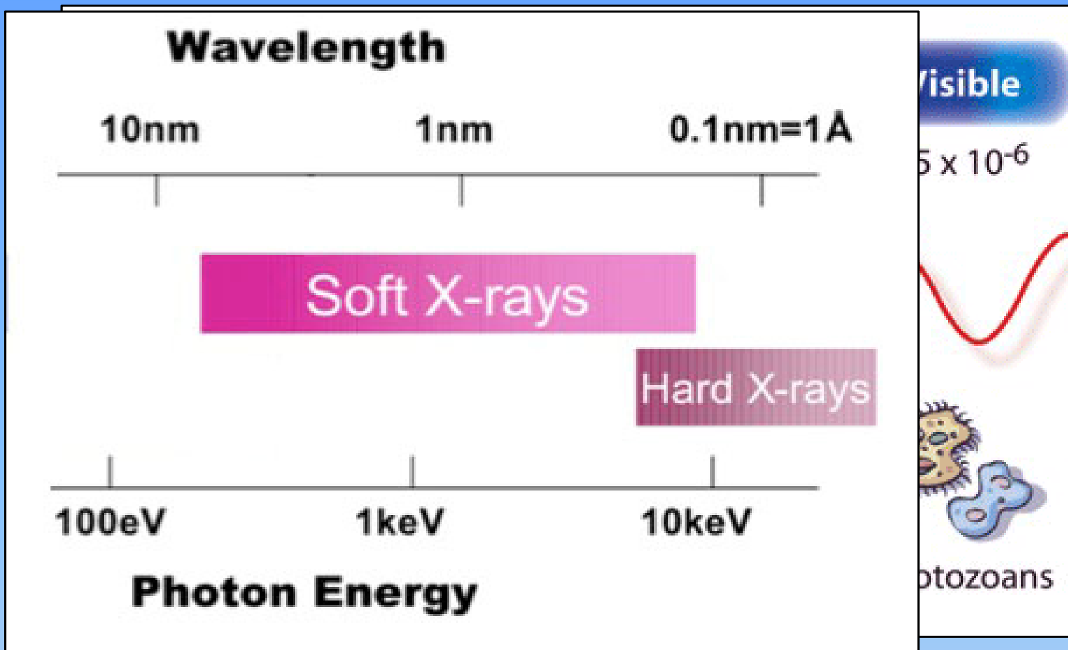
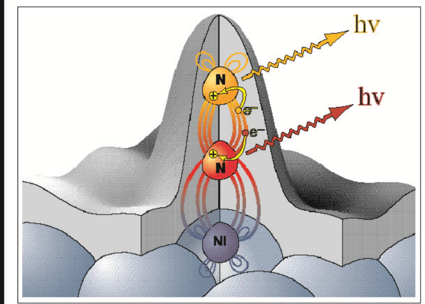
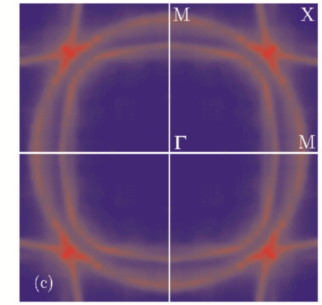
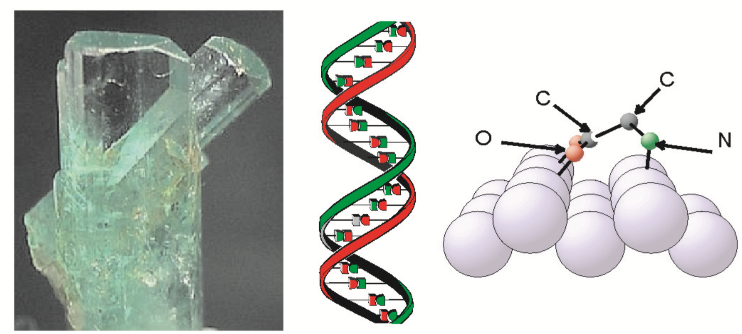


Where are the electrons?

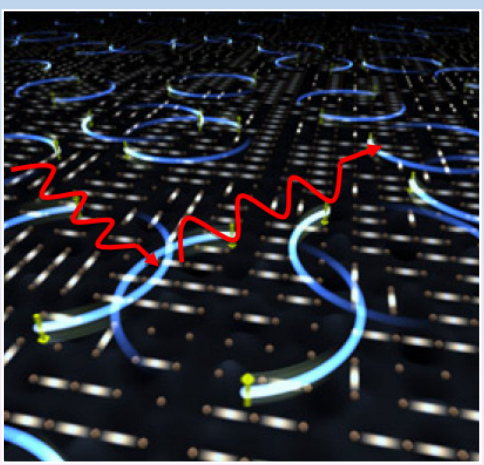


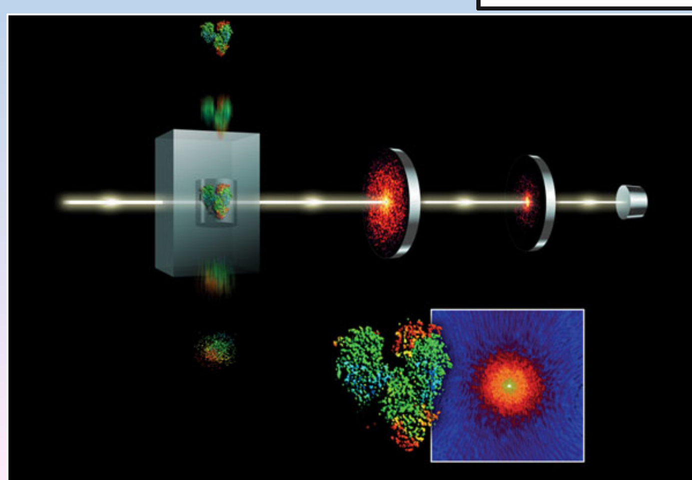


Where are the atoms?



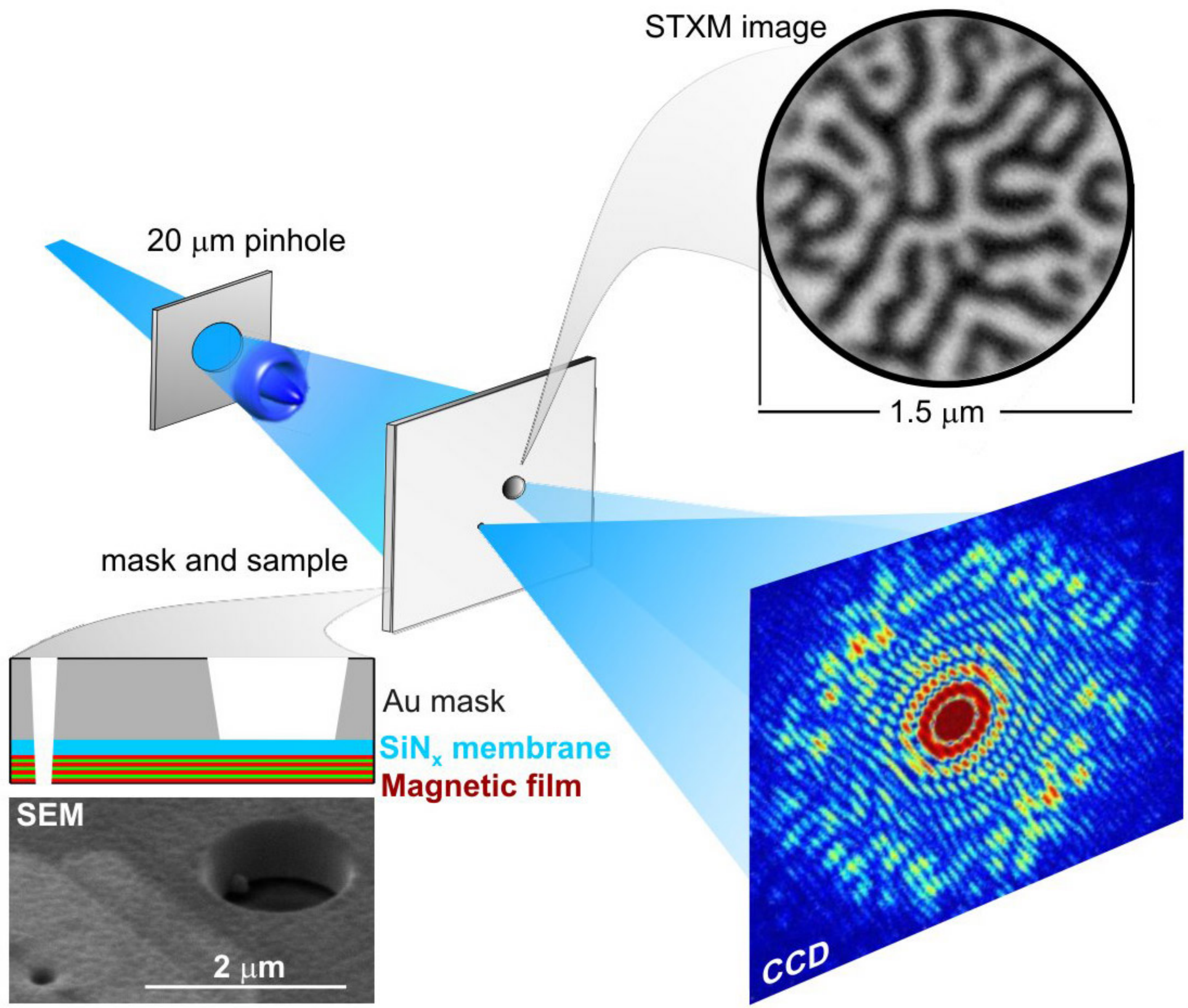
Brighter sources, better vision





Coherence Wanted

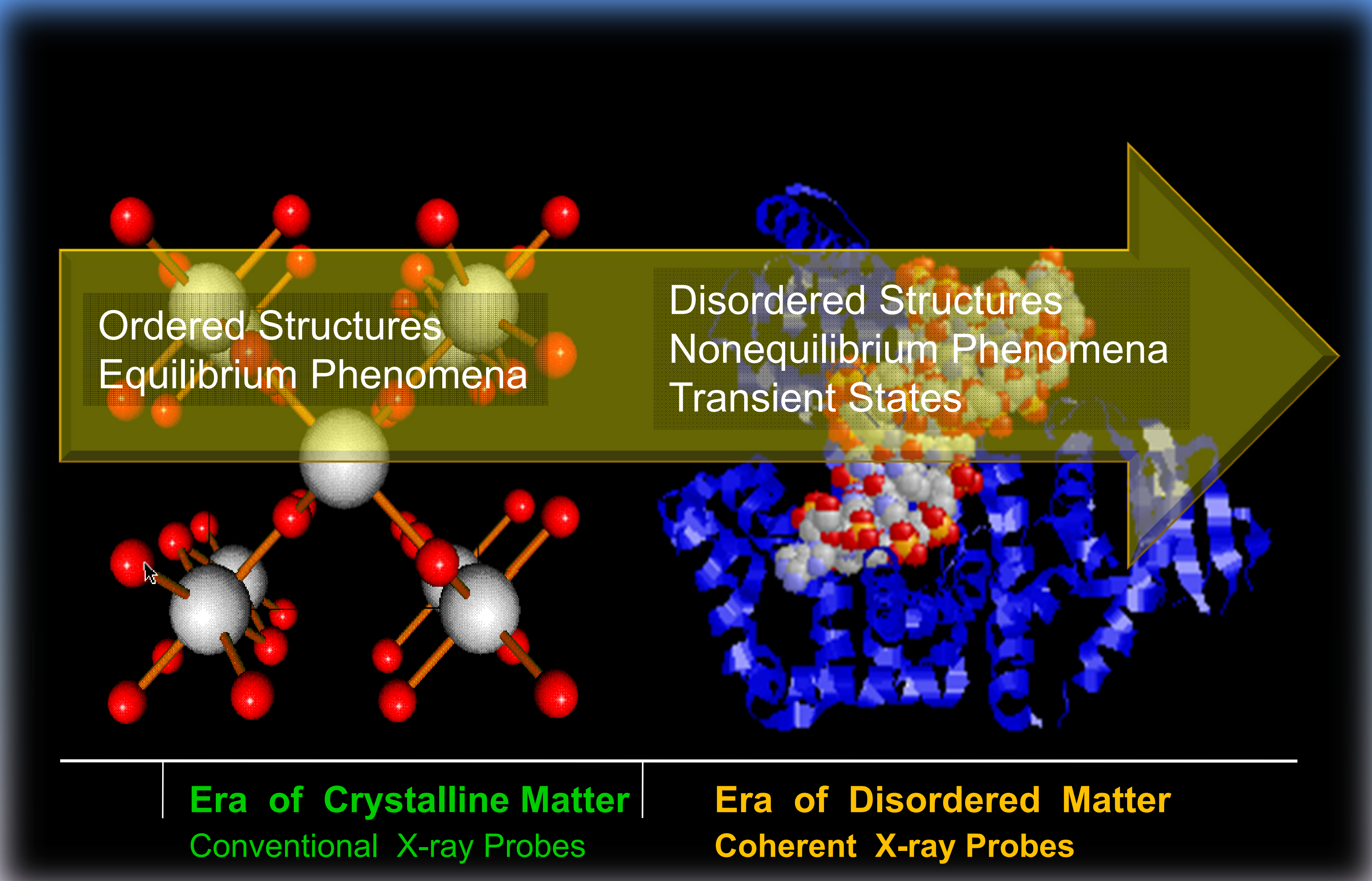
Lensless imaging of magnetic nanostructures by x-ray holography



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

LenslessImagingF1.ai

Future Role of FELs and Advanced Sources



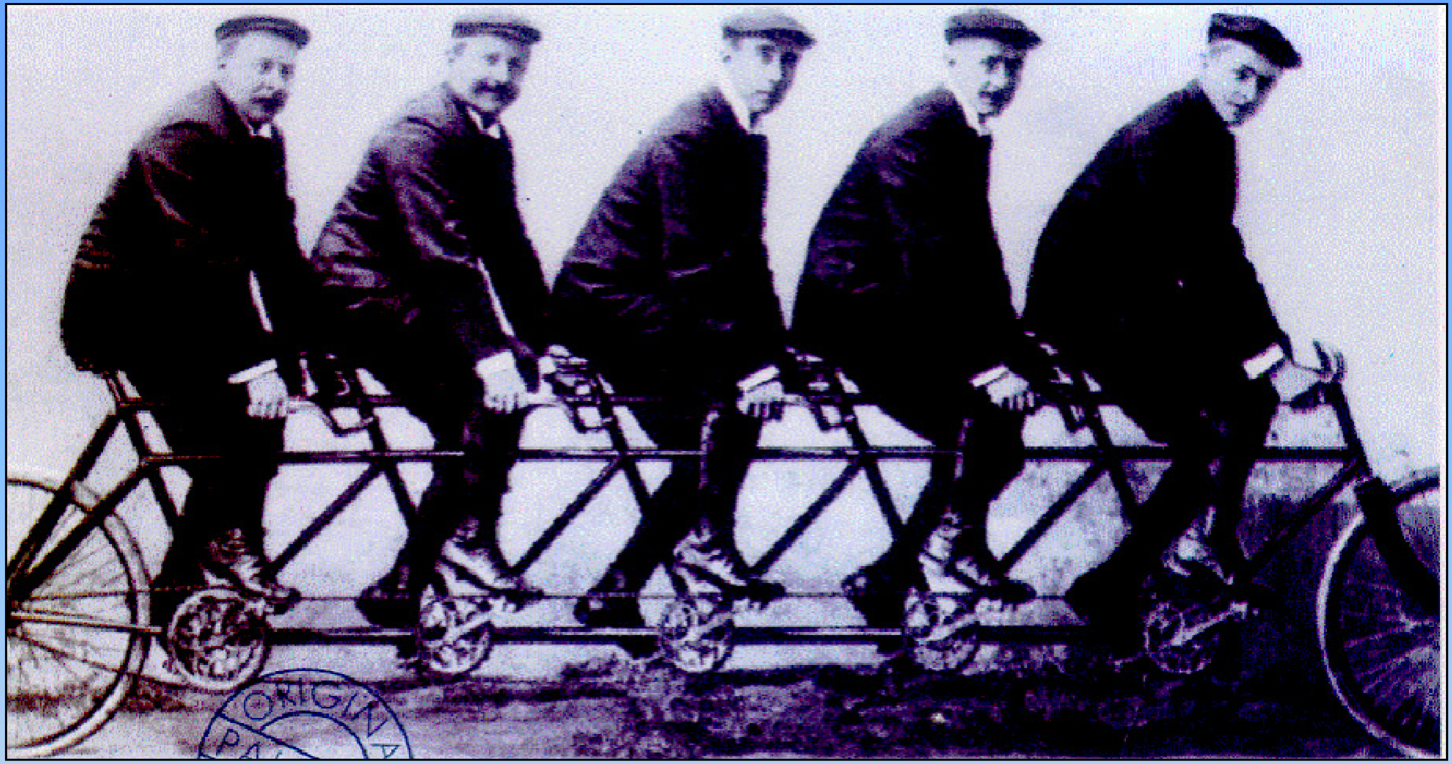
1900 2000 *future*

H. Dosch (DESY)

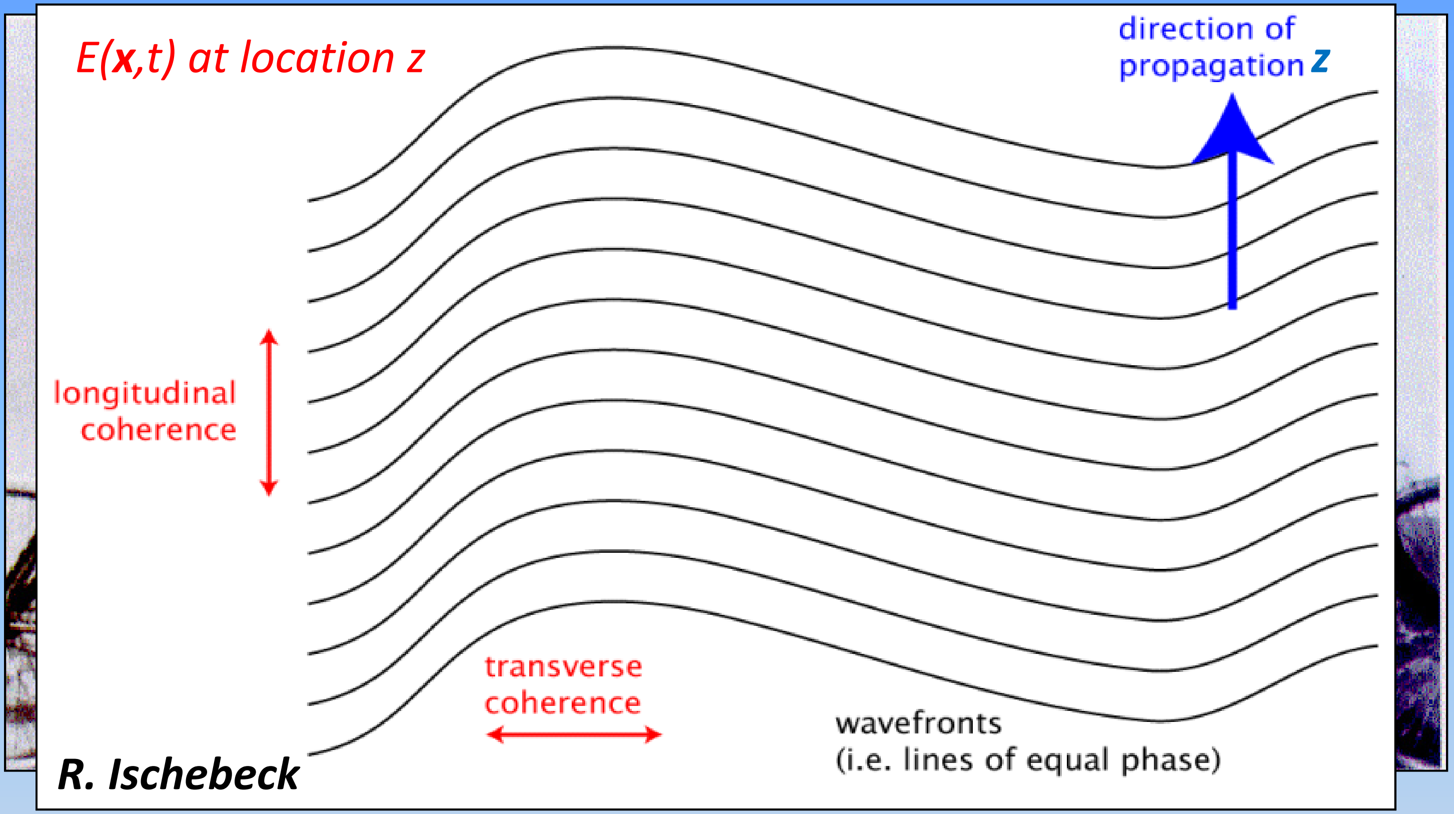
Outline

- *Introduction*
- *Coherence*
- *Brightness*
- *Undulator Radiation*
- *Free Electron Lasers*
- *Summary*

What is coherence?



What is coherence?



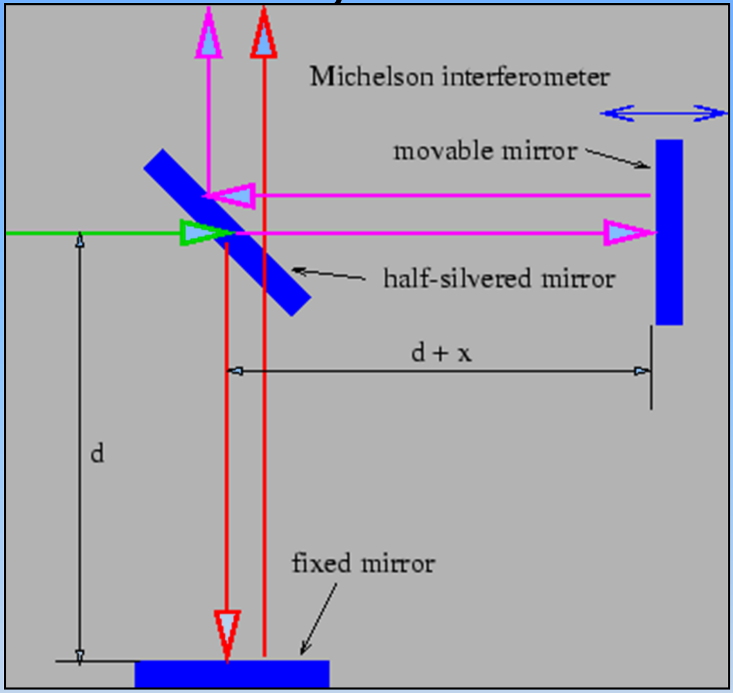
- *Complex degree of coherence*

$$\gamma(\boldsymbol{x}_1, \boldsymbol{x}_2, \tau) = \frac{\langle E(\boldsymbol{x}_1, t) E^*(\boldsymbol{x}_2, t+\tau) \rangle}{\sqrt{\langle |E(\boldsymbol{x}_1, t)|^2 \rangle \langle |E(\boldsymbol{x}_2, t+\tau)|^2 \rangle}}$$

$\gamma(\boldsymbol{x}_1, \boldsymbol{x}_2, 0)$ describes the transverse coherence, $\gamma(0, 0, \tau)$ characterizes the temporal coherence.

Temporal (Longitudinal) Coherence

- *Coherence time is determined by measuring the path length difference over which fringes can be observed in a Michelson interferometer.*



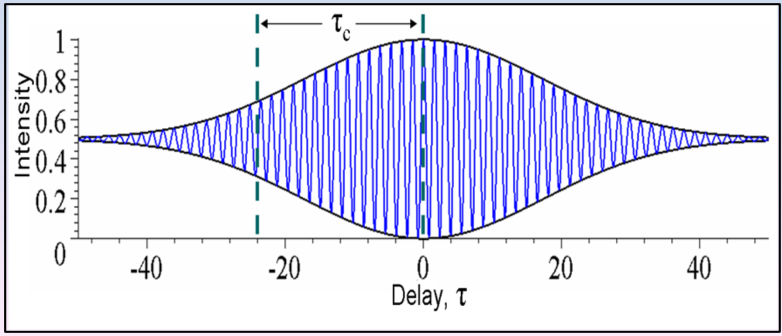
$$\tau_c = \int_{-\infty}^{\infty} d\tau |\gamma(\tau)|^2$$

- *Temporal coherence function and the radiation spectrum forms a Fourier pair*

$$\gamma(\tau) = \frac{\int_{-\infty}^{\infty} d\omega |E(\omega)|^2 e^{-i\omega\tau}}{\int_{-\infty}^{\infty} d\omega |E(\omega)|^2}$$

- *For a Gaussian radiation spectrum,*

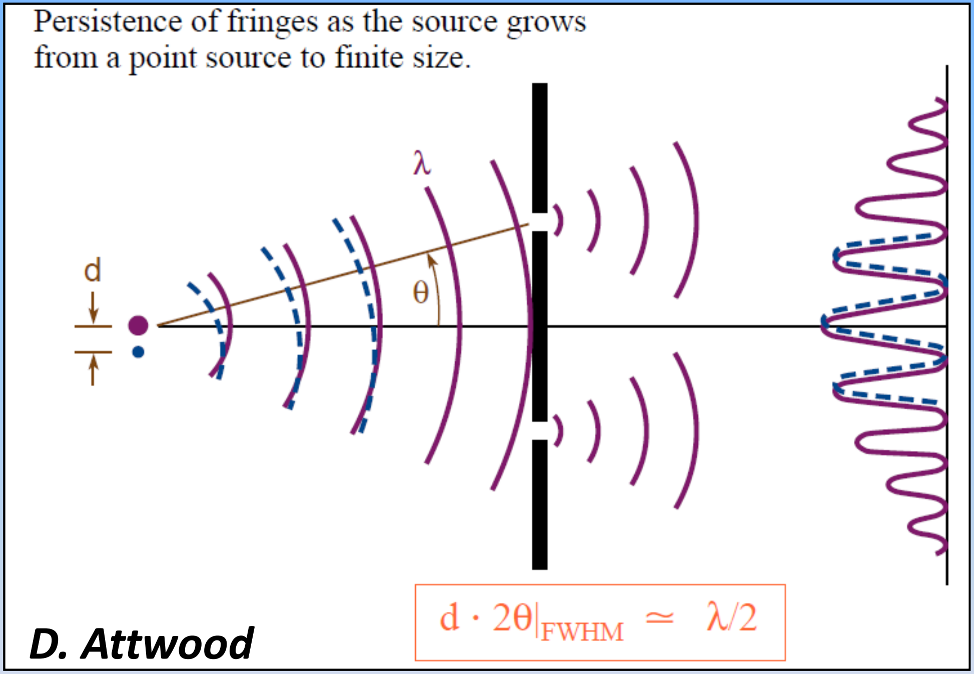
$$\tau_c = \frac{\sqrt{\pi}}{\sigma_\omega}$$



Transverse (Spatial) Coherence

- *Transverse coherence can be measured via the interference pattern in Young's double slit experiment.*

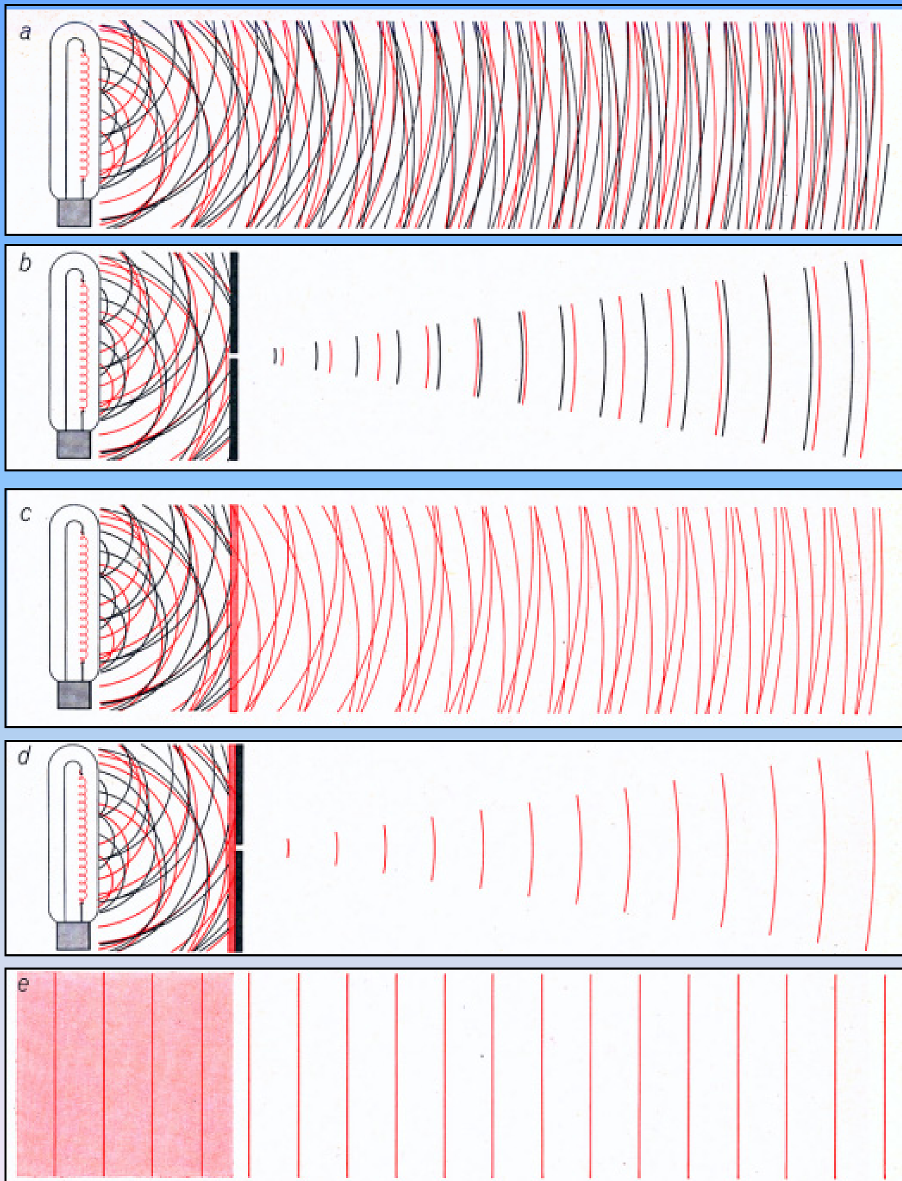
- *Near the center of screen, fringe visibility is described by $\gamma(\mathbf{x}_1,\mathbf{x}_2,0)$.*



- *Degree of transverse coherence (coherence fraction):*

$$\zeta = \frac{\int\int |\gamma(\boldsymbol{x}_1, \boldsymbol{x}_2, 0)|^2 I(\boldsymbol{x}_1) I(\boldsymbol{x}_2) d\boldsymbol{x}_1 d\boldsymbol{x}_2}{\int I(\boldsymbol{x}_1) d\boldsymbol{x}_1 \int I(\boldsymbol{x}_2) d\boldsymbol{x}_2}$$

Light Bulb vs. Laser



Radiation emitted from light bulb is chaotic.

Pinhole can be used to obtain spatial coherence.

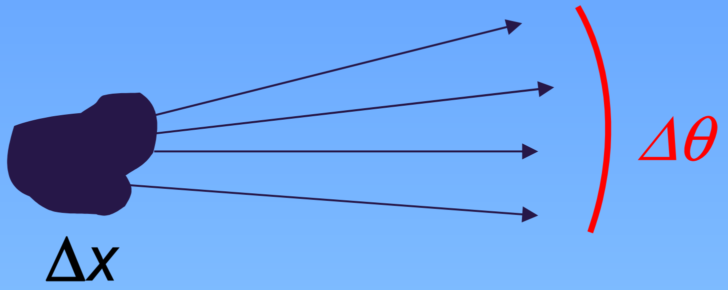
Monochromator can be used to obtain temporal coherence.

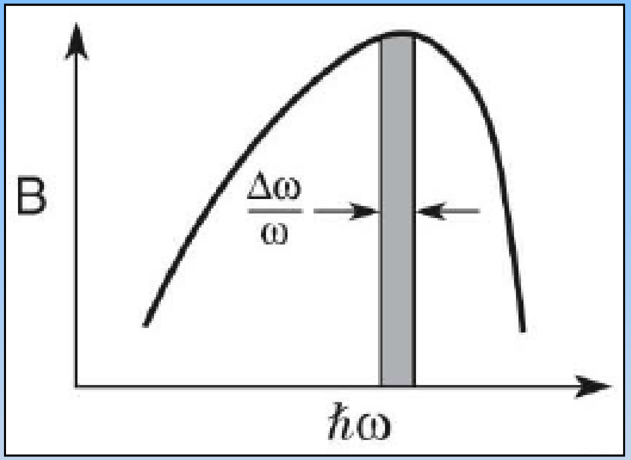
Pinhole and Monochromator can be combined for coherence.

Laser light is spatially and temporally coherent.

A. Schawlow (co-inventor of laser concept), Scientific Americans, 1968

Brightness





$$B = \frac{\text{Photons in unit spectral range in unit time}}{(\text{source size} \times \text{divergence})^2}$$

→ **Peak** / **Average**

Units: photons/s/mm²/mrad²/0.1%BW

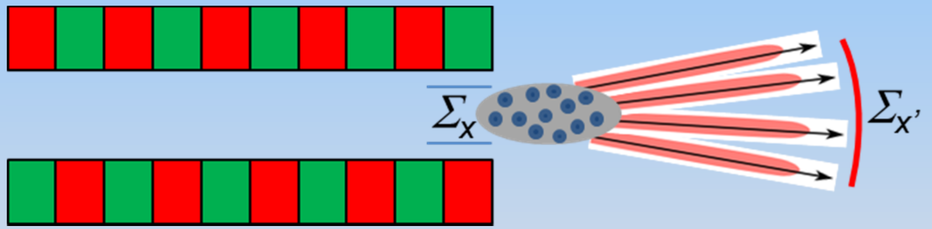
Brightness via Wigner Function

- *Spectral brightness defined via Wigner function, which is Fourier transformation of the transverse correlation function (K.J. Kim, 1986).*

$$B(\boldsymbol{x},\boldsymbol{\phi};z) = \frac{d\omega}{\hbar\omega}\frac{\omega^2\varepsilon_0}{\pi c T}\int d\boldsymbol{\xi} e^{ik\boldsymbol{\xi}\cdot\boldsymbol{\phi}}\left\langle E\left(\boldsymbol{x}+\tfrac{1}{2}\boldsymbol{\xi};z\right)E^*\left(\boldsymbol{x}-\tfrac{1}{2}\boldsymbol{\xi};z\right)\right\rangle$$

- *Brightness is conserved in a perfect optical system: cannot increase brightness once the source is born.*

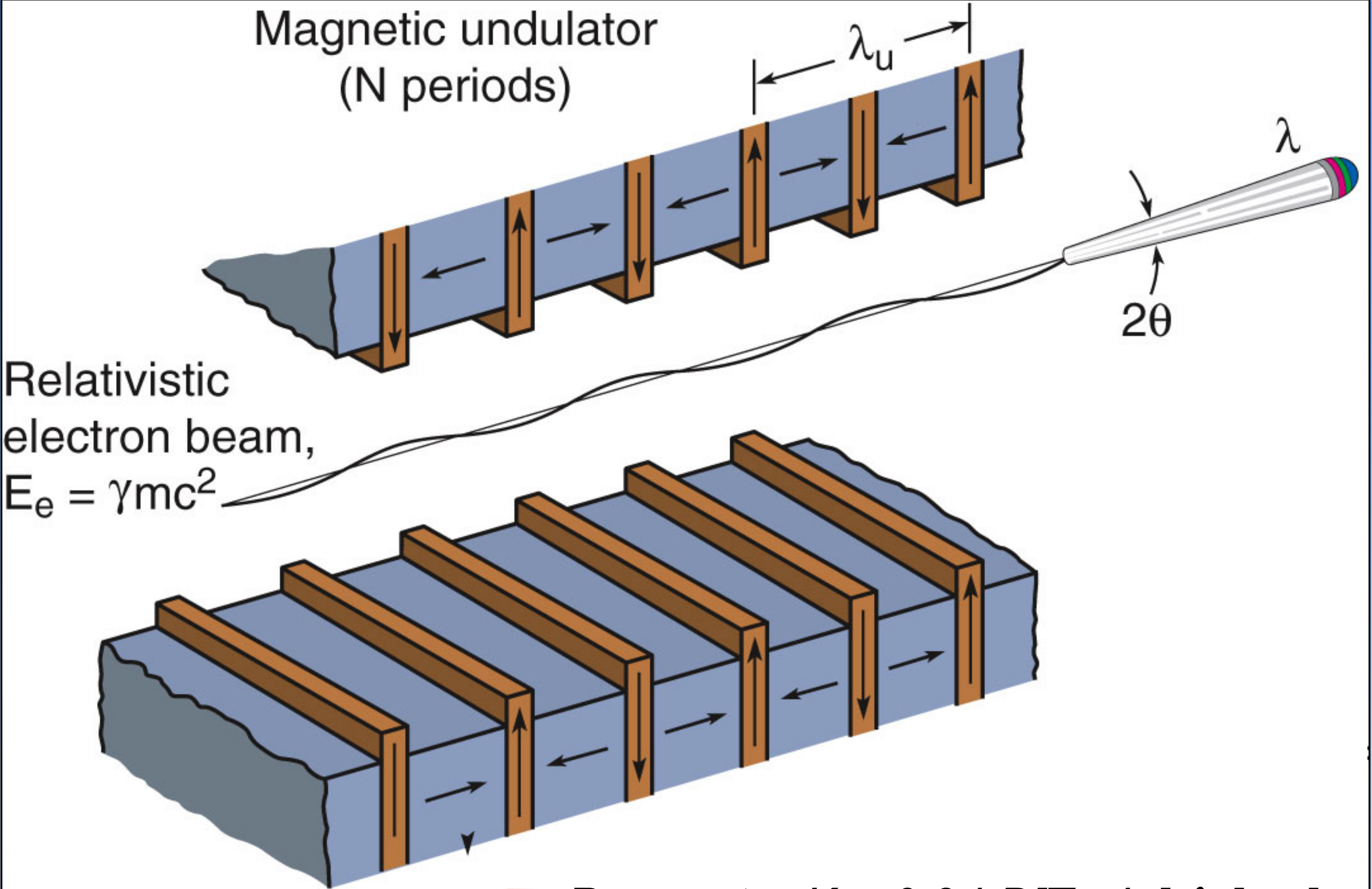
- *Brightness convolution theorem*



$$B(\boldsymbol{x},\boldsymbol{\phi},z) = N_e\int d\boldsymbol{x}_j d\boldsymbol{x}'_j B_j(\boldsymbol{x}-\boldsymbol{x}_j,\boldsymbol{\phi}-\boldsymbol{x}'_j,z) f(\boldsymbol{x}_j,\boldsymbol{x}'_j,z)$$

single electron rad. brightness ***electron distribution function***

Undulator Radiation



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

- *Parameter K = 0.94 B[Tesla] λ_u[cm]*
- *Quasi-monochromatic central cone*

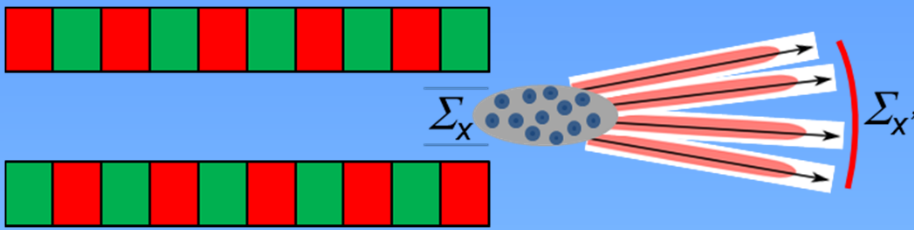
D. Attwood

Under Gaussian approximation, central radiation cone has

$$\sigma_{r'} = \sqrt{\frac{\lambda}{2L_u}}, \quad \sigma_r = \frac{\sqrt{2\lambda L_u}}{4\pi}$$

Undulator Radiation Brightness

- *Brightness convolution theorem*



$$B(\boldsymbol{x},\boldsymbol{\phi}) = \frac{N_e F_1(\omega)}{(2\pi)^2 \Sigma_x \Sigma_y \Sigma_{x'} \Sigma_{y'}} \exp\left(-\frac{x^2}{2\Sigma_x^2} - \frac{y^2}{2\Sigma_y^2} - \frac{\phi_x^2}{2\Sigma_{x'}^2} - \frac{\phi_y^2}{2\Sigma_{y'}^2}\right)$$

$$\Sigma_{x,y}^2 \equiv \sigma_{x,y}^2 + \sigma_r^2\,, \quad \Sigma_{x',y'}^2 \equiv \sigma_{x',y'}^2 + \sigma_{r'}^2$$

- *Emittance dominated regime* $\varepsilon_{x,y} = \sigma_{x,y}\sigma_{x',y'} \gg \frac{\lambda}{4\pi}$

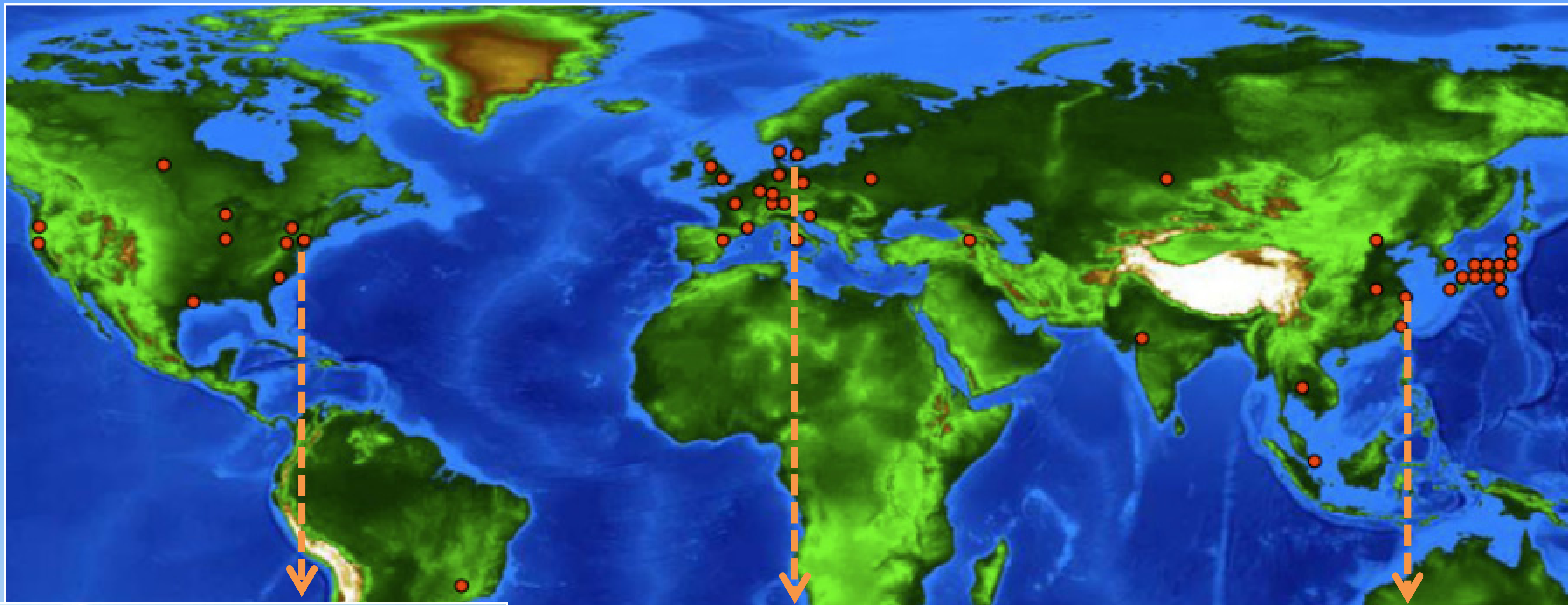
$$B(\mathbf{0},\mathbf{0}) = \frac{N_e F_1(\omega)}{(2\pi)^2 \sigma_x \sigma_{x'} \sigma_y \sigma_{y'}} = \frac{F(\omega)}{(2\pi)^2 \varepsilon_x \varepsilon_y}$$

- *Radiation dominated regime* $\varepsilon_{x,y} \ll \frac{\lambda}{4\pi}$

$$B(\mathbf{0},\mathbf{0}) = \frac{F(\omega)}{(2\pi)^2 \sigma_r^2 \sigma_{r'}^2} = \frac{F(\omega)}{(\lambda/2)^2}$$

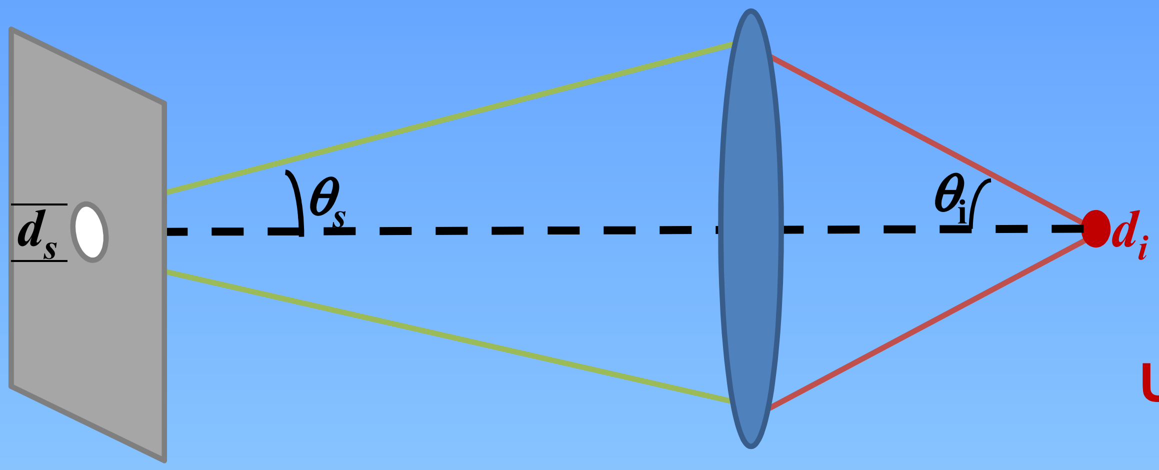
Diffraction limit

Synchrotron Radiation Facilities



- *State-of-art storage rings have* ***pulse duration ~10 ps, emittance ~1 nm.***
- *Diffraction-limited storage rings and energy recovery linacs with* ***emittance ~10 pm*** *are under active R&D.*

Diffraction Limit

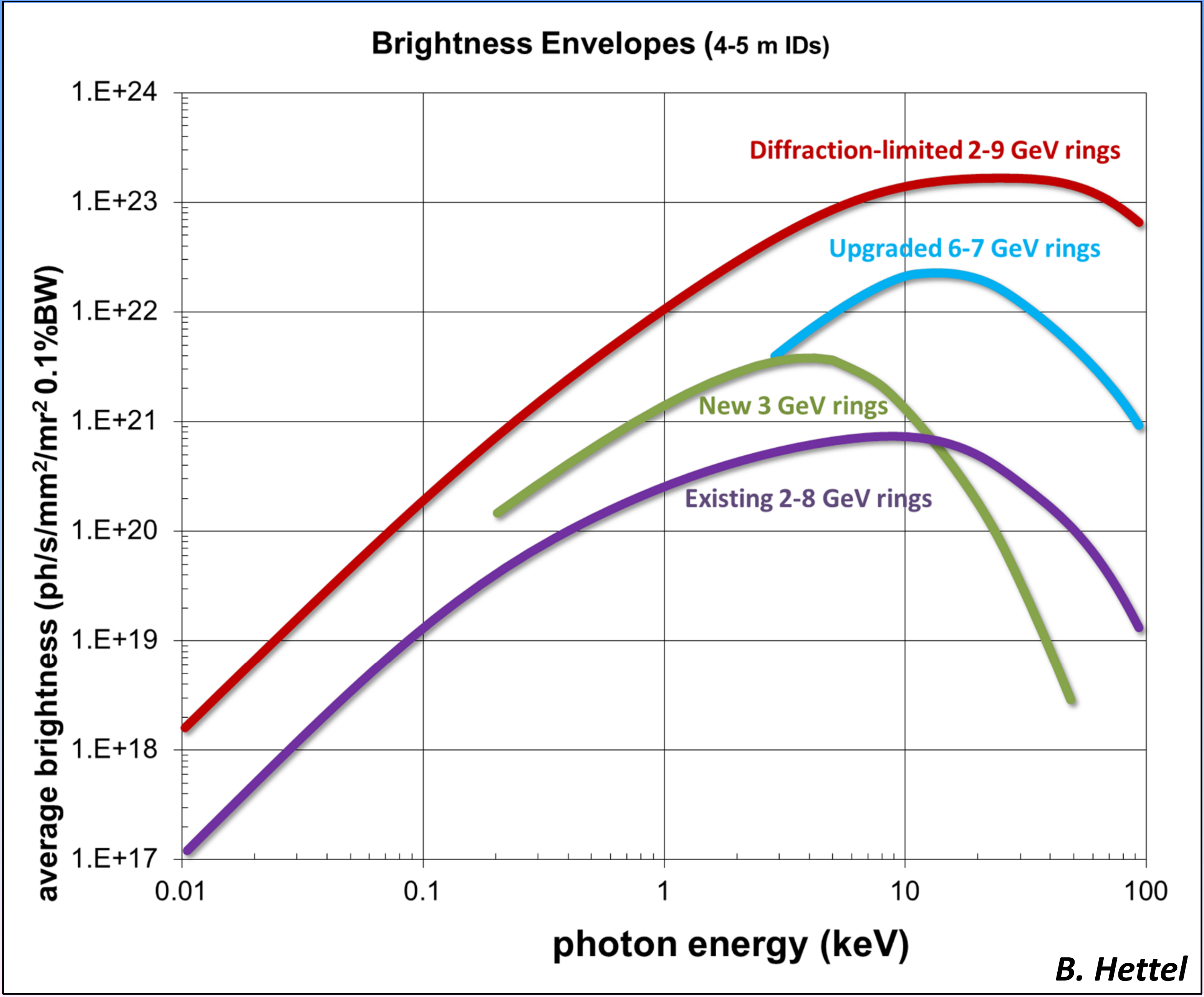


$$\varepsilon_x \sim \varepsilon_y \sim \frac{\lambda_r}{4\pi}$$

Ultimate spatial resolution

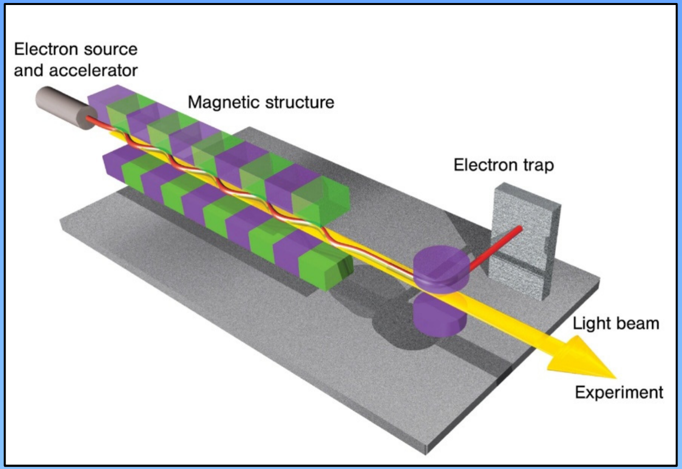
- *Perfect optical system has* $d_s\theta_s = d_i\theta_i$
  θ_i *is the numerical aperture of focusing system*
- *Reducing pinhole size until* $d_s\theta_s \sim \lambda/2$
  since $d_i \sim \lambda/(2\theta_i)$ *reaches diffraction limit.*
- *A even smaller pinhole does not reduce the image size but only hurts the photon flux*
- ***Diffraction limited source does not require a pinhole and provide the most coherent flux***

Storage Ring Spectral Brightness

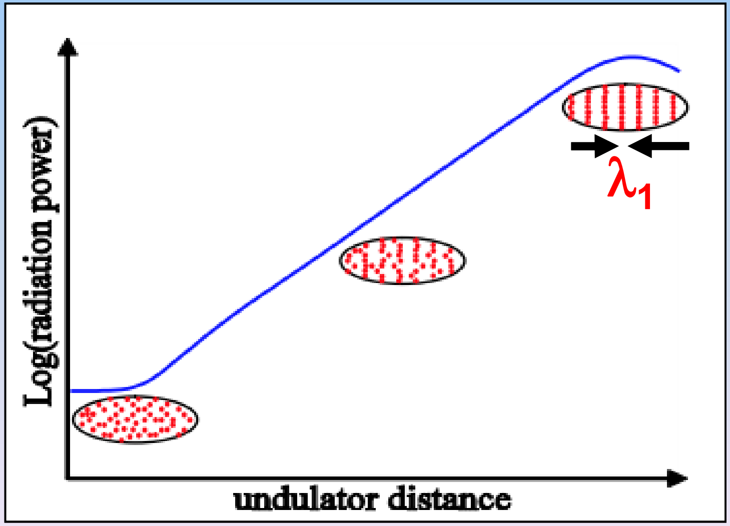


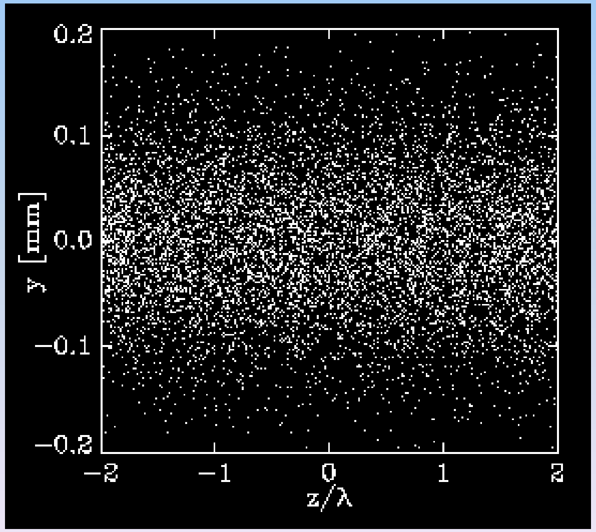
Free Electron Laser (FEL)

- ***Resonant interaction** of electrons with EM radiation in an undulator^*
- ***Coherent radiation intensity $\propto N^2$ due to beam microbunching***
  (N: # of e^- involved ~10^6 to 10^9)



- *At x-ray wavelengths, use **Self-Amplified Spontaneous Emission* (a wonderful instability!)** to reach high peak power*





S. Reiche

^ J. Madey, J. Appl. Phys., 1971

** Kondradenko, Saldin, Part. Accel., 1980*
** Bonifacio, Pellegrini, Narducci, Opt. Com., 1984*

X-ray FELs

- *FEL power grows exponentially with gain length*

$$P = P_0 \exp\left(\frac{z}{L_G}\right)$$

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

ρ is the FEL efficiency parameter ~ 10^{-3} for x-ray FELS

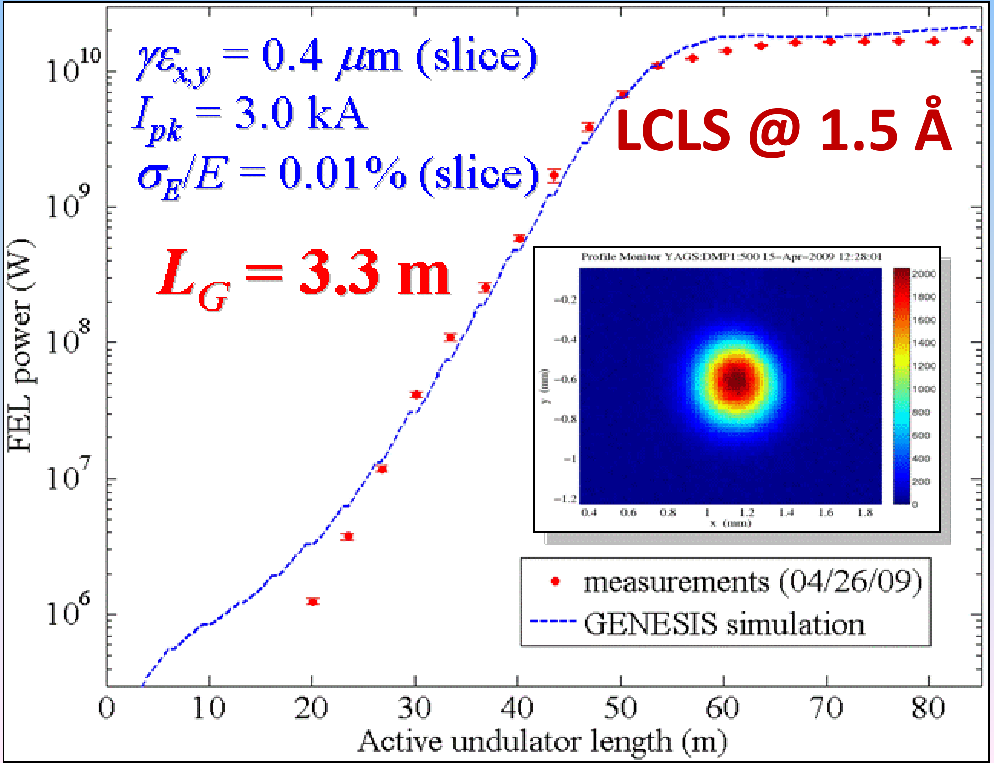
- *Exponential gain process selects a Gaussian-like transverse mode with excellent transverse coherence*

- *Mode size and divergence*

$$\sigma_r \approx \sqrt{\sigma_x \sigma_D}$$

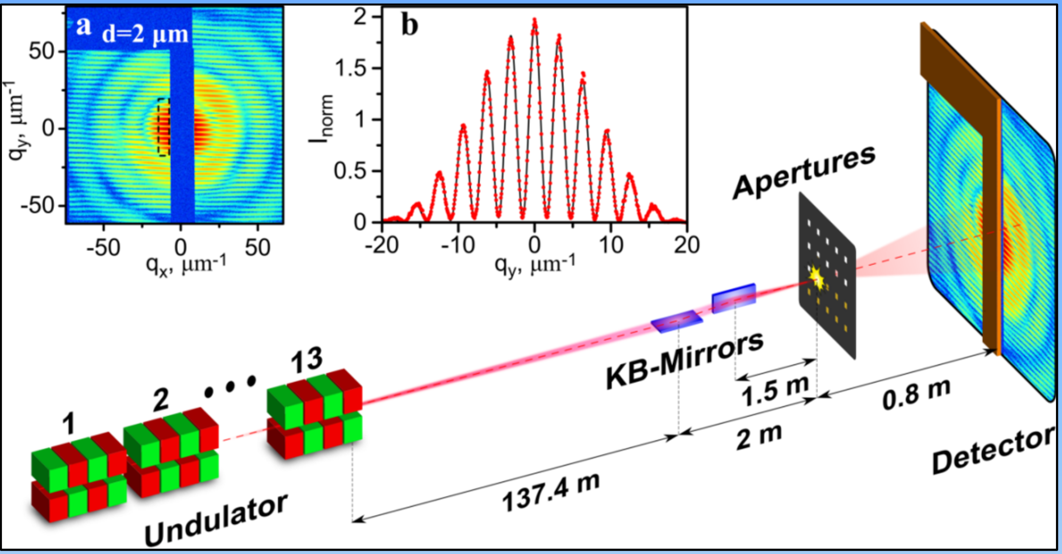
$$\sigma_{r'} \approx \frac{\lambda/(4\pi)}{\sigma_r}$$

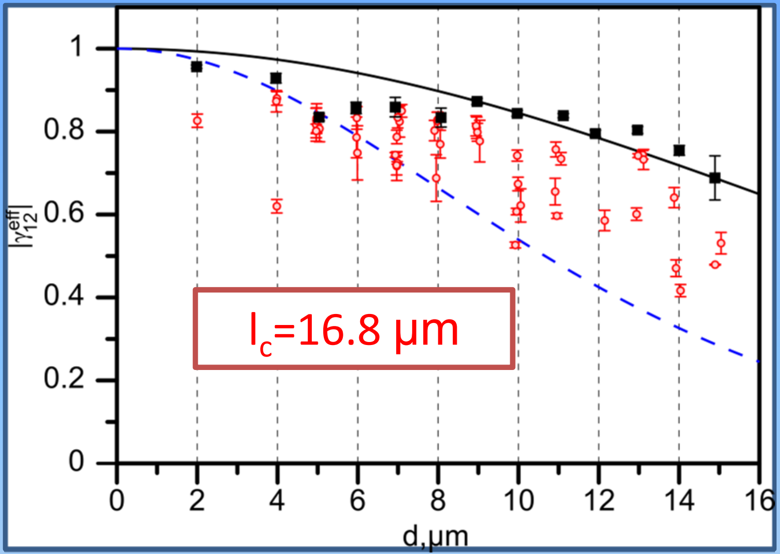
$$\sigma_D = \sqrt{L_G \lambda/(4\pi)}$$

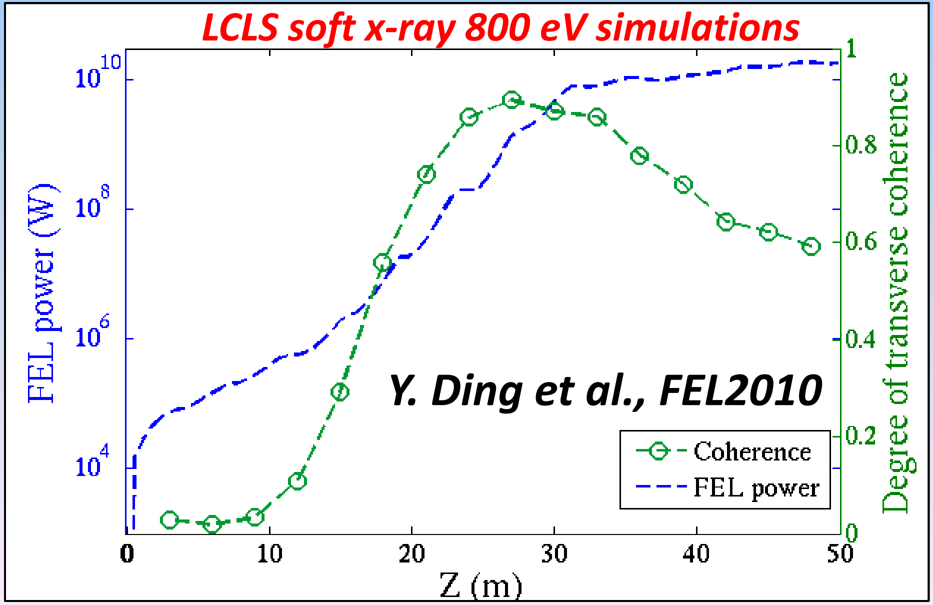


Measured LCLS Transverse Coherence

LCLS SXR at 780 eV



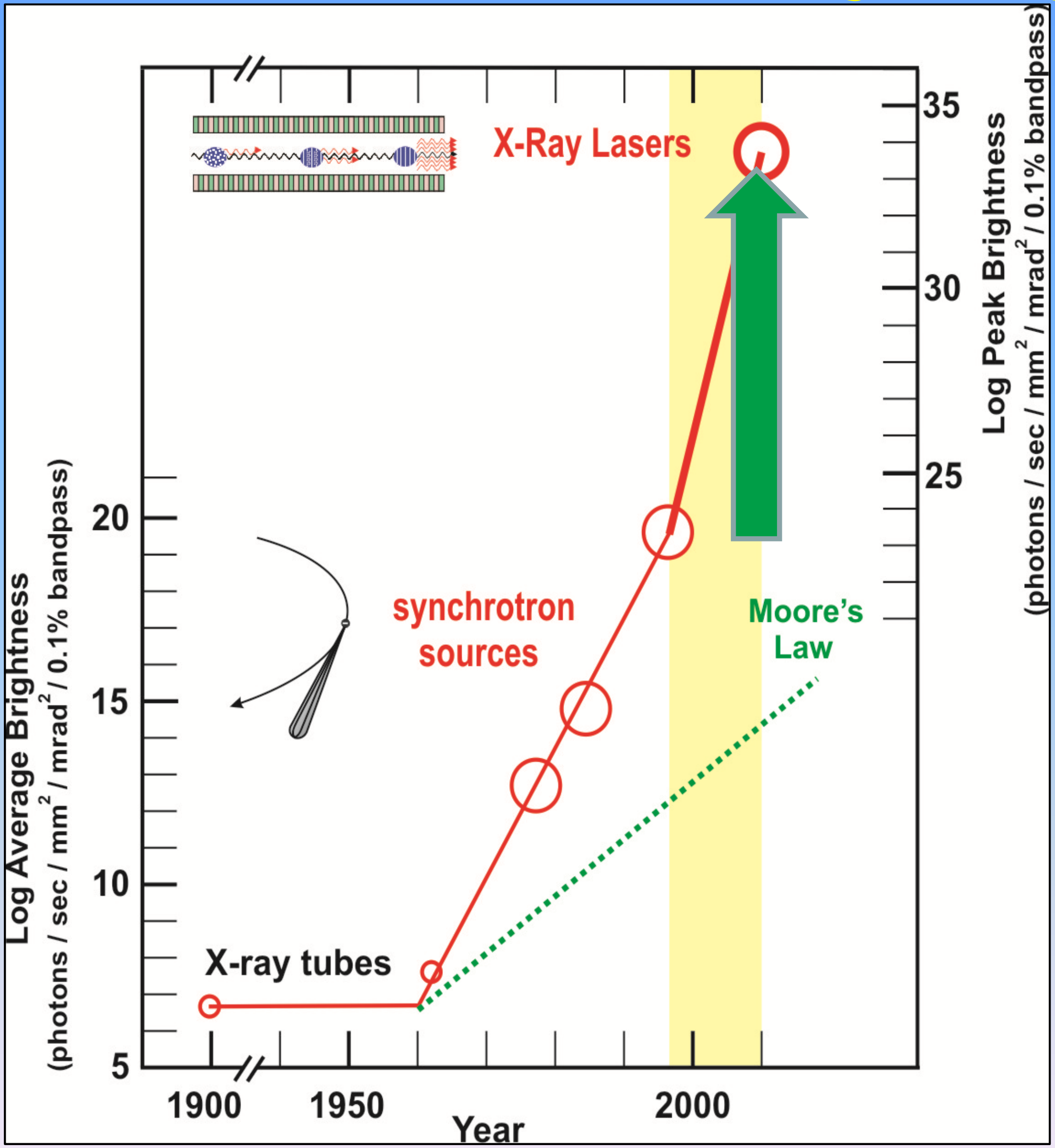


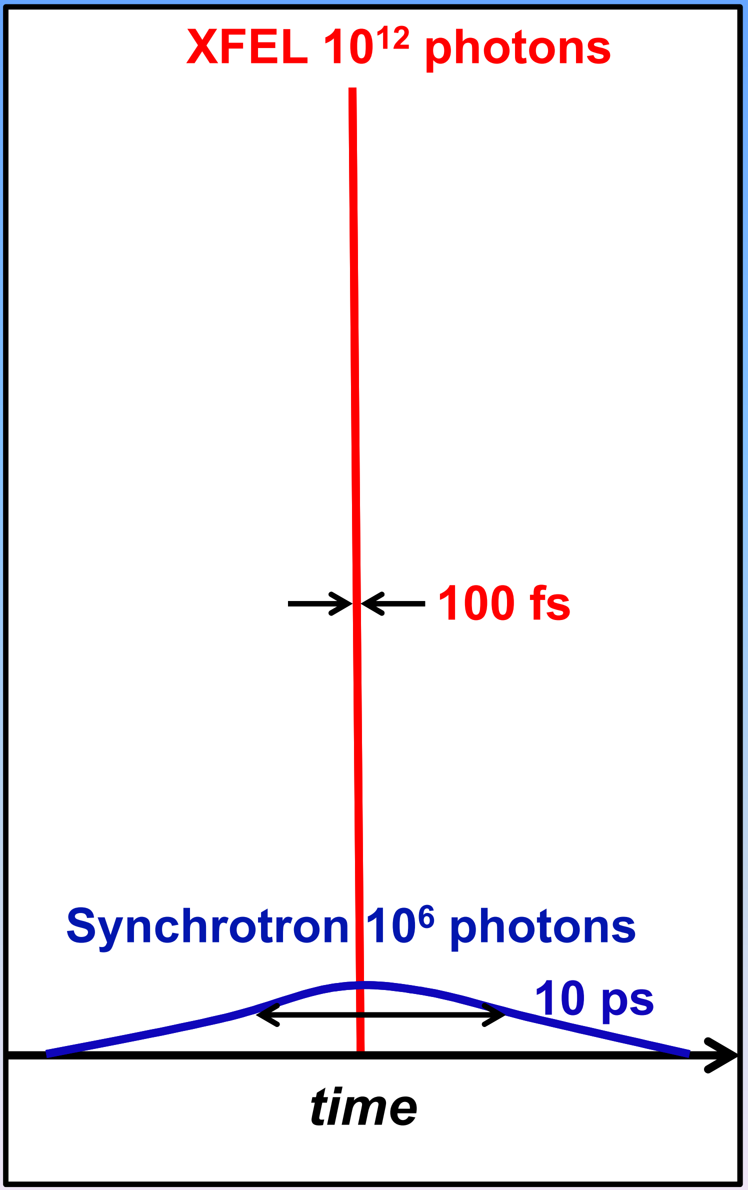


Beam size (FWHM) 17 µm
Trans. Coherence length 16.8 µm
Vertical degree of coherence: ~75 %
Global degree of coherence: ~56%

Vartanyants et al. PRL 107, 144801 (2011)

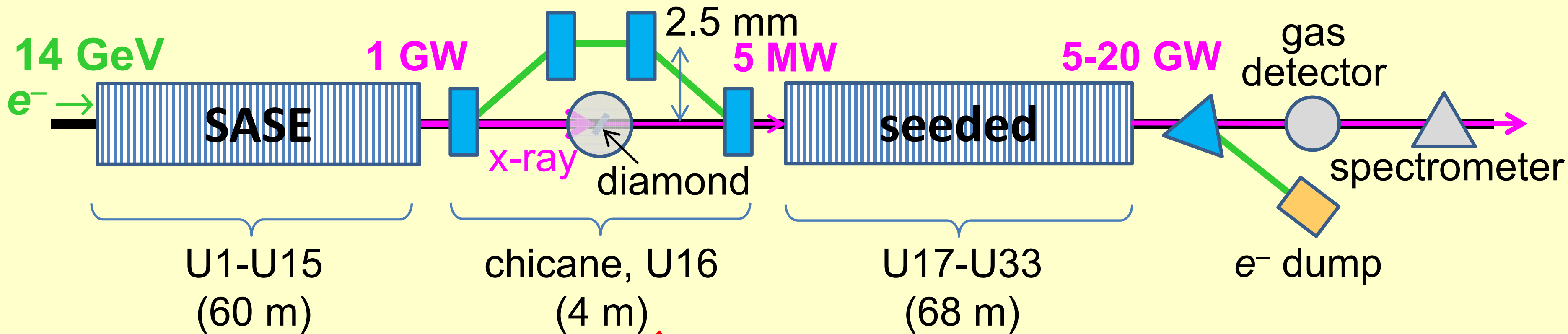
XFELs are Extremely Bright and Ultrafast



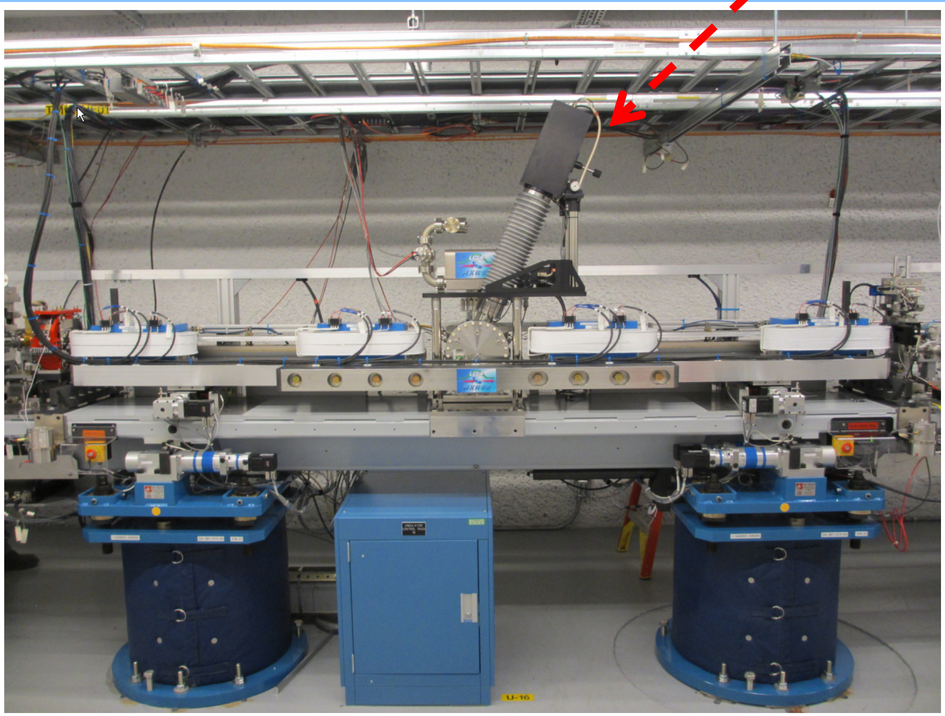


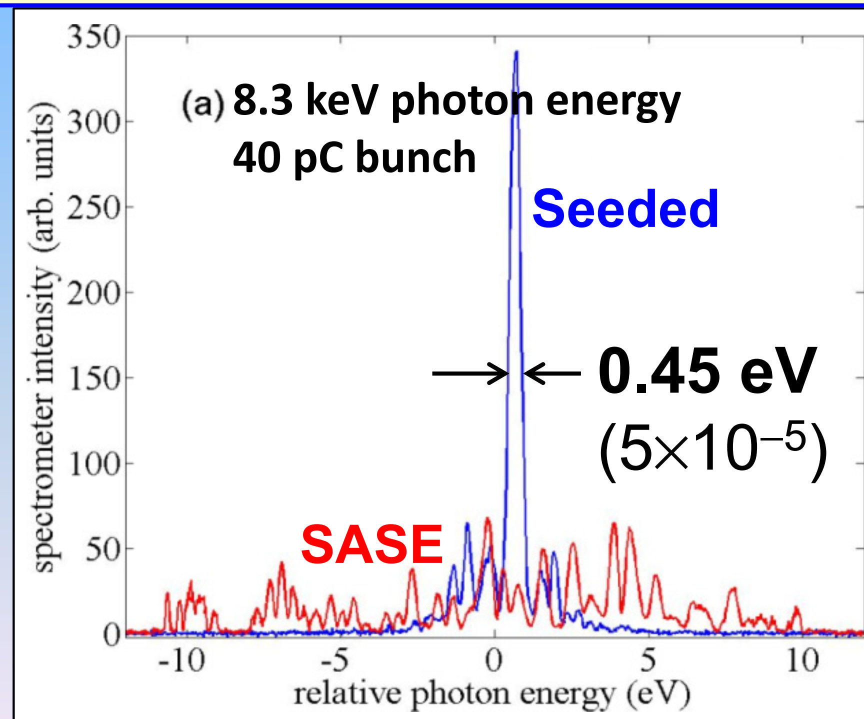
Note: synchrotron sources are much higher rep. rate than XFELs

Seeding to Improve Temporal Coherence



Geloni, Kocharyan, Saldin 2010 (DESY)

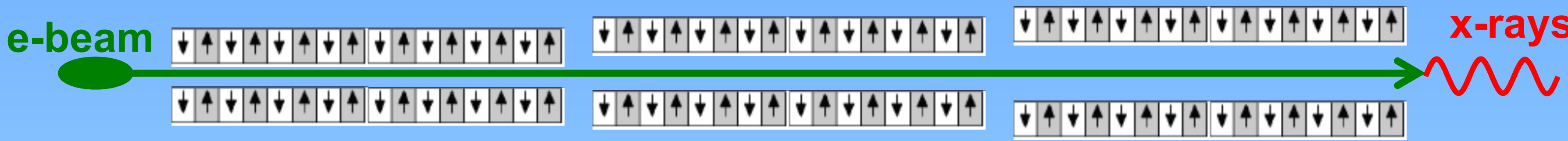




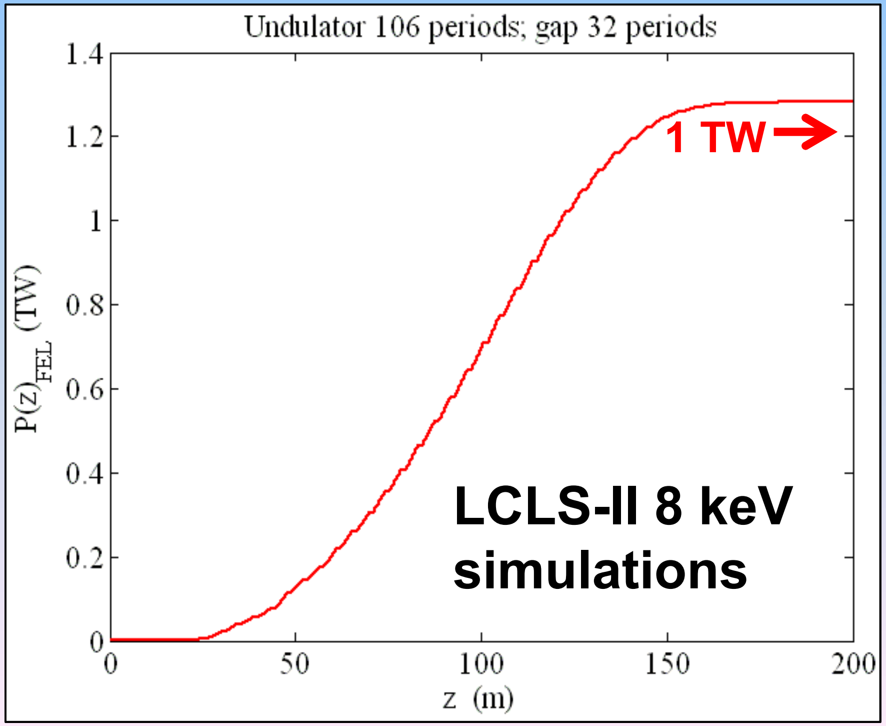
J. Amann et al., Nature Photon., 2012

Terawatt FEL with Tapered Undulator

- *FEL power saturates due to significant E-loss*
- *Tapered undulator keeps FEL resonance and increase power*



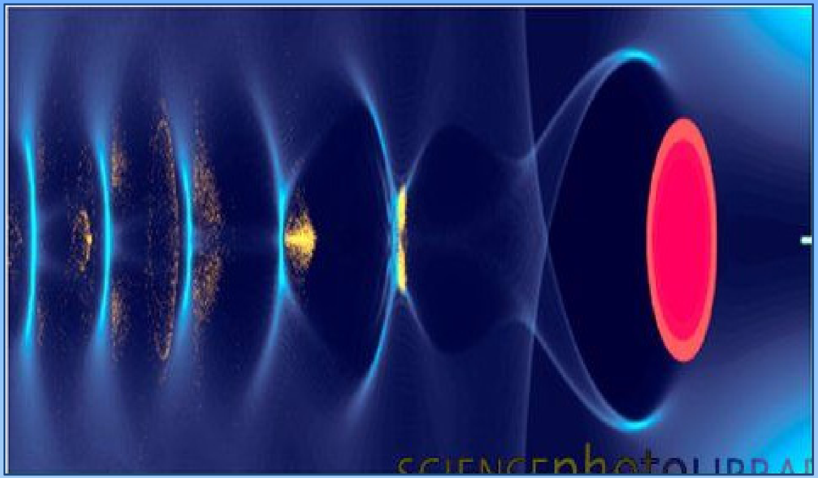
- ***Taper works well for a seeded FEL. Seeded TW FEL increases peak brightness over SASE by another two orders of magnitude!***



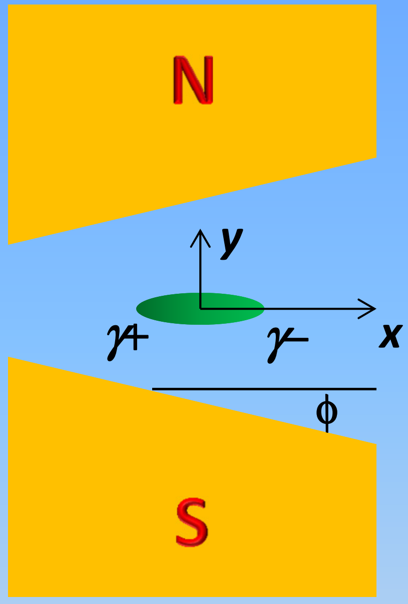
J. Wu et al., FEL2011
Y. Jiao et al., PRSTAB 2012.

Compact X-Ray FELs

Laser Plasma Accelerator (LPA) or Beam-driven Plasma Accelerator



Transverse Gradient Undulator (TGU)*



*LPA beam parameters**

- *Beam energy (0.5-1 GeV)*
- *Norm. emittance (~0.1 μm)*
- *Peak current (3-10 kA)*
- ***Energy spread (1-2%)***

- *FEL resonance can be kept for a large energy spread by TGU + Dispersion*

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

- ***W. Leemans, et. al., Nat. Phys. (2006).***
- ***S. Kneip et al., Phys. Rev. Lett. (2009).***
- ***J. S. Liu et al., Phys. Rev. Lett. (2011).***

- ***T. Smith et al., J. Appl. Phys. 1979***
- ***Z. Huang et al., Phys. Rev. Lett., 2012***

Compact X-Ray FELs

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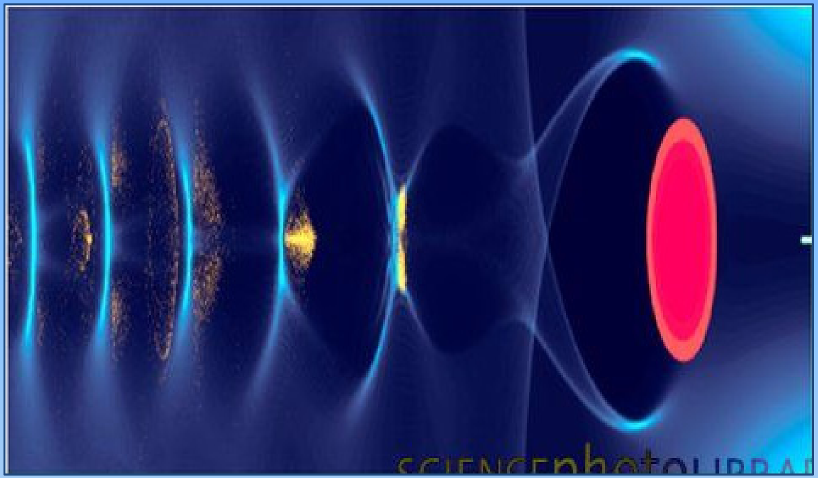

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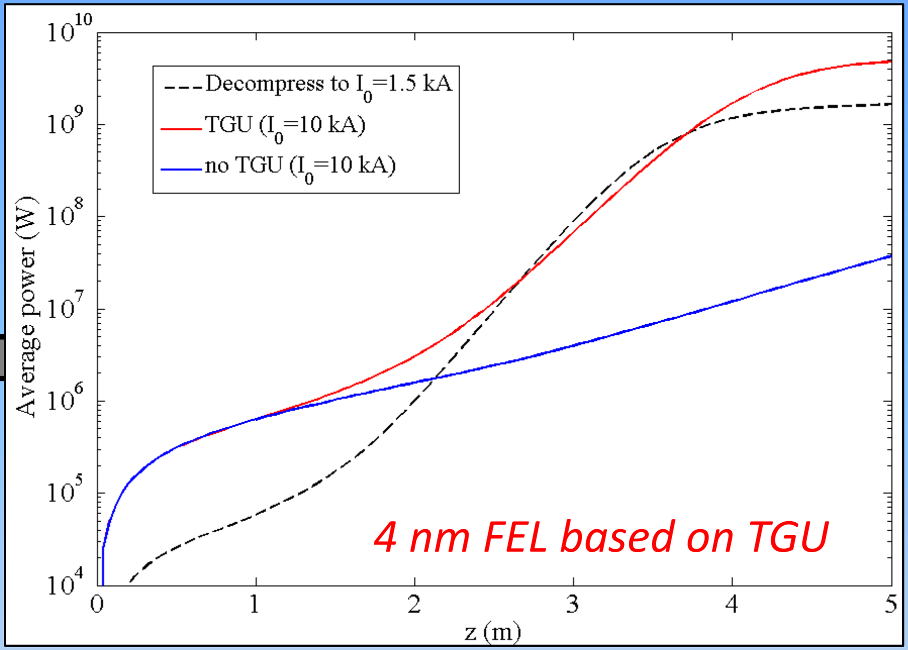

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Summary

- ***Despite spectacular successes in synchrotron radiation and FELs, the quest for brightness and coherence continues, with no sign of slowing down.***

- ***Future light source development includes diffraction-limited light sources, high-peak and average power FELs, compact coherent sources and many more possibilities.***

- ***The future of synchrotron radiation and FELs is as bright as Shanghai's skyline!***

Thanks for your attention， 谢谢！