SLAC-PUB-17216

X-Ray Free Electron Lasers

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Fundamentals of Accelerator Physics
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Old Dominion University
Norfolk, VA

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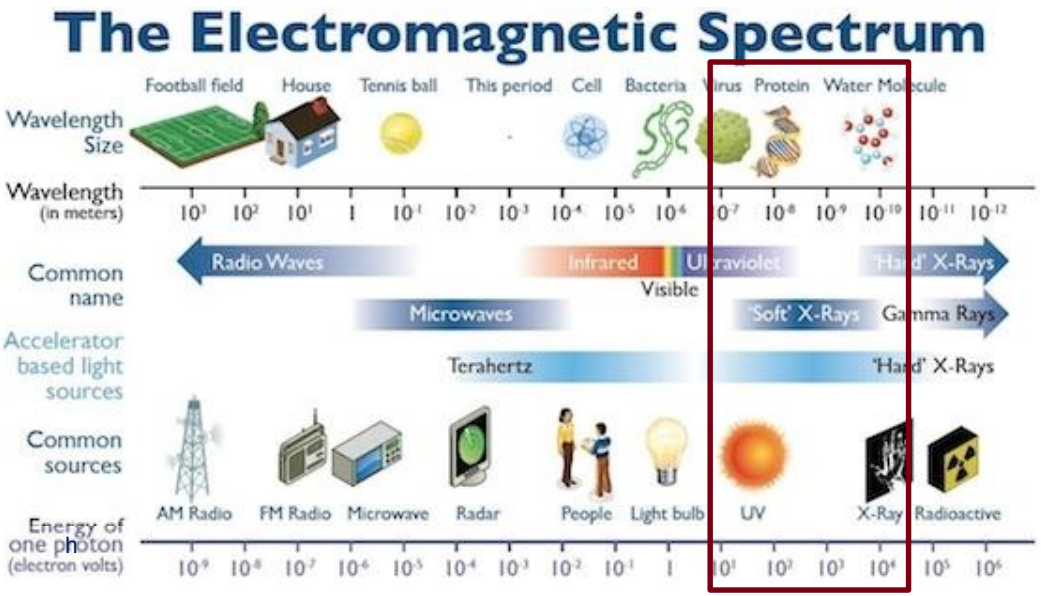
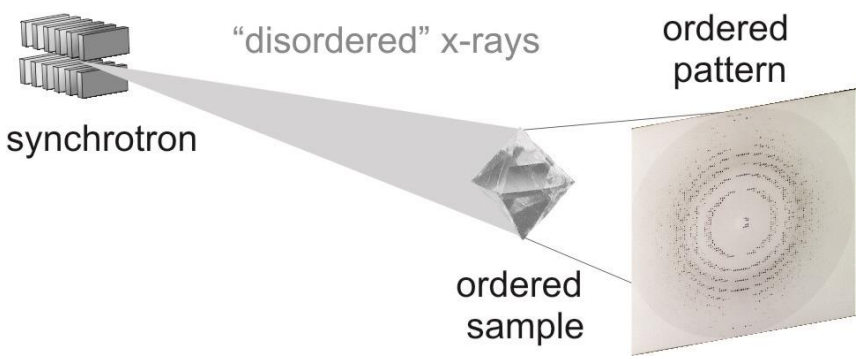
Desirable properties of Free Electron Laser

- Wavelength-tunable
  - 10 eV → 20 keV
- Variable polarization
- Spatial and temporal coherence
- Intense ultrafast pulses (fs and shorter)



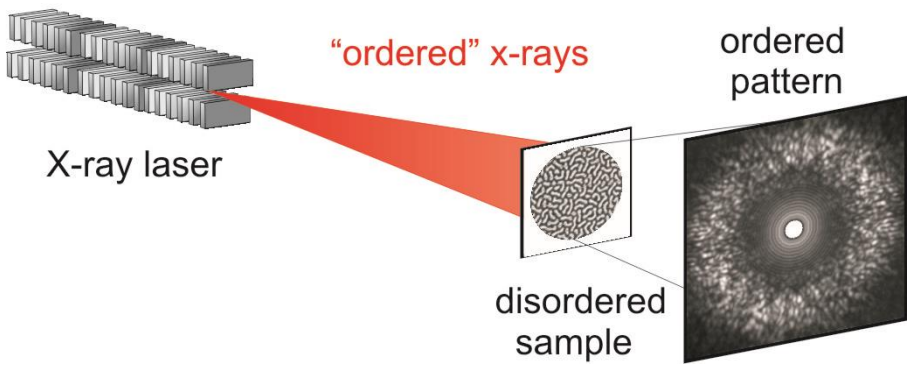
Source: lightsources.org

X-ray FELs offer a new paradigm in SR Science



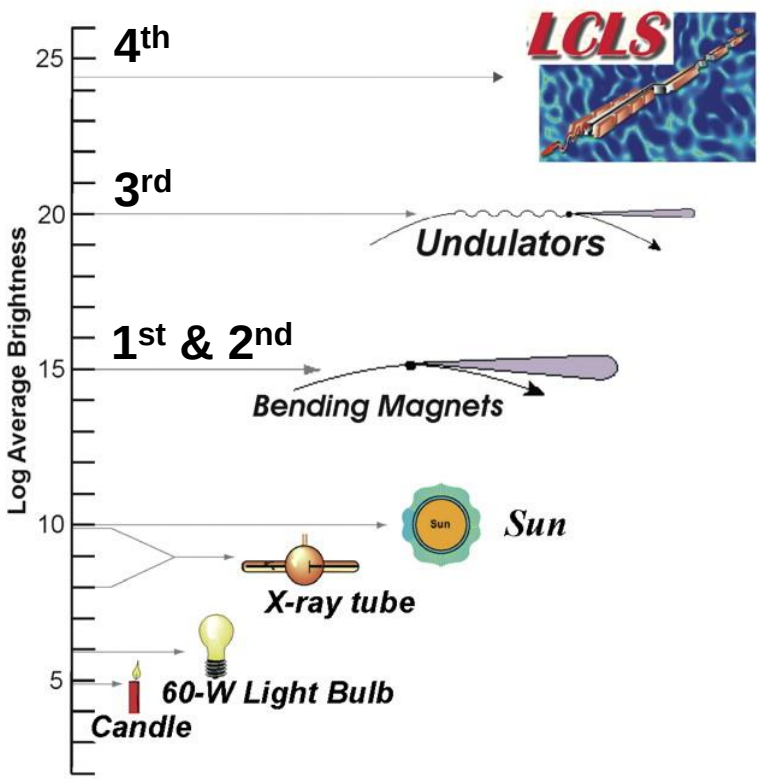
- 3rd gen storage ring
- Relies on making a large, ordered crystal
- What if you can't make a large crystal?

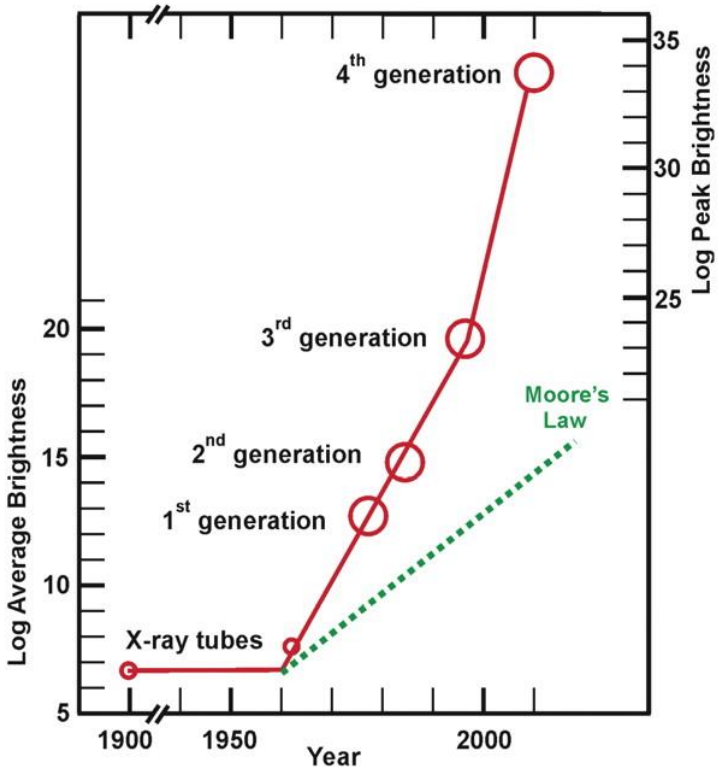
- Small crystal, or single molecule
- Require a much brighter source



Peak brilliance (intensity)

Brilliance/brightness $\mathcal{B} = \dfrac{F}{4\pi^2 \varepsilon_x \varepsilon_y}$

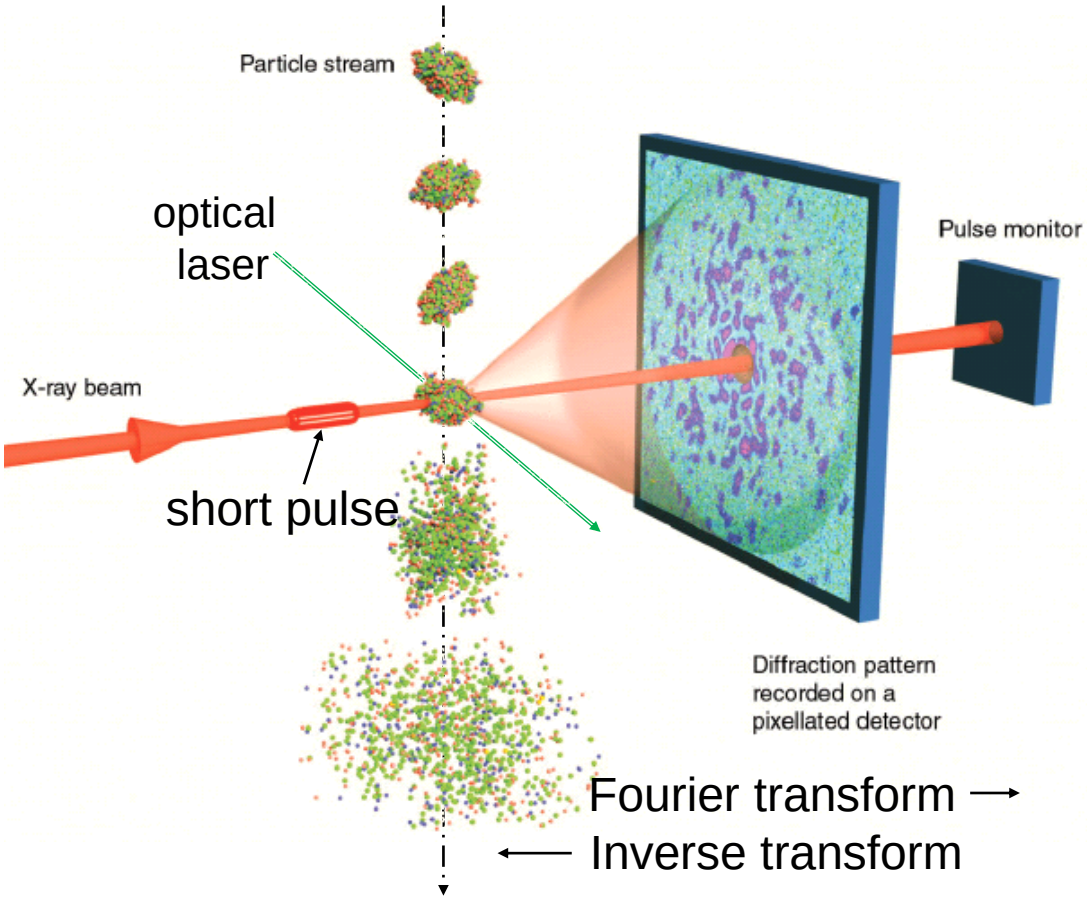




K. Wille, The Physics of Particle Accelerators: An Introduction, Oxford University Press, Oxford, UK (2000).
J. B. Parise and G. E. Brown, Jr., Elements, 2, 37-42 (2006).

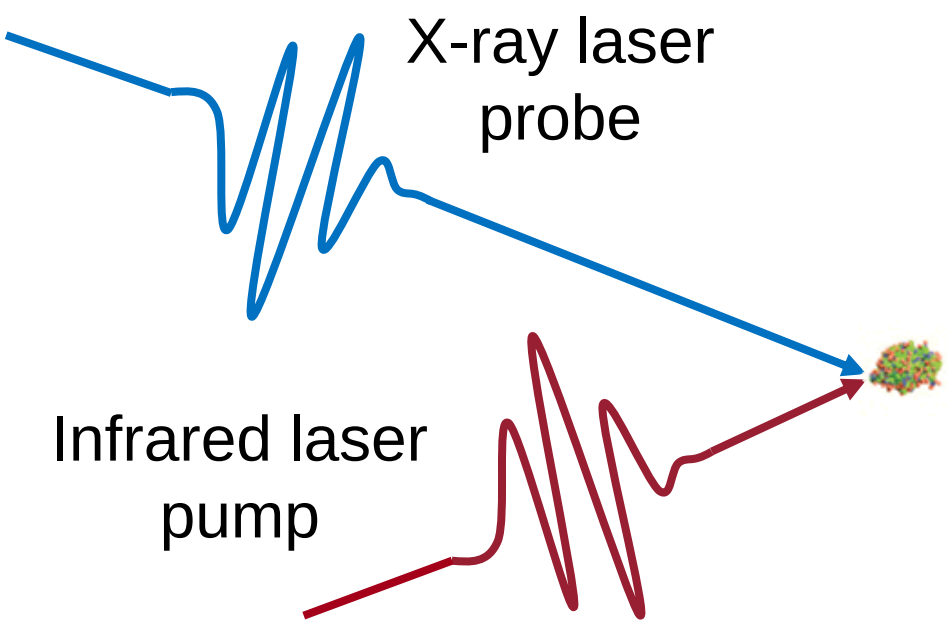
Diffraction from single molecules

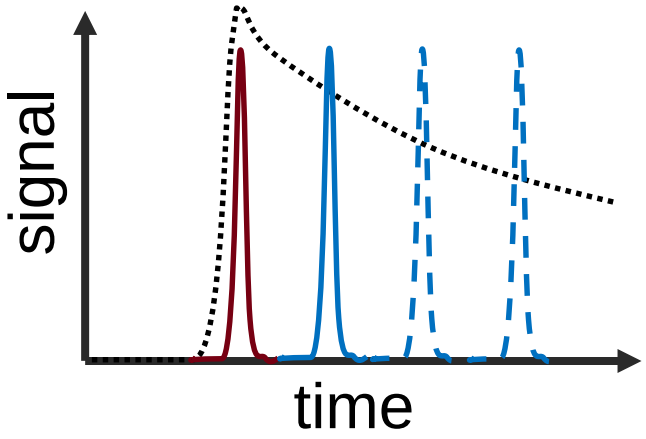
- Not all proteins crystallise
- Drop molecule in the beam
- Diffract before destruct
- Possibly accompanied by infrared laser pump
- Quickly becomes a ‘big data’ problem



Molecular movies

- Observing chemistry on its timescale
- Infrared pump, X-ray probe (separated in time)
- Advantage is that in addition to form, also get function of molecule



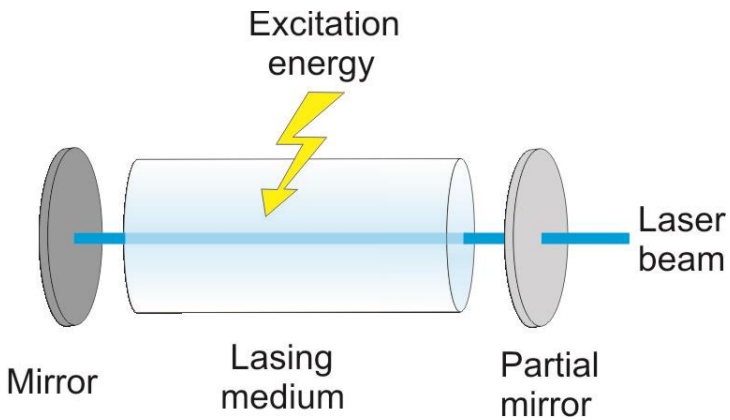


Outline – X-Ray Free Electron Lasers

- Ultrafast photon science
- Wigglers, undulators and coherent radiation
- Overview of an X-ray free electron laser
- Self-Amplified Spontaneous Emission (SASE)
- Free electron laser seeding schemes

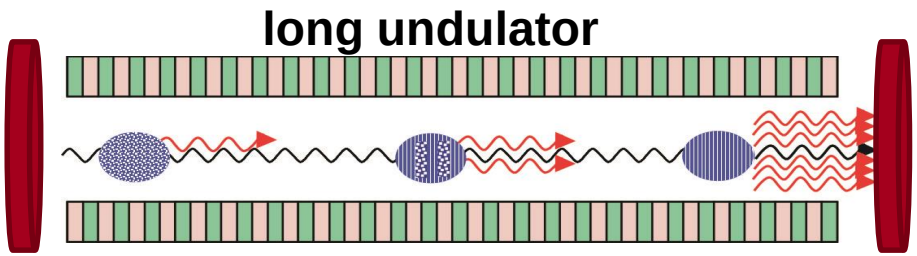
Conventional laser and Free Electron Laser

optical laser



- Light Amplification through Stimulated Emission of Radiation
- Photon energy ~ 1 eV
- Tabletop size

X-ray free electron laser

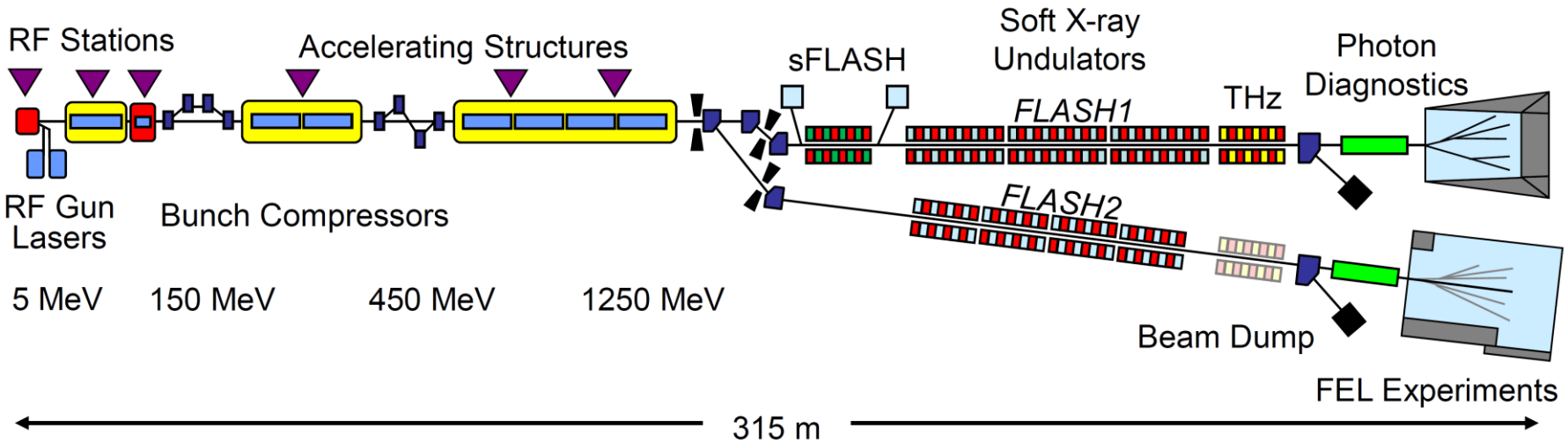


- Amplification through charge ordering
- Tunable photon energy 200-20000 eV
- Very large facilities (1 km)

Why don't we use mirrors to make an X-ray laser cavity?

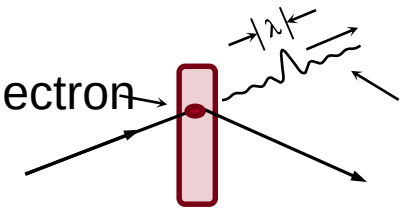
Free-electron lasers

- Storage ring light sources are **spontaneous** sources
- Photon emission is random, uncorrelated in phase
- Photon emission can be **stimulated**



Source: flash.desy.de

When does the charge radiate coherently?

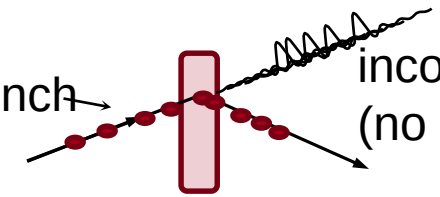


single electron

electric field of a 'wave packet'

$P=P_1$

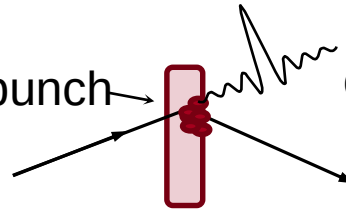
Bending magnet



long electron bunch

incoherent emission (no time correlation)

$P_i=N_e \cdot P_1$



short electron bunch

coherent emission (superposition)

$P_c=(N_e)^2 \cdot P_1 \cdot$[form factor]

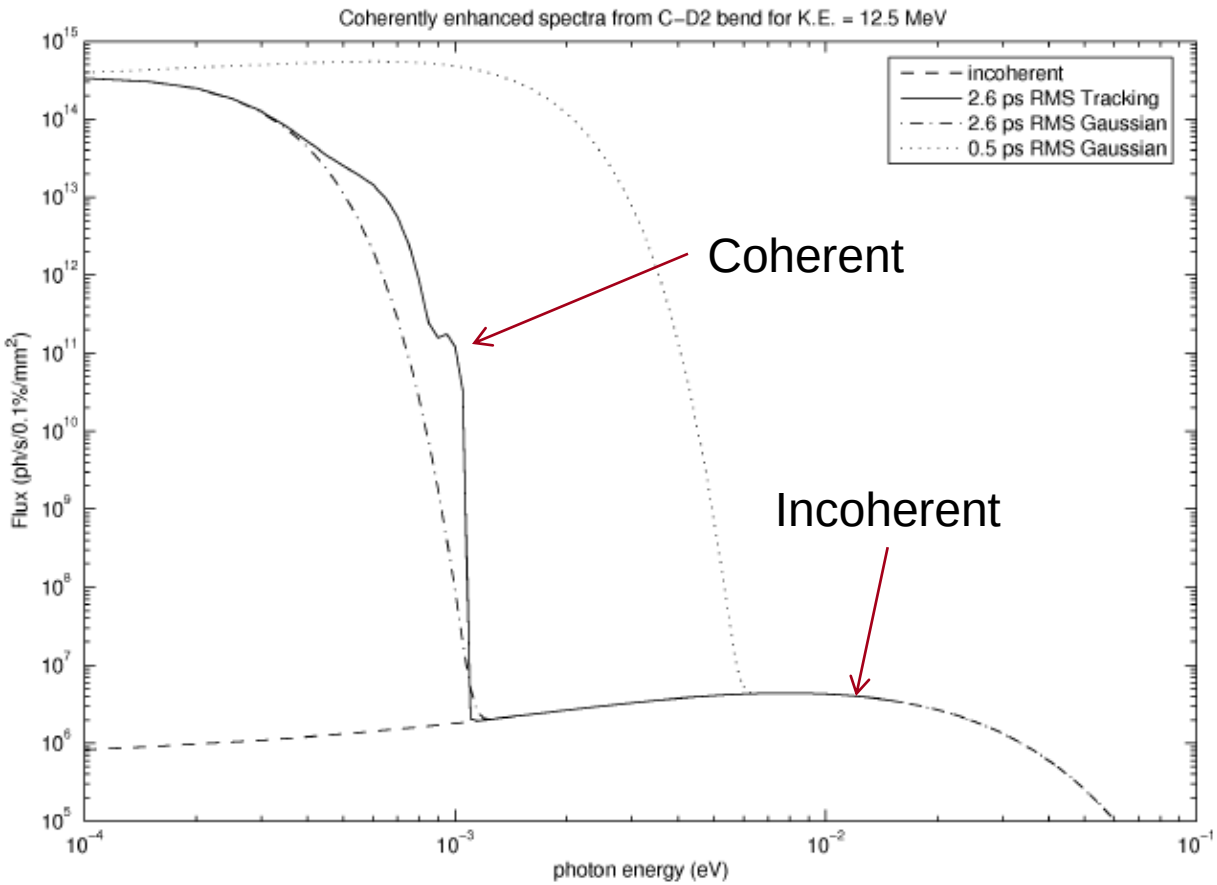
Power ~ E^2

Answer: coherent emission when $\sigma_{bunch} \sim \lambda_{radiation}$

$\sigma_{ring} \sim$ 10mm $\lambda_{x\text{-}ray} \sim$1-10 Angstrom

Coherent synchrotron radiation

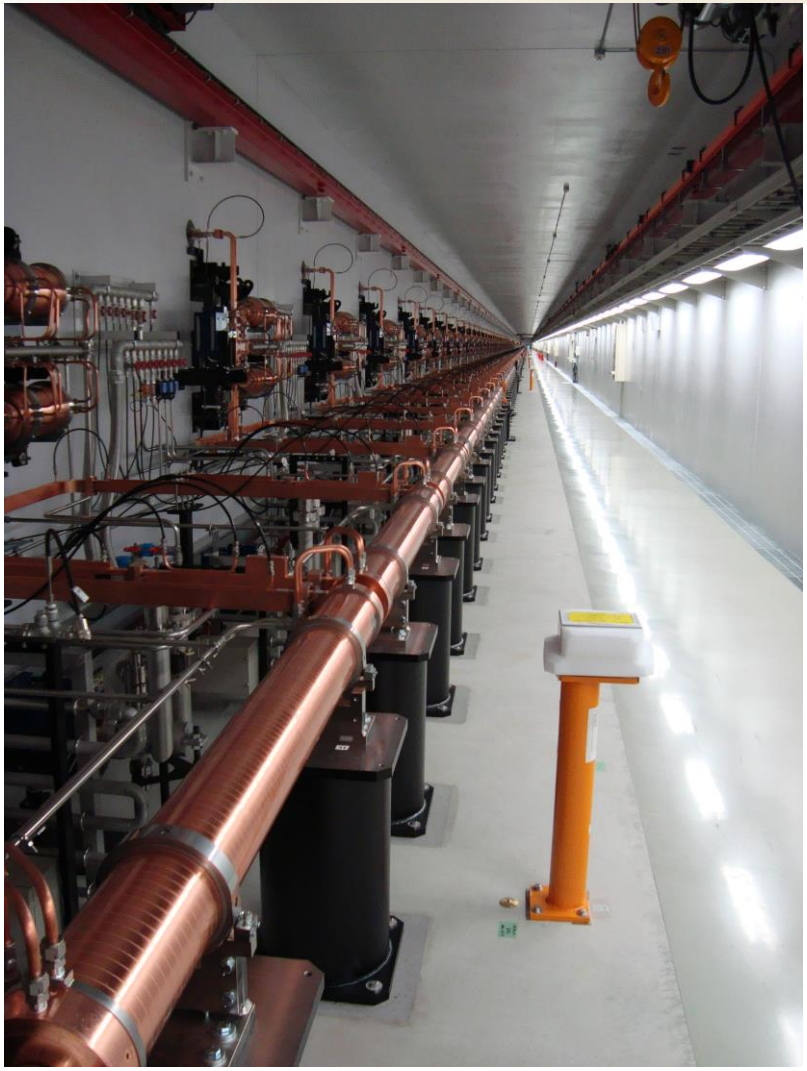
- Bunch length shorter than SR wavelength?
  - Coherent, for wavelengths longer than bunch
- ~1 ps bunch
  - Far infrared "THz" source



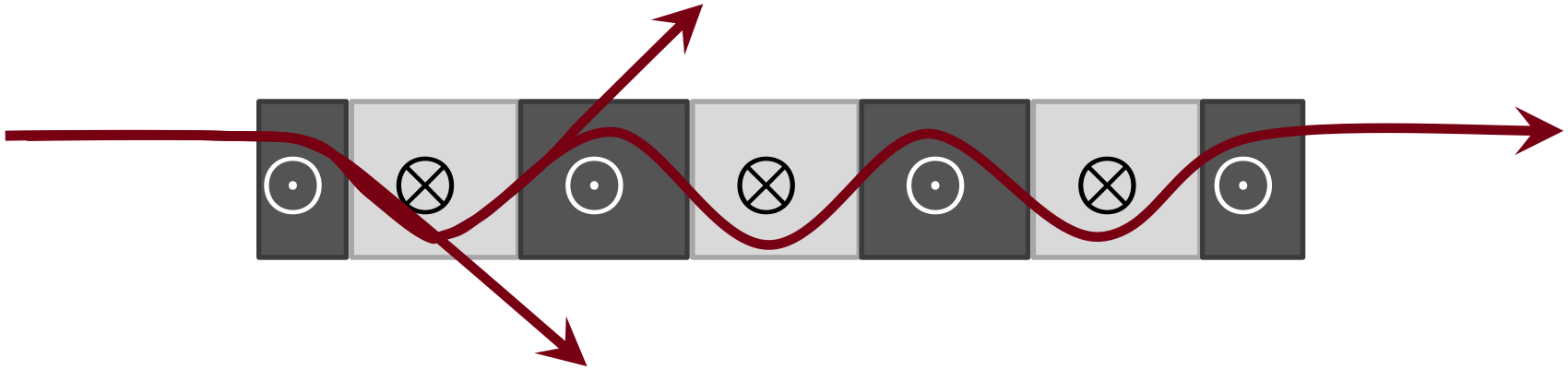
Source: http://www.lns.cornell.edu/~ib38/research.html

J. Schwinger, "On Radiation by Electrons in a Betatron", A Quantum Legacy: Seminal Papers of Julian Schwinger, World Scientific, 307-331, (2000) (LBNL-39088).

Free-electron laser (SACLA, Japan)

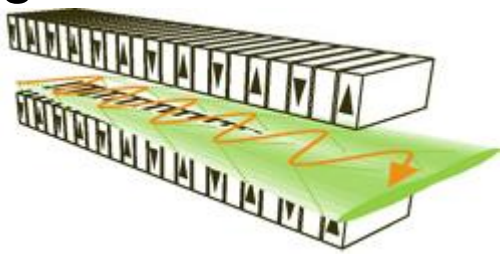


Wigglers



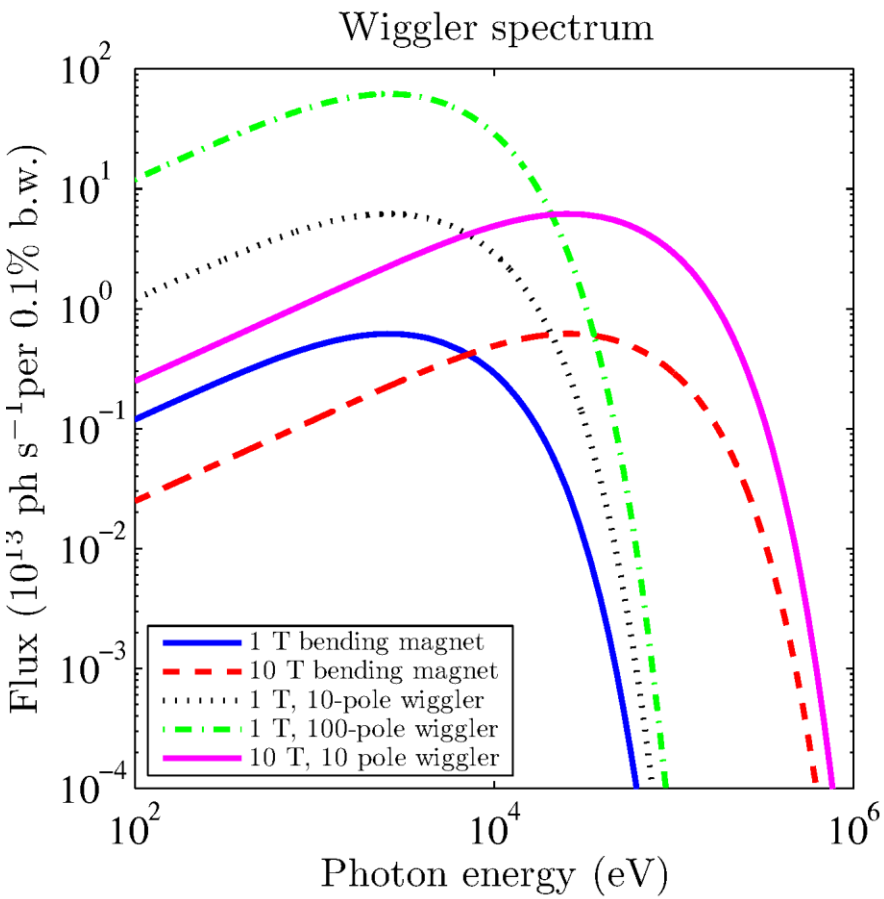
Wigglers

- Incoherent superposition of many bending magnets



Source: Australian Synchrotron

- Flux scales linearly with number of periods
- Critical photon energy linear with magnetic field
  - Same as bending magnet

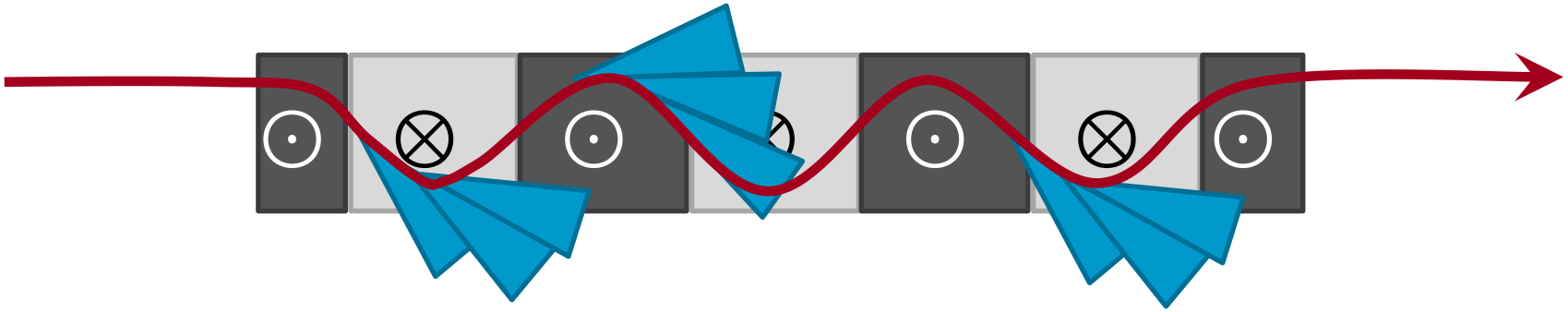


Difference between undulators and wigglers

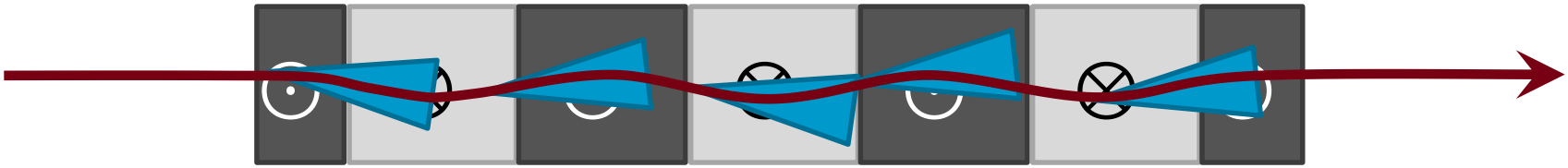
- Fundamentally, there is no difference!

$$\theta_w = \frac{K}{\gamma}$$

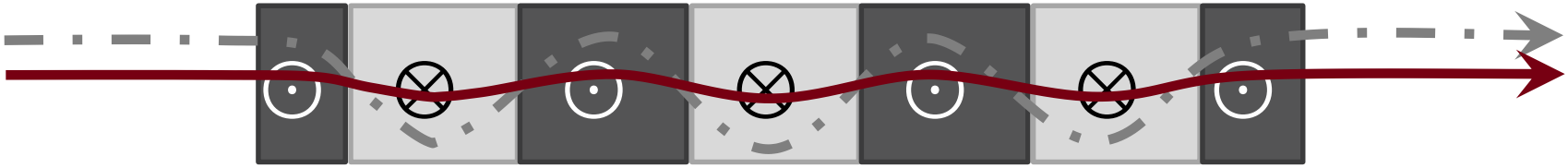
Wiggler, if $K \gg 1$

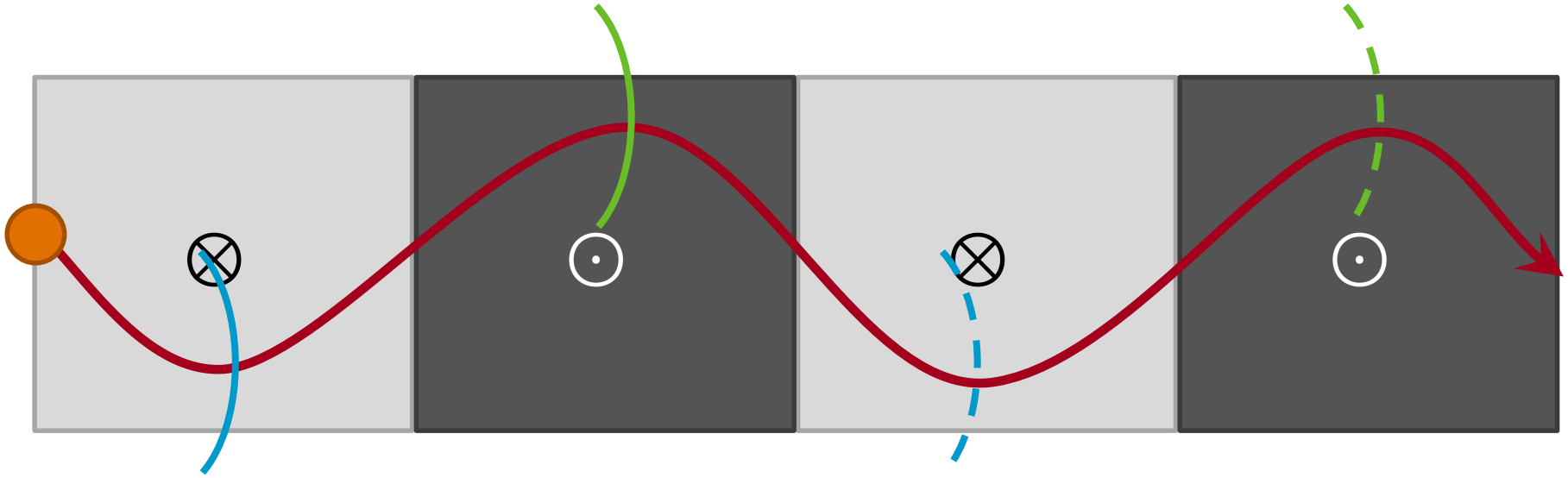


Undulator, if $K \leq 1$

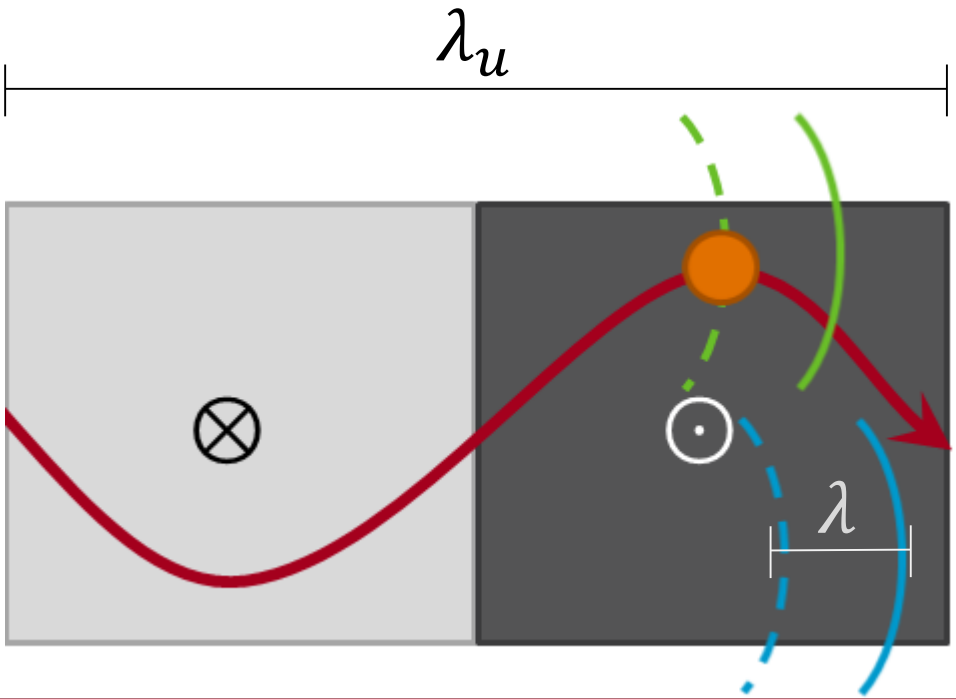


Undulators





Undulators

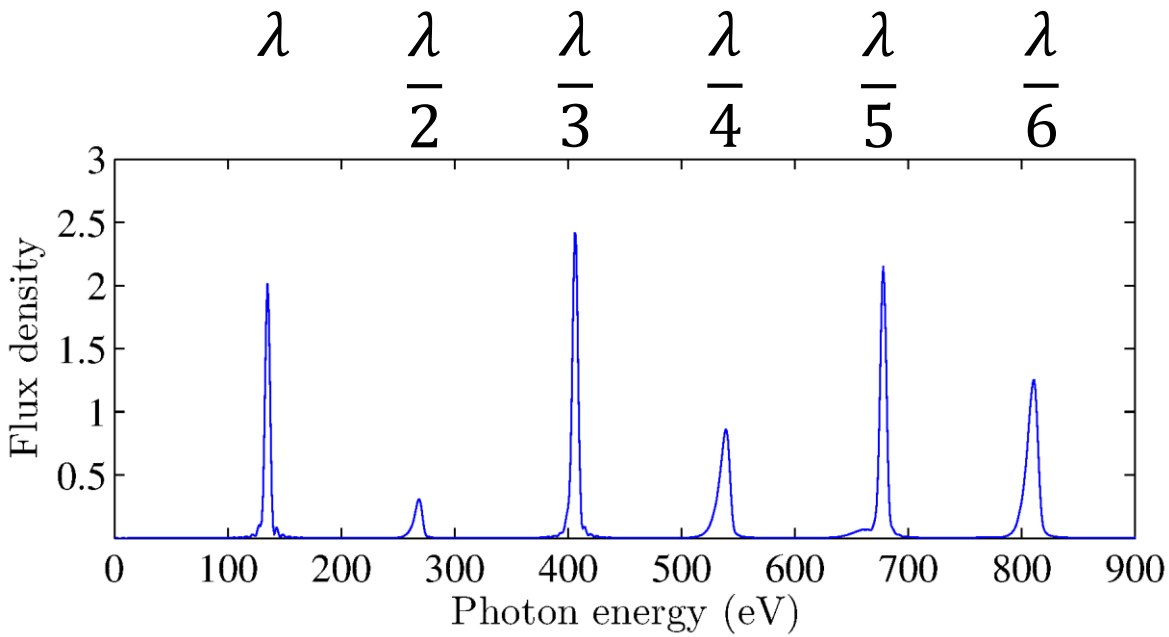


$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right),$$

$$K = \frac{q_e}{2\pi\beta m_e c}\,\lambda_u B \approx 93.4\,\lambda_u[\mathrm{m}]B[\mathrm{T}]$$

Undulator radiation

- Bright odd harmonics, null even harmonics
- Even harmonics don't perfectly cancel
  - Non-zero emittance

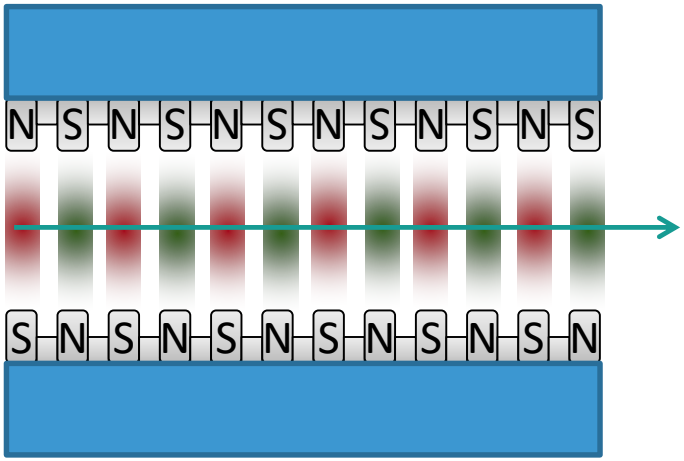


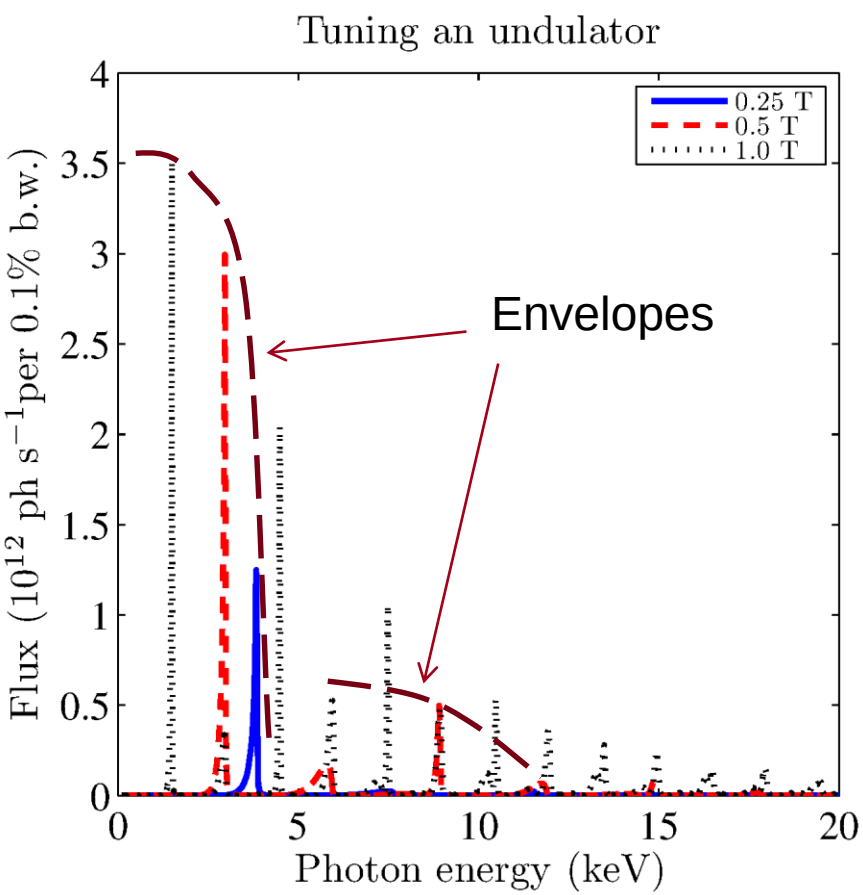
- What if you want a different photon energy?

Tuning an undulator – deflection parameter

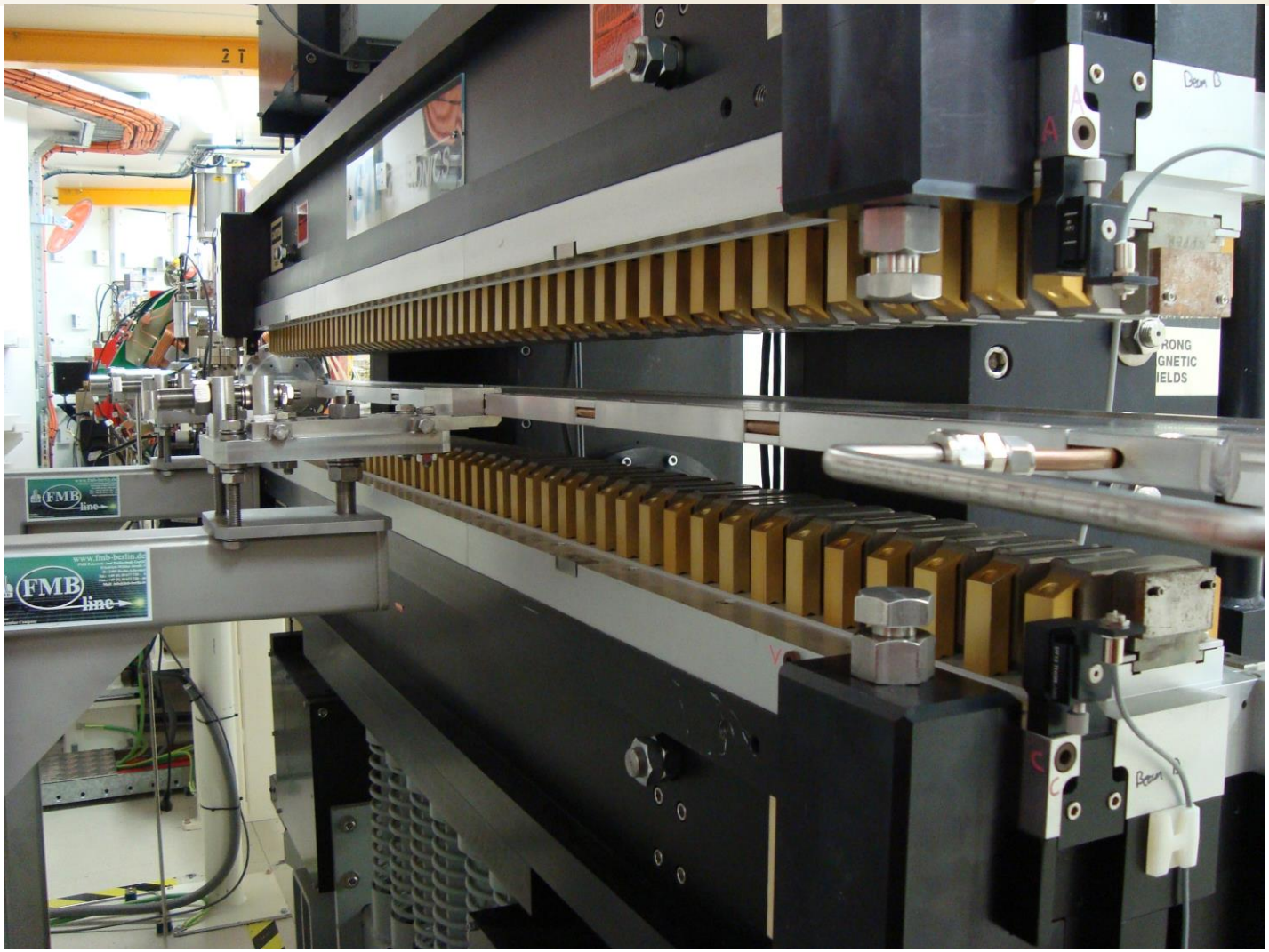
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

- Assume λ_u fixed, vary $K = 93.4\,\lambda_u B$
- Magnetic field B or energy γ
- Use permanent magnets, vary B by varying gap



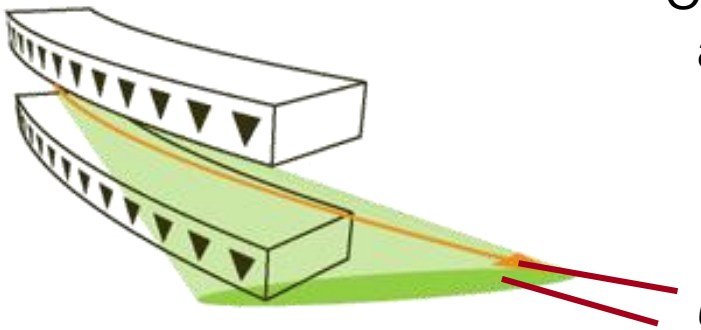


A real undulator



Comparison of radiation sources

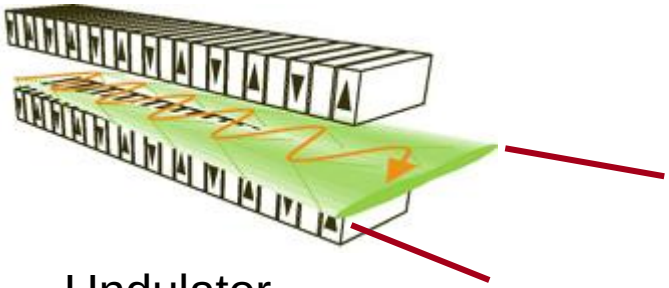
Bending magnet



Opening angle

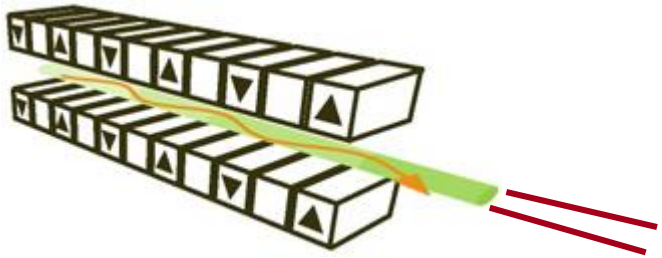
$$\theta \approx \frac{1}{\gamma}$$

Wiggler

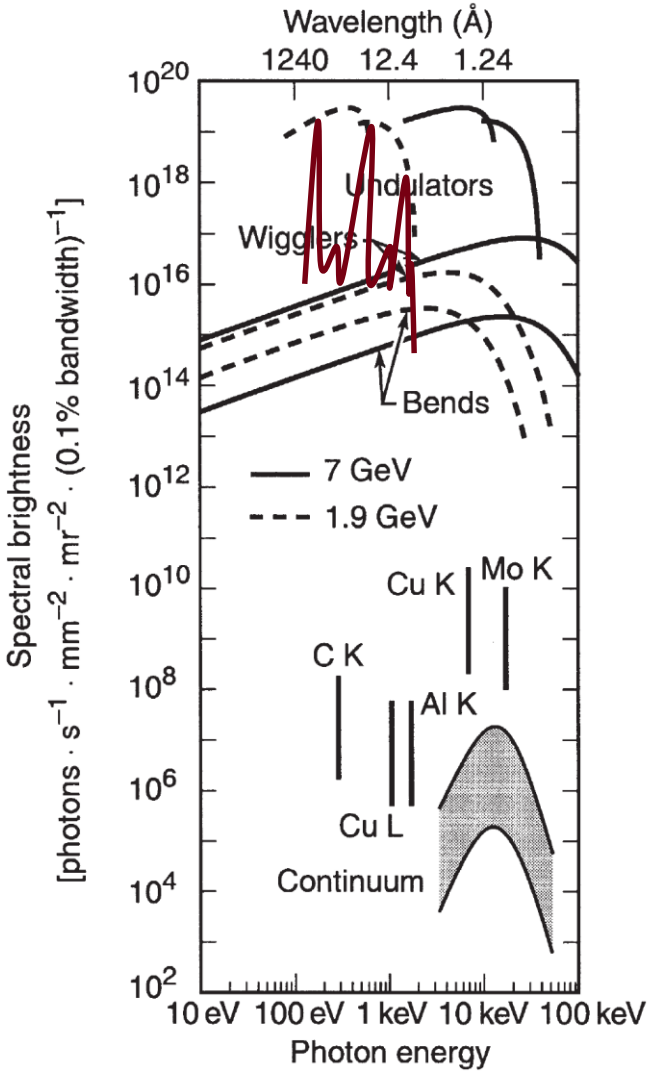


$$\theta \approx \frac{K}{\gamma}$$

Undulator



$$\theta \approx \frac{1}{\sqrt{N}\gamma}$$

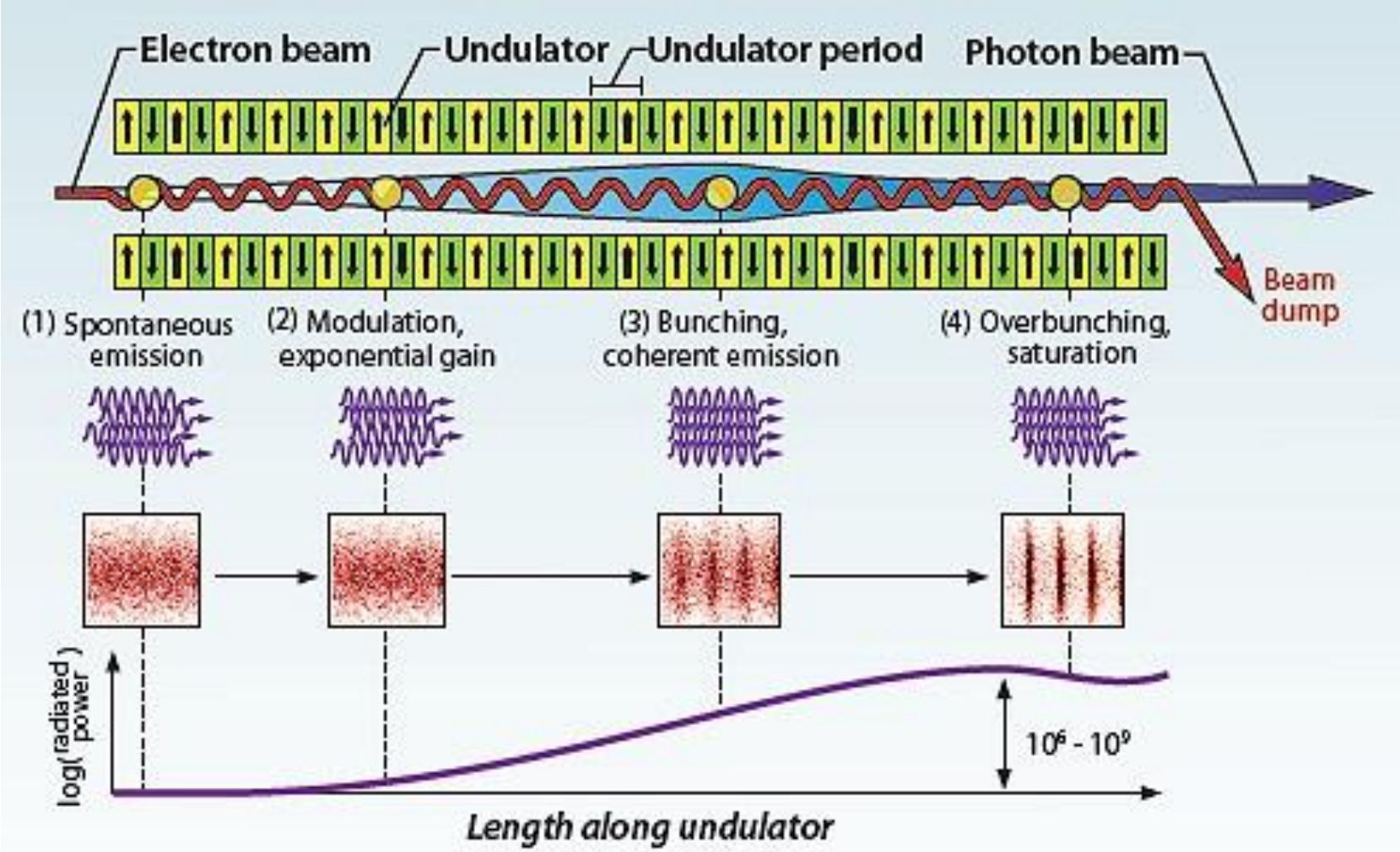


After D. Attwood, ‘Soft X-Rays and Extreme Ultraviolet Radiation’, Lecture Notes, UC Berkeley (2009).
Center for X-Ray Optics and Advanced Light Source, ‘X-Ray Data Booklet’, LBNL/PUB-490 Rev. 3 (2009).

Options for making FEL radiation

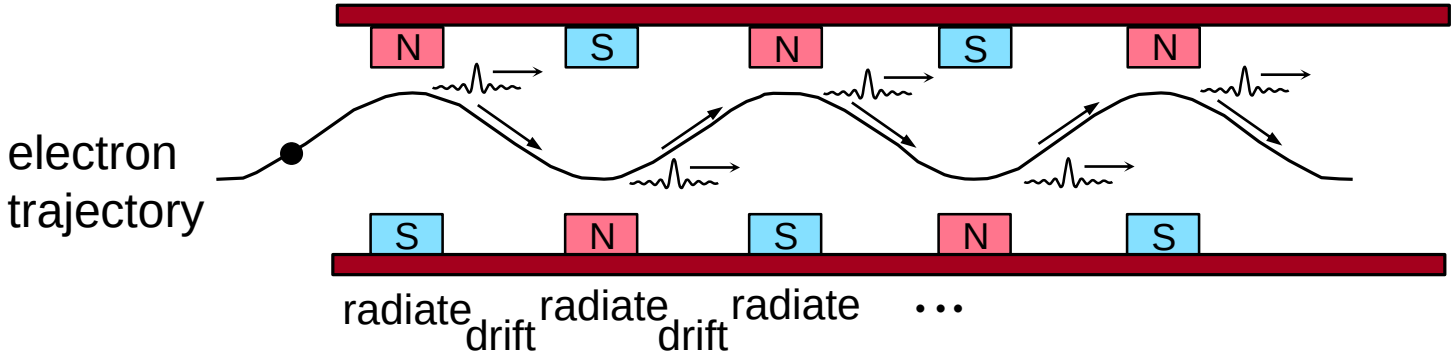
1. Undulator in a cavity
   (limited by mirror reflectivity)
2. Inject a ‘seed’ laser beam
   (where do we get an x-ray seed beam?)
3. Self-Amplified Spontaneous Emission (SASE)
   (inherent noise in the electron distribution grows resonantly)
4. Self-seeding
   (select a single frequency from broadband SASE spectrum)
5. Harmonic Generation

Free-electron lasers



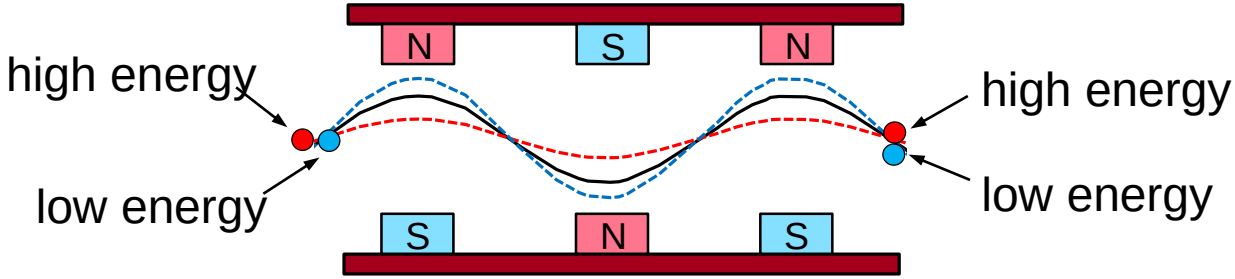
Source: Los Alamos National Accelerator Laboratory (2010).

FEL Physics: Electron motion in the undulator



For coherent radiation we want a short bunch in the 'radiate' region

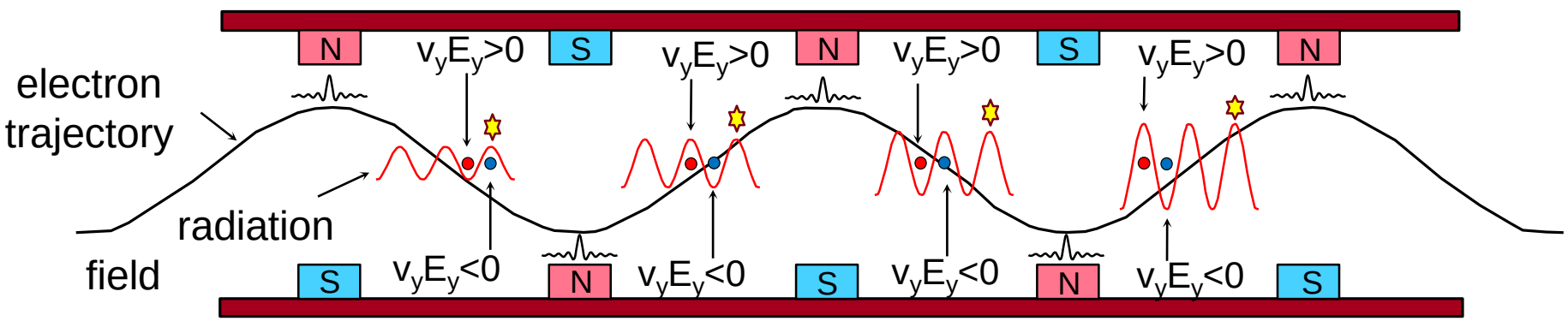
How do we make the bunch short? Answer: ***Dispersion***



FEL Physics: microbunching

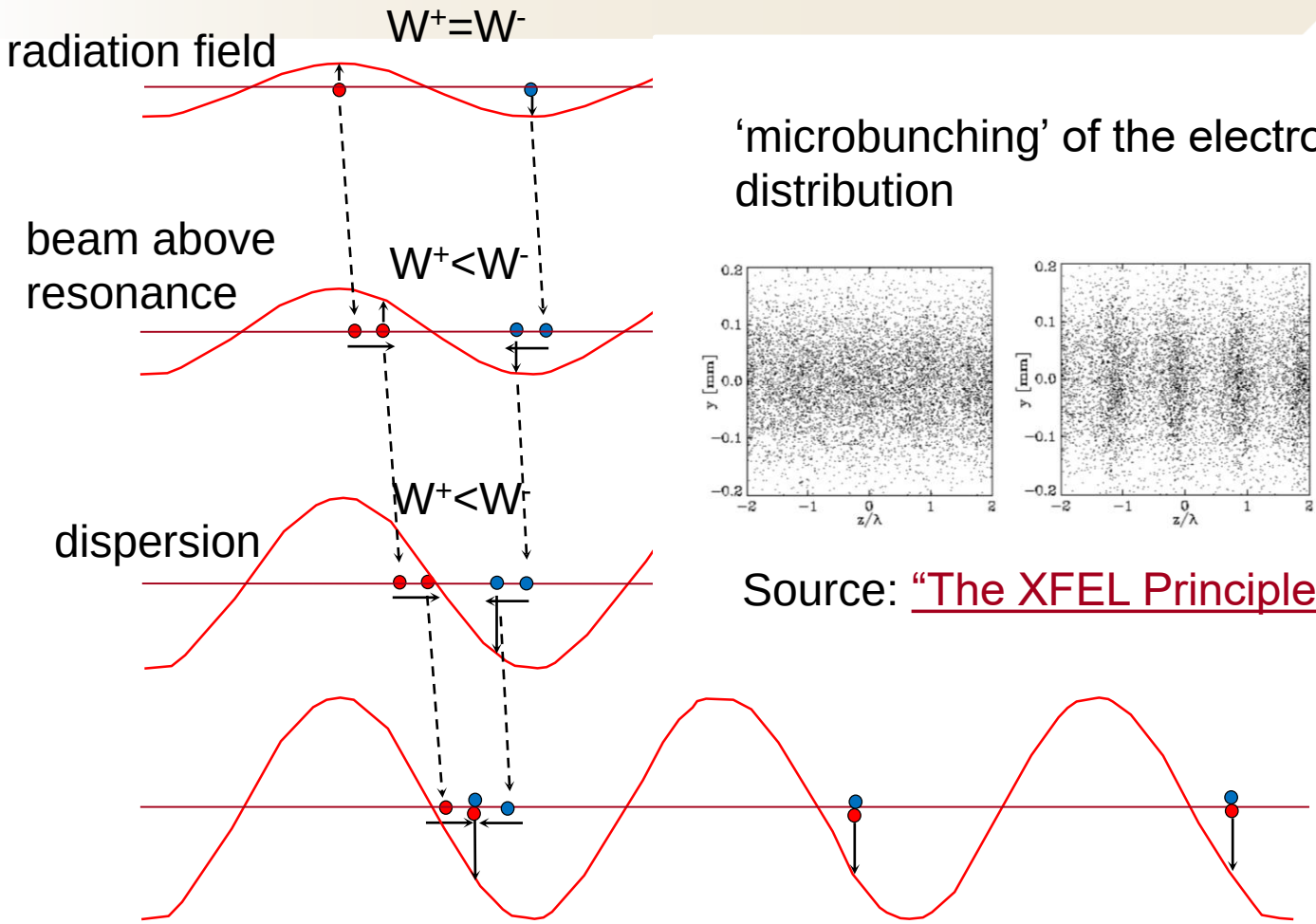
- Electrons slip one radiation wavelength per undulator period
- "Electrons losing energy to the light wave travel on a wavelike trajectory of larger amplitude than electrons gaining energy from the light wave."

Source: DESY Photon Science

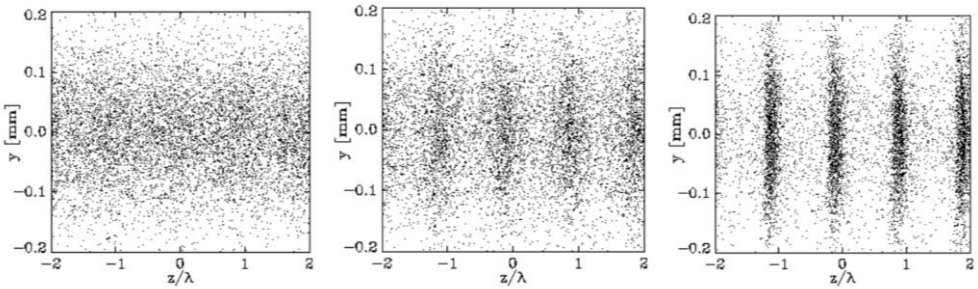


Note 'slippage' of one radiation wavelength per undulator period

Looking closer for more detail…



'microbunching' of the electron charge distribution



Source: "The XFEL Principle", DESY

Question: What is an 'inverse FEL'?

FEL gain length

Gain length

$$L_{G0} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

Pierce parameter, ρ

$$\rho = \left(\frac{1}{16}\frac{I_e}{I_A}\frac{K_0^2[JJ]^2}{\gamma_0^2\sigma_x^2 k_u^2}\right)^{1/3}$$

$$[JJ] = J_0(\xi) - J_1(\xi)$$

$$\xi = \frac{K_0^2}{4 + 2K_0^2}$$

$$K_0 = 93.4\,\lambda_u[\mathrm{m}]B[\mathrm{T}]$$

Alfvén current:

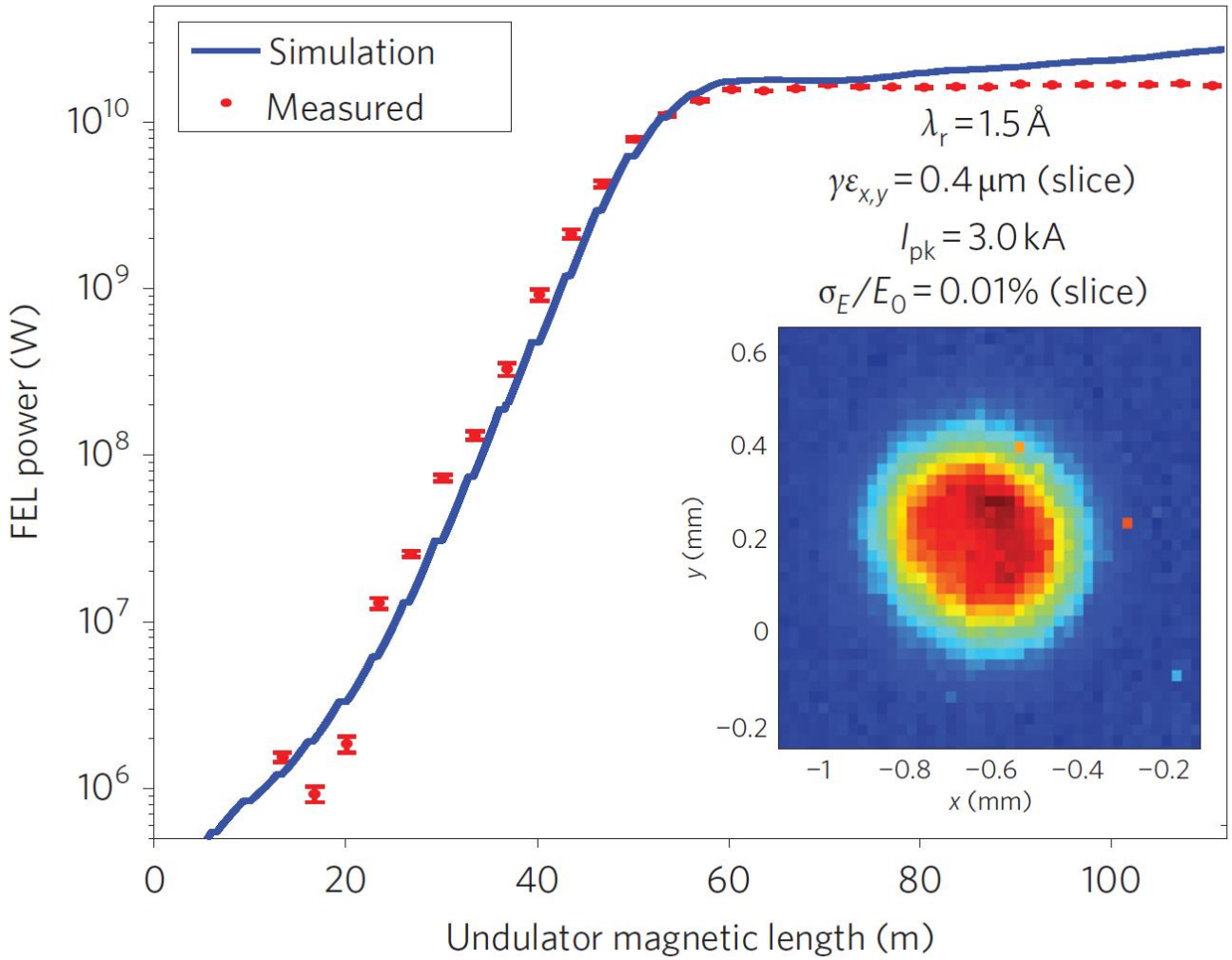
$$I_A = \frac{ec}{r_e} \approx 17\ kA$$

$$k_u = \frac{2\pi}{\lambda_u}$$

For a hard X-ray FEL, $\rho \approx 10^{-3}$, $\lambda_u = 10^{-2} \rightarrow L_{G0} \approx 2 - 4\ \mathrm{m}$

Z. Huang and K.-J. Kim, Phys. Rev. ST – Accel. Beams, 10, 034801 (2007).
R. Bonifacio, et al., Opt. Commun., 50, 373 (1984).

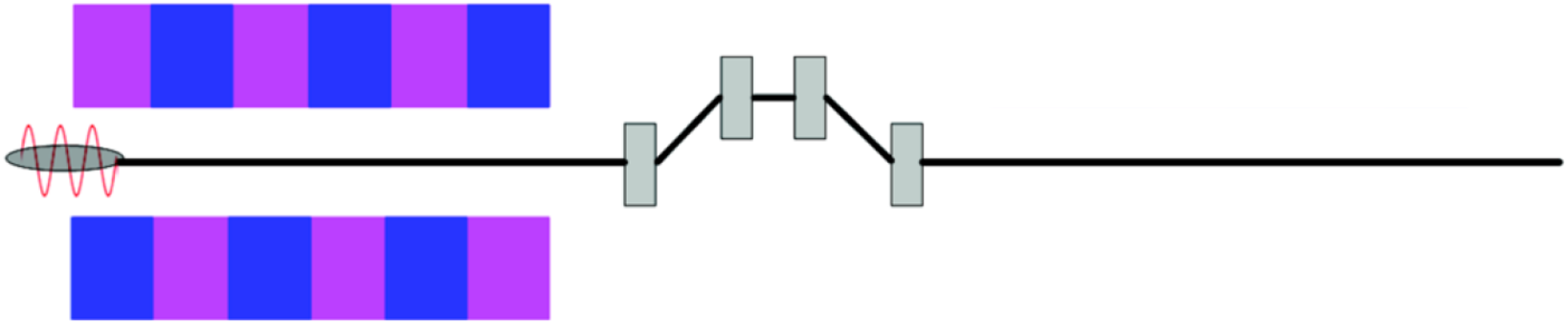
FEL gain length

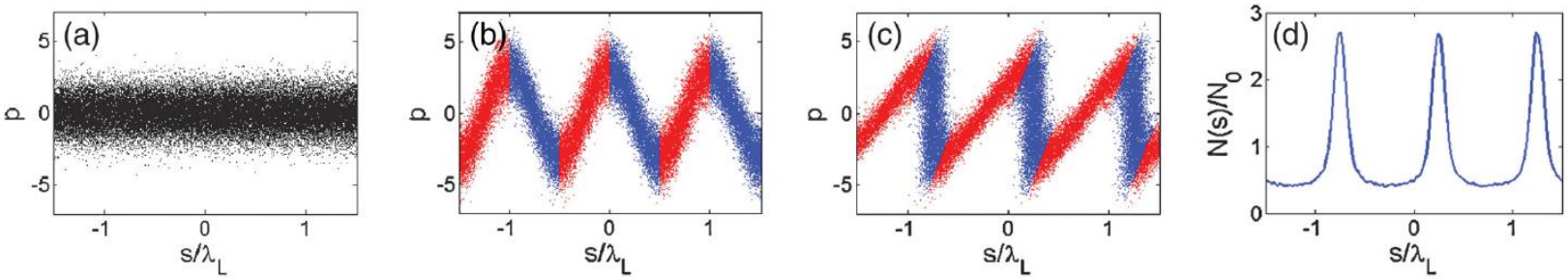


P. Emma, et al., Nat. Photon., 4, 641 (2010).

High-Gain Harmonic Generation (HGHG)

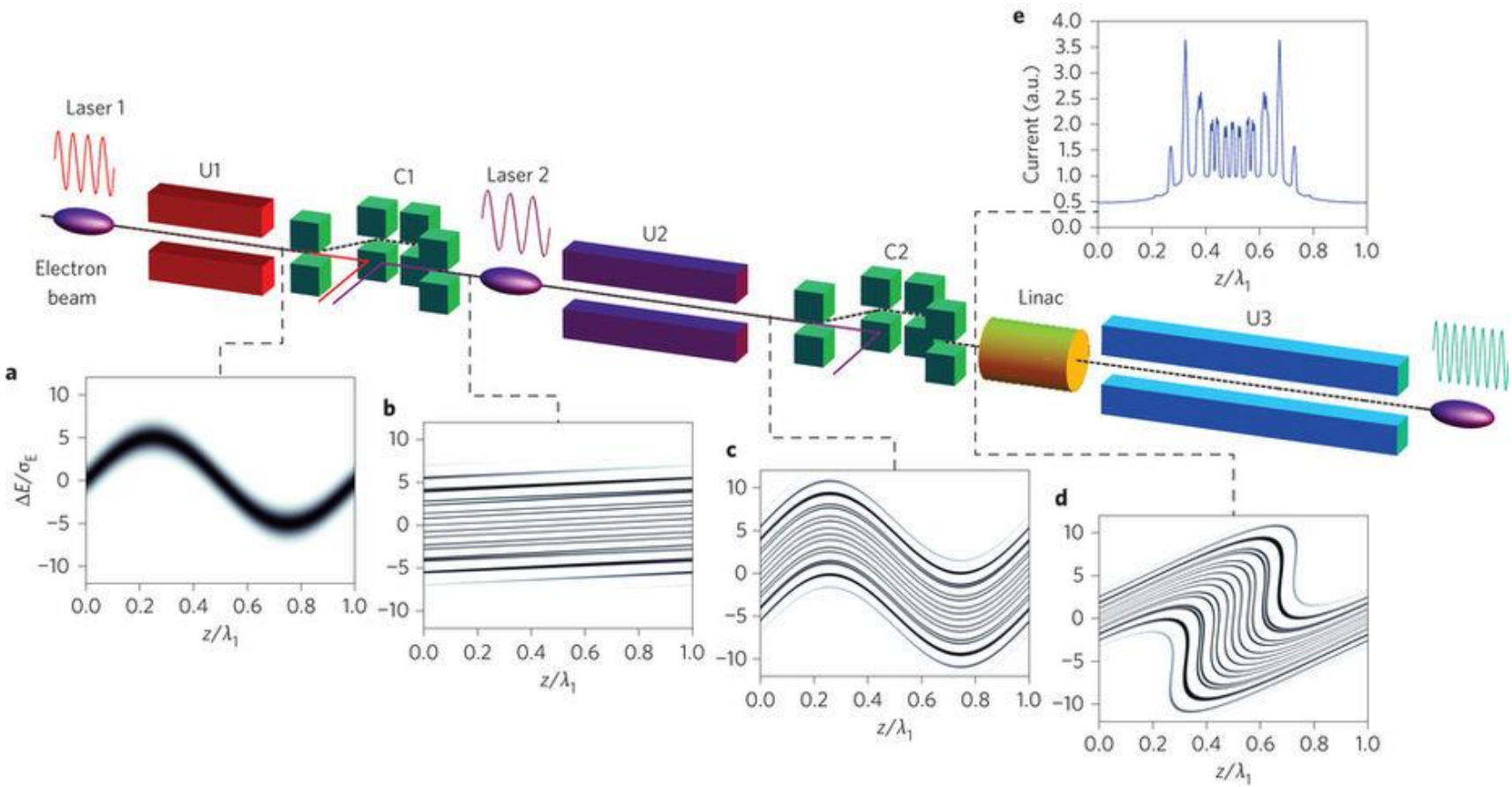
- Modulator, chicane (Inverse Free-Electron Laser)
- Radiator





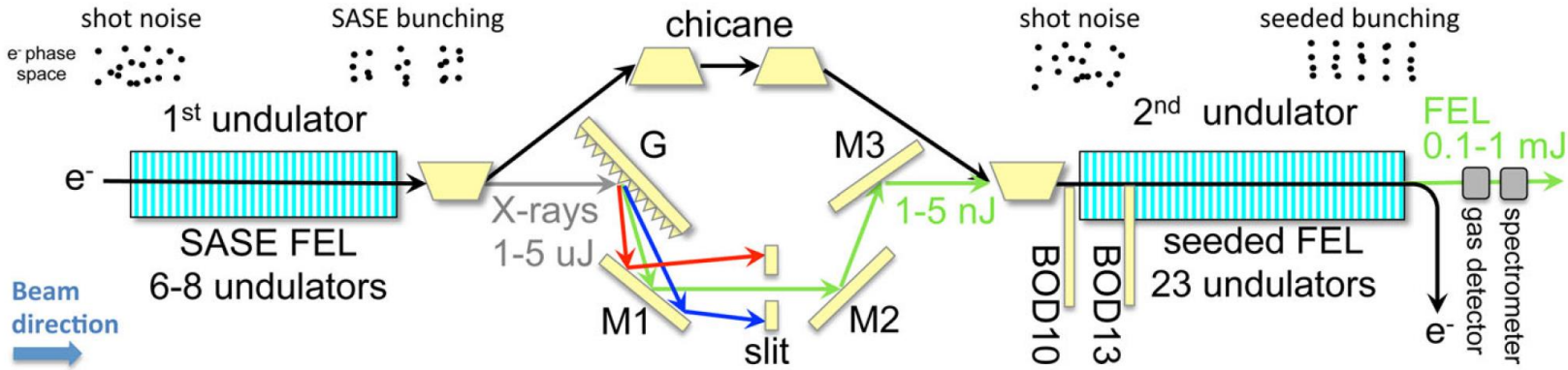
E. Hemsing, et al., Rev. Mod. Phys., 86, 897 (2014).

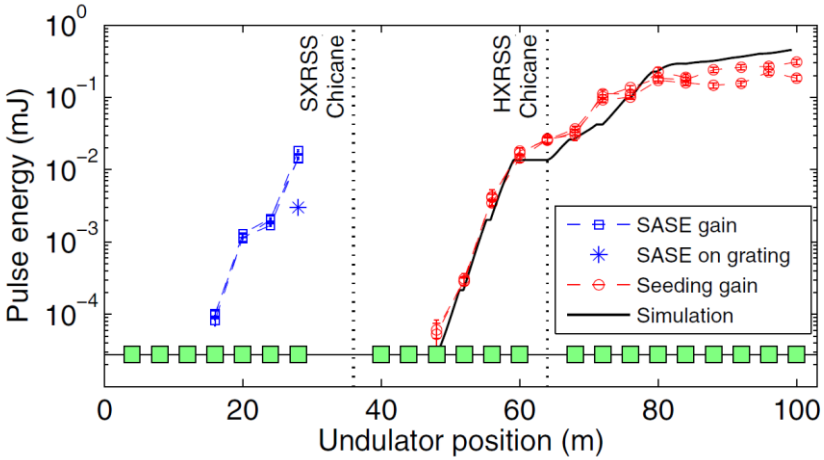
Echo-Enabled Harmonic Gain (EEHG)



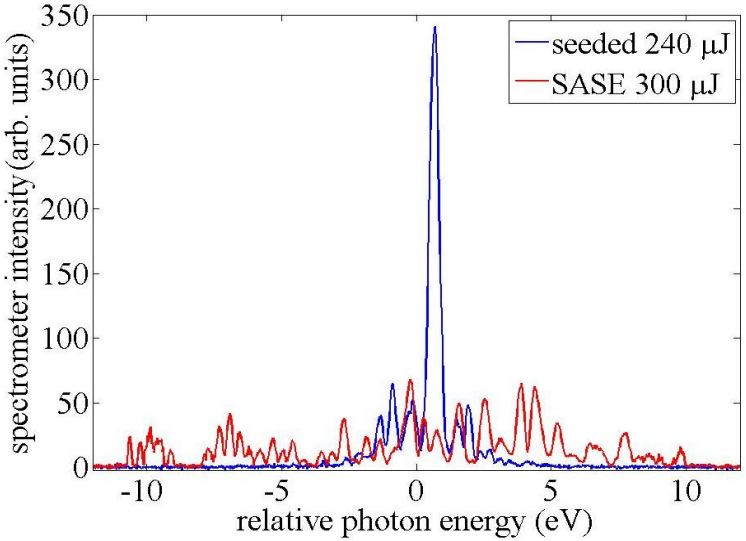
E. Hemsing, et al., Nat. Photon., 10, 512-515 (2016).

Self-seeded operation





D. Ratner, et al., Phys. Rev. Lett., 114, 054801 (2015).



J. Amann, et al., Nat. Photon., 6, 693 (2012).

Summary

- Light source technology developing in two main directions
  - Average brightness (Diffraction-Limited Storage Rings)
  - Peak brightness (Free-Electron Lasers)
- Complementary and different
- Techniques to increase brightness mostly involve seeding

This work was supported in part by the Department of Energy contract DE-AC02-76SF00515.

Key references

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Virtual tours of LCLS

LCLS undulator hall

https://my.matterport.com/show/?m=YudBtDqUACB

Near Experimental Hall

https://my.matterport.com/show/?m=GrfGyzojZZP