UNDULATOR RADIATION AND X-RAY FREE-ELECTRON LASERS

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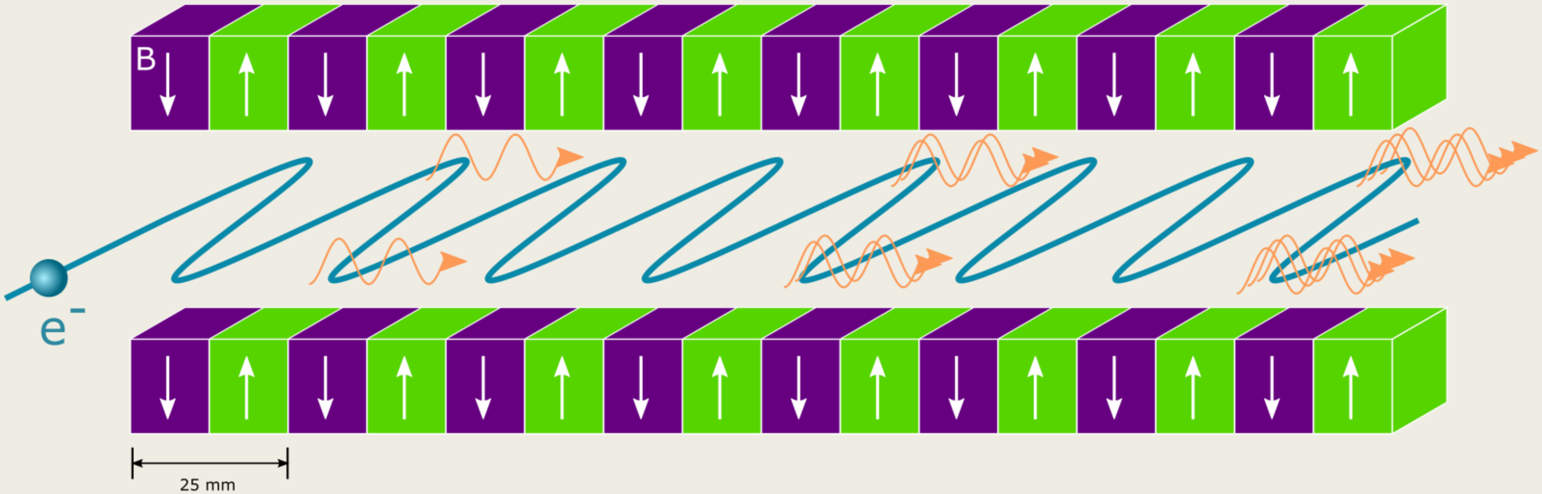
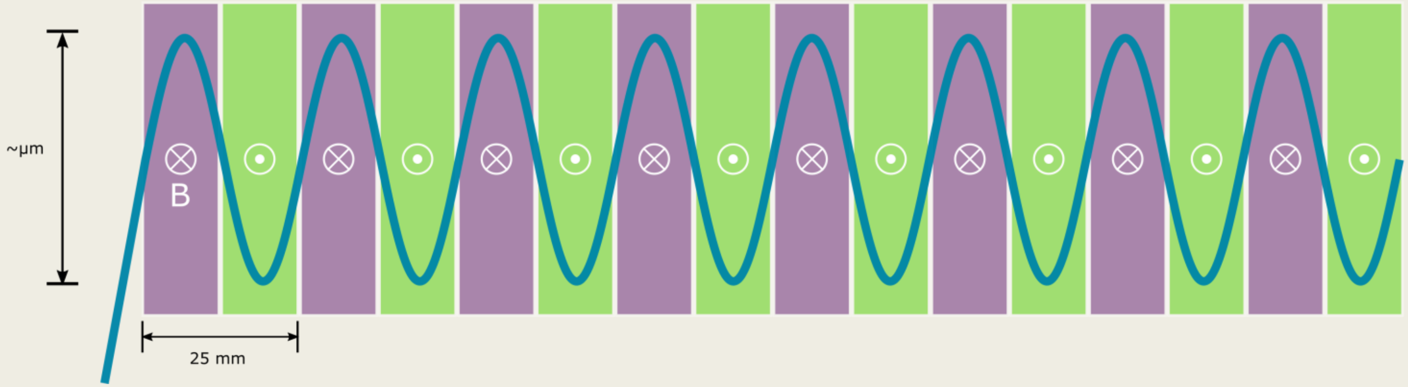
Undulator





Magnetic Field in the Undulator

- $\boldsymbol{B} = -\boldsymbol{\nabla}\phi_{\mathbf{mag}}, \quad \boldsymbol{\nabla}^2\phi_{\mathbf{mag}} = \mathbf{0}$

- $\phi_{\mathbf{mag}}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) = \frac{\boldsymbol{B_0}}{\boldsymbol{k_u}} \sinh(k_u y) \sin(k_u z) \qquad k_u = 2\pi/\lambda_u$

- $B_x = 0, \quad B_y = -B_0 \cosh(k_u y) \sin(k_u z),$
  $B_z = -B_0 \sinh(k_u y) \cos(k_u z)$

- Along the electron path, we assume $y = 0$ and get
  $$\boldsymbol{B} = -B_0 \sin(k_u z)\, \hat{\boldsymbol{y}}$$

Electron Path through the Undulator

- Force on the electron: $\gamma m_e \boldsymbol{a} = -e\boldsymbol{v} \times \boldsymbol{B}$
  - $\ddot{x} = \frac{e}{\gamma m_e} B_y \dot{z} \qquad \ddot{z} = \frac{e}{\gamma m_e} B_y \dot{x}$
- Define: Undulator Parameter $K = 0.934 \cdot \frac{B_0}{[\mathrm{T}]} \cdot \frac{\lambda_u}{[\mathrm{cm}]}$
- First order, set $\dot{z} = v = \mathrm{const} \gg \dot{x}$
  - $x(z) = \frac{K}{\beta \gamma k_u} \sin(k_u z)$
- Second order, $\dot{z} = \sqrt{v^2 - \dot{x}^2}$
  - $x(t) = \frac{K}{\gamma k_u} \sin(\omega_u t) \qquad z(t) = \bar{v}_z t - \frac{K^2}{8\gamma^2 k_u} \sin(2\omega_u t)$

$$\bar{v}_z = \left(1 - \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)\right) c \equiv \bar{\beta} c$$

X-ray Radiation from an Electron in the Undulator

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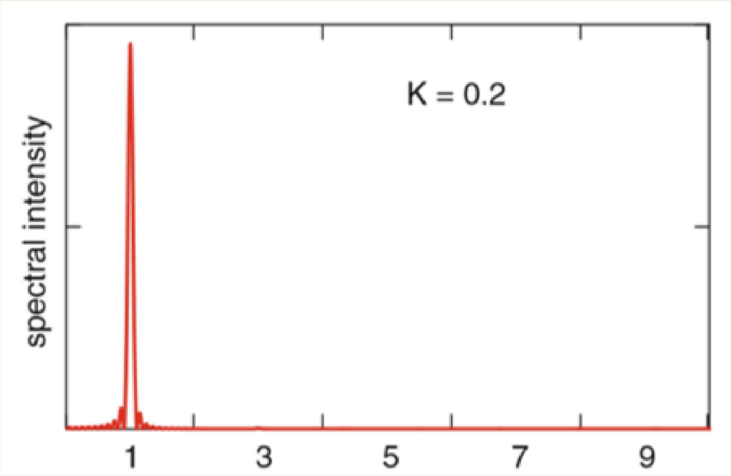
- In the limit that $K \to 0$, the radiation emitted from various points in space interferes constructively such that the radiation spectrum is a narrow spectrum with well-defined frequency.



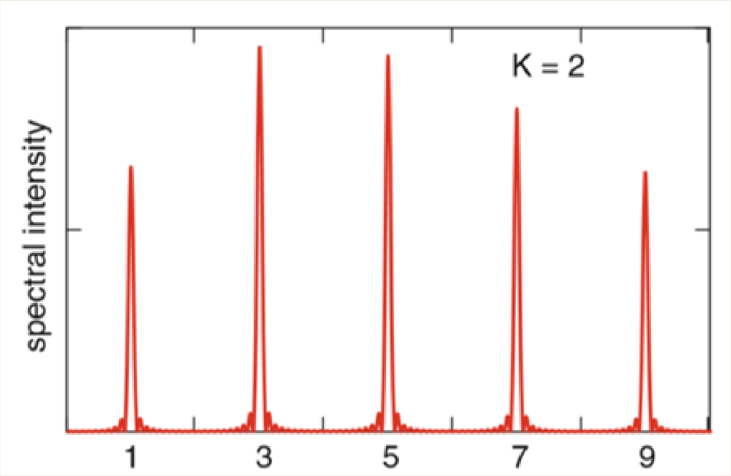


Fig. from Schmüser

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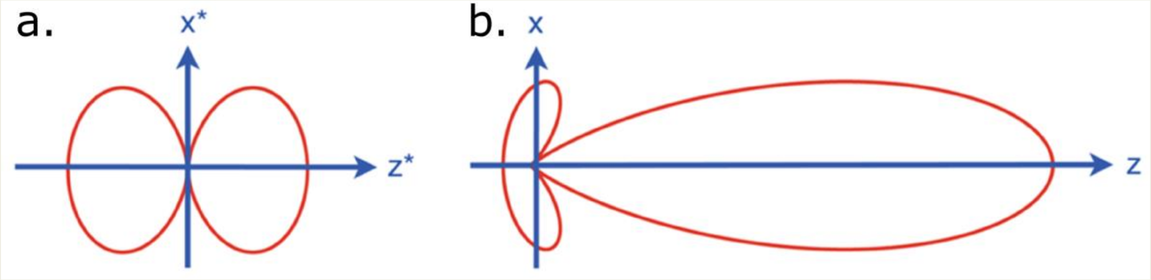
- The power is concentrated in the forward direction in the laboratory frame.



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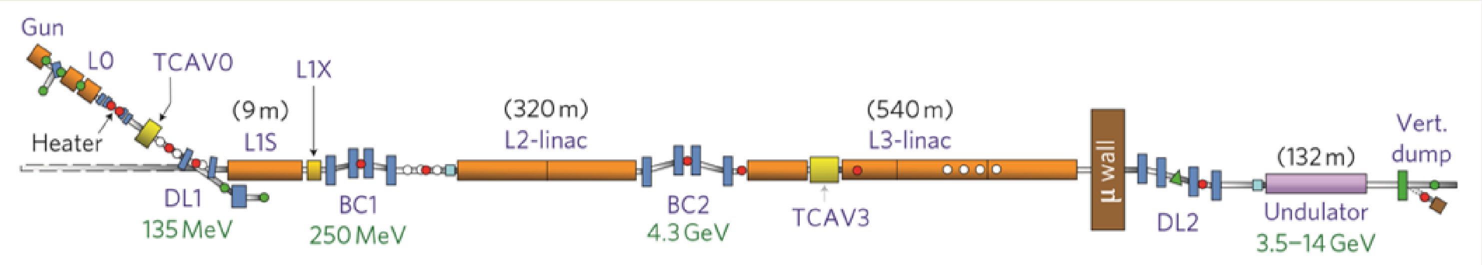
- The power is concentrated in the forward direction in the laboratory frame.
- Wavelength of undulator radiation near $\theta = 0$

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

Radiation from Electron Bunches

- Electrons travel through the undulator in “bunches.” They respond to the radiation fields from other electrons in the bunch and modulate into microbunches separated spatially by the X-ray wavelength.
- The radiation field increases along the undulator.
- Microbunching and radiation are enhanced through Self-Amplified Stimulated Emission (SASE).
- Microbunches result in shorter X-ray pulses and SASE results in a higher intensity X-ray beam.

The X-ray Free-Electron Laser
(ex. Linac Coherent Light Source LCLS)



- Electrons are produced in a copper photocathode and boosted to 135 MeV.
- Electrons are injected into the linear accelerator (normal-conducting traveling-wave accelerators L0-3 and bunch compressors BC1-2).
- Electrons are deflected and enter the undulator.

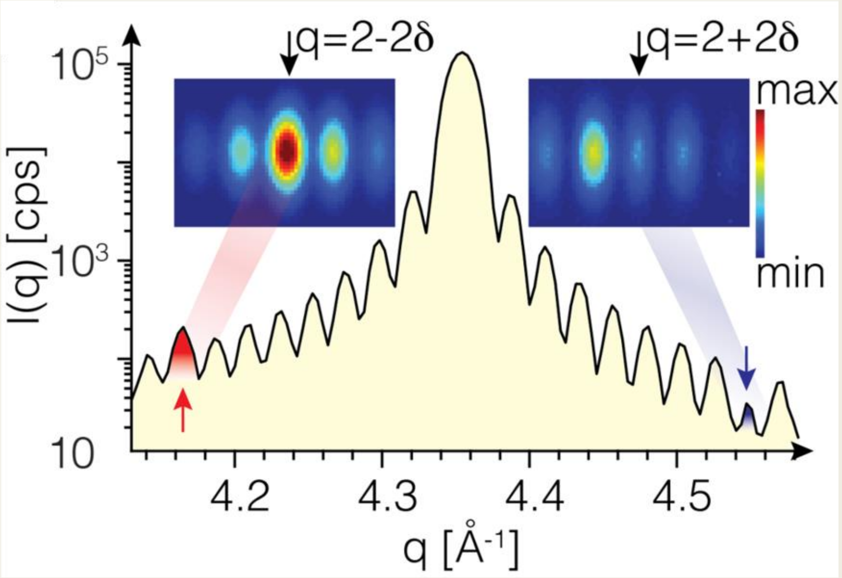
Fig. from Emma

The X-ray Free-Electron Laser

- Advantages
  - *High intensity X-ray beam (eight orders of magnitude higher than synchrotron X-ray beams)*
  - *Monochromatic X-ray spectrum (narrow spectrum at a well-defined frequency)*
  - *Ultrafast pulses (femtosecond pulses)*
- Disadvantages
  - *Only one X-ray beam, not multiple beams set up tangentially as in synchrotrons*

Fig. from Emma

Studying charge-spin-lattice interactions in Cr through X-ray diffraction



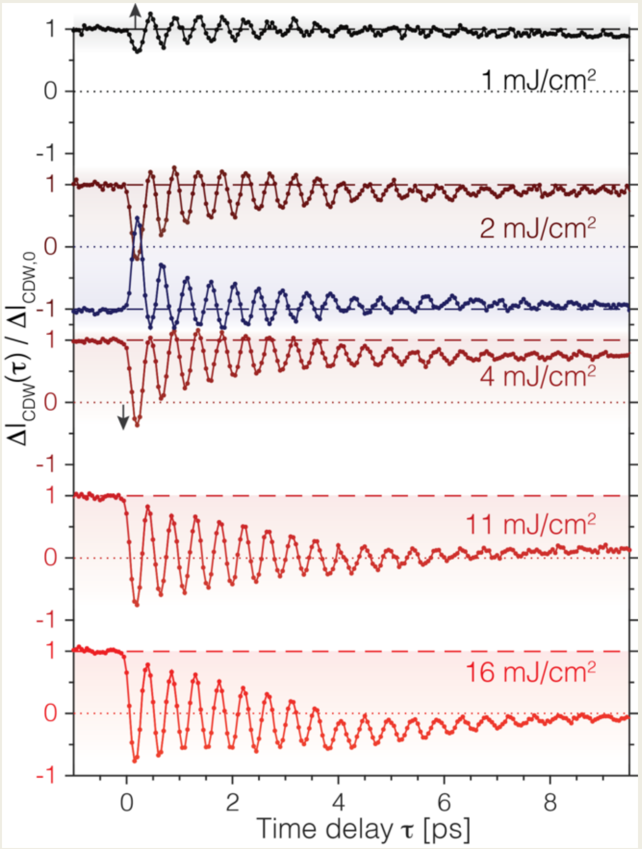


Fig. from Singer, Patel

Imaging the structure of biomolecules such as Photosystem II

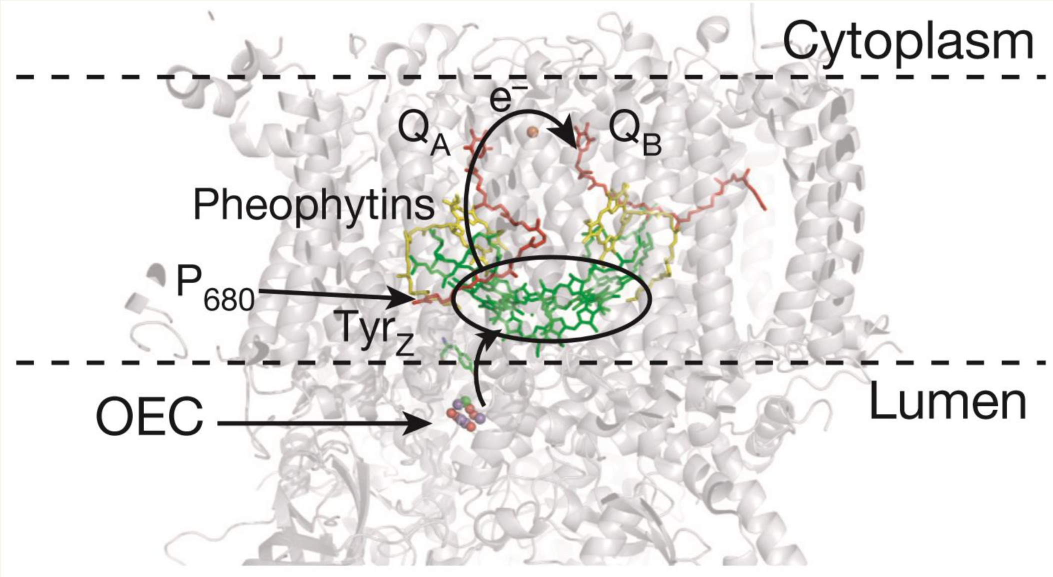


Fig. from Young

Conclusion

- Undulator radiation is the radiation emitted from electrons traveling between two series of alternating dipole magnets.
- Undulator radiation can be used to build X-ray free-electron lasers as the most powerful X-ray sources for physical studies.
- X-ray free-electron lasers provide a high-intensity monochromatic X-ray beam with ultrashort pulses.

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