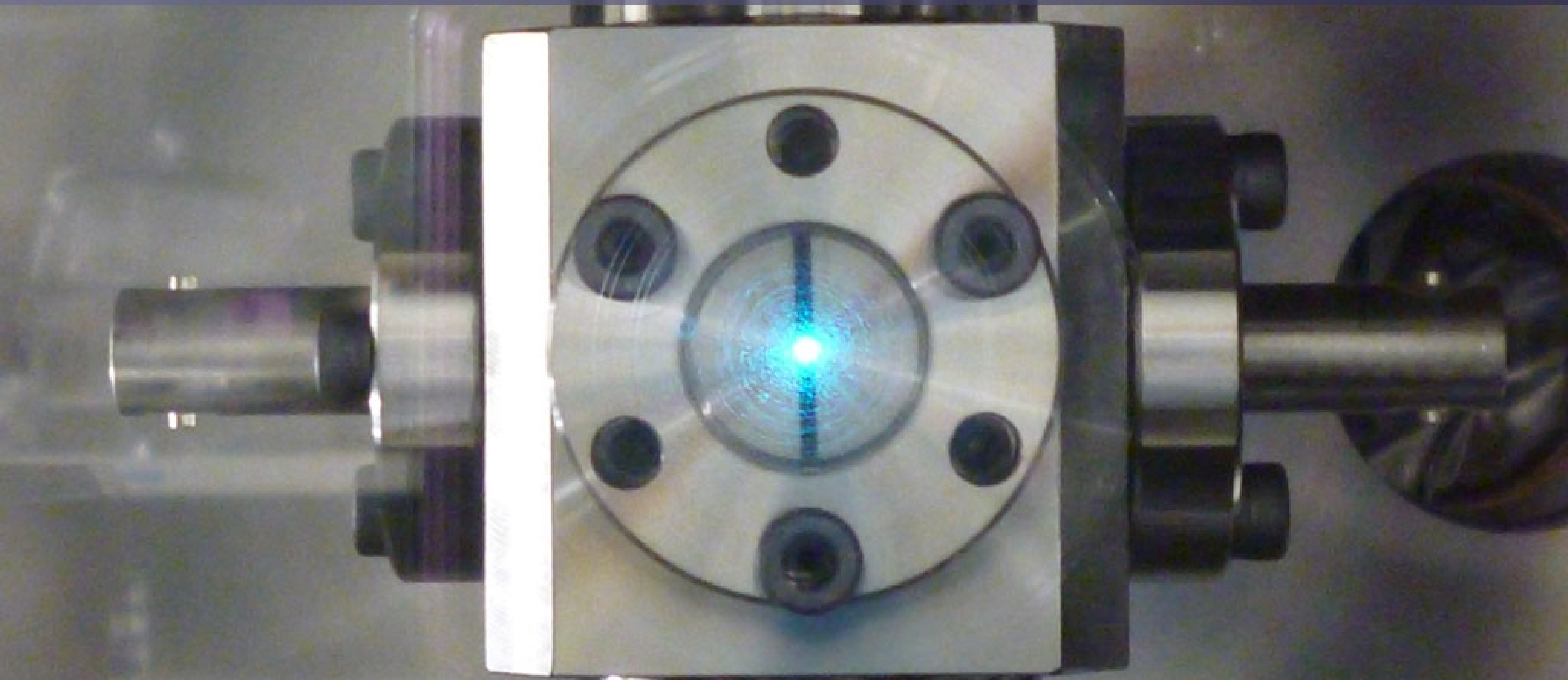
Free Electron Lasers



PHY4311

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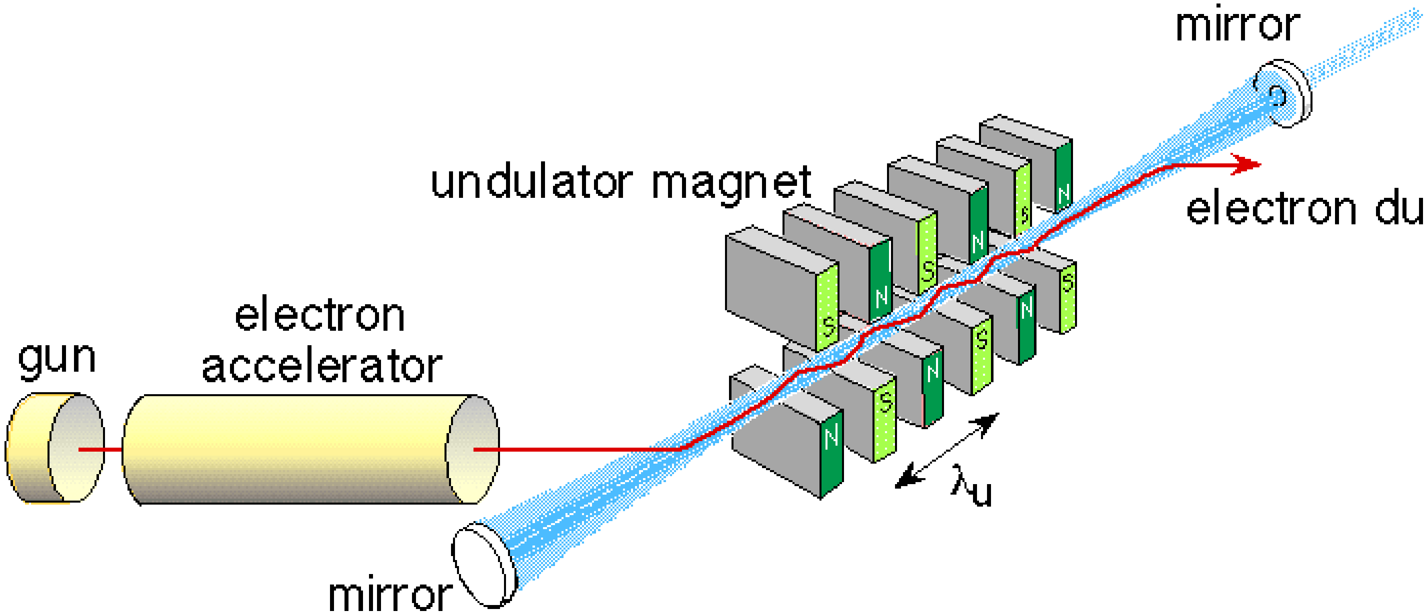
April 29 2015

All About Free Electron Lasers

- **Basic Properties**
  - What characteristics do these types of lasers have?
- **Operating Principles and Theory**
  - Basic FEL Cavity
  - Emitted Wavelength Formula
- **SASE Free Electron Lasers**
  - Xray Free Electron Lasers
  - Temporal Coherence Limit
- **An Application**
  - Molecular Imaging

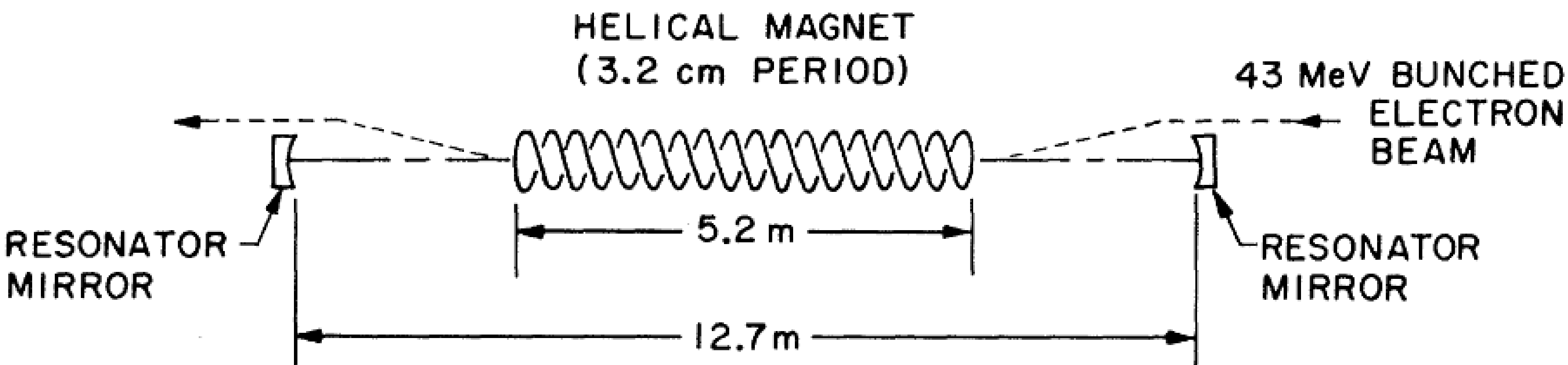
Basic Properties

- No Medium. What instead?
- Relativistic, free electrons are the source of the radiation.
- The output wavelength is tunable.



Operating Principles

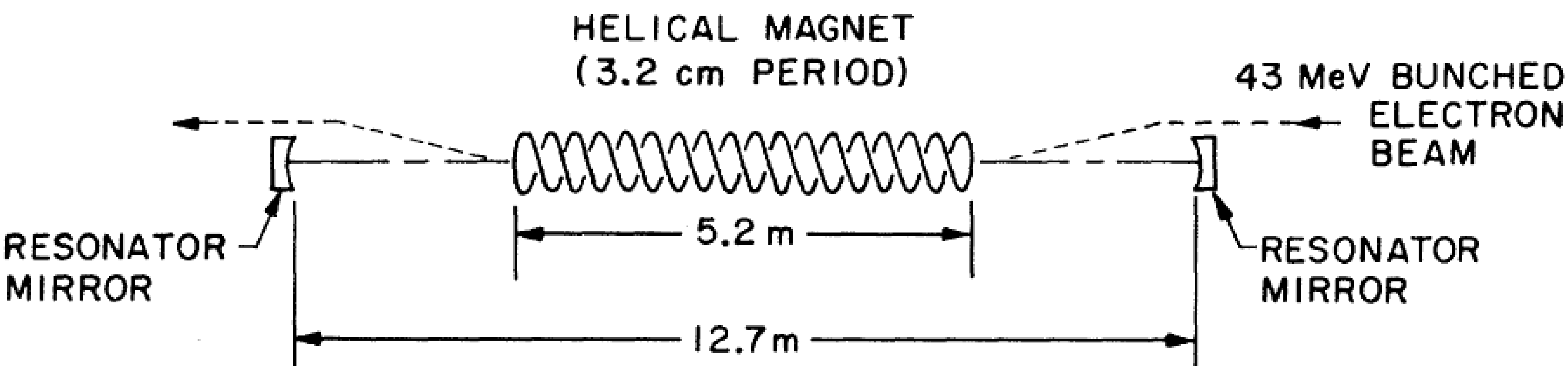
- **A Basic Cavity**
  - Electron Beam
  - Helical Magnet (Wiggler)
  - Light Travelling parallel to the electrons.



"*First Operation of a Free Electron Laser*", Deacon et al. Phys. Rev. Lett. 38, 892 (1977)

Operating Principles

- Radiation arises from the interaction of three components
  - Electron Beam
  - Magnetic Field of the Wiggler
  - EM Field of the light traveling parallel to the electrons
- Decelerating charges emit radiation.
  - **Bremsstrahlung**, The magnetic field of the wiggler changes the direction of the electron

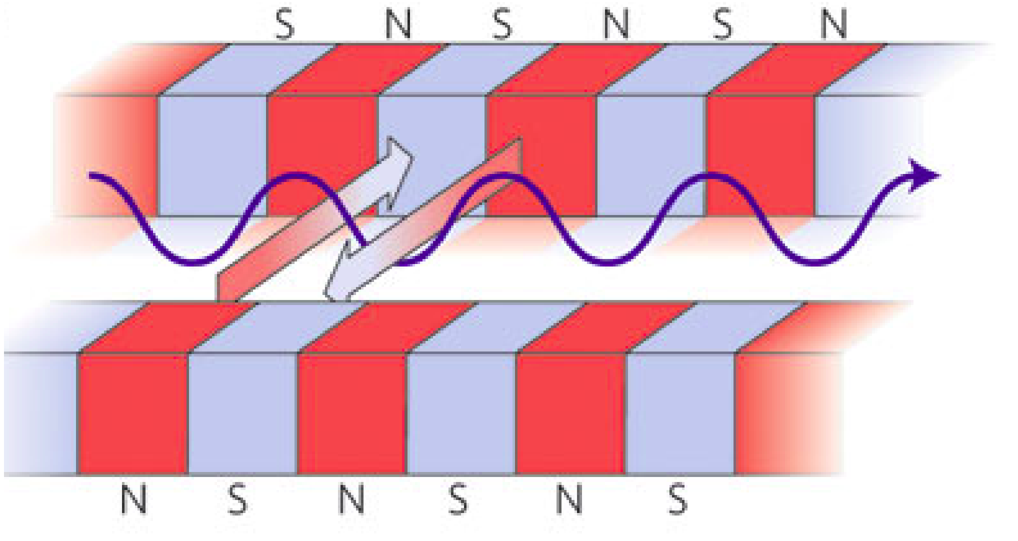


“*First Operation of a Free Electron Laser*”, Deacon et al. Phys. Rev. Lett. 38, 892 (1977)

Operating Principles

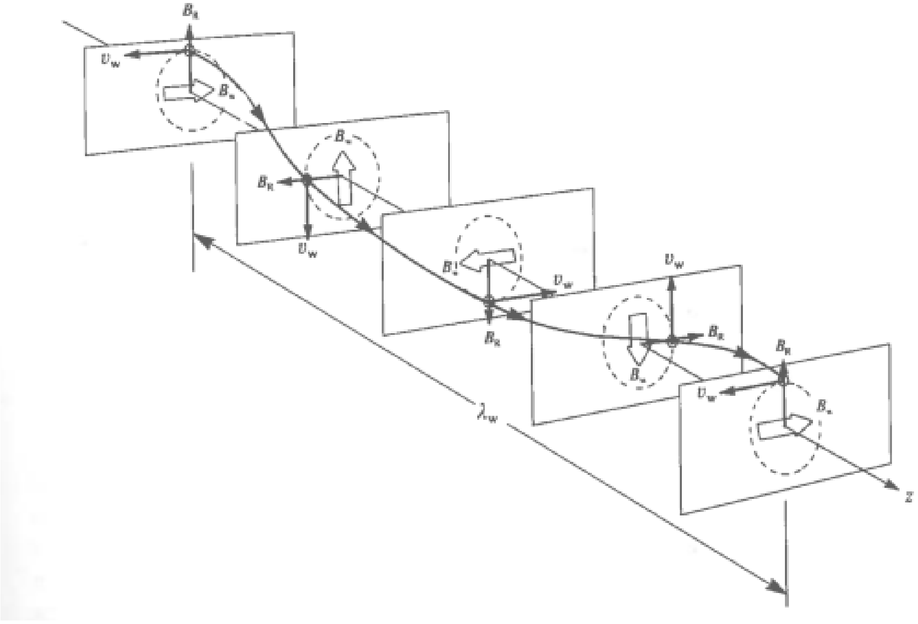
- **The Wiggler (aka The Undulator)**
  - Creates a **transverse**, **spatially periodic**, **constant**, magnetic field
  - Magnetic Force tells us the direction the electron will go. The electron starts to wiggle.

$$\mathbf{F}_M = e(\mathbf{v} \times \mathbf{B})$$

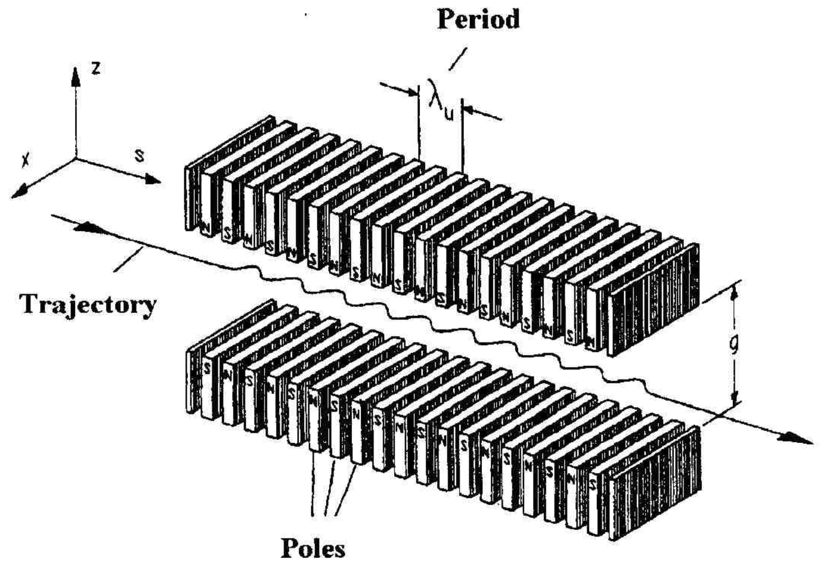


Operating Principles

Trajectory in a Helical Wiggler

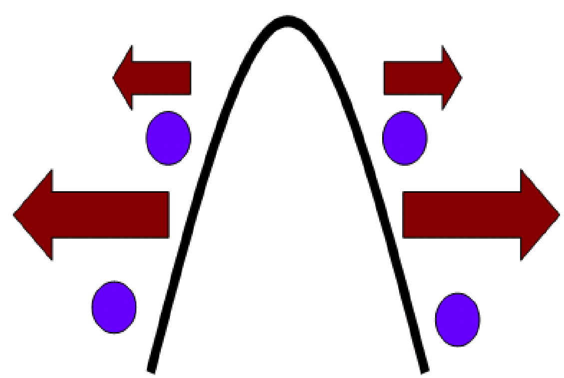


Trajectory in a Linear Wiggler



Operating Principles

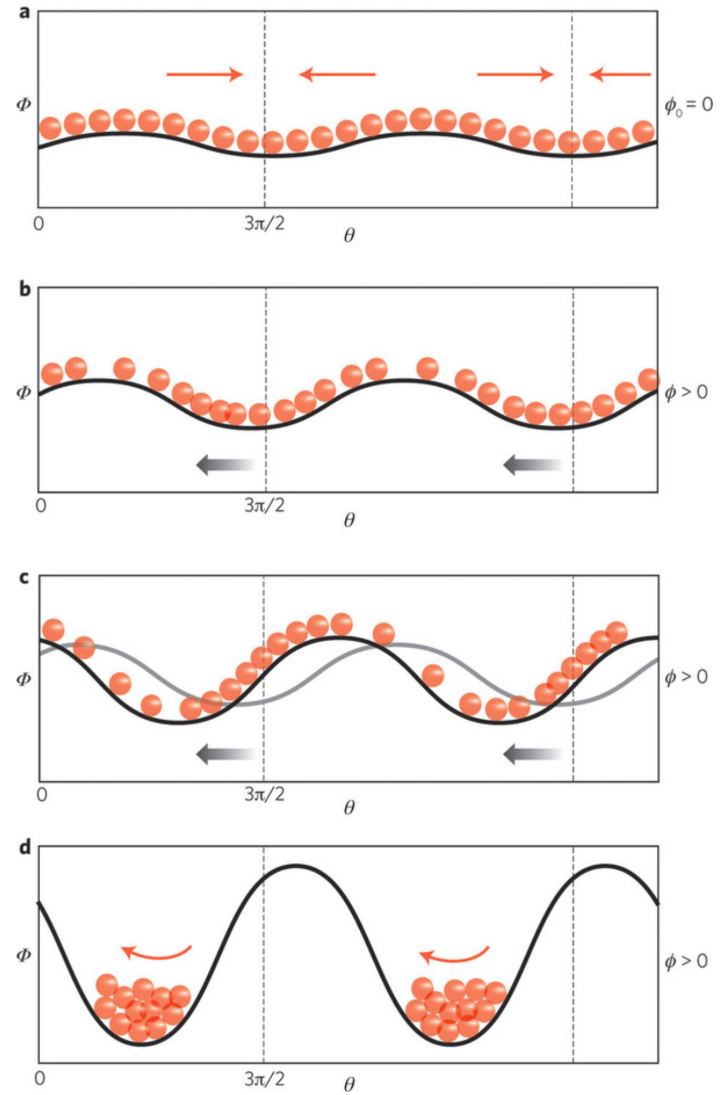
- **Ponderomotive Force**: $$\mathbf{F}_p = -\frac{e^2}{4m\omega^2}\nabla E^2$$
  - This is the force an electron feels due to an oscillating field (like an EM wave)
  - The magnetic field of wiggler + radiation field = **ponderomotive wave.** This wave is slower than **c**, so electrons can travel with it.



Operating Principles

Light Amplification and Electron Bunching

- The electrons travel near the speed of the ponderomotive wave
- The electrons can gain energy from the wave or lose energy to it
- The electron's speed changes from being close to the speed of the wave to being in resonance with it.
- The electrons form bunches



Operating Principles

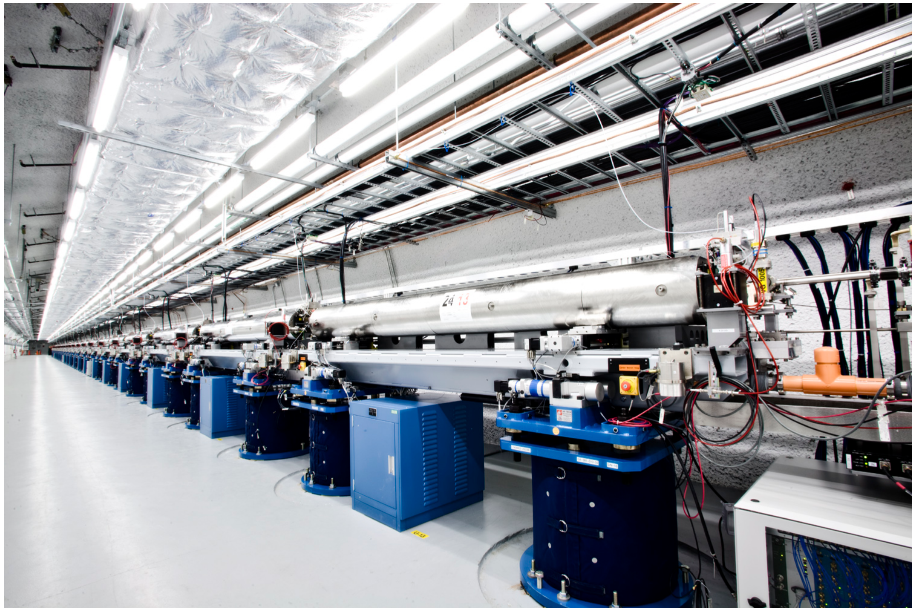
- **Emitted Wavelength**:
  - Electrons travelling through the wiggler are relativistic and experience a length contraction. The wiggler wavelength they experience is λ_u/γ
  - The emitted radiation is then measured in the lab frame. Because the source of the radiation is moving close to c, we measure a Doppler shifted wavelength. So we have a second factor of γ
  - Tuning: Pick wiggler period and B strength, vary electron energy

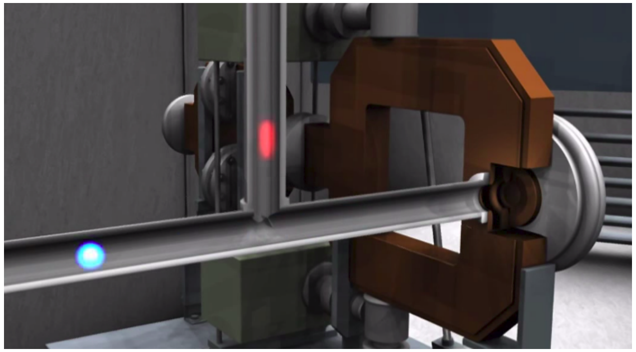
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left[1 + K^2\right] \qquad K^2 = \frac{1}{4\pi^2}\left(\frac{\lambda_u^2 r_0 B^2}{mc^2}\right)$$

$$\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$

Xray Free Electron Lasers

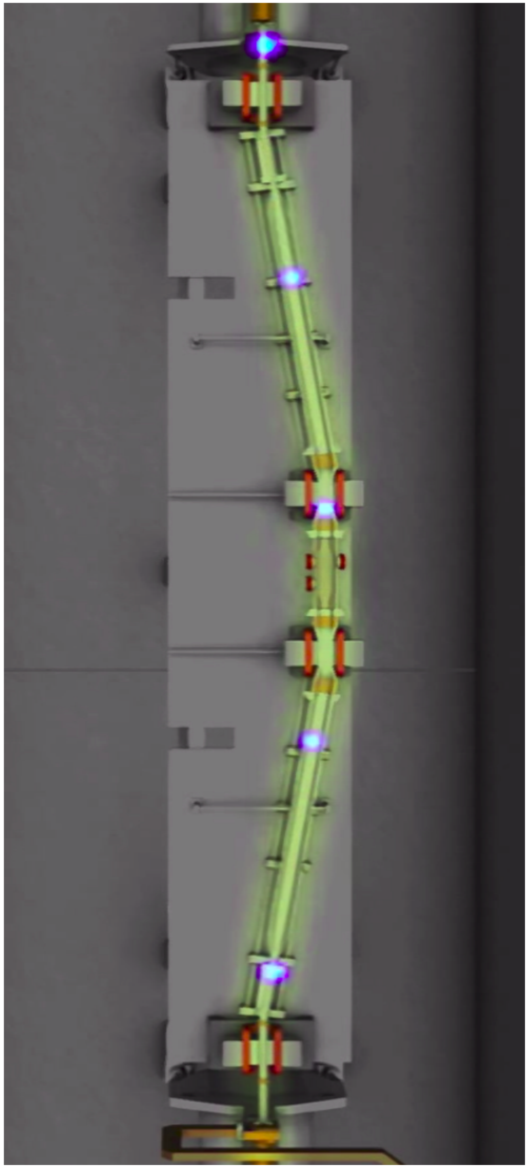
- **SASE Free Electron Lasers**
  - **No cavity**, just one long wiggler (like at LCLS)
  - Xray pulses are made by **injecting electrons in bunches**
  - **SASE**: Electrons emit xray radiation, travel with the radiation, and amplify it.
  - As the electrons travel they bunch together more and more. At saturation they form regularly spaced '**microbunches**'. So the radiation is coherent and very intense.





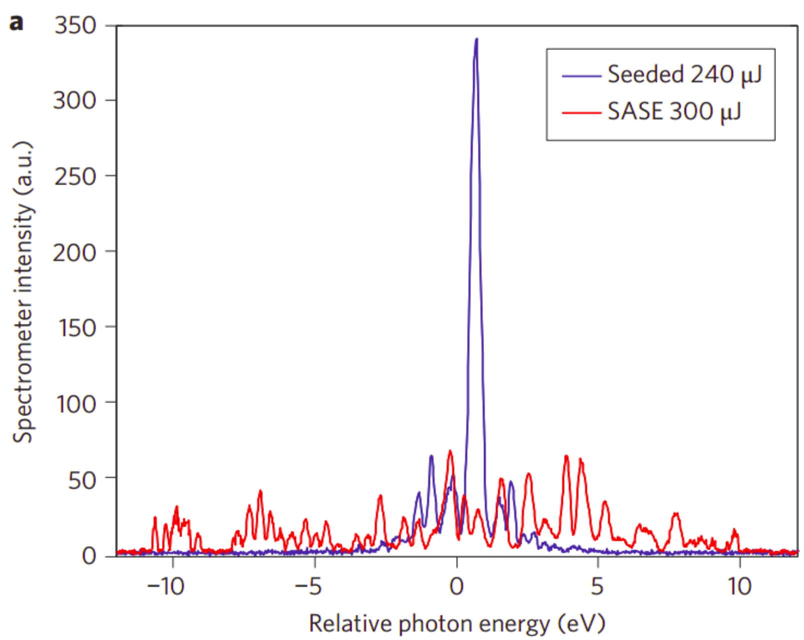
Xray Free Electron Lasers

- **Bunch Compressors (Chicanes)**
  - LCLS compresses the spacing between the electrons before entering the wiggler. This gives control over the duration between pulses.



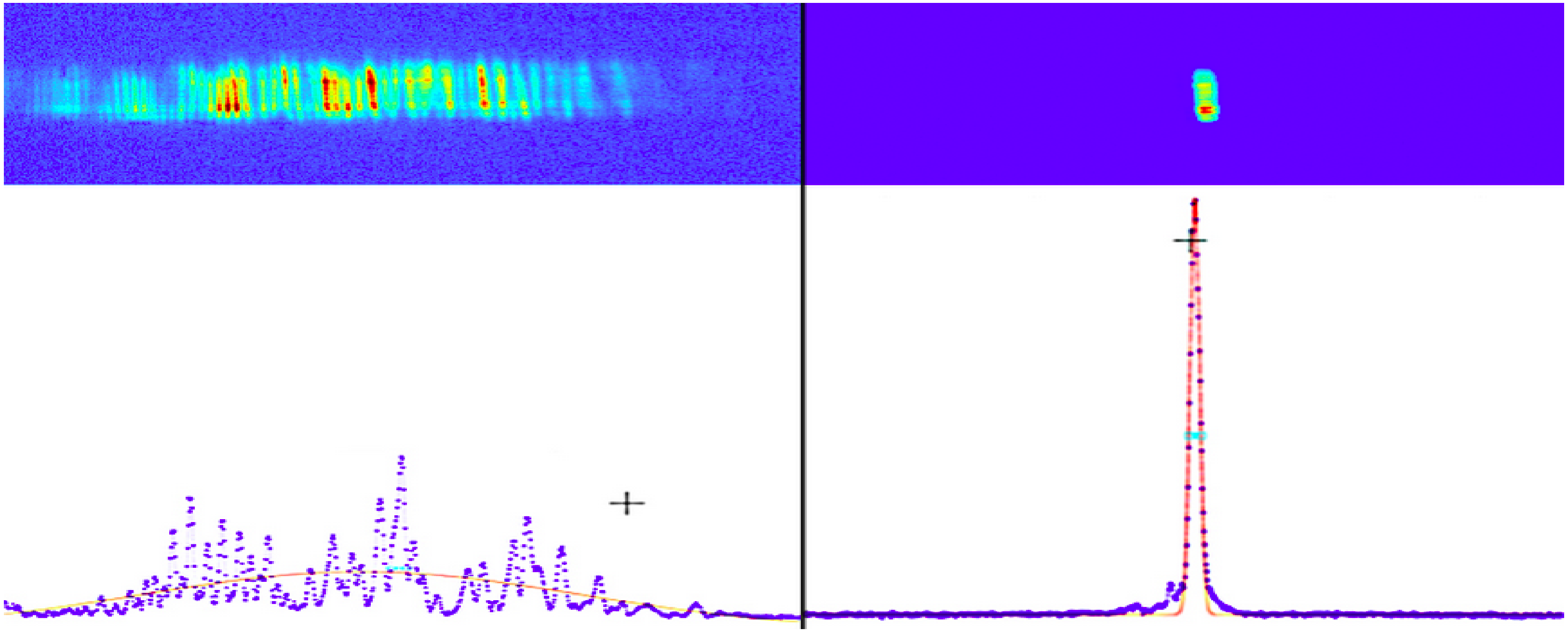
Xray Free Electron Lasers

- **Temporal Coherence Limitation**
  - SASE leads to noise. The electrons start off incoherent and emit incoherent radiation. This limits the temporal coherence of the beam.
  - Possible Solution: Filter out noisy frequencies to get a smaller bandwidth. This hampers intensity.
  - Possible Solution: Inject a temporally coherent pulse tuned to the speed of the electrons and the wiggler. The electrons then amplify this signal. This is called **seeding**. No easy access to Xray seeds.



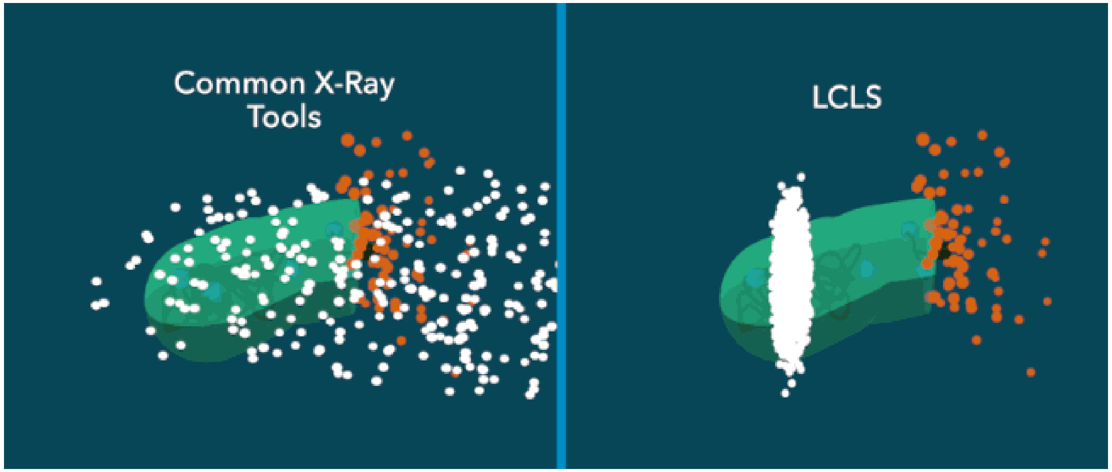
Xray Free Electron Lasers

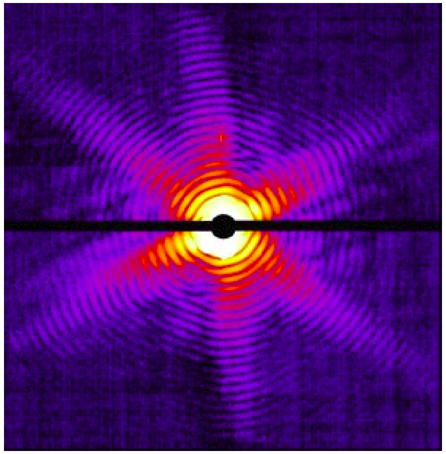
- **LCLS 2012: Self-Seeding as a Solution**
  - Take Xrays from the first half of the undulator, pass it through a diamond monochromator. This selects a very sharp bandwidth of xrays.
  - Use the pulse that comes out of the monochromator to seed the second half of the undulator. The result is a huge increase in intensity and a much sharper bandwith.

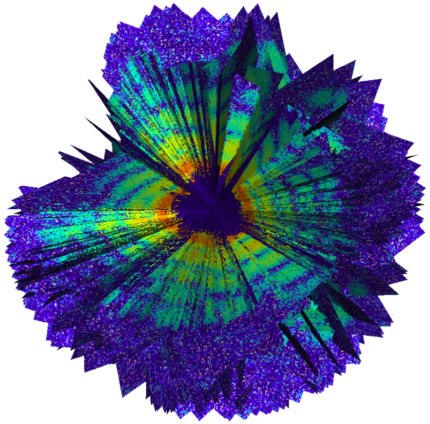


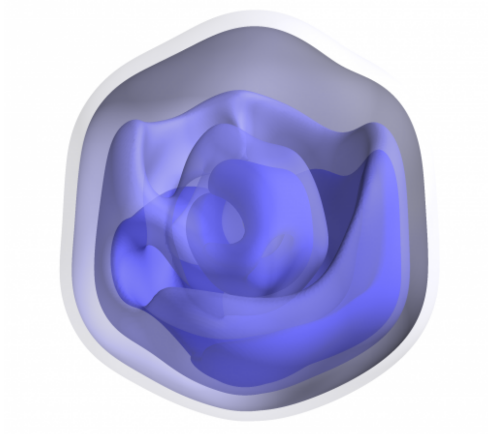
An Application: Molecule Imaging

- **Molecule Imaging**
  - Made possible by High Intensity + Short Pulses
  - “Diffract before Destroying”









Thanks!
References and Further Reading

- **Cool Video**
  - "X-ray Laser Animated Fly-through" https://www.youtube.com/watch?v=pgaG7f96SKM
- **Cool Papers**
  - "First Operation of a Free Electron Laser". Deacon et al., *PRL* Vol. 38, 1977.
  - "Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field". John Madey. *Journal of Applied Physics* Vol 42, 1971.
  - "X-ray free electron lasers". Mcneil et al., Nature Photonics 2010.
  - "Demonstration of self-seeding in a hard-X-ray free-electron laser". Amann et al., Nature Photonics 2012.
- **Cool Books**
  - "Principles of Free-electron Lasers". H.P. Freund and T. M. Antonsen Jr. Chapman & Hall 1996.