

Synchrotron Light Generation, Manipulation and Applications



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Lead Physicist for Infrared Beamlines

National Synchrotron Light Source II

Outline: Producing Synchrotron Radiation (Light)

- Basics of Electromagnetic Radiation:
 - Accelerating charge (electrons)
 - Special Relativity – why it's important for producing X-rays
- How an Electron Synchrotron Works: achromatic “lattices”, focusing and RF
- Magnetic Devices for Generating Synchrotron Light:

Transverse (centripetal) acceleration in a magnetic field

 - Bending Magnets See <https://journals.iucr.org/s/issues/2018/04/00/yn5030/yn5030.pdf>
 - Insertion Devices (wigglers and undulators)



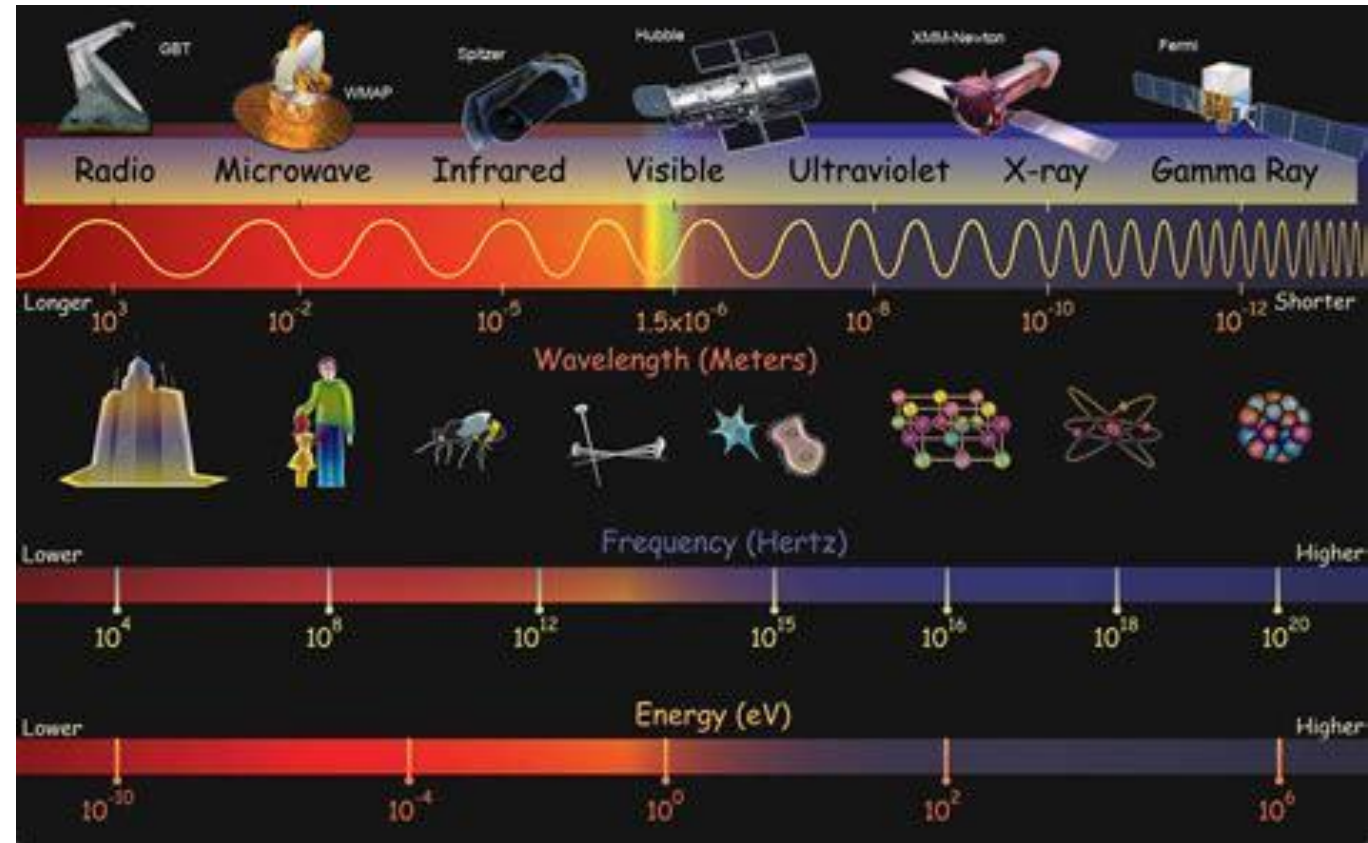
Outline: Applications of Synchrotron Light

- Diffraction / Crystallography: “Hard” X-rays for crystal structure
 - Diffraction from Crystals and Periodic Structures
 - ▶ Powders (small crystals)
 - ▶ Single Crystals
 - ▶ Proteins
- Scattering:
 - Resonance, Inelastic (soft x-rays)
 - Small angle
- Spectroscopies
 - X-ray Absorption Spectroscopy (XAS) - excitations from electronic “core” levels: medium energies (soft & tender). Sense elemental content and local environment (EXAFS, XANES)
 - X-ray and UV Photoelectron Spectroscopy (XPS, UPS, ARPES): Absorbed x-ray ejects electron.



Our “Favorite” Unit for Energy: The electron Volt (eV)

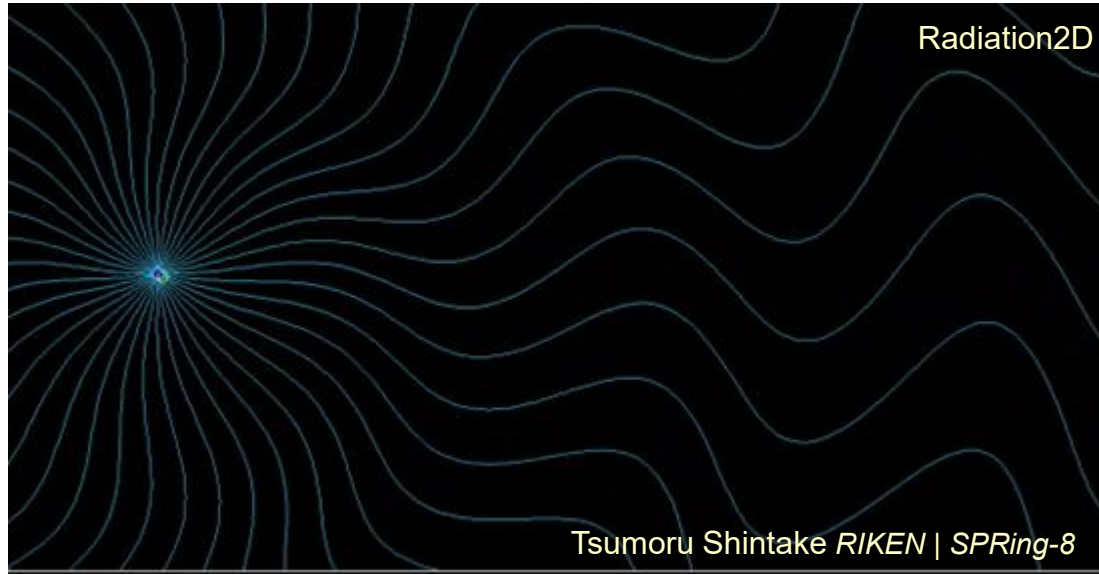
- Energy an electron gains when crossing a 1V potential => 1.6×10^{-19} J/eV
 - Visible light photons span 1.7 (red) to 3 (violet) eV.
 - UV from 4 eV to ~100 eV
 - X-rays from a few hundred eV to ~100 keV
 - Infrared from ~1 meV to ~1 eV
 - Rest mass of an electron: 511 keV (0.511 MeV)
 - “ “ “ “ proton: 938 MeV
(proton at rest is about 2000x more massive than electron at rest).
- Synchrotron light sources can produce photons with energies from ~ 1meV to 100 keV and beyond.



The Electromagnetic Spectrum | Physics LibreTexts



Relativity: E-Field of an electron moving at constant velocity

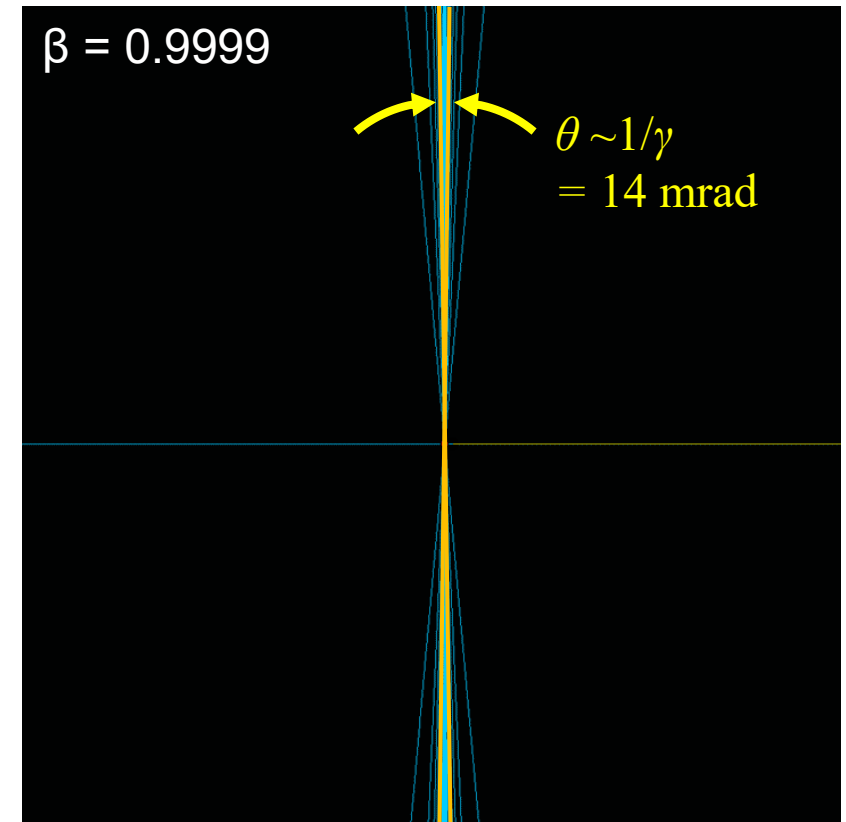


Velocity $v = \beta c$ (i.e. $\beta = v/c$)

Mass enhancement $m = \gamma \cdot m_0$; $\gamma = \sqrt{\frac{1}{1 - \beta^2}}$

At NSLS-II, $\gamma = 5871$, $\beta = 0.999999998549$

At this velocity, electron mass is about 3X that of a proton at rest

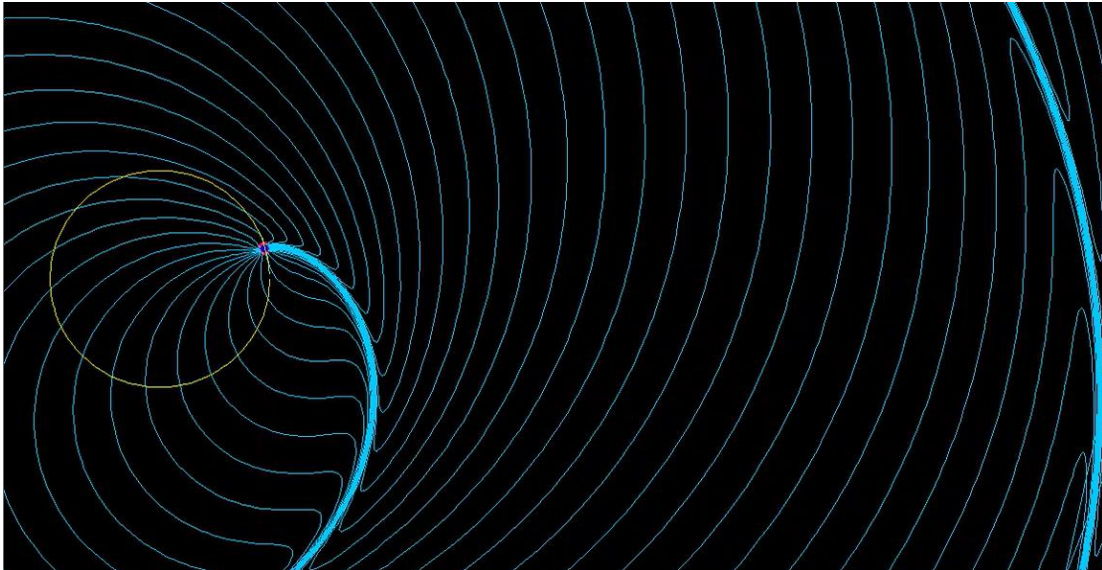


Back to Emission of Electromagnetic Waves (Photons)



Charged particles emit when they are accelerated.

Example: circular motion (centripetal acceleration)



Relativistic electron at 98% of c ($\beta = 0.98$)

Radiated fields have a sharp (fast) “kink” due to the relativistically compressed Coulomb field PLUS Doppler effect.

Rapidly changing radiated fields

=> emission to very high frequencies (i.e. x-rays)

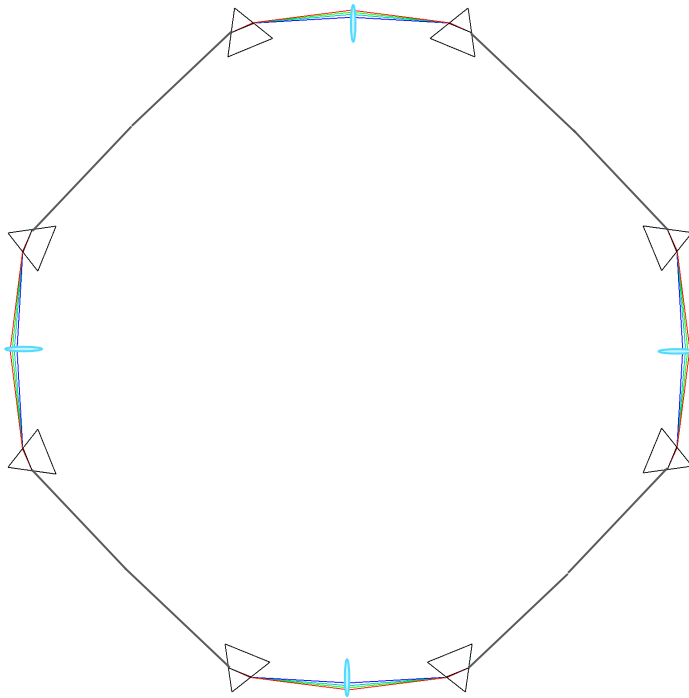
Emission is from very small electron beam into narrow angle

=> Very high brightness/brilliance/radiance

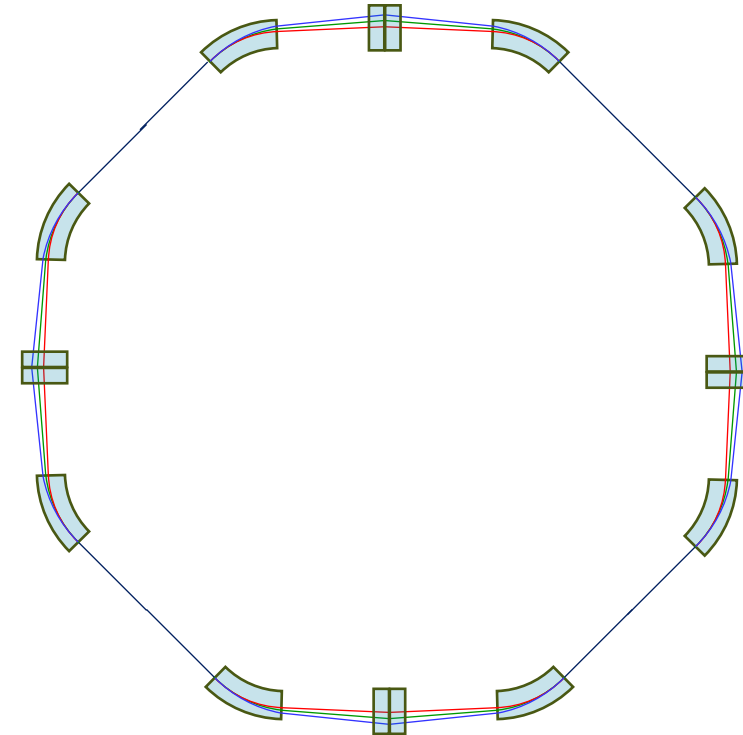


Electron Synchrotrons (and Storage Rings) as Light Sources

Photons and Prisms

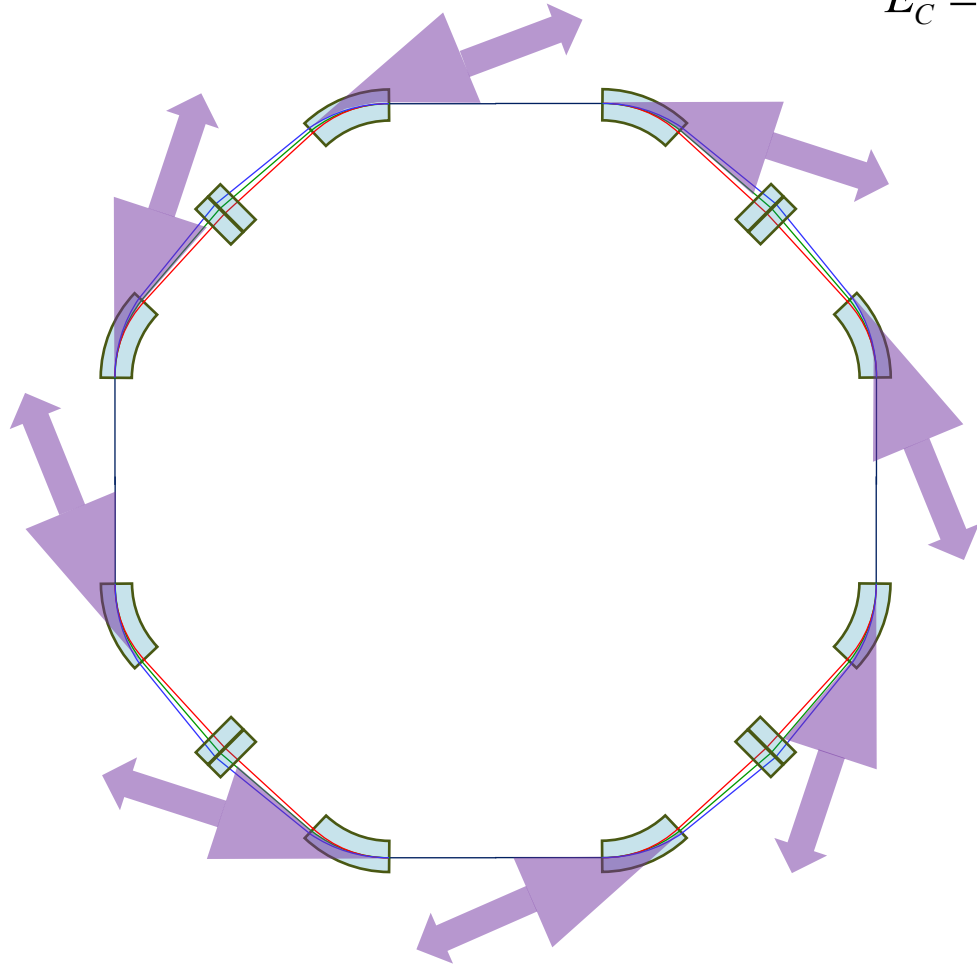


Electrons and Magnets

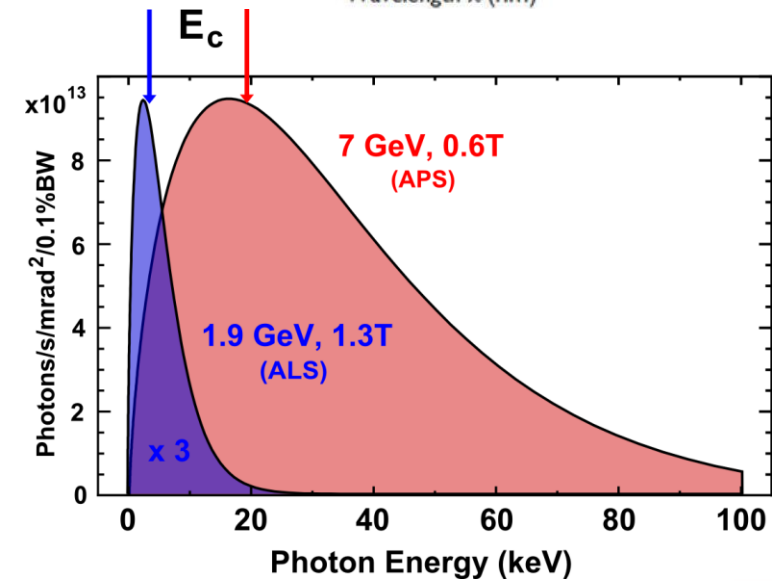
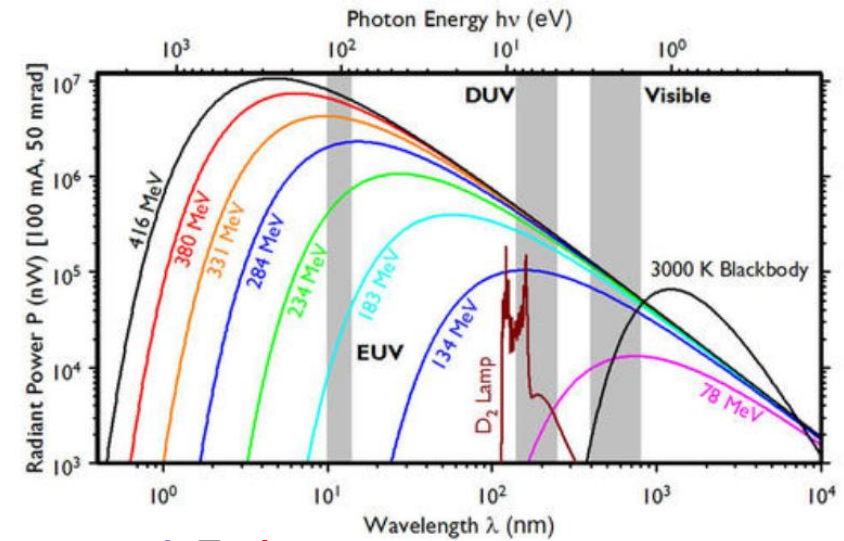


Electron Synchrotrons (and Storage Rings) as Light Sources

$$E_C = h\nu_C = \frac{3h}{4\pi} \frac{c}{\rho} \gamma^3$$

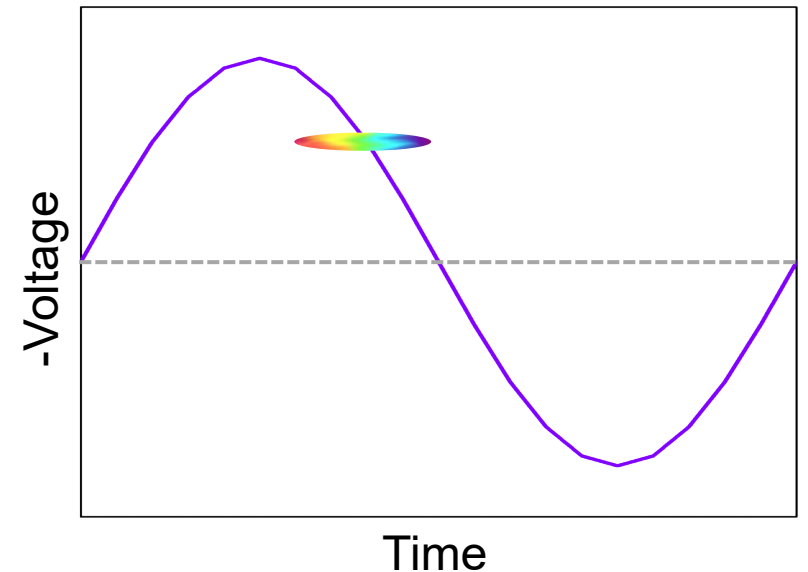


Bending Magnet Radiated Output



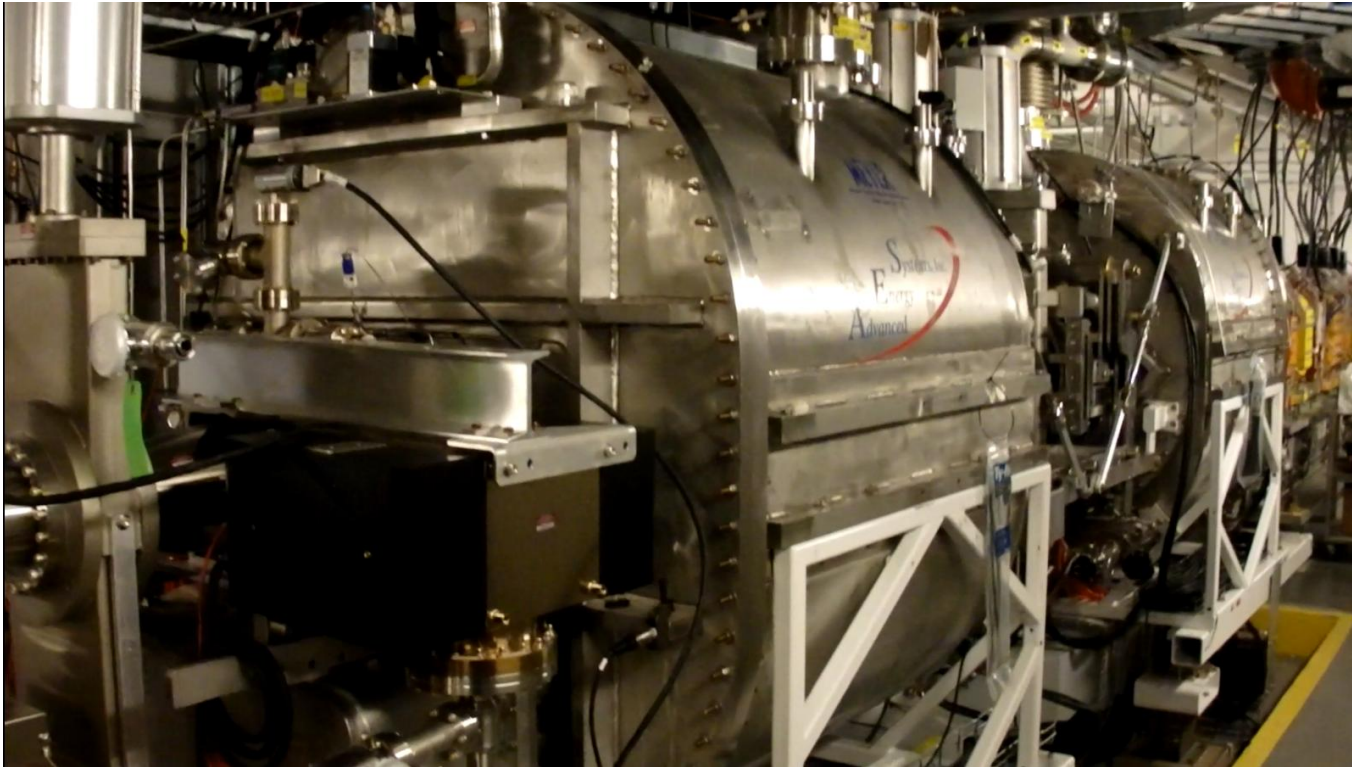
Electrons Emit EM radiation (what we want!)

- Electrons lose energy => Needs to be restored.
- Use time-varying E-field (voltage) from a powered radio-frequency (RF) cavity
 - Electrons circulate in bunches to arrive at the correct RF voltage (time or phase) to restore the lost energy. $V(t \text{ or } \phi) = \Delta E_{\text{avg}}/e$
 - Note: Electrons do not all have the exact same energy.
 - ▶ Electrons with energy excess (heavier) follow longer orbit, arrive later.
 - ▶ Electrons with energy deficit (lighter) take shorter orbit, arrive earlier.
 - Have electrons arrive on the correct $V(t)$ slope.
 - ▶ Early (lower energy) electrons cross a larger potential
 - ▶ Late (higher energy) electrons cross a smaller potential
 - ⇒ Energy correction and orbit stability.
 - ⇒ Electrons intrinsically “find” the appropriate potential, follow the RF synchronously -> *synchrotron*



NSLS-II Superconducting RF Cavities

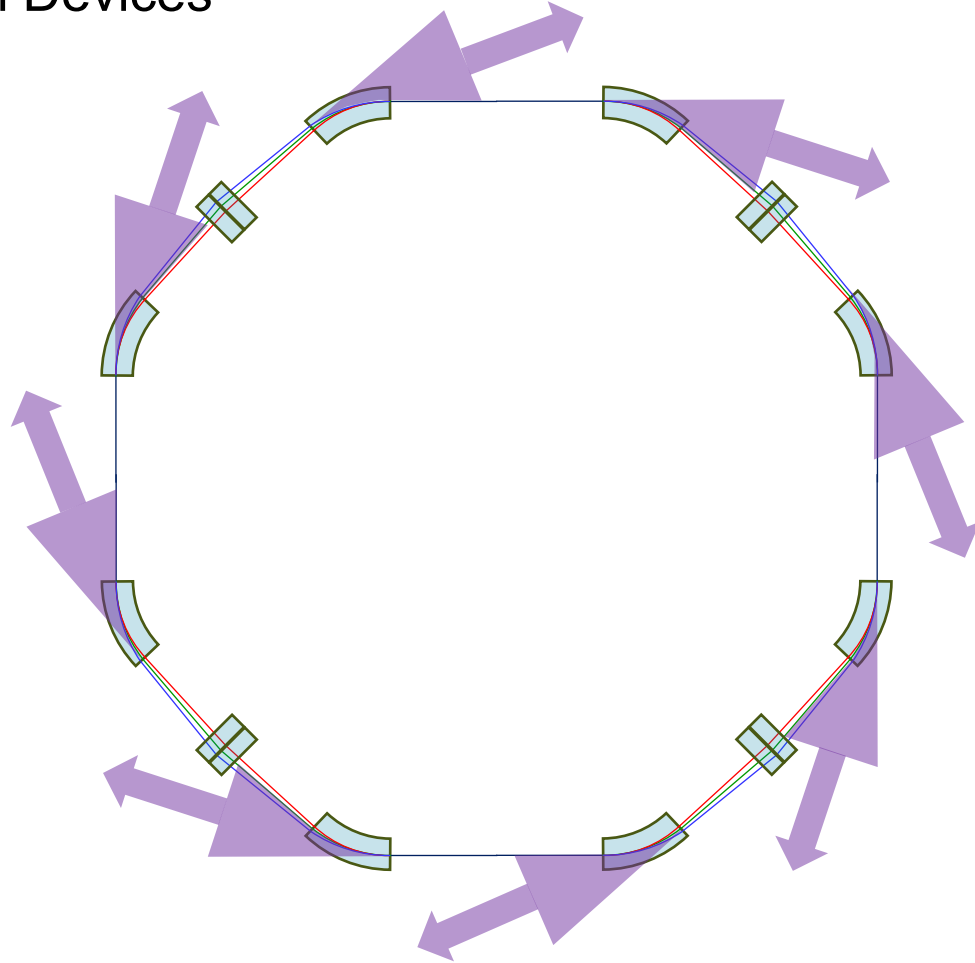
- 1.2 MV during normal operations
- ~150 kW of radiated power from dipoles alone (IDs add a lot more ...)
- Presently three RF cavities, plans for a total of four.



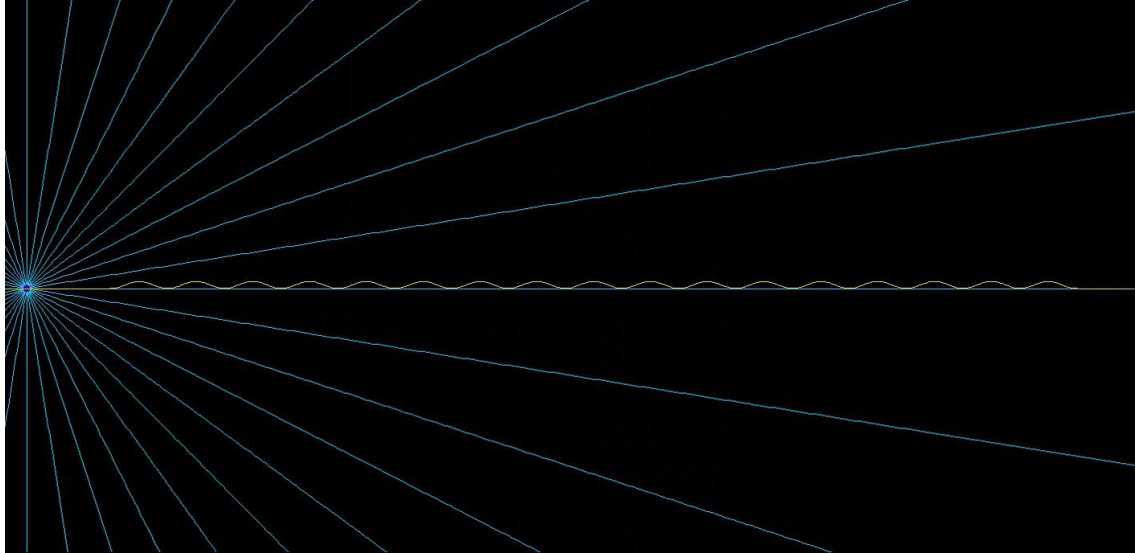
Electron Synchrotrons (and Storage Rings) as Light Sources

Can insert more magnets in the straight sections if electrons remain on orbit => periodic magnet structures

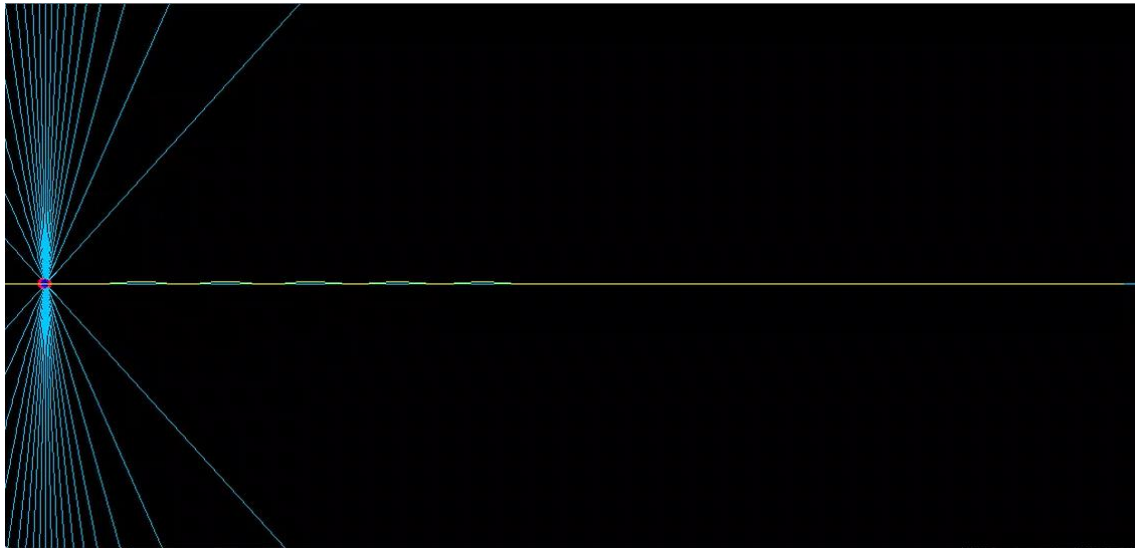
“Insertion Devices”



Insertion Devices for Synchrotron Light Sources

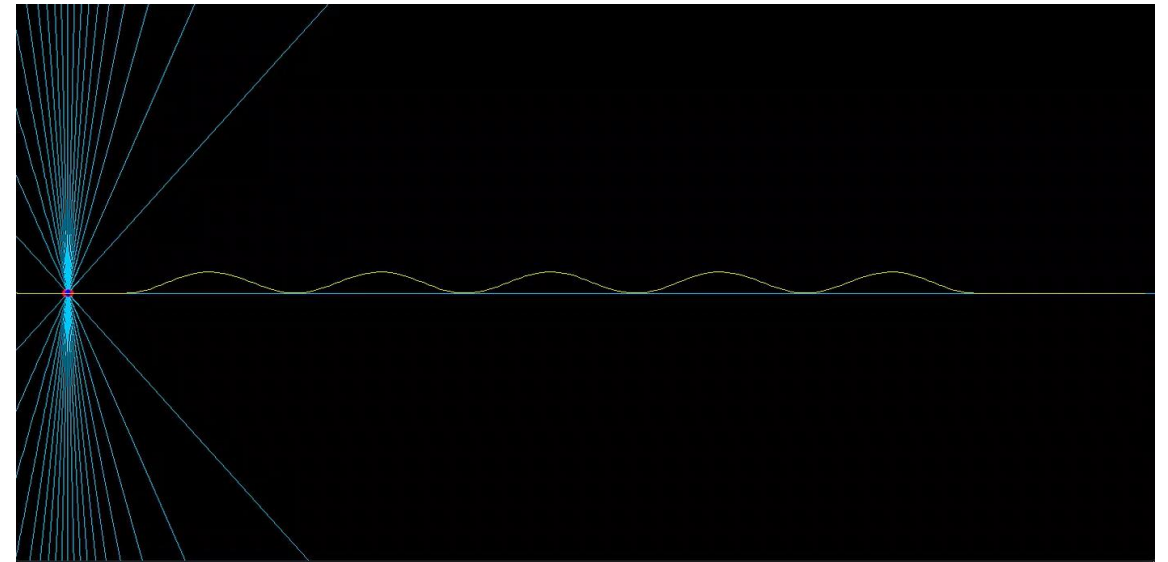


Non-relativistic



Relativistic - Undulator

Relativistic - Wiggler



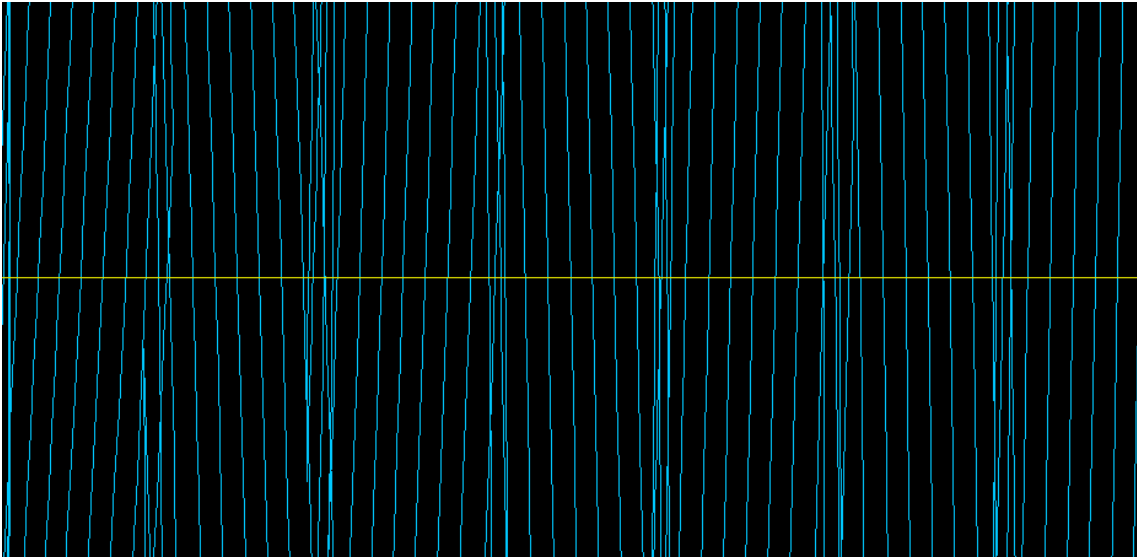
Undulators and Wigglers

$$\lambda_{on-axis} = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right)$$

$$K(B) = \frac{eB\lambda_u}{2\pi mc} = 0.934\lambda_u[cm]B[T]$$

Undulators:

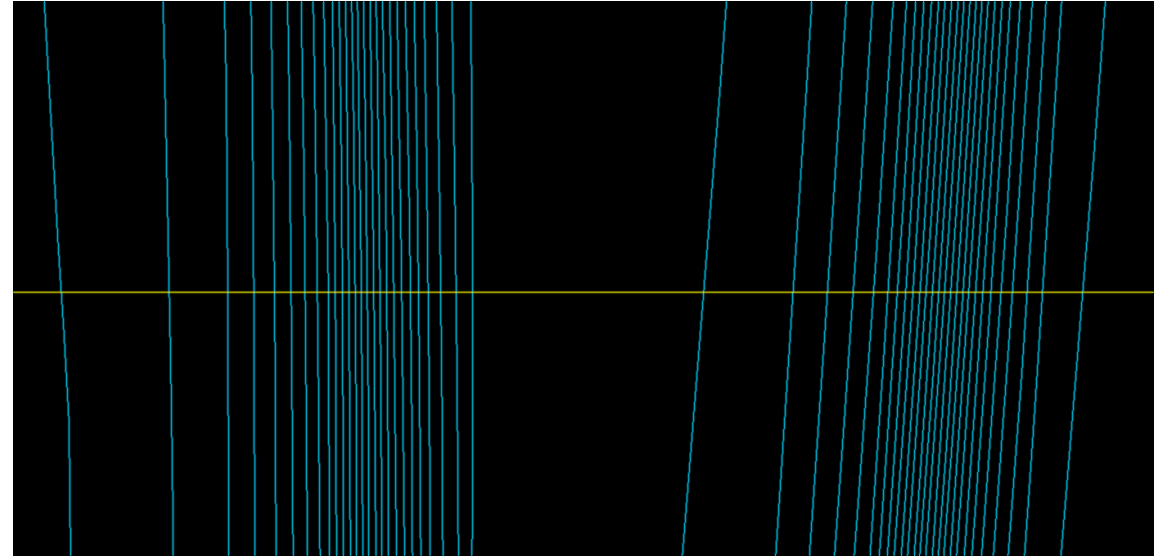
Waveform with somewhat evenly spaced E-field cycles
=> Moderately discrete frequencies and wavelengths



Wigglers:

E-field has less well-defined periodicity

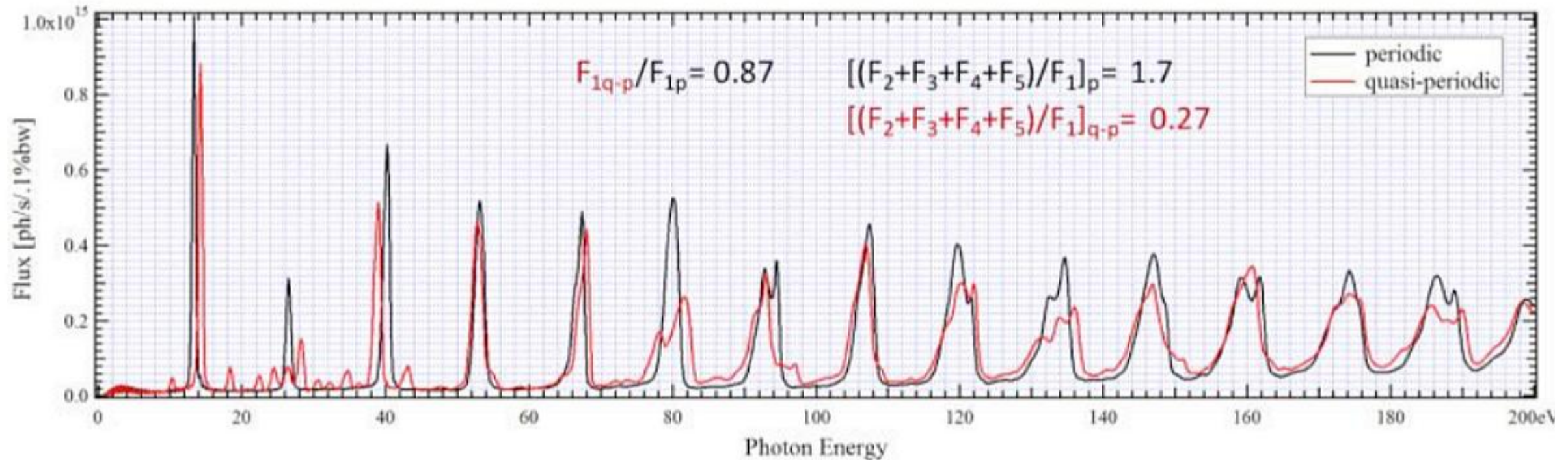
=> Smoother spectral output, reaches higher frequencies



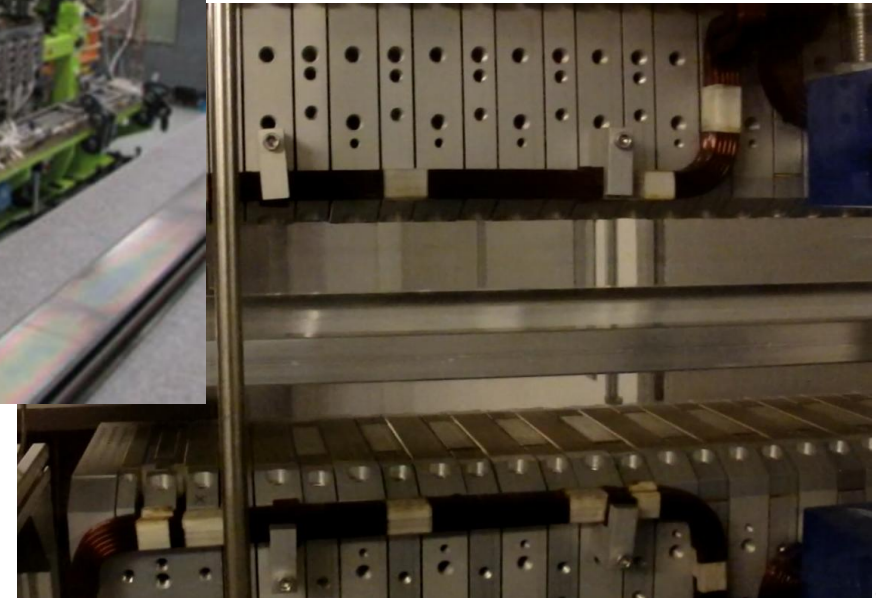
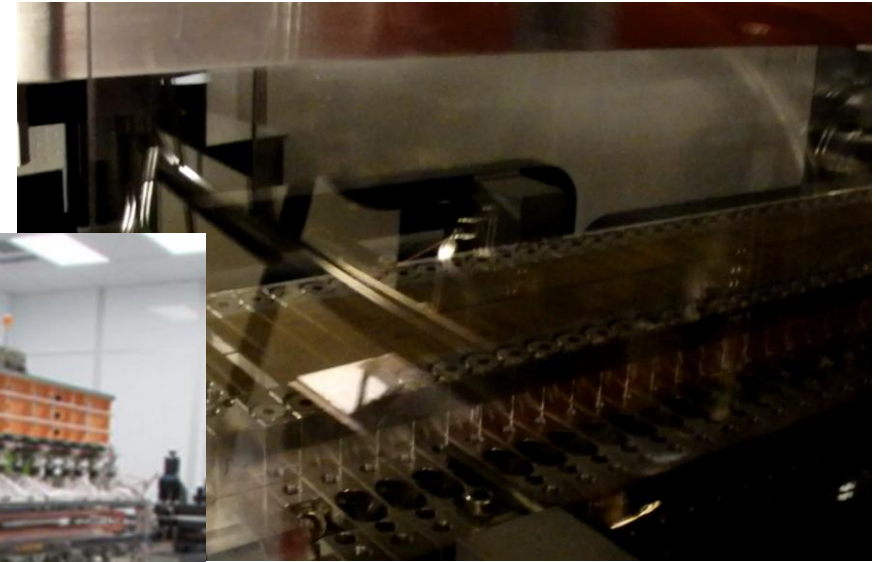
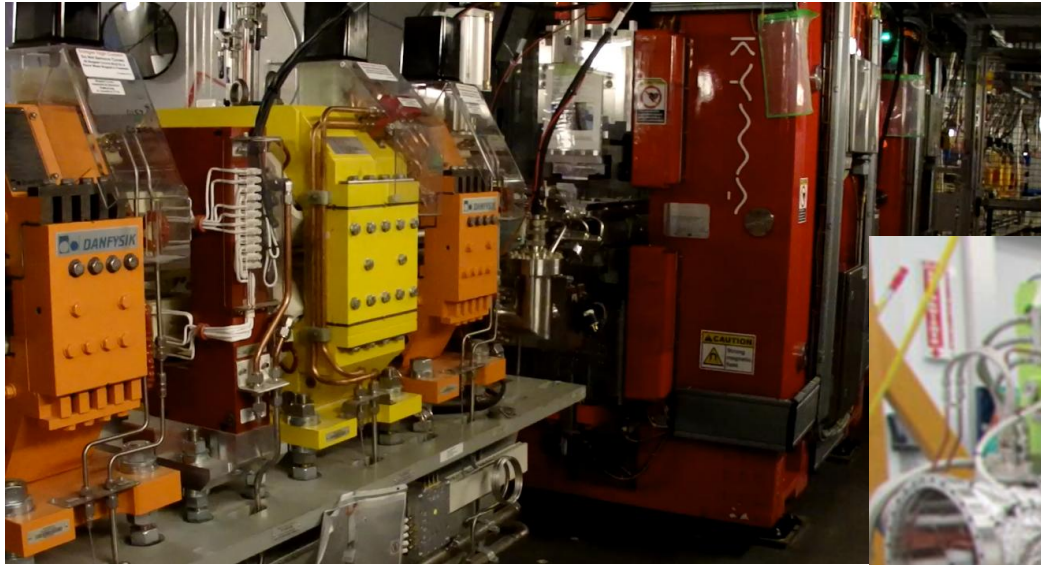
Undulator Spectral Output

$$\lambda_{on-axis} = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} \right)$$

$$K(B) = \frac{eB\lambda_u}{2\pi mc} = 0.934\lambda_u[cm]B[T]$$

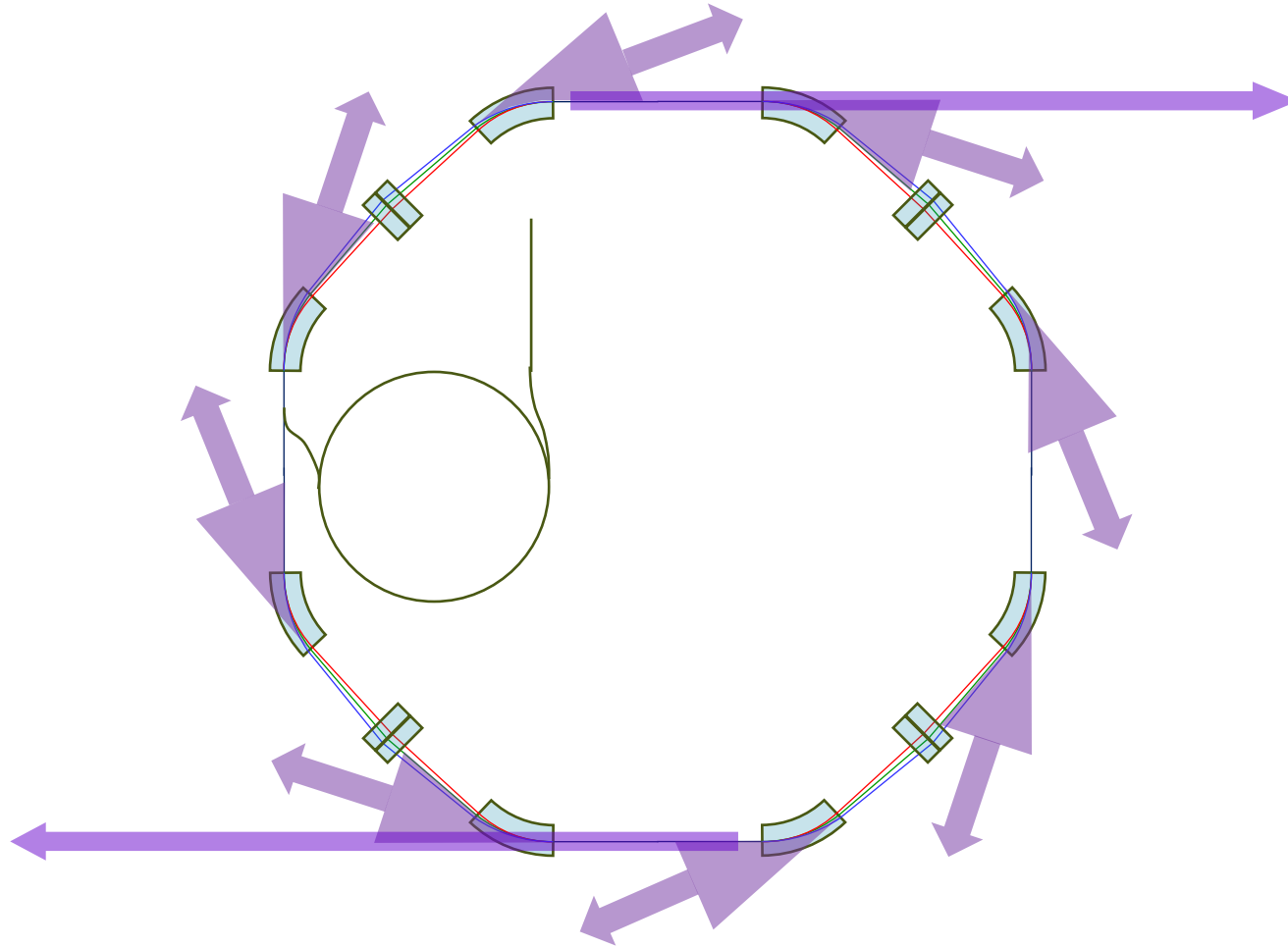


Insertion Devices at NSLS-II

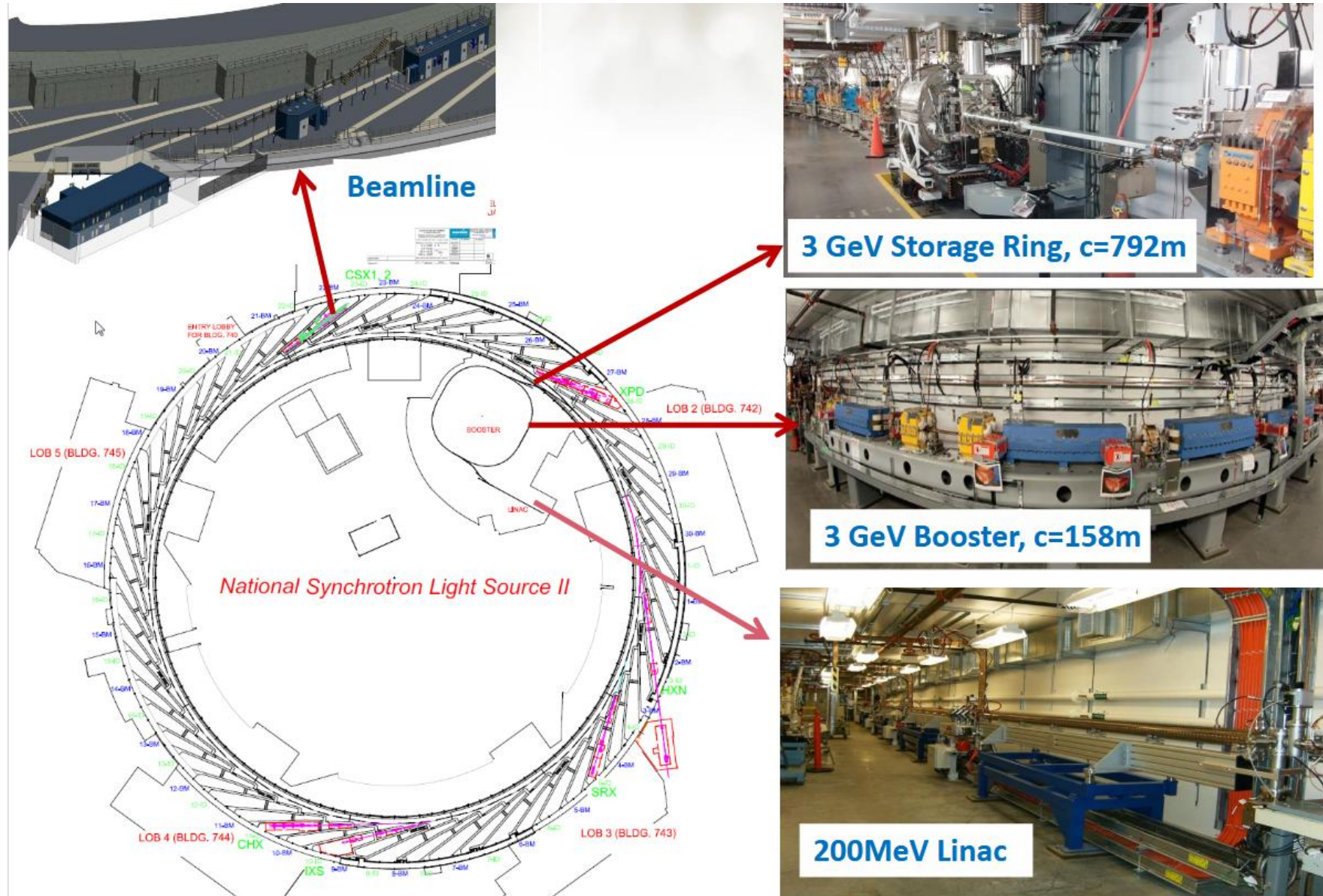


Electron Synchrotrons (and Storage Rings) as Light Sources

Can insert more magnets in the straight sections if electrons emerge on same orbit => periodic magnet structures

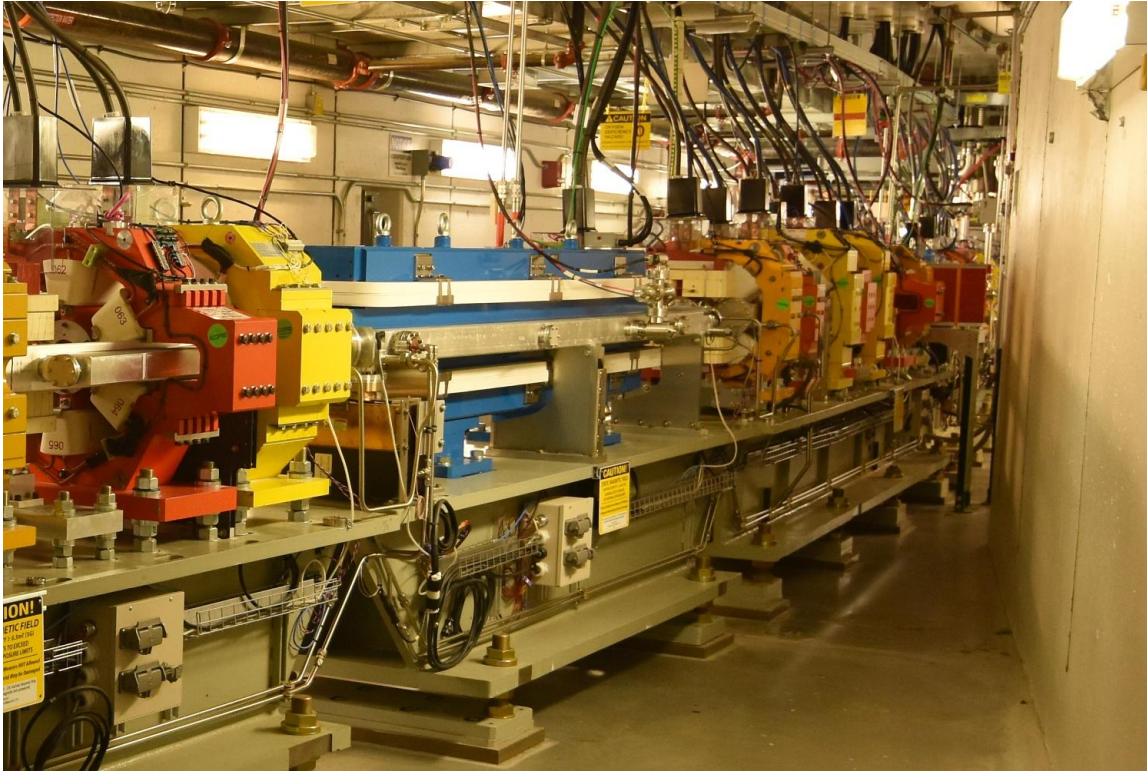


National Synchrotron Light Source II: Accelerator Components



Dipole Bend Source: 90mm gap, 0.4T ($\rho = 25\text{m}$ for $E=3\text{ GeV}$)

NSLS-II, Dipole



Optics for X-Rays: Needed for beam Steering and Focusing

Reflection: Mostly metals at near grazing incidence

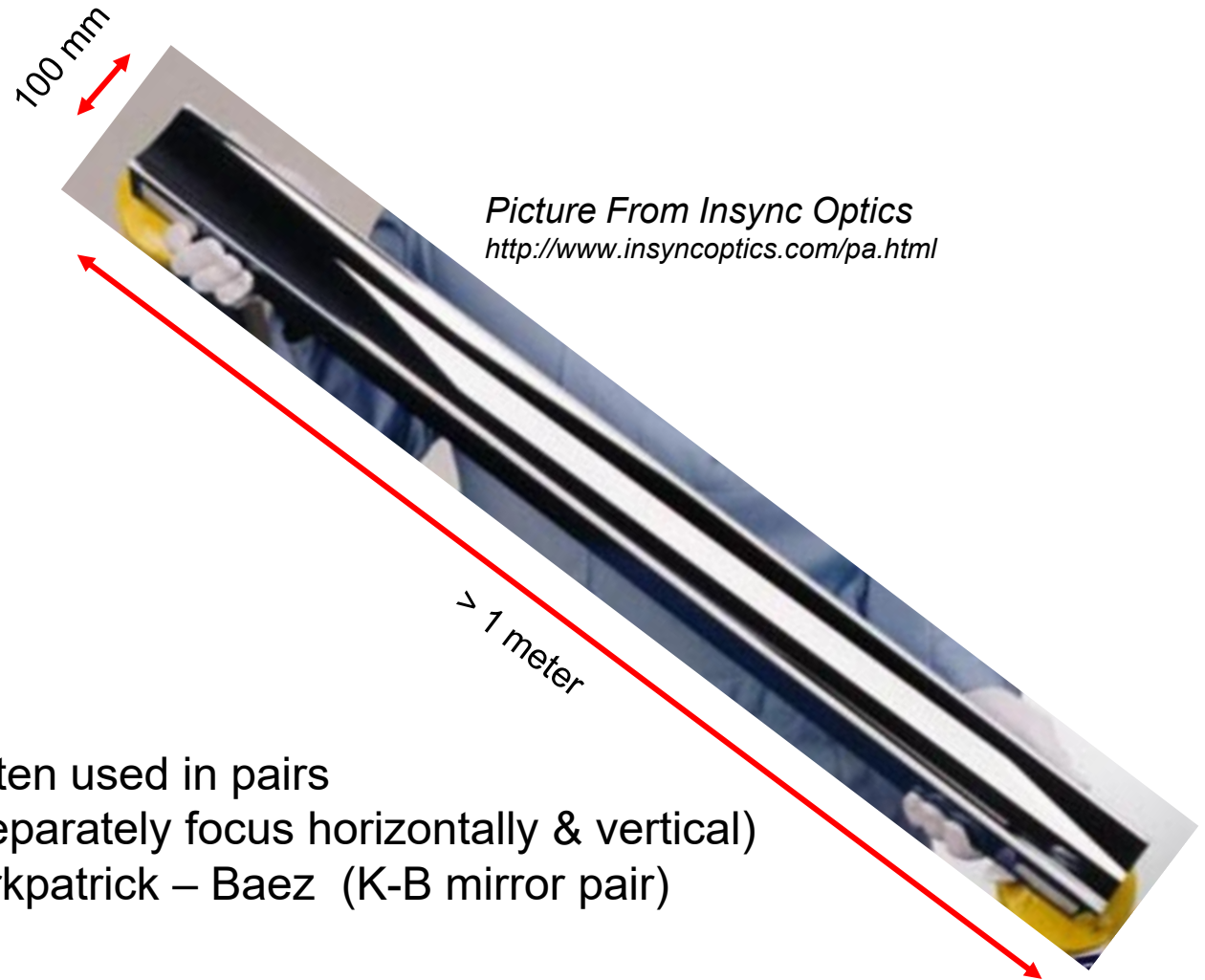
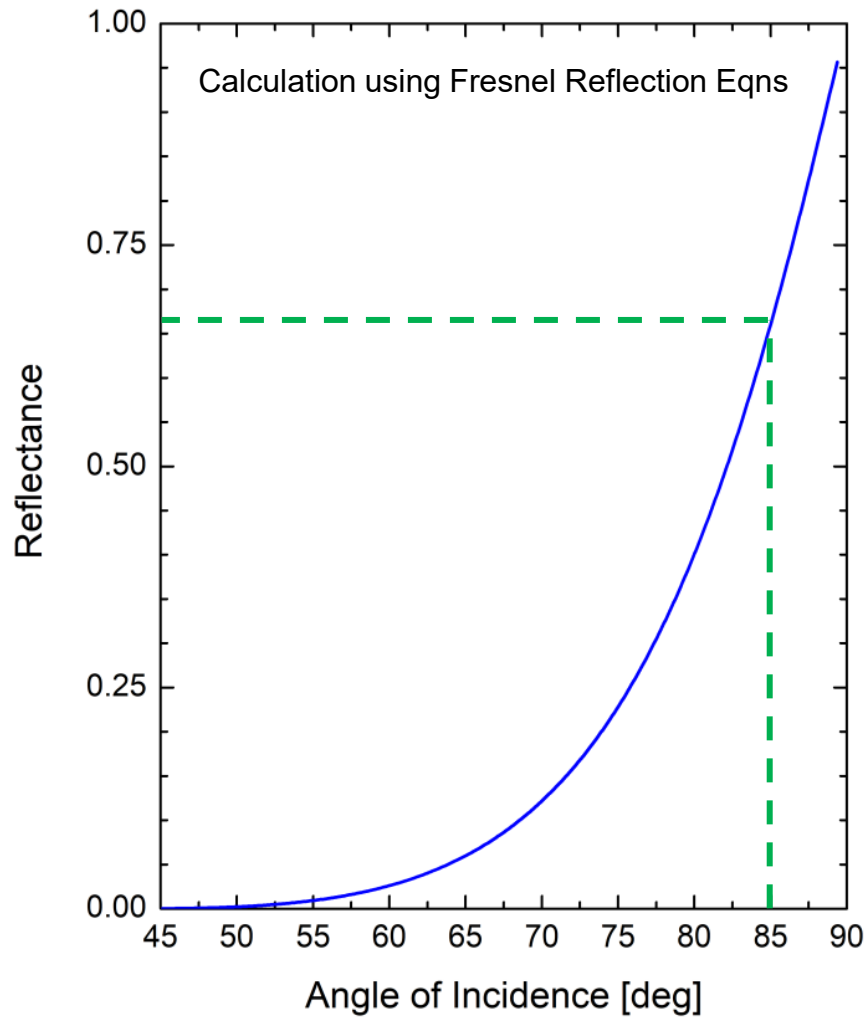
- Kirkpatrick-Baez (KB) mirror pairs
 - Grazing incidence
 - Focus vertical and horizontal separately

Transmission: Low Z elements

- Compound lenses (beryllium, diamond)
- Fresnel Zone Plates



X-ray Mirrors: Grazing Incidence



Often used in pairs
(separately focus horizontally & vertical)
Kirkpatrick – Baez (K-B mirror pair)



X-ray Lenses: Compound Refractive Lens (CRL)

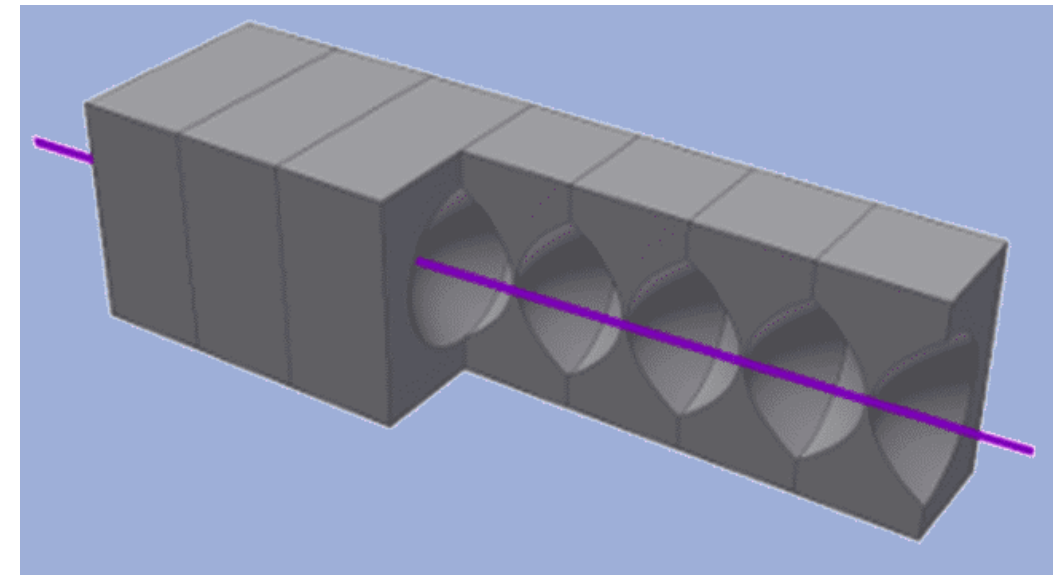
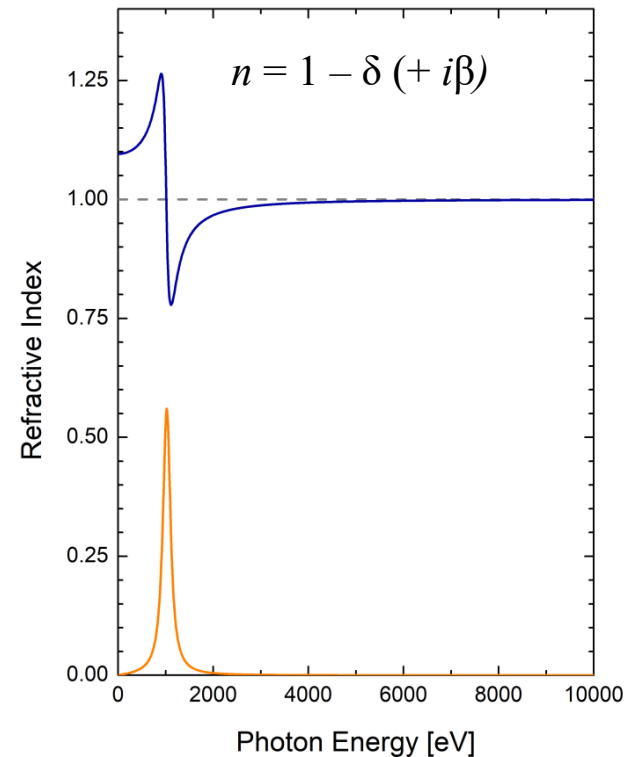
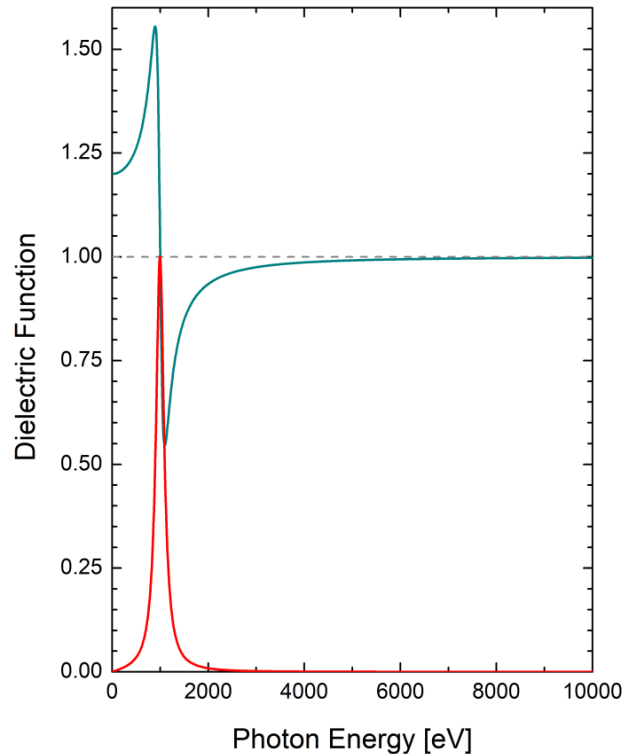
“Conventional” -> use low absorbing material
=> low Z elements: Beryllium, Carbon (Diamond)

$$f = \frac{R}{2(n-1)} = \frac{R}{2\delta} \quad \delta \sim 10^{-6}$$

but can stack *many* (e.g. N) lenses in series

$$f = \frac{R}{2\delta \cdot N} \quad \text{Can get } f < 4 \text{ m and spotsize } < 1 \mu\text{m}$$

with $N = 30$ and $R = 200 \mu\text{m}$



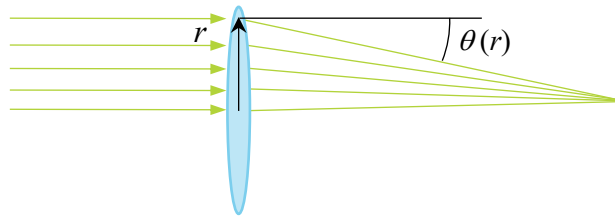
X-ray Lenses: Zone Plates

Micromachines 2020, 11(3), 301; <https://doi.org/10.3390/mi11030301>

Grating with groove spacing d diffracts light of wavelength λ into an angle θ according to

$$d \sin(\theta) = n\lambda \quad \text{or} \quad \theta \cong \frac{n\lambda}{d} \quad (\text{small angle approx.})$$

A convex lens bends light at an angle proportional to radial distance from center



⇒ make a “circular” diffraction grating with groove spacing $d \sim 1/r \rightarrow$ “Zone Plate”

Spotsize (Airy disk) $D = 1.22\lambda/\sin(\theta_{\text{MAX}})$

⇒ Special lithography methods needed make the small grating spacing d needed for D to reach nanoscale.

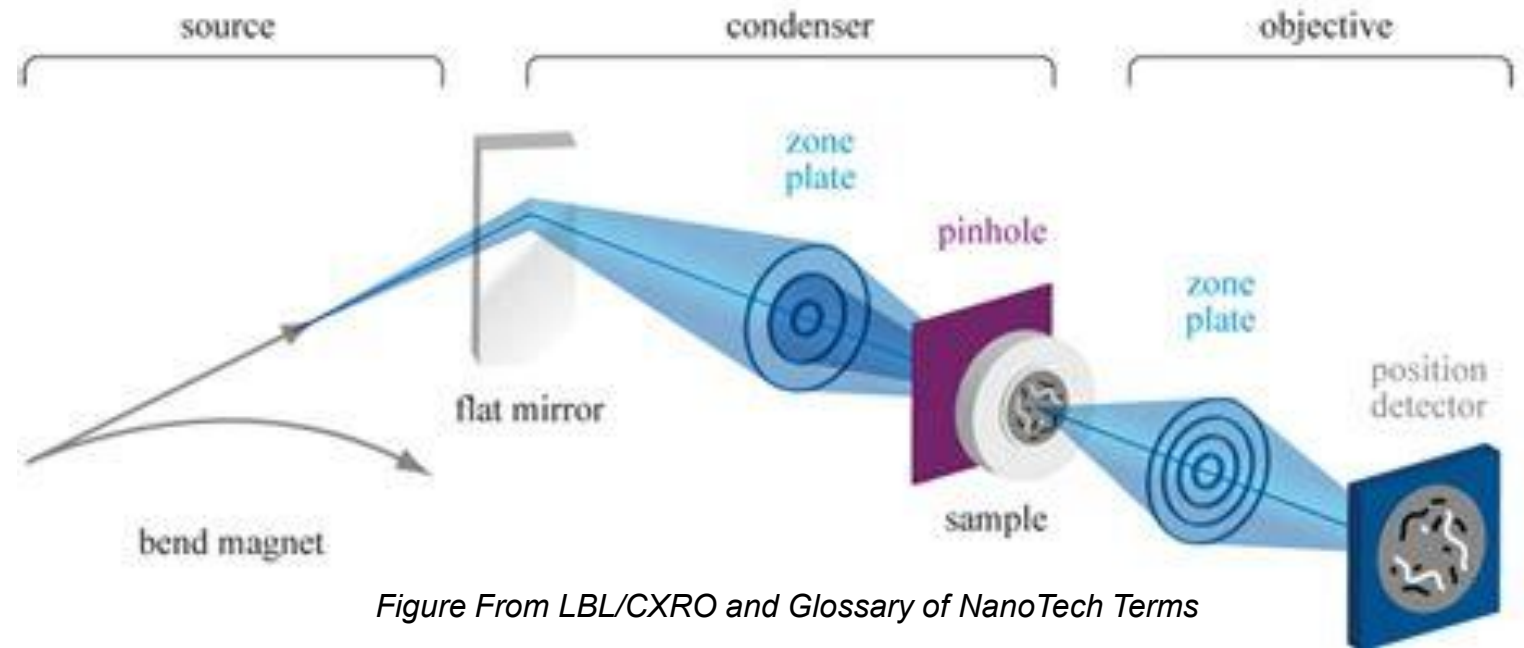
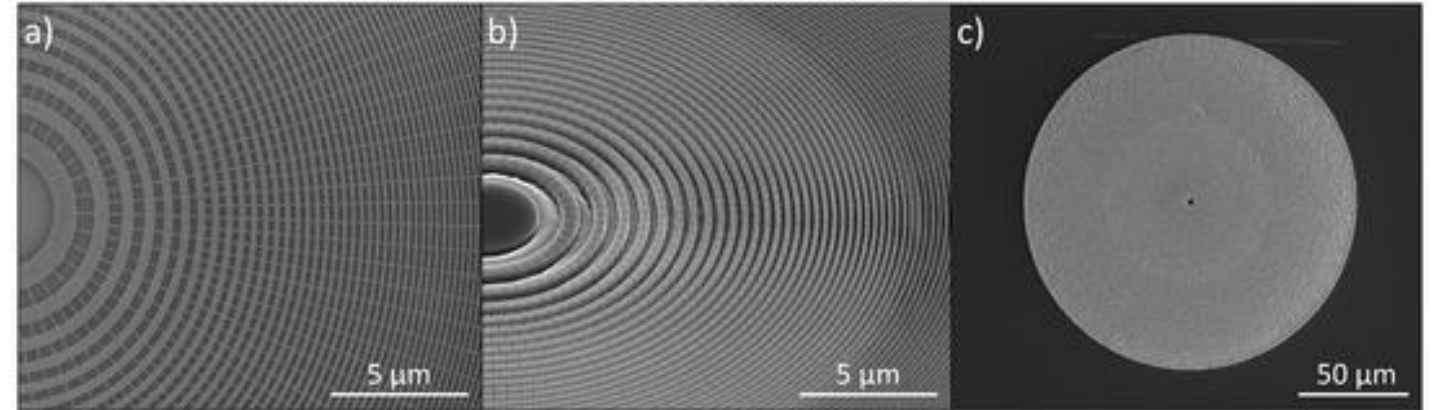


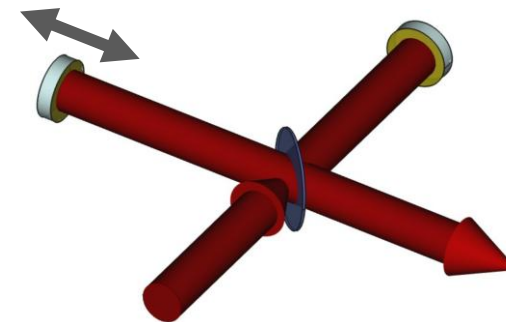
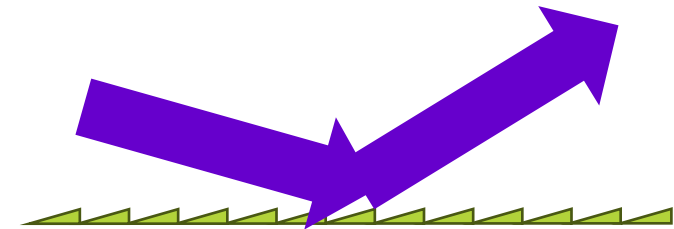
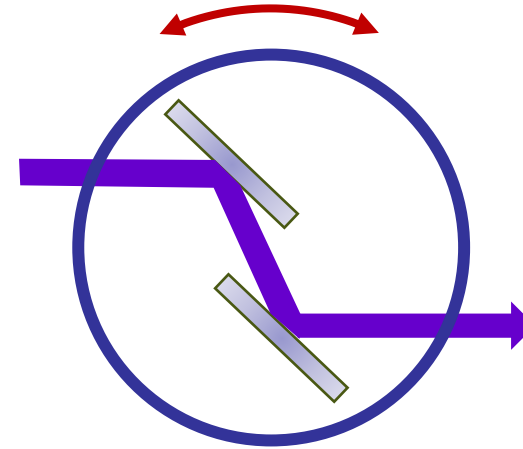
Figure From LBL/CXRO and Glossary of NanoTech Terms



Optics Instruments for Spectroscopy:

Spectrometers

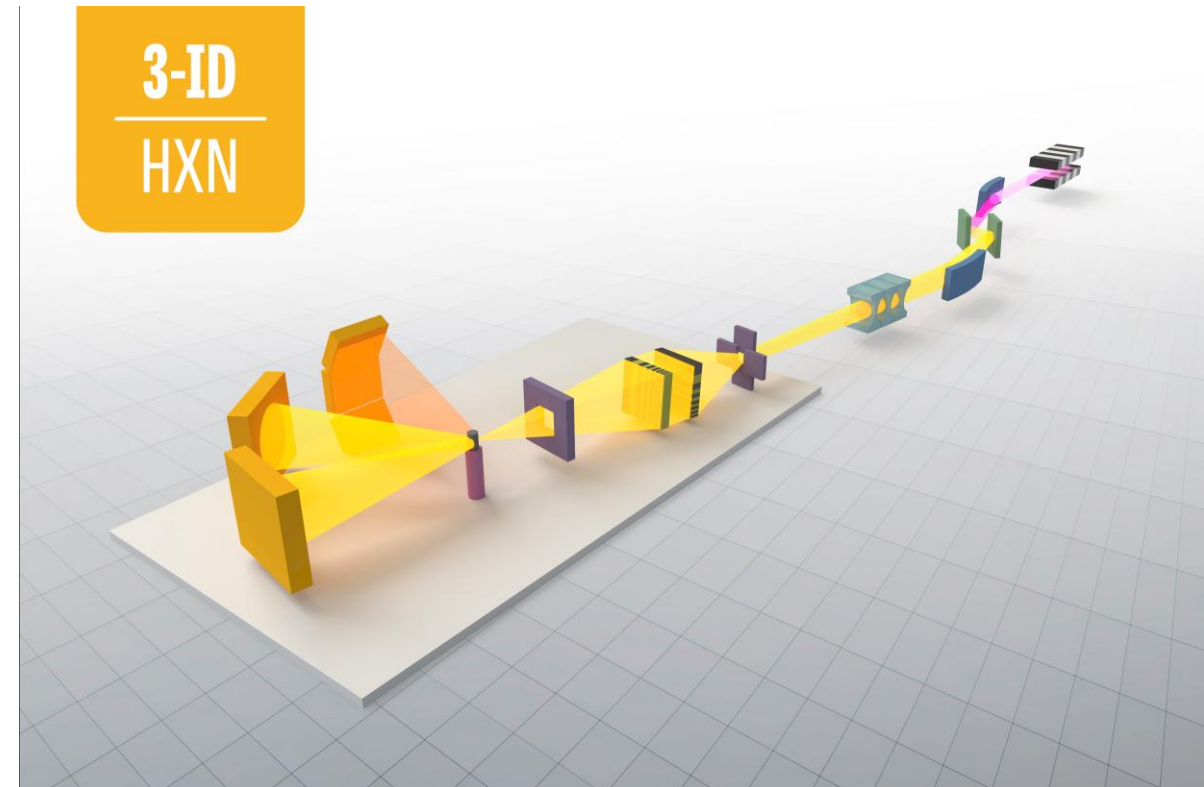
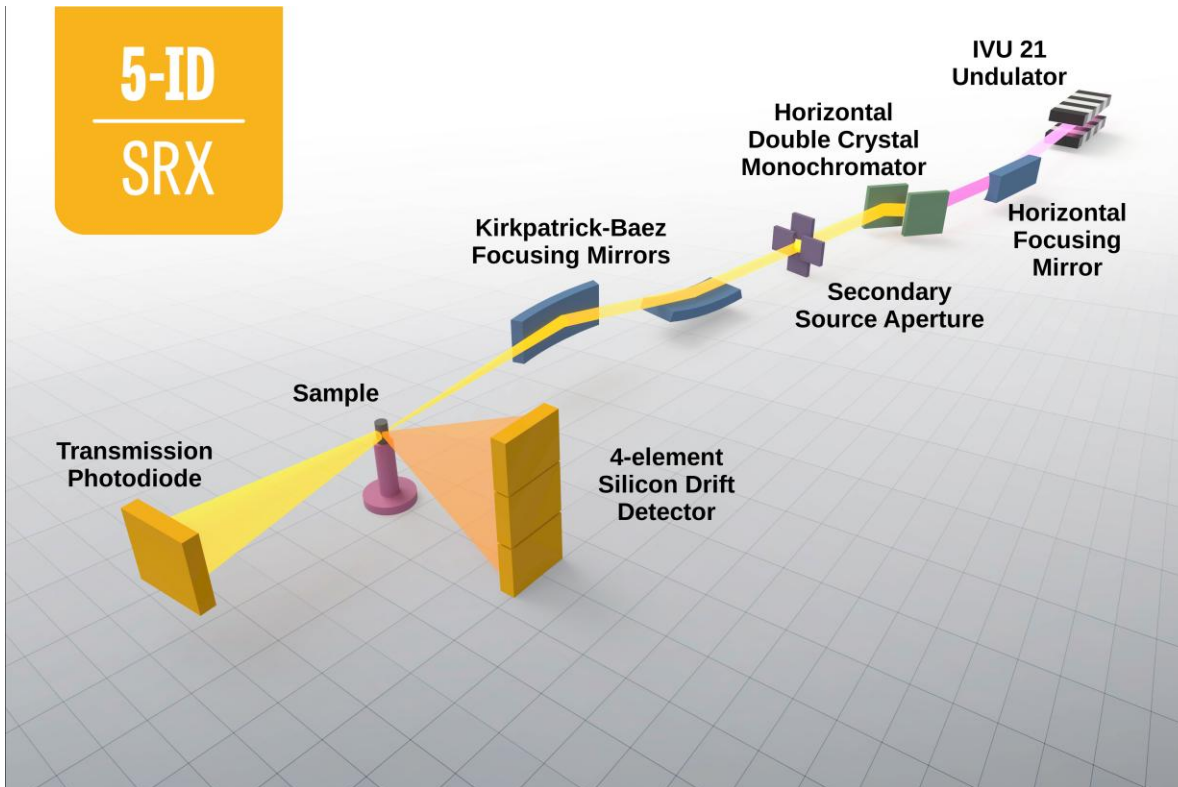
- Medium and hard X-rays: Bragg “scattering” using high quality silicon crystals – “ d ” is accurately known.
 $\lambda = 2d \cdot \sin(\theta) / m$. Tune with θ .
Do it twice (double crystal monochromator – “DCM”) for improved spectral discrimination and output direction control.
- Soft X-rays – use diffraction gratings (reflection type, at grazing incidence) $d \sin(\theta) = n\lambda$.
Can use variable grating (line) spacing to vary θ and achieve focusing.
- Infrared – Michelson type interferometers + Fourier Transform



Example Beamlines at NSLS-II for Hard X-ray Energies

Sub-micron Resolution X-ray Spectroscopy

Hard X-ray Nanoprobe

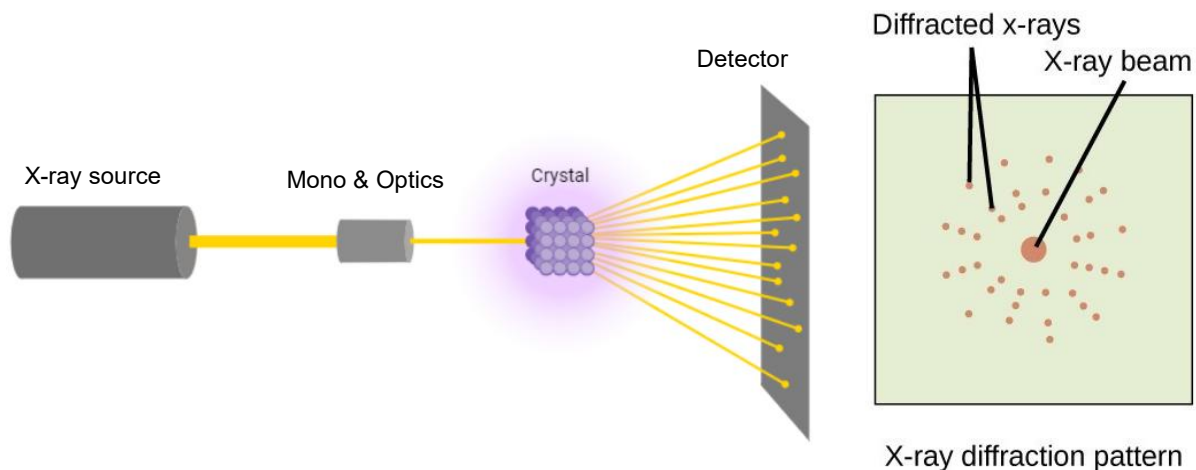
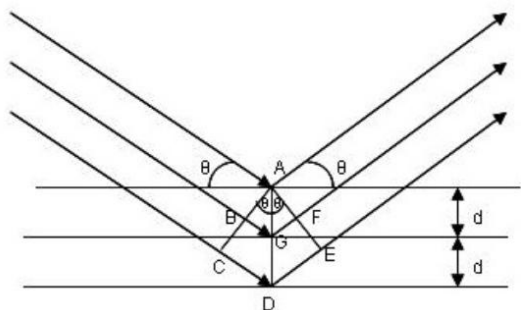


Diffraction Examples: Crystallography

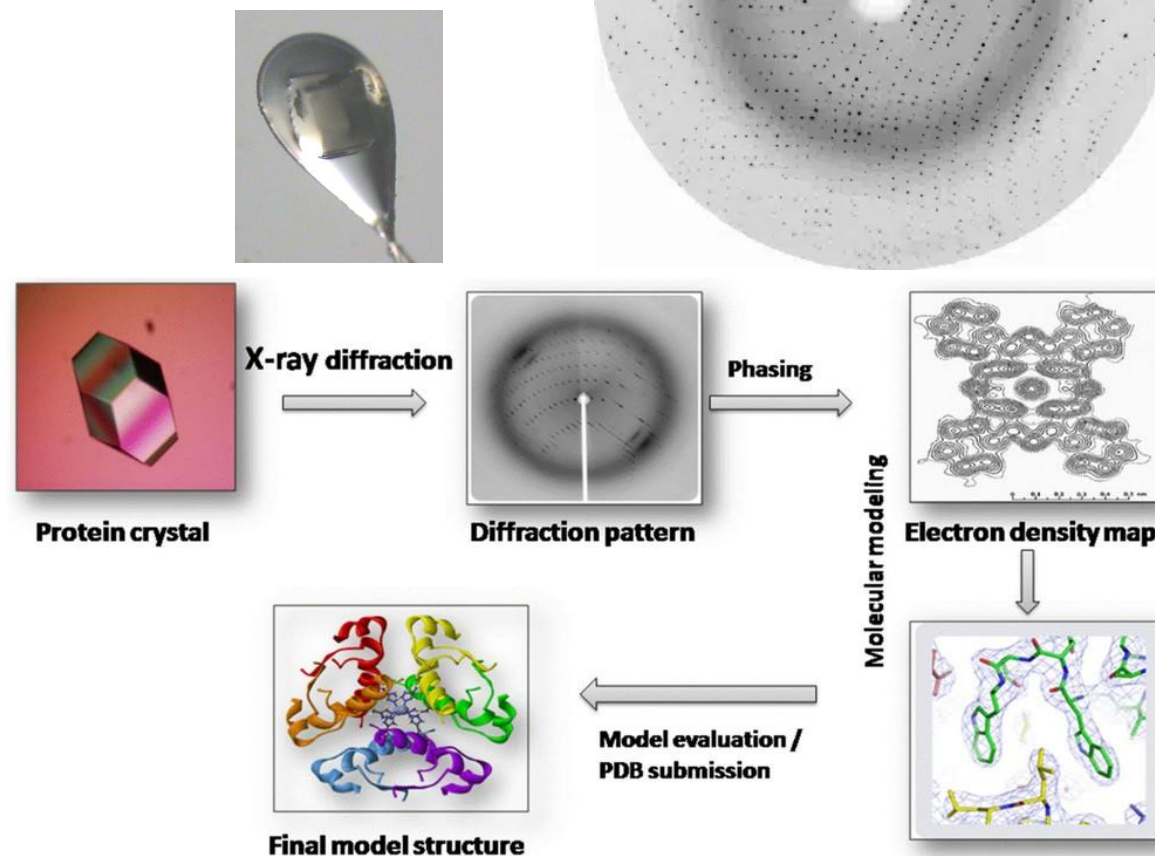
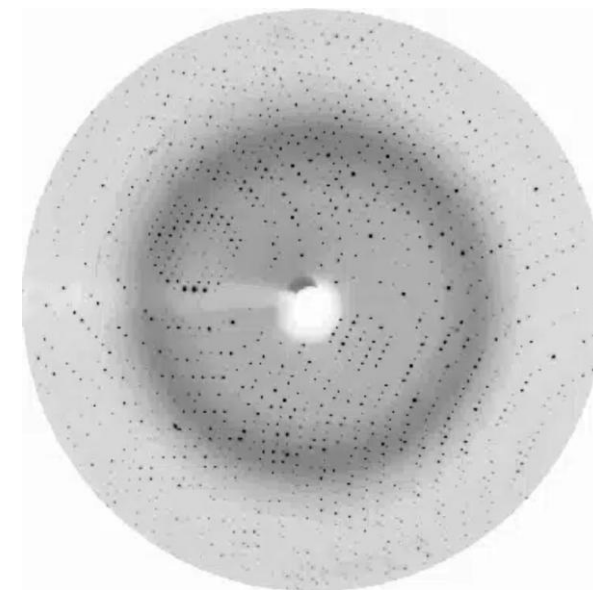
Bragg's Law: X-rays are diffracted at an angle given by

$$\sin \theta = \frac{n\lambda}{2d}$$

where d is the (atomic) layer spacing



Protein or Macromolecular Crystallography



<https://sciencevidid.com/x-ray-crystallography-introduction-workflow-braggs-law-applications/>

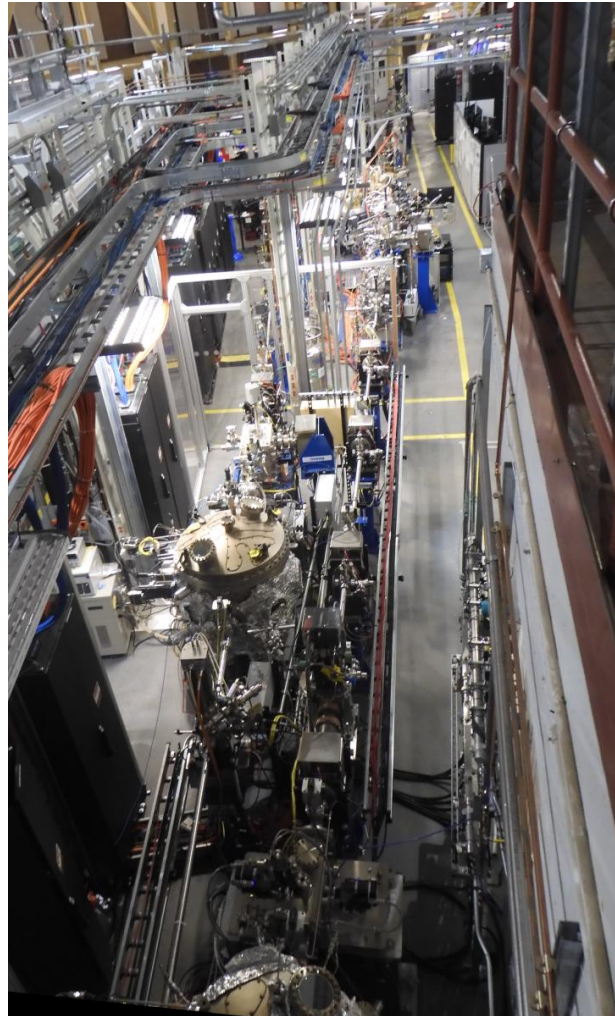
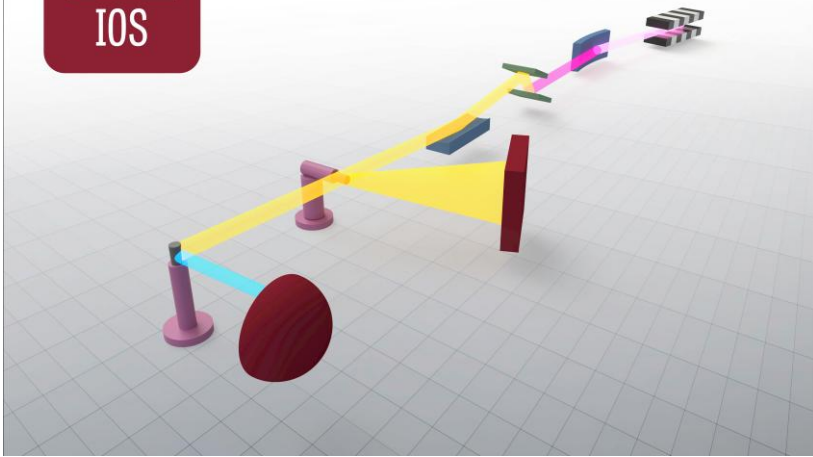
<https://www.creative-biostructure.com/protein-crystallography-452.htm>



Example Beamlines at NSLS-II for Soft X-ray Energies

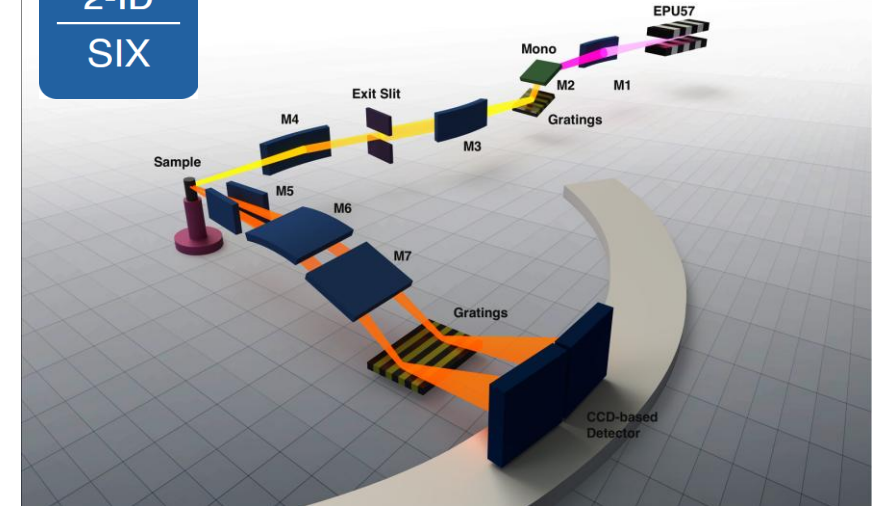
In situ and Operando Soft X-ray Spectroscopy

23-ID-2
IOS



Soft Inelastic X-ray Scattering

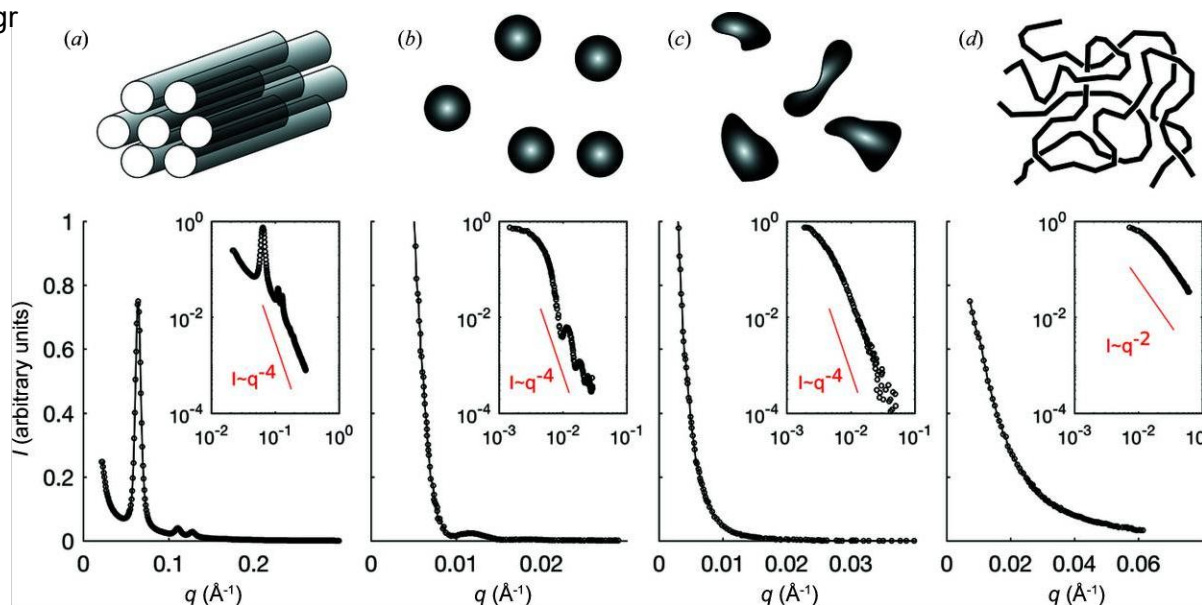
2-ID
SIX



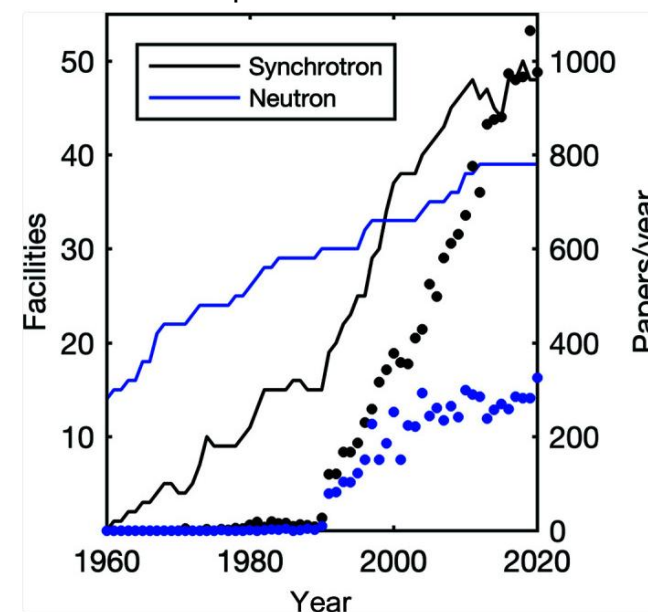
Scattering Examples: Structure and Interactions

- Materials can have structures on scales larger than atomic and crystalline
 - e.g. polymers, geological, biological ...
 - Can provide useful information on protein shapes when crystallography fails.
- Larger structure => scattering into smaller angles: Small Angle X-ray Scattering (SAXS)
 - Scattered intensity analyzed in terms of “ q ” where $q = \frac{4\pi}{\lambda} \sin\left(\frac{\theta}{2}\right)$

From Gommès et al, J Appl Crystallogr
2021 Nov 25;54(Pt 6):1832–1843.
doi: [10.1107/S1600576721010293](https://doi.org/10.1107/S1600576721010293)

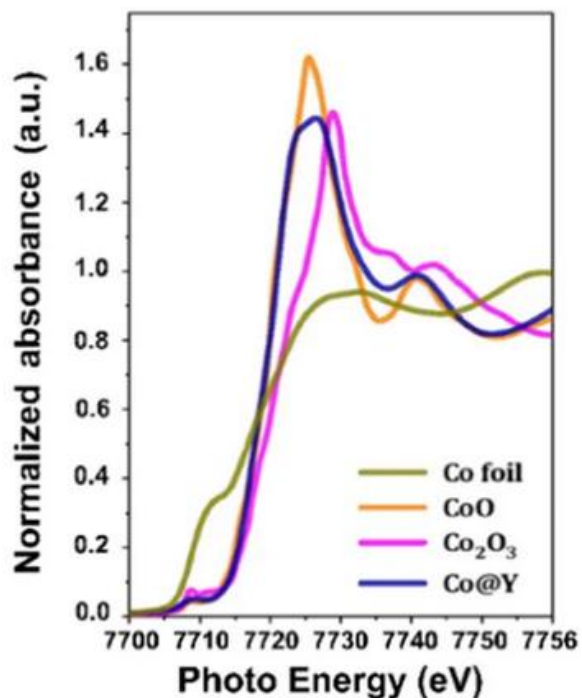


Note rapid growth of technique with availability of synchrotron facilities, large area detectors and computational facilities

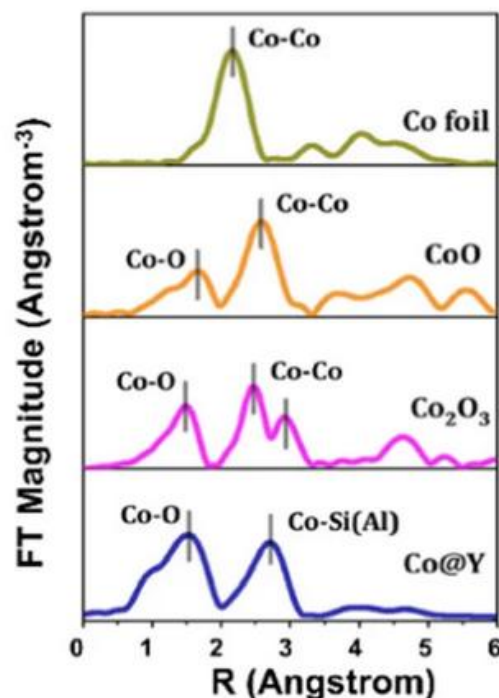


Spectroscopy Examples: Absorption, Photoemission

X-ray absorption spectra (XAS) showing XANES and EXAFS

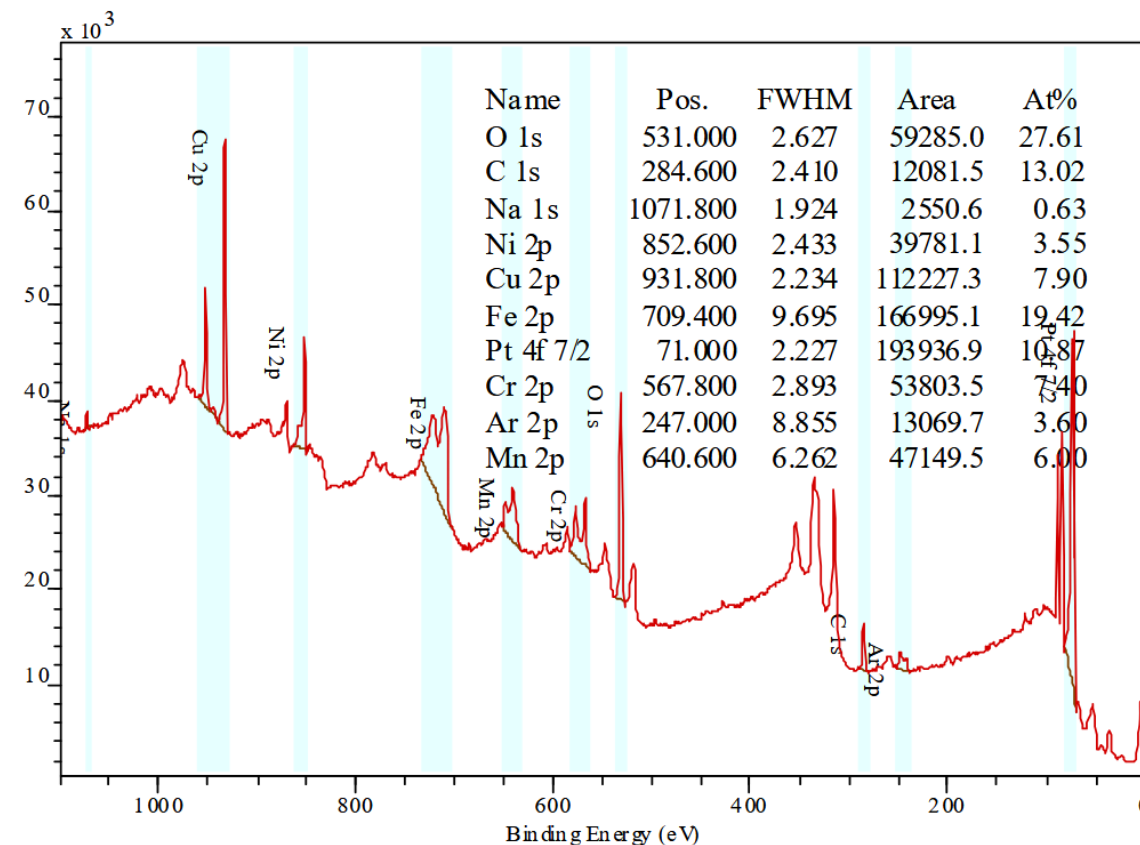


M. Liu et al, Industrial Chemistry & Materials (2023)



DOI:10.1039/D3IM00074E

X-ray Photoemission Spectroscopy (XPS)



CasaXPS (Washington State University, Pullman, Wa)

https://public.archive.wsu.edu/scudiero/public_html/documents/Examples.pdf



Summary

- Synchrotron Light Sources serve a wide and diverse range of measurement methods that are used by scientists from almost all disciplines.
- National Synchrotron Light Source II is one of four DOE synchrotron light sources
 - Advanced Photon Source @ Argonne NL, Advanced Light Source @ Berkeley Lab, Stanford Synchrotron Light Source @ SLAC
 - Others (non-DOE): Cornell High Energy Synchrotron Source (CHESS @ Cornell), Center for Advanced Microelectronic Devices (CAMD at LSU), Synchrotron Ultraviolet Radiation Facility (SURF III at NIST).
- Next Generation of synchrotron light sources (APS-U, ALS-U, NSLS-IIU)
 - Will have even smaller electron beams to yield diffraction-limited performance => Advanced scattering methods that utilize transverse coherence, e.g. X-ray speckle imaging, dynamics, ...

