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Advanced School on Synchrotron and Free Electron Laser Sources and their Multidisciplinary Applications

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X-Ray Transport and Tailoring Optics: Mirrors and Gratings

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X-Ray Transport and Tailoring Optics: Mirrors and Gratings

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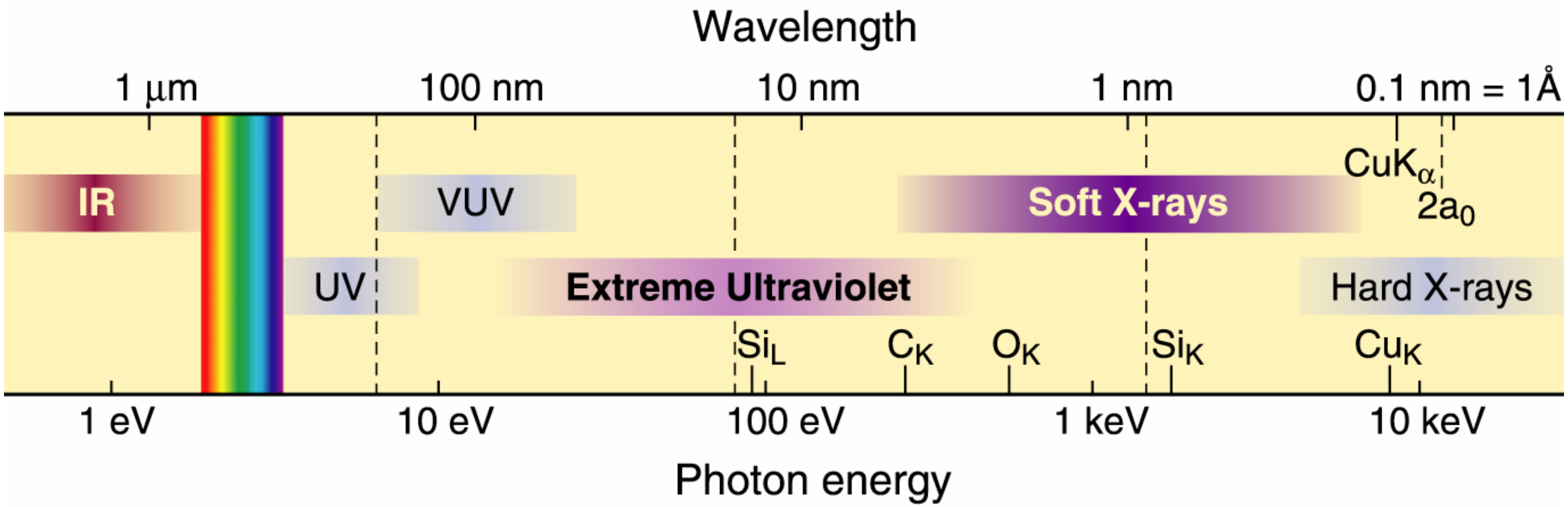
The Short Wavelength Region of the Electromagnetic Spectrum

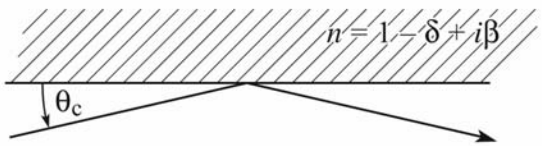


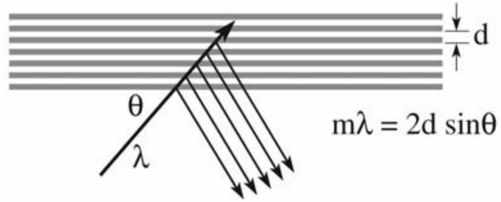
- **See smaller features**
- **Write smaller patterns**
- **Elemental and chemical sensitivity**

$$\hbar\omega \cdot \lambda = hc = 1239.842 \text{ eV nm} \quad (1.1)$$

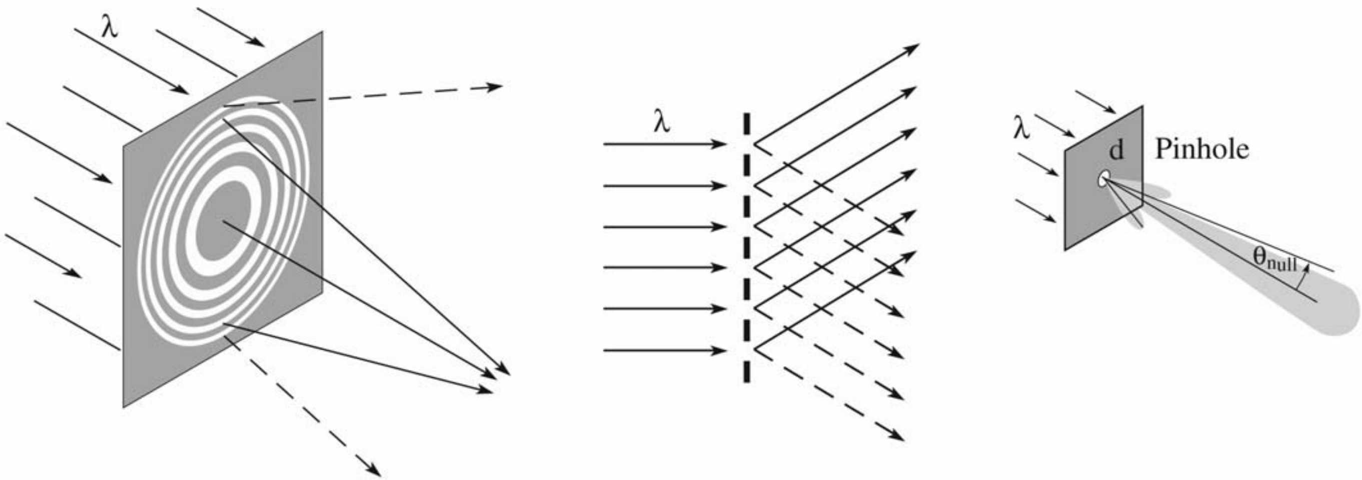
Available Optical Techniques for Soft X-Rays and EUV

- Reflection (glancing incidence or multilayer coatings)

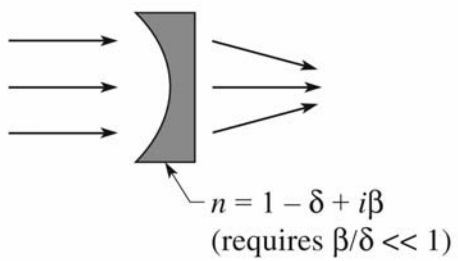


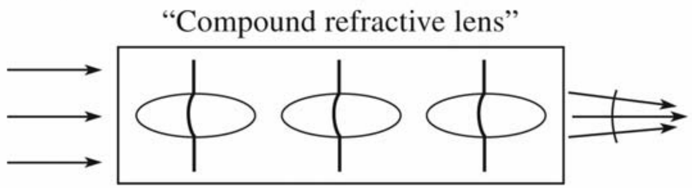


- Diffraction (zone plates, gratings, pinholes)



- Refraction (only for hard x-rays, > 20 keV)





A. Snigerev et al., *Nature* 384, 49 (7Nov.1996)
B. Lengeler et al., *J. Appl. Phys.* 84, 5855 (1Dec.1998)

AvaiOpticTechSXREUV.ai

Refractive Index

$$n = 1 - \delta + i\beta = \frac{n_a r_e \lambda^2}{2\pi}\; 1 - (f_1^0 - i f_2^0)$$

Atomic scattering factor (scattered electric field relative to single free electron)

$f \rightarrow f^0$ for $\lambda >> a_0$, or $\theta = 0$ (forward scattering)

Atomic scattering cross-section

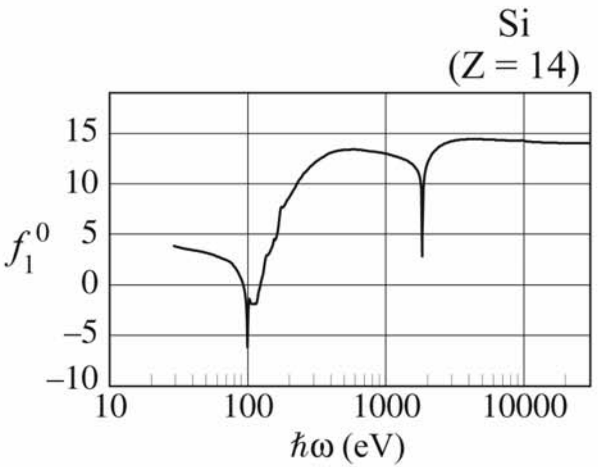
$$\sigma = \frac{8\pi}{3} r_e^2 \sum_s \frac{\omega^4}{(\omega^2 - \omega_s^2) - \gamma^2\omega^2} = \frac{8\pi}{3} r_e^2 (f_1^{0^2} + f_2^{0^2}) = \frac{8\pi}{3} r_e^2 |f^0|^2$$

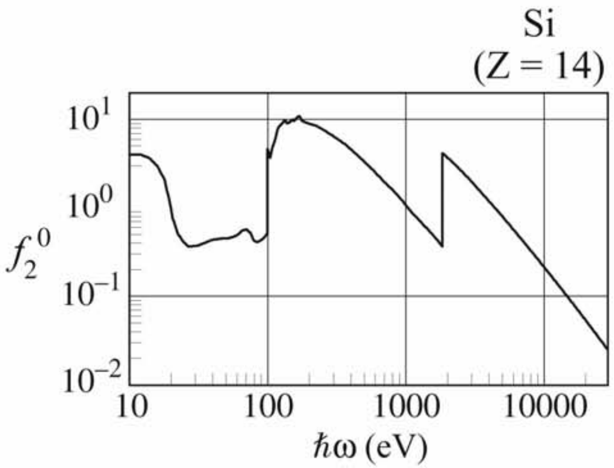
Thomson: $\omega^2 >> \omega_s^2$

$$\sigma_T = \frac{8\pi}{3} r_e^2$$

Rayleigh: $\omega^2 << \omega_s^2$

$$\sigma_R = \frac{8\pi}{3} r_e^2 \left[\frac{\lambda_s}{\lambda}\right]^4$$





Note:

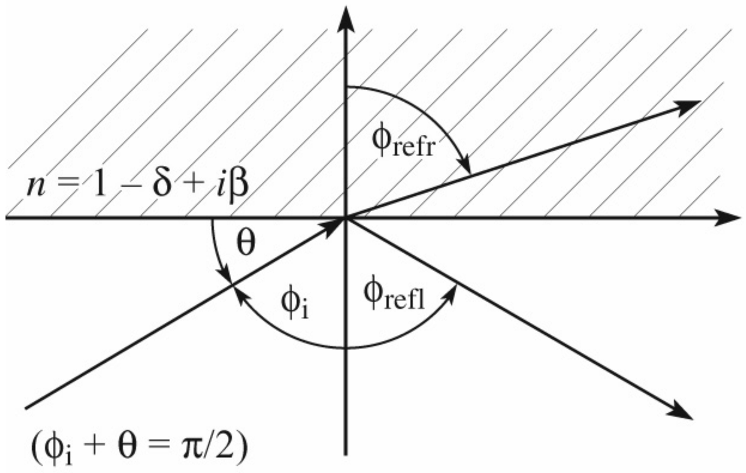
for $\lambda >> a_0$, and $\omega^2 >> \omega_s^2$

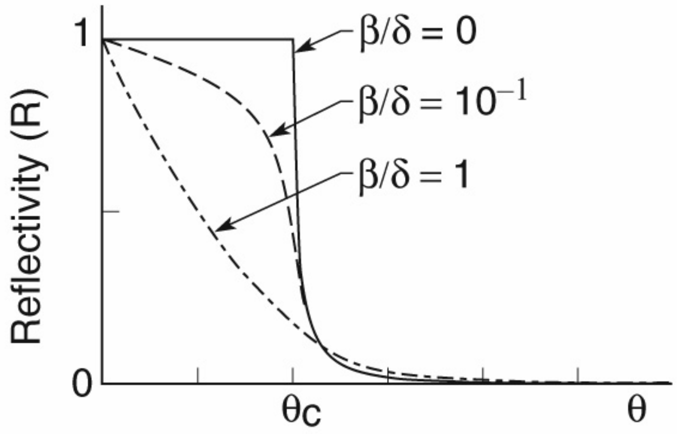
$f_1^0 \rightarrow Z$

$f_2^0 \rightarrow 0$

ScattrngRefracIndex.ai

Glancing Incidence Optics





Snell's Law: $\sin \phi_{refr.} = \dfrac{\sin \phi_i}{n}$

Total external Reflection:

$$\phi_{refr.} \rightarrow \frac{\pi}{2} \quad \text{as } \phi_i \rightarrow \phi_{critical}$$

$$\text{Snell's Law: } 1 = \frac{\sin \phi_c}{1 - \delta}$$

$$\sin(90° - \theta_c) = 1 - \delta$$

$$\cos \theta_c = 1 - \delta$$

$$1 - \frac{\theta_c^{\,2}}{2} = 1 - \delta$$

$$\theta_c = \sqrt{2\delta}$$

For gold at 1 keV

$$\delta = 2.1 \times 10^{-3}$$

$$\theta_c = 3.7°$$

(www.cxro.LBL.gov ;
"X-ray properties of the elements"
"X-ray interaction with matter")

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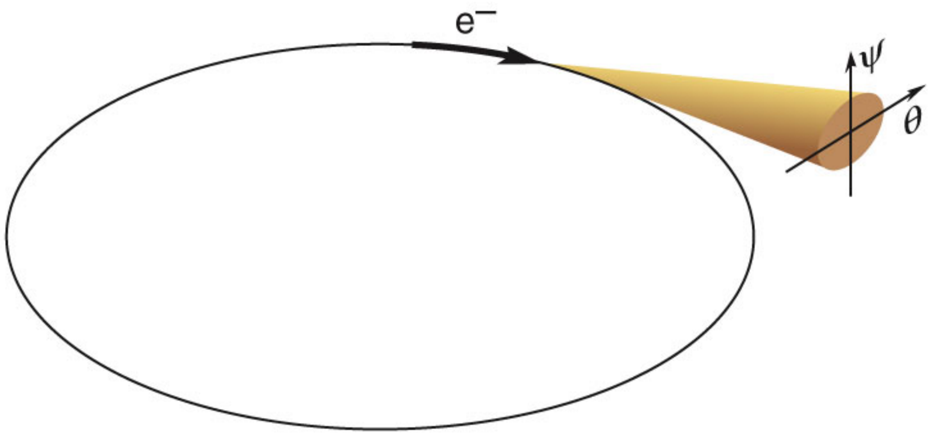
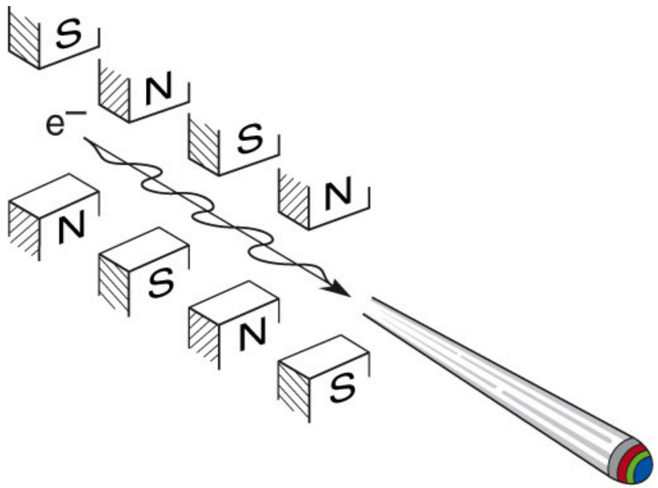
Bright and Powerful X-Rays from Relativistic Electrons



Synchrotron radiation

- 10^{10} brighter than the most powerful (compact) laboratory source
- An x-ray “light bulb” in that it radiates all “colors” (wavelengths, photons energies)

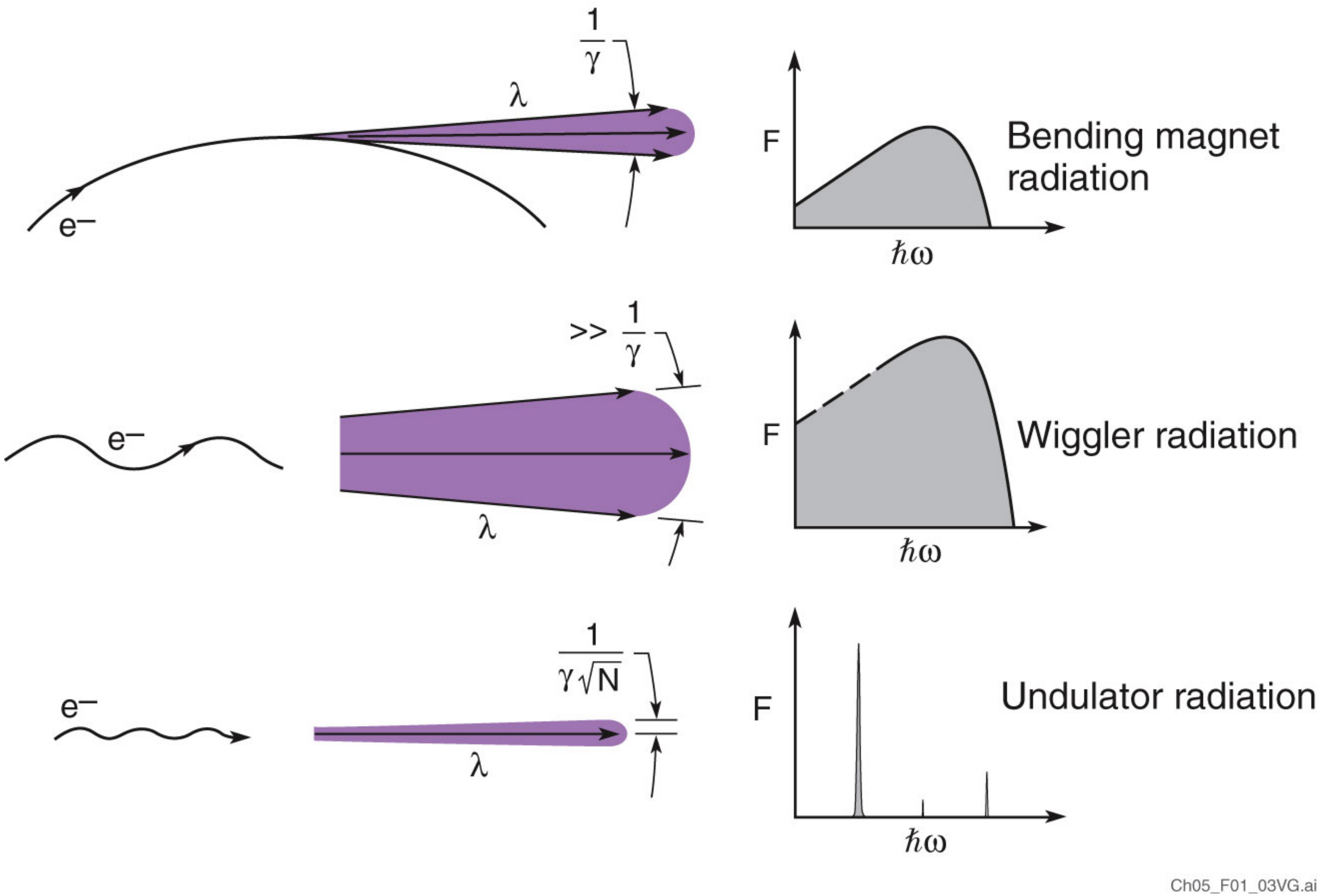


Undulator radiation

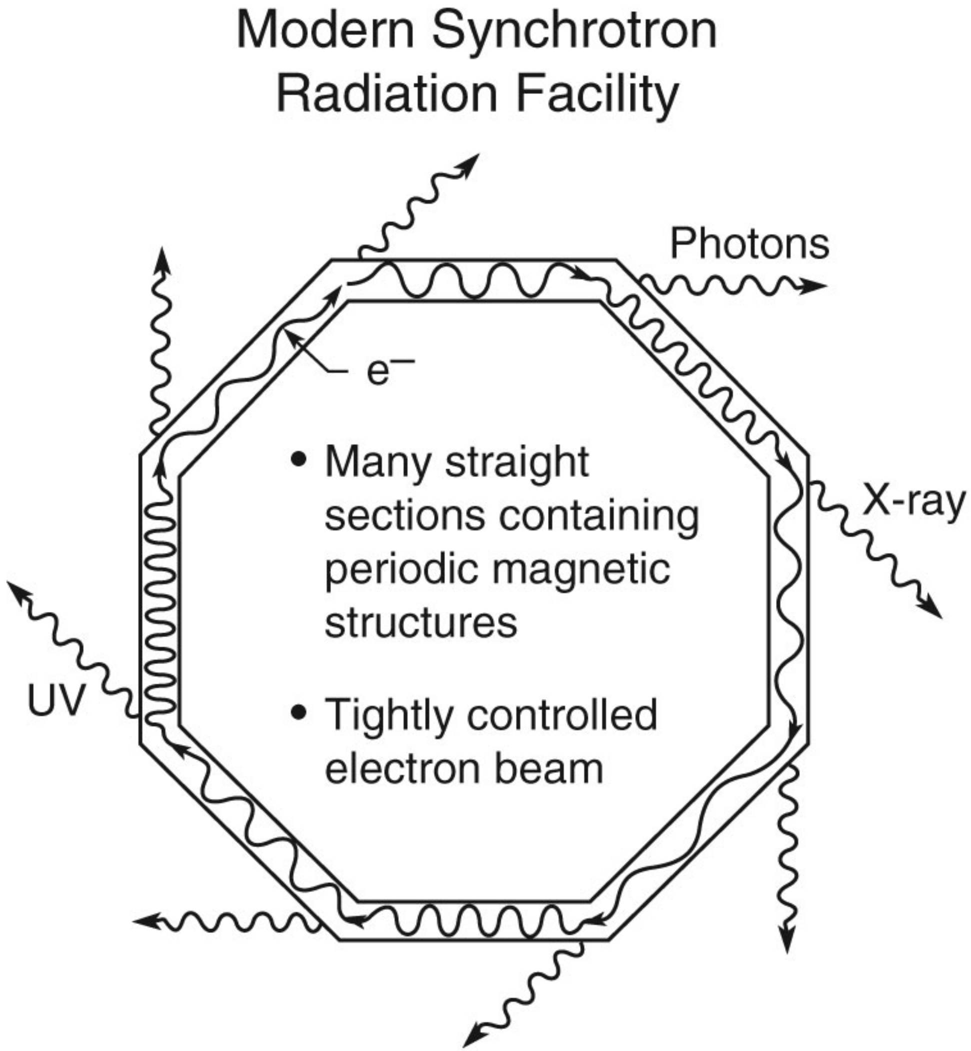
- Lasers exist for the IR, visible, UV, VUV, and EUV
- Undulator radiation is quasi-monochromatic and highly directional, approximating many of the desired properties of an x-ray laser

BrightPowrfulXRs.ai

Three Forms of Synchrotron Radiation



Third Generation Facilities, Like Elettra, Have Many Straight Sections and a Small Electron Beam



- Many straight sections for undulators and wigglers
- Brighter radiation for spatially resolved studies (smaller beam more suitable for microscopies)
- Interesting coherence properties at very short wavelengths

3rdGenFacilitiesrev3.04.ai

Third Generation Synchrotron Facilities

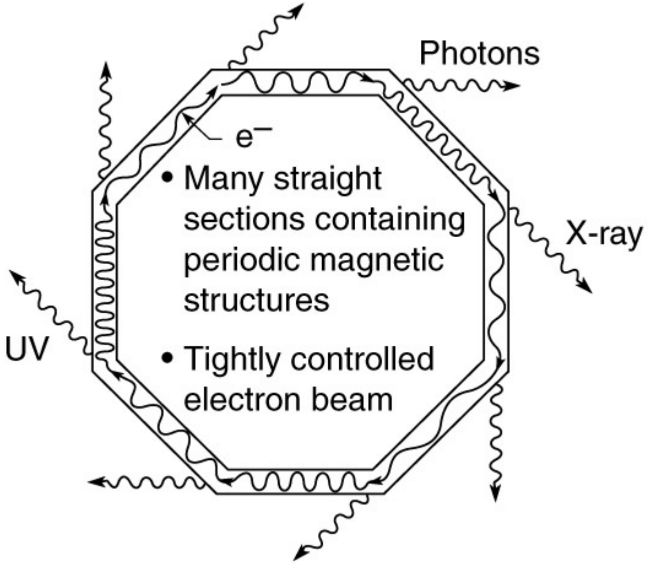
ESRF	6 GeV	France
ALS	1.9 GeV	USA
APS	7 GeV	USA
BESSY II	1.7 GeV	Germany
ELETTRA	2.0 GeV	Italy
SPring-8	8 GeV	Japan
MAX II	1.5 GeV	Sweden
SLS	2.4 GeV	Switzerland
PLS	2 GeV	Korea
SRRC	1.4 GeV	Taiwan
SSRL	3 GeV	USA
CLS	2.9 GeV	Canada
Soleil	2.5 GeV	France
Diamond	3 GeV	UK
Australian Light Source	3 GeV	Australia

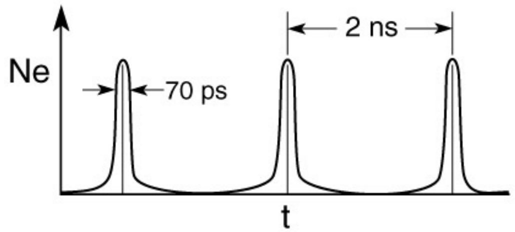
Facilities Under Construction

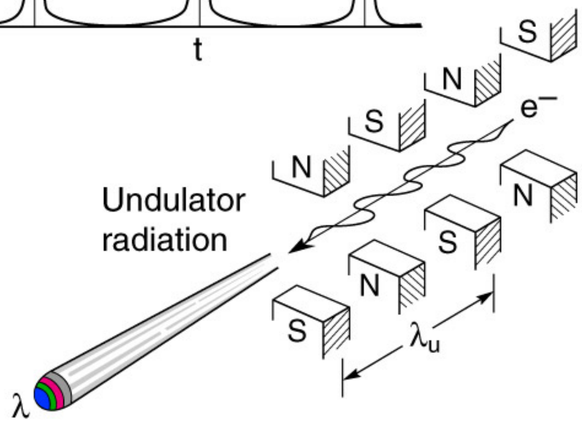
Alba	2 GeV	Barcelona

3rdGenSynchFacil_Jan08.ai

Synchrotron Radiation







Bending Magnet:

$$\hbar\omega_c = \frac{3e\hbar B\gamma^2}{2m} \quad (5.7)$$

Wiggler:

$$\hbar\omega_c = \frac{3e\hbar B\gamma^2}{2m} \quad (5.80)$$

$$n_c = \frac{3K}{4}\left(1 + \frac{K^2}{2}\right) \quad (5.82)$$

$$P_T = \frac{\pi e K^2 \gamma^2 I N}{3\epsilon_0 \lambda_u} \quad (5.85)$$

Undulator:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \quad (5.28)$$

$$K = \frac{eB_0\lambda_u}{2\pi mc} \quad (5.18)$$

$$\theta_{\text{cen}} = \frac{1}{\gamma^*\sqrt{N}} \quad (5.15)$$

$$\left.\frac{\Delta\lambda}{\lambda}\right|_{\text{cen}} = \frac{1}{N} \quad (5.14)$$

$$\bar{P}_{\text{cen}} = \frac{\pi e \gamma^2 I}{\epsilon_0 \lambda_u} \frac{K^2}{\left(1 + \frac{K^2}{2}\right)^2} f(K) \quad (5.41)$$

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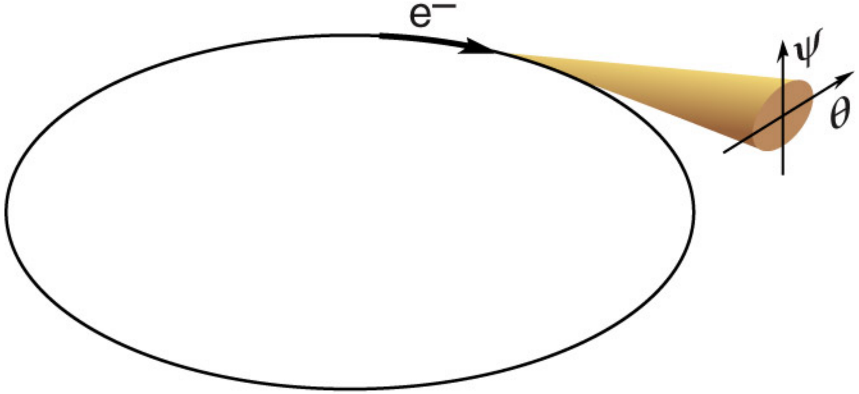
Bending Magnet Radiation Covers a Broad Region of the Spectrum, Including the Primary Absorption Edges of Most Elements



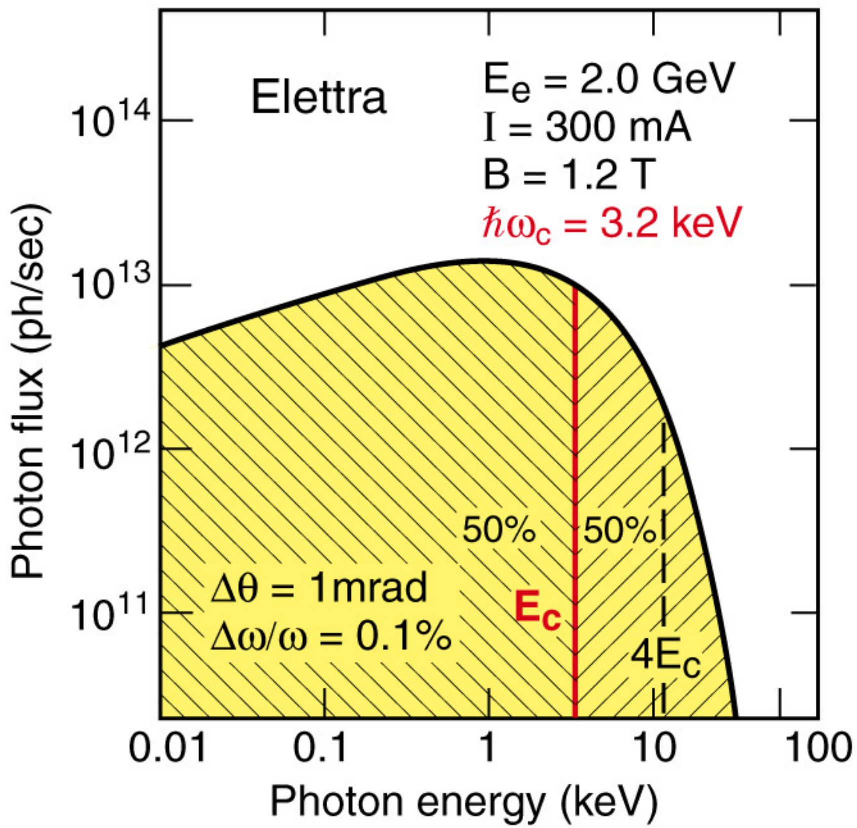
$$E_c = \hbar\omega_c = \frac{3e\hbar B\gamma^2}{2m} \qquad (5.7a)$$

$$E_c(\text{keV}) = 0.6650 E_e^2(\text{GeV}) B(\text{T}) \qquad (5.7b)$$

$$\gamma = \frac{E_e}{mc^2} = 1957 E_e(\text{GeV}) \qquad (5.5)$$

Advantages:
- covers broad spectral range
- least expensive
- most accessable

Disadvantages:
- limited coverage of hard x-rays
- not as bright as undulator



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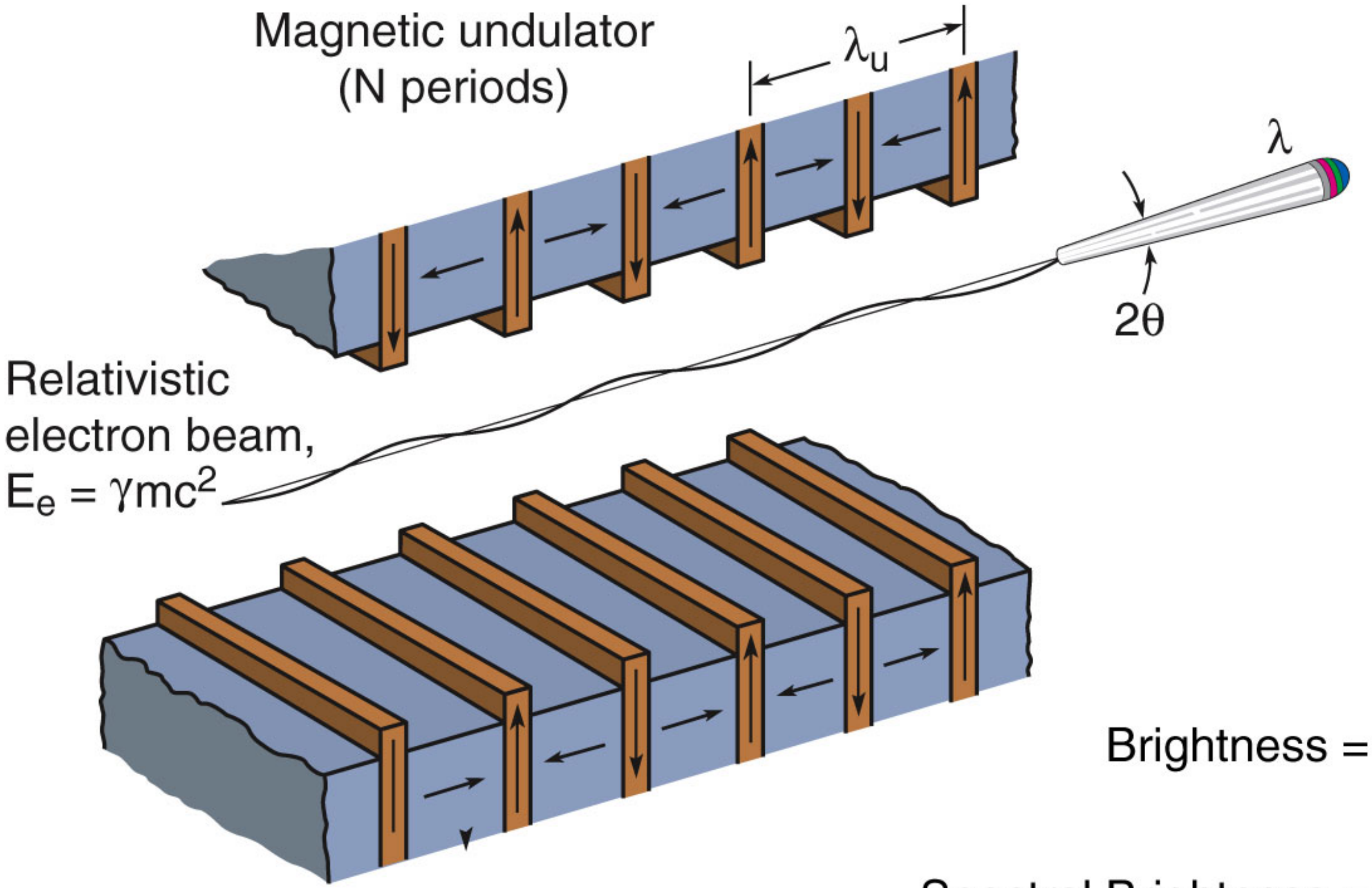
Undulator Radiation from a Small Electron Beam Radiating into a Narrow Forward Cone is Very Bright



$$\lambda \simeq \frac{\lambda_u}{2\gamma^2}$$

$$\theta_{cen} \simeq \frac{1}{\gamma\sqrt{N}}$$

$$\left[\frac{\Delta\lambda}{\lambda}\right]_{cen} = \frac{1}{N}$$

$$\text{Brightness} = \frac{\text{photon flux}}{(\Delta A)\,(\Delta\Omega)}$$

$$\text{Spectral Brightness} = \frac{\text{photon flux}}{(\Delta A)\,(\Delta\Omega)\,(\Delta\lambda/\lambda)}$$

Ch05_F08VG_1.04.ai

Typical Parameters for Synchrotron Radiation

Facility	ALS	ELETTRA	ESRF	APS
Electron energy	1.90 GeV	2.0 GeV	6.04 GeV	7.00 GeV
γ	3720	3910	11,800	13,700
Current (mA)	400	300	200	100
Circumference (m)	197	259	884	1100
RF frequency (MHz)	500	500	352	352
Pulse duration (FWHM) (ps)	35-70	37	70	100
Bending Magnet Radiation:				
Bending magnet field (T)	1.27	1.2	0.806	0.599
Critical photon energy (keV)	3.05	3.2	19.6	19.5
Critical photon wavelength	0.407 nm	0.39 nm	0.634 Å	0.636 Å
Bending magnet sources	24	12	32	35
Undulator Radiation:				
Number of straight sections	12	12	32	40
Undulator period (typical) (cm)	5.00	5.6	4.20	3.30
Number of periods	89	81	38	72
Photon energy ($K = 1$, $n = 1$)	457 eV	452 eV	5.50 keV	9.40 keV
Photon wavelength ($K = 1$, $n = 1$)	2.71 nm	2.74 nm	0.225 nm	1.32 Å
Tuning range ($n = 1$)	230-620 eV	2.0-6.7 nm	2.6-7.3 keV	3.5-12 keV
Tuning range ($n = 3$)	690-1800 eV	0.68-2.2 nm	7.7-22 keV	10-38 keV
Central cone half-angle ($K = 1$)	35 μrad	35 μrad	17 μrad	11 μrad
Power in central cone ($K = 1$, $n = 1$) (W)	2.3	1.7	14	12
Flux in central cone (photons/s)	3.1×10^{16}	2.3×10^{16}	1.6×10^{16}	7.9×10^{15}
σ_x, σ_y (μm)	260, 16	255, 23	395, 9.9	320, 50
σ'_x, σ'_y (μrad)	23, 3.9	31, 9	11, 3.9	23, 7
Brightness ($K = 1$, $n = 1$)[a] [(photons/s)/mm^2 · mrad^2 · (0.1%BW)]	2.3×10^{19}	9.9×10^{18}	5.1×10^{18}	5.9×10^{18}
Total power ($K = 1$, all n, all θ) (W)	83	126	480	350
Other undulator periods (cm)	3.65, 8.00, 10.0	8.0, 12.5	2.3, 3.2, 5.2, 8.5	2.70, 5.50, 12.8
Wiggler Radiation:				
Wiggler period (typical) (cm)	16.0	14.0	8.0	8.5
Number of periods	19	30	20	28
Magnetic field (maximum) (T)	2.1	1.5	0.81	1.0
K (maximum)	32	19.6	6.0	7.9
Critical photon energy (keV)	5.1	4.0	20	33
Critical photon wavelength	0.24 nm	0.31 nm	0.62 Å	0.38 Å
Total power (max. K) (kW)	13	7.2	4.8	7.4

[a]Using Eq. (5.65). See comments following Eq. (5.64) for the case where $\sigma'_{x,y} \simeq \theta_{cen}$.

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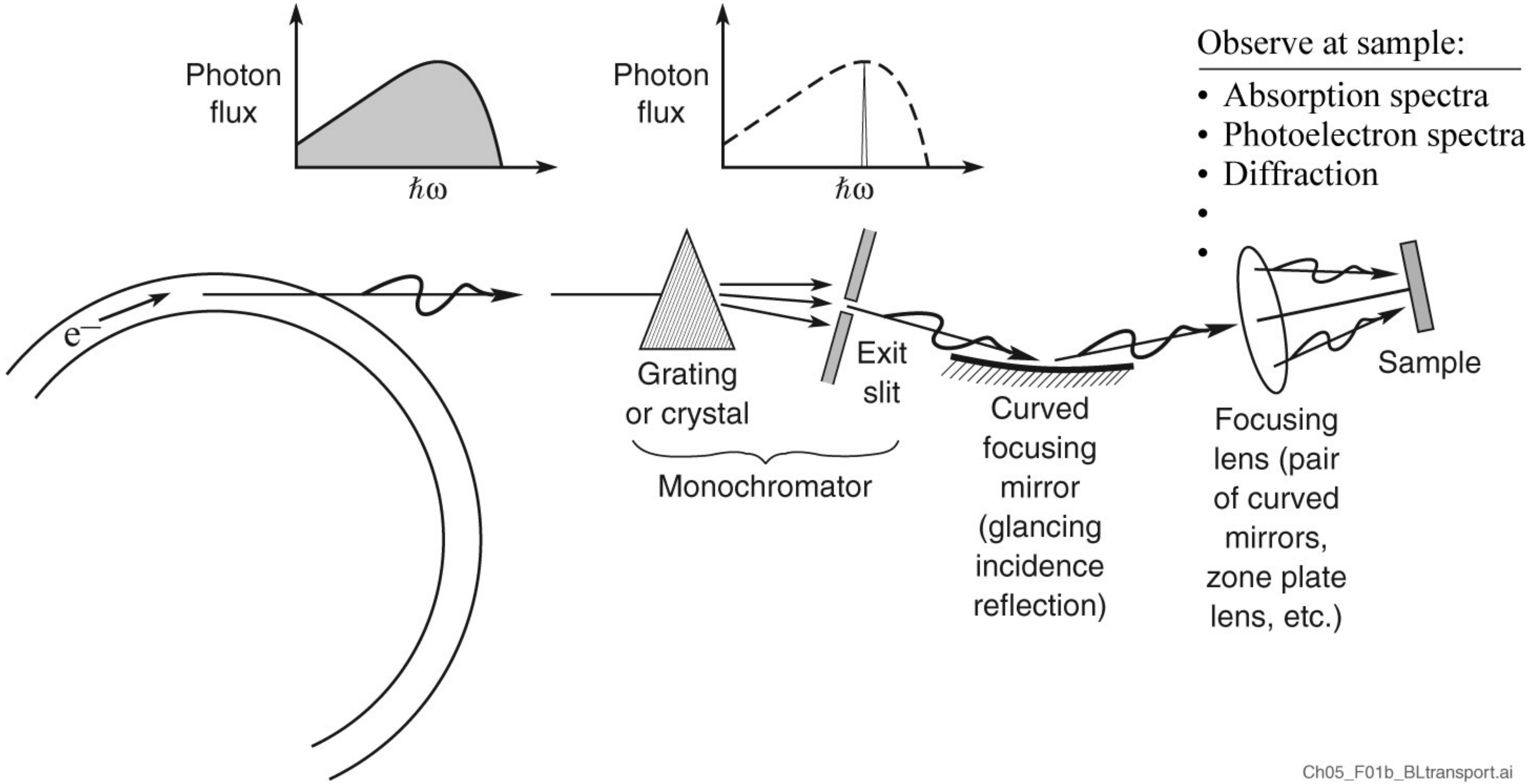
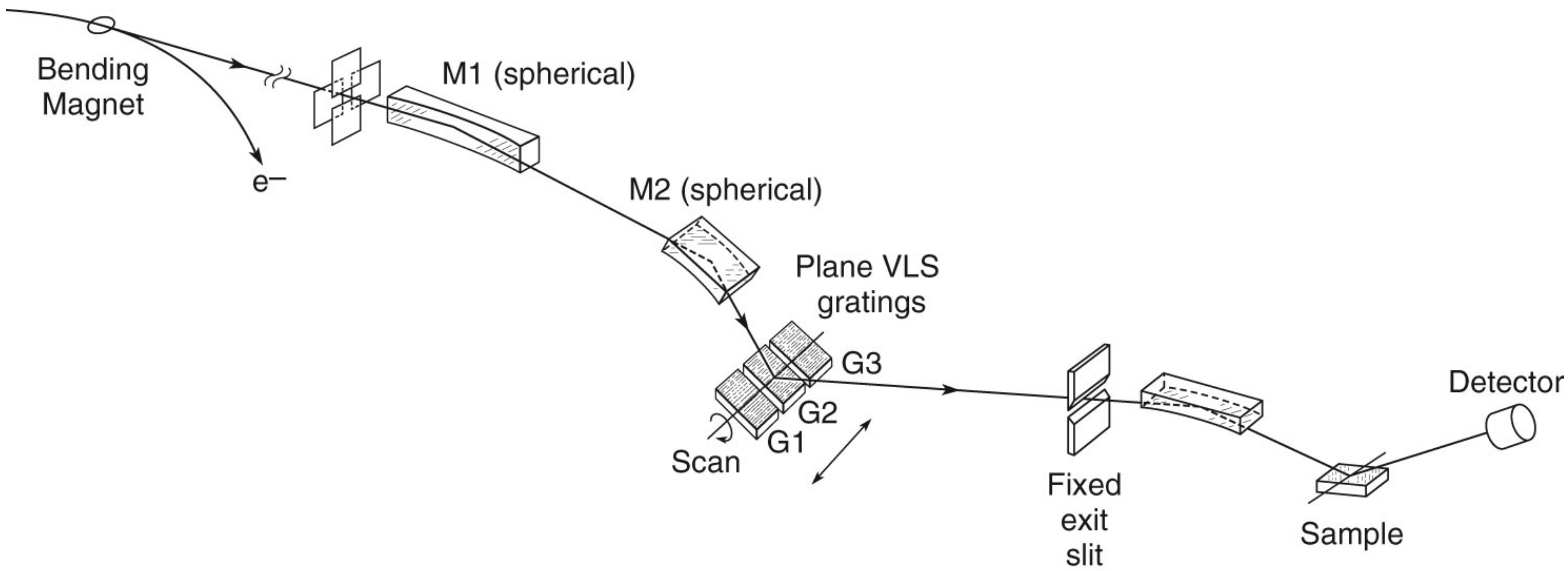
Beamlines are Used to Transport Photons to the Sample, and Take a Desired Spectral Slice



A Typical Beamline: Monochromator Plus Focusing Optics to Deliver Radiation to the Sample



Courtesy of James Underwood (EUV Technology Inc.)

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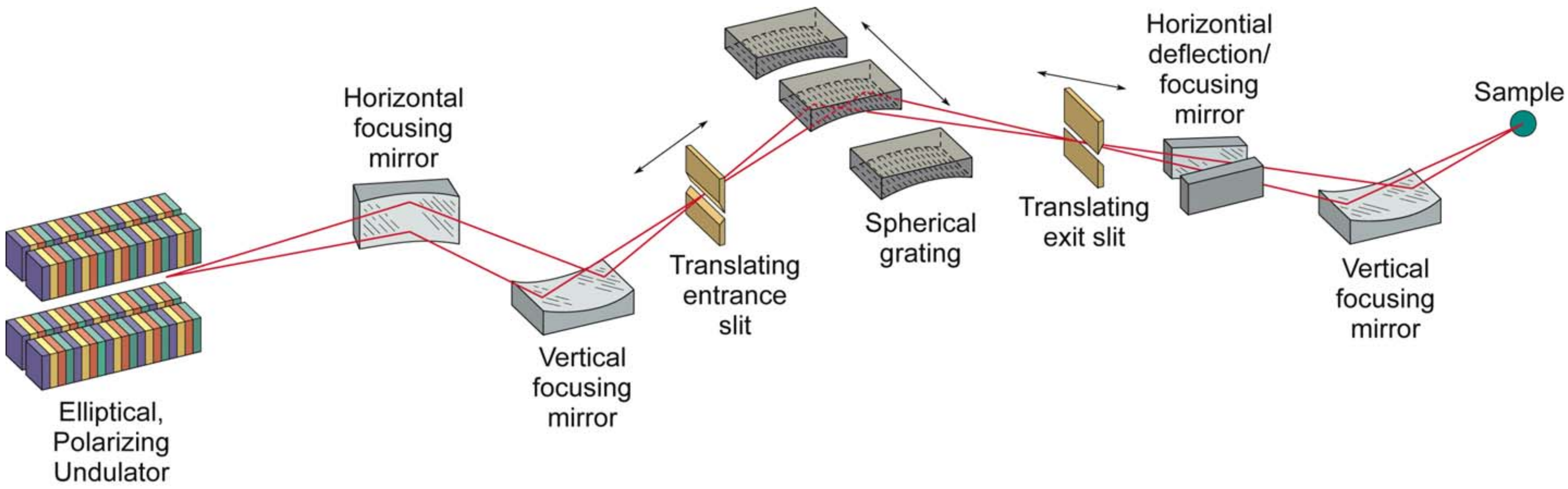
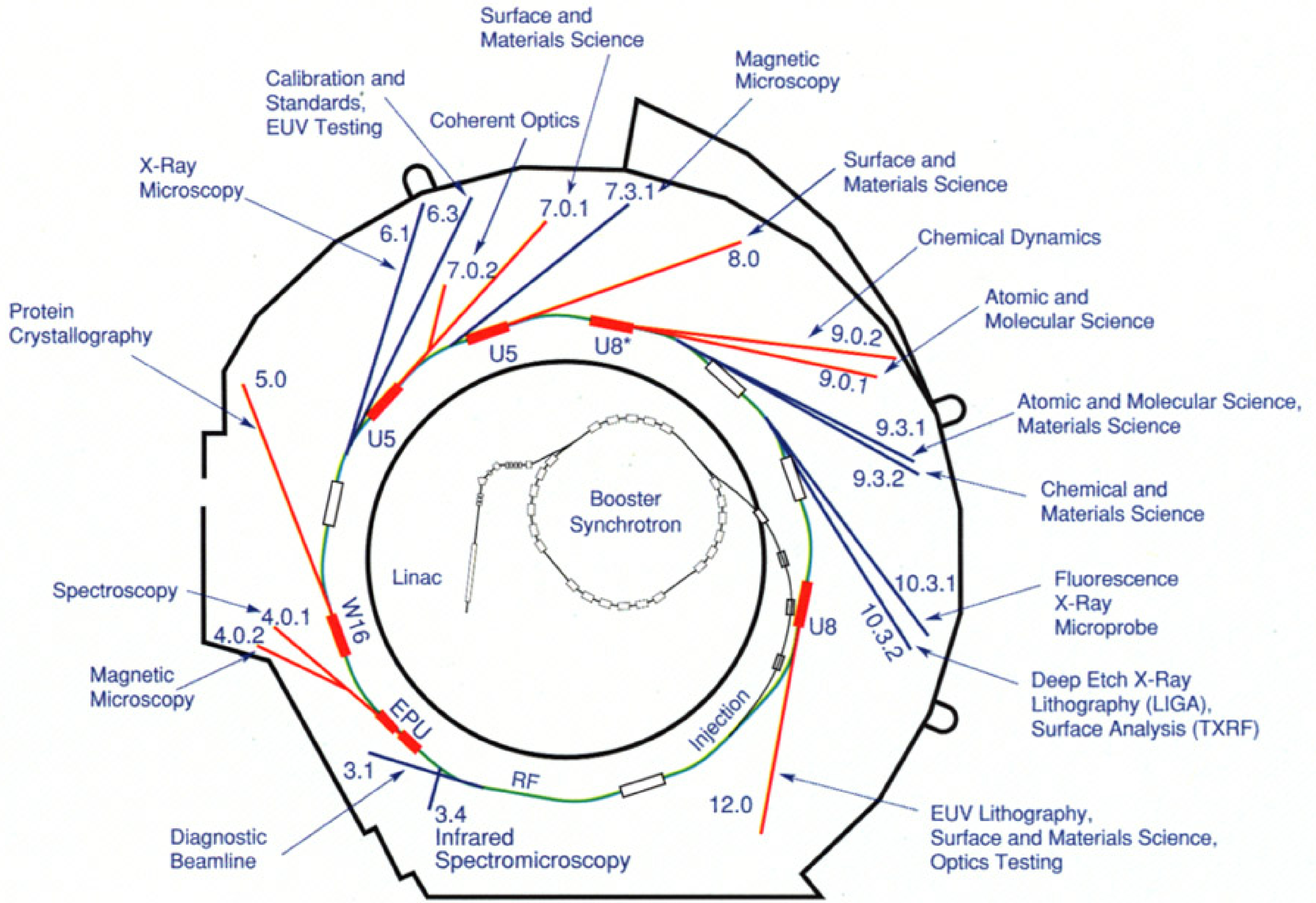
High Spectral Resolution (meV) Beamline



Beamline 7.0 at Berkeley's Advanced Light Source

A Single Storage Ring Serves Many Scientific User Groups



What are the Relative Merits?

Bending magnet radiation	Wiggler radiation	Undulator radiation
• Broad spectrum	• Higher photon energies	• Brighter radiation
• Good photon flux	• More photon flux	• Smaller spot size
• No heat load	• Expensive magnet structure	• Partial coherence
• Less expensive	• Expensive cooled optics	• Expensive
• Easier access	• Less access	• Less access

References

1) D. Attwood, *Soft X-Rays and Extreme Ultraviolet Radiation* (Cambridge, UK, 2000); available at Amazon.com.
2) P. Duke, *Synchrotron Radiation* (Oxford, UK, 2000).
3) J. Als-Nielsen and D. McMorrow, *Elements of Modern X-ray Physics* (Wiley, New York, 2001).
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