Introduction to Synchrotron Radiation and it's Applications

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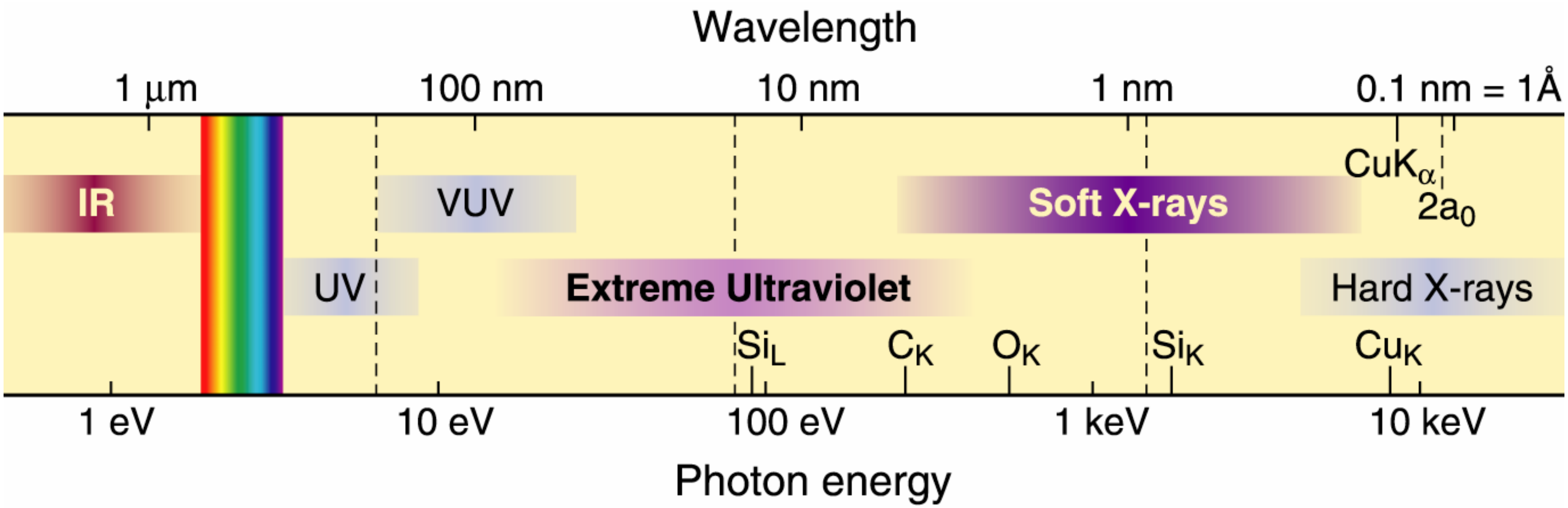
(http://www.coe.berkeley.edu/AST/sxreuv)

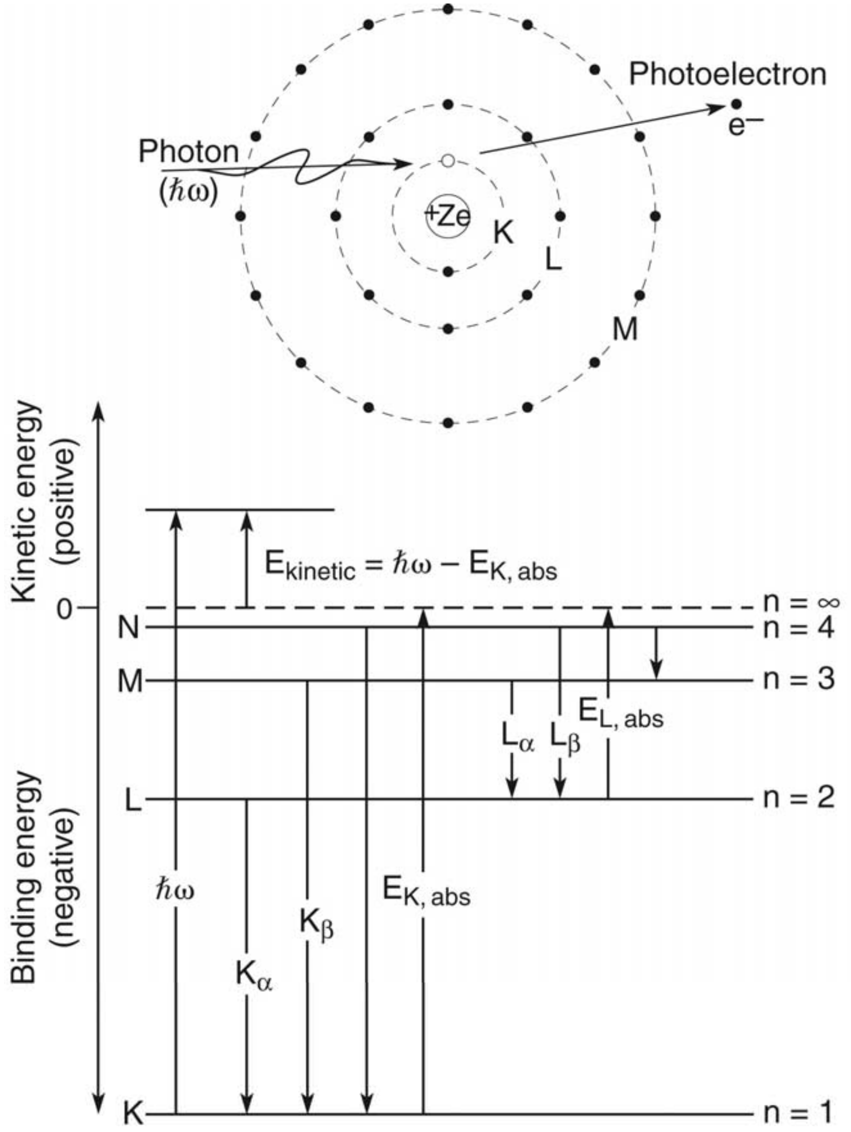
The Short Wavelength Region of the Electromagnetic Spectrum

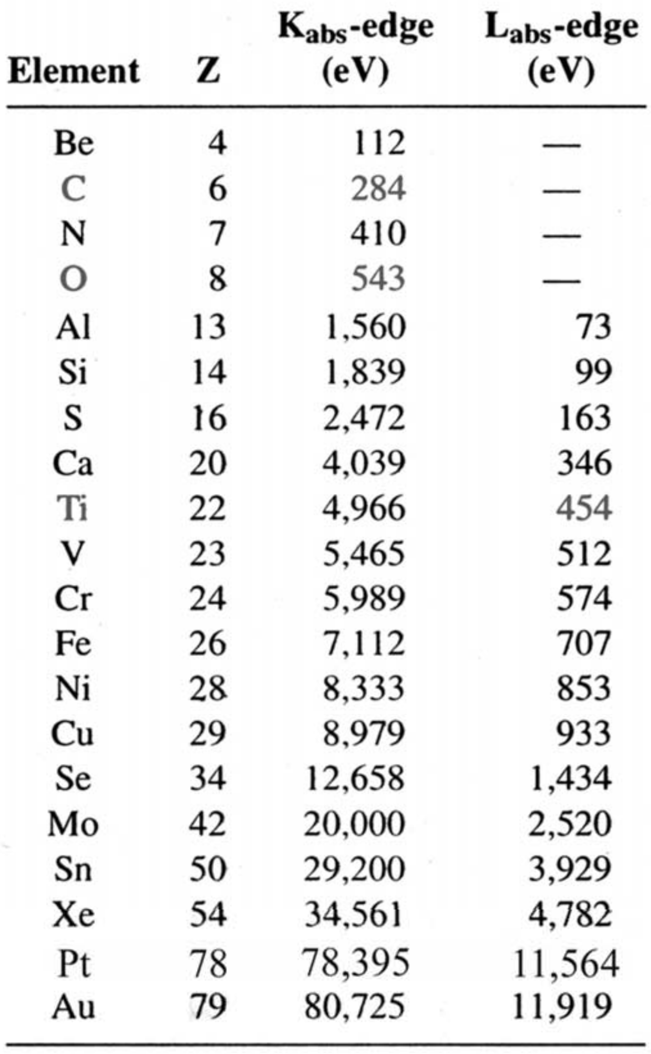


- **See smaller features**
- **Write smaller patterns**
- **Elemental and chemical sensitivity**

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

Characteristic Absorption Edges for Almost all Elements in this Spectral Region





Element	Z	K_{abs}-edge (eV)	L_{abs}-edge (eV)
Be	4	112	—
C	6	284	—
N	7	410	—
O	8	543	—
Al	13	1,560	73
Si	14	1,839	99
S	16	2,472	163
Ca	20	4,039	346
Ti	22	4,966	454
V	23	5,465	512
Cr	24	5,989	574
Fe	26	7,112	707
Ni	28	8,333	853
Cu	29	8,979	933
Se	34	12,658	1,434
Mo	42	20,000	2,520
Sn	50	29,200	3,929
Xe	54	34,561	4,782
Pt	78	78,395	11,564
Au	79	80,725	11,919

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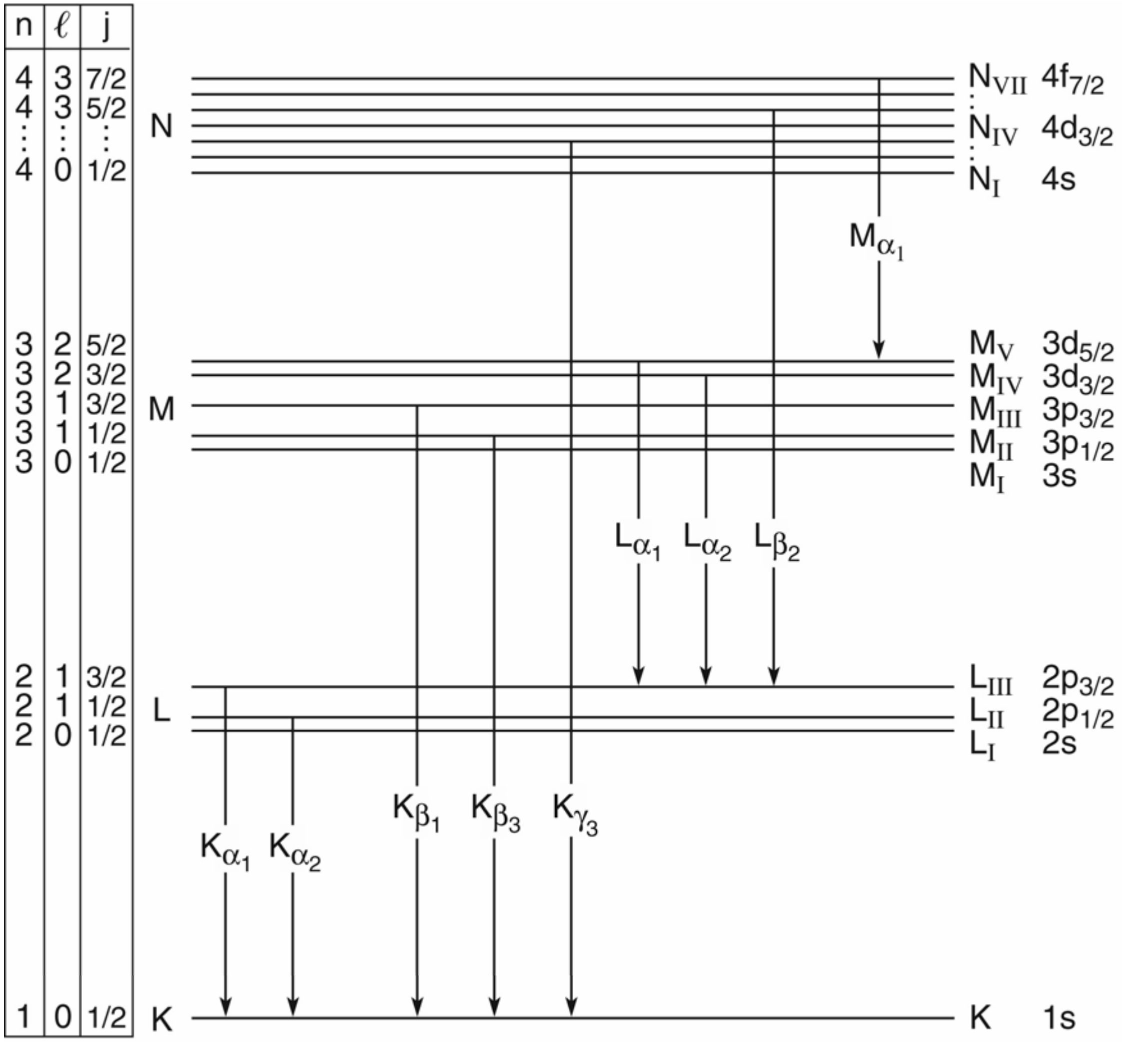
Energy Levels, Quantum Numbers, and Allowed Transitions for the copper Atom



Absorption edges for copper (Z = 29):

$E_{N_1,\ abs} = 7.7$ eV

$E_{M_3,\ abs} = 75$ eV

$E_{M_1,\ abs} = 123$ eV

$E_{L_3,\ abs} = 933$ eV

$E_{L_2,\ abs} = 952$ eV

$E_{L_1,\ abs} = 1{,}097$ eV

$E_{K,\ abs} = 8{,}979$ eV (1.381 Å)

Cu K_{α_1} = 8,048 eV (1.541Å)
Cu K_{α_2} = 8,028 eV (1.544Å)
Cu K_{β_1} = 8,905 eV

Cu L_{α_1} = 930 eV
Cu L_{α_2} = 930 eV
Cu L_{β_1} = 950 eV

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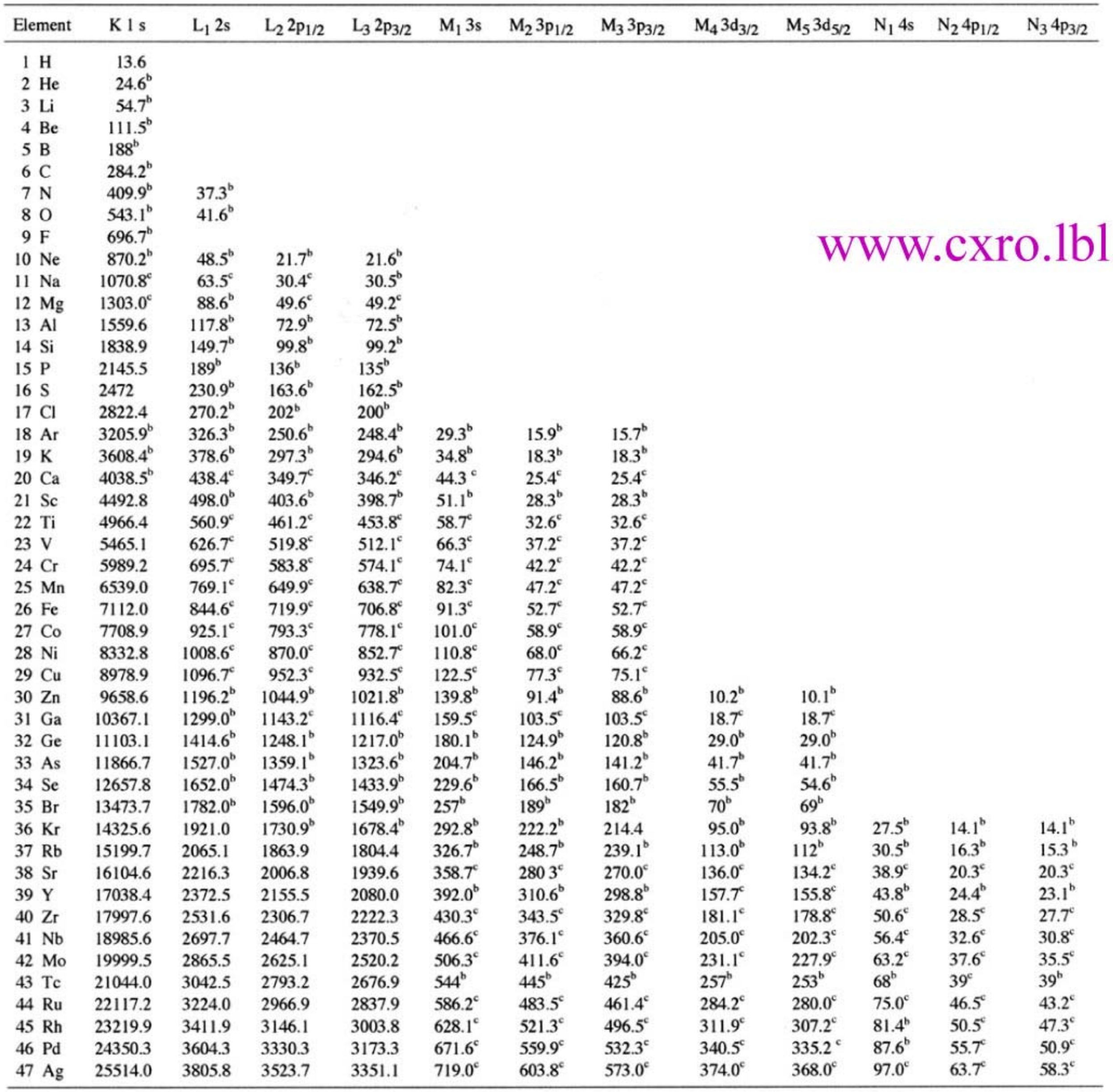
Electron Binding Energies, in Electron Volts (eV), for the Elements in their Natural Forms



Element	K 1s	L$_1$ 2s	L$_2$ 2p$_{1/2}$	L$_3$ 2p$_{3/2}$	M$_1$ 3s	M$_2$ 3p$_{1/2}$	M$_3$ 3p$_{3/2}$	M$_4$ 3d$_{3/2}$	M$_5$ 3d$_{5/2}$	N$_1$ 4s	N$_2$ 4p$_{1/2}$	N$_3$ 4p$_{3/2}$
1 H	13.6											
2 He	24.6^{b}											
3 Li	54.7^{b}											
4 Be	111.5^{b}											
5 B	188^{b}											
6 C	284.2^{b}											
7 N	409.9^{b}	37.3^{b}										
8 O	543.1^{b}	41.6^{b}										
9 F	696.7^{b}											
10 Ne	870.2^{b}	48.5^{b}	21.7^{b}	21.6^{b}								
11 Na	1070.8^{c}	63.5^{c}	30.4^{c}	30.5^{b}								
12 Mg	1303.0^{c}	88.6^{b}	49.6^{c}	49.2^{c}								
13 Al	1559.6	117.8^{b}	72.9^{b}	72.5^{b}								
14 Si	1838.9	149.7^{b}	99.8^{b}	99.2^{b}								
15 P	2145.5	189^{b}	136^{b}	135^{b}								
16 S	2472	230.9^{b}	163.6^{b}	162.5^{b}								
17 Cl	2822.4	270.2^{b}	202^{b}	200^{b}								
18 Ar	3205.9^{b}	326.3^{b}	250.6^{b}	248.4^{b}	29.3^{b}	15.9^{b}	15.7^{b}					
19 K	3608.4^{b}	378.6^{b}	297.3^{b}	294.6^{b}	34.8^{b}	18.3^{b}	18.3^{b}					
20 Ca	4038.5^{b}	438.4^{c}	349.7^{c}	346.2^{c}	44.3^{c}	25.4^{c}	25.4^{c}					
21 Sc	4492.8	498.0^{b}	403.6^{b}	398.7^{b}	51.1^{b}	28.3^{b}	28.3^{b}					
22 Ti	4966.4	560.9^{c}	461.2^{c}	453.8^{c}	58.7^{c}	32.6^{c}	32.6^{c}					
23 V	5465.1	626.7^{c}	519.8^{c}	512.1^{c}	66.3^{c}	37.2^{c}	37.2^{c}					
24 Cr	5989.2	695.7^{c}	583.8^{c}	574.1^{c}	74.1^{c}	42.2^{c}	42.2^{c}					
25 Mn	6539.0	769.1^{c}	649.9^{c}	638.7^{c}	82.3^{c}	47.2^{c}	47.2^{c}					
26 Fe	7112.0	844.6^{c}	719.9^{c}	706.8^{c}	91.3^{c}	52.7^{c}	52.7^{c}					
27 Co	7708.9	925.1^{c}	793.3^{c}	778.1^{c}	101.0^{c}	58.9^{c}	58.9^{c}					
28 Ni	8332.8	1008.6^{c}	870.0^{c}	852.7^{c}	110.8^{c}	68.0^{c}	66.2^{c}					
29 Cu	8978.9	1096.7^{c}	952.3^{c}	932.5^{c}	122.5^{c}	77.3^{c}	75.1^{c}					
30 Zn	9658.6	1196.2^{b}	1044.9^{b}	1021.8^{b}	139.8^{b}	91.4^{b}	88.6^{b}	10.2^{b}	10.1^{b}			
31 Ga	10367.1	1299.0^{b}	1143.2^{c}	1116.4^{c}	159.5^{c}	103.5^{c}	103.5^{c}	18.7^{c}	18.7^{c}			
32 Ge	11103.1	1414.6^{b}	1248.1^{b}	1217.0^{b}	180.1^{b}	124.9^{b}	120.8^{b}	29.0^{b}	29.0^{b}			
33 As	11866.7	1527.0^{b}	1359.1^{b}	1323.6^{b}	204.7^{b}	146.2^{b}	141.2^{b}	41.7^{b}	41.7^{b}			
34 Se	12657.8	1652.0^{b}	1474.3^{b}	1433.9^{b}	229.6^{b}	166.5^{b}	160.7^{b}	55.5^{b}	54.6^{b}			
35 Br	13473.7	1782.0^{b}	1596.0^{b}	1549.9^{b}	257^{b}	189^{b}	182^{b}	70^{b}	69^{b}			
36 Kr	14325.6	1921.0	1730.9^{b}	1678.4^{b}	292.8^{b}	222.2^{b}	214.4	95.0^{b}	93.8^{b}	27.5^{b}	14.1^{b}	14.1^{b}
37 Rb	15199.7	2065.1	1863.9	1804.4	326.7^{b}	248.7^{b}	239.1^{b}	113.0^{b}	112^{b}	30.5^{b}	16.3^{b}	15.3^{b}
38 Sr	16104.6	2216.3	2006.8	1939.6	358.7^{c}	280 3^{c}	270.0^{c}	136.0^{c}	134.2^{c}	38.9^{c}	20.3^{c}	20.3^{c}
39 Y	17038.4	2372.5	2155.5	2080.0	392.0^{b}	310.6^{b}	298.8^{b}	157.7^{c}	155.8^{c}	43.8^{b}	24.4^{b}	23.1^{b}
40 Zr	17997.6	2531.6	2306.7	2222.3	430.3^{c}	343.5^{c}	329.8^{c}	181.1^{c}	178.8^{c}	50.6^{c}	28.5^{c}	27.7^{c}
41 Nb	18985.6	2697.7	2464.7	2370.5	466.6^{c}	376.1^{c}	360.6^{c}	205.0^{c}	202.3^{c}	56.4^{c}	32.6^{c}	30.8^{c}
42 Mo	19999.5	2865.5	2625.1	2520.2	506.3^{c}	411.6^{c}	394.0^{c}	231.1^{c}	227.9^{c}	63.2^{c}	37.6^{c}	35.5^{c}
43 Tc	21044.0	3042.5	2793.2	2676.9	544^{b}	445^{b}	425^{b}	257^{b}	253^{b}	68^{b}	39^{c}	39^{b}
44 Ru	22117.2	3224.0	2966.9	2837.9	586.2^{c}	483.5^{c}	461.4^{c}	284.2^{c}	280.0^{c}	75.0^{c}	46.5^{c}	43.2^{c}
45 Rh	23219.9	3411.9	3146.1	3003.8	628.1^{c}	521.3^{c}	496.5^{c}	311.9^{c}	307.2^{c}	81.4^{b}	50.5^{c}	47.3^{c}
46 Pd	24350.3	3604.3	3330.3	3173.3	671.6^{c}	559.9^{c}	532.3^{c}	340.5^{c}	335.2^{c}	87.6^{b}	55.7^{c}	50.9^{c}
47 Ag	25514.0	3805.8	3523.7	3351.1	719.0^{c}	603.8^{c}	573.0^{c}	374.0^{c}	368.0^{c}	97.0^{c}	63.7^{c}	58.3^{c}

www.cxro.lbl.gov

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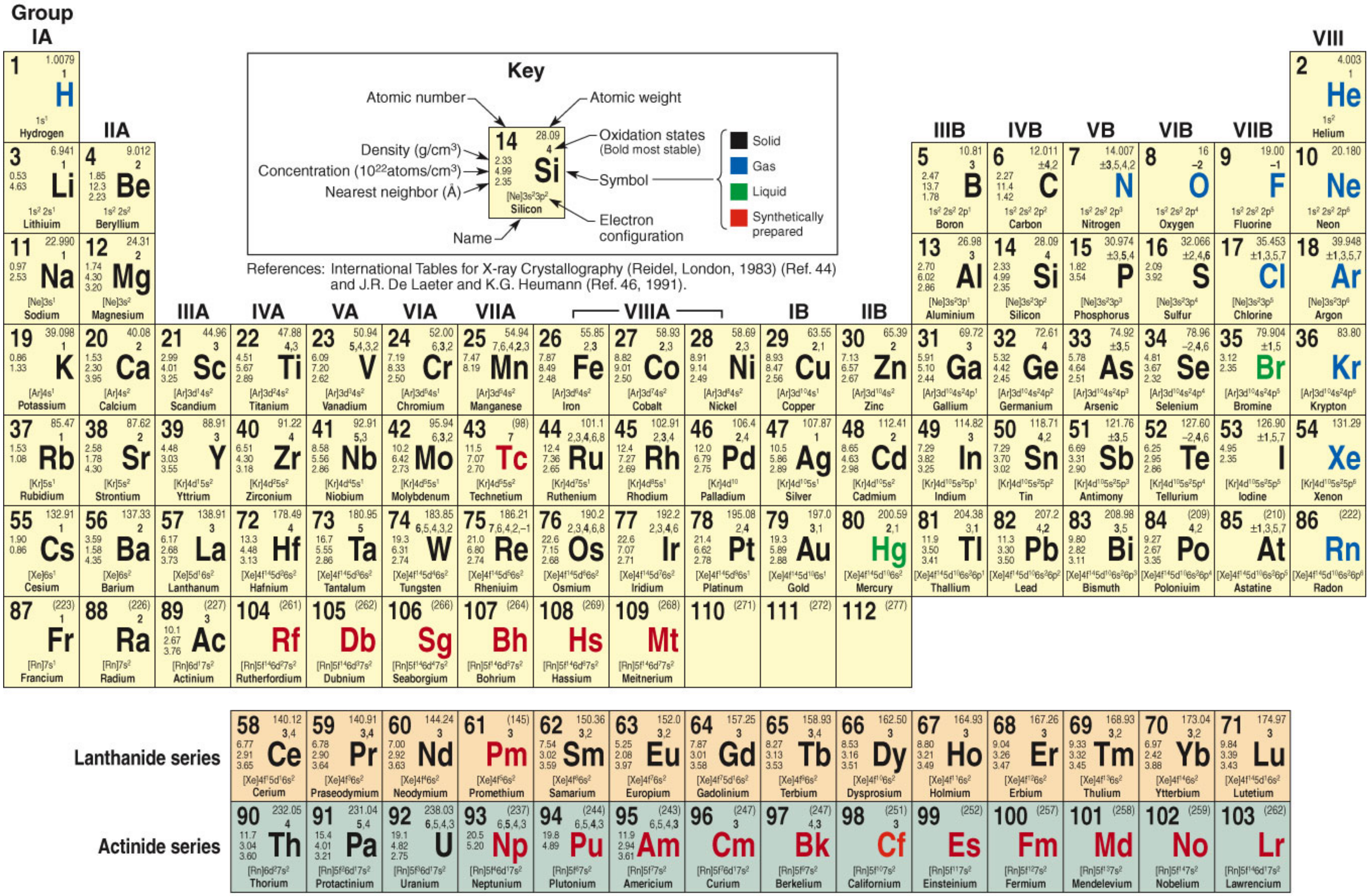
Broadly Tunable Radiation is Needed to Probe the Primary (n = 1 & n = 2) Resonances of the Elements



Key

Atomic number
Atomic weight
Density (g/cm³)
Concentration (10²²atoms/cm³)
Nearest neighbor (Å)
Oxidation states (Bold most stable)
Symbol
Electron configuration
Name

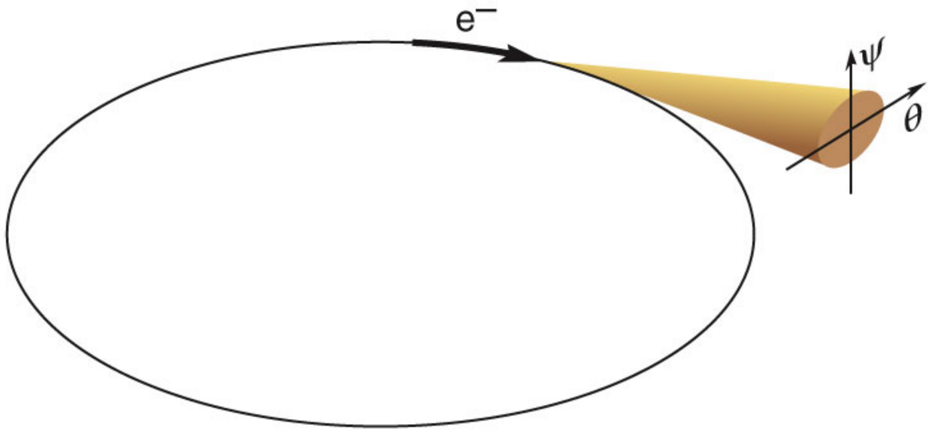
■ Solid
■ Gas
■ Liquid
■ Synthetically prepared

References: International Tables for X-ray Crystallography (Reidel, London, 1983) (Ref. 44) and J.R. De Laeter and K.G. Heumann (Ref. 46, 1991).

Typical Applications of Synchrotron Radiation

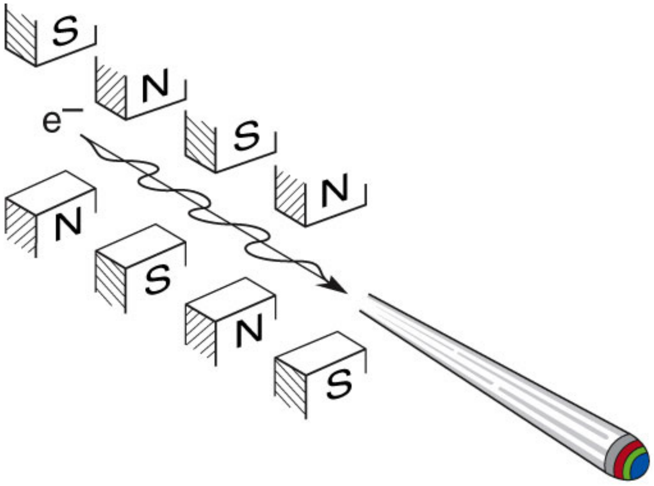
- Surface science
- Magnetic materials
- Materials chemistry
- Environmental sciences
- Protein crystallogrphy
- Biomicroscopy
- Chemical dynamics

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)

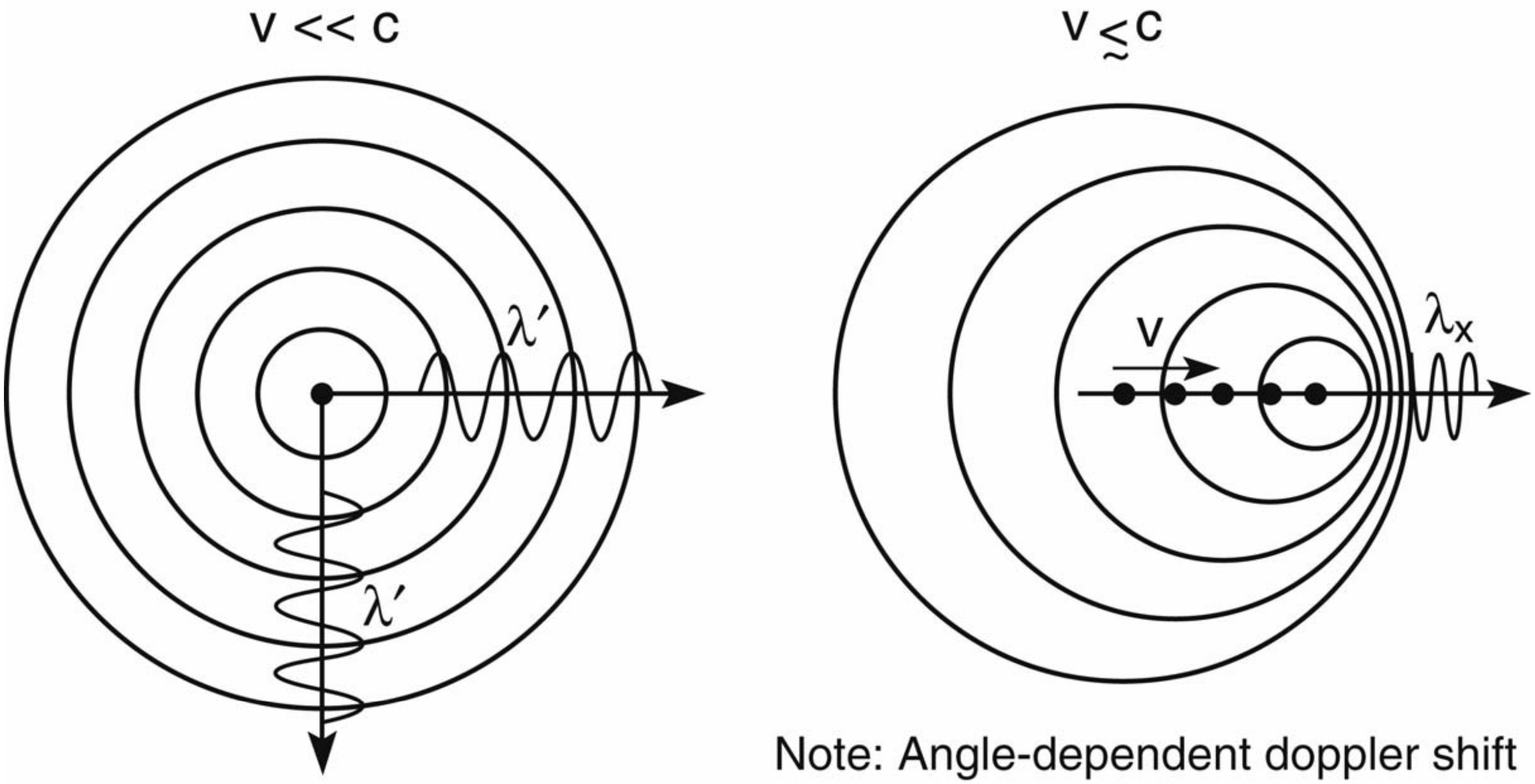


Undulator radiation

- 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

Synchrotron Radiation from Relativistic Electrons



Note: Angle-dependent doppler shift

$$\lambda = \lambda' \left(1 - \frac{v}{c}\cos\theta\right) \qquad \lambda = \lambda' \gamma \left(1 - \frac{v}{c}\cos\theta\right)$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c}}}$$

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Some Useful Formulas for Synchrotron Radiation

$$\gamma = \frac{1}{\sqrt{1-\frac{\text{v}^2}{c^2}}} = \frac{1}{\sqrt{1-\beta^2}} \ ; \quad \beta \equiv \frac{\text{v}}{c}$$

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

$$E_e = \gamma mc^2, \quad \boldsymbol{p} = \gamma m\mathbf{v}$$

$$\hbar\omega \cdot \lambda = 1239.842 \text{ eV} \cdot \text{nm}$$

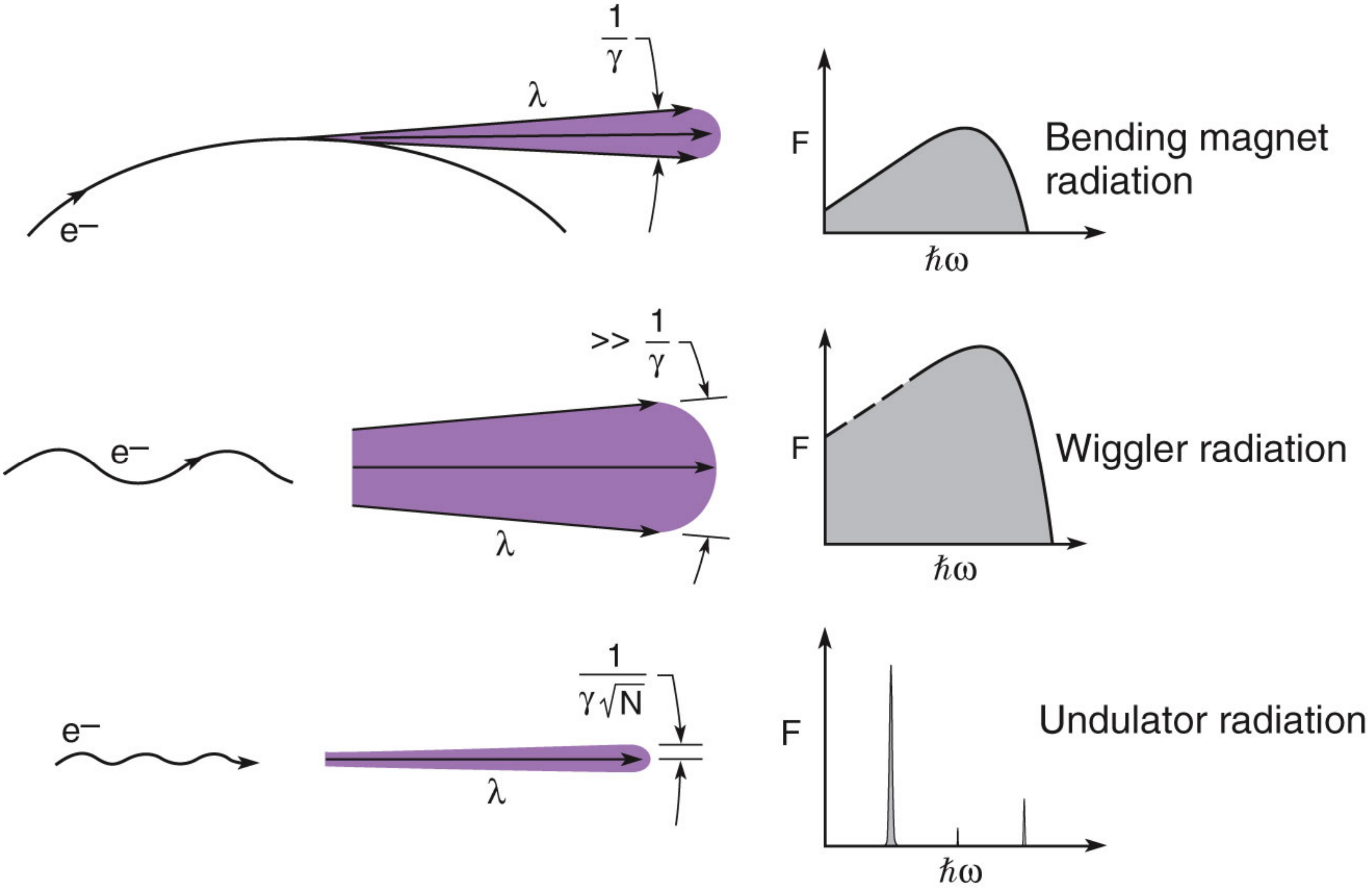
$$1 \text{ watt} \Rightarrow 5.034 \times 10^{15} \lambda[\text{nm}] \ \frac{\text{photons}}{\text{s}}$$

$$\text{Bending Magnet:} \quad E_c = \frac{3e\hbar B\gamma^2}{2m} \ , \quad E_c(\text{keV}) = 0.6650 E_e^2(\text{GeV}) B(\text{T})$$

$$\text{Undulator:} \quad \lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right); \ E(\text{keV}) = \frac{0.9496 E_e^2(\text{GeV})}{\lambda_u(\text{cm})\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)}$$

$$\text{where} \quad K \equiv \frac{eB_0\lambda_u}{2\pi mc} = 0.9337 B_0(\text{T})\lambda_u(\text{cm})$$

Three Forms of Synchrotron Radiation



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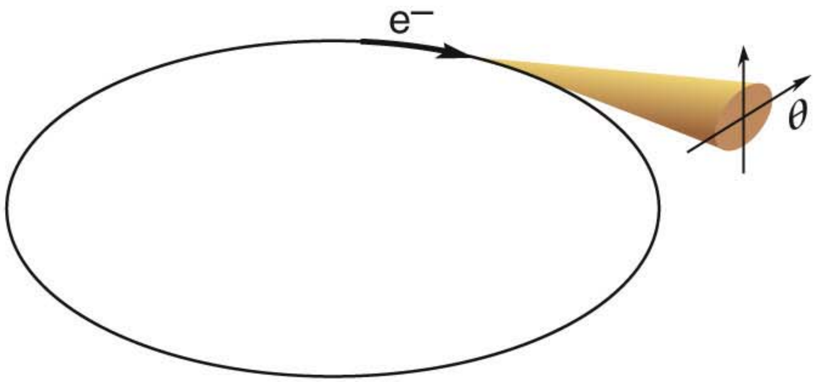
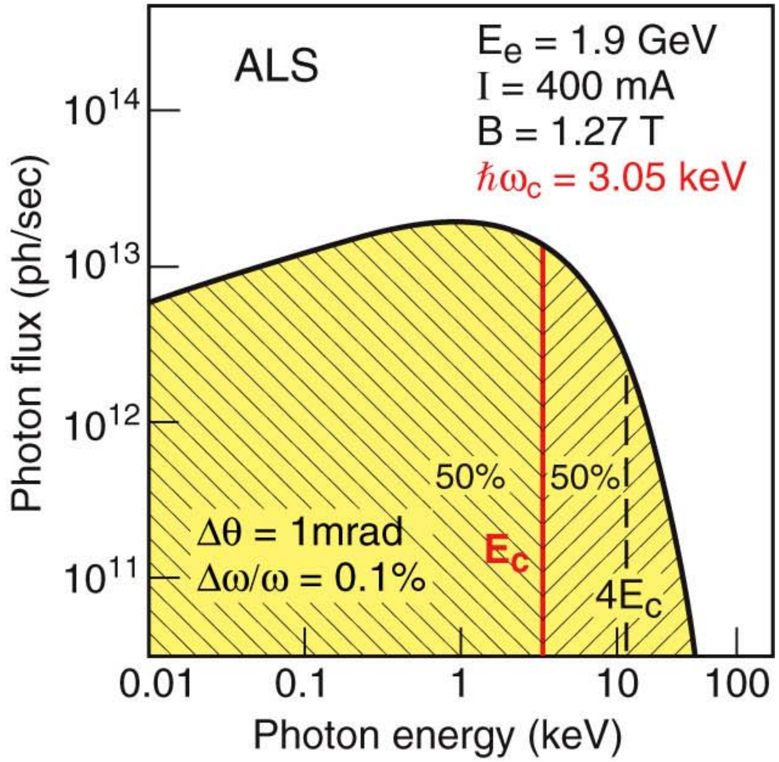
Bending Magnet Radiation Covers a Broad Region of the Spectrum, Including the Primary Absorption Edges of Most Elements



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

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

$$\frac{d^2F_B}{d\theta\, d\omega/\omega} = 2.46\times 10^{13} E_e(\text{GeV}) I(\text{A}) G_1(E/E_c) \frac{\text{photons/s}}{\text{mrad}\cdot(0.1\%\text{BW})} \qquad (5.8)$$



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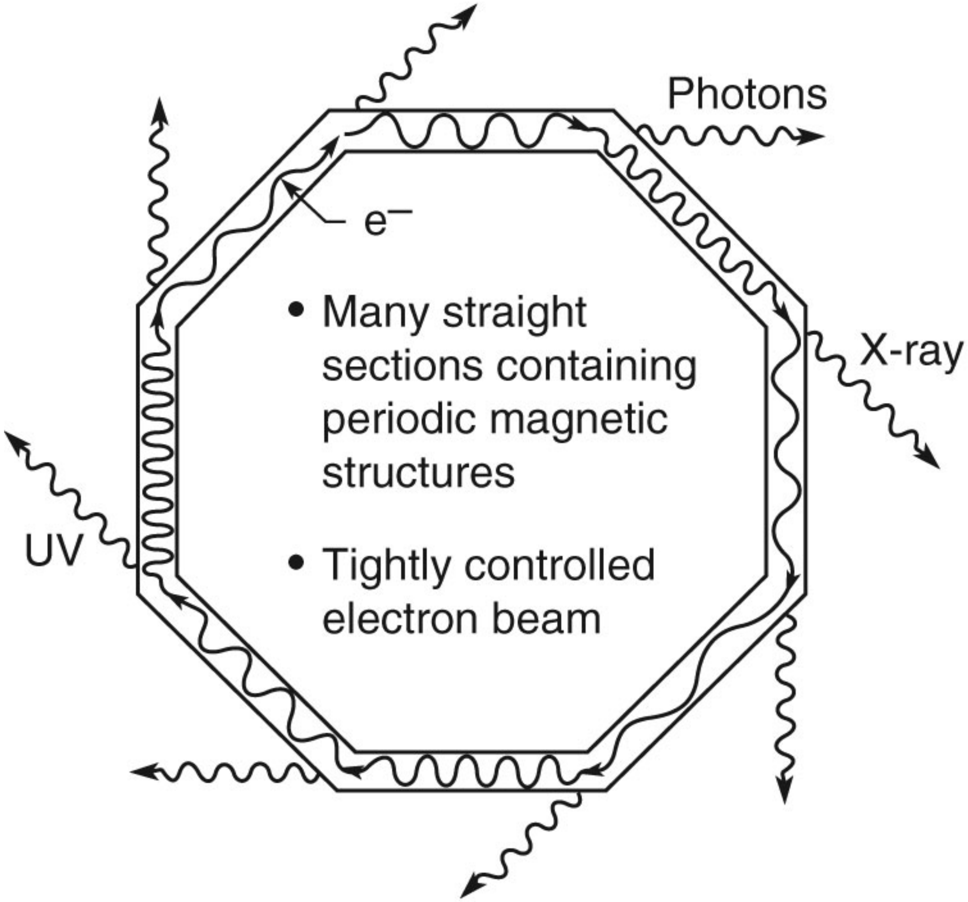
Advantages:
- covers broad spectral range
- least expensive
- most accessable

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

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

Modern Synchrotron Radiation Facility



- Many straight sections containing periodic magnetic structures
- Tightly controlled 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

Third Generation Synchrotron Facilities Under Construction

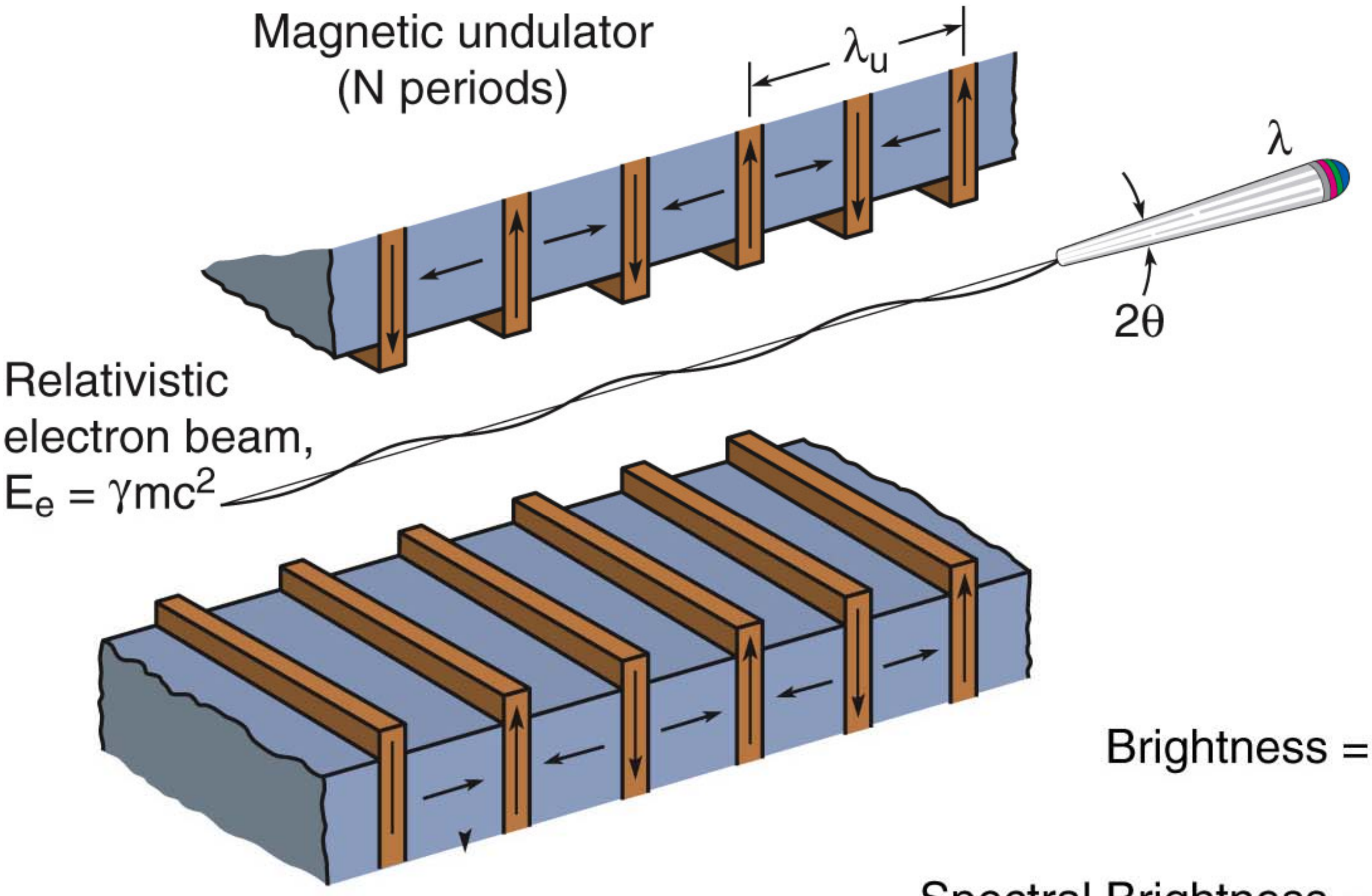
Soleil	2.5 GeV	France
Diamond	3 GeV	UK
Australian Light Source	3 GeV	Australia

Others are in the design stage or planning an upgrade to third generation.

Courtesy of Herman Winick, SSRL, Stanford
www-ssrl.slac.stanford.edu/SR_SOURCES.HTML

3rdGenSynchFacil.ai

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



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

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

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

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

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

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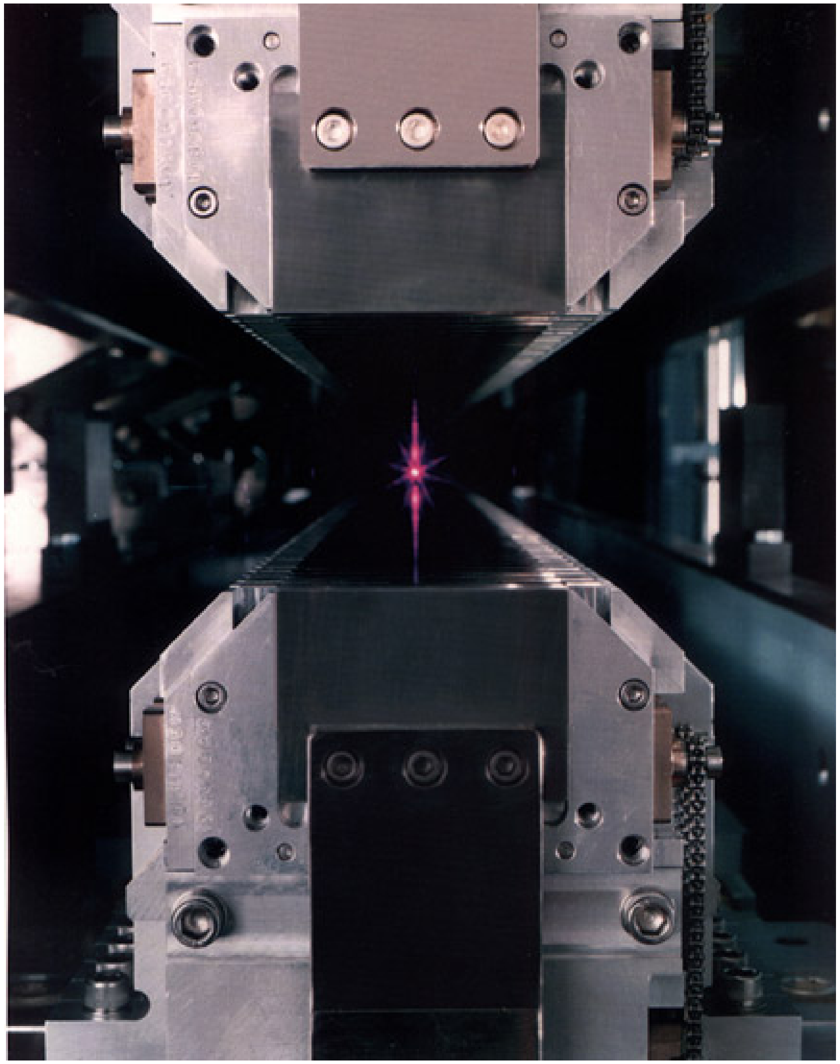
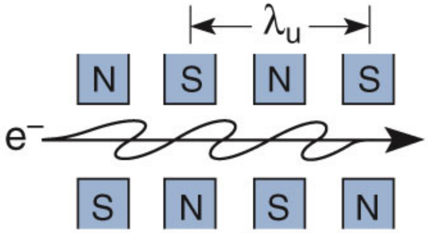
An Undulator Up Close



ALS U5 undulator, beamline 7.0,
N = 89, λ_u = 50 mm

Undulator Radiation

Laboratory Frame of Reference

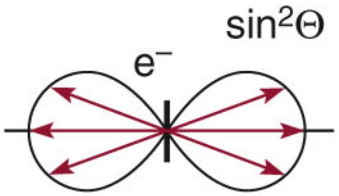


$$E = \gamma mc^2$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

N = # periods

Frame of Moving e⁻



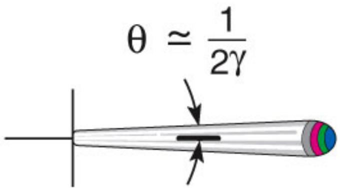
e⁻ radiates at the Lorentz contracted wavelength:

$$\lambda' = \frac{\lambda_u}{\gamma}$$

Bandwidth:

$$\frac{\lambda'}{\Delta\lambda'} \simeq N$$

Frame of Observer



Doppler shortened wavelength on axis:

$$\lambda = \lambda'\gamma(1 - \beta\cos\theta)$$

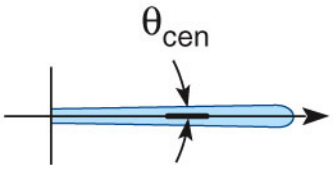
$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + \gamma^2\theta^2)$$

Accounting for transverse motion due to the periodic magnetic field:

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

where $K = eB_0\lambda_u/2\pi mc$

Following Monochromator



For $\frac{\Delta\lambda}{\lambda} \simeq \frac{1}{N}$

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

typically

$$\theta_{cen} \simeq 40\ \mu\text{rad}$$

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Power in the Central Cone

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

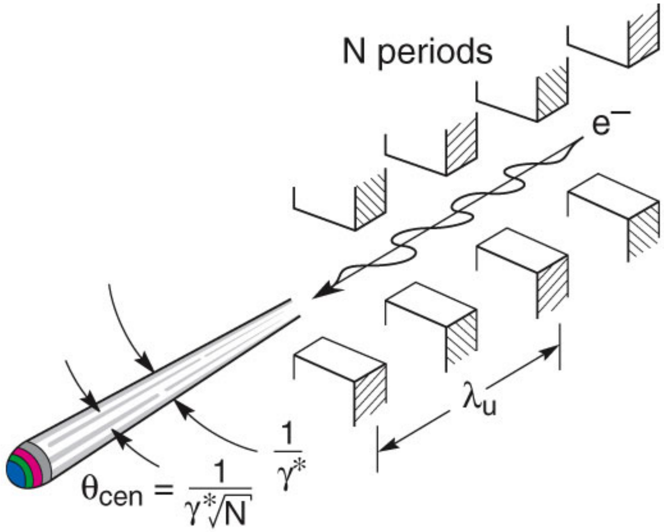
$$\bar{P}_{cen} = \frac{\pi e \gamma^2 I}{\epsilon_0 \lambda_u} \, \frac{K^2}{\left(1 + \frac{K^2}{2}\right)^2} \, f(K)$$

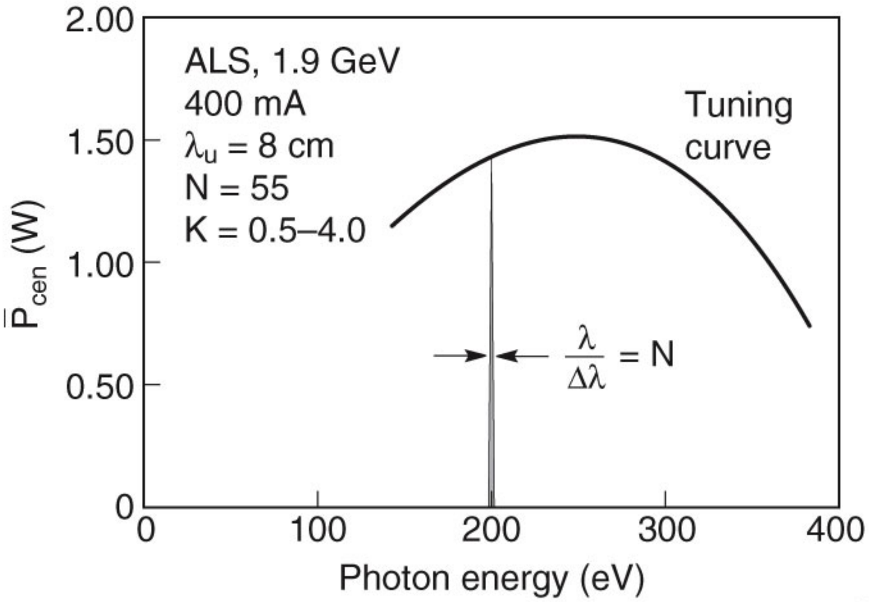
$$\theta_{cen} = \frac{1}{\gamma^* \sqrt{N}}$$

$$\left(\frac{\Delta\lambda}{\lambda}\right)_{cen} = \frac{1}{N}$$

$$K = \frac{eB_0\lambda_u}{2\pi m_0 c}$$

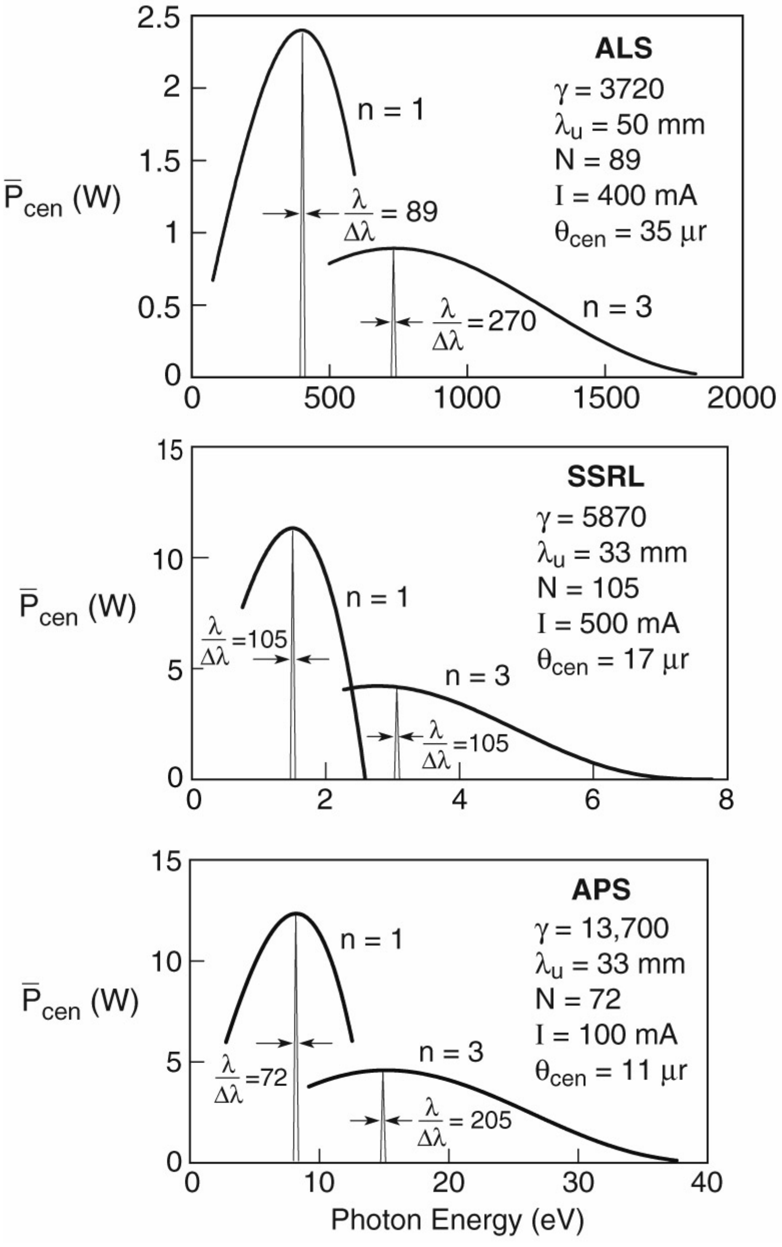
$$\gamma^* = \gamma \Big/ \sqrt{1 + \frac{K^2}{2}}$$





Ch05_LG189

Power in the Central Radiation Cone for Three Soft X-Ray Undulators



$$\theta_{cen} = \frac{1}{\gamma^* \sqrt{N}}$$

$$\left[\frac{\Delta\lambda}{\lambda}\right]_1 = \frac{1}{N}$$

$$\left[\frac{\Delta\lambda}{\lambda}\right]_3 = \frac{1}{3N}$$

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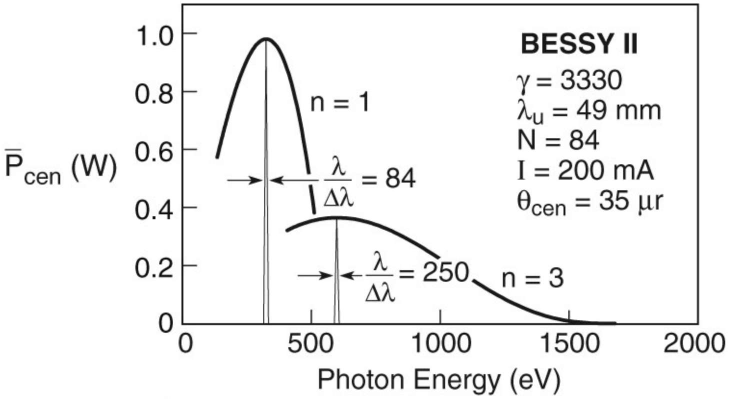
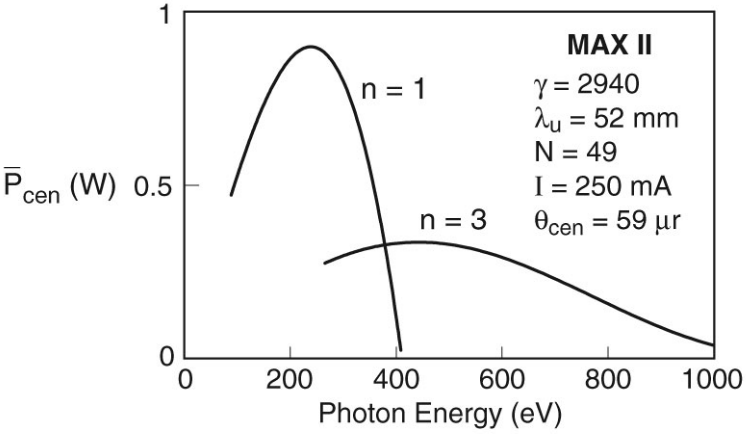
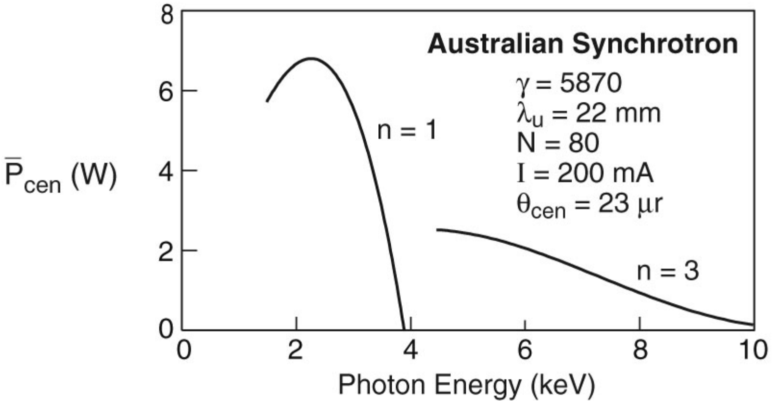
Power in the Central Radiation Cone for Three Soft X-Ray Undulators





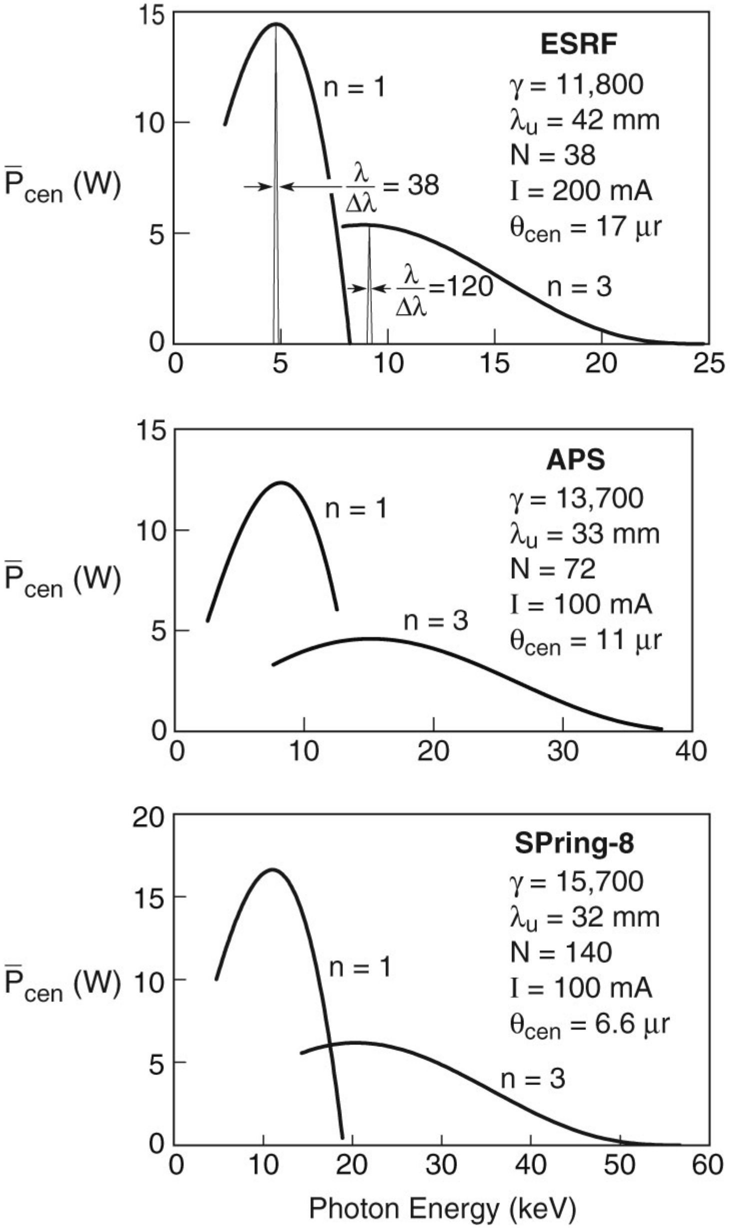


$$\theta_{cen} = \frac{1}{\gamma^* \sqrt{N}}$$

$$\left[\frac{\Delta\lambda}{\lambda}\right]_1 = \frac{1}{N}$$

$$\left[\frac{\Delta\lambda}{\lambda}\right]_3 = \frac{1}{3N}$$

Power in the Central Radiation Cone for Three Soft X-Ray Undulators



$$\theta_{cen} = \frac{1}{\gamma^*\sqrt{N}}$$

$$\left[\frac{\Delta\lambda}{\lambda}\right]_1 = \frac{1}{N}$$

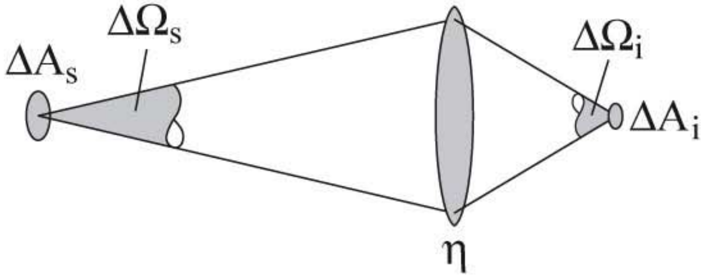
$$\left[\frac{\Delta\lambda}{\lambda}\right]_3 = \frac{1}{3N}$$

Ch05_PwrCenRadCone3.ai

Brightness and Spectral Brightness

Brightness is defined as radiated power per unit area and per unit solid angle at the source:

$$\boxed{B = \frac{\Delta P}{\Delta A \cdot \Delta\Omega}} \qquad (5.57)$$

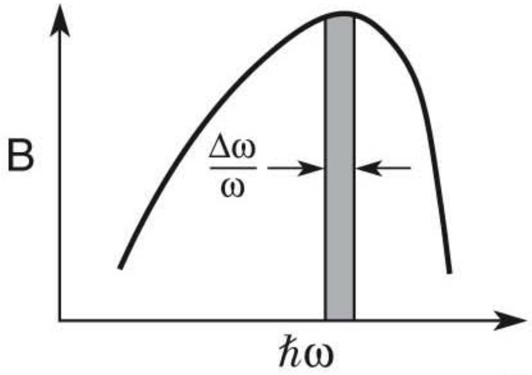


Brightness is a conserved quantity in perfect optical systems, and thus is useful in designing beamlines and synchrotron radiation experiments which involve focusing to small areas.

Perfect optical system:
$\Delta A_s \cdot \Delta\Omega_s = \Delta A_i \cdot \Delta\Omega_i$; $\eta = 100\%$

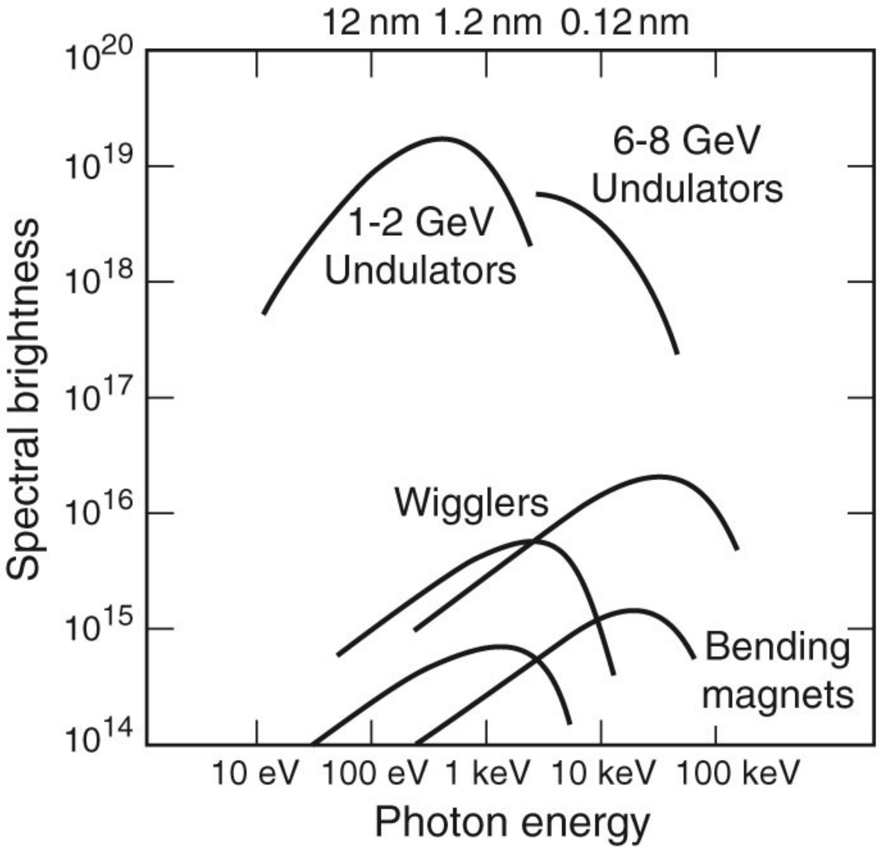
Spectral brightness is that portion of the brightness lying within a relative spectral bandwidth $\Delta\omega/\omega$:

$$\boxed{B_{\Delta\omega/\omega} = \frac{\Delta P}{\Delta A \cdot \Delta\Omega \cdot \Delta\omega/\omega}} \qquad (5.58)$$

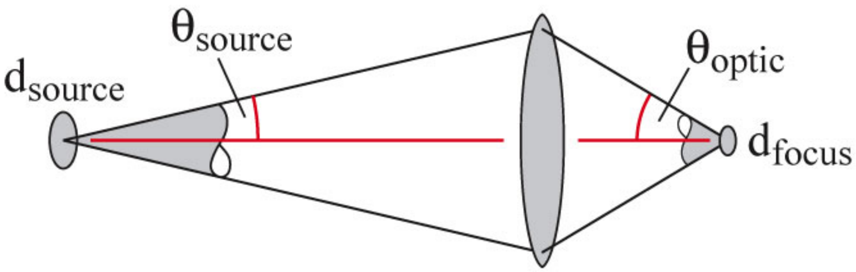


Ch05_Eq57_58VG.ai

Spectral Brightness is Useful for Experiments that Involve Spatially Resolved Studies



- Brightness is conserved (in lossless optical systems)

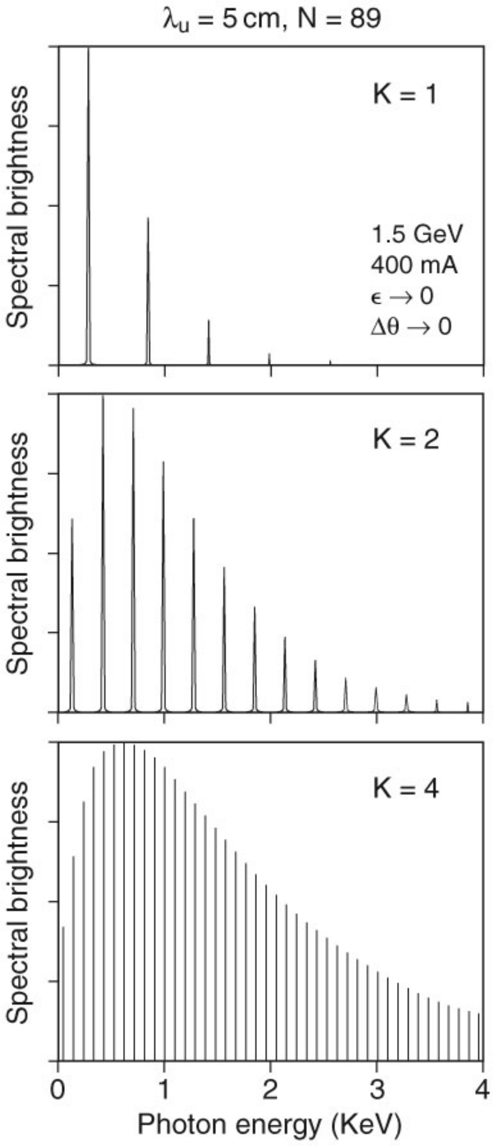


$$d_{source} \cdot \theta_{source} = \underset{\substack{\uparrow \\ \text{Smaller after focus}}}{d_{focus}} \cdot \underset{\substack{\uparrow \\ \text{Large in a focusing optic}}}{\theta_{optic}}$$

- Starting with many photons in a small source area and solid angle, permits high photon flux in an even smaller area

Ch05_F24VG_2.04.ai

The Transition from Undulator Radiation (K ≤ 1) to Wiggler Radiation (K >>1)



(Courtesy of K.-J. Kim)

Undulator radiation (K ≲ 1)

- Narrow spectral lines
- High spectral brightness
- Partial coherence

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

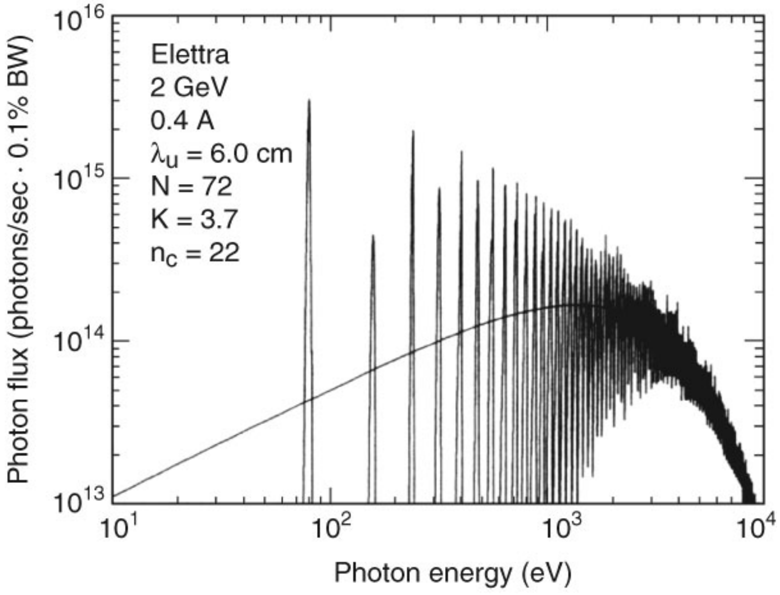
$$K = \frac{eB_o\lambda_u}{2\pi mc}$$

Wiggler radiation (K >> 1)

- Higher photon energies
- Spectral continuum
- Higher photon flux (2N)

$$\hbar\omega_c = \frac{3}{2}\,\frac{\hbar\gamma^2 eB_o}{m}$$

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



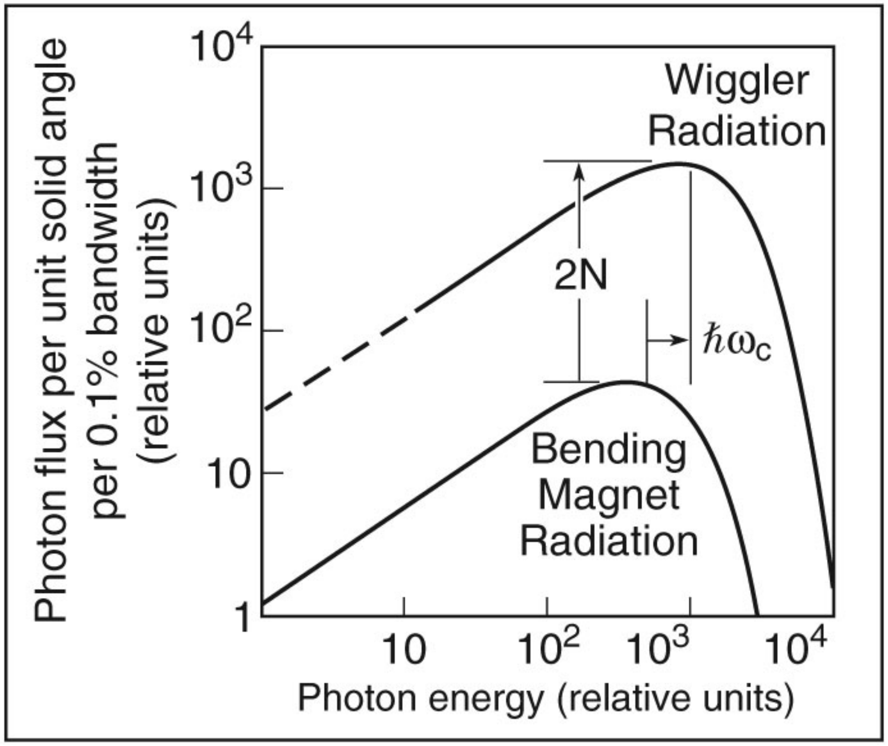
(Courtesy of R.P. Walker and B. Diviacco)

Ch05_F30_32VGrev3.04.ai

Wiggler Radiation

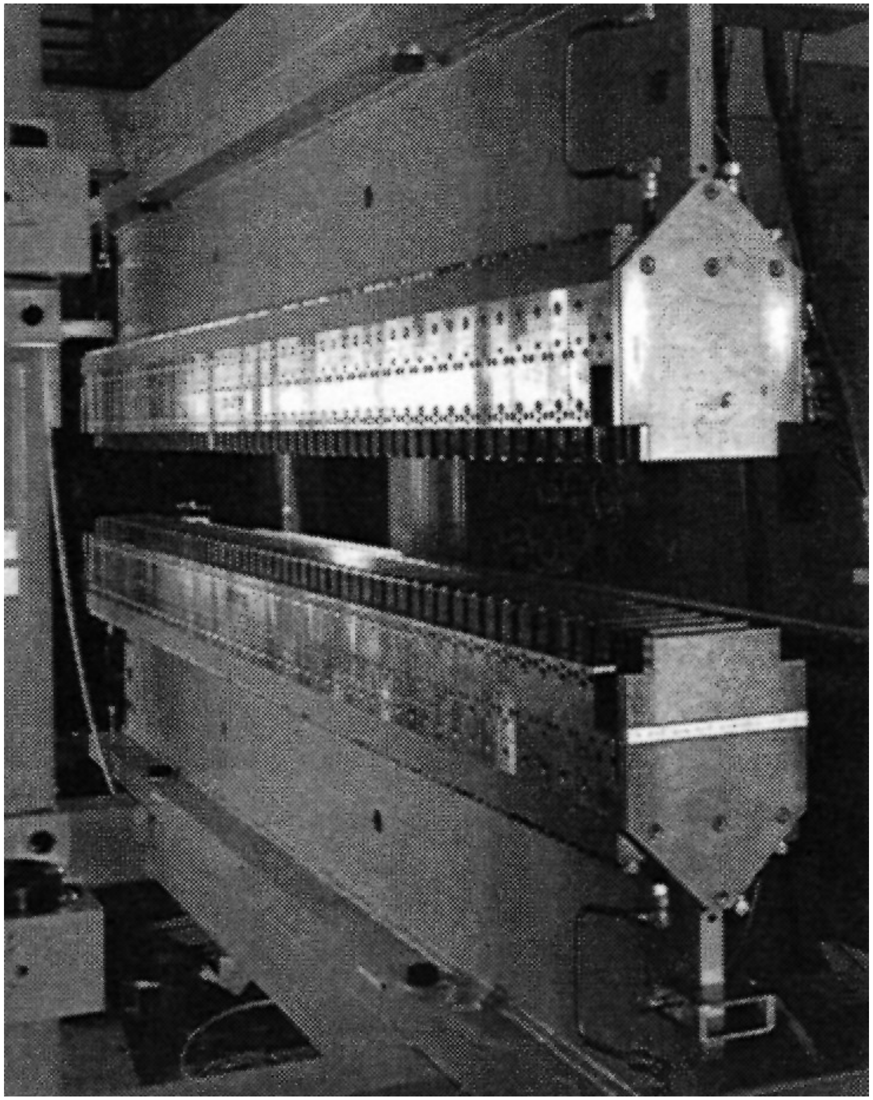
At very high K >> 1, the radiated energy appears in very high harmonics, and at rather large horizontal angles $\theta \simeq \pm K/\gamma$ (eq. 5.21). Because the emission angles are large, one tends to use larger collection angles, which tends to spectrally merge nearby harmonics. The result is a continuum at very high photon energies, similar to that of bending magnet radiation, but increased by 2N (the number of magnet pole pieces).

$$E_c = \hbar\omega_c = \frac{3e\hbar B\gamma^2}{2m} \quad ; \quad n_c = \frac{3K}{4}\left(1 + \frac{K^2}{2}\right) \qquad (5.7a \,\&\, 82)$$



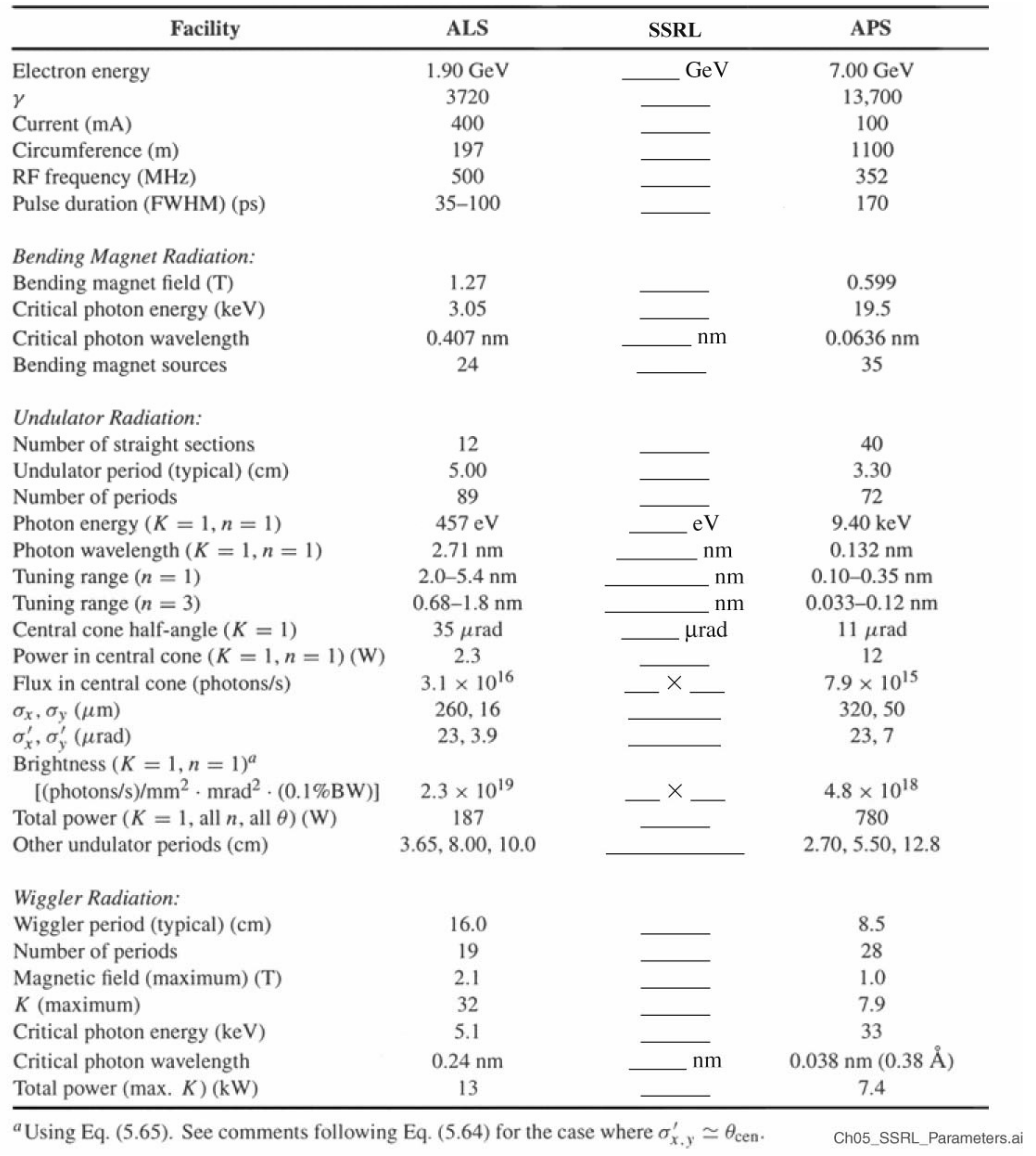
Ch05_Eq82_87_F33rev3.02.ai

Stanford Permanent Magnet Wiggler



LBNL/EXXON/SSRL (1982), SSRL Beamline VI
55 pole (N = 27.5), λ_W = 7 cm

Typical Parameters for Synchrotron Radiation

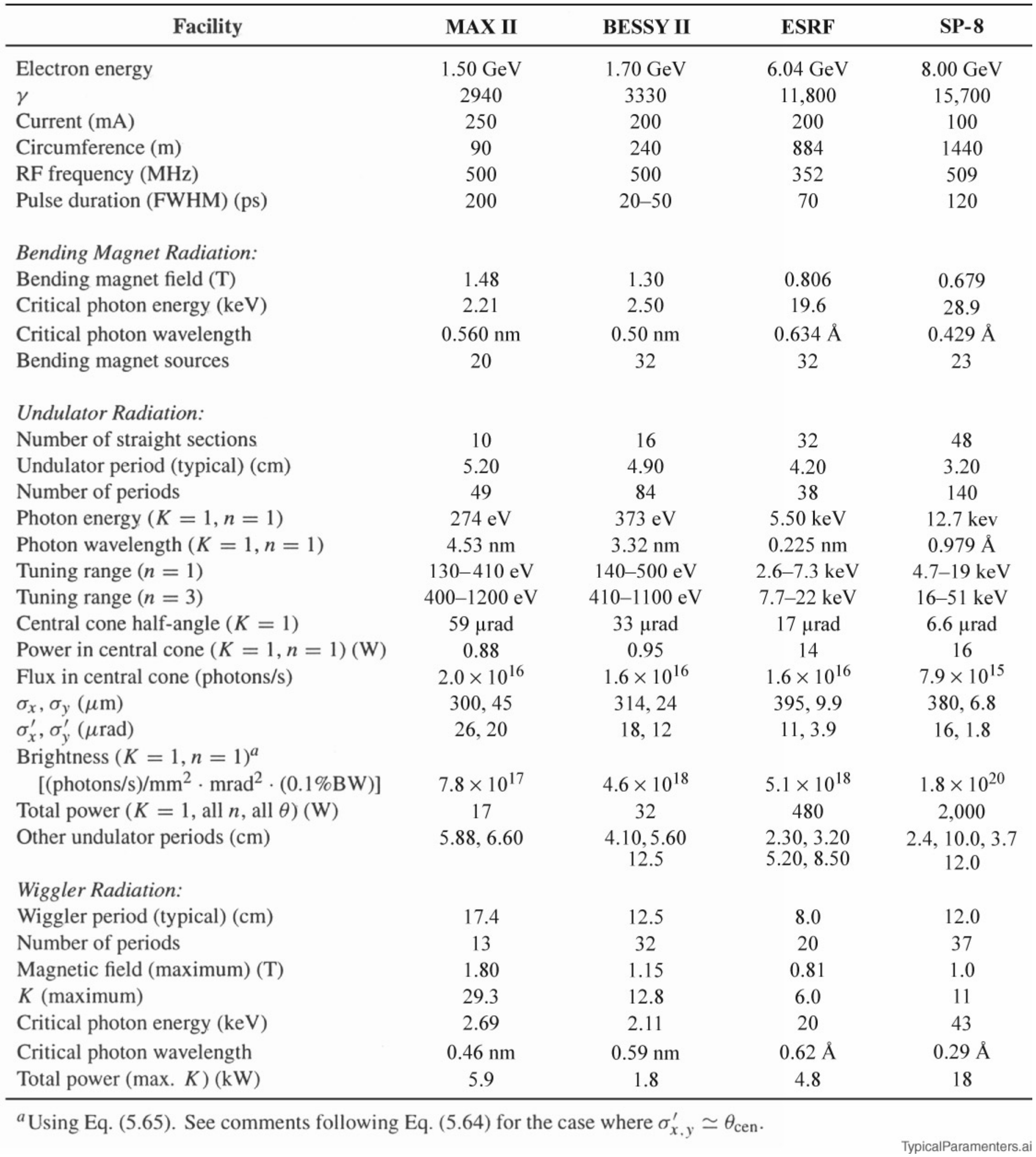


Facility	ALS	SSRL	APS
Electron energy	1.90 GeV	_____ GeV	7.00 GeV
γ	3720	______	13,700
Current (mA)	400	______	100
Circumference (m)	197	______	1100
RF frequency (MHz)	500	______	352
Pulse duration (FWHM) (ps)	35–100	______	170
Bending Magnet Radiation:			
Bending magnet field (T)	1.27	______	0.599
Critical photon energy (keV)	3.05	______	19.5
Critical photon wavelength	0.407 nm	______ nm	0.0636 nm
Bending magnet sources	24	______	35
Undulator Radiation:			
Number of straight sections	12	______	40
Undulator period (typical) (cm)	5.00	______	3.30
Number of periods	89	______	72
Photon energy ($K = 1, n = 1$)	457 eV	_____ eV	9.40 keV
Photon wavelength ($K = 1, n = 1$)	2.71 nm	_______ nm	0.132 nm
Tuning range ($n = 1$)	2.0–5.4 nm	_________ nm	0.10–0.35 nm
Tuning range ($n = 3$)	0.68–1.8 nm	_________ nm	0.033–0.12 nm
Central cone half-angle ($K = 1$)	35 μrad	_____ µrad	11 μrad
Power in central cone ($K = 1, n = 1$) (W)	2.3	______	12
Flux in central cone (photons/s)	3.1×10^{16}	___ × ___	7.9×10^{15}
σ_x, σ_y (μm)	260, 16	________	320, 50
σ'_x, σ'_y (μrad)	23, 3.9	________	23, 7
Brightness ($K = 1, n = 1$)[a] [(photons/s)/mm^2 · mrad^2 · (0.1%BW)]	2.3×10^{19}	___ × ___	4.8×10^{18}
Total power ($K = 1$, all n, all θ) (W)	187	______	780
Other undulator periods (cm)	3.65, 8.00, 10.0	____________	2.70, 5.50, 12.8
Wiggler Radiation:			
Wiggler period (typical) (cm)	16.0	______	8.5
Number of periods	19	______	28
Magnetic field (maximum) (T)	2.1	______	1.0
K (maximum)	32	______	7.9
Critical photon energy (keV)	5.1	______	33
Critical photon wavelength	0.24 nm	_____ nm	0.038 nm (0.38 Å)
Total power (max. K) (kW)	13	______	7.4

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

Ch05_SSRL_Parameters.ai

Typical Parameters for Synchrotron Radiation

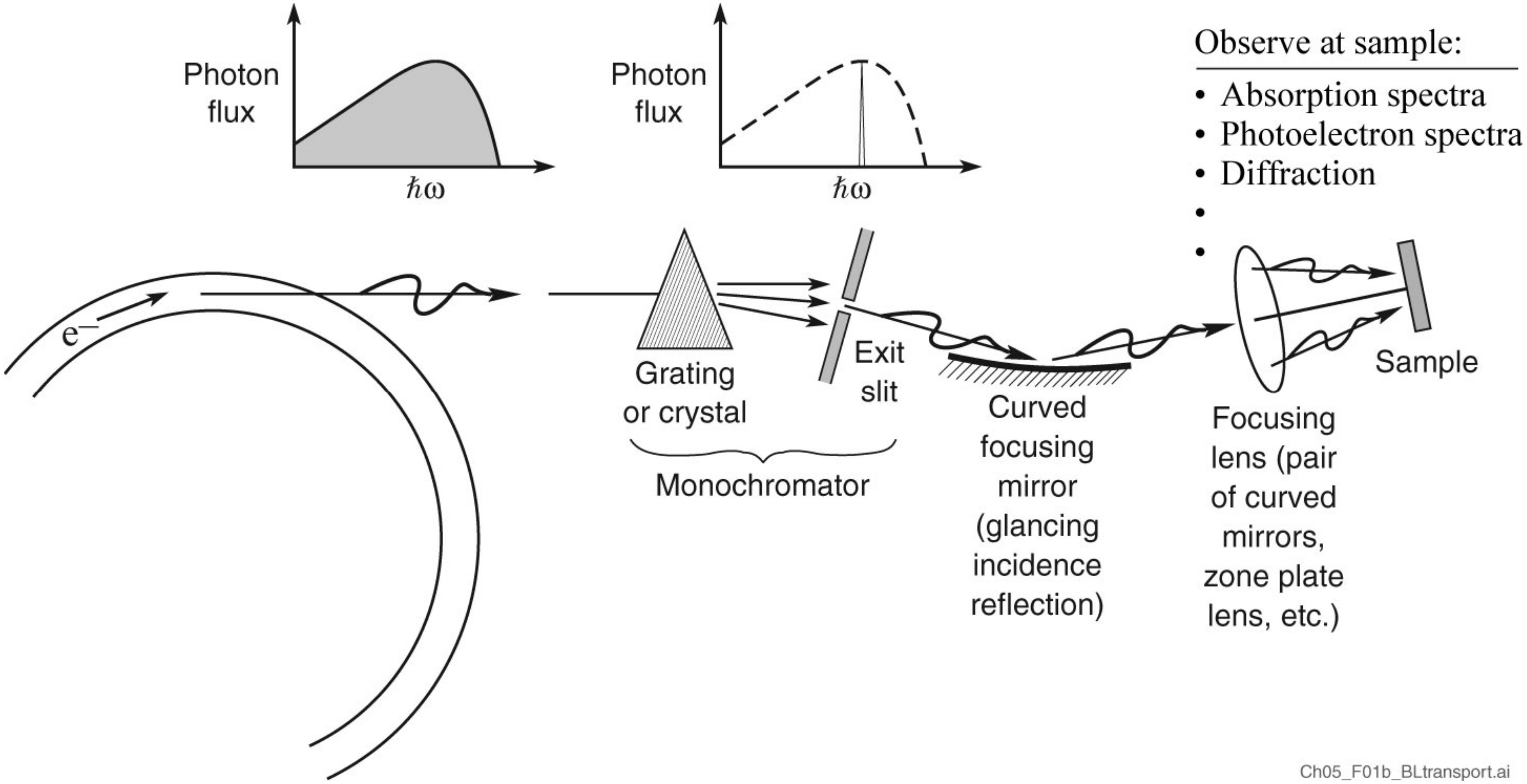


Facility	MAX II	BESSY II	ESRF	SP-8
Electron energy	1.50 GeV	1.70 GeV	6.04 GeV	8.00 GeV
γ	2940	3330	11,800	15,700
Current (mA)	250	200	200	100
Circumference (m)	90	240	884	1440
RF frequency (MHz)	500	500	352	509
Pulse duration (FWHM) (ps)	200	20–50	70	120
Bending Magnet Radiation:				
Bending magnet field (T)	1.48	1.30	0.806	0.679
Critical photon energy (keV)	2.21	2.50	19.6	28.9
Critical photon wavelength	0.560 nm	0.50 nm	0.634 Å	0.429 Å
Bending magnet sources	20	32	32	23
Undulator Radiation:				
Number of straight sections	10	16	32	48
Undulator period (typical) (cm)	5.20	4.90	4.20	3.20
Number of periods	49	84	38	140
Photon energy ($K = 1, n = 1$)	274 eV	373 eV	5.50 keV	12.7 kev
Photon wavelength ($K = 1, n = 1$)	4.53 nm	3.32 nm	0.225 nm	0.979 Å
Tuning range ($n = 1$)	130–410 eV	140–500 eV	2.6–7.3 keV	4.7–19 keV
Tuning range ($n = 3$)	400–1200 eV	410–1100 eV	7.7–22 keV	16–51 keV
Central cone half-angle ($K = 1$)	59 μrad	33 μrad	17 μrad	6.6 μrad
Power in central cone ($K = 1, n = 1$) (W)	0.88	0.95	14	16
Flux in central cone (photons/s)	2.0×10^{16}	1.6×10^{16}	1.6×10^{16}	7.9×10^{15}
σ_x, σ_y (μm)	300, 45	314, 24	395, 9.9	380, 6.8
σ'_x, σ'_y (μrad)	26, 20	18, 12	11, 3.9	16, 1.8
Brightness ($K = 1, n = 1$)^a [(photons/s)/mm^2 · mrad^2 · (0.1%BW)]	7.8×10^{17}	4.6×10^{18}	5.1×10^{18}	1.8×10^{20}
Total power ($K = 1$, all n, all θ) (W)	17	32	480	2,000
Other undulator periods (cm)	5.88, 6.60	4.10, 5.60 12.5	2.30, 3.20 5.20, 8.50	2.4, 10.0, 3.7 12.0
Wiggler Radiation:				
Wiggler period (typical) (cm)	17.4	12.5	8.0	12.0
Number of periods	13	32	20	37
Magnetic field (maximum) (T)	1.80	1.15	0.81	1.0
K (maximum)	29.3	12.8	6.0	11
Critical photon energy (keV)	2.69	2.11	20	43
Critical photon wavelength	0.46 nm	0.59 nm	0.62 Å	0.29 Å
Total power (max. K) (kW)	5.9	1.8	4.8	18

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

TypicalParamenters.ai

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

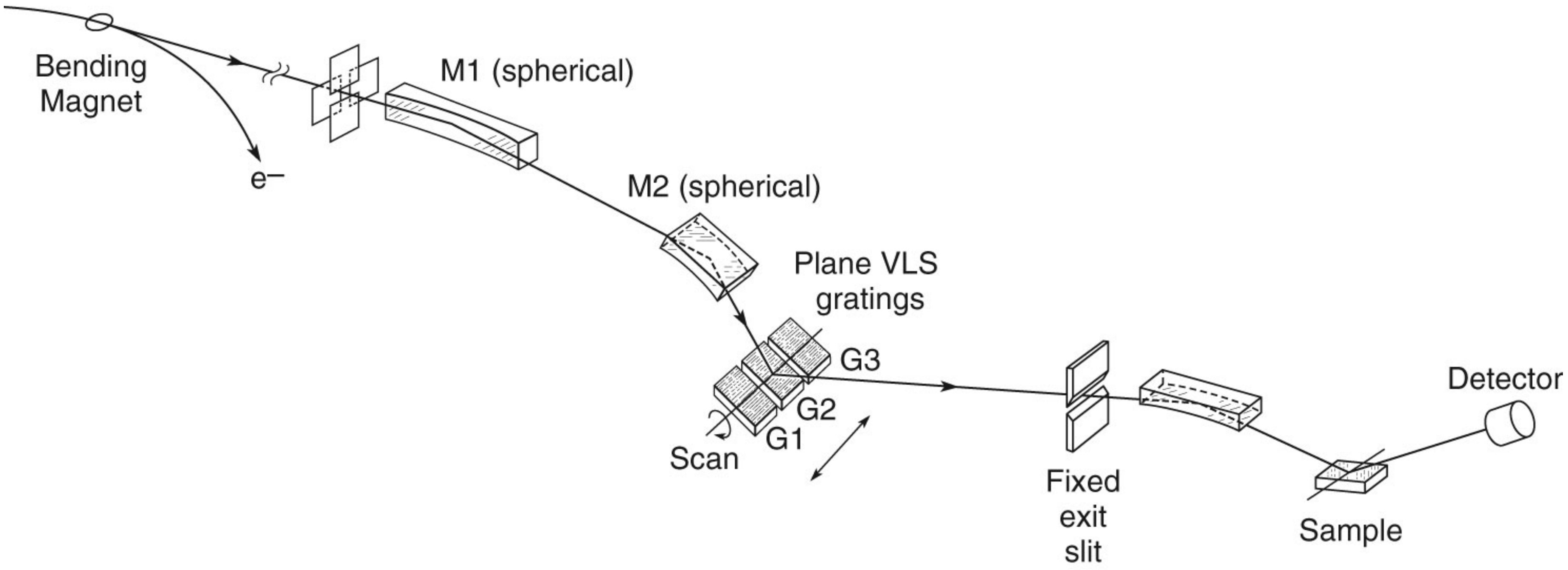


Observe at sample:

- Absorption spectra
- Photoelectron spectra
- Diffraction
-
-

Ch05_F01b_BLtransport.ai

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



Courtesy of James Underwood (EUV Technology Inc.)

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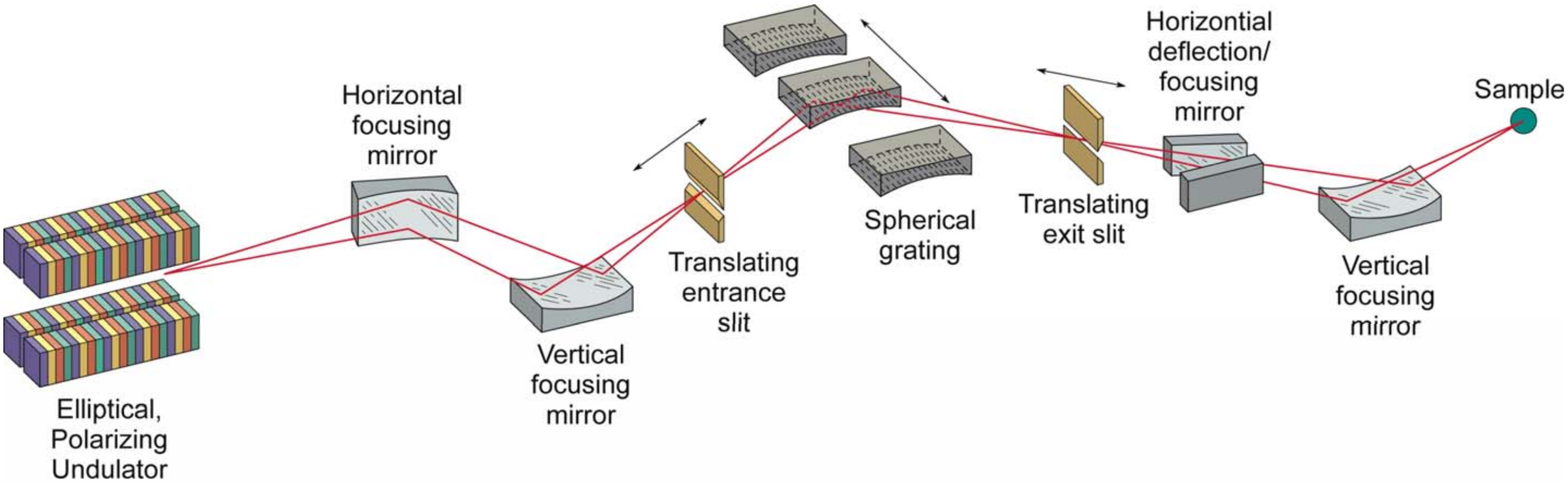
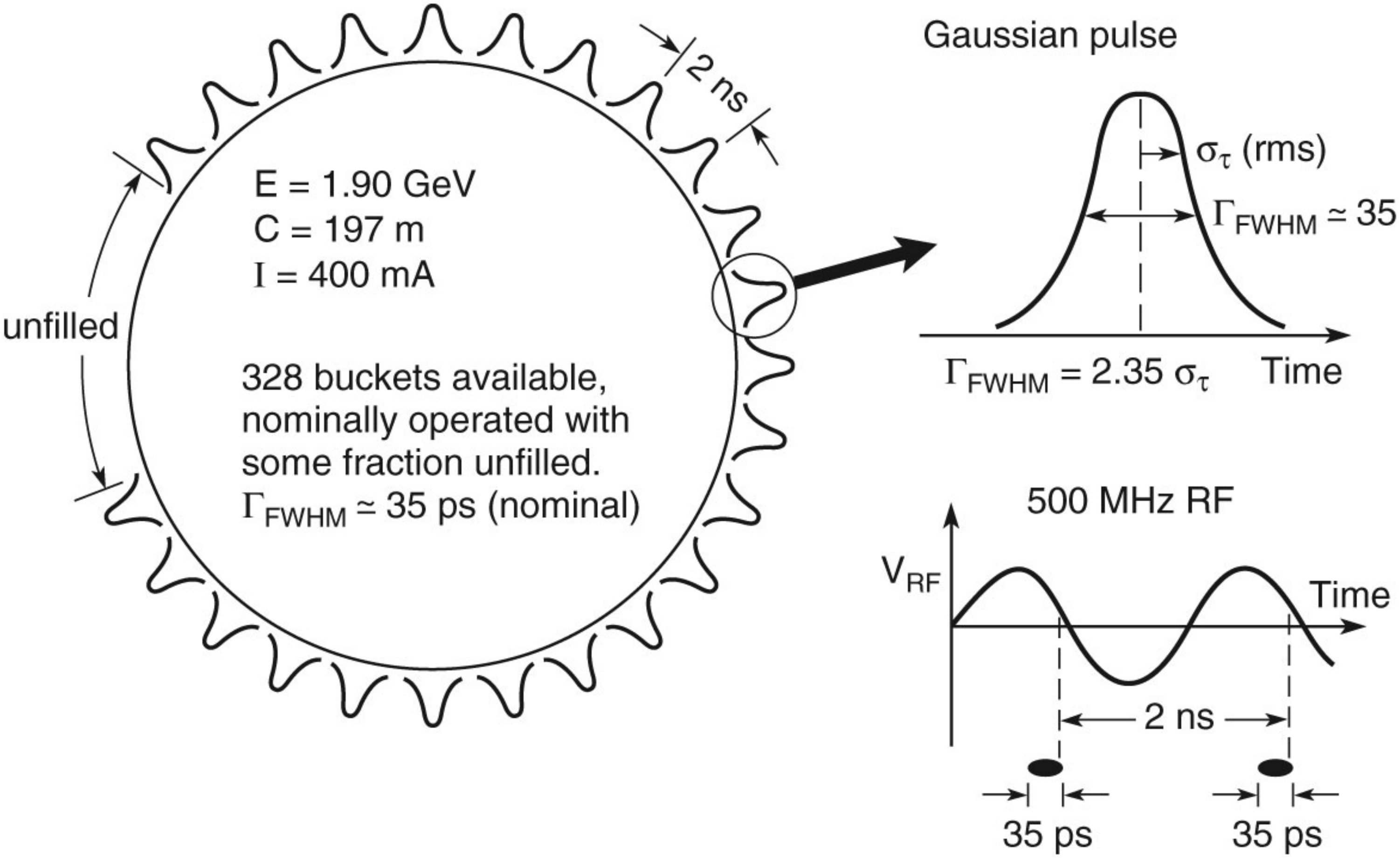
High Spectral Resolution (meV) Beamline



Beamline 7.0 at Berkeley's Advanced Light Source

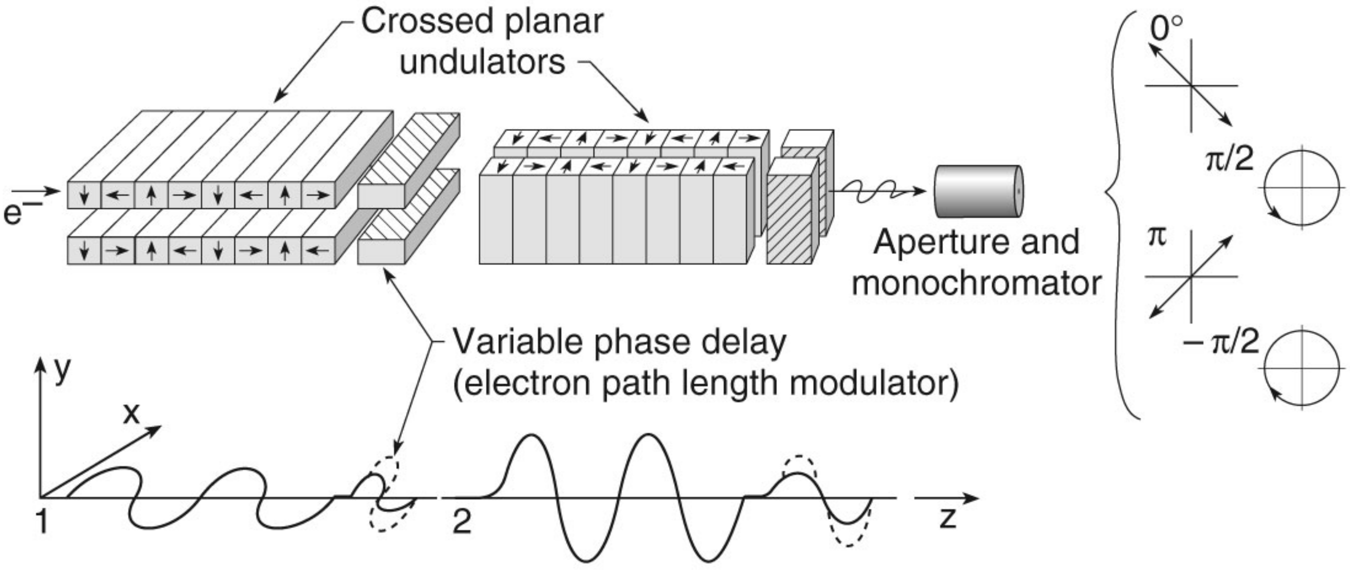
Time Structure of Synchrotron Radiation

The axial electric field within the RF cavity, used to replenish lost (radiated) energy, forms a potential well “bucket” system that forces electrons into axial electron “bunches”. This leads to a time structure in the emitted radiation.

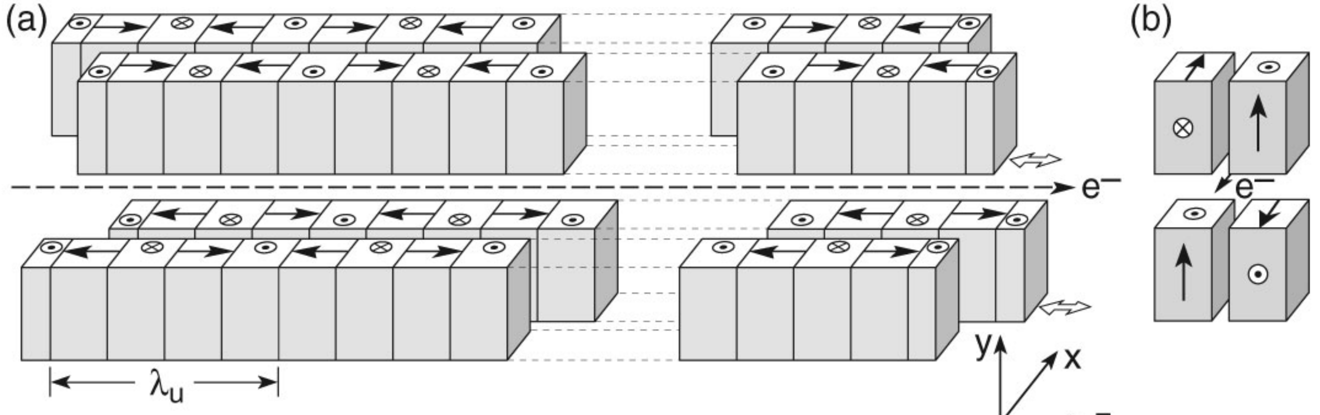


Ch05_TimeStruc.ai

Variable Polarization Undulator Radiation



(Courtesy of Kwang-Je Kim)

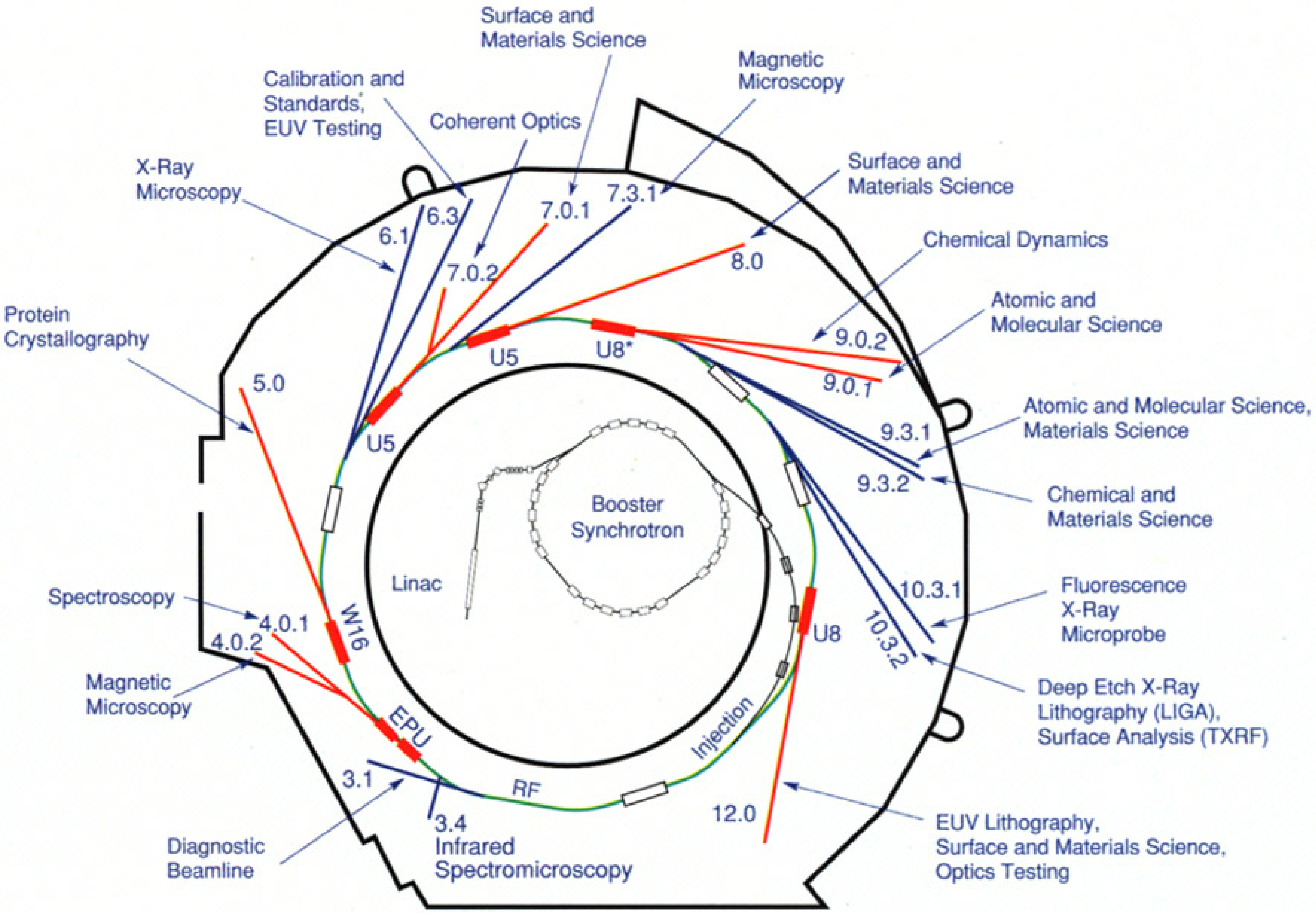


(Following S. Sasaki)

What are the Relative Merits?

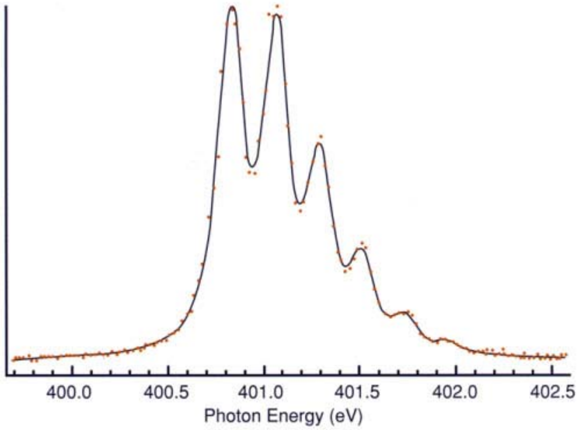
Bending magnet radiation	**Wiggler radiation**	**Undulator radiation**
• Broad spectrum	• Higher photon energies	• Brighter radiation
• Good photon flux	• More photon flux	• Smaller spot size
• No heat load	• Expensive magnet structure	• Partial coherence
• Less expensive	• Expensive cooled optics	•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

A Single Storage Ring Serves Many Scientific User Groups



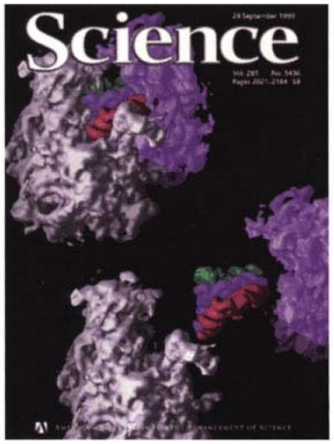
Some Sample Applications

Absorption Fine Structure



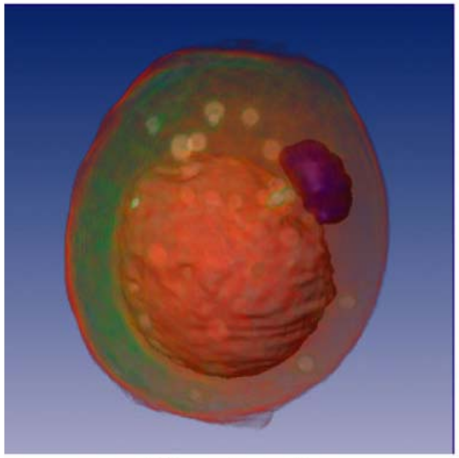
$1s \rightarrow \pi^*$ in N_2

Protein Crystallography



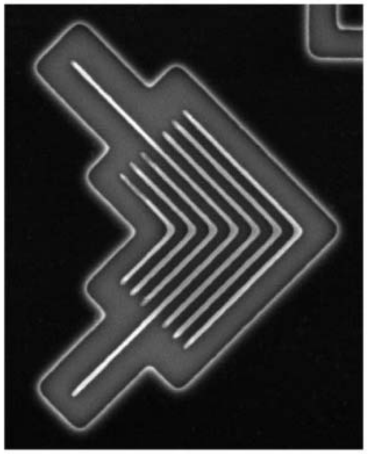
Ribosome structure

Soft X-ray Microscopy



Yeast cell

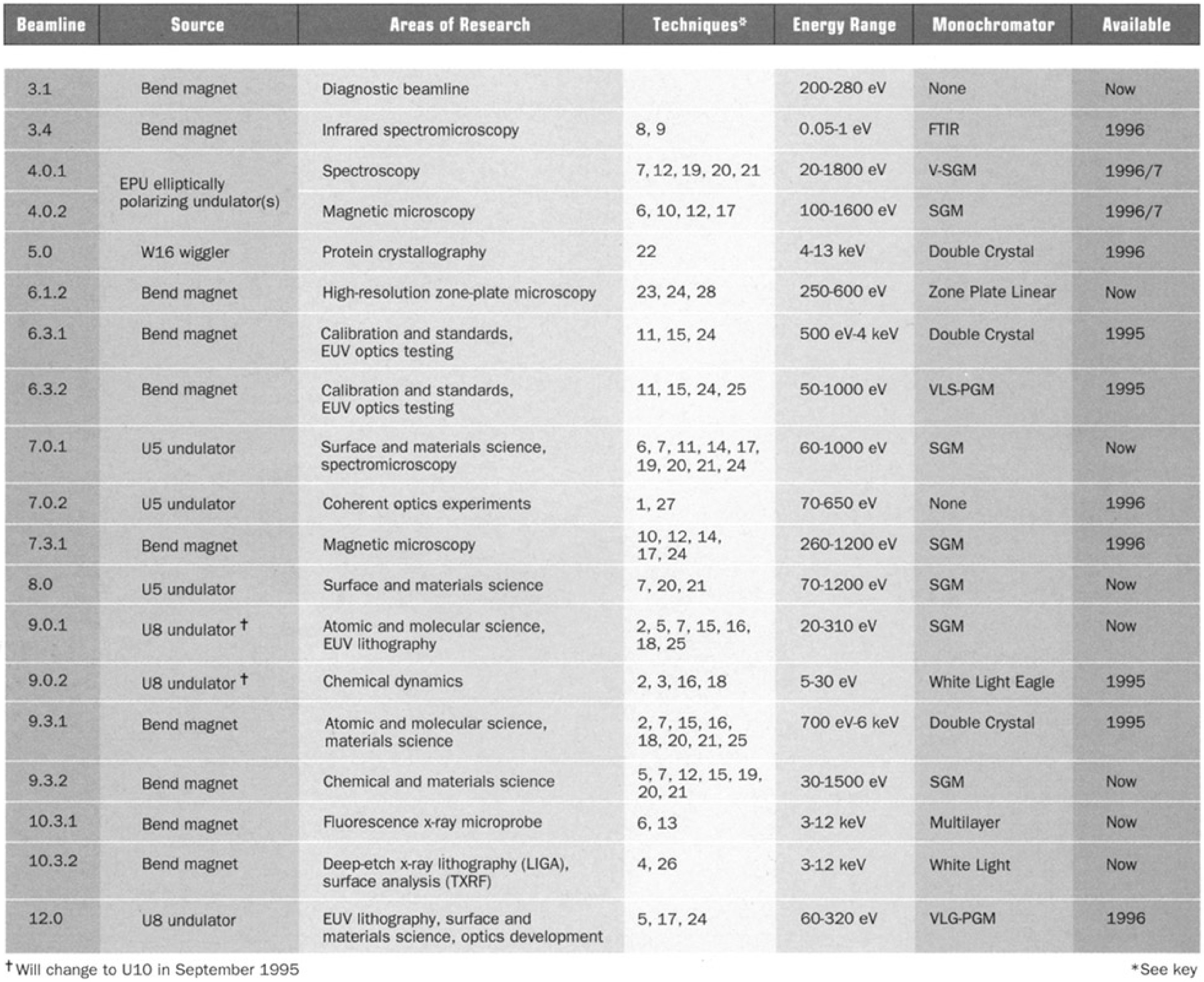
Printing Nanochip Patterns



39 nm elbow pattern

SampleApps.ai

ALS Beamlines After 5 Years

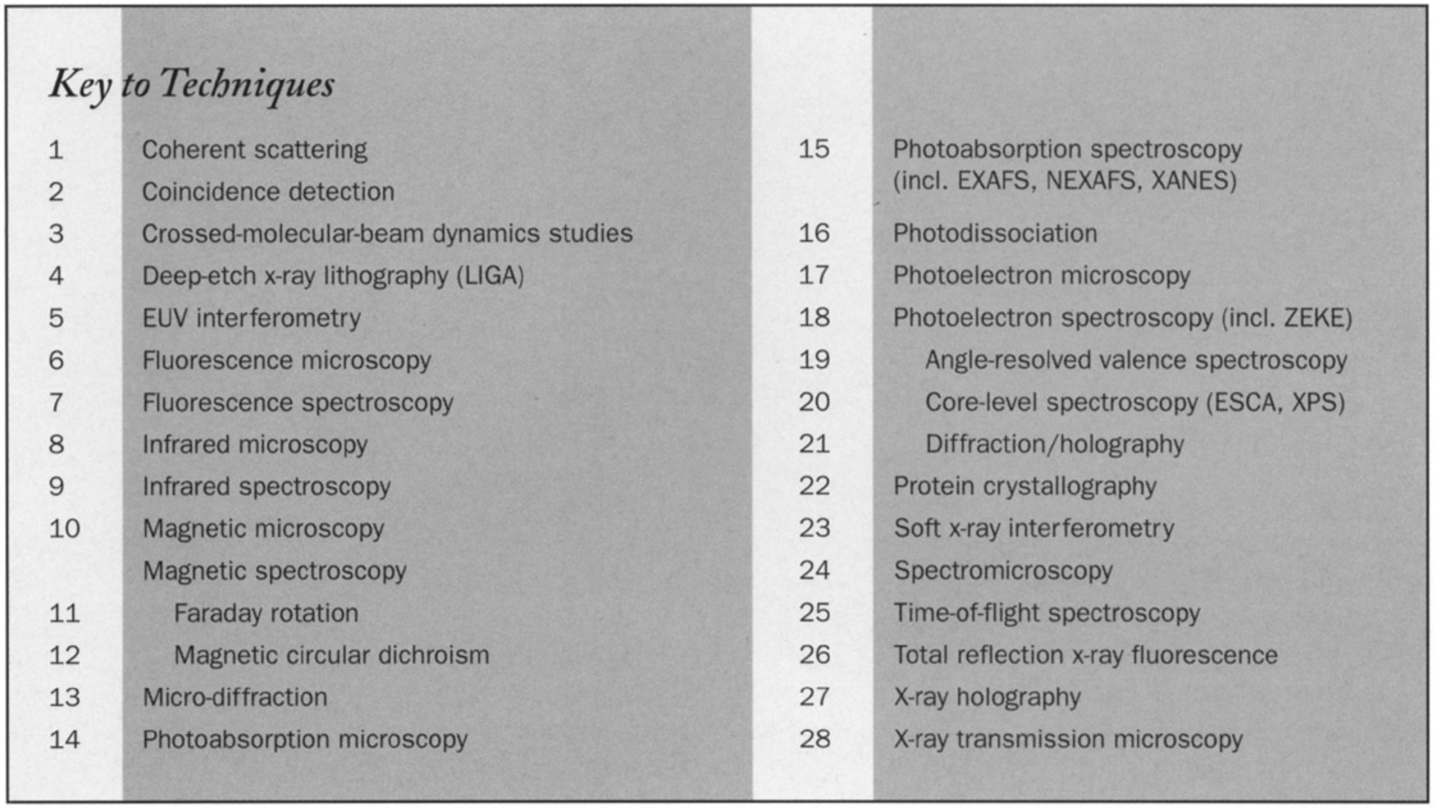


Beamline	Source	Areas of Research	Techniques*	Energy Range	Monochromator	Available
3.1	Bend magnet	Diagnostic beamline		200-280 eV	None	Now
3.4	Bend magnet	Infrared spectromicroscopy	8, 9	0.05-1 eV	FTIR	1996
4.0.1	EPU elliptically polarizing undulator(s)	Spectroscopy	7, 12, 19, 20, 21	20-1800 eV	V-SGM	1996/7
4.0.2		Magnetic microscopy	6, 10, 12, 17	100-1600 eV	SGM	1996/7
5.0	W16 wiggler	Protein crystallography	22	4-13 keV	Double Crystal	1996
6.1.2	Bend magnet	High-resolution zone-plate microscopy	23, 24, 28	250-600 eV	Zone Plate Linear	Now
6.3.1	Bend magnet	Calibration and standards, EUV optics testing	11, 15, 24	500 eV-4 keV	Double Crystal	1995
6.3.2	Bend magnet	Calibration and standards, EUV optics testing	11, 15, 24, 25	50-1000 eV	VLS-PGM	1995
7.0.1	U5 undulator	Surface and materials science, spectromicroscopy	6, 7, 11, 14, 17, 19, 20, 21, 24	60-1000 eV	SGM	Now
7.0.2	U5 undulator	Coherent optics experiments	1, 27	70-650 eV	None	1996
7.3.1	Bend magnet	Magnetic microscopy	10, 12, 14, 17, 24	260-1200 eV	SGM	1996
8.0	U5 undulator	Surface and materials science	7, 20, 21	70-1200 eV	SGM	Now
9.0.1	U8 undulator †	Atomic and molecular science, EUV lithography	2, 5, 7, 15, 16, 18, 25	20-310 eV	SGM	Now
9.0.2	U8 undulator †	Chemical dynamics	2, 3, 16, 18	5-30 eV	White Light Eagle	1995
9.3.1	Bend magnet	Atomic and molecular science, materials science	2, 7, 15, 16, 18, 20, 21, 25	700 eV-6 keV	Double Crystal	1995
9.3.2	Bend magnet	Chemical and materials science	5, 7, 12, 15, 19, 20, 21	30-1500 eV	SGM	Now
10.3.1	Bend magnet	Fluorescence x-ray microprobe	6, 13	3-12 keV	Multilayer	Now
10.3.2	Bend magnet	Deep-etch x-ray lithography (LIGA), surface analysis (TXRF)	4, 26	3-12 keV	White Light	Now
12.0	U8 undulator	EUV lithography, surface and materials science, optics development	5, 17, 24	60-320 eV	VLG-PGM	1996

† Will change to U10 in September 1995

*See key

ALS Beamlines After 5 Years (continued)



Key to Techniques

1	Coherent scattering
2	Coincidence detection
3	Crossed-molecular-beam dynamics studies
4	Deep-etch x-ray lithography (LIGA)
5	EUV interferometry
6	Fluorescence microscopy
7	Fluorescence spectroscopy
8	Infrared microscopy
9	Infrared spectroscopy
10	Magnetic microscopy
	Magnetic spectroscopy
11	Faraday rotation
12	Magnetic circular dichroism
13	Micro-diffraction
14	Photoabsorption microscopy
15	Photoabsorption spectroscopy (incl. EXAFS, NEXAFS, XANES)
16	Photodissociation
17	Photoelectron microscopy
18	Photoelectron spectroscopy (incl. ZEKE)
19	Angle-resolved valence spectroscopy
20	Core-level spectroscopy (ESCA, XPS)
21	Diffraction/holography
22	Protein crystallography
23	Soft x-ray interferometry
24	Spectromicroscopy
25	Time-of-flight spectroscopy
26	Total reflection x-ray fluorescence
27	X-ray holography
28	X-ray transmission microscopy

www.als.LBL.gov

www-ssrl.slac.stanford.edu

References

1) D. Attwood, *Soft X-Rays and Extreme Ultraviolet Radiation* (Cambridge, UK, 2000).
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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5) A. Hofmann, *Synchrotron Radiation* (Cambridge, UK, 2004).
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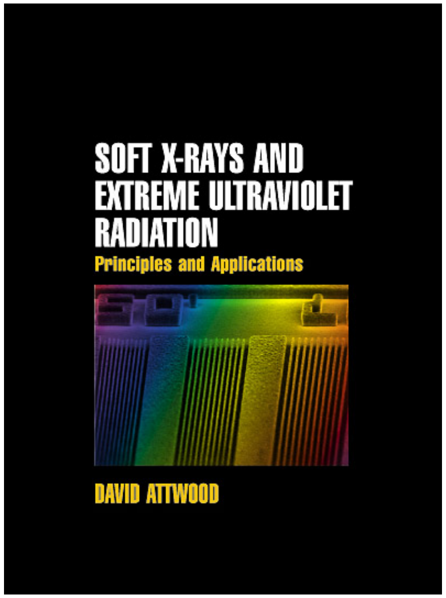
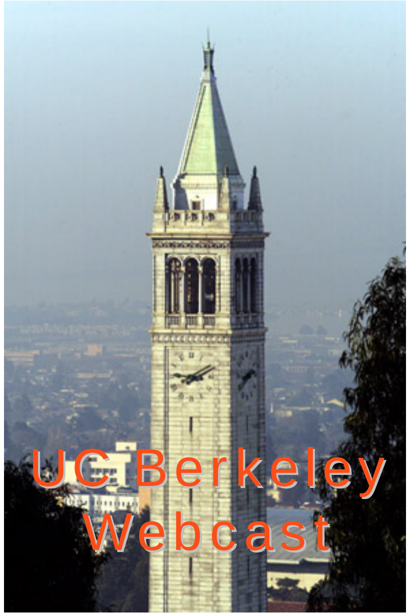


SOFT X-RAYS AND EXTREME ULTRAVIOLET RADIATION

Principles and Applications

DAVID ATTWOOD



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