Introduction to Synchrotron Radiation and Beamlines

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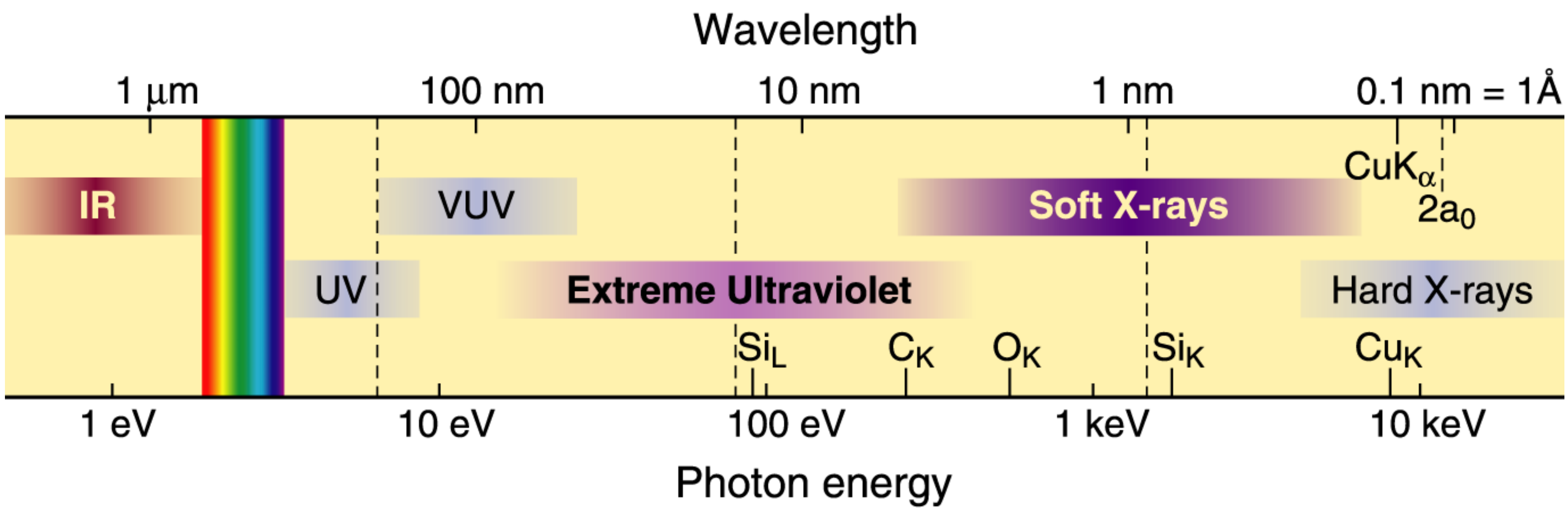
The short wavelength region of the electromagnetic spectrum

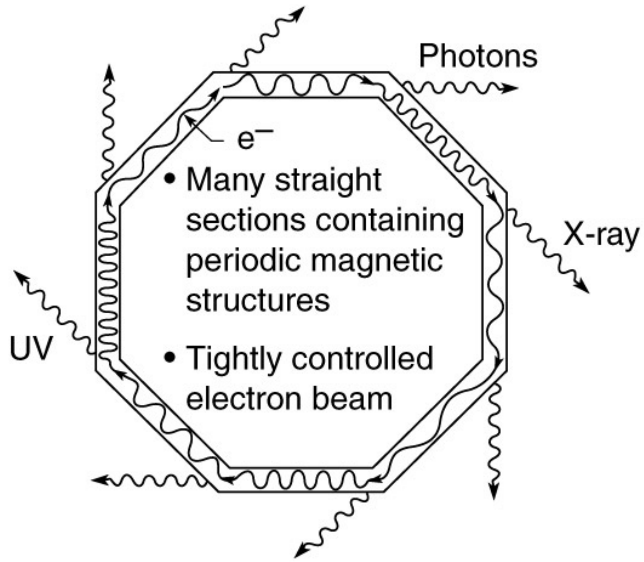


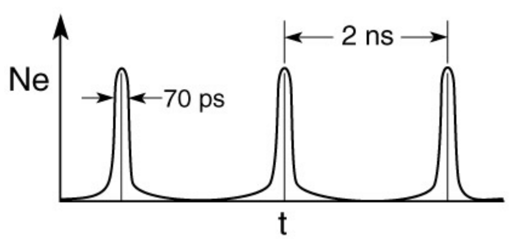
- **See smaller features**
- **Write smaller patterns**
- **Elemental and chemical sensitivity**

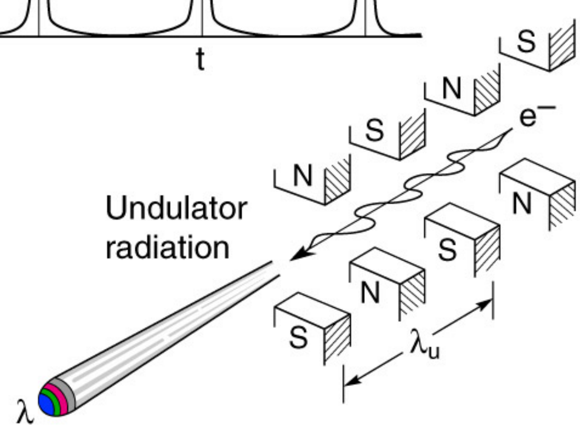
$$\hbar\omega \cdot \lambda = hc = 1239.842 \text{ eV nm}$$

$$n = 1 - \delta + i\beta \qquad \delta, \beta << 1$$

Synchrotron radiation







Bending Magnet:

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

Wiggler:

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

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

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

Undulator:

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

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

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

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

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

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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]

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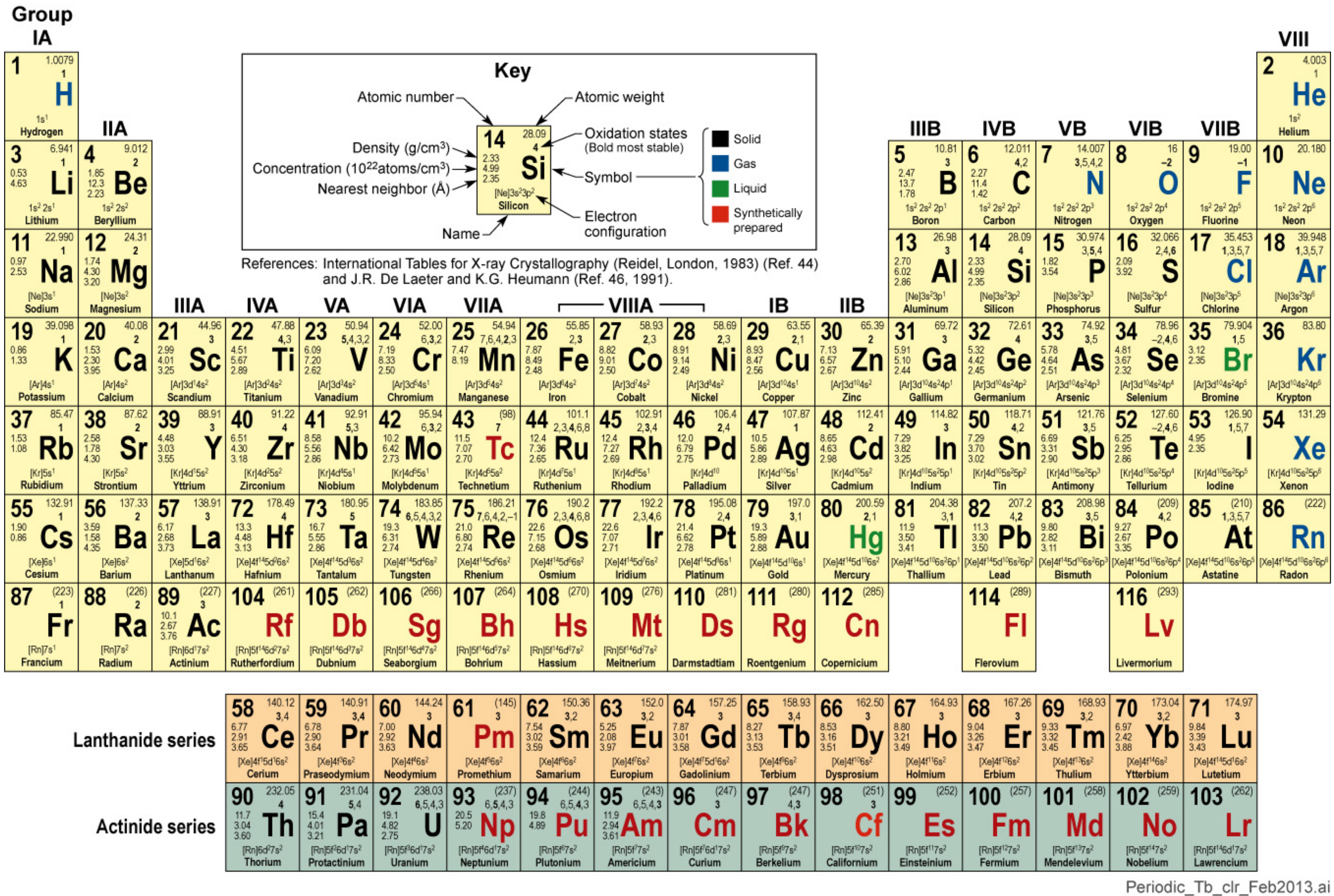
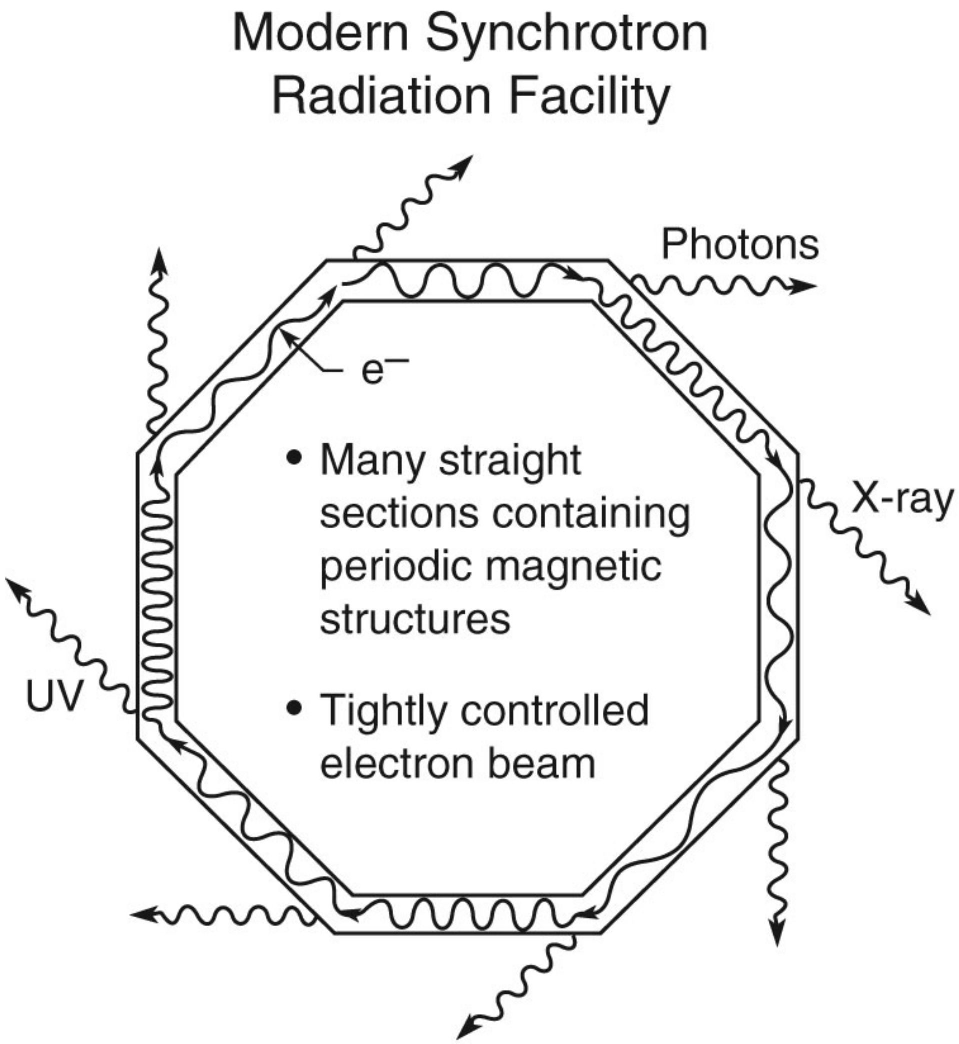
Broadly tunable radiation is needed to probe the primary (n = 1 & n = 2) resonances of the elements



Typical applications of synchrotron radiation

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

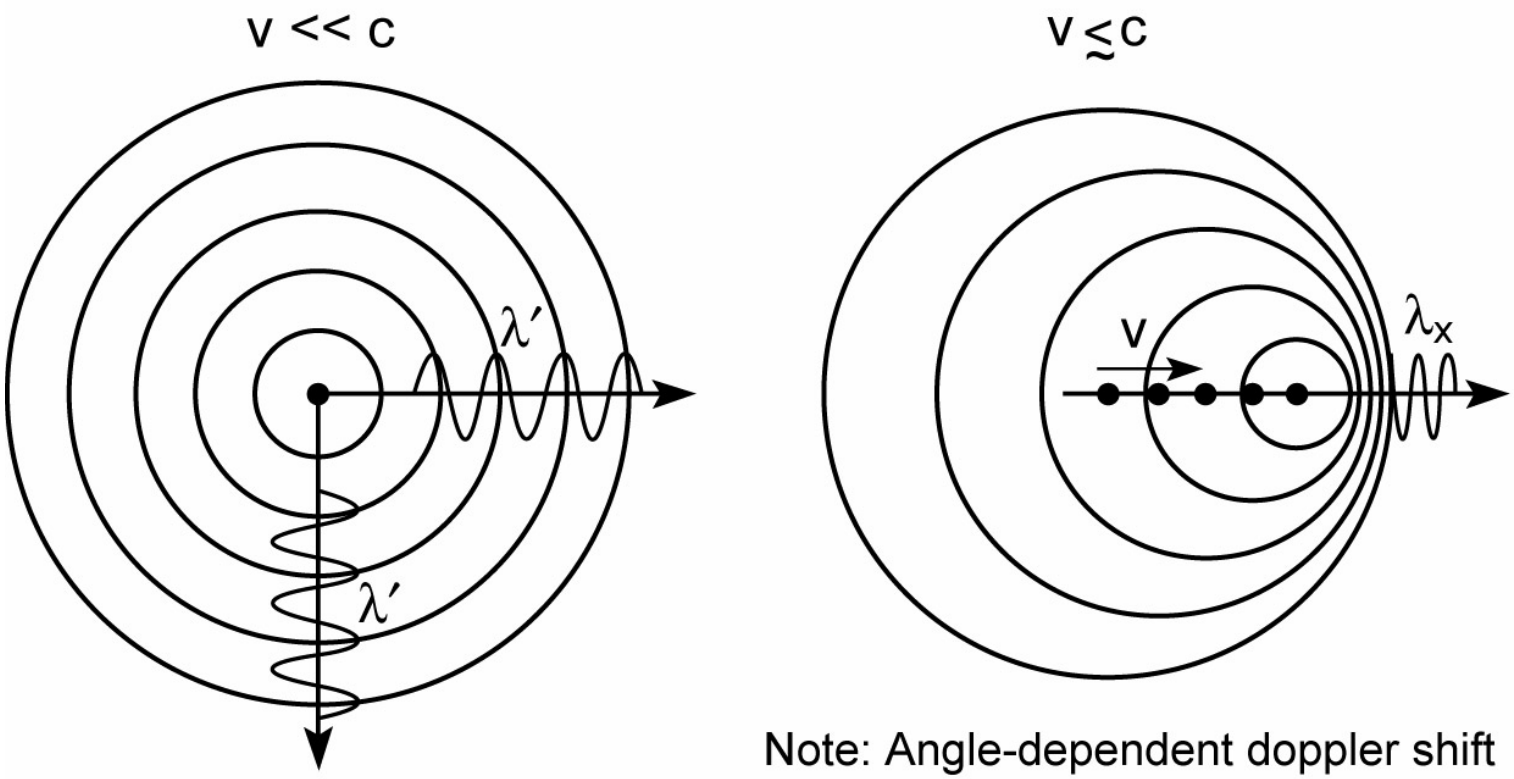
3^{rd} Generation facilities, like Elettra, have many straight sections and a small electron beam



- 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

Synchrotron radiation from relativistic electrons



Note: Angle-dependent doppler shift

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

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

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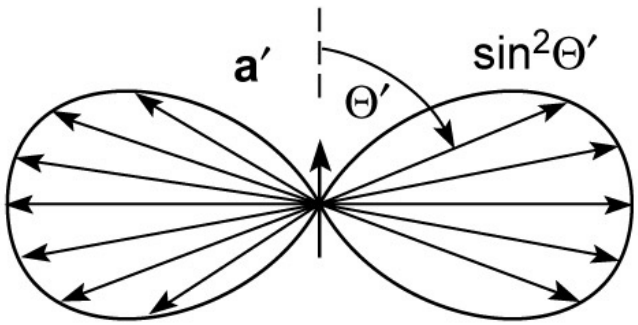
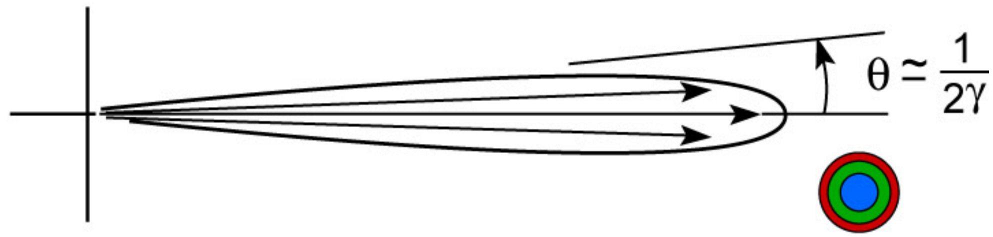
Synchrotron radiation in a narrow forward cone

Frame moving with electron | **Laboratory frame of reference**





$$\tan\theta = \frac{\sin\theta'}{\gamma(\beta + \cos\theta')} \tag{5.1}$$

$$\theta \simeq \frac{1}{2\gamma} \tag{5.2}$$

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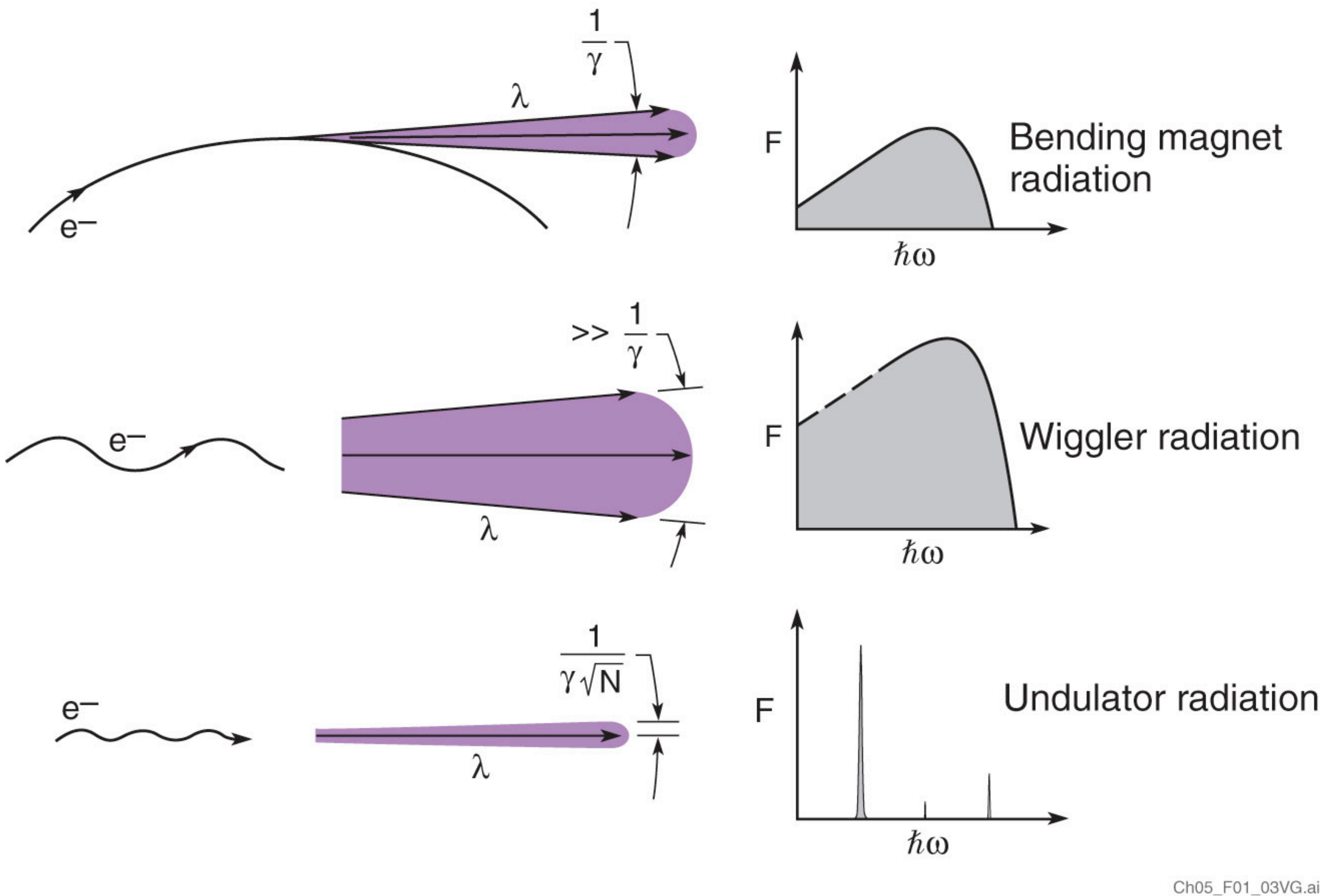
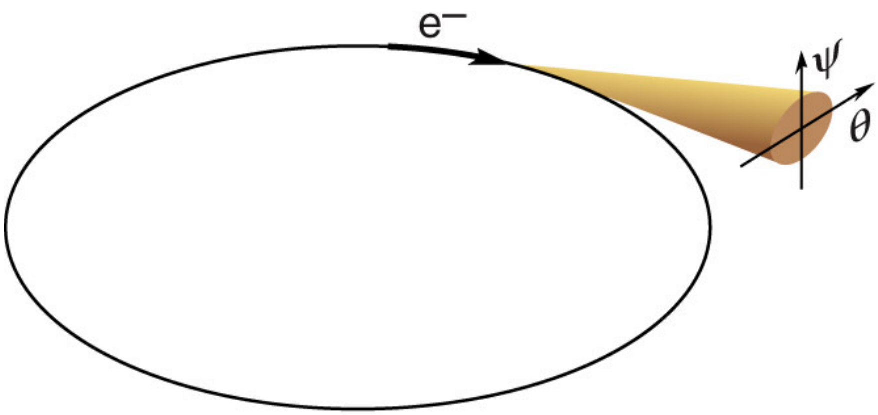
Three forms of synchrotron radiation



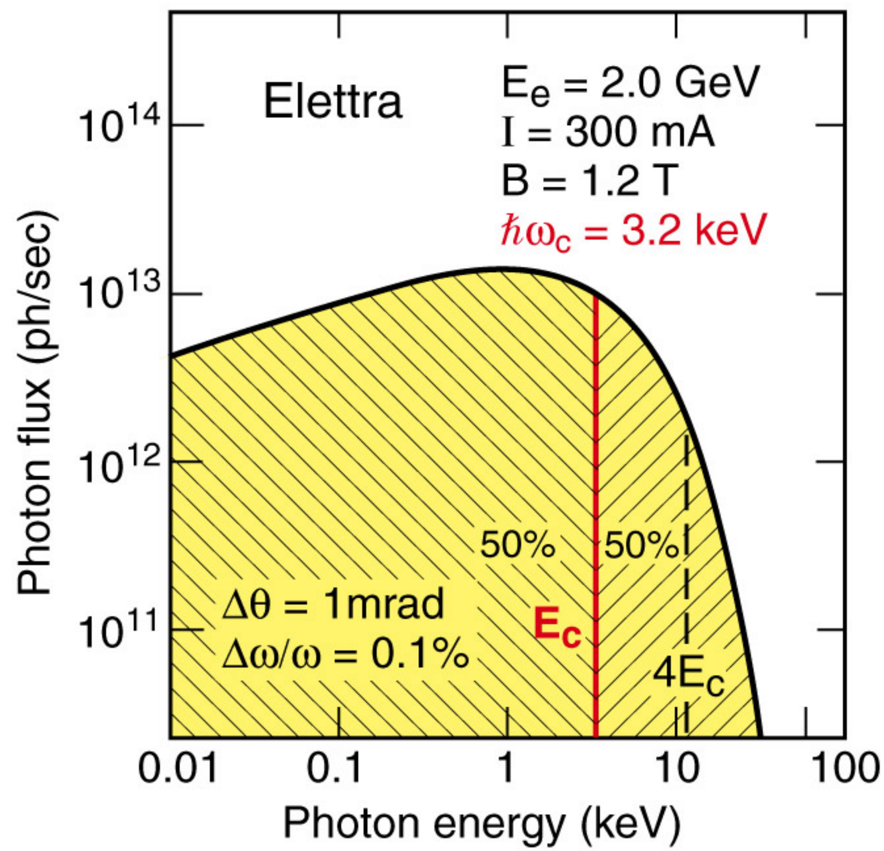
Bending magnet radiation covers a broad region of the spectrum, including the primary absorption edges of most elements



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

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

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



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

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

What is E_c at a facility near you?
What is $4E_c$?

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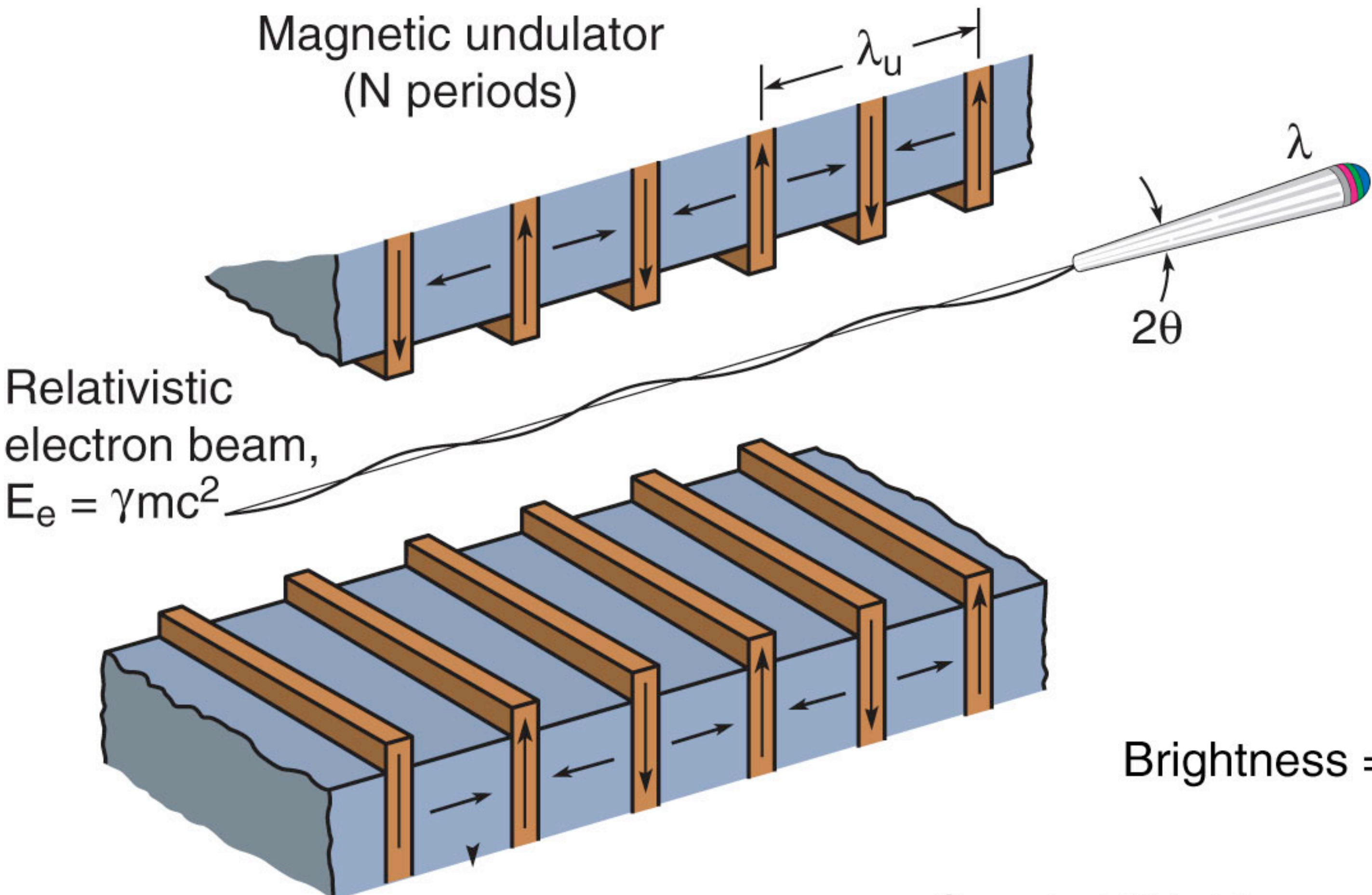
Undulator radiation from a small electron beam radiating into a narrow forward cone is very bright



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

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

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

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

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

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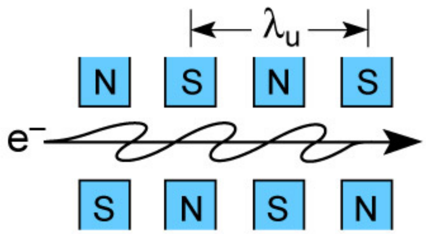
Undulator radiation

Laboratory Frame of Reference

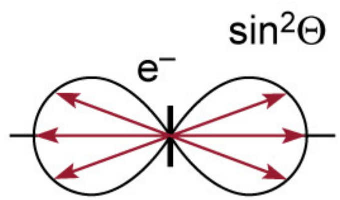


$E = \gamma mc^2$

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

N = # periods

Frame of Moving e⁻



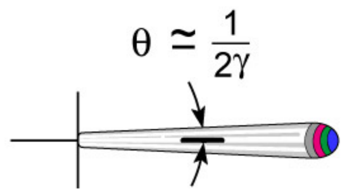
e^- radiates at the Lorentz contracted wavelength:

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

Bandwidth:

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

Frame of Observer



Doppler shortened wavelength on axis:

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

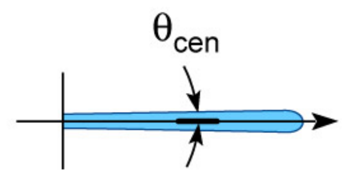
$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + \gamma^2\theta^2)$$

Accounting for transverse motion due to the periodic magnetic field:

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

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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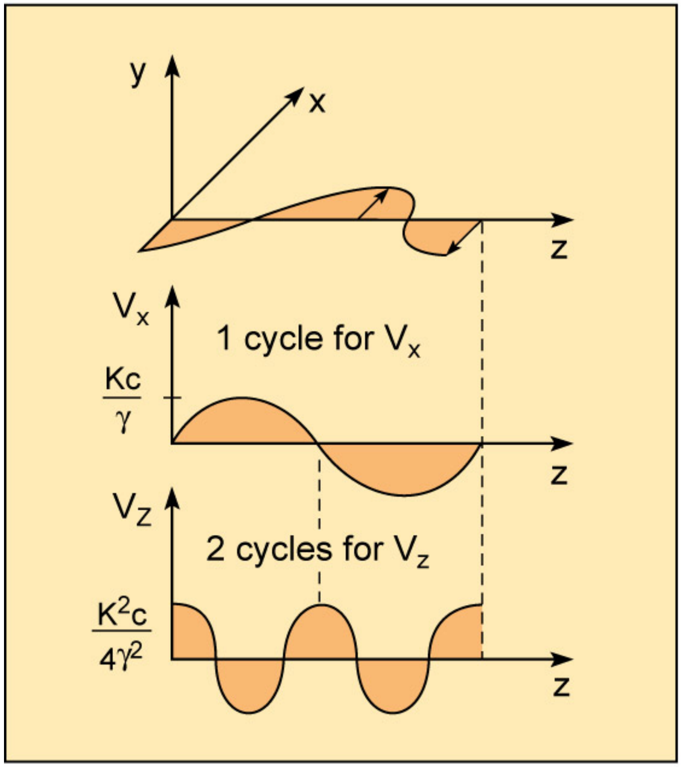
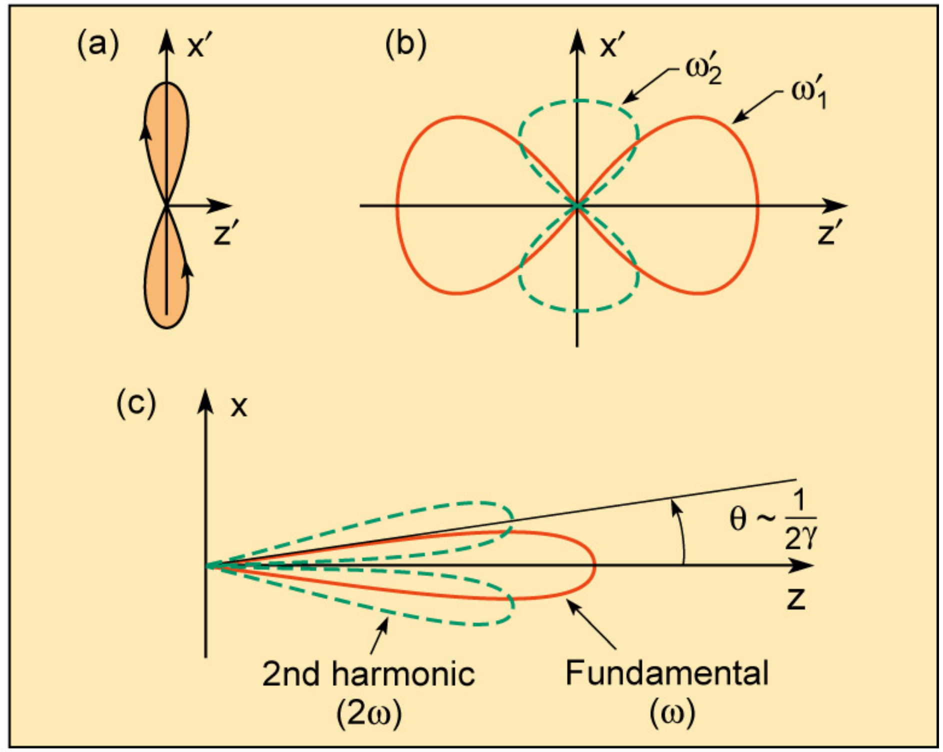
Comments on undulator harmonics

First and second harmonic motions



Radiation patterns in the electron and laboratory frames



$$\lambda_n = \frac{\lambda_u}{2\gamma^2 n}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \qquad (5.30)$$

$$\left(\frac{\Delta\lambda}{\lambda}\right)_n = \frac{1}{nN} \qquad (5.31)$$

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Undulator harmonics

Recall that the axial velocity has a double frequency component

$$v_z = c\left[1 - \frac{1+K^2/2}{2\gamma^2} + \frac{K^2}{4\gamma^2}\cos(2k_u z)\right]$$

which in the frame of reference moving with the electrons, gives

$$z'(t') \simeq \frac{K^2}{8k'_u}\sin 2\omega'_u t' \tag{5.70}$$

where $k'_u = \gamma^* k_u$ and $\omega'_u = \gamma^* \omega_u$. The transverse motion in this frame is

$$x'(t') \simeq -\frac{K}{k_u \gamma}\cos\omega_u\gamma^*\left(t' + \frac{z'}{c}\right)$$

To a higher degree of accuracy, we now keep the z'/c term

$$x'(t') \simeq -\frac{K}{k'_u}\cos\left(\omega'_u t' + \frac{K^2}{8}\sin 2\omega'_u t'\right) \tag{5.71}$$

for small K

$$x'(t') \simeq -\frac{1}{k'_u}\left[K\cos\omega'_u t' + \frac{K^3}{16}\cos 3\omega'_u t'\right] \tag{5.72}$$

Taking second derivatives to find acceleration, and squaring $|a'(t')|^2$

$$\frac{dP'}{d\Omega'} \propto n^4 K^{2n}$$

Thus harmonics grow very rapidly for K > 1.

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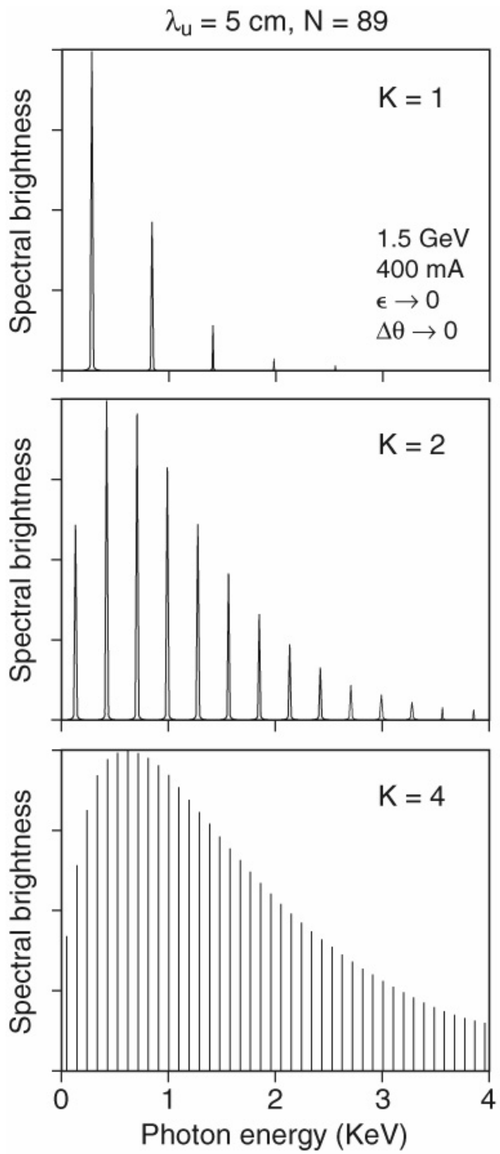
The transition from undulator radiation (K ≲ 1) to wiggler radiation (K >> 1)



Courtesy of K.-J. Kim

Undulator radiation (K ≲ 1)

- Narrow spectral lines
- High spectral brightness
- Partial coherence

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

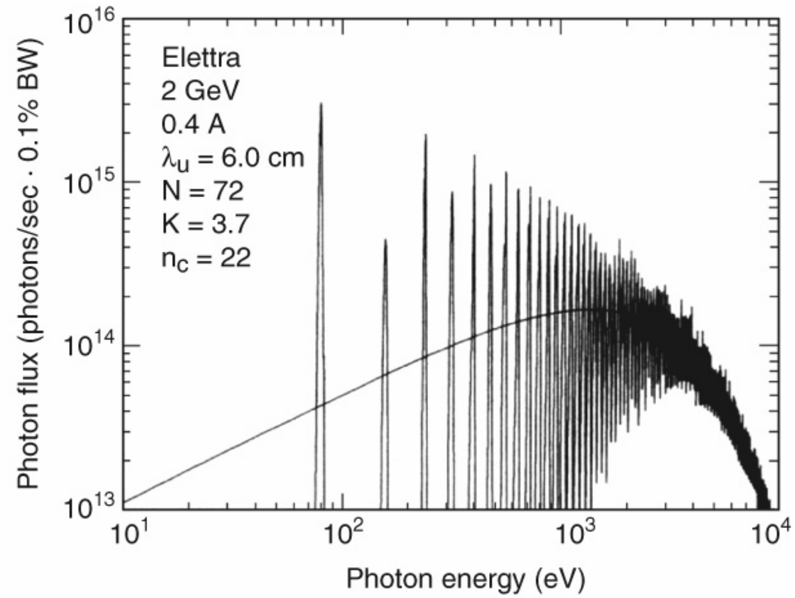
$$K = \frac{eB_o\lambda_u}{2\pi mc}$$

Wiggler radiation (K >> 1)

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

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

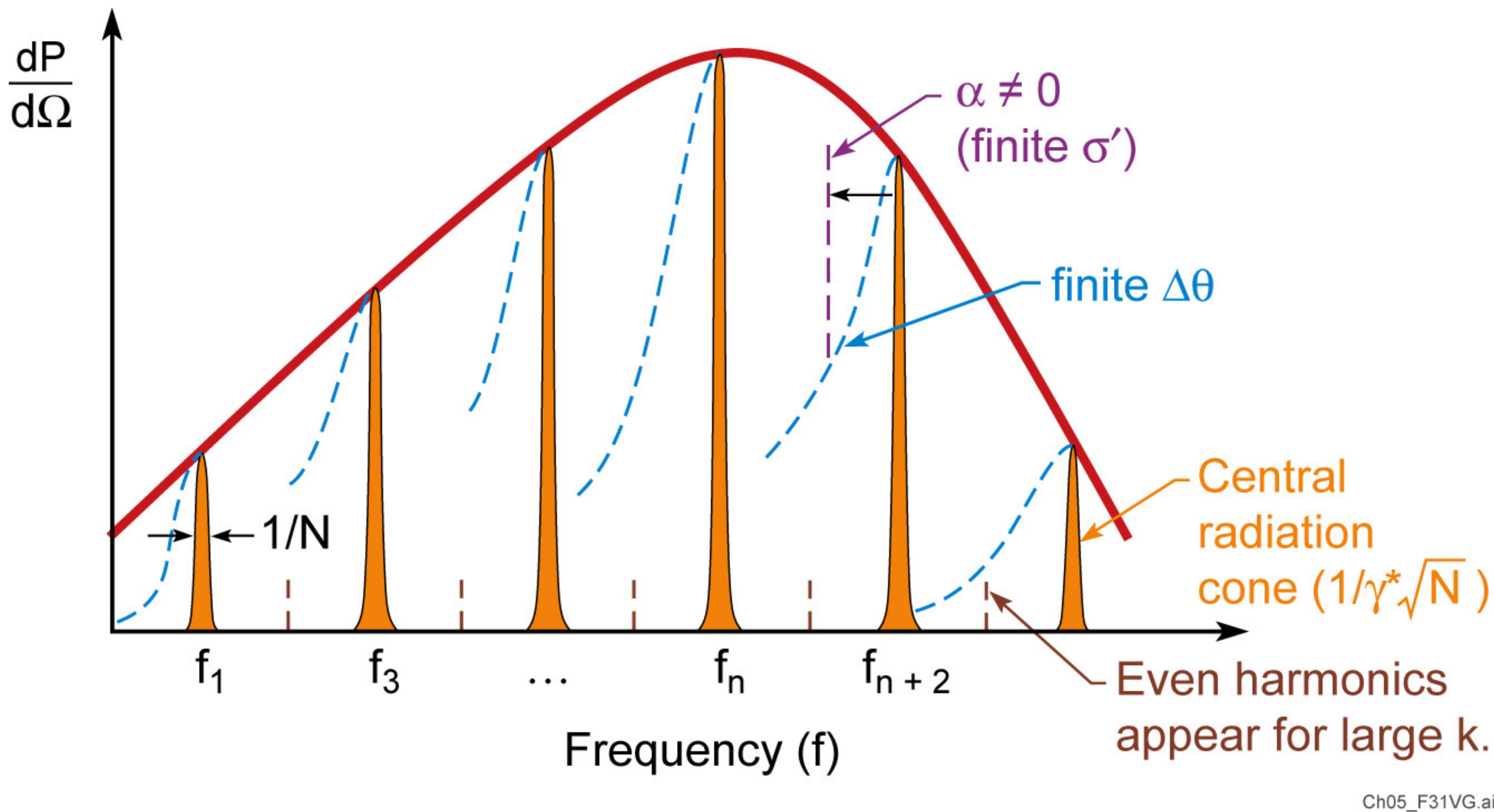
$$n_c = \frac{3K}{4}\left(1 + \frac{K^2}{2}\right)$$



Courtesy of R.P. Walker (Diamond, UK) and B. Diviacco (Elettra, Trieste, Italy)

TransUndRad_WigglerRad.ai

For very large K >> 1, and large Δθ, a continuum emerges



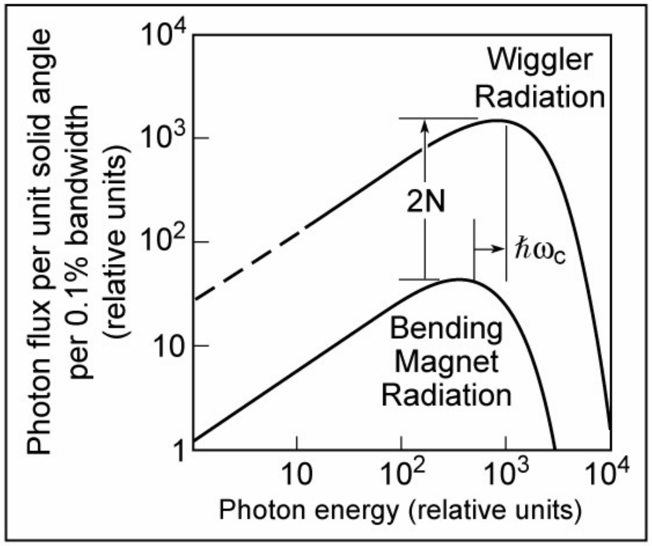
Wiggler radiation

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).

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

$$\left.\frac{d^2F}{d\theta\, d\Psi\, d\omega/\omega}\right|_0 = 2.65\times 10^{13} N E_e^2(\text{GeV}) I(\text{A}) H_2(E/E_c)\frac{\text{photons/s}}{\text{mrad}^2(0.1\%\text{BW})} \qquad (5.86)$$

$$\frac{d^2F}{d\theta\, d\omega/\omega} = 4.92\times 10^{13} N E_e(\text{GeV}) I(\text{A}) G_1(E/E_c)\frac{\text{photons/s}}{\text{mrad}\cdot(0.1\%\text{BW})} \qquad (5.87)$$



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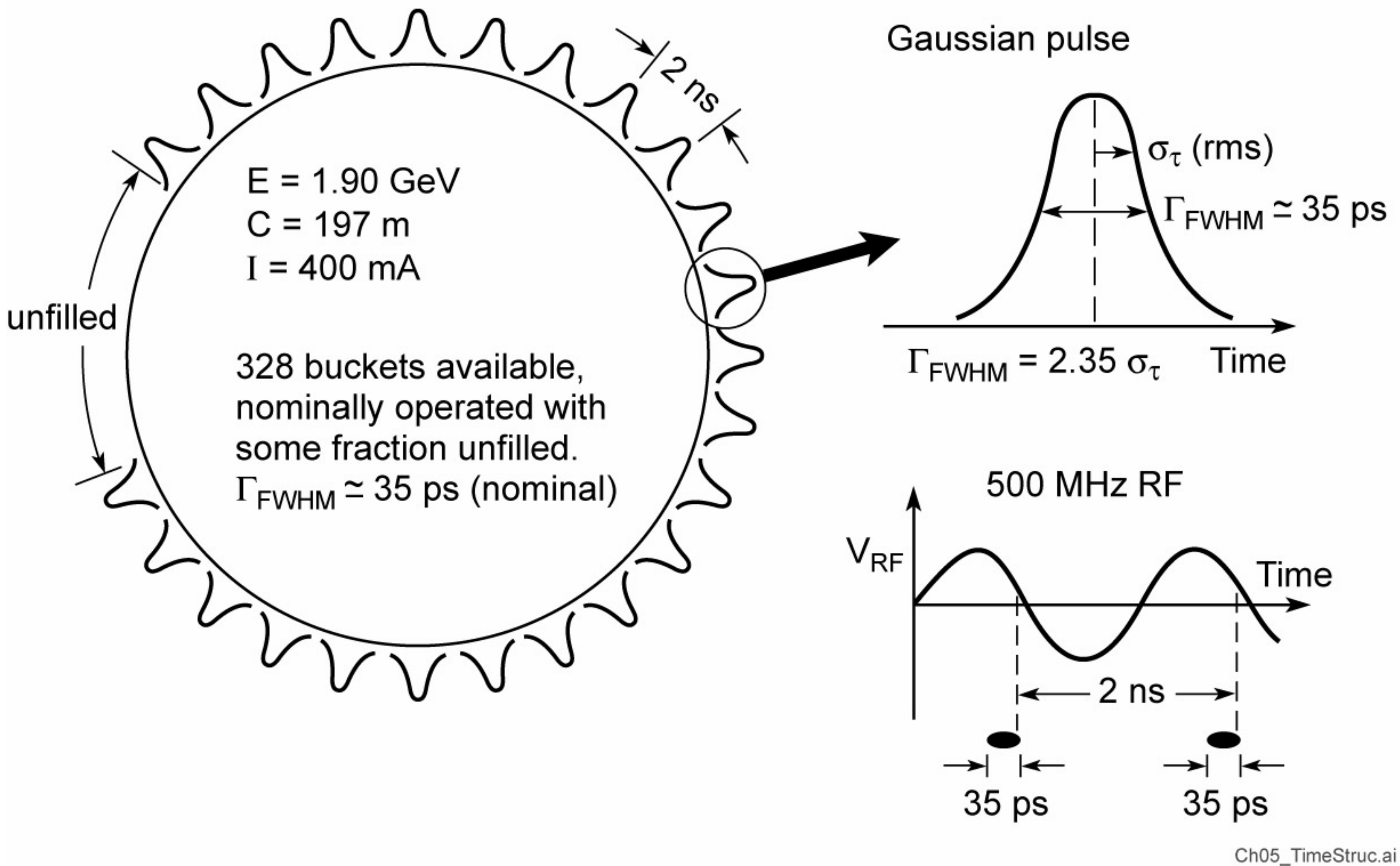
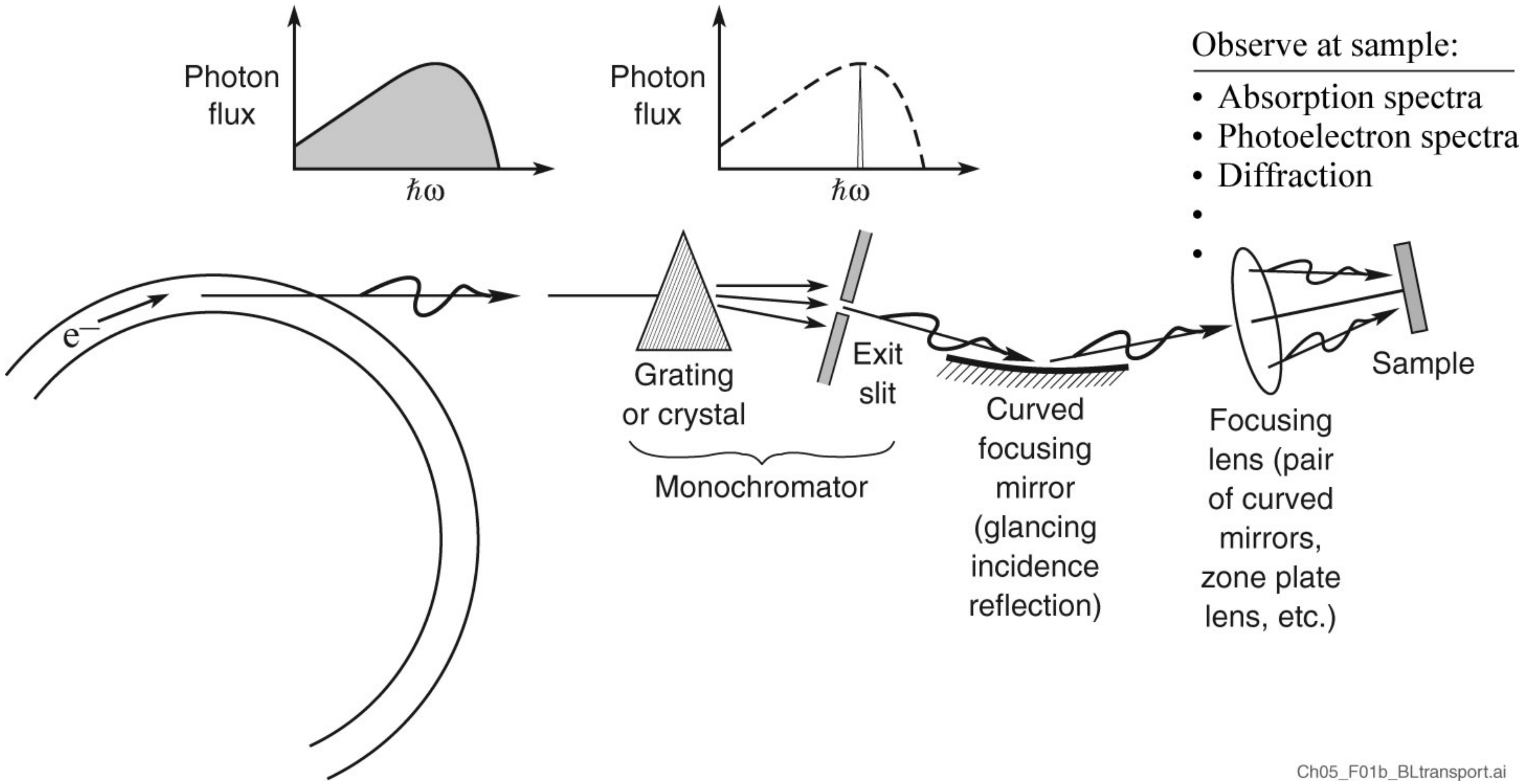
Time structure of synchrotron radiation

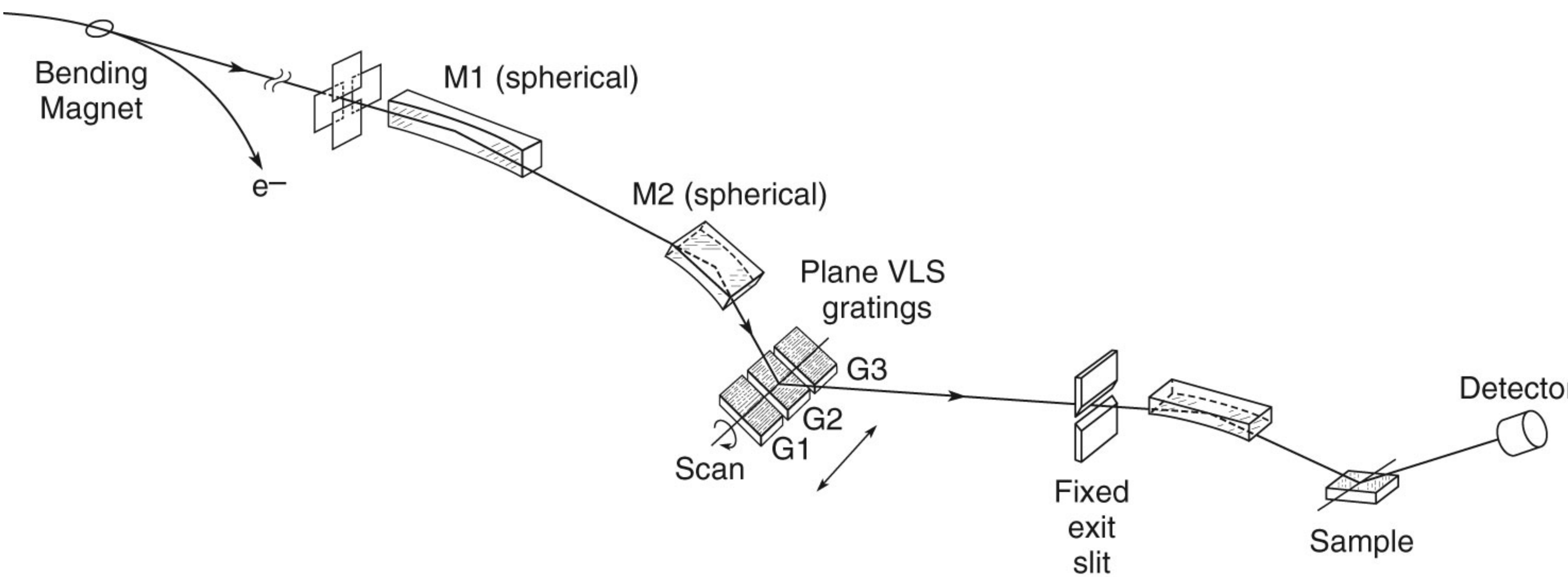
The axial electric field within the RF cavity, used to replenish lost (radiated) energy, forms a potential well "bucket" system that forces electrons into axial electron "bunches". This leads to a time structure in the emitted radiation.



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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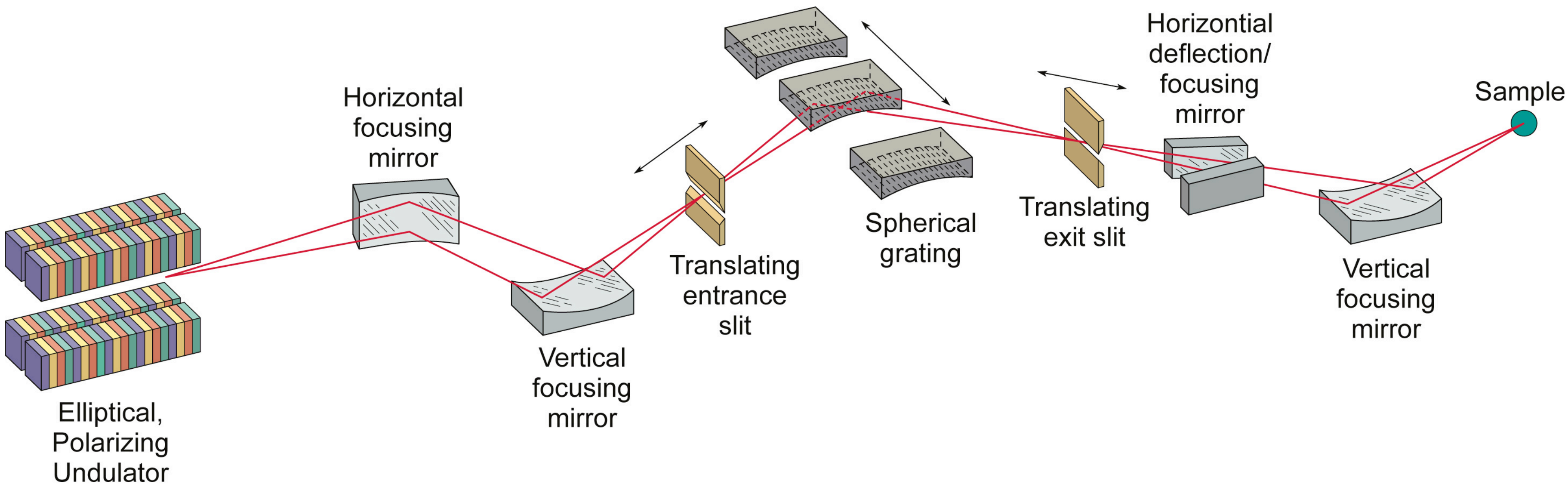
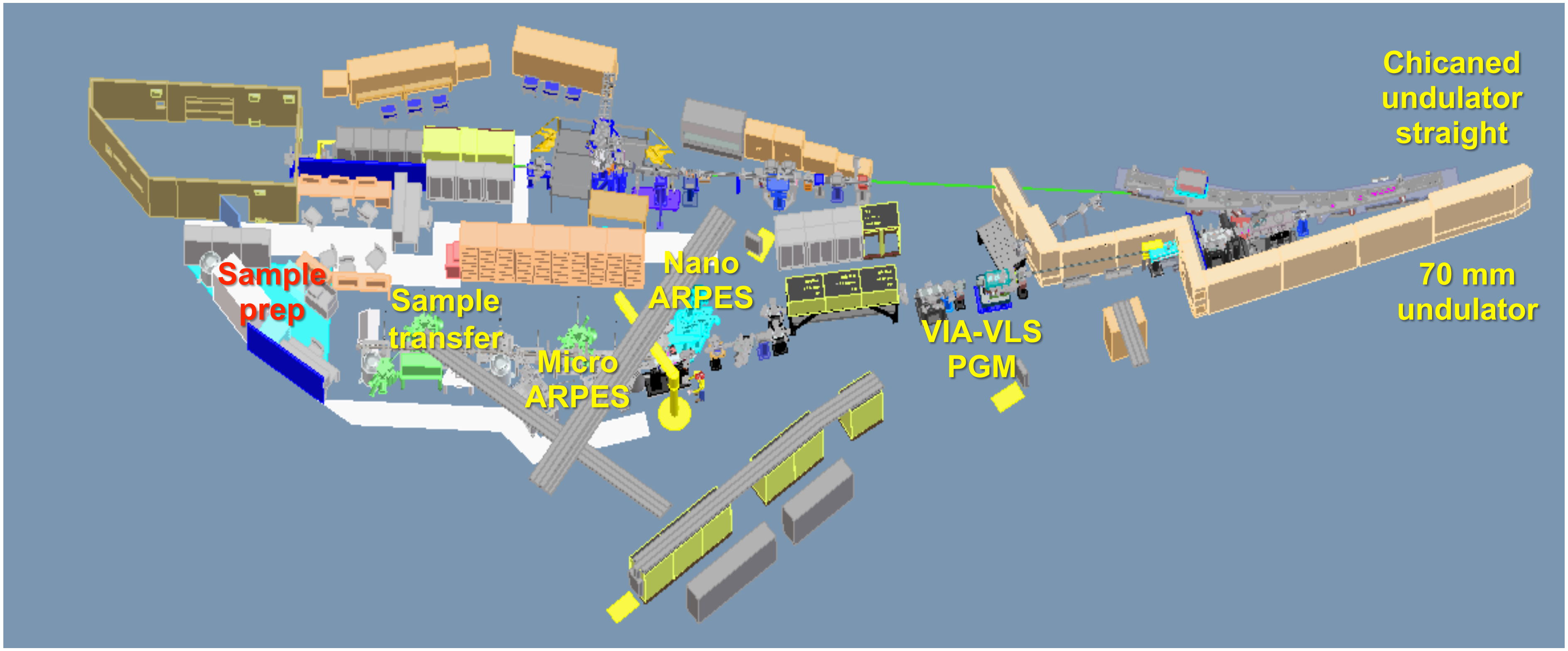
High spectral resolution (meV) beamline



Beamline 7.0 at Berkeley's Advanced Light Source

MAESTRO: A new varied-line-space grating monochromator beam line for angle-resolved-photo-electron-spectroscopy with high spectral and spatial resolution at the Advanced Light Source

Jason Wells, Derek Yegian, Ken Chow, Eli Rotenberg, Aaron Bostwick, Geoff Gaines and Tony Warwick

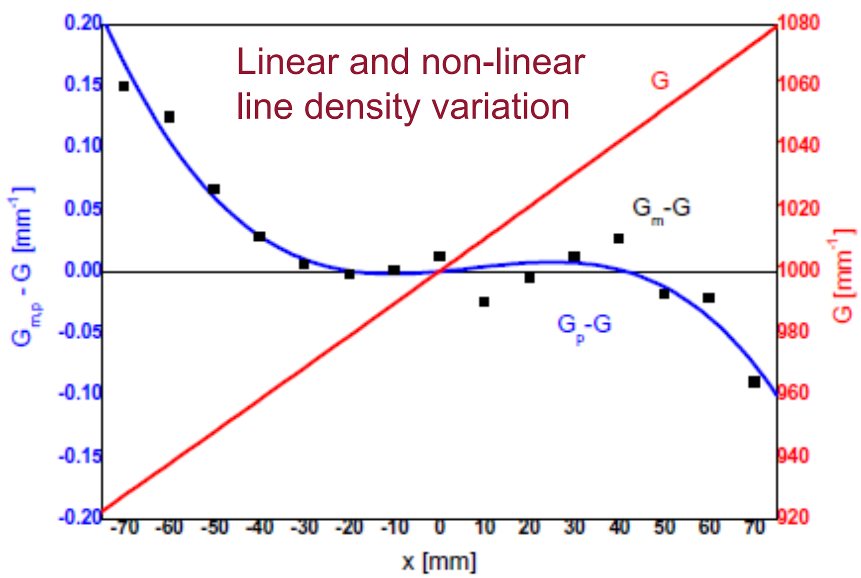


The latest soft x-ray undulator spectroscopy beam line planned for the ALS serves **MAESTRO** a new high resolution Angle Resolved Photo Emission facility with zone-plate focused nano-ARPES. The beam line design offers spectral resolution 1:30000 from 60eV to 400eV with an extended energy range from 20eV to 1000eV. Challenges include optical figure quality, thermal engineering, source size and stability and vibrations in the monochromator. The optical design is radical in that a VLS grating will provide all of the focusing in the dispersion direction, and the mirrors are plane, except for a sphere to collect and focus horizontally.

Courtesy of Eli Rotenberg and Tony Warwick (ALS)

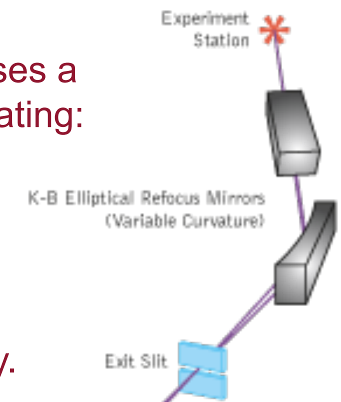
Varied line space gratings

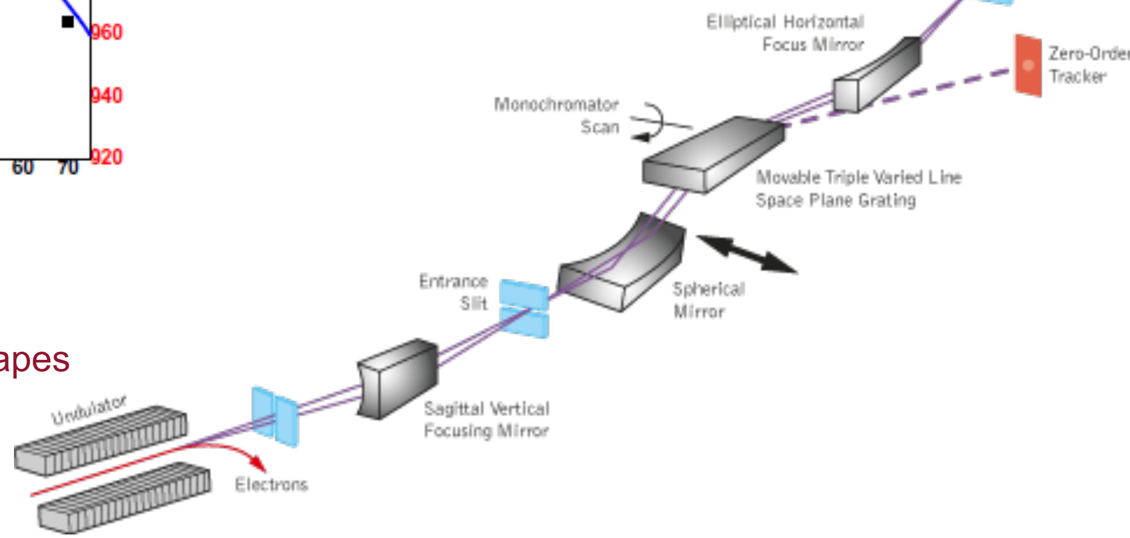
Varied-Line-Space Plane Gratings provide focusing and aberration correction along with the dispersion that they generate in the monochromator. They can be used to erect the monochromator focal plane, making the position of the focus at the exit slit (almost) stationary as the grating rotates to select the photon energy. Beyond that, they are now being used to replace the focusing from shaped optics, making beam lines cheaper and easier to align.

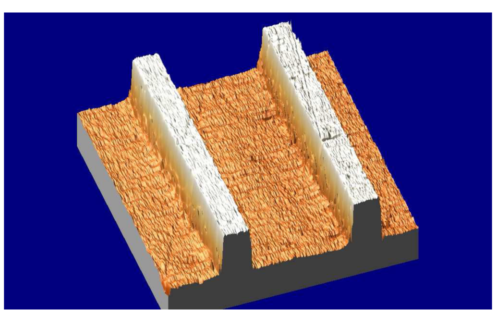


The PEEM3 beam line at 11.0.2 uses a Triple-Ruled Varied-Line-Space grating:

1) to erect the focal plane on a stationary set of exit slits
2) to keep the zero-order light in focus, for easy tuning, and for monitoring of the photon energy.



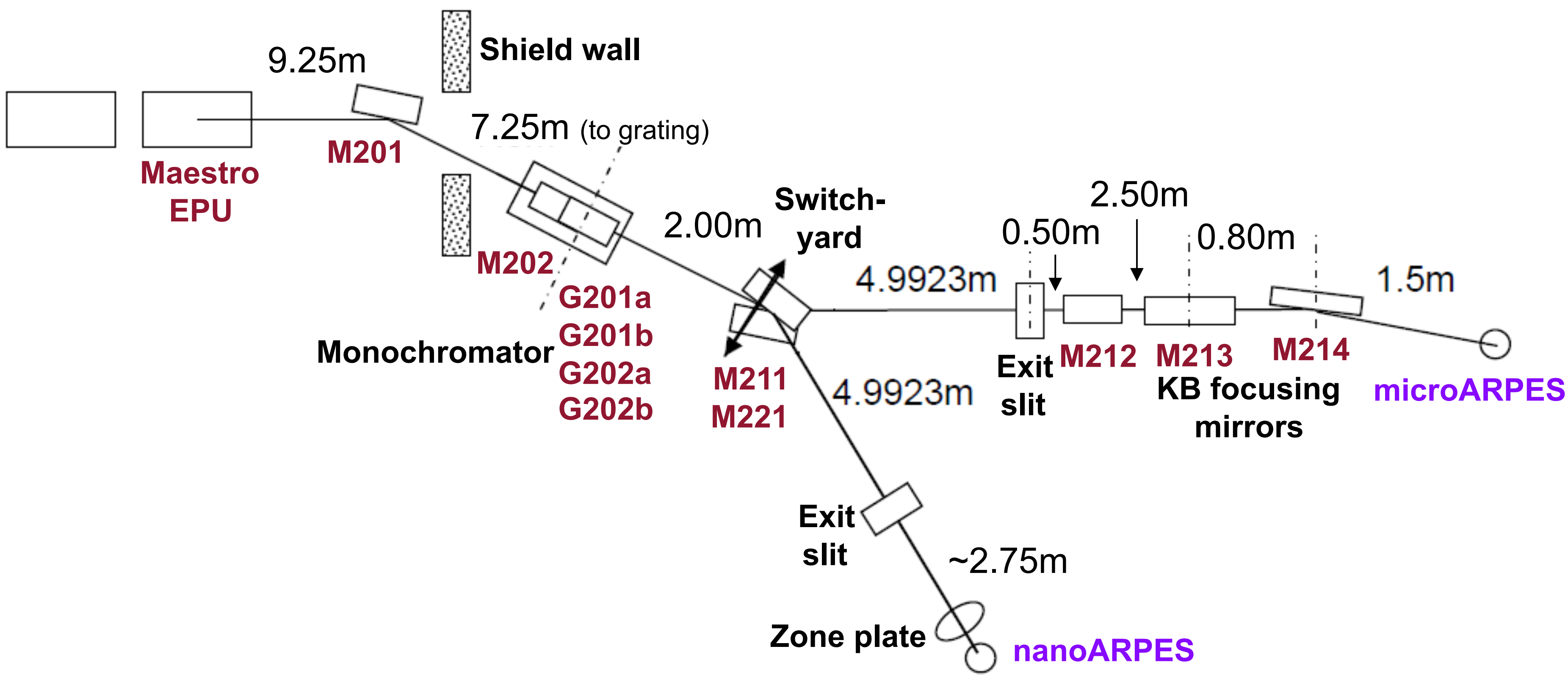




AFM measured groove shapes

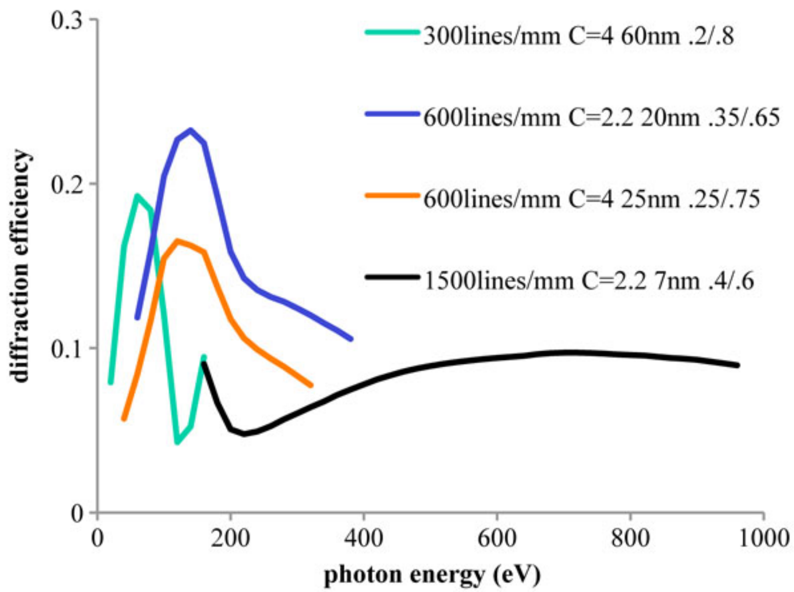
Courtesy of Tony Warwick (ALS)

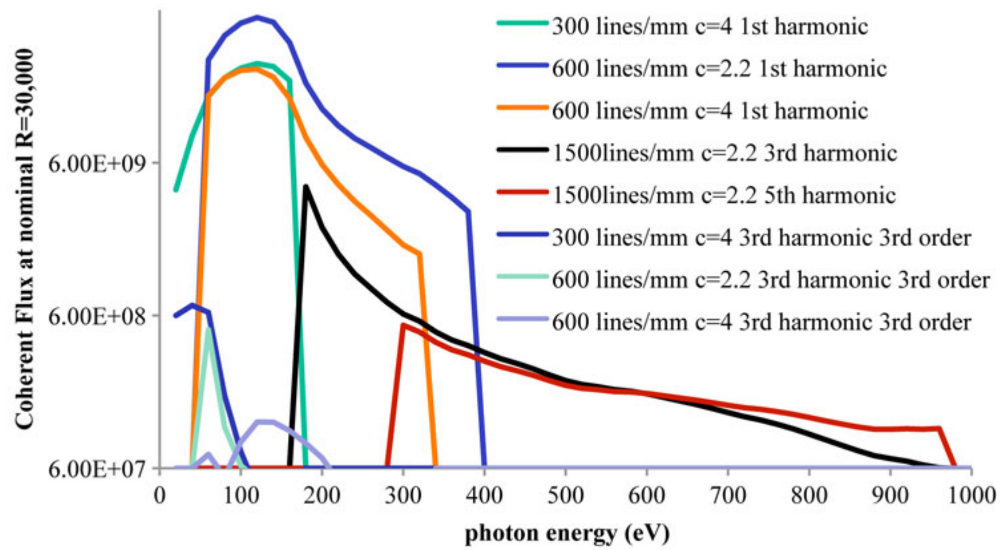
MAESTRO: A new varied-line-space grating monochromator beam line at the ALS



Courtesy of Tony Warwick (ALS)

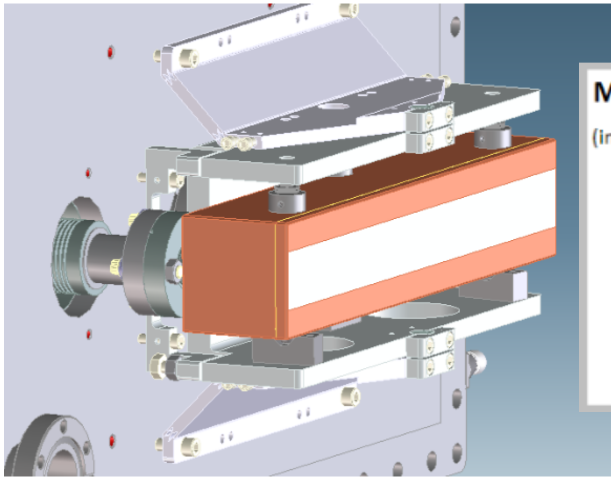
MAESTRO at the ALS: gratings and efficiencies



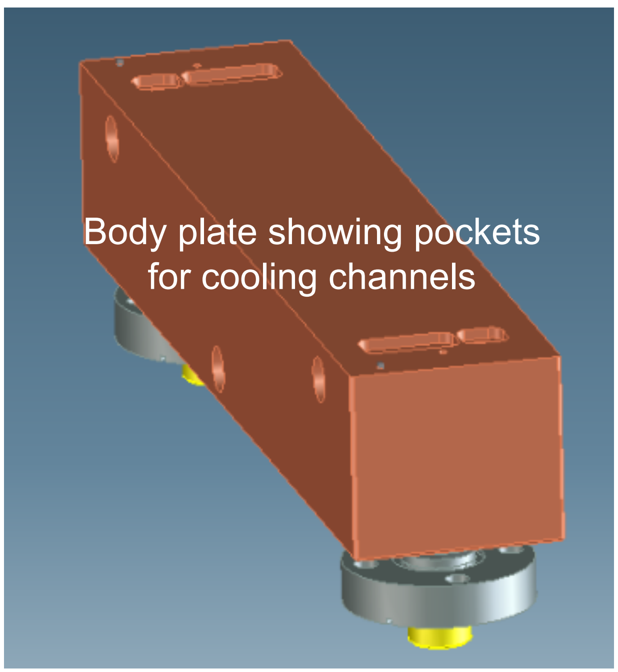


Courtesy of Tony Warwick (ALS)

Water-cooled optics are essential: correcting slope errors due to a thermal bump



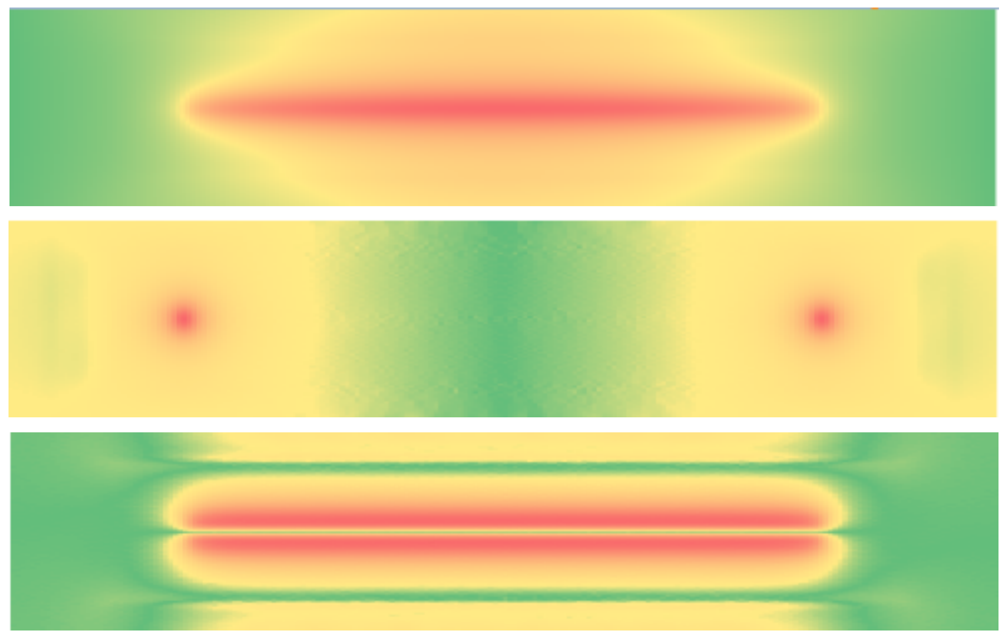
M201 Plane - Slope Errors (μRad)	over full mirror substrate		over clear aperture	
(internally cooled Glidcop, 10K W/m²K)	60eV	20eV	60eV	20eV
Maximum Tangential Slope Error	28.2	61.3	28.2	61.3
Average Tangential Slope Error	2.4	4.9	3.0	6.1
RMS Tangential Slope Error	3.3	7.0	4.4	9.3
Maximum Sagittal Slope Error	36.4	75.1	36.4	75.1
Average Sagittal Slope Error	7.3	15.3	13.9	29.2
RMS Sagittal Slope Error	12.2	25.6	18.0	38.0



Height error

Tangential slope error

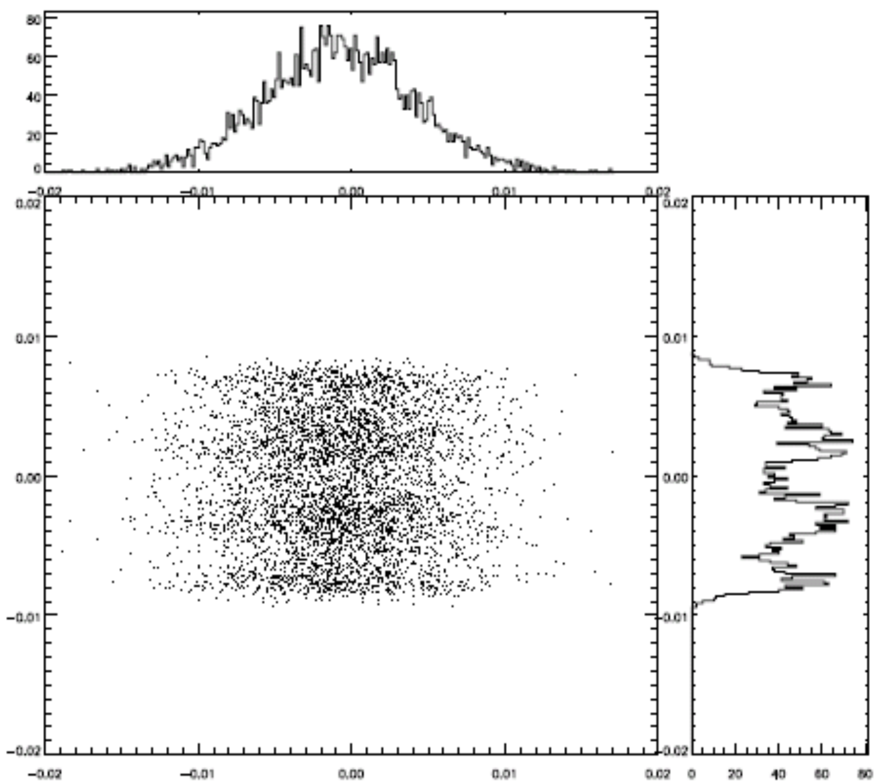
Sagittal slope error



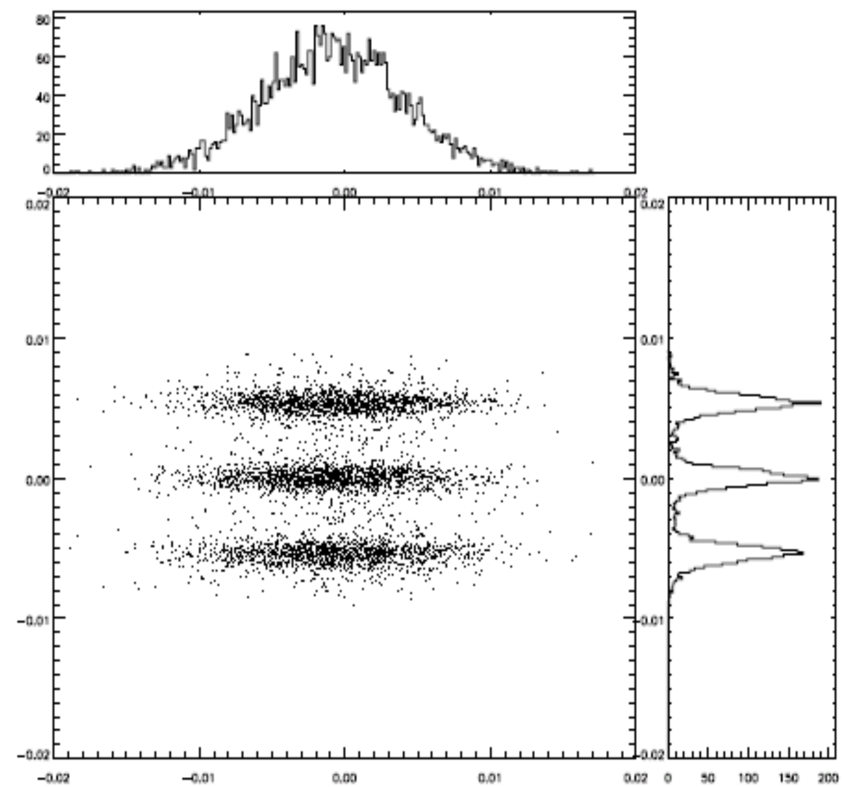
Courtesy of Tony Warwick (ALS)

Ray tracing beamlines is an important tool

Significant degradation of the spectral resolution occurs due to localized heating of M202. It is almost entirely corrected by adjusting the monochromator focusing parameter from 3.93 to 4.02. The engineering design will allow this mirror to be built with 1mm thick hot-wall and the actual thermal deformation is expected to be less.



600lines_60eV_10000_c=3.93034_18.7_0.038_
1.5mmheatbump



600lines_60eV_10000_c=4.02_18.7_0.038_
1.5mmheatbumpcorrected

Courtesy of Tony Warwick (ALS)

References

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The original SHADOW package is available at www.nanotech.wisc.edu/CNTLABS/shadow.html and with an IDL user interface at www.esrf.fr/computing/scientific/xop

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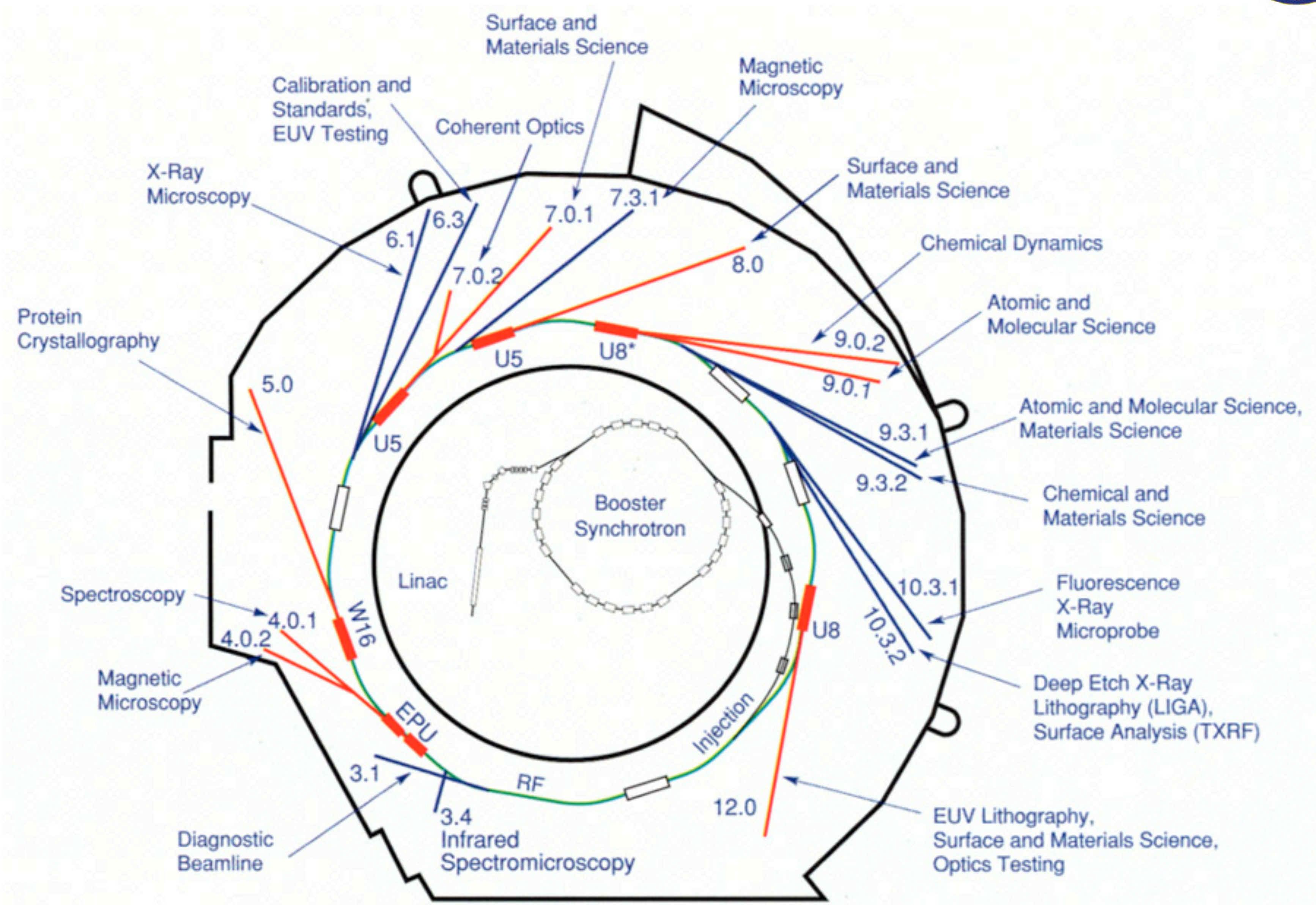
D Fluckiger - Grating Solver Development Company Dec 2006 www.gsolver.com

Courtesy of Tony Warwick (ALS)

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



Typical parameters for synchrotron radiation

Facility	ALS	ELETTRA	Australian Synchrotron	APS
Electron energy	1.90 GeV	2.0 GeV	3.0 GeV	7.00 GeV
γ	3720	3910	5871	13,700
Current (mA)	400	300	200	100
Circumference (m)	197	259	216	1100
RF frequency (MHz)	500	500	500	352
Pulse duration (FWHM) (ps)	35-70	37	~100	100
Bending Magnet Radiation:				
Bending magnet field (T)	1.27	1.2	1.31	0.599
Critical photon energy (keV)	3.05	3.2	7.84	19.5
Critical photon wavelength	0.407 nm	0.39 nm	1.58 Å	0.636 Å
Bending magnet sources	24	12	28	35
Undulator Radiation:				
Number of straight sections	12	12	14	40
Undulator period (typical) (cm)	5.00	5.6	22.0	3.30
Number of periods	89	81	80	72
Photon energy ($K = 1, n = 1$)	457 eV	452 eV	2.59 keV	9.40 keV
Photon wavelength ($K = 1, n = 1$)	2.71 nm	2.74 nm	0.478 nm	1.32 Å
Tuning range ($n = 1$)	230-620 eV	2.0-6.7 nm	0.319-0.835 nm	3.5-12 keV
Tuning range ($n = 3$)	690-1800 eV	0.68-2.2 nm	0.106-0.278 nm	10-38 keV
Central cone half-angle ($K = 1$)	35 μrad	35 μrad	23 μrad	11 μrad
Power in central cone ($K = 1, n = 1$) (W)	2.3	1.7	6.6	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	320, 16	320, 50
σ'_x, σ'_y (μrad)	23, 3.9	31, 9	34, 6	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}	1.3×10^{19}	5.9×10^{18}
Total power ($K = 1$, all n, all θ) (W)	83	126	476	350
Other undulator periods (cm)	3.65, 8.00, 10.0	8.0, 12.5	6.8, 18.3	2.70, 5.50, 12.8
Wiggler Radiation:				
Wiggler period (typical) (cm)	16.0	14.0	6.1	8.5
Number of periods	19	30	30	28
Magnetic field (maximum) (T)	2.1	1.5	1.9	1.0
K (maximum)	32	19.6	12	7.9
Critical photon energy (keV)	5.1	4.0	11.4 keV	33
Critical photon wavelength	0.24 nm	0.31 nm	0.11 nm	0.38 Å
Total power (max. K) (kW)	13	7.2	9.3	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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Typical parameters for synchrotron radiation

Facility	ALS	MAX II	BESSY II	APS	ESRF
Electron energy	1.90 GeV	1.50 GeV	1.70 GeV	7.00 GeV	6.04 GeV
γ	3720	2940	3330	13,700	11,800
Current (mA)	400	250	200	100	200
Circumference (m)	197	90	240	1100	884
RF frequency (MHz)	500	500	500	352	352
Pulse duration (FWHM) (ps)	35-70	200	20-50	100	70
Bending Magnet Radiation:					
Bending magnet field (T)	1.27	1.48	1.30	0.599	0.806
Critical photon energy (keV)	3.05	2.21	2.50	19.5	19.6
Critical photon wavelength	0.407 nm	0.560 nm	0.50 nm	0.636 Å	0.634 Å
Bending magnet sources	24	20	32	35	32
Undulator Radiation:					
Number of straight sections	12	10	16	40	32
Undulator period (typical) (cm)	5.00	5.20	4.90	3.30	4.20
Number of periods	89	49	84	72	38
Photon energy ($K = 1, n = 1$)	457 eV	274 eV	373 eV	9.40 keV	5.50 keV
Photon wavelength ($K = 1, n = 1$)	2.71 nm	4.53 nm	3.32 nm	1.32 Å	0.225 nm
Tuning range ($n = 1$)	230-620 eV	130-410 eV	140-500 eV	3.5-12 keV	2.6-7.3 keV
Tuning range ($n = 3$)	690-1800 eV	400-1200 eV	410-1100 eV	10-38 keV	7.7-22 keV
Central cone half-angle ($K = 1$)	35 μrad	59 μrad	33 μrad	11 μrad	17 μrad
Power in central cone ($K = 1, n = 1$) (W)	2.3	0.88	0.95	12	14
Flux in central cone (photons/s)	3.1×10^{16}	2.0×10^{16}	1.6×10^{16}	7.9×10^{15}	1.6×10^{16}
σ_x, σ_y (μm)	260, 16	300, 45	314, 24	320, 50	395, 9.9
σ'_x, σ'_y (μrad)	23, 3.9	26, 20	18, 12	23, 7	11, 3.9
Brightness ($K = 1, n = 1$)^a [(photons/s)/mm^2 · mrad^2 · (0.1%BW)]	2.3×10^{19}	7.8×10^{17}	4.6×10^{18}	5.9×10^{18}	5.1×10^{18}
Total power ($K = 1$, all n, all θ) (W)	83	17	32	350	480
Other undulator periods (cm)	3.65, 8.00, 10.0	5.88, 6.60	4.1, 5.6, 12.5	2.70, 5.50, 12.8	2.3, 3.2, 5.2, 8.5
Wiggler Radiation:					
Wiggler period (typical) (cm)	16.0	17.4	12.5	8.5	8.0
Number of periods	19	13	32	28	20
Magnetic field (maximum) (T)	2.1	1.80	1.15	1.0	0.81
K (maximum)	32	29.3	12.8	7.9	6.0
Critical photon energy (keV)	5.1	2.69	2.11	33	20
Critical photon wavelength	0.24 nm	0.46 nm	0.59 nm	0.38 Å	0.62 Å
Total power (max. K) (kW)	13	5.9	1.8	7.4	4.8

^{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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Principles and Applications

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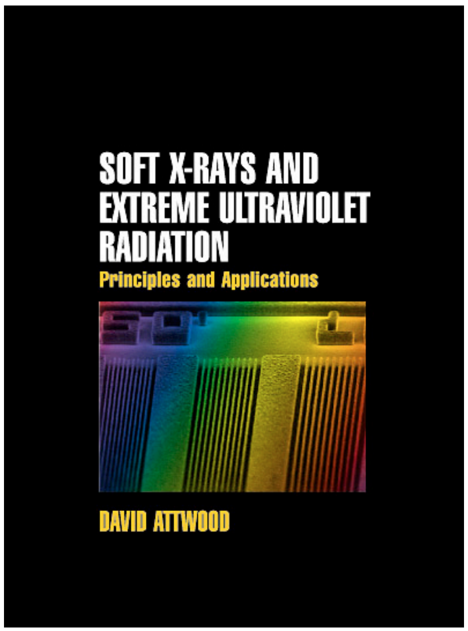

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