

Soft X-ray Physics

- Overview of research in Prof. Tonner's group
- Introduction to synchrotron radiation physics
- Photoemission spectroscopy: band-mapping and photoelectron diffraction
- Magnetic spectroscopy
- X-ray microscopy and spectro-microscopy

Research Projects in Brian Tonner's Group

Magnetic
Nanostructures

Biophysical
Processes in the
Environment

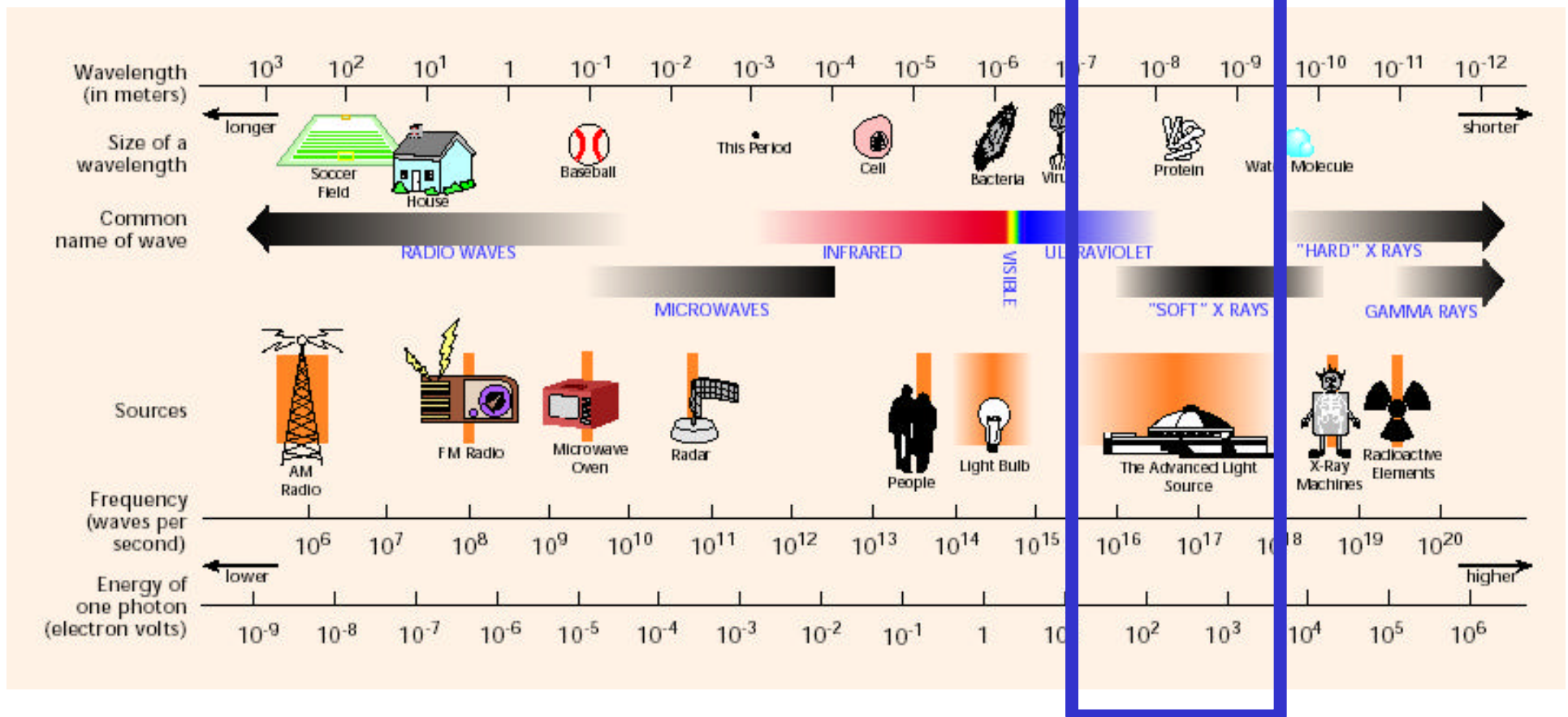
Soft X-ray Spectroscopy

Atomic structure of
surfaces and
interfaces

Biogenic Materials
(Bio-nanostructures)

X-ray Absorption Spectroscopy (XAS), X-ray Photoelectron Spectroscopy (XPS), X-ray Photoelectron Diffraction (XPD), X-ray Magnetic Circular Dichroism (XMCD)

The Soft X-ray Spectrum



Lower Bound: VUV cut-off of absorption in Quartz (about 10 eV) [200nm or 6 eV]

Upper Bound: Absorption edges of light solids, like Be (about 2000 eV).

What makes Soft X-ray Science Important?

- The photon energy exceeds the work function of most materials, so electrons can be removed from the sample
- The photon energy matches the binding energy of the “shallow core-levels” of atoms, which are the narrowest lines with the most chemical information
- It is possible to create beams of soft x-rays with very high coherence, allowing us to do sophisticated x-ray interference experiments

$$\hbar\omega \geq e\Phi$$

$$\hbar\omega \approx eV_B$$

$$I \geq a \cdot \Delta\Theta$$

What makes development of Soft X-ray Science so difficult?

- Sources of radiation were weak, until introduction of synchrotron radiation in early 1970's
- Strong absorption by air requires the use of vacuum beamlines
- Low reflectivity of metals in soft x-ray region (high absorption) means new methods of optics had to be developed

The growth of synchrotron light sources

Brilliance/brightness:

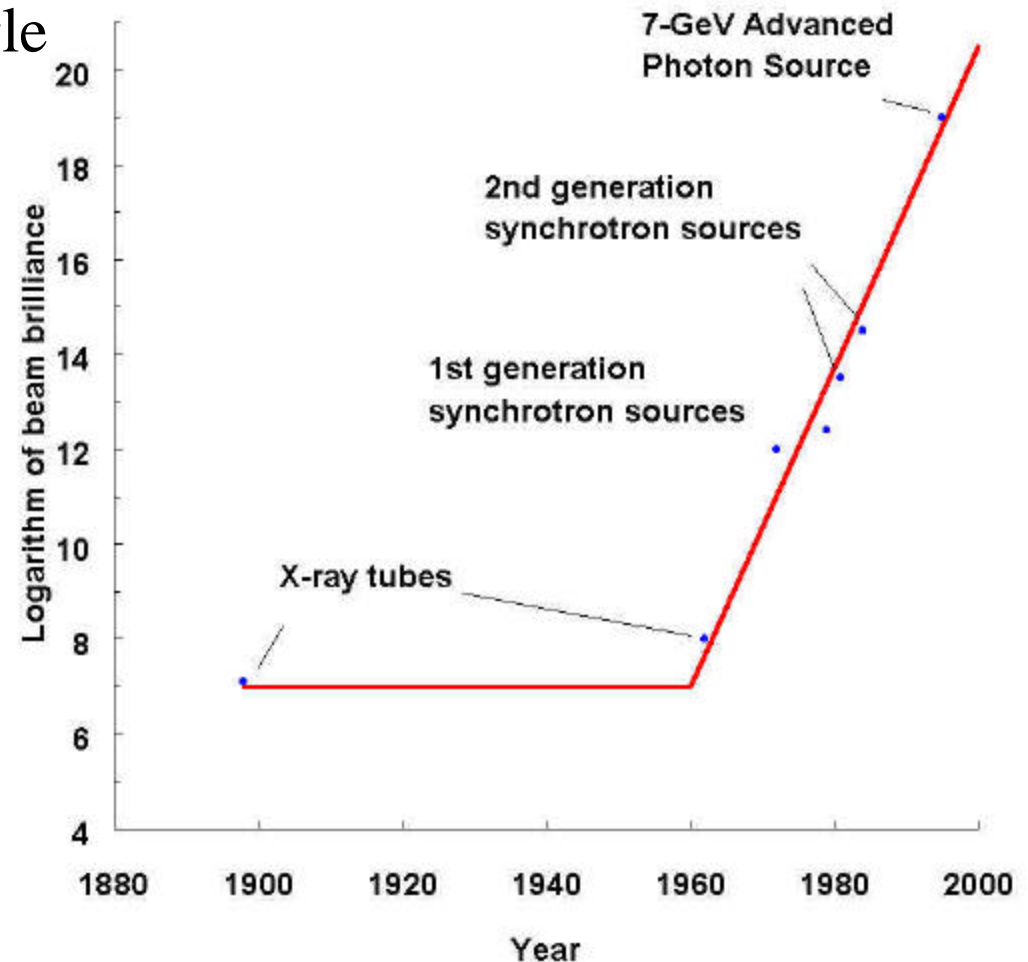
Photons/time/area/solid-angle

Brilliance (brightness) is determined by the emittance of the stored beam in the synchrotron. The emittance is the product of the particle beam cross-sectional area and the angular divergence of the particle beam. It is a few nanometers in modern 3rd generation machines.

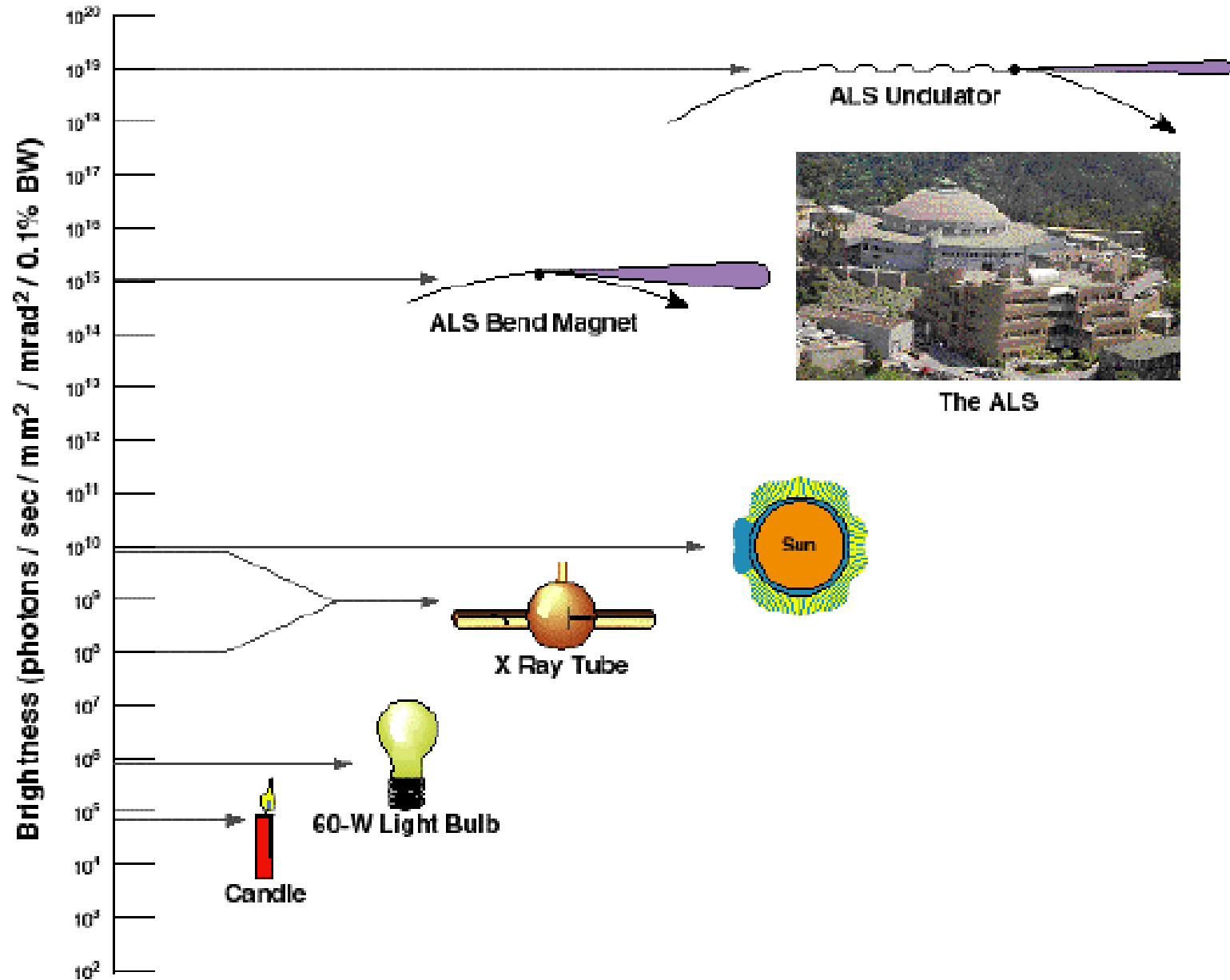
Flux:

Photons/time/area

Flux is determined by the optical system that delivers light to the sample. It is often the parameter most important to the experiment. Because of the limitations of optics, not all light can be collected—only that in a narrow cone of angles. Because of this, FLUX usually scales with BRIGHTNESS.



Brightness of various sources



Synchrotron facilities are flexible soft x-ray sources



The Advanced Light Source at Lawrence Berkeley Lab

Facility layout of a synchrotron

4. Storage Ring

The booster ring feeds electrons into the storage ring, a many-sided donut-shaped tube. The tube is maintained under vacuum, as free as possible of air or other stray atoms that could deflect the electron beam. Computer-controlled magnets keep the beam absolutely true.

Synchrotron light is produced when the bending magnets deflect the electron beam; each set of bending magnets is connected to an experimental station or beamline. Machines filter, intensify, or otherwise manipulate the light at each beamline to get the right characteristics for experiments.

5. Focusing the Beam

Keeping the electron beam absolutely true is vital when the material you're studying is measured in billionths of a metre. This precise control is accomplished with computer-controlled quadrupole (four pole) and sextupole (six pole) magnets. Small adjustments with these magnets act to focus the electron beam.

3. An Energy Boost

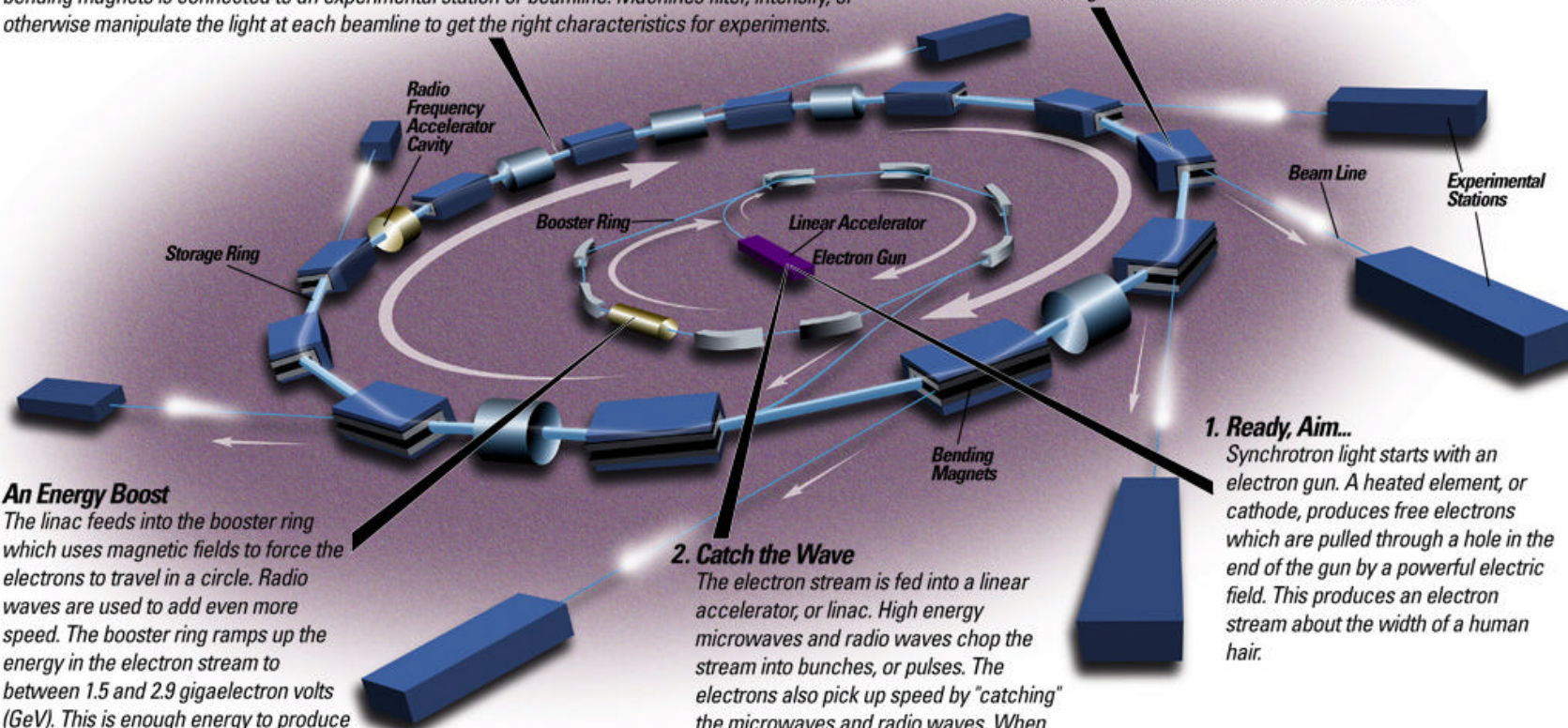
The linac feeds into the booster ring which uses magnetic fields to force the electrons to travel in a circle. Radio waves are used to add even more speed. The booster ring ramps up the energy in the electron stream to between 1.5 and 2.9 gigaelectron volts (GeV). This is enough energy to produce synchrotron light in the infrared to hard X-ray range.

2. Catch the Wave

The electron stream is fed into a linear accelerator, or linac. High energy microwaves and radio waves chop the stream into bunches, or pulses. The electrons also pick up speed by "catching" the microwaves and radio waves. When they exit the linac, the electrons are travelling at 99.99986 per cent of the speed of light and carry about 300 million electron

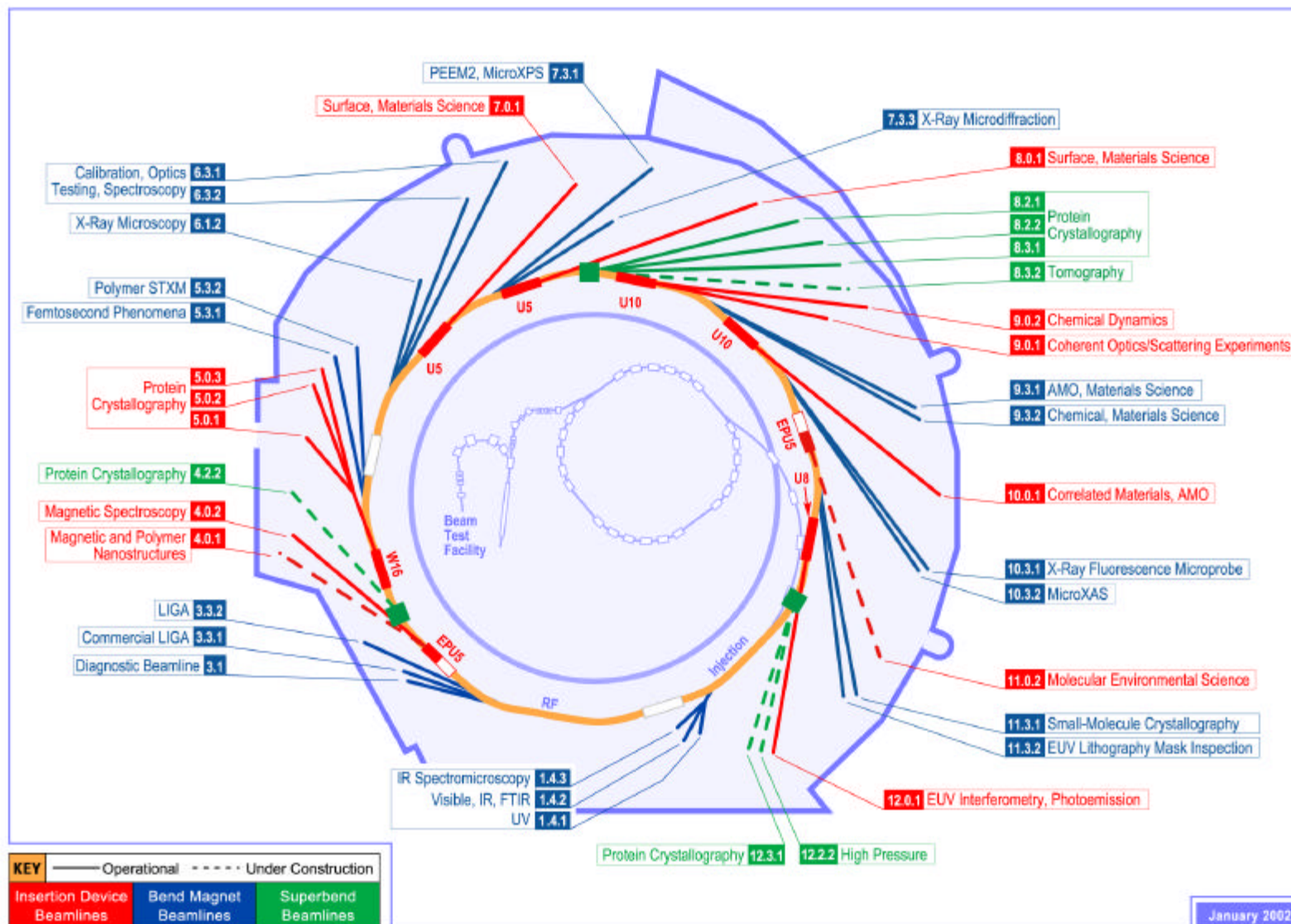
1. Ready, Aim...

Synchrotron light starts with an electron gun. A heated element, or cathode, produces free electrons which are pulled through a hole in the end of the gun by a powerful electric field. This produces an electron stream about the width of a human hair.



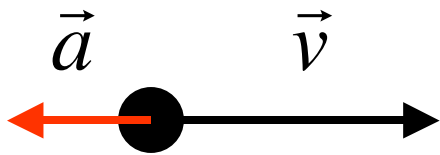
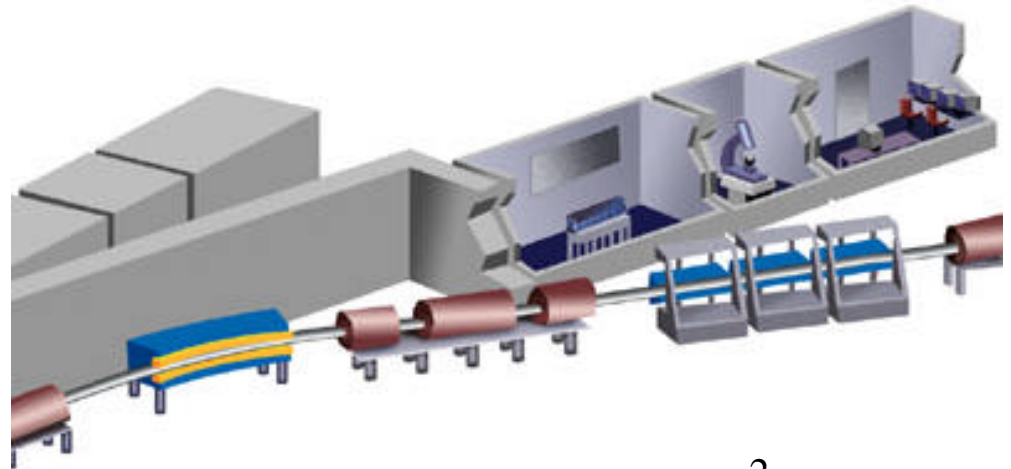
Source: University of Saskatchewan /
Paradigm Media Group Inc.

ALS beamlines



Production of Synchrotron Radiation

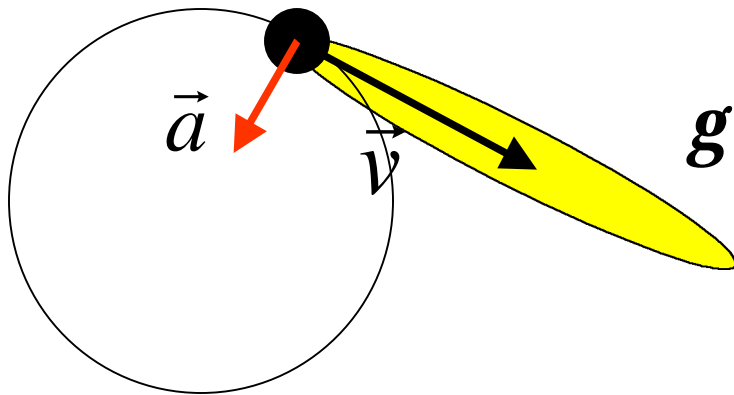
Synchrotron radiation is the electromagnetic radiation produced when a charged particle is subjected to a *time-varying* acceleration. It is significant only at highly relativistic velocities. Because it leads to a loss of power in a relativistic particle beam, it was originally considered “waste radiation”. Linear accelerators are designed to minimize the production of synchrotron radiation.



No synchrotron radiation. Bremsstrahlung (braking radiation) is small as v approaches c .

$$P = \frac{2}{3} \frac{e^2}{c^3} |\dot{\mathbf{v}}|^2$$

Synchrotron radiation focussed in forward direction. The time rate of change of the velocity does not vanish as v approaches c .



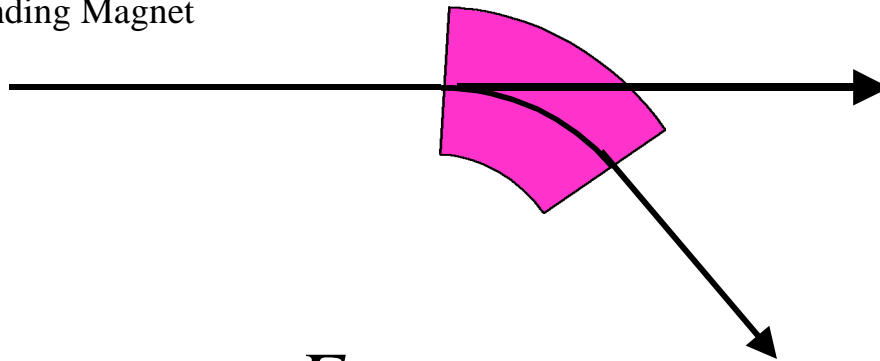
$$g = \frac{E}{m_0 c^2}$$

At 1 GeV, γ is about 2000.

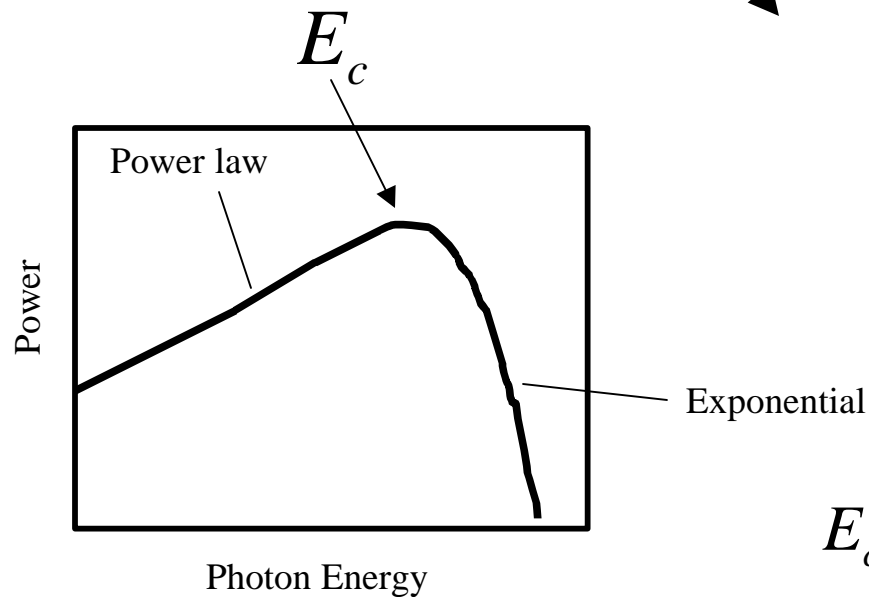
$$\Delta\Theta \approx \frac{1}{g}$$

Types of synchrotron radiation sources: Bending magnets

Bending Magnet



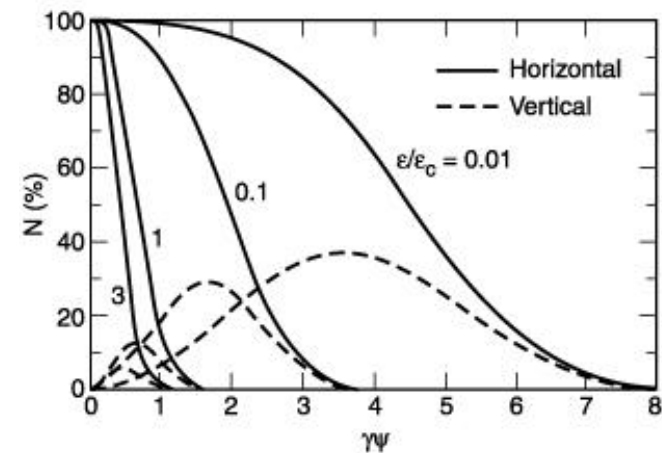
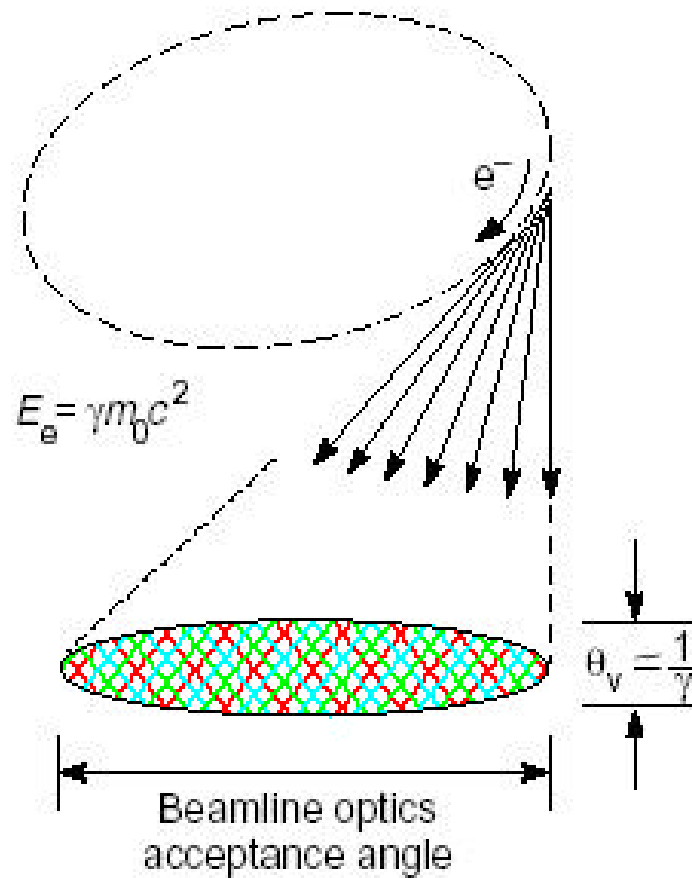
Large horizontal divergence.
Vertical divergence $1/\gamma$.
Broad energy spectrum.



The critical energy is determined by the kinetic energy of the stored beam, and the strength of the magnetic deflection field.

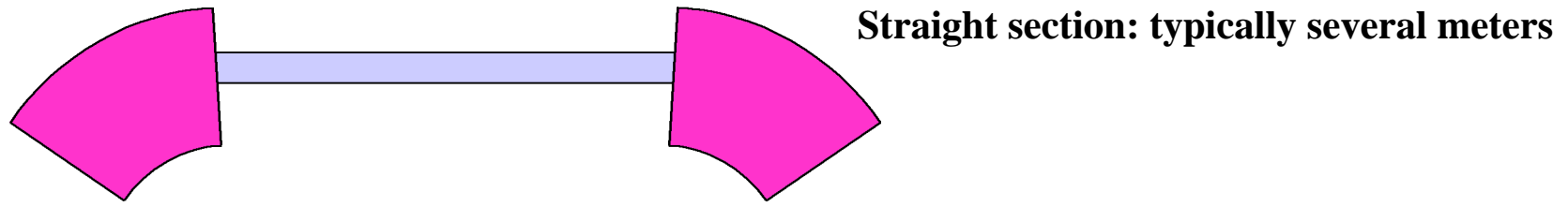
$$E_c [keV] = 0.665 E^2 [GeV] B [T]$$

Bend-magnet radiation pattern

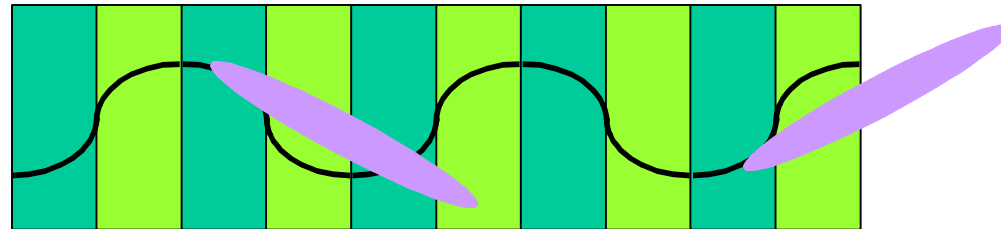


Angular distributions of horizontal and vertical polarizations of Bending Magnet radiation.

Types of synchrotron sources: Insertion devices



Periodic Magnet Array: 1 meter to 10 meters long

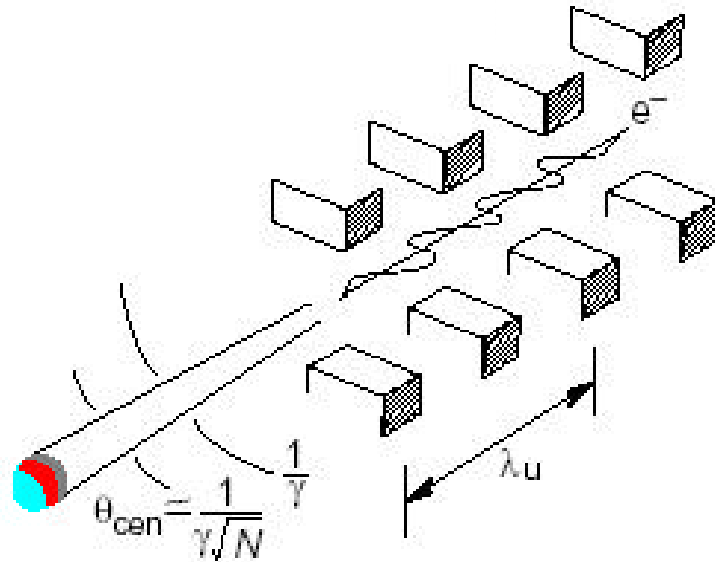


Radiation produced at each bend.

WIGGLER: about 10 periods, very strong fields, large deflections. Intensity builds linearly with number of periods N . Broadband radiation similar to a bending magnet.

UNDULATOR: about 100 periods, weak fields, small deflections. Intensity builds quadratically with number of periods N . Harmonic radiation.

Undulator radiation pattern

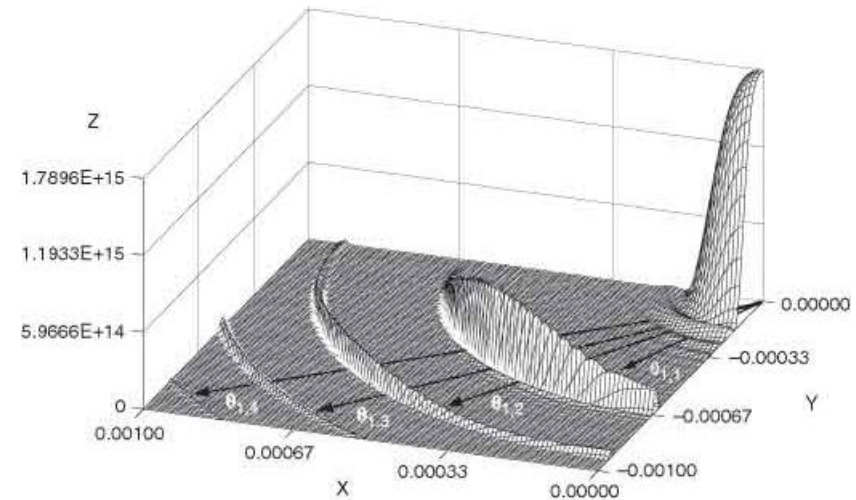


$$\lambda_x = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right)$$

In the central radiation cone:

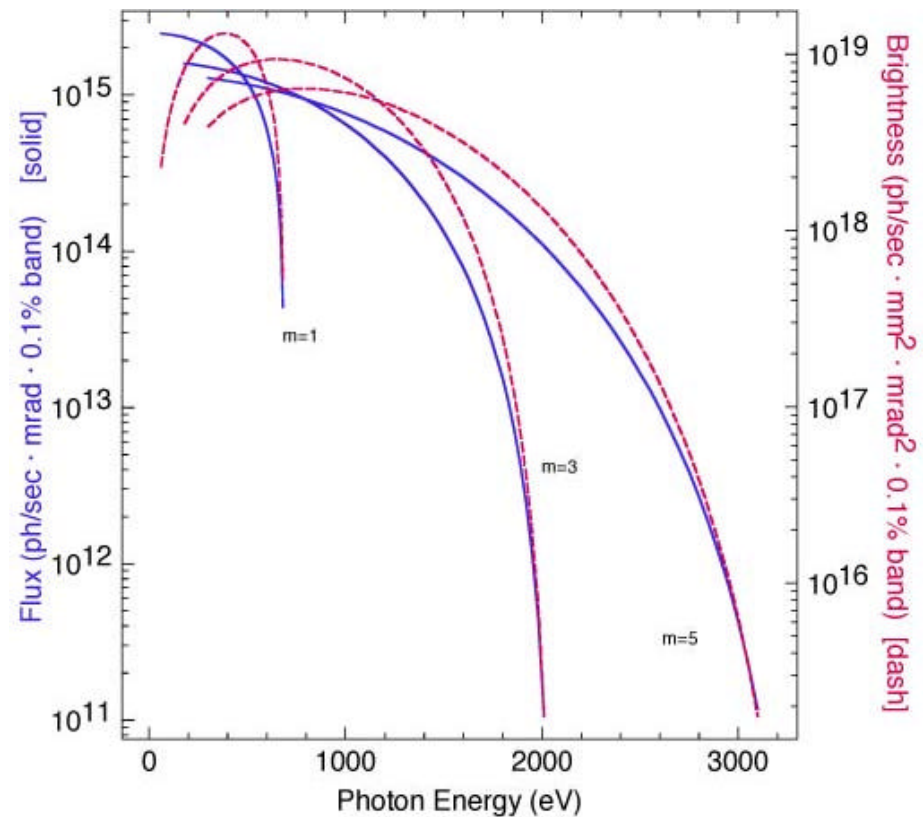
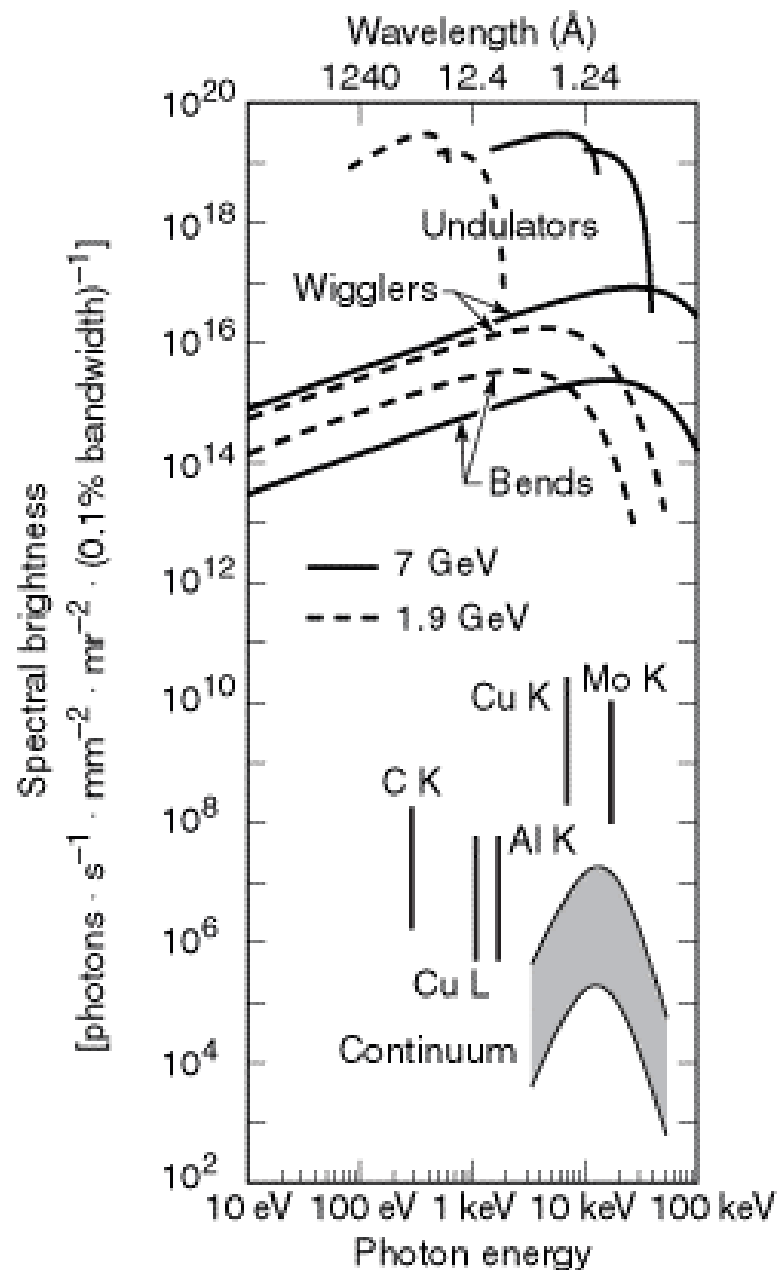
$$\frac{\Delta\omega}{\omega} = \frac{1}{N}$$

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



Angular distribution of
Undulator radiation.

Intensity of synchrotron radiation from bending magnets and undulators



Flux and brightness curves for U5 undulator.

Characteristics of synchrotron radiation

- Broadband radiation from infrared to x-ray wavelengths—tunable source with a monochromator
- High average intensity compared to all other sources
- Pulsed: about 1ns pulses at 100MHz repetition rates
- Polarized: highly linearly polarized in plane of storage ring. Elliptical or circular polarization available off-axis or with special insertion devices.
- Collimated to $1/\gamma$ in vertical direction for all types of sources
- Collimated to $1/\gamma$ in horizontal direction for undulator sources

An undulator beamline ALS 7.0

