A Tutorial on Accelerator-Based Light Sources

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March 29, 2011

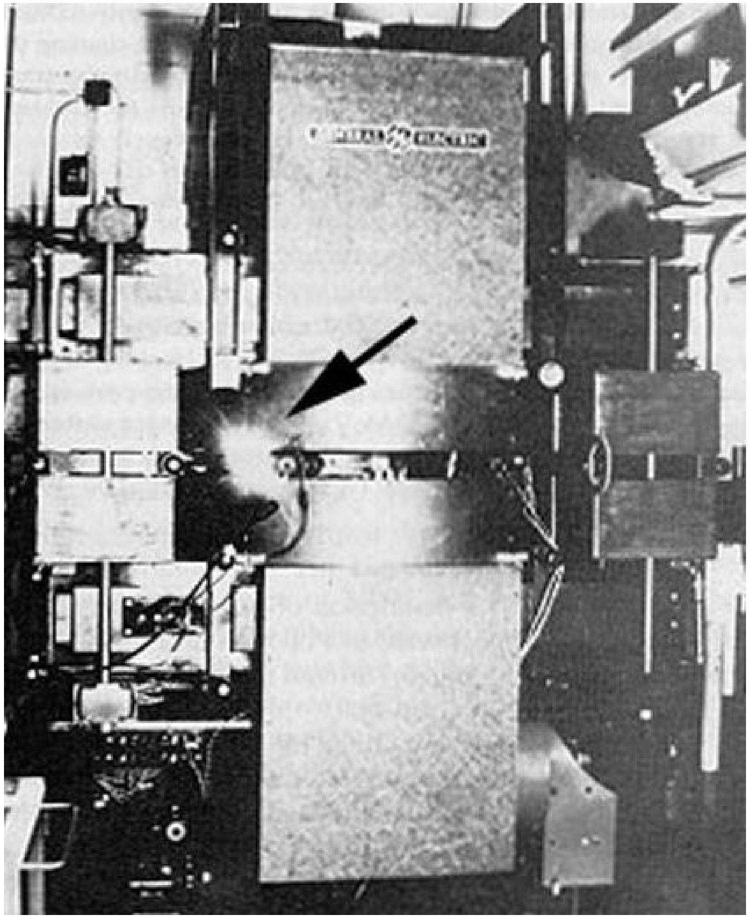
Outline

- Discovery and nature of synchrotron radiation
- Applications of synchrotron radiation
- Radiation-producing devices
- Basics of electron accelerators for light sources
- Storage ring light sources
- Energy recovery linac light sources
- Free-electron lasers
- Conclusion

- Slides mostly contain references to learning resources, not necessarily to seminal papers

Discovery of Synchrotron Radiation

- Lienard predicted in 1898 that a charged particle moving on a circular trajectory would radiate
  - Analysis shows that *acceleration* causes the radiation
- Accidental direct observation of visible radiation in 1947
  - General Electric 70 MeV electron synchrotron
  - Hence the name "synchrotron radiation"



H. C. Pollock, Am. J. Phys. 51 (1983).
G. C. Baldwin, Physics Today, Jan. 1975.

Properties of Synchrotron Radiation

- Radiation power is related to γ and the acceleration

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}} \approx \frac{E(\text{MeV})}{0.511}$$

$$P \propto \gamma^4 \dot{v}^2$$

- Deflection of relativistic particles is easily accomplished with magnetic fields

$$\vec{F} = q\vec{E} + \boxed{q\vec{v} \times \vec{B}}$$

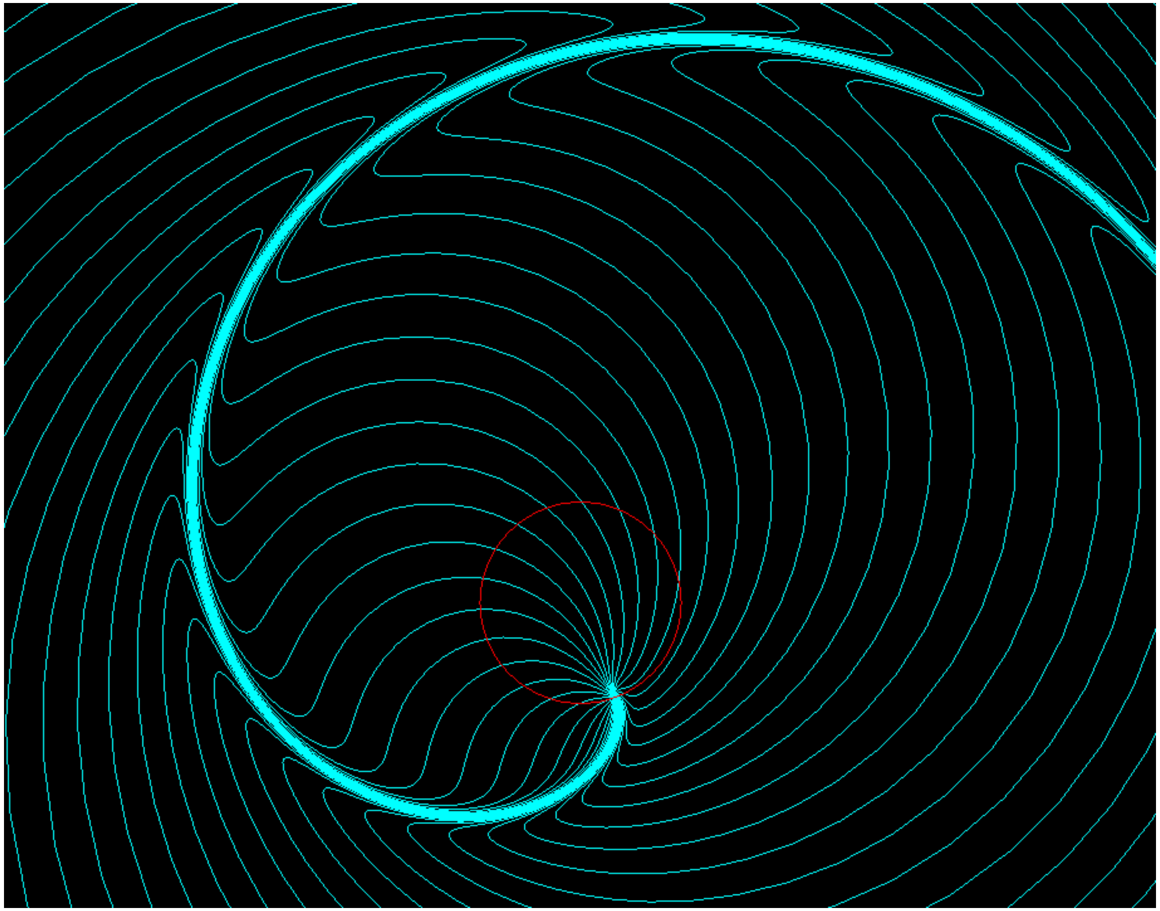
See, e.g., J. D. Jackson, Classical Electrodynamics, Ch. 14
and K. J. Kim, AIP Conf. Proc. 184 (1989).

Radiation2D Demo (K. Shirasawa, T. Shintake)

$$\Delta\theta \sim \frac{1}{\gamma}$$

$$\Delta t_r = \frac{\rho}{2c\gamma^3}$$

$$\omega_c \sim \frac{c}{\rho}\gamma^3$$



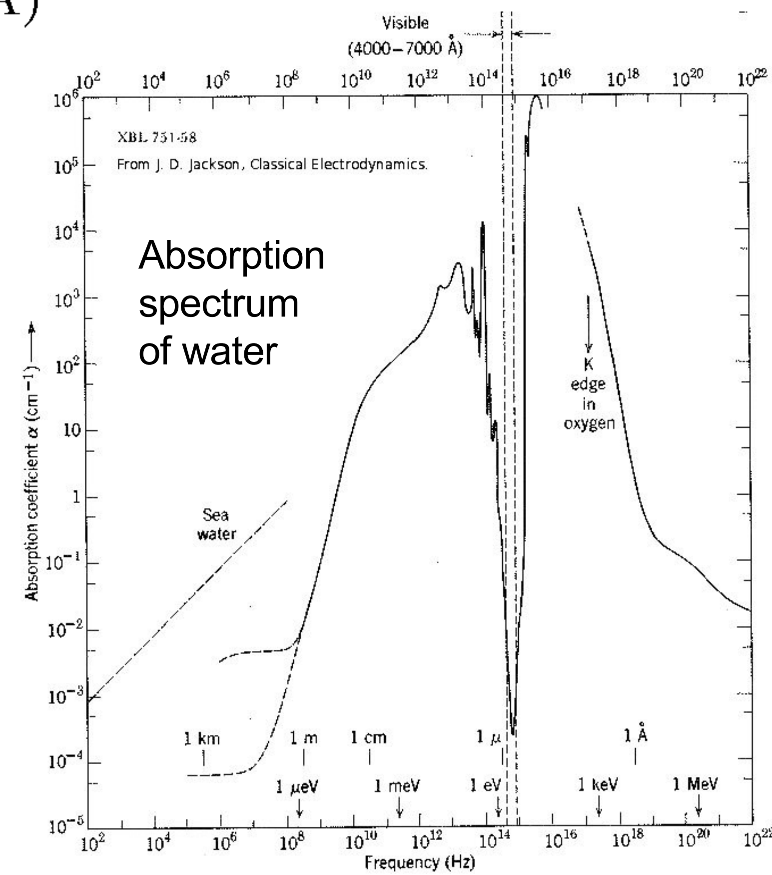
Available from www-xfel.spring8.or.jp/cband/e/index.html

Interaction of Radiation with Matter

- Radiation energy, frequency, and wavelength are related

$$e(\mathrm{keV}) = 4.14 f(\mathrm{EHz}) = \frac{12.39}{\lambda(\mathring{\mathrm{A}})}$$

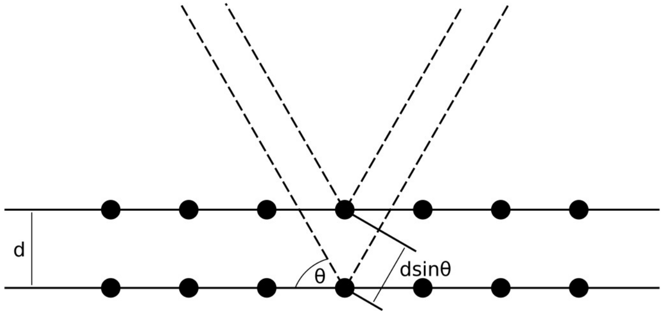
- Low-frequency radiation interacts with vibrational modes of molecules
- High-frequency radiation interacts with light, tightly-bound electrons
- Absorption spectra are molecule and element-specific

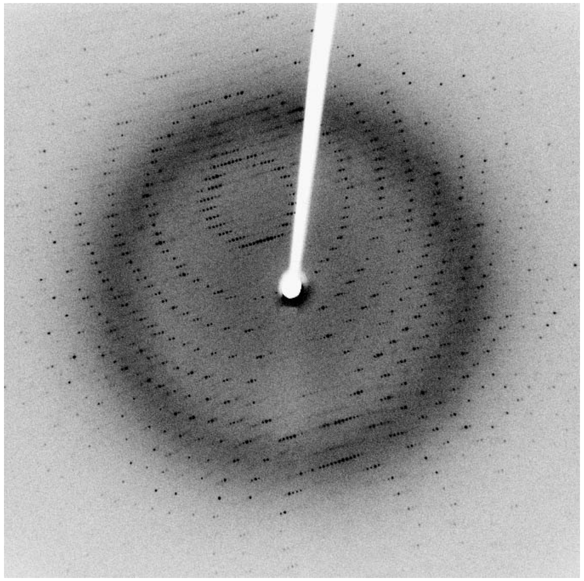


Some Applications of Synchrotron Radiation

- Imaging
  - E.g., Diagnostic x-ray takes advantage of differences in absorption for bone and flesh
- Bragg diffraction
  - Typical inter-atomic distances in solids are a few Å
  - X-ray scattering from crystal planes can result in interference effects
  - Used to understand structure of ordered solids

$$2d\sin\theta = n\lambda_r$$



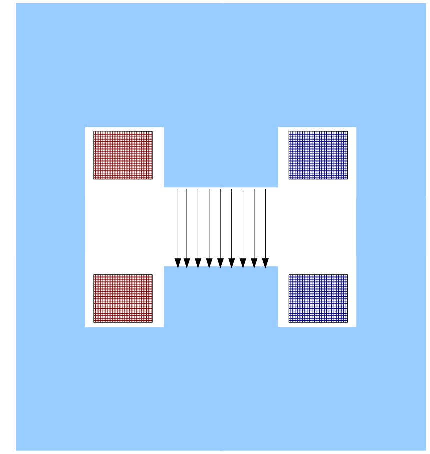


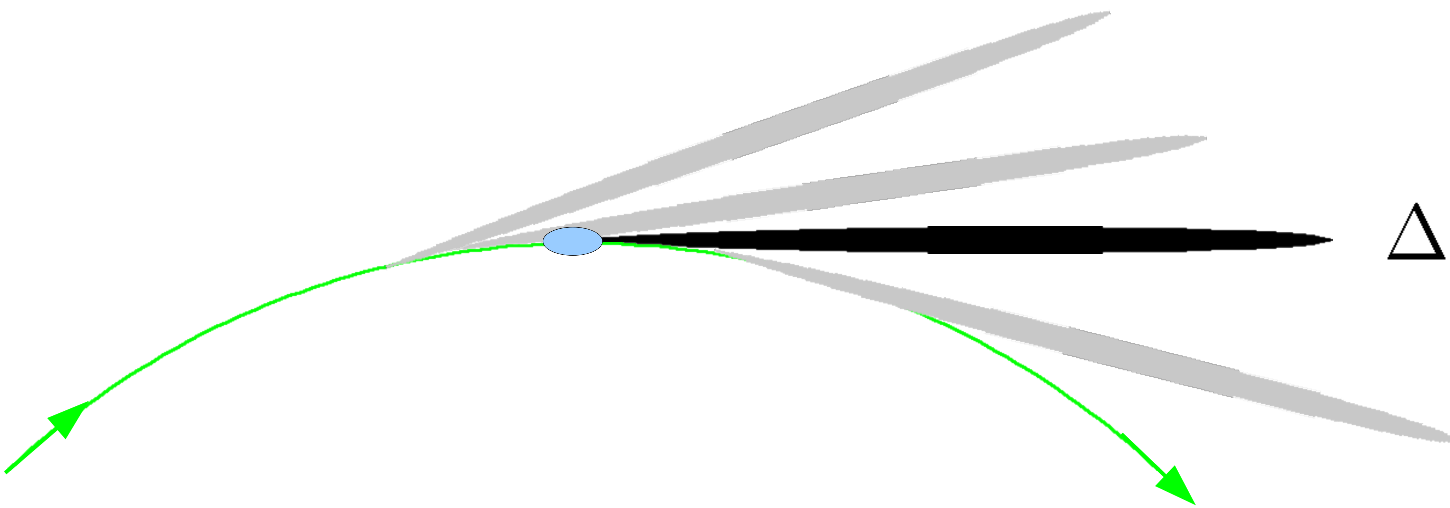
See, e.g., Yale Course “X-Ray Diffraction” on Youtube

Images: Wikipedia

Radiation Producing Devices: Bending Magnets

- Synchrotron radiation originally observed for beam circulating in a “bend” or “dipole” magnet
- Modern rings have many bends to force the beam into a closed path
  - The radiation they produce may or may not be used
- Bend magnet radiation is like a “moving searchlight”



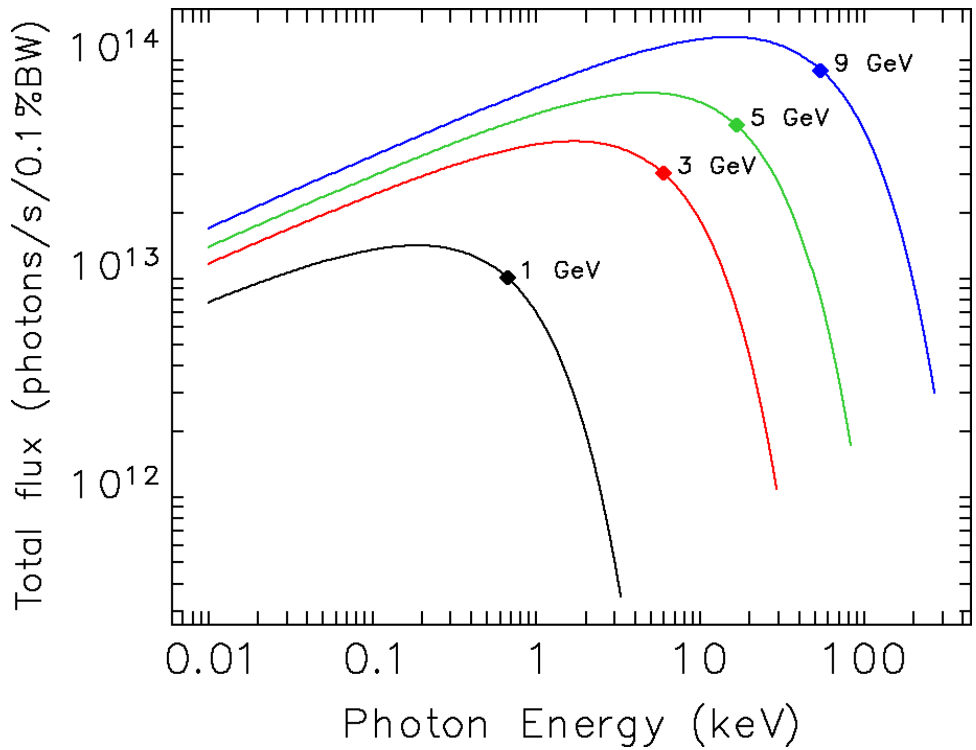


$$\Delta\theta \sim \frac{1}{\gamma}$$

Properties of Bend Magnet Radiation

- Broad fan of radiation can serve a series of users
- Broad spectrum
- "Critical energy" divides power spectrum in half

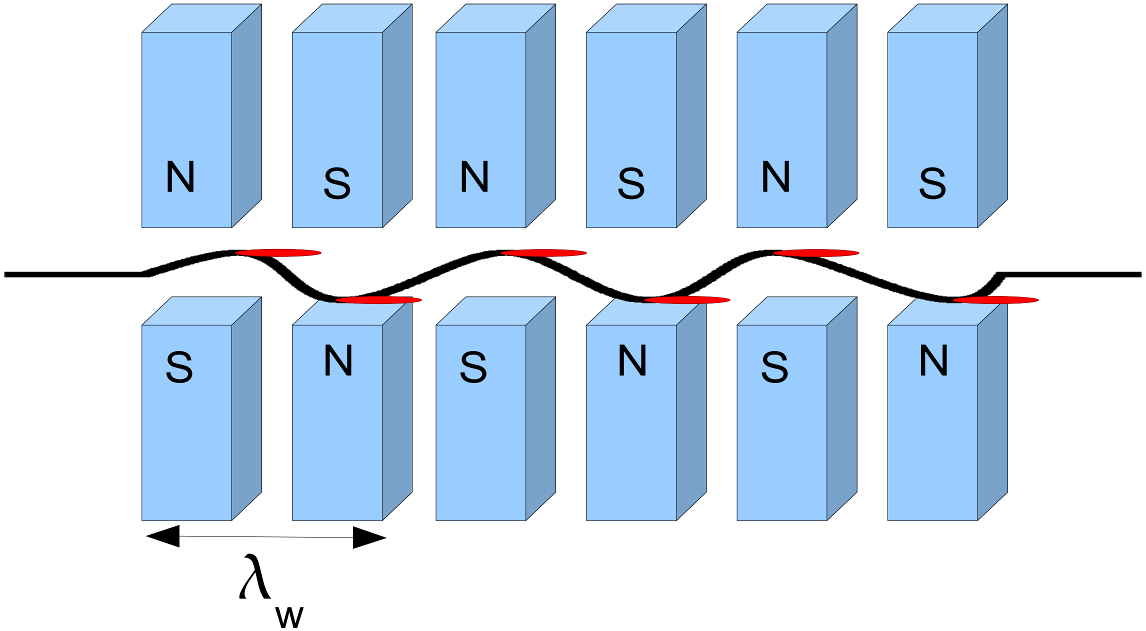
$$e_c(\mathrm{keV}) = 0.66E(\mathrm{GeV})^2 B(\mathrm{T}) = 2.22\frac{E(\mathrm{GeV})^3}{\rho(\mathrm{m})}$$



Total flux from 100 mA beam circulating in a 1T field

Radiation Producing Devices: Wigglers

- A wiggler is a series of N_w strong bends of alternating sign
- The beam "wiggles" in a sinusoidal trajectory



- Trajectory angle and amplitude characterized by K parameter

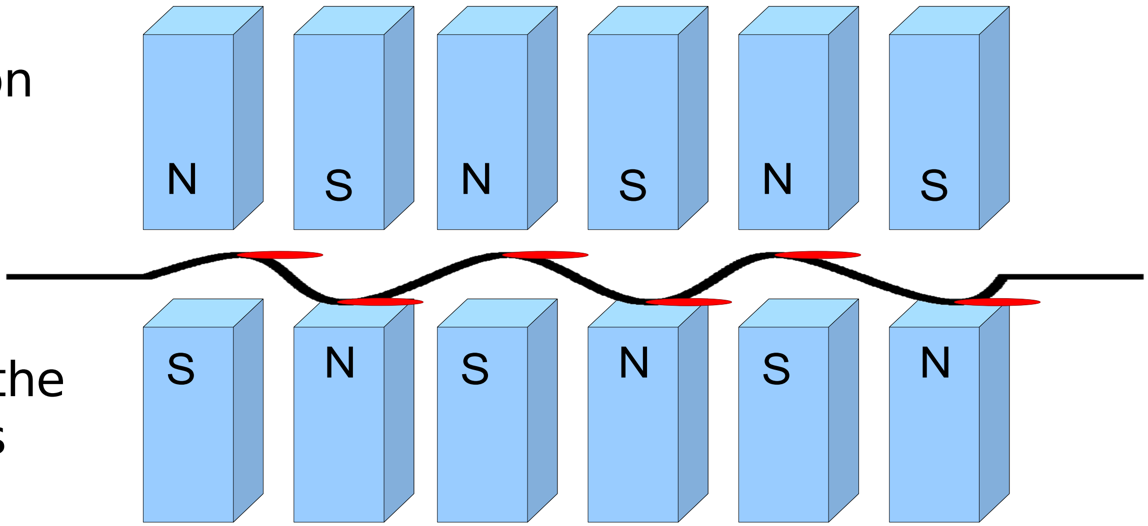
$$K = \frac{\theta_{\mathrm{max}}}{1/\gamma} \qquad x_{\mathrm{max}} = \frac{K\lambda_w}{2\pi\gamma}$$

See, e.g., K. J. Kim, AIP Conf. Proc. 184 (1989).

Properties of Wiggler Radiation

- In wigglers, the deflection angle is large

$$K \gg 1$$



- Only the radiation from the cusps of the trajectory is pointed at the observer
  - Dipole-like radiation
  - N_w times the flux
- Can make field stronger, since there is no net deflection
- Dipole-like radiation with higher flux and higher energy

$$e_c(\mathrm{keV}) = 0.66E(\mathrm{GeV})^2B(\mathrm{T}) = 2.22\frac{E(\mathrm{GeV})^3}{\rho(\mathrm{m})}$$

Radiation Producing Devices: Undulators

- If K≤3 radiation from successive periods interferes constructively
- Average forward velocity of a wiggling electron is

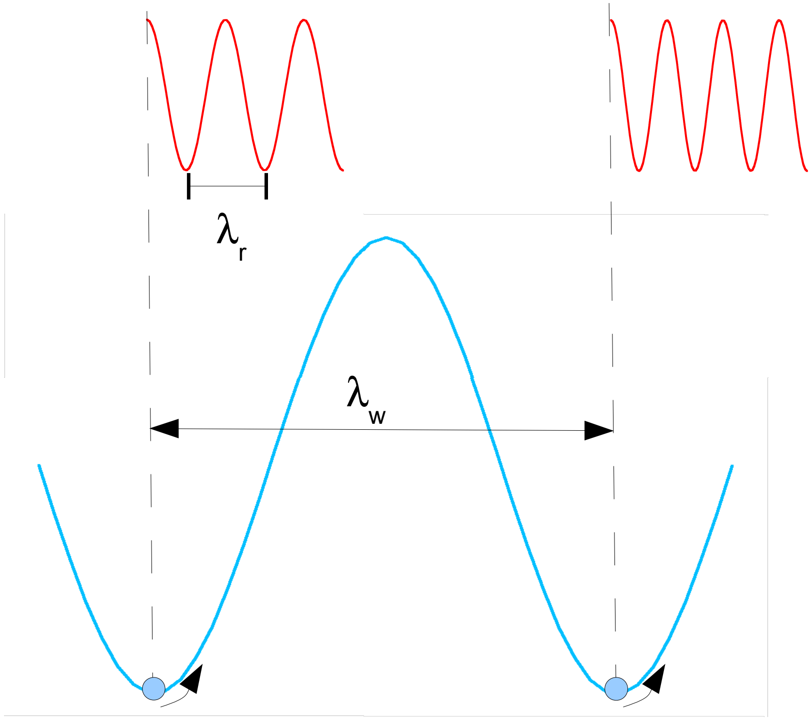
$$\bar{v}_z = c\left(1 - \frac{1+\frac{1}{2}K^2}{2\gamma^2}\right)$$

- Radiation has v=c, so after each period it slips ahead by

$$\Delta l = \frac{\lambda_w\left(1+\frac{1}{2}K^2\right)}{2\gamma^2}$$

- Coherent addition between poles for certain radiation wavelengths

$$\lambda_r n = \Delta l, \qquad n = 1, 2, 3, \ldots$$



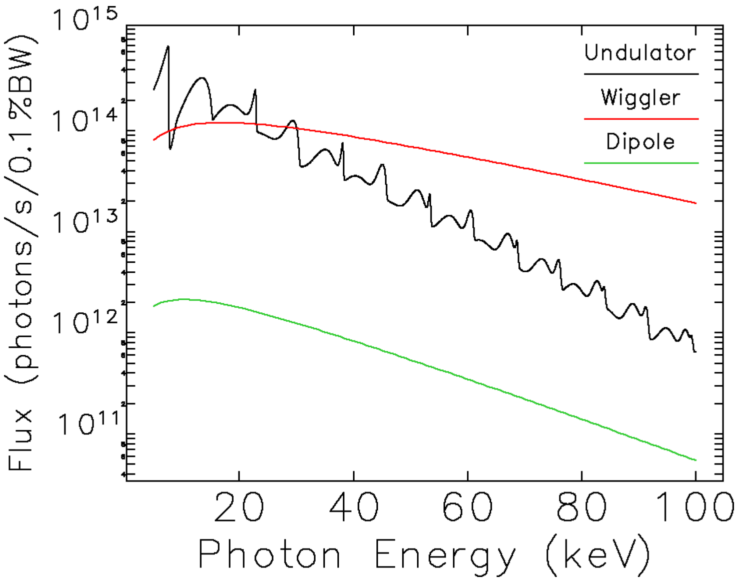
- Undulator radiation peaked harmonics

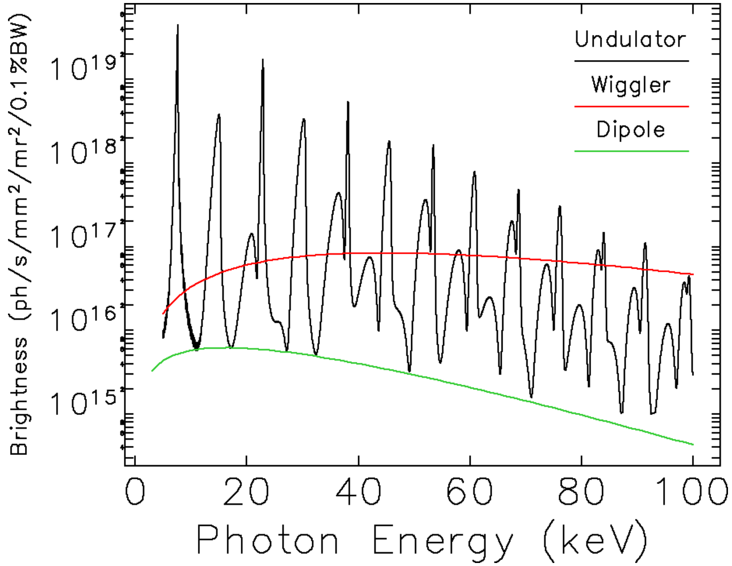
$$\lambda_{r,n} = \frac{\lambda_w\left(1+\frac{1}{2}K^2\right)}{2n\gamma^2}$$

Even harmonics nominally absent on-axis due to symmetry of trajectory

Diagram after B. McNeil, "How an FEL works FEL2010"

Comparison of Radiation Spectra





- With realistic electron beam, undulator shows even harmonics as well as odd harmonics
- Undulators preferred for high-brightness applications
- Wigglers provide high energy and flux

Undulator: K=1.3, 3.3cm period, 2.4m length
Wiggler: B=1.0T, 8.5 cm period, 2.4m length
Dipole: B=0.6T

Flux computed through 5x5 mm^2 pinhole at 30 m for 100 mA APS beam.

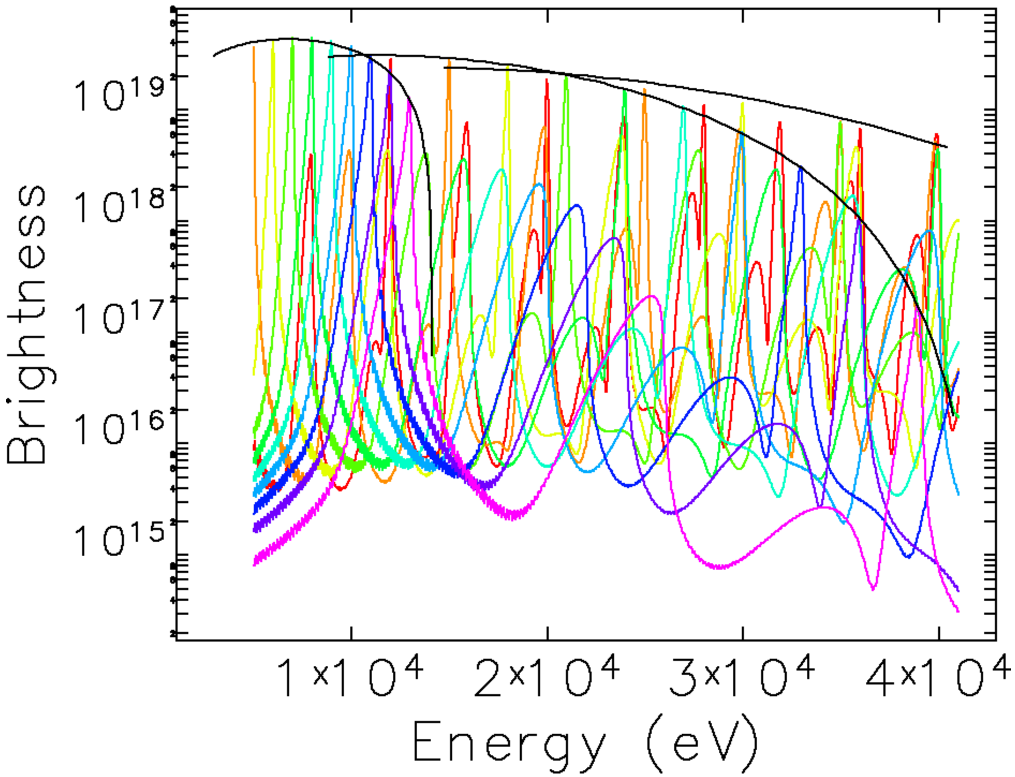
Computed with SPECTRA (T. Tanaka, H. Kitamura).

Tuning Curve for Undulator

- Undulators have adjustable gaps that allow changing the field

$$K = 93.4 B(\mathrm{T}) \lambda_w(\mathrm{m})$$

- Hence, users can move the location of the maximum brightness to correspond to experimental needs
- Maximum brightness occurs for first harmonic when K=1.3



Basic Electron Beam Properties

- Accelerators don't just provide energetic electrons, but energetic *beams* of electrons
  - Electron beam properties strongly affect the properties of the radiation
- Important measures of beam quality
  - Low energy spread (0.02~0.1%)
  - Brief time duration (20 fs ~ 50 ps)
  - Small transverse size and divergence (10~100 μm by 1~10 μrad)
- The quality of a beam is expressed by the brightness

$$B \propto \frac{N_e}{\sigma_E \sigma_t \sigma_x \sigma'_x \sigma_y \sigma'_y}$$

(simplified form)

- Commonly combine transverse quantities into "emittances"

$$\epsilon_x = \sigma_x \sigma_{x'}$$

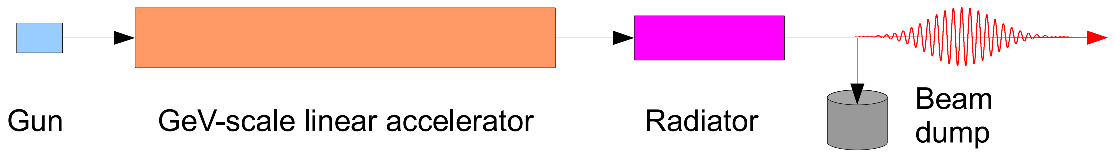
Geometric emittance (simplified)
Constant in absence of radiation

$$\epsilon_{x,n} = \gamma \sigma_x \sigma_{x'}$$

Normalized emittance (simplified)
Constant under acceleration.

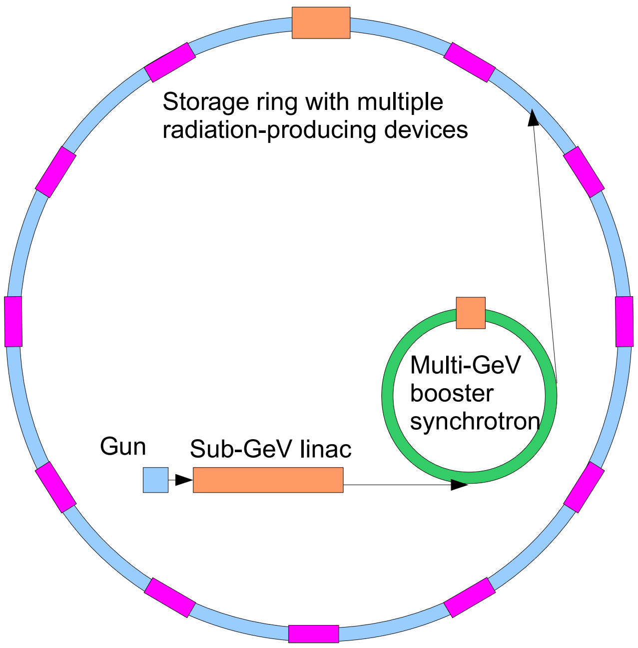
Two Basic Types of Light Source Facility

- Single-pass light source
  - Beam used once and then discarded

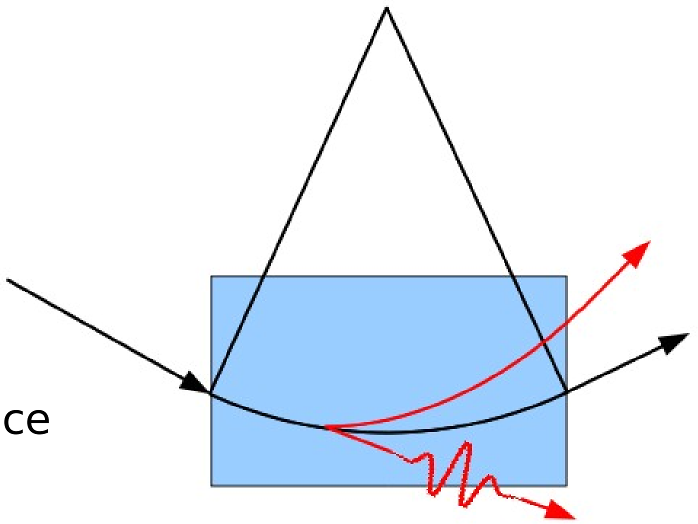


  - Beam quality determined primarily by the electron gun
    - See D. Dowell's tutorial on Friday morning
  - Operating examples: LCLS, FLASH, SCSS, JLab ERL, ...

- Circulating-beam light source
  - Beam circulates for hours in a "storage ring"
  - Beam quality determined by storage ring optical design
  - Operating examples: ALS, APS, NSLS, SPEAR, ...



Quantum Excitation of Electron Beams



- Radiation emission has a random component
  - Different electrons emit differently
  - Quantum-mechanical effect
- Bending will diminish beam brightness
  - Directly by increasing energy spread
  - Indirectly by increasing bend-plane emittance
- Hence, when electron beam brightness requirements are very demanding, use system with very minimal bending
- Effect can be reduced to some extent (more later)

See, e.g., M. Sands, SLAC-121 (1972).

Radiation Damping

- Geometric emittance is the product of size and divergence

$$\epsilon_x = \sigma_x \sigma_{x'}$$

- Divergence decreases when beam is accelerated

$$x' = \frac{p_x}{p_z} \longrightarrow \frac{p_x}{p_z + \Delta p_z}$$

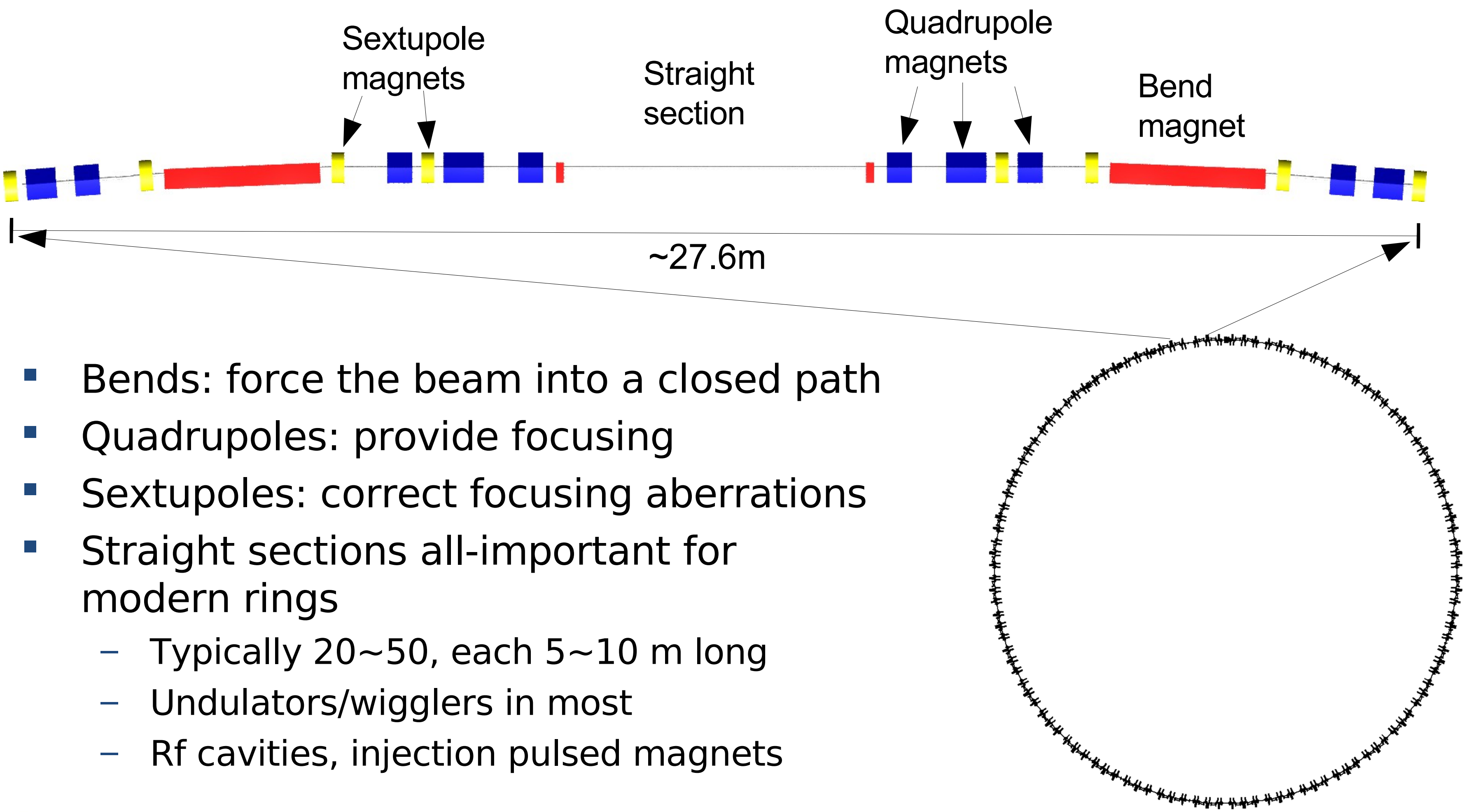
  – "Adiabatic damping" of emittance in a linac
- Results in damping of emittance in rings
- In storage rings, an equilibrium is reached between QE and damping

$$\epsilon_0 \sim \frac{E^2}{N_d^3} \qquad \left(\frac{\sigma_E}{E}\right)_0 \sim \frac{E}{\sqrt{\rho}}$$

See, e.g., M. Sands, op. cit., and
J. Murphy, Light Source Data Book.

Contemporary Storage Ring Light Sources

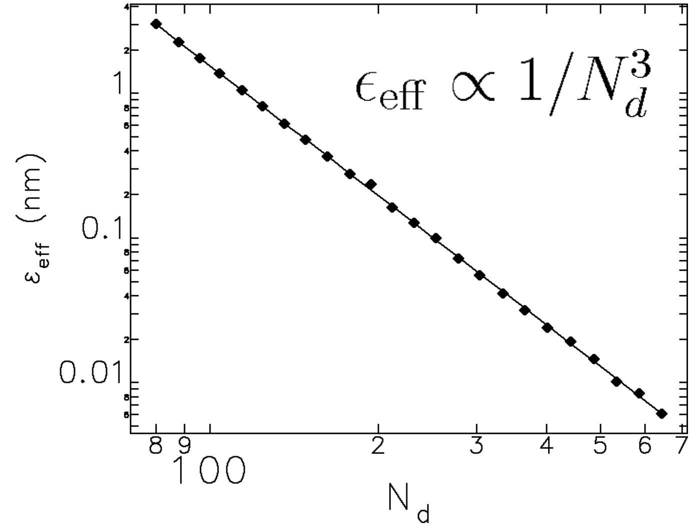
- Most rings are highly periodic and symmetric
  - APS cell is a typical Chasman-Green configuration



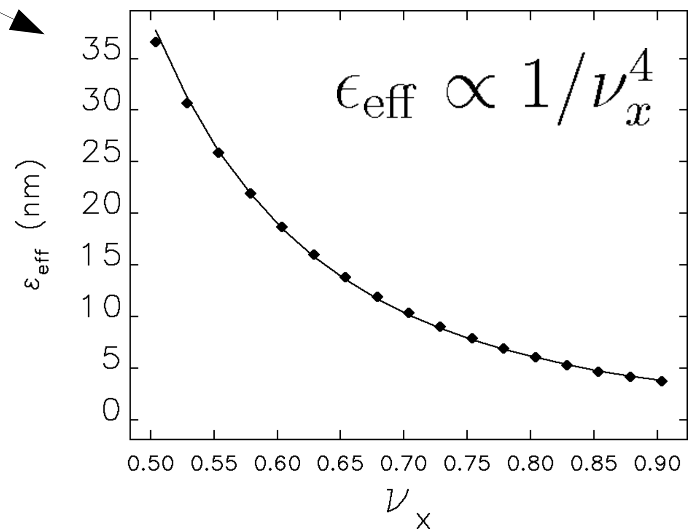
- Bends: force the beam into a closed path
- Quadrupoles: provide focusing
- Sextupoles: correct focusing aberrations
- Straight sections all-important for modern rings
  - Typically 20~50, each 5~10 m long
  - Undulators/wigglers in most
  - Rf cavities, injection pulsed magnets

Methods of Decreasing Emittance

- Reduce the energy
- Increase circumference with more cells
- More frequent focusing
- Stronger focusing
- Damping wigglers



- All of these involve trade-offs
  - Reduced spectral reach
  - Higher cost
  - Difficult non-linear dynamics
  - Collective effects
- Damping wigglers are a popular choice for new machines
  - PETRA-III (1 nm)
  - NSLS-II (0.5 nm)
  - MAX-IV (0.25 nm)
- MAX-IV is also using N_d=7/cell



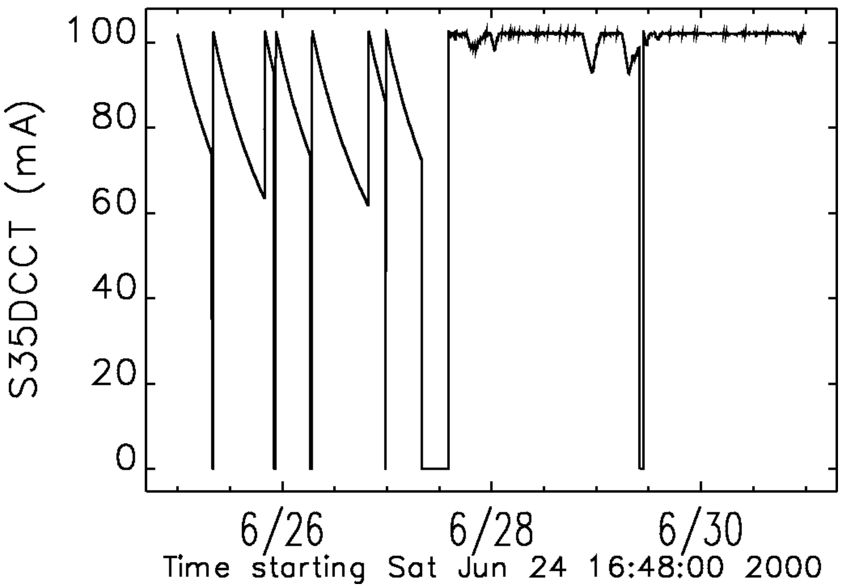
Simulations for APS cell.

Beam Lifetime and Top-Up Injection

- Beam circulating in ring is gradually lost
  - Scattering on residual gas molecules
  - Electron-electron collisions within a bunch (Touschek effect)
- Touschek effect dominates in low-emittance rings

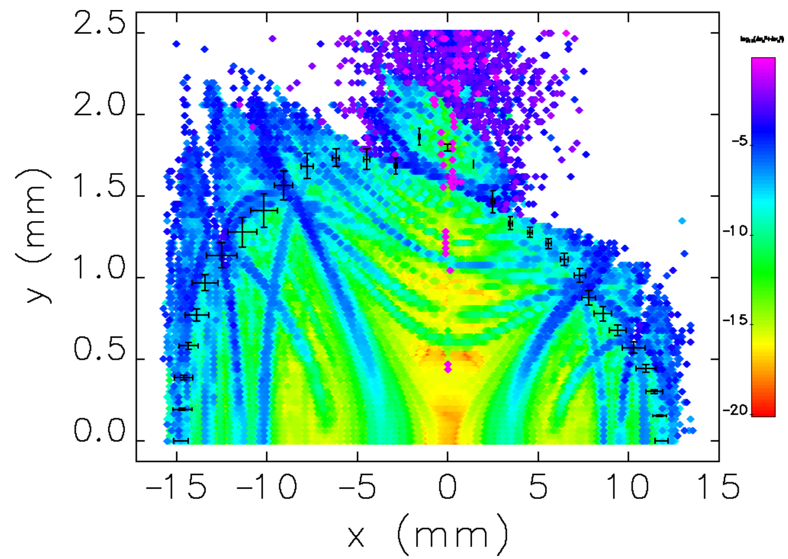
$$\frac{1}{I}\frac{dI}{dt} \sim \frac{I}{N_b \sigma_x \sigma_y \sigma_t}$$

- Prior to 2000, all rings operated in "decay mode"
- In June 2000, APS began "top-up" operation
  - Add current every few minutes
- Widely used, supporting
  - Lower emittance
  - Higher bunch current
  - Greater stability



Dynamic and Momentum Acceptance

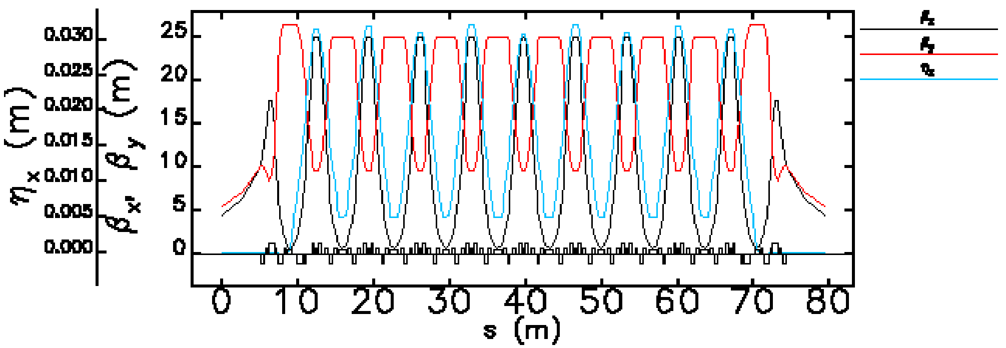
- Problem: must get beam into the ring and keep it there for a long time (billions of turns!)
- "Dynamic Acceptance" is the region within which particles can stably exist
  - Determines the aperture available for injection of beam
- "Local momentum acceptance" describes how large a momentum kick a particle can tolerate before being lost
  - Determines Touschek lifetime
- Designer must adjust quadrupoles and sextupoles to maximize these apertures
  - Avoid resonances
  - Taylor amplitude- and momentum-dependent focusing ("tune") variation



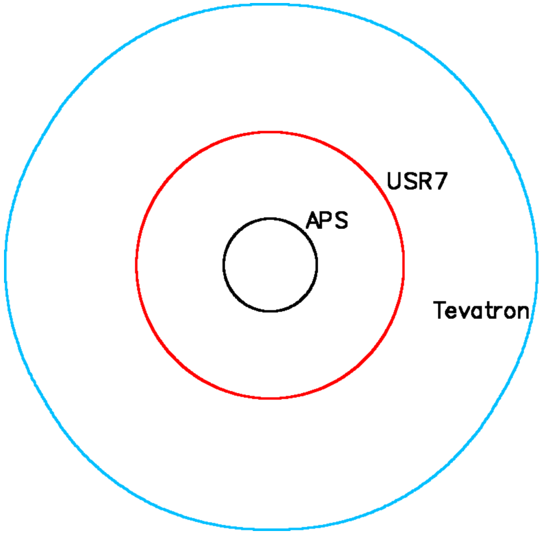
Frequency-map analysis of an APS upgrade

Ultimate Storage Rings

- Present rings have asymmetric emittance, e.g., 1 nm x 10 pm
- Some users want small, equal emittances, e.g,. 10 pm x 10 pm
- Combining several ideas gives one possible approach
  - Large (~3 km circum.) ring with N_d ~ 10/cell
    - Makes $\varepsilon_0 \approx 30$ pm possible
  - Run on coupling resonance to get $\varepsilon_x = \varepsilon_y = \varepsilon_0/2 = 15$ pm
  - Fill thousands of buckets to get reasonable lifetime
  - Use "swap-out" injection to replace depleted bunch trains
  - 2~3 orders of magnitude brighter present rings
- Challenges are similar to present rings



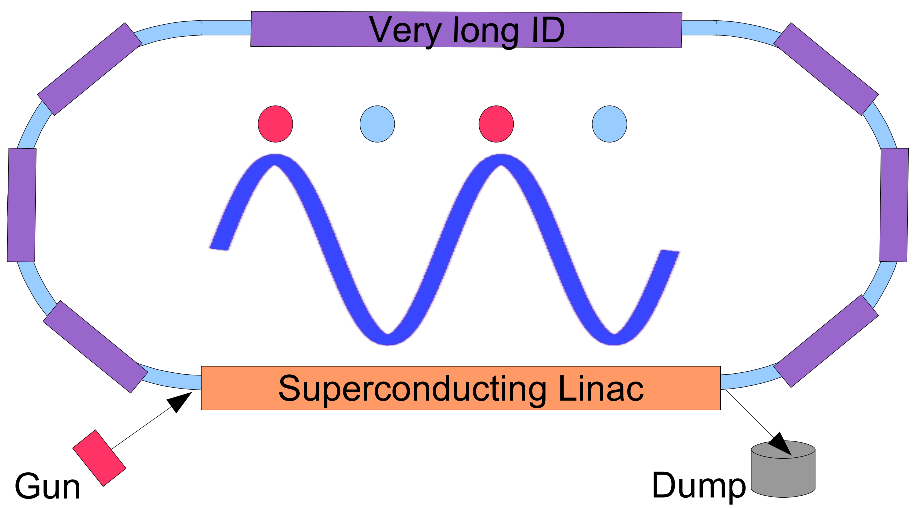
Cell optics for "USR7."



See, e.g., M. Bei *et al*., NIM A 622 (2010).

Energy Recovery Linac X-ray Sources

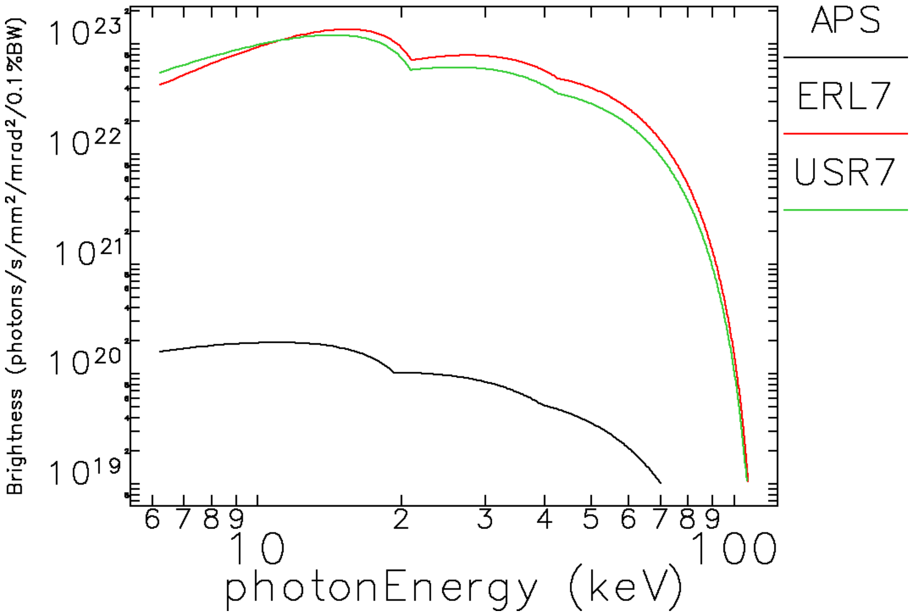
- Linac emittances can be very small compared to rings
  - State-of-art linac: 20 pm x 20 pm (LCLS at 14.1 GeV)
  - State-of-art ring: 1000 pm x 10 pm (PETRA-III at 6 GeV)
- However
  - PETRA-III has 100 mA average current, 14 beamlines
  - LCLS has 30 nA average current, 1 beamline
- ERL is attempt to have some of the best of both worlds
  - High brightness gun
  - Beam not stored, modest emittance dilution
  - “Round beams,” like USR
  - High average current made possible by energy recovery
- Operating example at JLab (135 MeV)



See, e.g., I. Bazarov *et al.*, PAC 2001, 230 (2001).

Challenges for Hard X-ray ERLs

- Obtaining required emittance to beat storage rings
  - High-voltage DC gun design
  - Limited choice of cathode material
- Need ~24 hour cathode lifetime for an operating facility
  - Difficult when average current must be several 10's of mA
  - Difficult when laser spot is very small (to get small emittance)
- Minimization of beam losses
  - May require transport losses at parts-per-billion level
  - Beam halo is a difficult problem to predict and manage
- Minimization of cryogenic power load
- Unclear if ERLs can compete with USRs

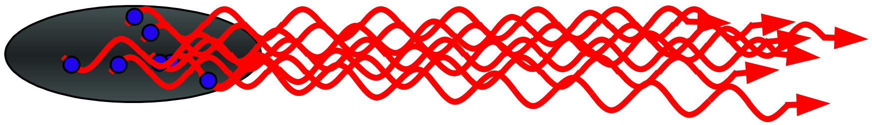


See, e.g., M. Borland, Ring-based sources overview, FLS2010.

From Undulators to Free Electron Lasers

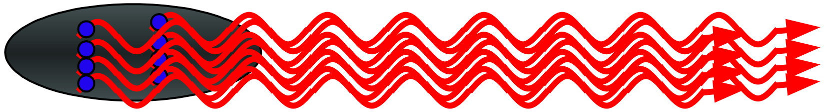
- Undulator radiation is bright because *individual* electrons emit in-phase at each period
- However, any two electrons have random relative phases, so no coherent addition

$$I_{\text{rad}} \propto N_e$$



- If electrons were locked at positions separated by the wavelength, they'd all emit coherently

$$I_{\text{rad}} \propto N_e^2$$



- Since $N_e \sim 10^9$, this is a huge <u>potential</u> improvement
  - FELs are devices that capitalize on this potential
- The wavelength is Angstroms
  - How can we arrange for electrons to bunch at that scale?

Graphics courtesy A. Zholents.
For more, Google, e.g., B. McNeil, "How an FEL works FEL2010"

Microbunching by Radiation in an Undulator

- Recall the undulator "resonance condition":
  - Radiation slips ahead by one wavelength for each period
    - Electron sees the radiation phase oscillate through 360 deg
  - In the same time, the electron makes a full oscillation in the undulator field
  - Depending on relative phase of oscillations, electron can gain or lose energy to the radiation

$$\Delta U = \vec{F} \cdot \Delta \vec{x} = -e\vec{E} \cdot \Delta \vec{x}$$

Work=Force*Distance

$$\frac{dU}{dt} = -e\vec{v} \cdot \vec{E}$$

Power=Force*Velocity

$$\left(\frac{dU}{dt}\right)_1 = -e(-v_x \sin kz)(E_x \sin kz)$$

Energy gain after 1 period

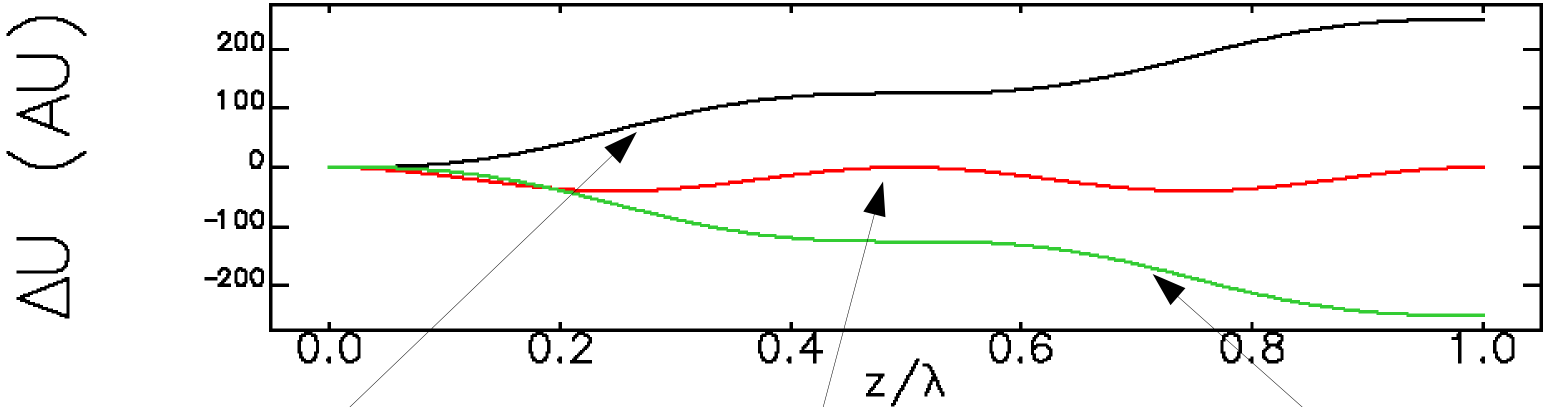
$$\left(\frac{dU}{dt}\right)_2 = -e(v_x \cos kz)(E_x \sin kz)$$

Energy constant

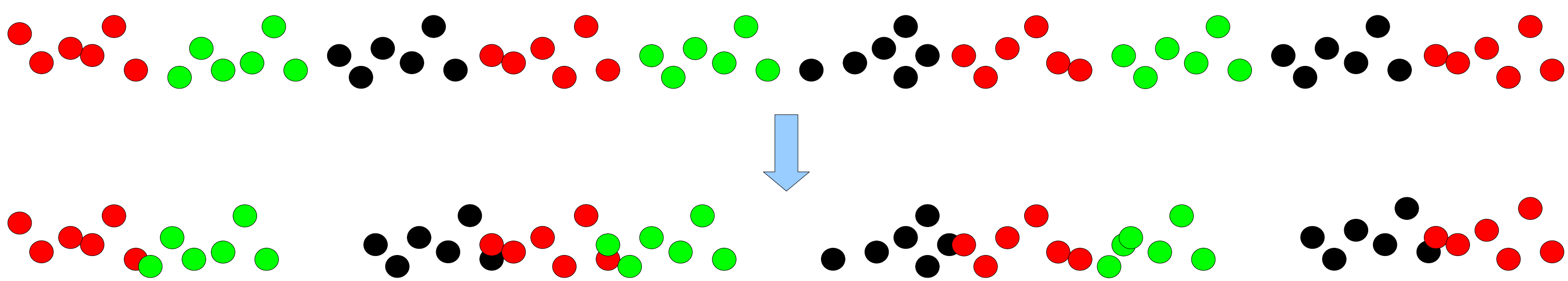
$$\left(\frac{dU}{dt}\right)_3 = -e(v_x \sin kz)(E_x \sin kz)$$

Energy loss after 1 period

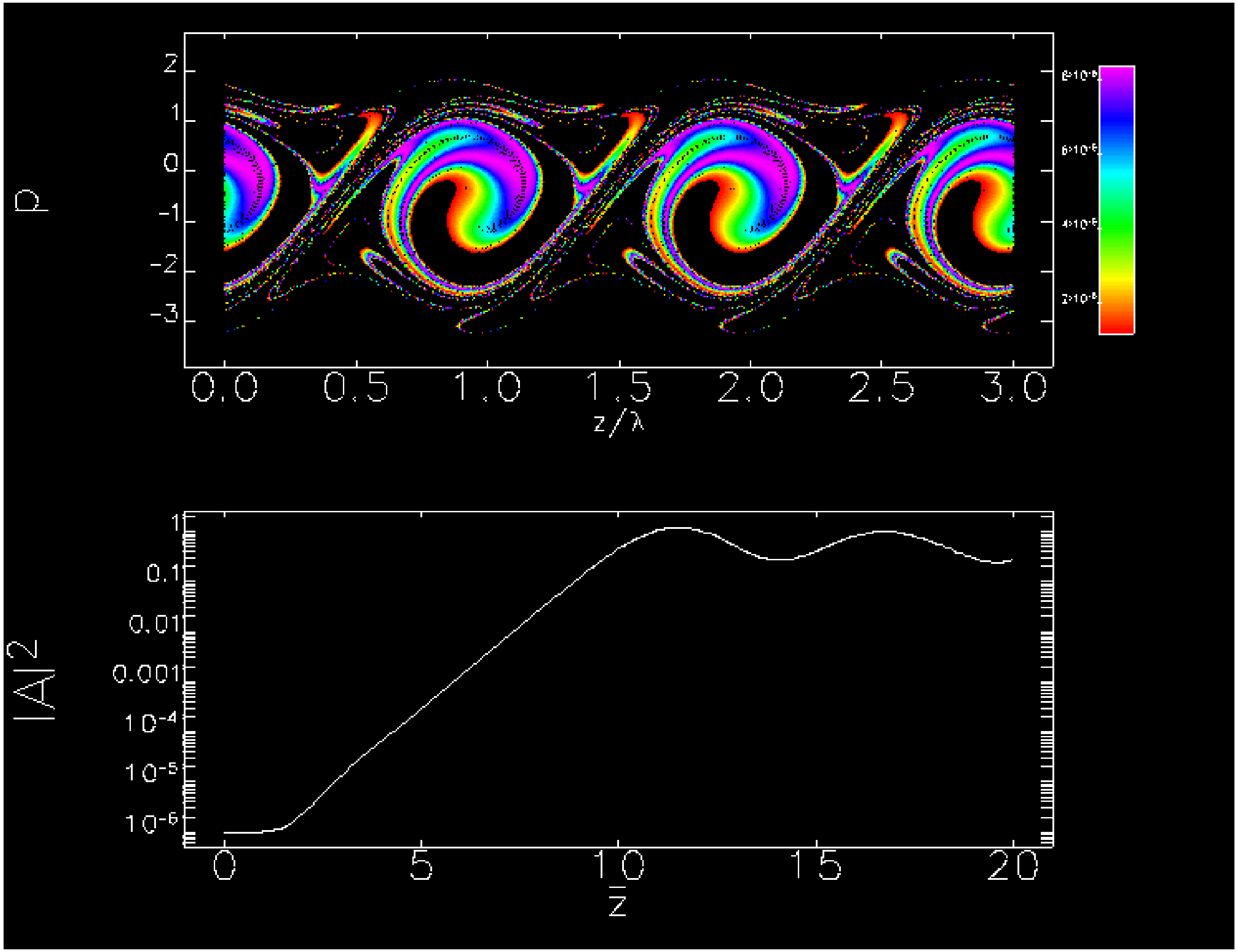
Energy Exchange Leads to Microbunching



Trailing e- gain energy	Central e- oscillates	Leading e- lose energy
↓	↓	↓
Take shorter path	Take same path	Take longer path
↓	↓	↓
Catch up	Stays put	Fall back



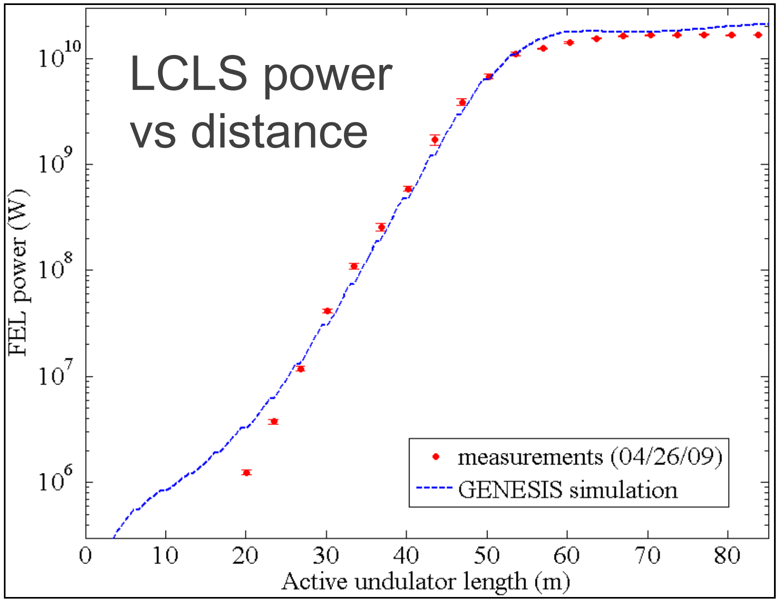
1D FEL Simulation



Program by B. McNeil, available from http://phys.strath.ac.uk/eurofel/rebs/rebs.htm

Amplifier FELs

- The process just described will amplify radiation at the first-harmonic wavelength
- Radiation power grows exponentially with characteristic length L_g
- Initial radiation may come from several sources
  - Ordinary laser: “seeded FEL”
  - Spontaneous radiation in the undulator: SASE FEL
  - Upstream FEL with spectral filtering: self-seeded FEL
- In SASE (Self-Amplified Spontaneous Emission) case, saturation occurs in about 16 gain lengths
  - About 10^7 gain over spontaneous



Courtesy P. Emma (SLAC).

See, e.g., S. Schreiber, Rev. Accel. Sci. Tech., Vol. 3 (2010); J. Feldhaus, et al., Opt. Commun. 140 (1997).

Beam Quality Requirements for SASE FELs

- X-ray FELs are only now becoming available
  - Beam quality requirements very demanding, hard to meet
- Geometric emittance must be less than radiation emittance

$$\frac{\epsilon_n}{\gamma} \lesssim \frac{\lambda_r}{4\pi}$$

Shorter wavelength requires higher beam quality and/or energy

- Energy spread must be less than Pierce parameter

$$\sigma_\delta \lesssim \rho = \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_w^2 K^2}{\beta_x \epsilon_n \gamma^2}\right)^{\frac{1}{3}}$$

Relative energy spread must be small, peak current must be high, emittance must be low.

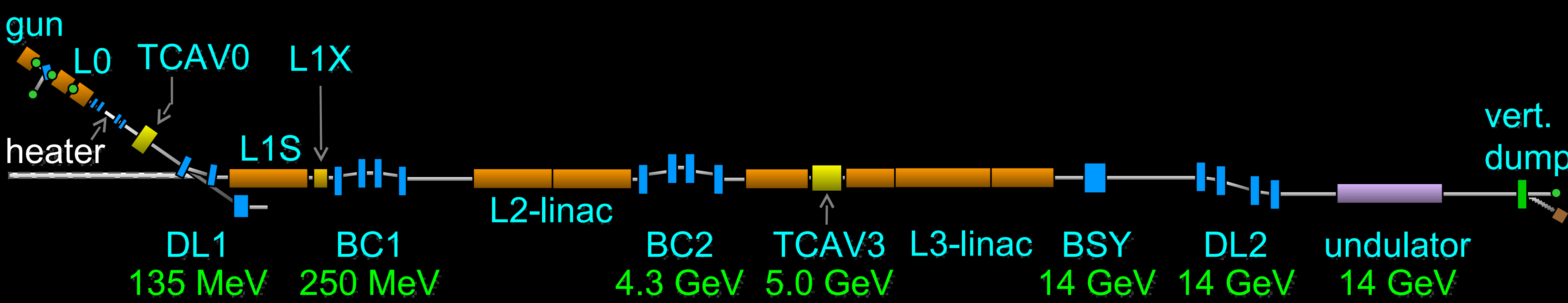
- Want gain length as short as possible

$$L_g \approx \frac{\lambda_w}{4\pi\sqrt{3}\rho}$$

Want short undulator period, high peak current, low emittance

See, e.g., P. Emma, SLAC Summer School Lecture, June 2010.

LCLS Hard X-ray FEL (1.5 to 15 Å)

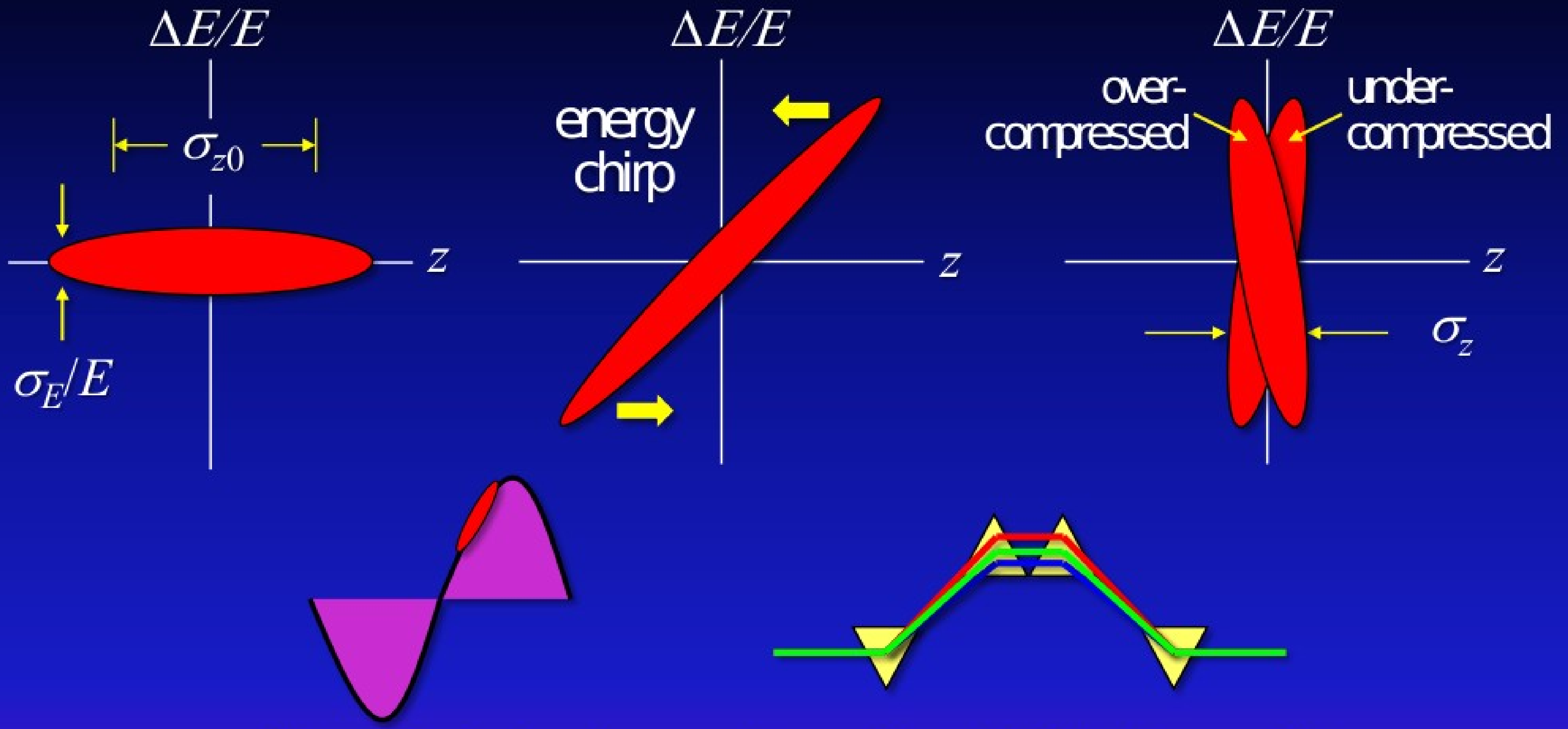


- Rf photocathode gun: 250 pC/bunch, ε_n=0.5 μm
- Energy up to 14 GeV
- ~130m long undulator
- Two magnetic bunch compressors (250 MeV and 4.3 GeV)
  - Compress bunch from 2 ps to ~20 fs rms

Figure courtesy P. Emma

See P. Emma, *et al*., Nature Photonics, Vol. 4 (2010).

Magnetic Bunch Compression



$V = V_0 \sin(\omega\tau)$ $\Delta z = R_{56}\Delta E/E \quad (\gamma >> 1)$

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

Courtesy P. Emma

Many Challenges Overcome Already for SASE FELs

- Microbunching can be suppressed if beam quality is poor
  - Emittance must be very good (0.5 ~ 1 um normalized)
  - Energy spread must be low (e.g,. well below 0.1% rms)
- To get workable gain length, peak current must be very high
  - To get gain length of a few meters need a few kA
  - Bunch compression must be used, but has side effects
    - Emittance and energy spread growth due to coherent radiation
    - Possible microbunching instability
- These challenges have been overcome by several operating facilities
  - E.g., LCLS, FLASH, SCSS
- Several others will come on line in the next few years
  - E.g., SPRing8 XFEL, Euro XFEL, LCLS-II

Challenges for SASE FELs

- SASE builds from spontaneous radiation, so output is noisy
  - Pulse-to-pulse jitter
  - Spectral jitter
  - Several approaches to improving this
    - Seeding with external laser
    - Self-seeding with spectrally-filtered upstream FEL radiation
- Hard to get high repetition rate from affordable linac, e.g., LCLS is 120 Hz, 1~100 kHz ideal
- Similarly, hard to support multiple users (one at a time for now)
  - Pulse sharing less palatable when linac rate is low
- Expensive to operate (10x cost per experiment compared to rings)
- Challenging to get very hard (>30 keV) x-rays
  - Higher energy, higher beam quality needed
- In spite of these issues, FELs have a decisive advantage for certain demanding experiments, e.g.,
  - Time-resolved studies requiring sub-picosecond resolution
  - Structure determination for very small crystals

Conclusions

- The basic physics behind accelerator light sources was discovered well over 100 years ago
- Storage ring sources are in high demand and ideal for many experiments
  - Mature, flexible, reliable, cost-effective technology
  - Very wide tuning range with dozens of independent users
  - Appears 10^2 to 10^3 brightness improvement possible, but expensive
- SASE FELs offer ~10^{10} higher peak brightness than rings
  - Full transverse coherence
  - Intense femtosecond pulses
  - Expensive but indispensable for some research
  - Very active research to improve characteristics
- ERLs serve a niche for coherent IR and THz radiation
  - Much R&D needed to prove potential for wider spectral range
- This talk has only scratched the surface
  - Exciting new ideas and opportunities abound