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Title: Navy Free-Electron Laser Program

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Navy Free-Electron Laser Program

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Los Alamos, NM

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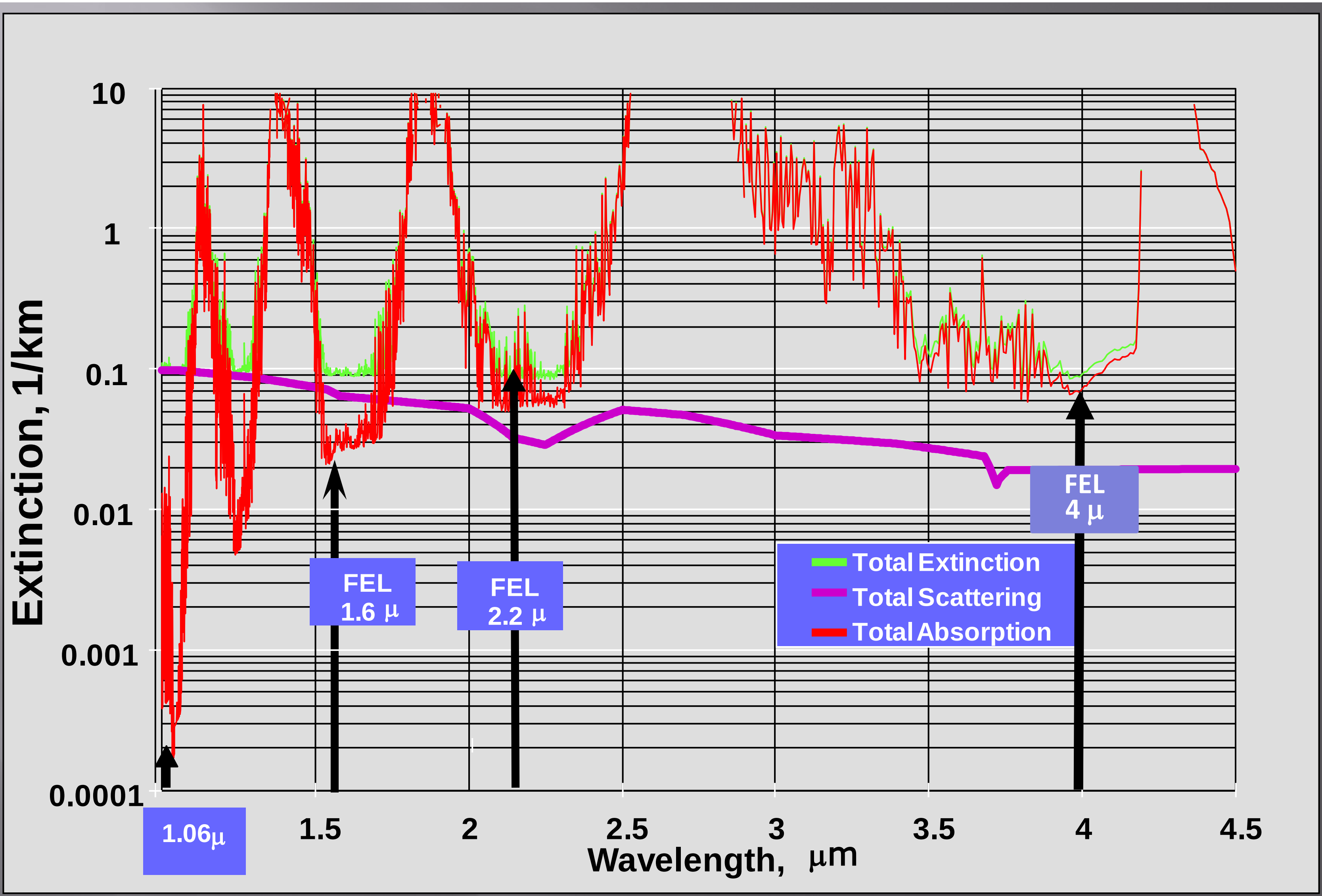
AOT-HPE

Part 1
Who cares?

Ship Self-Defense

The US Navy is interested in a speed-of-light weapon to defend against supersonic cruise missles. FEL is chosen because its wavelength selectability allows the Navy to operate the FEL in varying atmospheric conditions.

Atmospheric Windows



Part 2
How does it work?

Light consists of photons

Photons are packets of energy with no mass

Photon energy is proportional to the light frequency, inversely proportional to wavelength

$$\varepsilon = h\nu = \frac{hc}{\lambda}$$

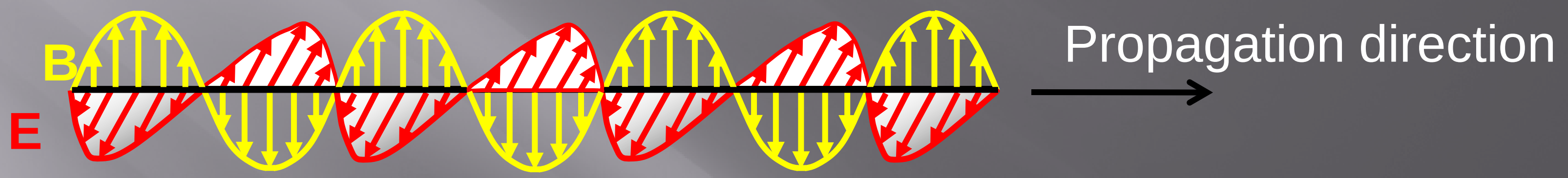
The shorter the wavelength, the more energetic the photons

Light at 1 μm (1,000 nm) wavelength has energy of 1.24 electron volts

$$\varepsilon[eV] = \frac{1.24}{\lambda[\mu m]}$$

Light is also electromagnetic (EM) waves

When there are many photons, light also behaves as a travelling electromagnetic (EM) wave

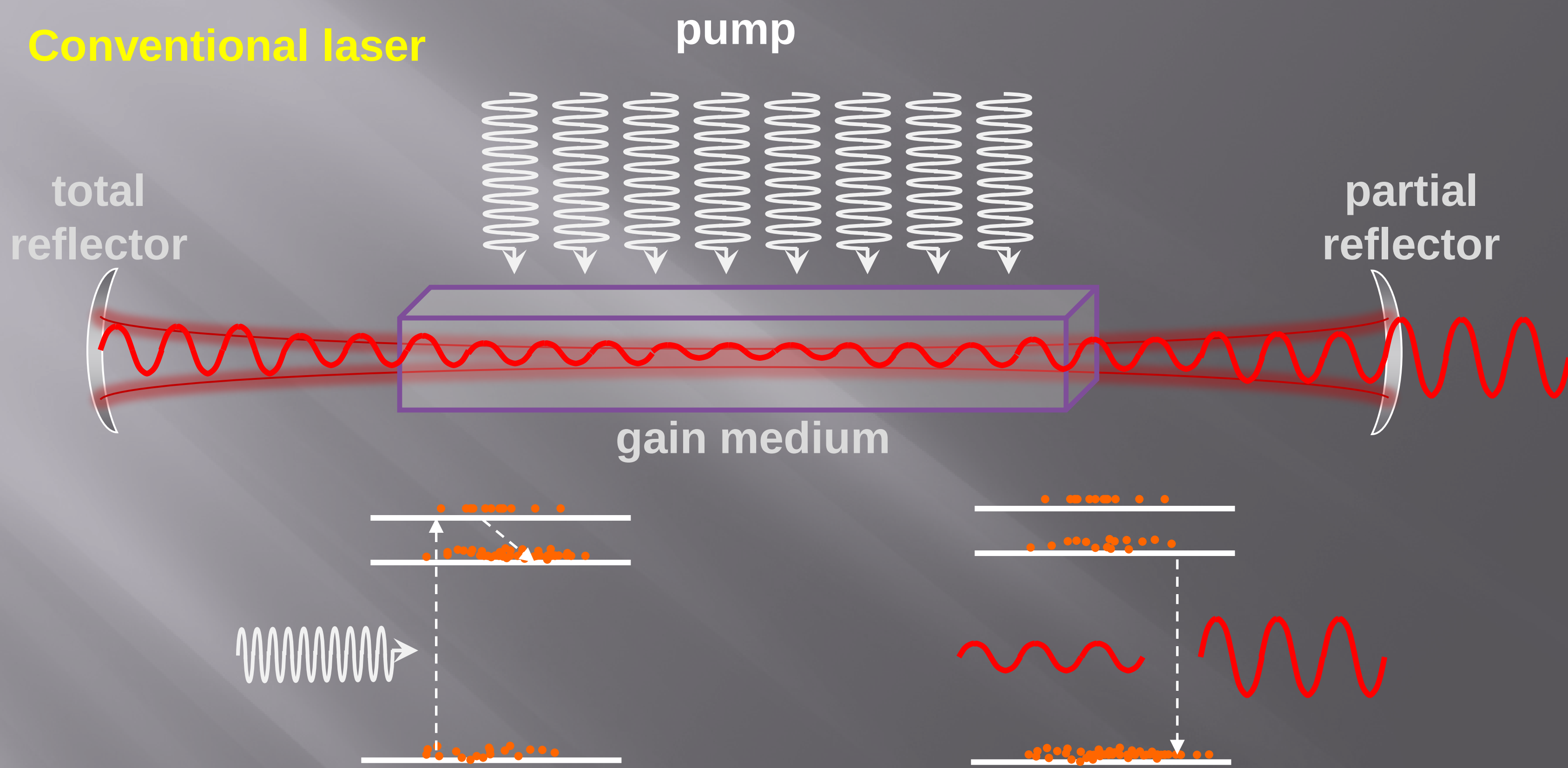


The electric field E and magnetic field B of a plane wave are perpendicular to each other and to the direction of propagation

In our convention, E oscillates along the x direction, B along the y, and z is the direction of light propagation.

$$\mathbf{E}(z,t) = \hat{\mathbf{x}} E_0 \cos(kz - \omega t + \varphi)$$
$$\mathbf{B}(z,t) = \hat{\mathbf{y}} B_0 \cos(kz - \omega t + \varphi)$$

Light Amplification by Stimulated Emission of Radiation (LASER)



Population inversion

Amplification (gain) by stimulated emission

Quantum lasers use electrons bound to discrete atomic or molecular energy levels and thus produce fixed wavelengths

FEL gain medium is free electrons traversing a wiggler (undulator)

FEL use free electrons traveling near the speed of light through a series of alternating magnets called a wiggler. Electrons undulating in the wiggler radiate electromagnetic waves at wavelength λ as given by

wiggler period

wavelength

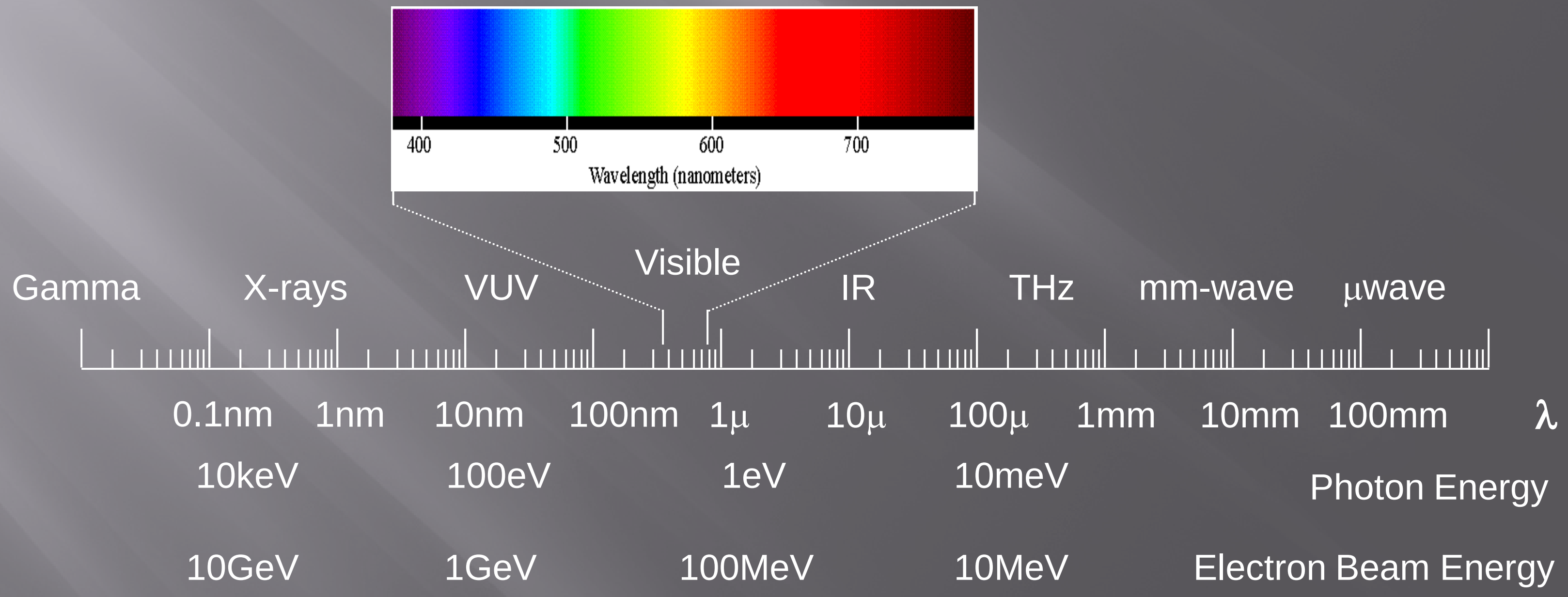
$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + a_w^2\right)$$

a parameter that depends on wiggler field and period

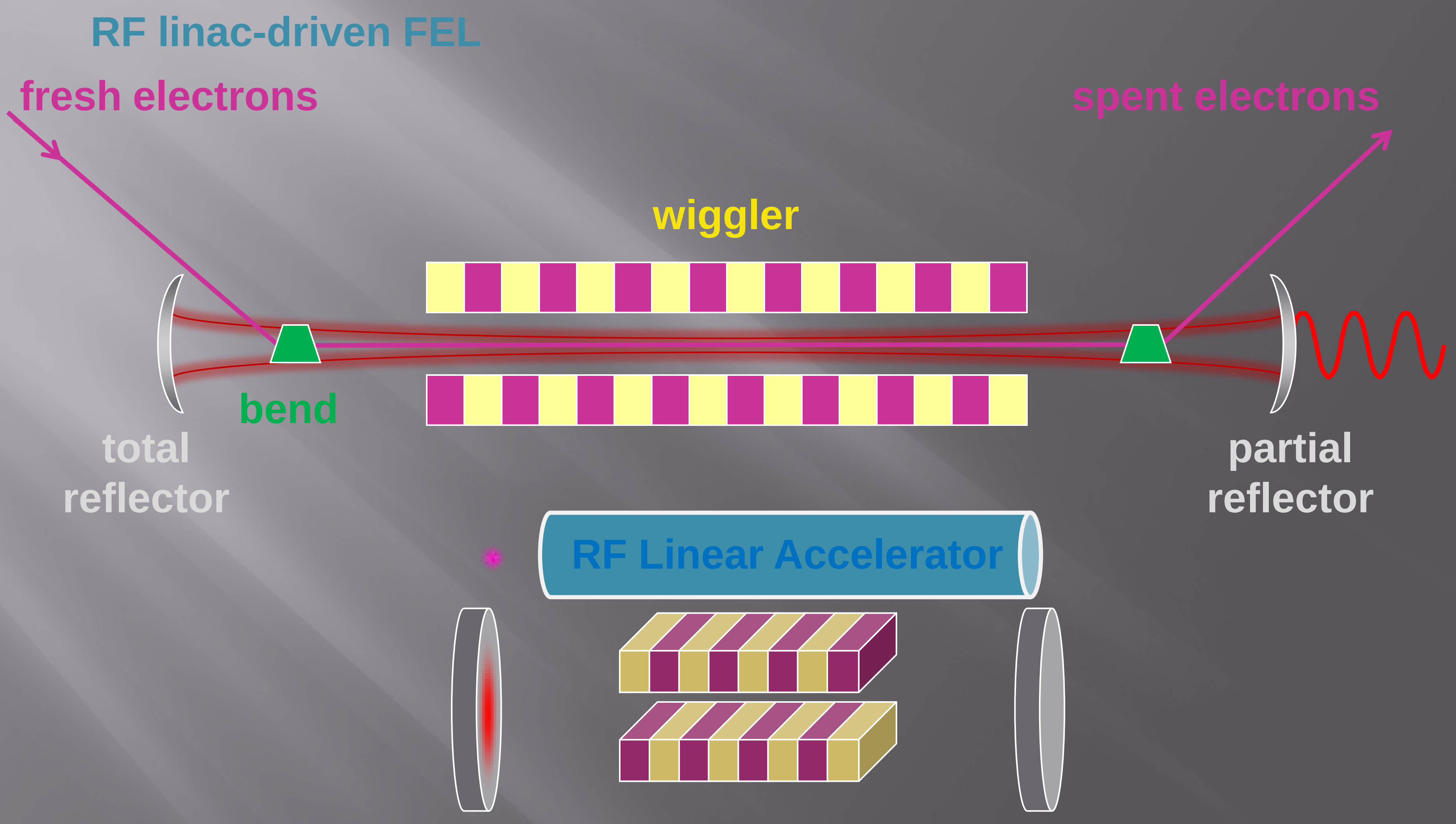
a parameter that depends on electron beam energy

Basic features of FEL

- Wavelength tunable
- Diffraction limited optical beam
- High power (GW peak, 10s of kW average)
- Flexible pulse format



How an RF-linac FEL works

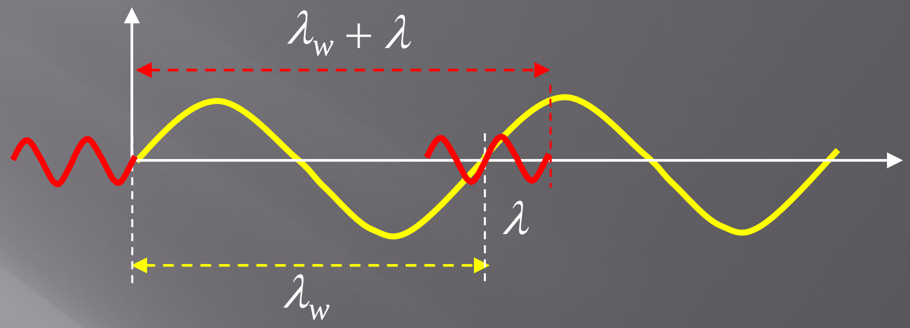


Courtesy of John Lewellen

Light slips over the electrons one wavelength every wiggler period

Relativistic factor

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



Electron average speed

$$\bar{\upsilon} \approx c\left(1-\frac{1}{2\gamma^2}\right)$$

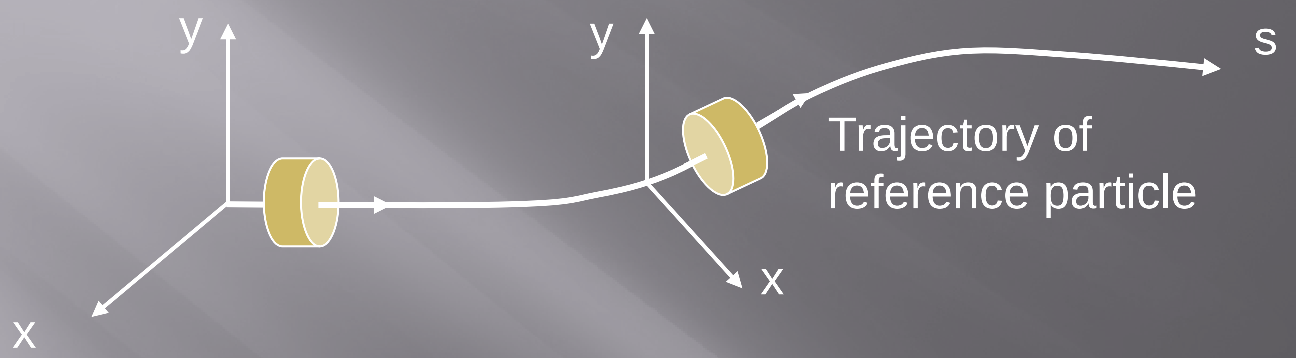
Electrons travel slightly slower than light so in the time electrons travel one period, light travels one wiggler period plus one wavelength

$$\frac{\lambda_w + \lambda}{c} = \frac{\lambda_w}{\bar{\upsilon}}$$

$$\lambda = \lambda_w\left(\frac{c}{\bar{\upsilon}} - 1\right)$$

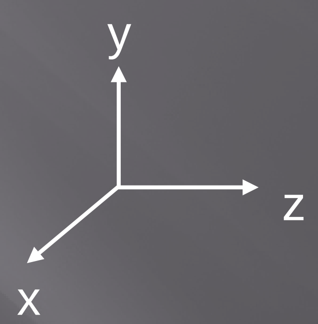
$$\lambda = \frac{\lambda_w}{2\gamma^2}$$

Curvilinear Coordinate System



Electrons travel in the s direction. Use (x, y, s) coordinate system to follow the reference electron, an ideal particle at the beam center with a curvilinear trajectory. The reference particle trajectory takes into account only pure dipole fields along the beam line. The x and y of the reference trajectory are thus affected only by the placement and strength of the dipole magnets.

Since the electron trajectory in the wiggler consists of very small deviations from a straight line, we will use the z axis (straight line) instead of s.



Force & Energy Transfer in FEL

Lorentz force on electrons

$$\mathbf{F} = -e\left[\mathbf{E} + \left(\mathbf{v} \times \mathbf{B}\right)\right]$$

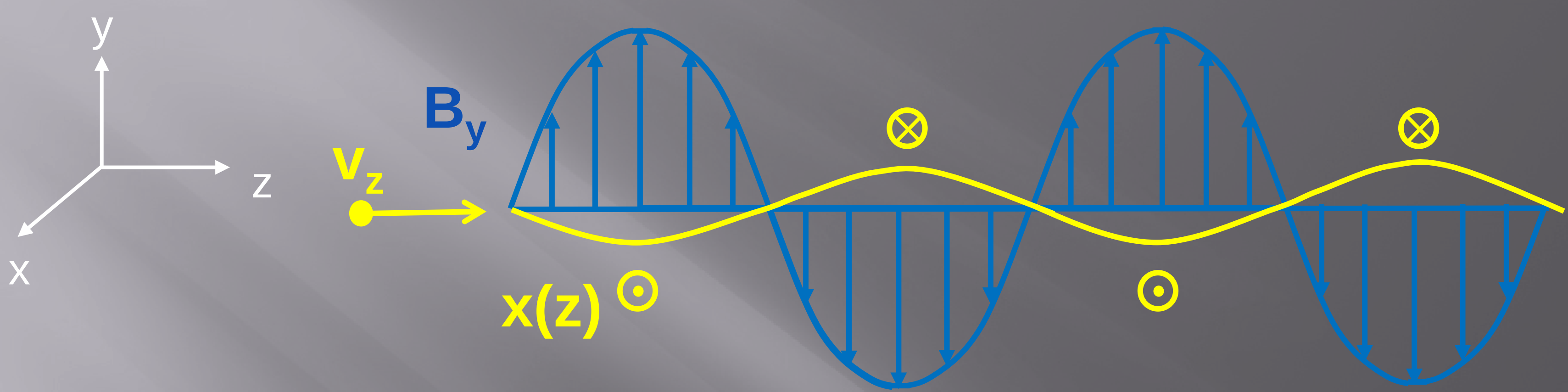
Magnetic field changes the electron beam's momentum but not its energy because the direction of magnetic force is always perpendicular to the electrons' motion.

Energy transfer happens when electrons interact with the light's electric field.

$$\Delta W = \int \mathbf{F} \cdot d\mathbf{s} = -\int e\mathbf{E} \cdot d\mathbf{s}$$

Light only has **transverse electric field**, so for energy transfer between co-propagating electron and light beams to happen, we need a **sinusoidal magnetic field** to give electrons **oscillatory transverse motion** to interact with the light beam's electric field.

Electron Motion in a Wiggler



Sinusoidal magnetic field along the y axis

$$B_y = B_0 \sin\left(k_w z\right)$$

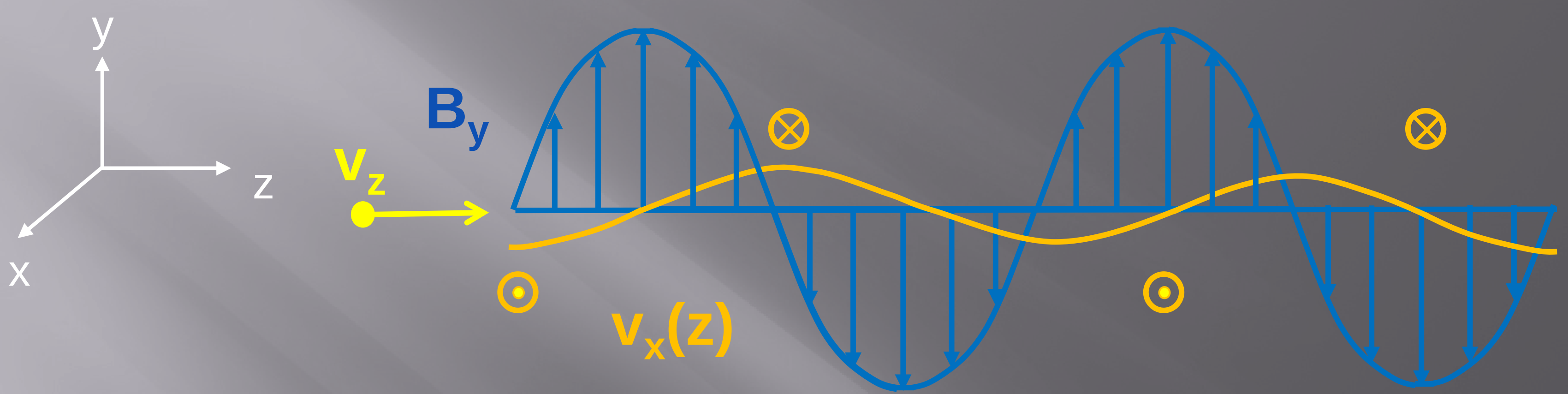
Lorentz force on electrons due to v x B (where v_z is almost c) causes a rate of change of electron momentum in x

$$\gamma m_0 \dot{\upsilon}_x = -e\upsilon_z B_y \approx -ecB_0 \sin\left(k_w z\right)$$

Lorenz force acceleration is in the opposite direction with electrons’ motion, similar to the restoring force of a spring.

$$\dot{\upsilon}_x = \frac{-ecB_0}{\gamma m_0}\sin\left(k_w z\right)$$

Transverse Electron Velocity



Rate of change in x velocity

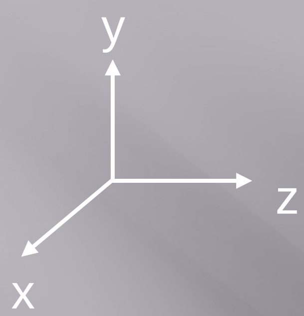
$$\dot{\upsilon}_x \approx \frac{-ecB_0}{\gamma m_0} \sin\left(k_w ct\right)$$

Integrate to obtain velocity in x

$$\upsilon_x = \frac{ecB_0}{\gamma m_0 c k_w} \cos\left(k_w z\right)$$

Transverse velocity is 90º out of phase with both motion and acceleration, i.e. transverse velocity is greatest when electrons cross the z axis (B = 0).

Axial Electron Velocity



$$\upsilon \approx c\left(1-\frac{1}{2\gamma^2}\right)$$

Using Pythagoras' theorem

$$\upsilon^2 = \upsilon_z{}^2 + \upsilon_x{}^2$$

$$\upsilon_x = \frac{c\sqrt{2}a_w}{\gamma}\cos\left(k_w z\right)$$

Calculate the electrons' axial velocity (along z direction)

$$\upsilon_z = c\left[1-\frac{1}{2\gamma^2}\left(1+a_w^2+a_w^2\cos\left(2k_w z\right)\right)\right]$$

Electrons' axial velocity is modulated at twice the wiggling frequency

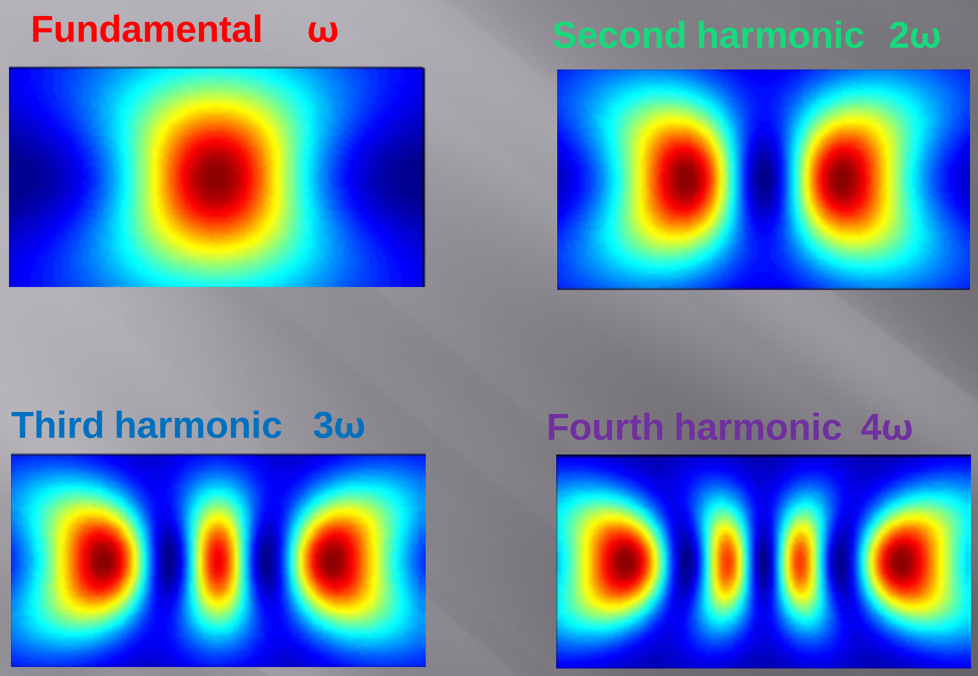
Synchrotron (Undulator) Radiation 3rd Generation Light Source

Advanced Photon Source

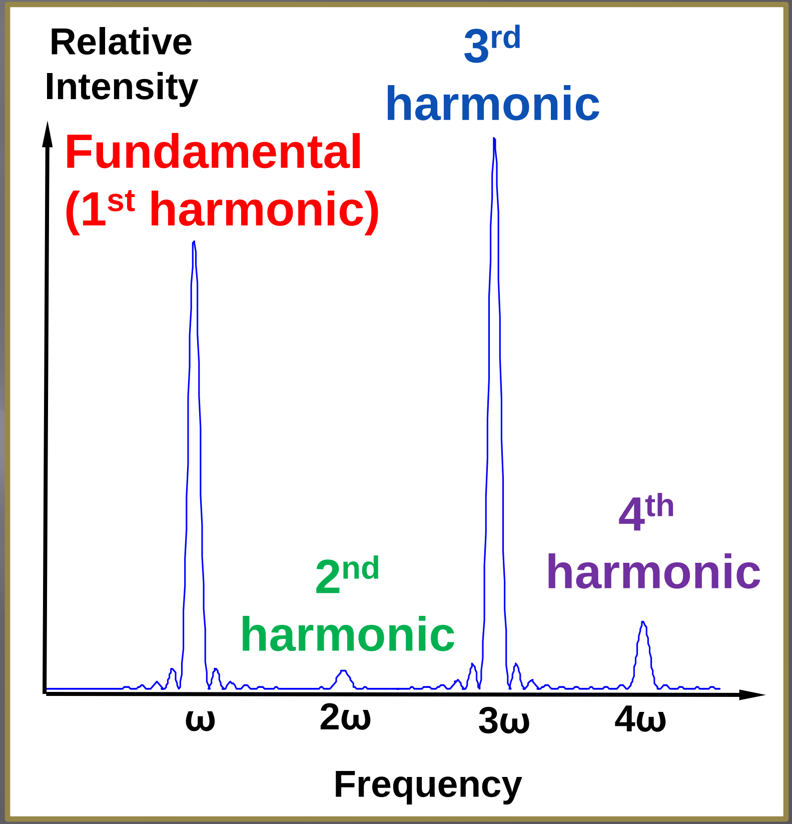
Undulator (aka

Insertion Devices)

Undulator Radiation Harmonics



Color codes depict radiation intensity not wavelength



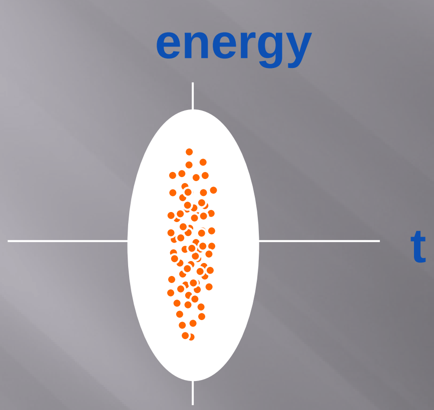
Odd harmonics are stronger and emitted on-axis (e- beam direction)

Even harmonics are weaker and emitted off-axis

Brilliance

Brilliance = $\dfrac{\text{Number of photons}}{\text{time} \quad \text{bandwidth} \times \text{beam area} \times \text{solid angle}}$

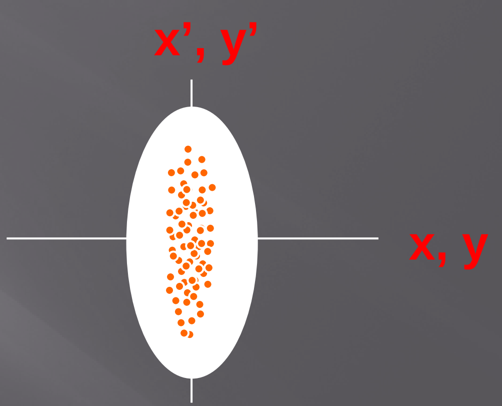
longitudinal phase space



$$\sigma_z\left(\frac{\sigma_\gamma}{\gamma}\right) \le \left(\frac{\Delta\lambda}{\lambda}\right) c\sigma_t$$

Longitudinal emittance is expressed in time % bandwidth

transverse phase space



$$\varepsilon_{x,y} \le \frac{\lambda}{4\pi}$$

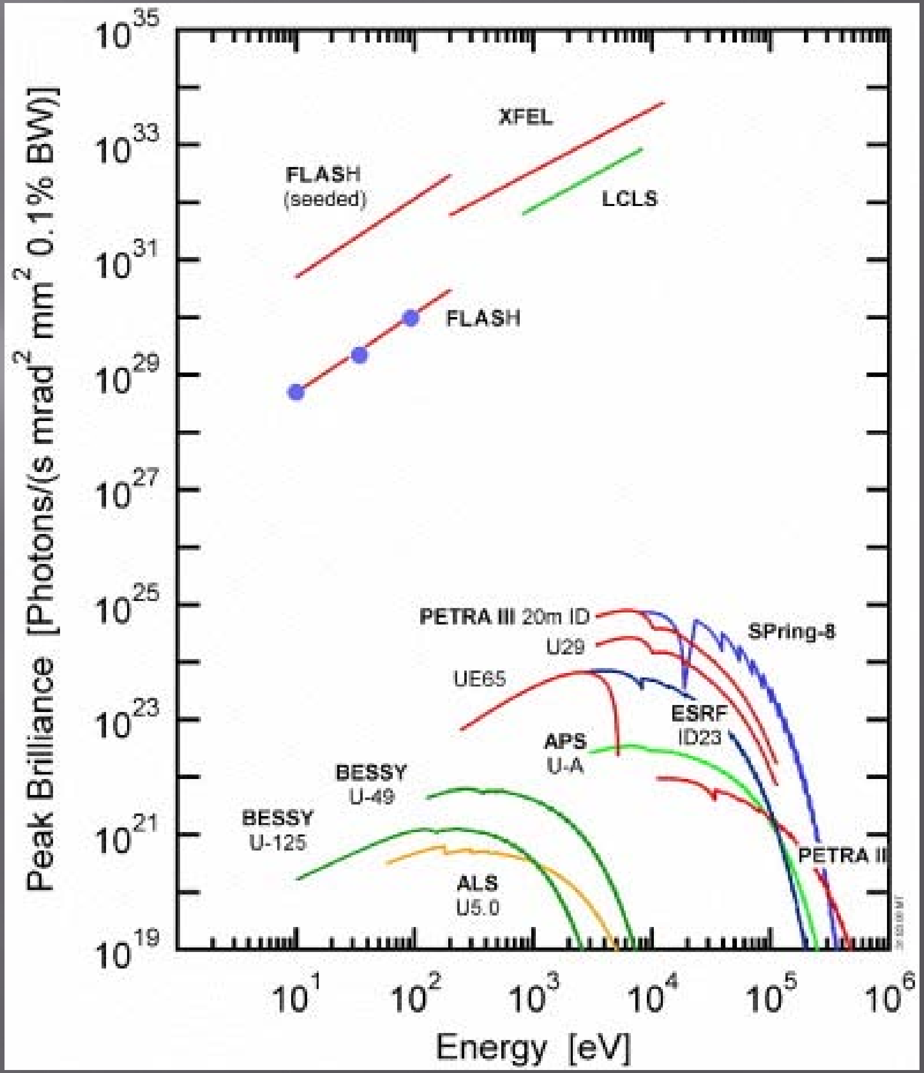
Transverse emittance is expressed in microns

FEL is a 4th Gen Light Source

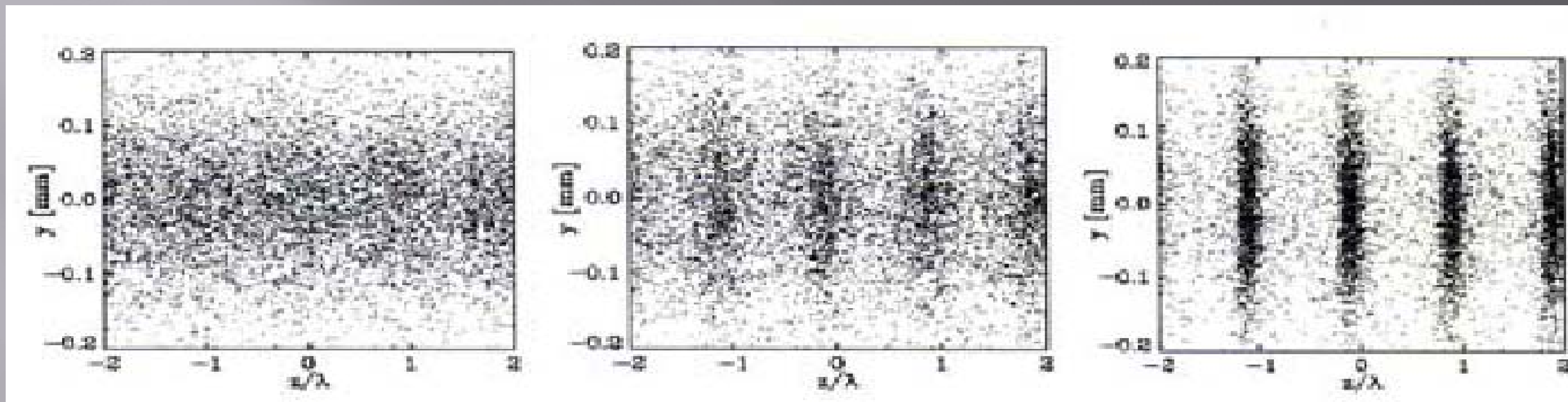
Brilliance

$$\mathfrak{B} = \frac{N_p}{\pi^2 \varepsilon_x \varepsilon_y \Delta t \frac{\Delta\omega}{\omega}}$$

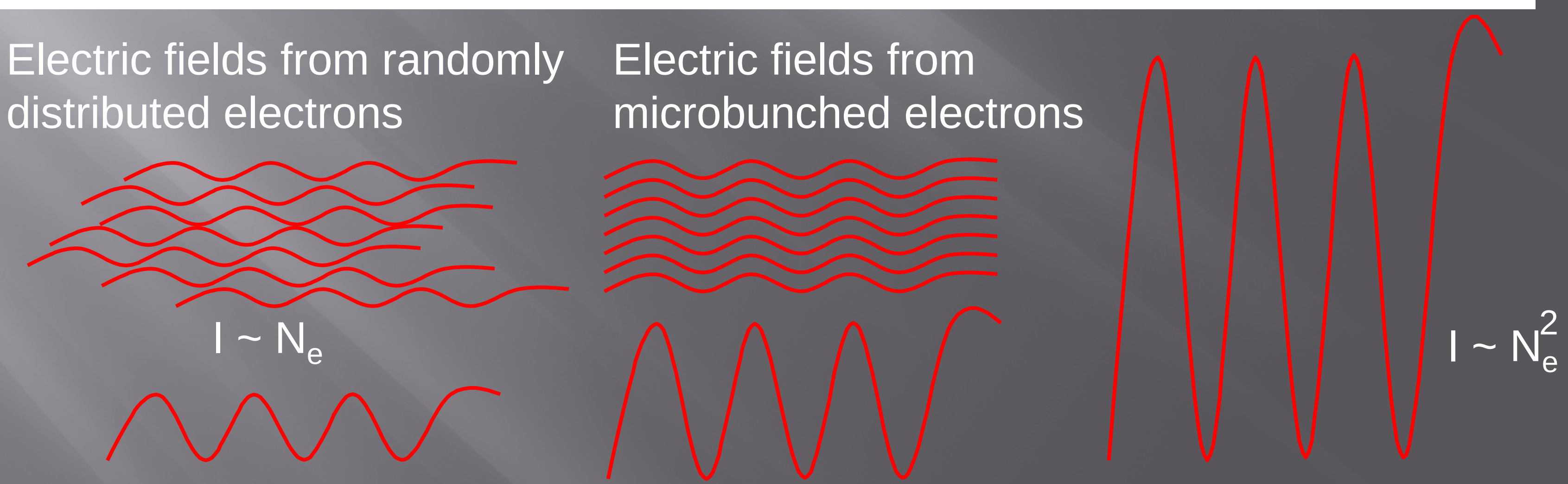
FEL peak brilliance is orders of magnitude above synchrotron radiation because FEL light is **magnified** by the **# of electrons** in each bunch and the FEL phase space area is small.



Electrons are microbunched with periodicity of one wavelength



At entrance to the undulator — Exponential gain regime — Saturation(maximum bunching)

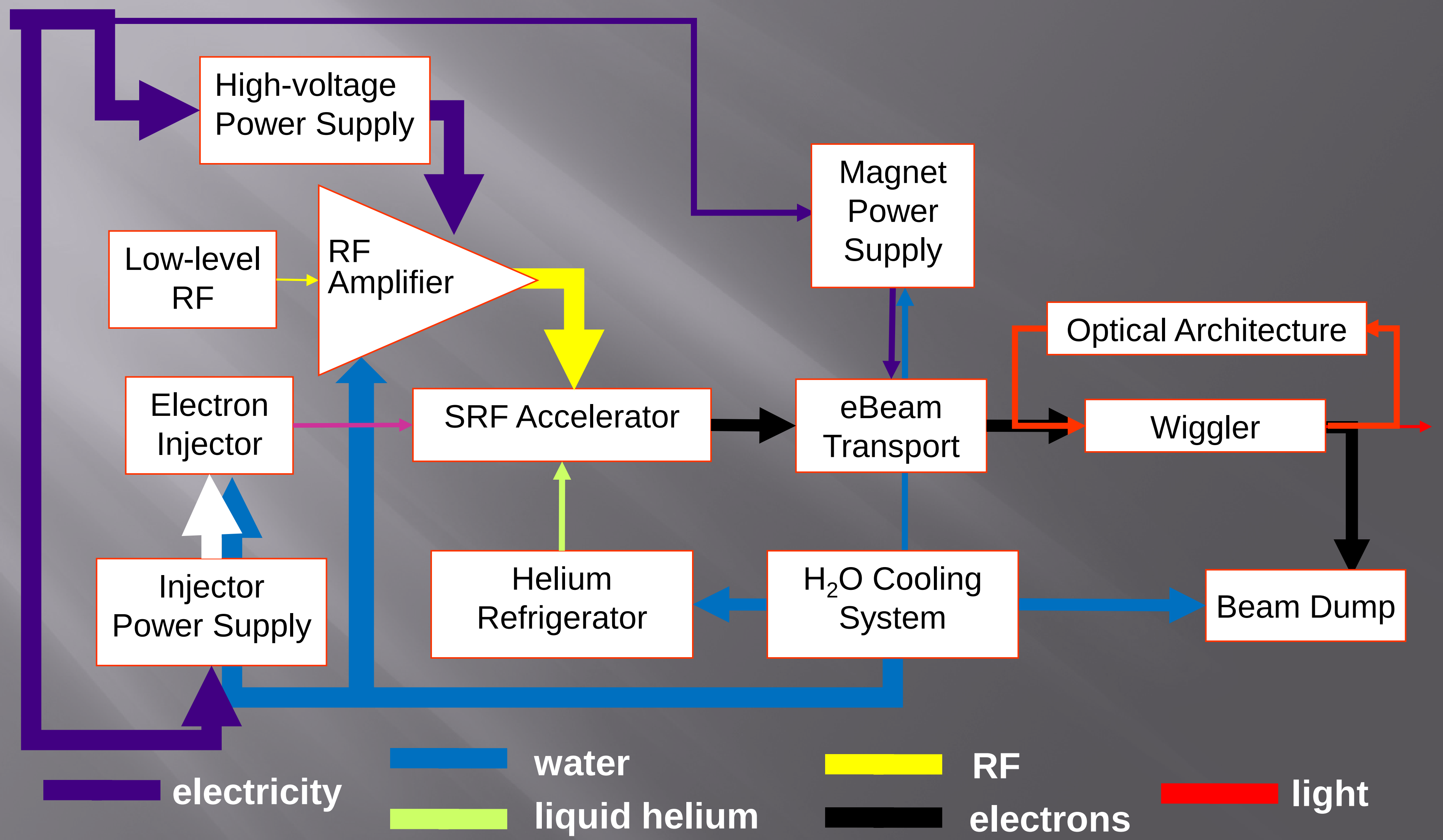


Intensity is proportional to E^2

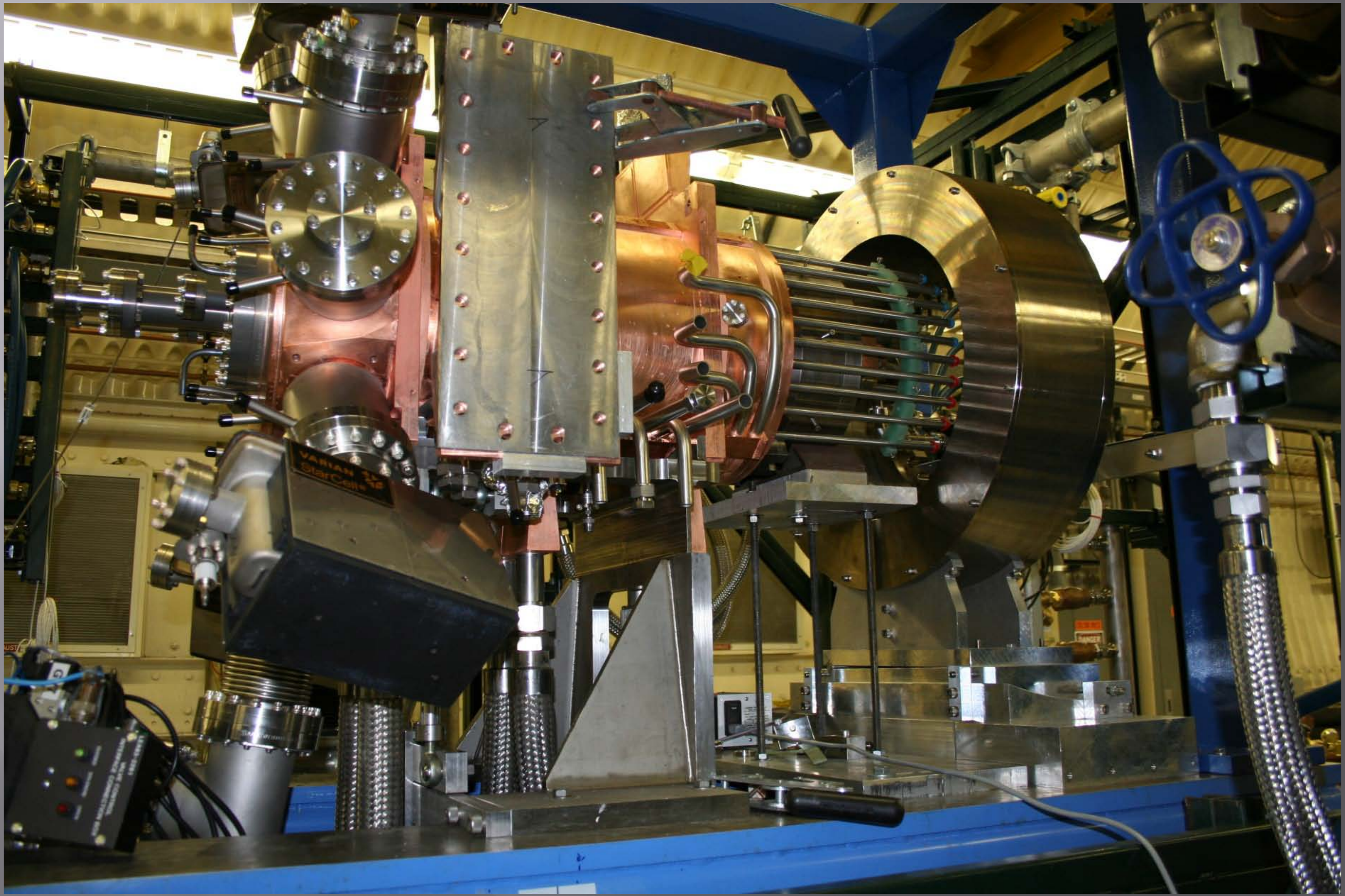
Light is amplified by N_e

Part 3
What does it take?

RF-linac Driven FEL Sub-systems

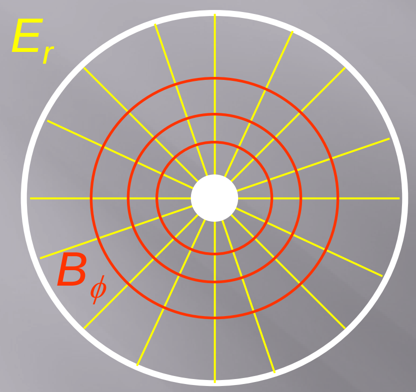


Electron Injectors



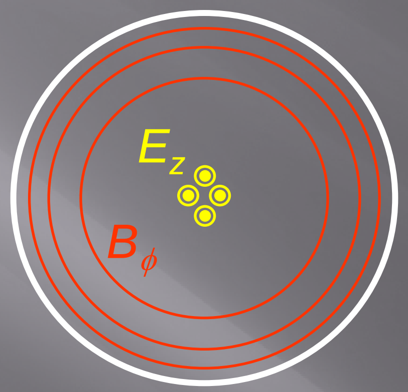
LANL 700MHz NCRF Gun

RF Waveguide Modes



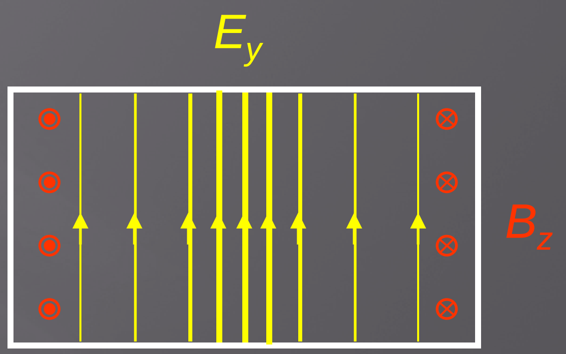
TEM
Transverse electric, magnetic

TEM modes in coaxial transmission lines; used for power transmission



TM
Transverse magnetic

TM modes in cylindrical waveguides; used for **acceleration**



TE
Transverse electric

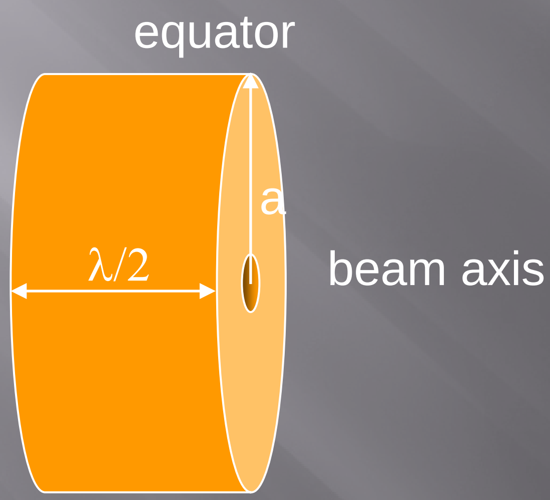
TE modes in rectangular waveguides; used for high-power transmission

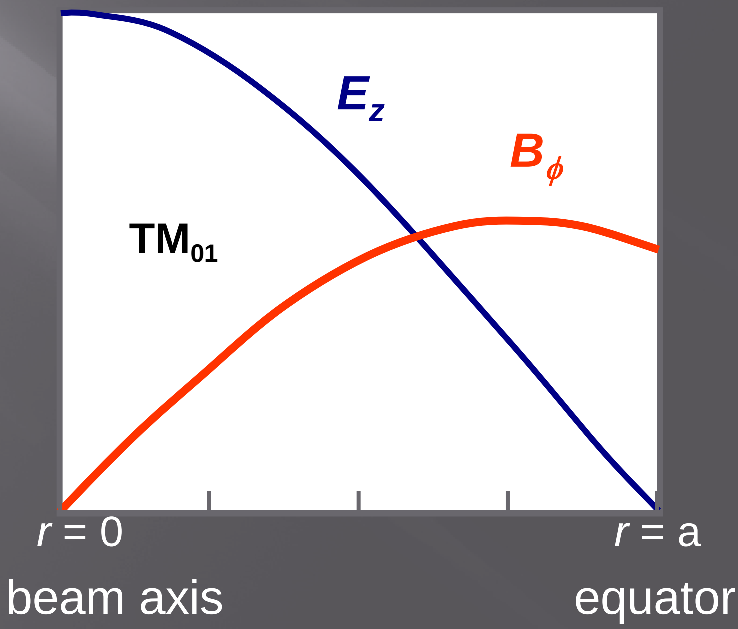
How an RF accelerator works

Electric field accelerates electrons and increases their energy.

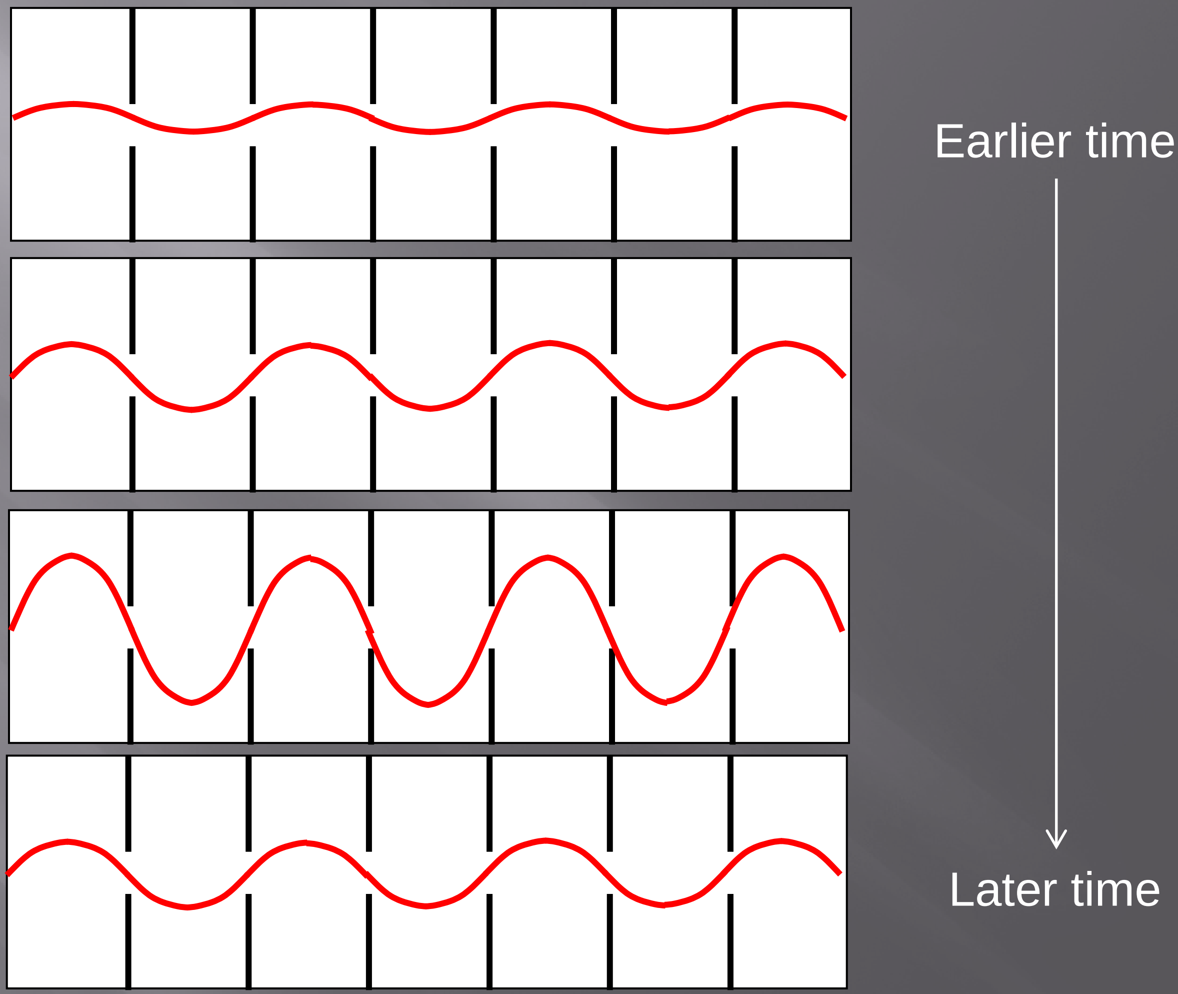
$$\Delta W = \int \mathbf{F} \cdot d\mathbf{s} = -\int e\mathbf{E} \cdot d\mathbf{s}$$

RF cavities store electromagnetic energy to produce high electric fields. Electric fields are maximum on axis and magnetic fields are maximum near the equator.



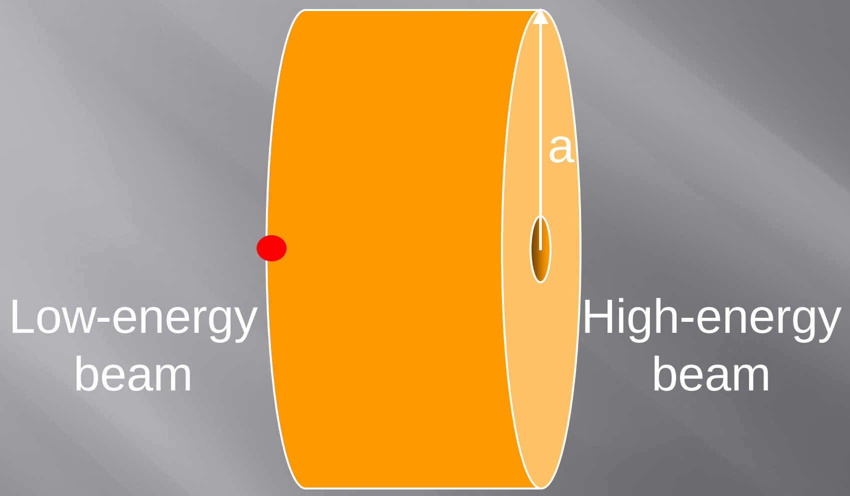


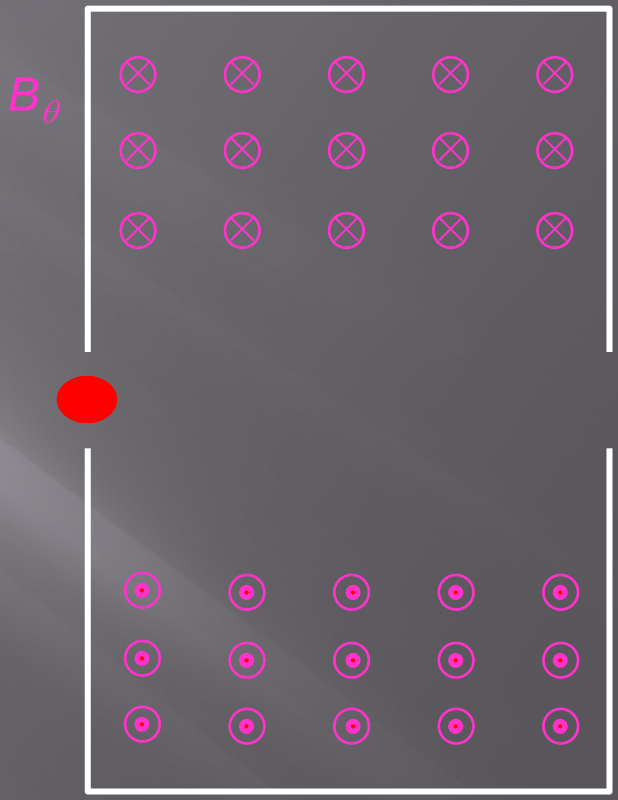
Standing-wave π-mode Cavity



Standing waves exist in multi-cell cavity if each cell is one-half wavelength long.

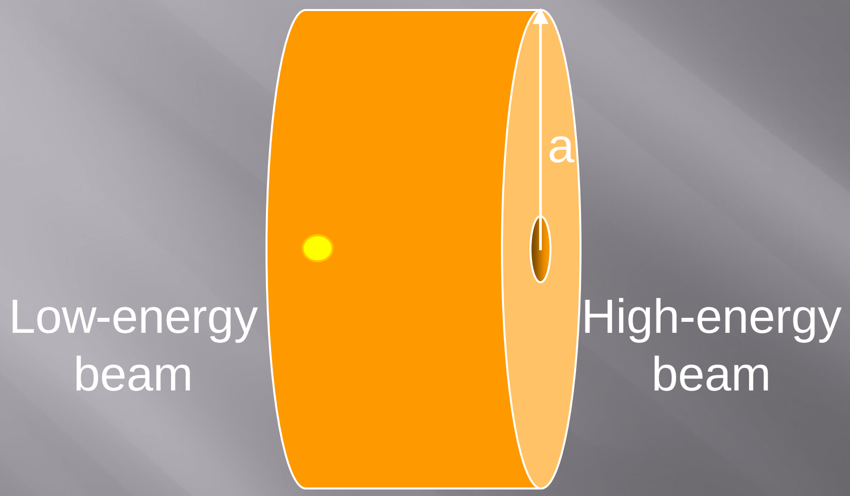
Single Pillbox Cavity

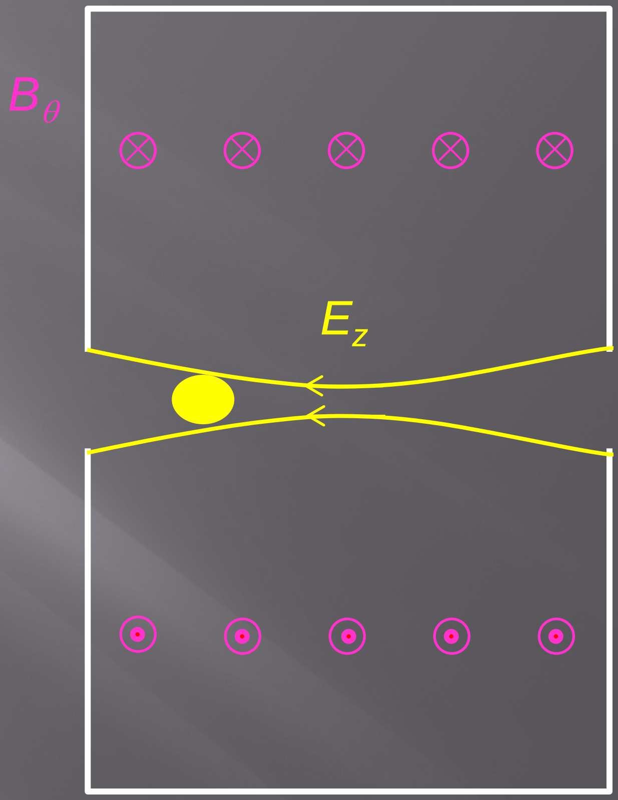




The color of the electron bunch denotes its energy (red = low; blue = high)

Single Pillbox Cavity





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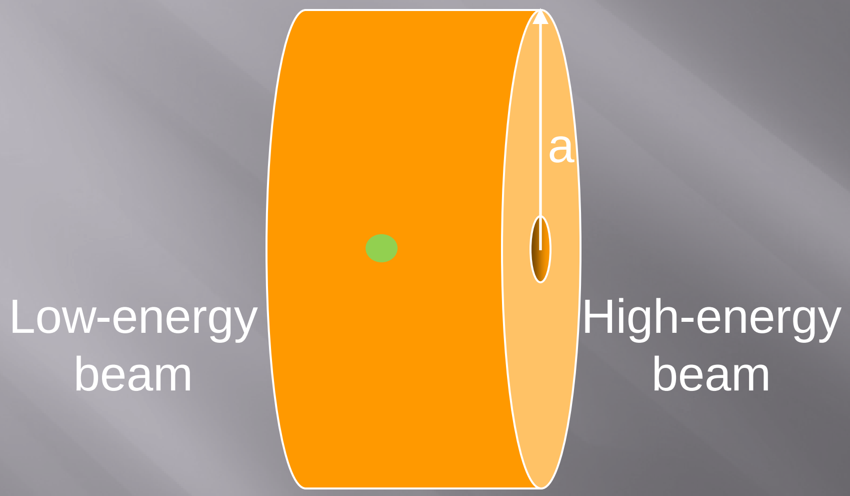
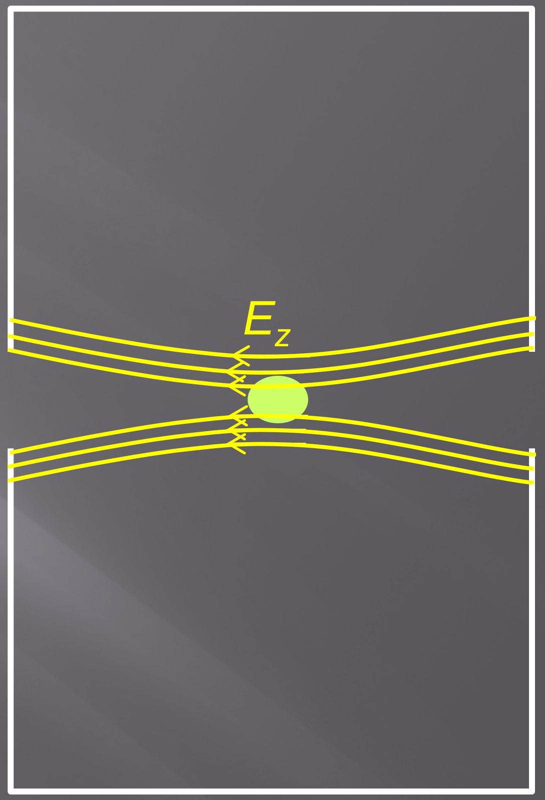
Single Pillbox Cavity





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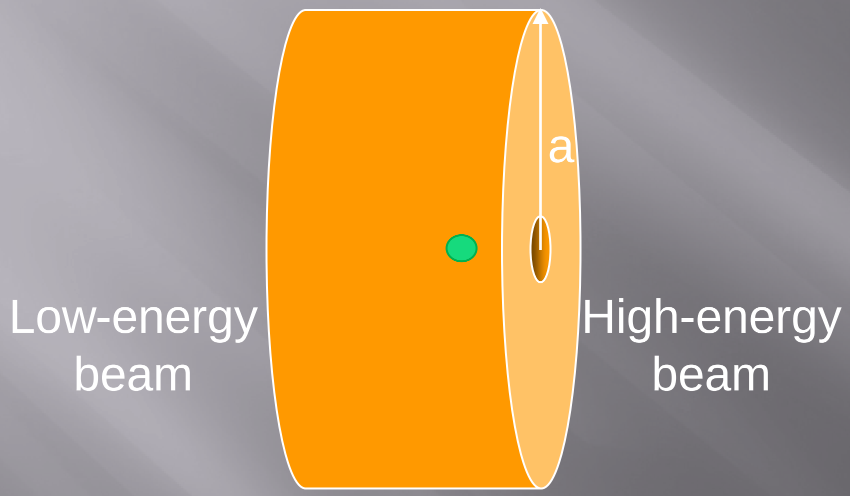

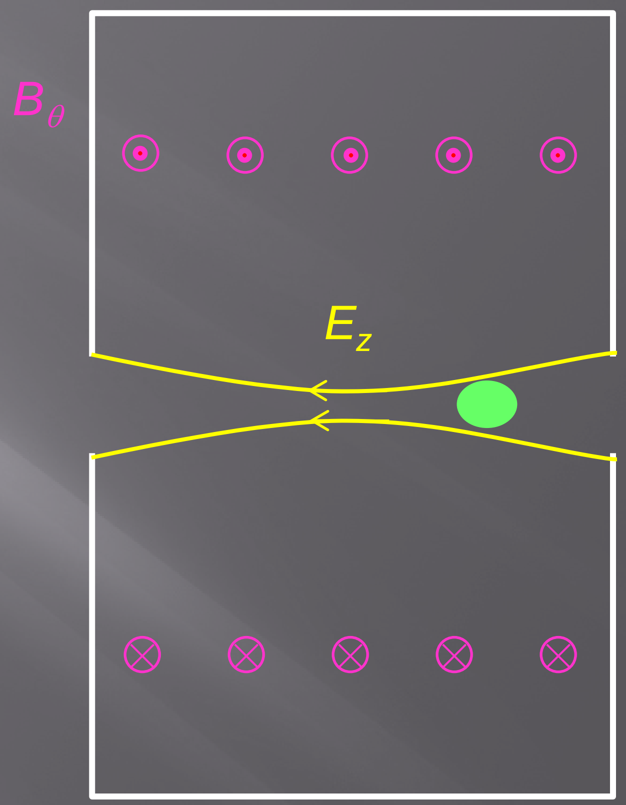

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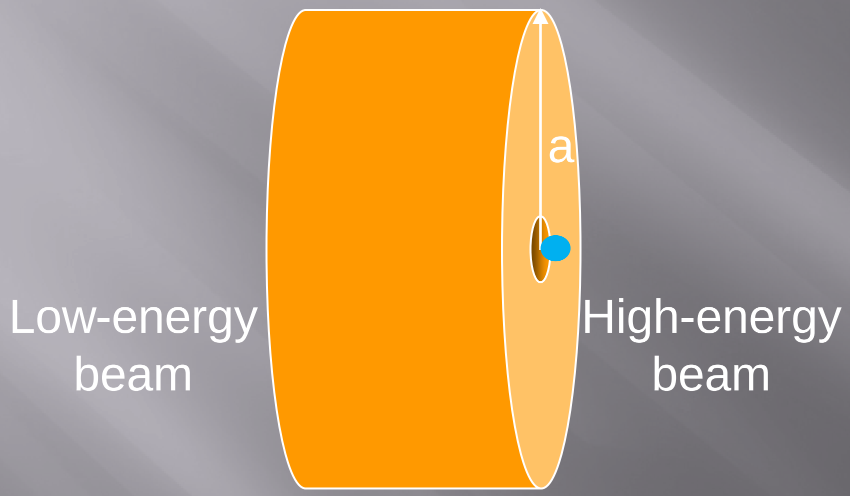
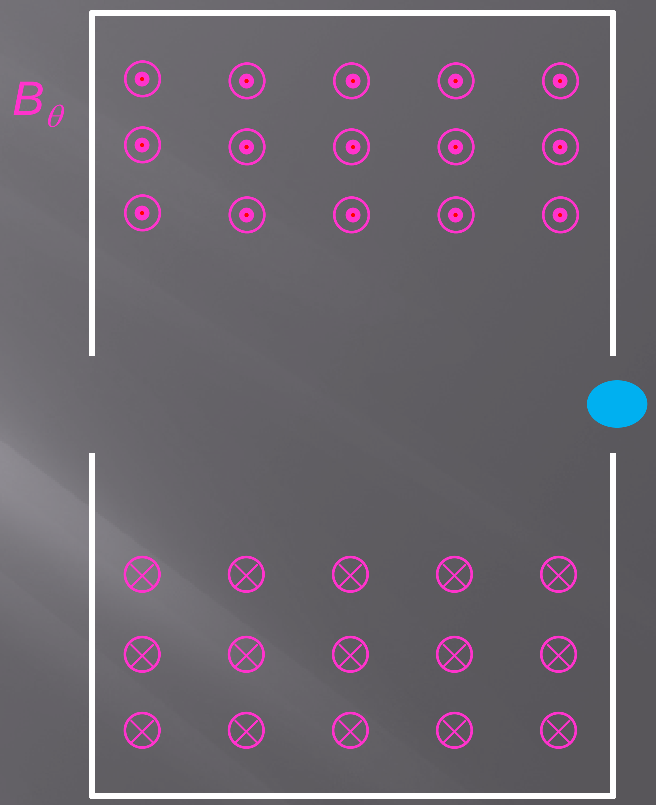
Single Pillbox Cavity





The color of the electron bunch denotes its energy (red = low; blue = high)

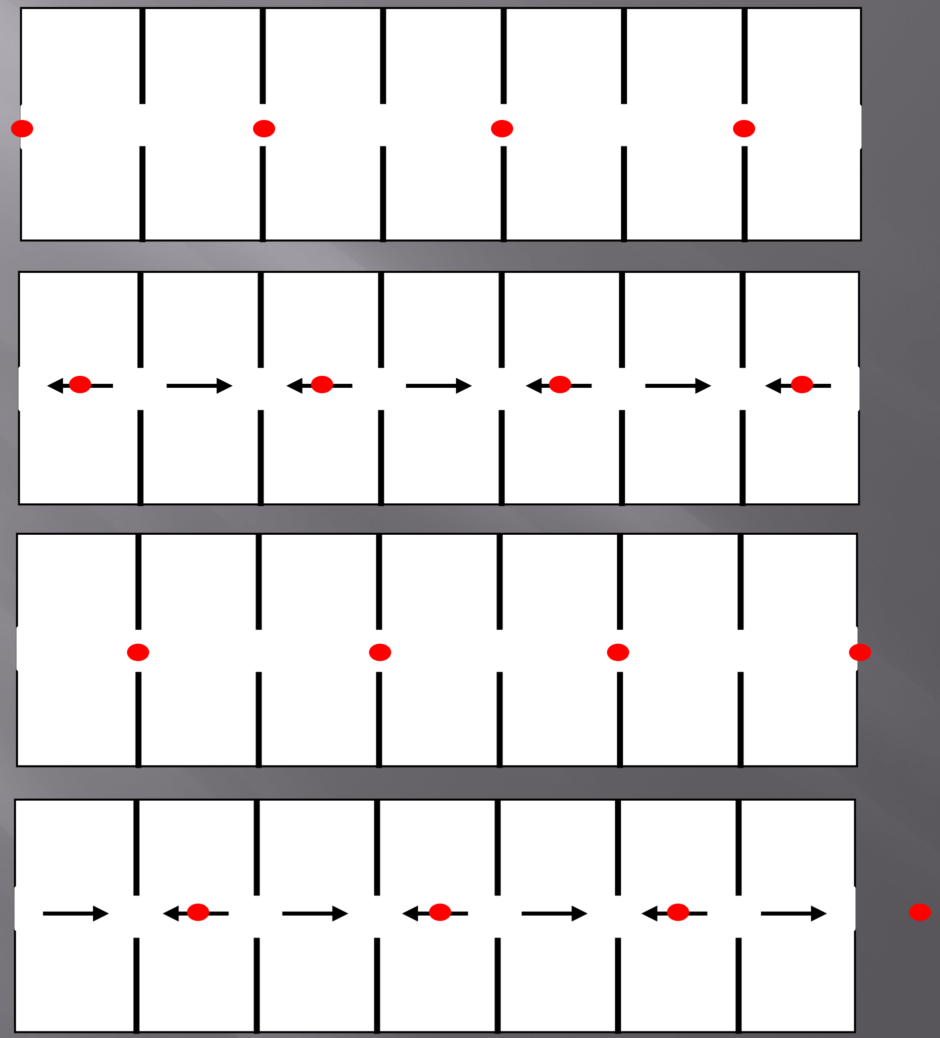
Multi-cell Acceleration

$\phi = 0$

$\phi = \pi/2$

$\phi = \pi$

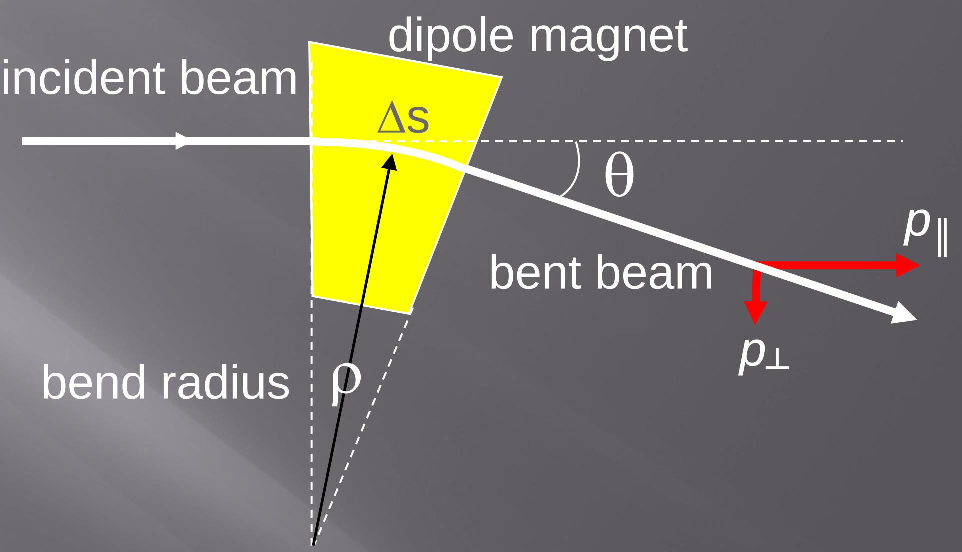
$\phi = 3\pi/2$



Electron Beam Transport

- Dipoles bend electron beams
  - Four dipoles can be arranged to compress the electron bunch in time to create high peak current
- Quadrupoles focus (defocus) electron beams
  - Three quadrupoles focus electron beams to a round spot
- Undulators both wiggle and focus electron beams
- Corrector magnets make small trajectory adjustments

Dipoles bend electron beams



Inverse bend radius

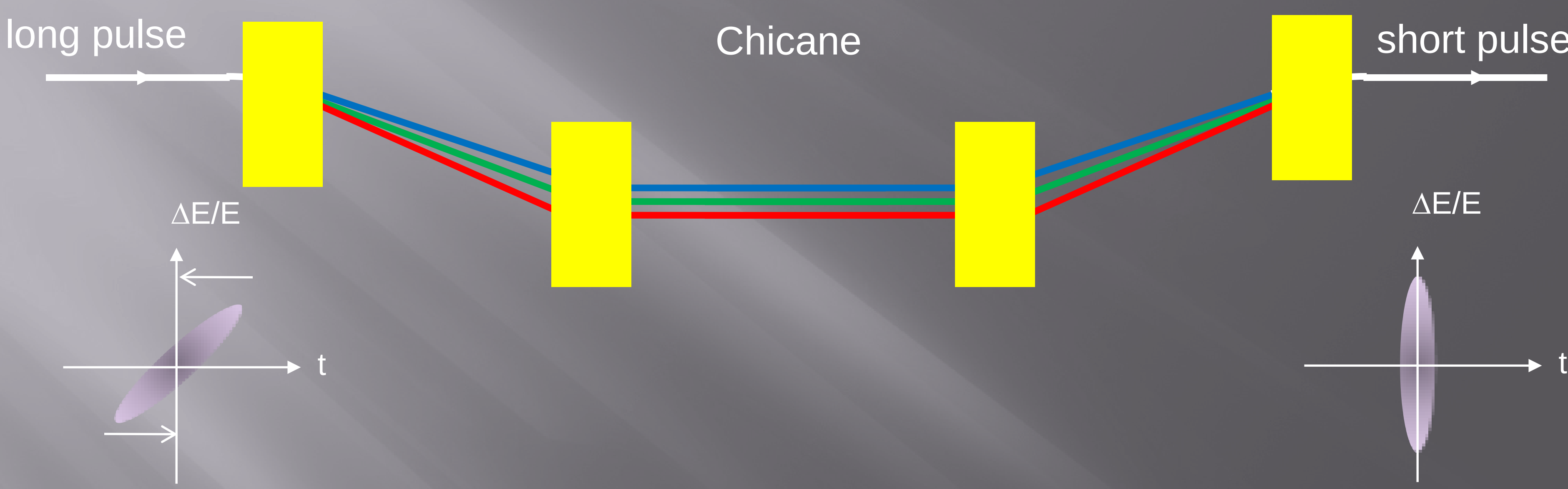
$$\frac{1}{\rho}\left(m^{-1}\right) = 299.8\frac{B(T)}{E_b\left(MeV\right)}$$

Magnetic rigidity

$$B\rho\left(T - m\right) = \frac{1}{299.8}E_b\left(MeV\right)$$

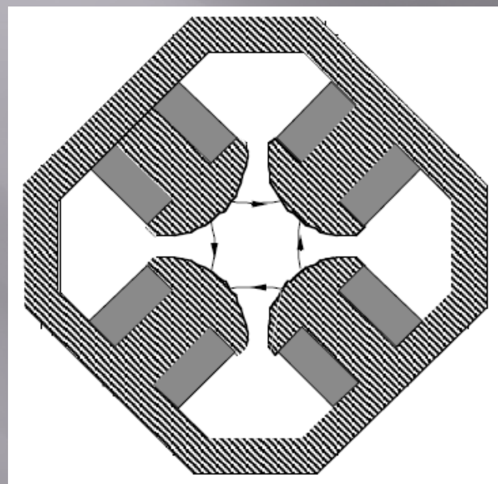
High-energy electrons are more “rigid” than low-energy ones. Different energies are bent at different angles, so the dipoles are also used as electron energy spectrometers.

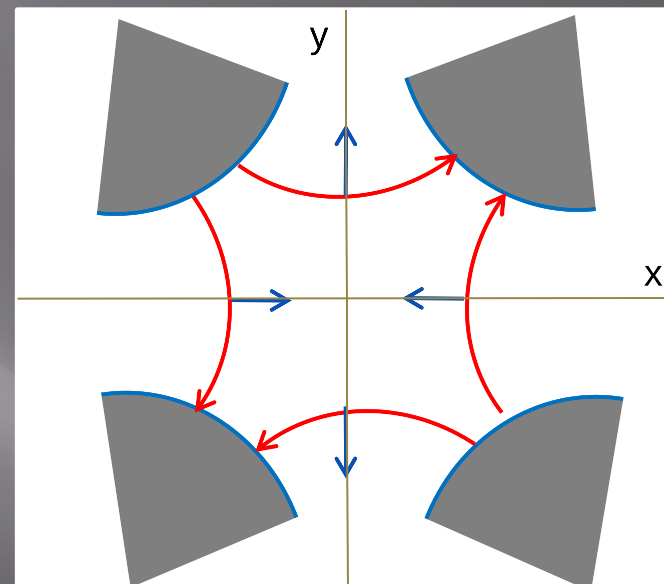
Dipoles are used to compress electron bunches



- Chirp electron bunch by accelerating it off-crest so the leading edge (left) has lower energy than the trailing edge (right)
- Put the energy-chirped electron bunch through a chicane
- Chicane compresses long bunch to shorter bunch (higher peak current)

Quadrupole Magnets



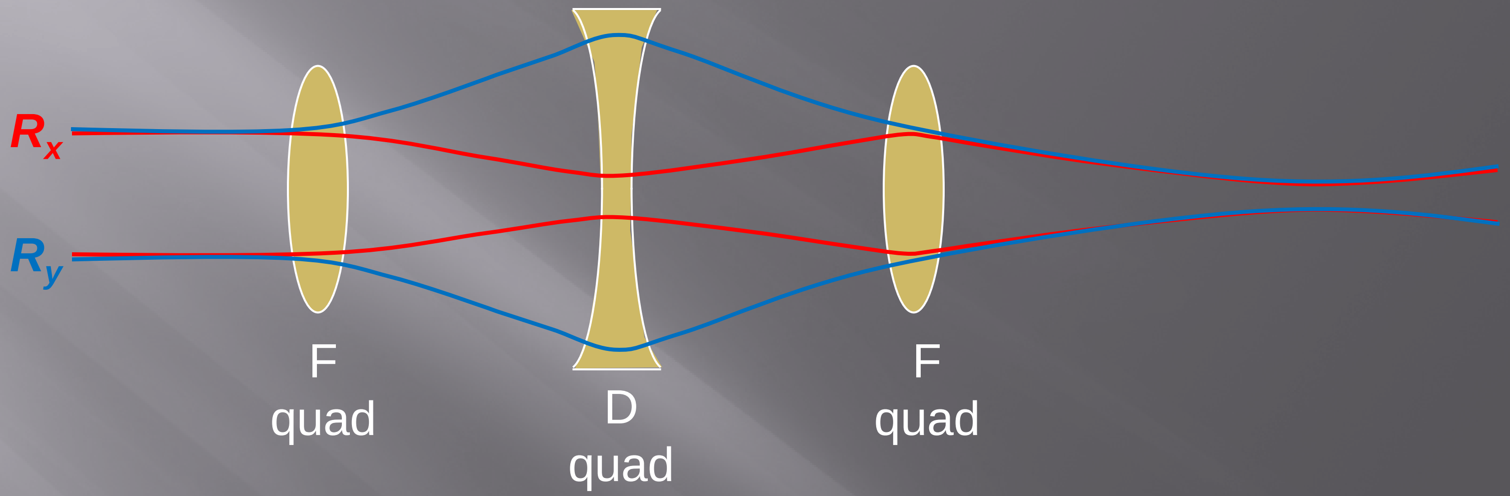


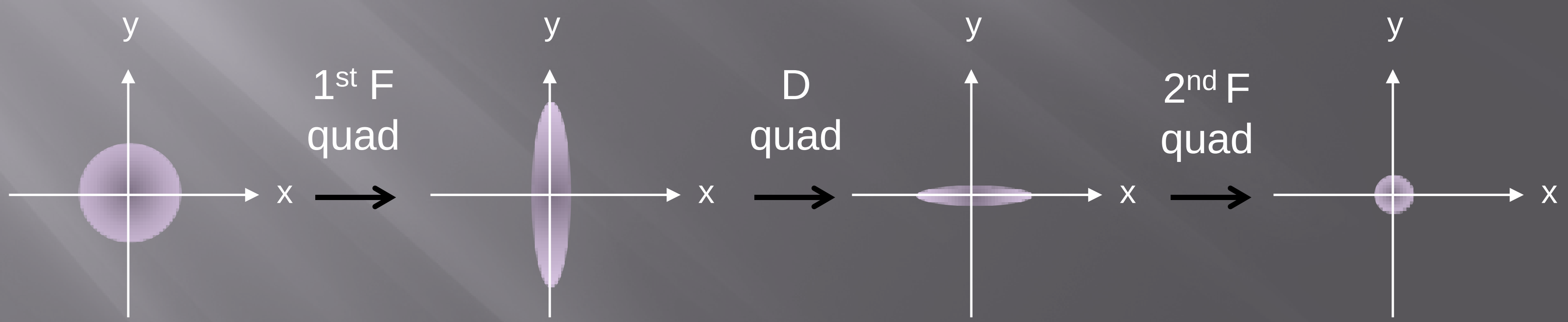
Magnetic field magnitude increases with distance from the center in both directions

Electrons get bent more as they stray away from the axis

In one direction, the beam is bent toward the axis (focused). In the perpendicular direction, the beam is defocused.

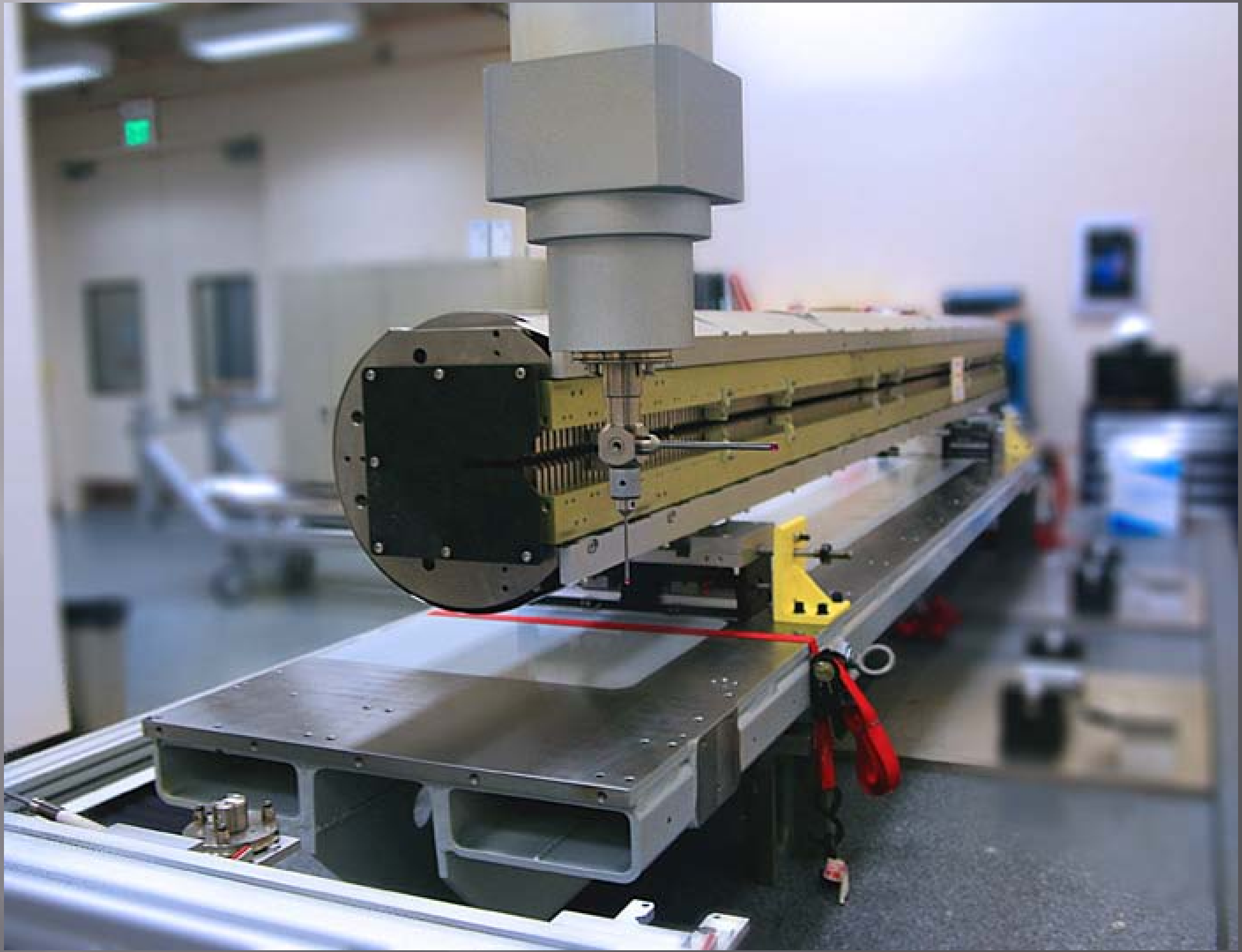
Triplets focus electron beams in both x and y directions



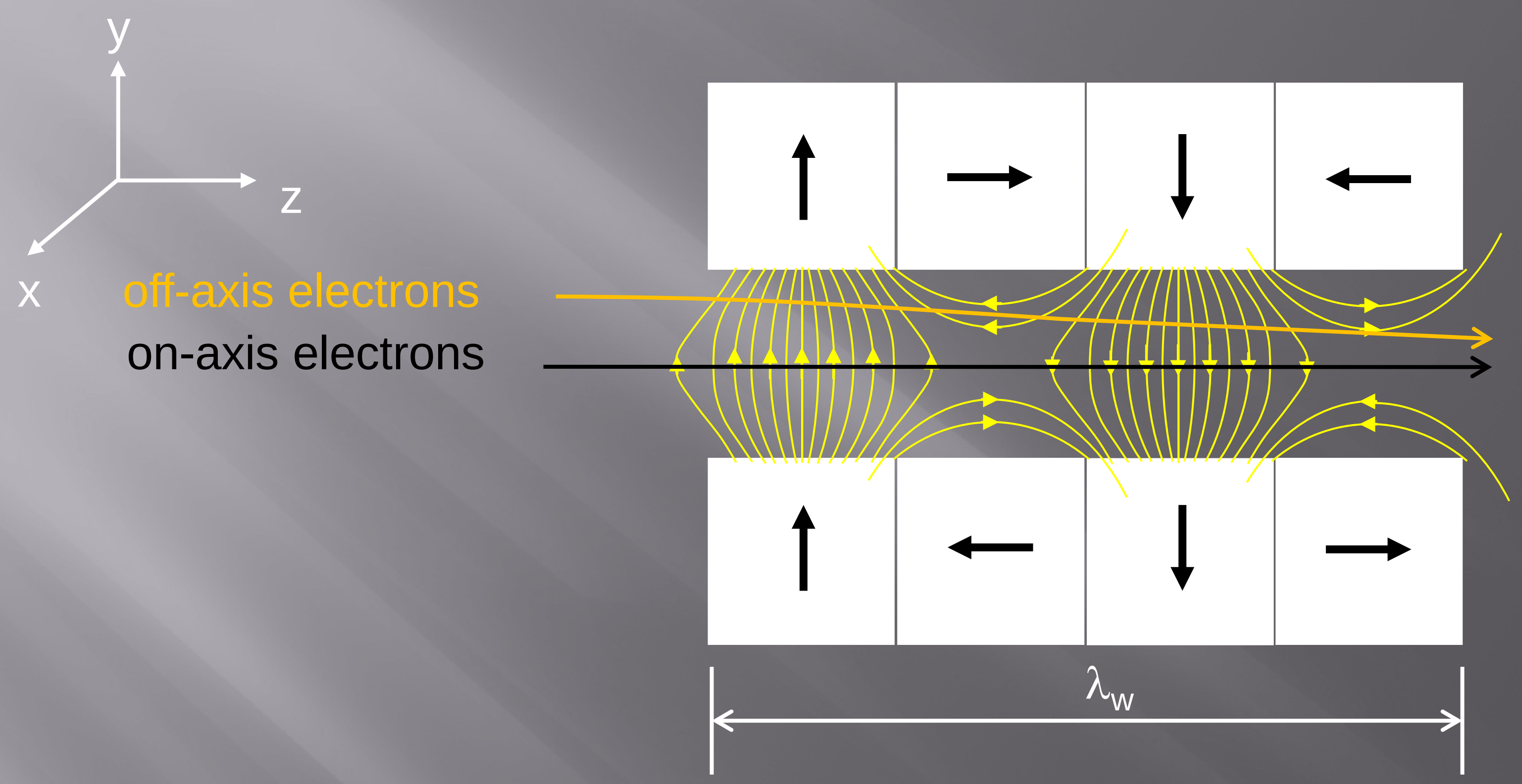


Evolution of electron beam envelope through a quadrupole triplet

Linac Coherent Light Source Undulator



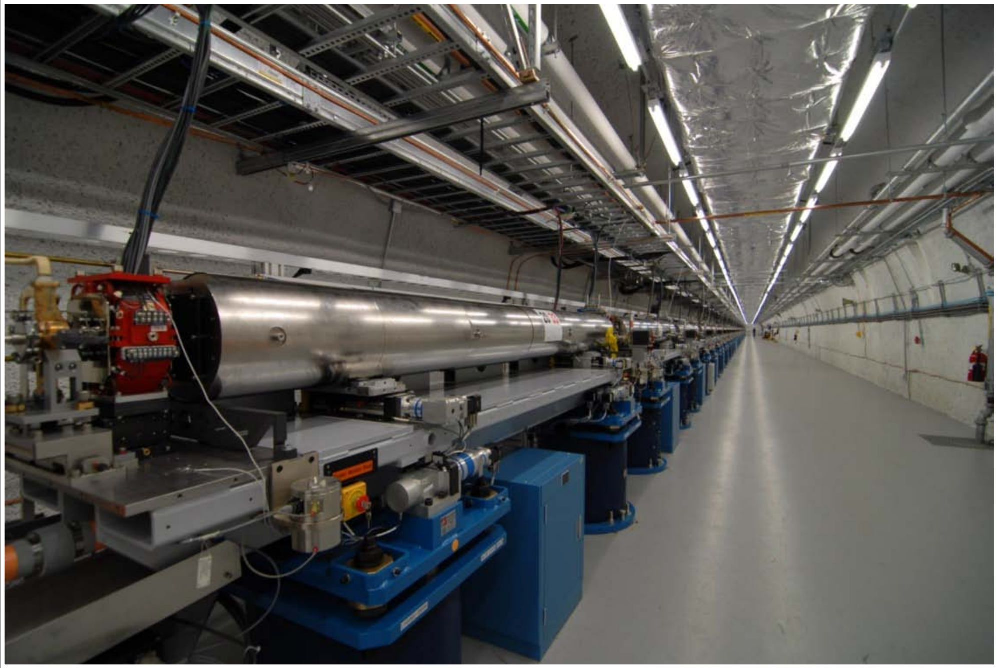
Undulators focus e-beam in y



The goal is to match the electron beam (with external focusing) to the natural focusing (beta) function of the undulator. When the beam is matched, its radius is constant throughout the undulator.

Self-Amplified Spontaneous Emission (SASE)

- Start from spontaneous emission (noise)
- Use very long undulators
- FEL power grows exponentially with undulator length
- FEL saturates in a single pass

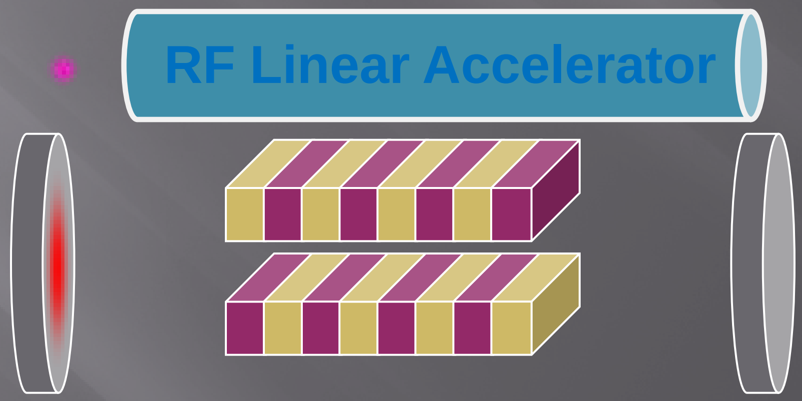


LCLS Undulators

Courtesy of SLAC

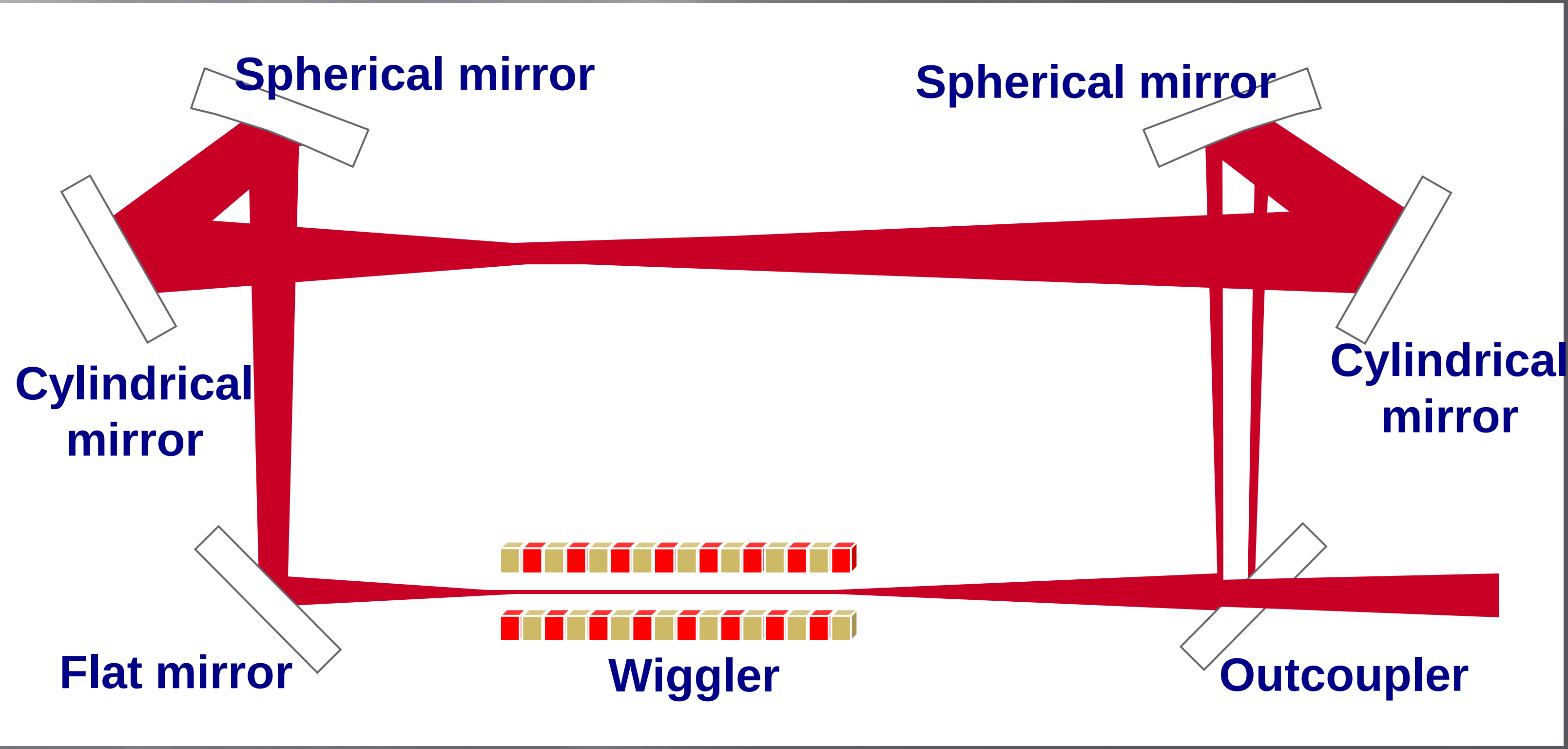
Oscillator

- Use mirrors to feedback a large fraction (>50%) of FEL beam
- If cavity loss is low, the remaining power exits the optical cavity
- Optical cavity determines the optical mode
- Cavity length has to be close to a multiple of electron bunch arrival time



Regenerative Amplifier FEL

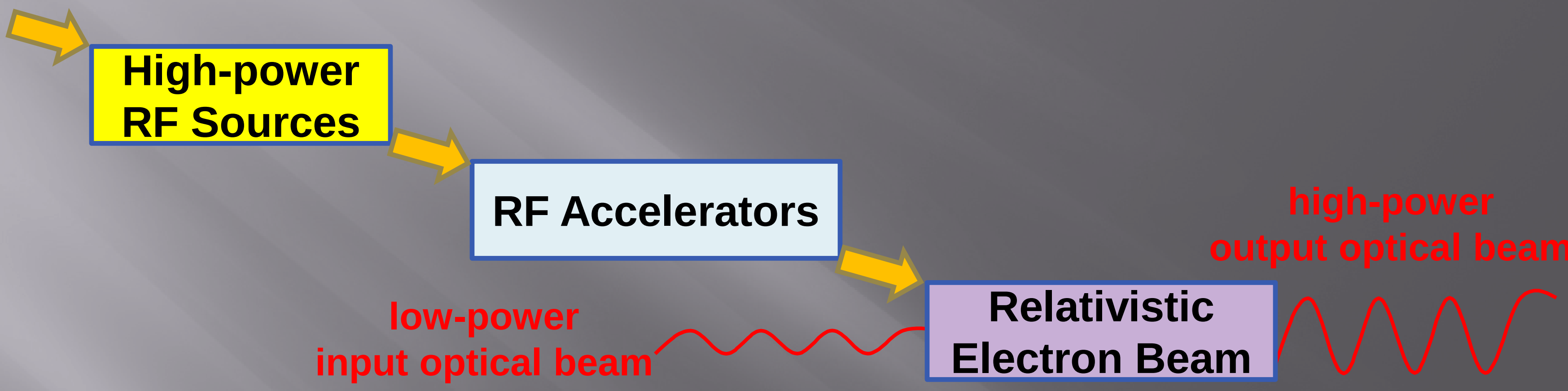
- Use mirrors to feedback a small fraction (<10%) of FEL beam
- RAFEL does not need a seed laser
- Feedback cavity length can be off by several wavelengths



Part 4
What can we expect?

Power Flow in an FEL

Energy is fed from the wall to high-power radio-frequency (RF) sources (e.g. klystrons) to power RF accelerators and relativistic electron beams



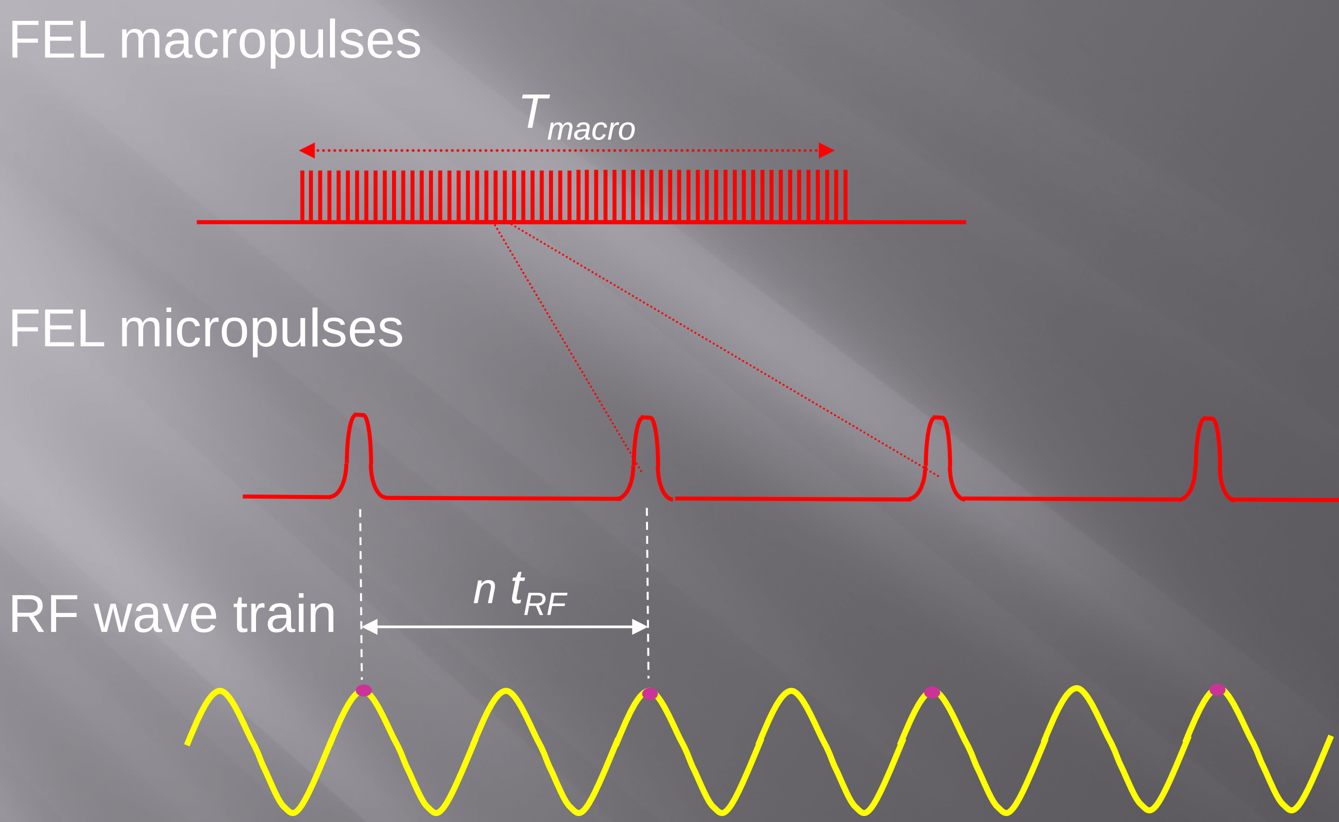
Relativistic electrons beams have MWs of power

$$P_e = \frac{IE_b}{e}$$

FEL power is a small fraction (~1%) of electron beam power into light.

$$P = \eta P_e$$

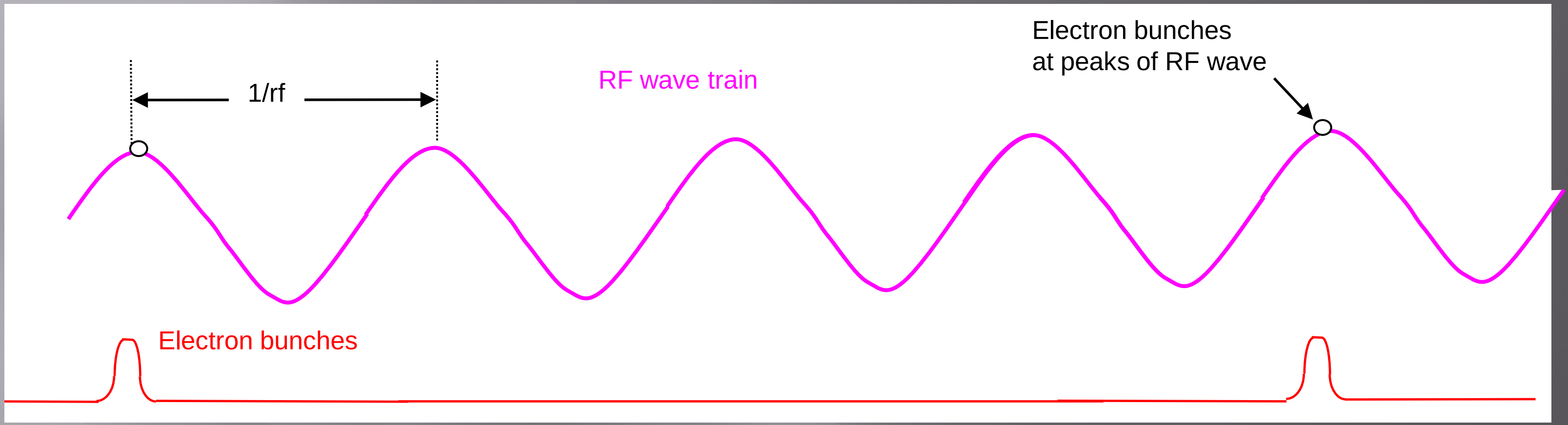
RF-linac FEL Pulse Format



$$t_{RF} = \frac{1}{f_{RF}}$$

FEL micropulses are typically a few picoseconds long and separated in time by a few nanoseconds. Macropulses range from μs to seconds.

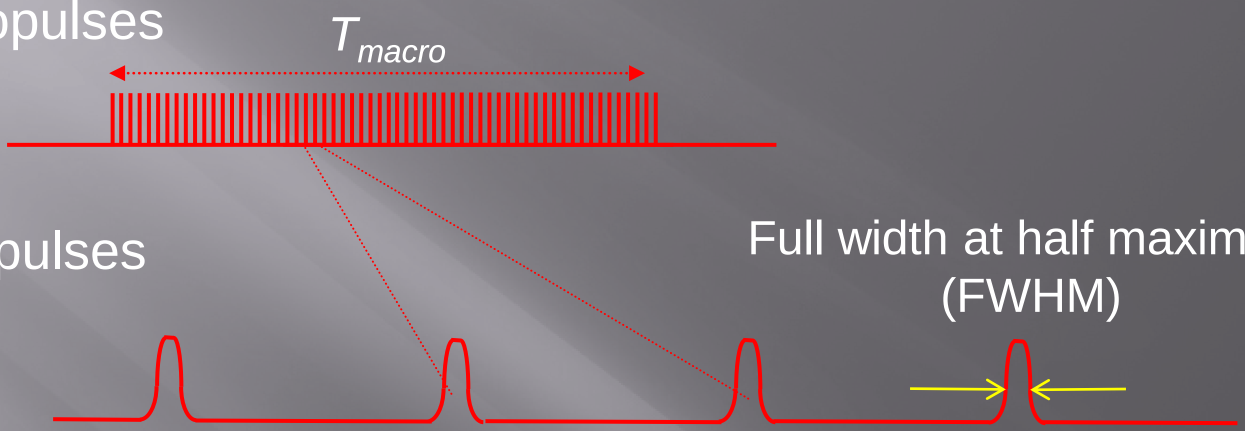
Typical Parameters of RF Linac



Typical RF frequency	400 MHz
Electron charge	1 nC
Bunch repetition rate	100 MHz
Electron average current	0.1 A
Electron beam energy	100 MeV
Electron beam's average power	10 MW
FEL extraction efficiency	1%
FEL average power	100 kW

Peak, Macropulse and Average Power

FEL macropulses



FEL micropulses

Peak power is approximately the micropulse energy divided by FWHM

Example: Micropulse energy = 1 mJ

FWHM = 1 ps P_{peak} = 1 GW

Macropulse power is macropulse energy divided by T_{macro}

Example: Macropulse energy = 1 J

T_{macro} = 10 μs P_{macro} = 100 kW

For continuous-wave FEL, average power is P_{macro}

Summary

- LANL is developing CW infrared FEL with ONR funding for ship self-defense applications. FEL is chosen because of its scalability to high average power and wavelength adjustability.
- LANL is also working on an X-ray FEL for MaRIE.
- The basic components of an FEL are the electron gun, RF linear accelerators, electron beam transporting system, a wiggler (undulator), and light optics.
- The high-average-power FEL can be achieved with today's RF accelerator technologies.