Today's outline - September 07, 2021

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- Undulator spectrum

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Reading Assignment: Chapter 3.1–3.3

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Reading Assignment: Chapter 3.1–3.3

Homework Assignment #02:
Problems on Blackboard
due Tuesday, September 21, 2021

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Reading Assignment: Chapter 3.1–3.3

Homework Assignment #02:
Problems on Blackboard
due Tuesday, September 21, 2021

Homework Assignment #03:
Chapter 3: 1,3,4,6,8
due Tuesday, October 05, 2021

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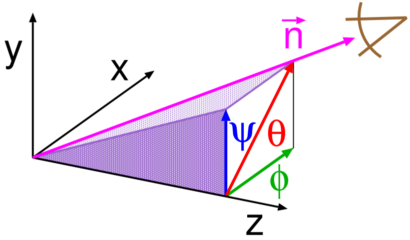
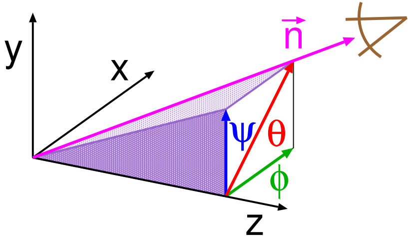
Now let us look at additional properties

Higher harmonics



Recall that we developed an expression for the Doppler time compression of the emission from a moving electron as a function of the observer angle.

Higher harmonics



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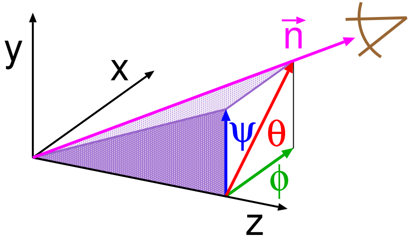

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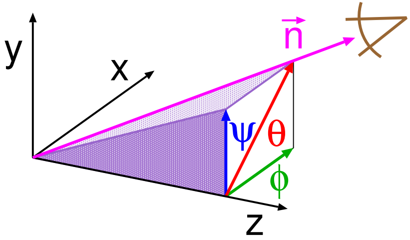

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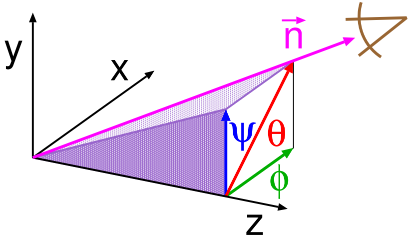

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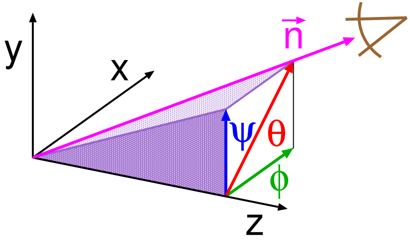

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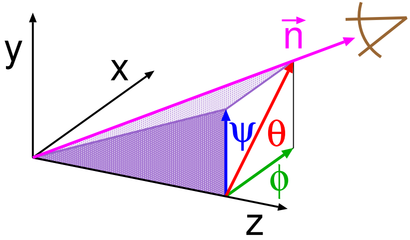

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The motion of the electron, $\sin \omega_u t'$, is always sinusoidal, but because of the additional terms, the motion as seen by the observer, $\sin \omega_1 t$, is not.

On-axis undulator characteristics

$$\omega_1 t = \omega_u t' - \frac{K^2/4}{1+(\gamma\theta)^2+K^2/2}\sin\left(2\omega_u t'\right) - \frac{2K\gamma}{1+(\gamma\theta)^2+K^2/2}\phi\sin\left(\omega_u t'\right)$$

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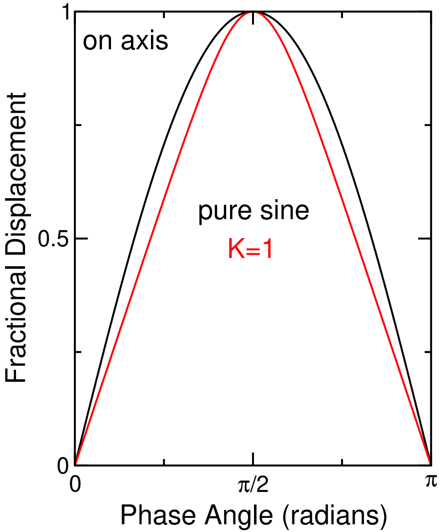
Plotting $sin\omega_u t'$ and $sin\omega_1 t$ shows the deviation from sinusoidal.



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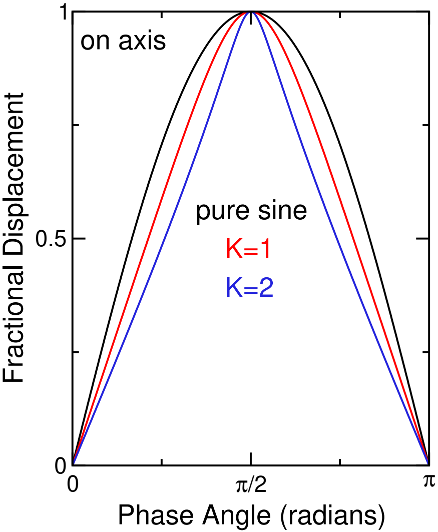
Similarly, for $K = 2$



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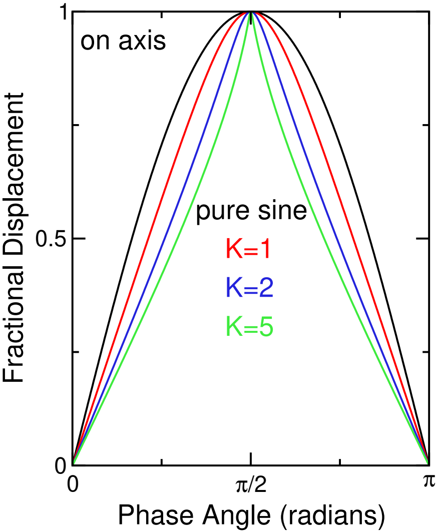
Similarly, for $K = 2$ and $K = 5$, the deviation becomes more pronounced.



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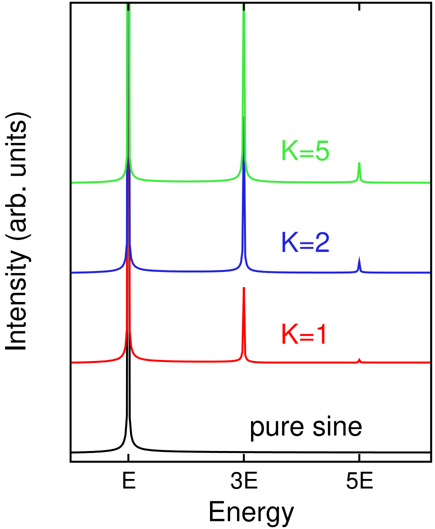
Similarly, for $K = 2$ and $K = 5$, the deviation becomes more pronounced. This shows how higher harmonics must be present in the radiation as seen by the observer.



Off-axis undulator characteristics

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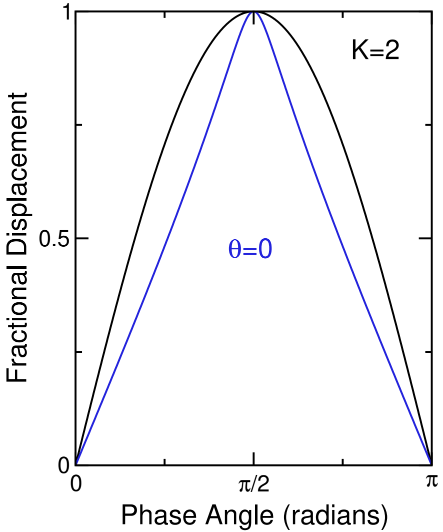

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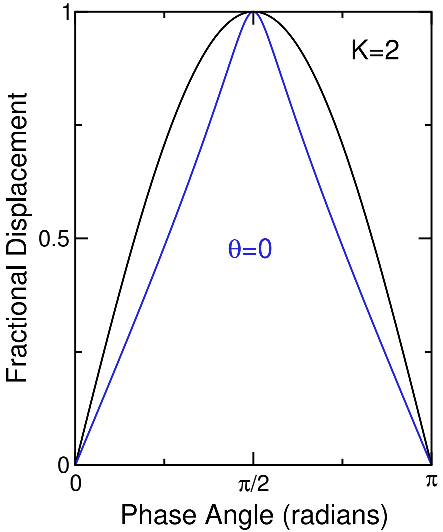

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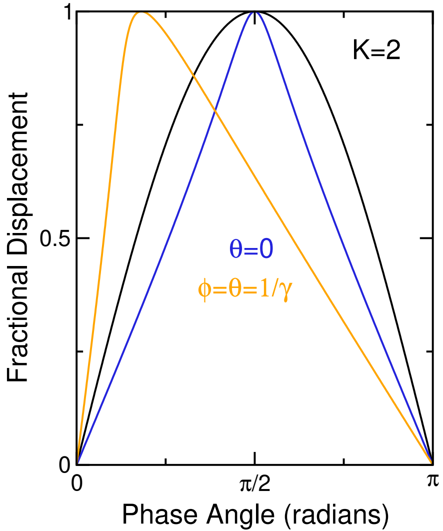

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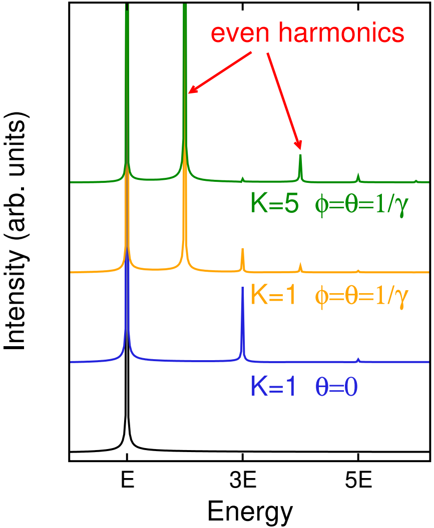
The last term introduces an antisymmetric term which skews the function and leads to the presence of forbidden harmonics (2^{nd}, 4^{th}, etc) in the radiation from the undulator compared to the on-axis radiation.



Diffraction grating

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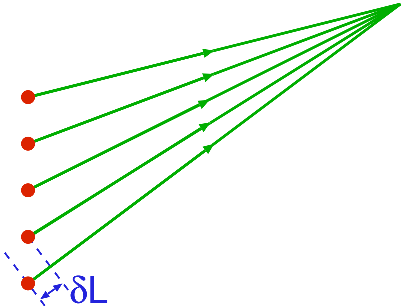

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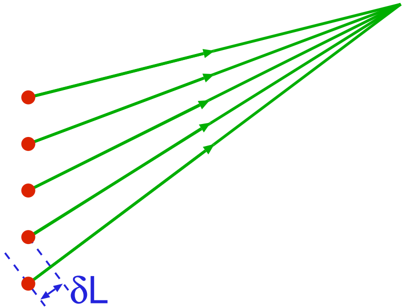

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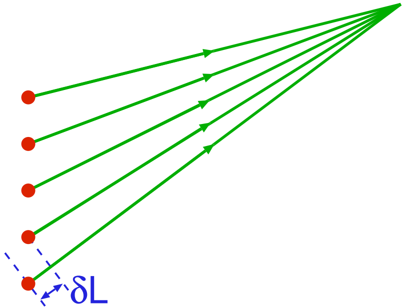

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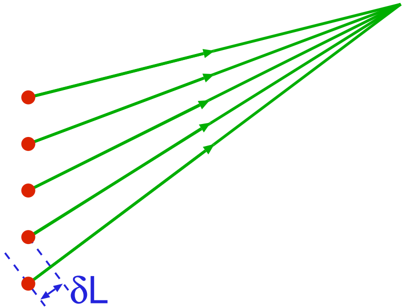

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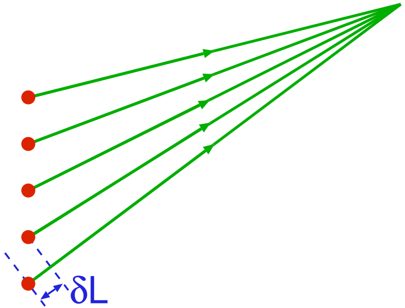

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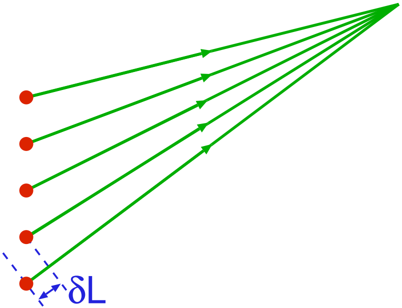

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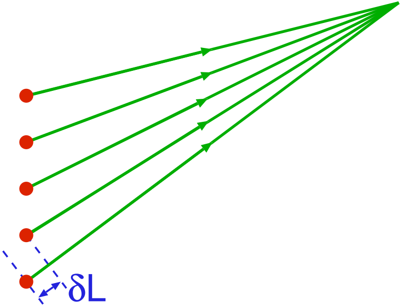

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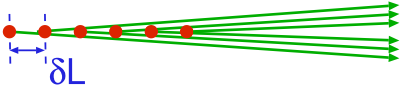

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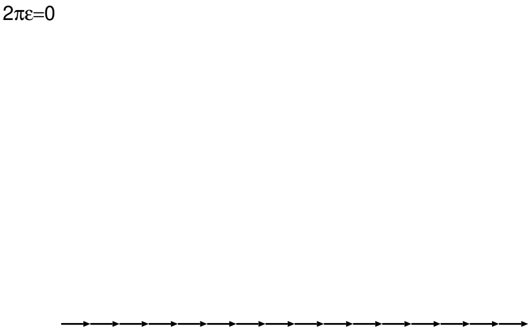

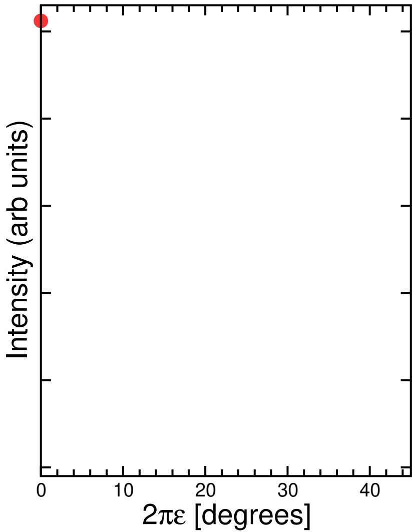

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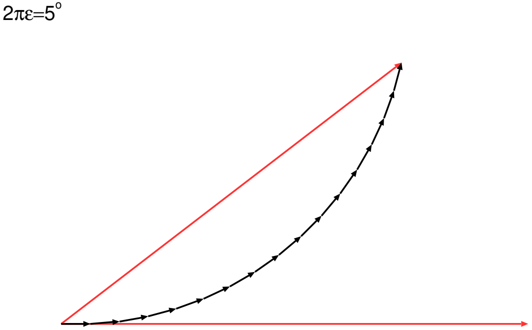

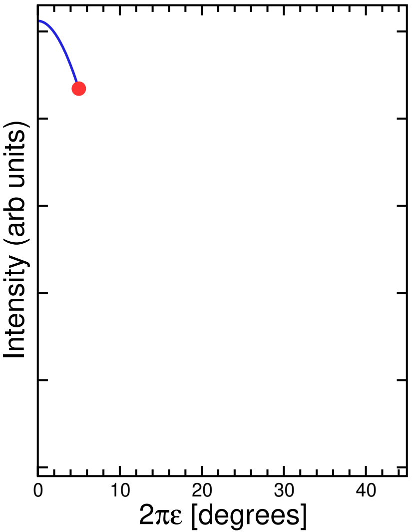

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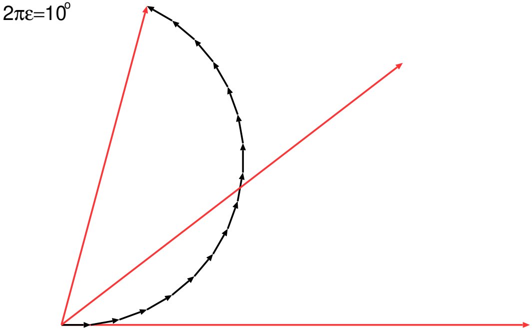

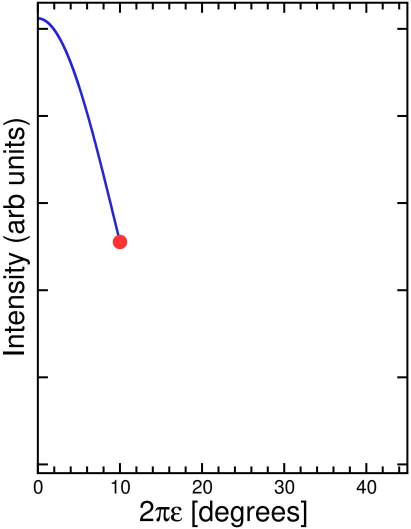

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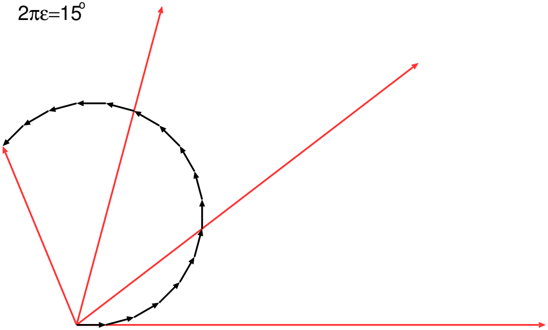

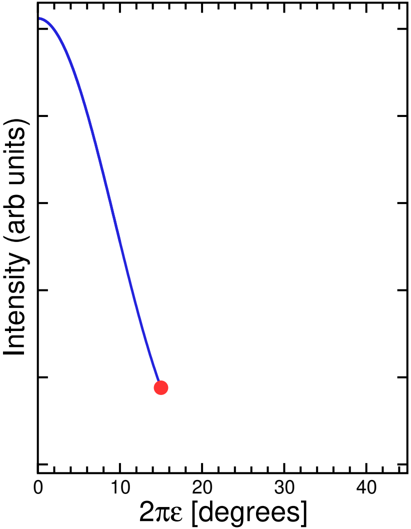

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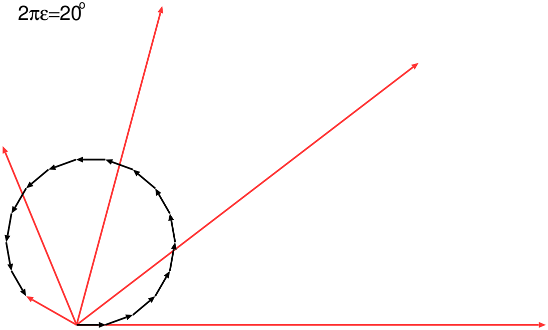

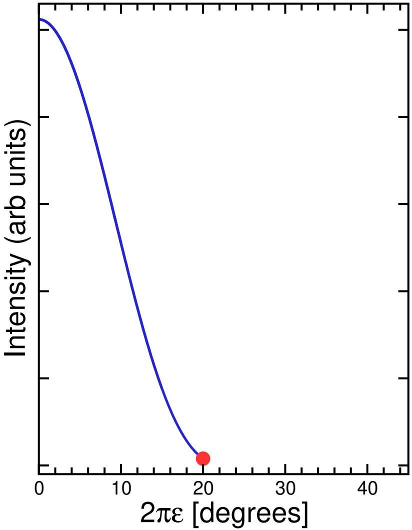

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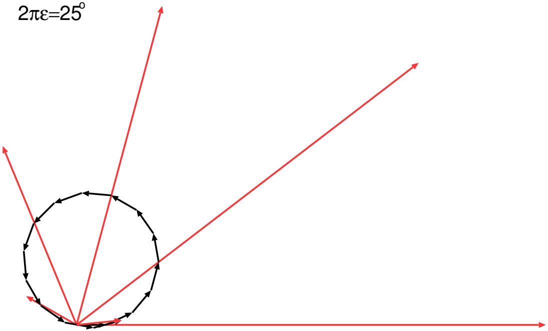

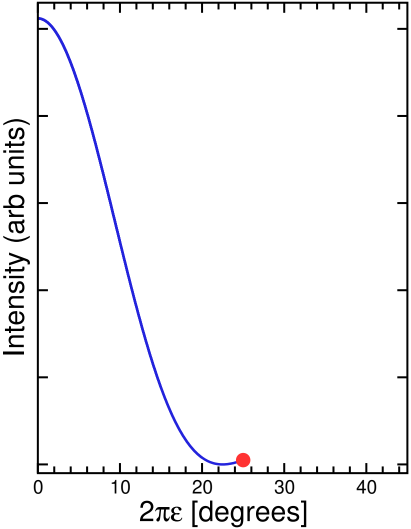

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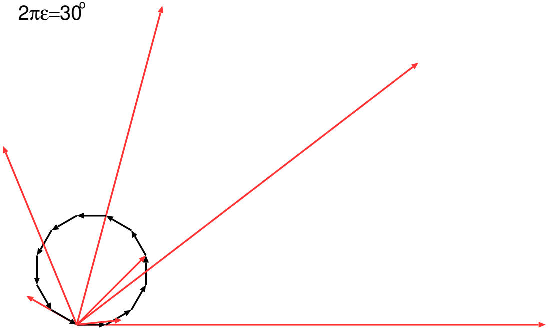

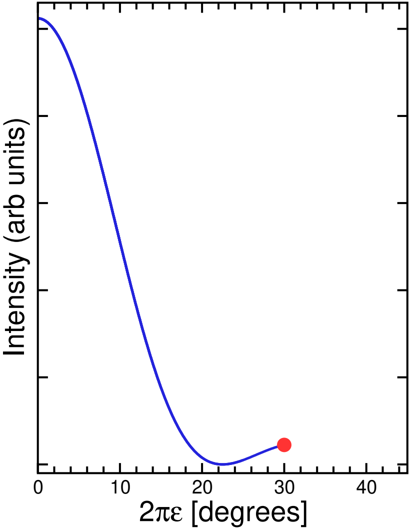

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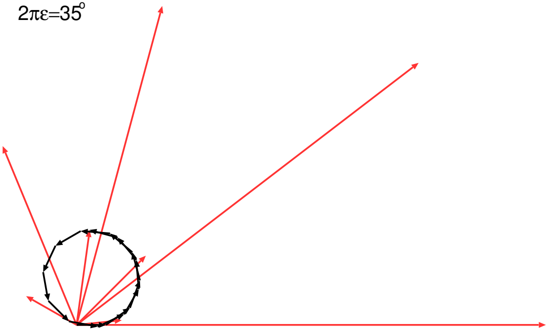

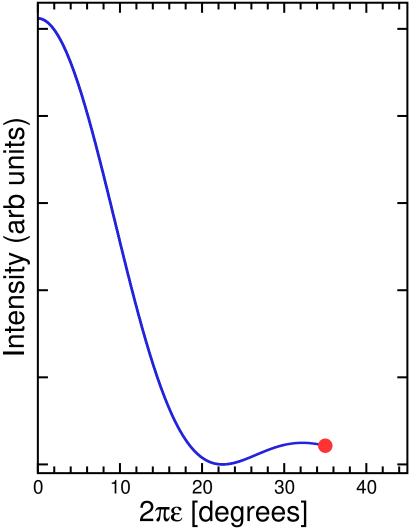

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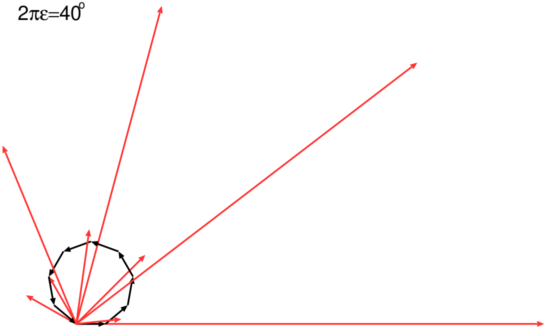

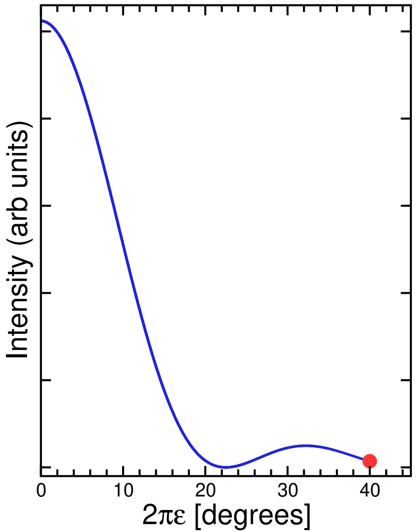

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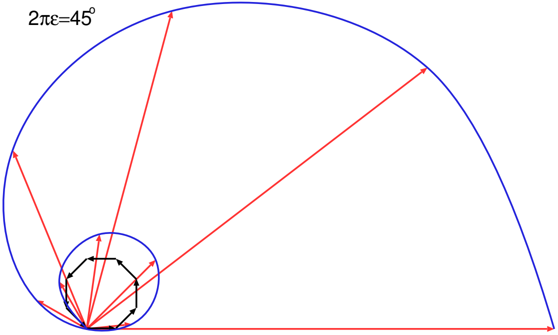

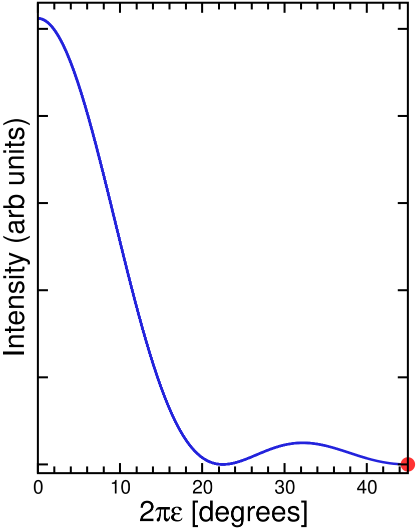

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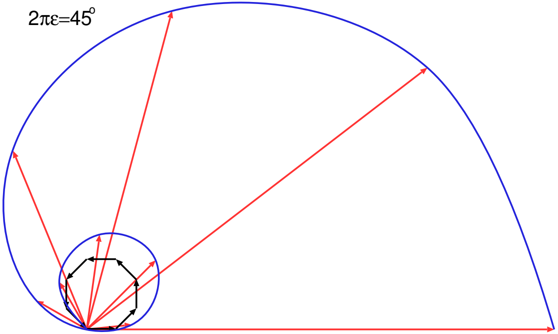
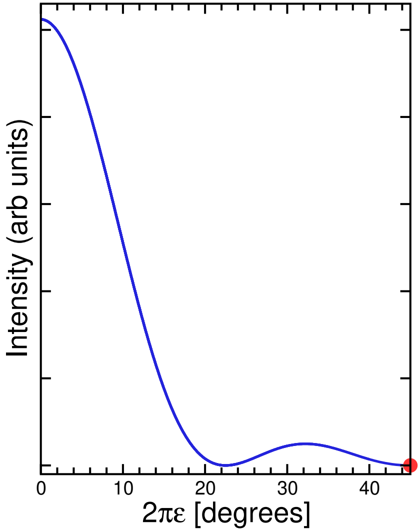
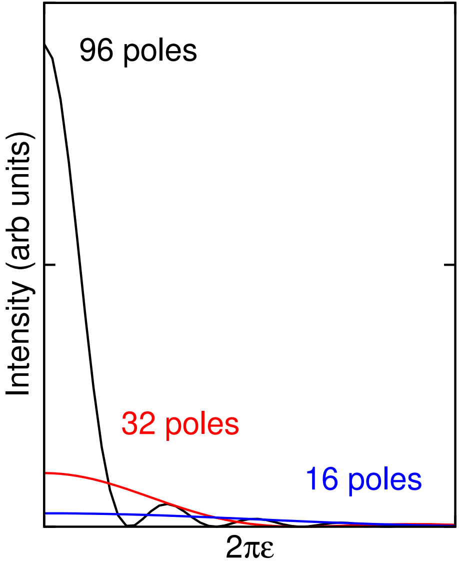




With the height and width of the peak dependent on the number of poles.

Undulator monochromaticity



The more poles in the undulator, the more monochromatic the beam since a slight change in $\epsilon = \delta L/\lambda$ implies a slightly different wavelength λ

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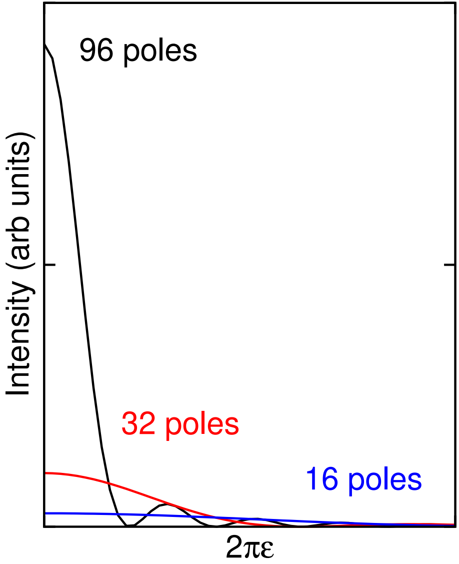

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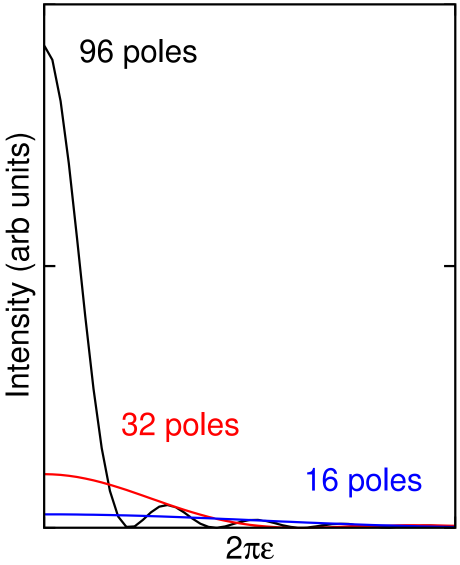

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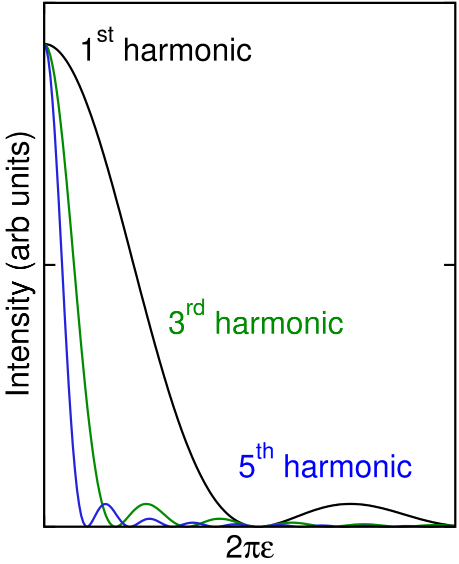

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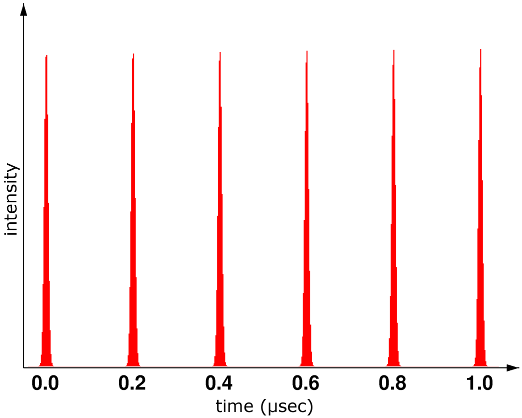
Higher order harmonics have narrower energy bandwidth but lower peak intensity

Synchrotron time structure



There are two important time scales for a storage ring such as the APS: pulse length and interpulse spacing

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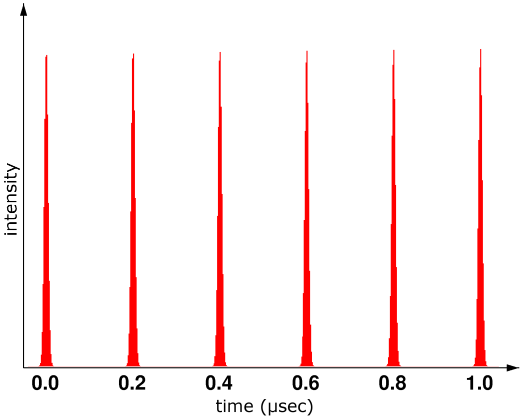

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The APS pulse length in 24-bunch mode is 90 ps while the pulses come every 154 ns

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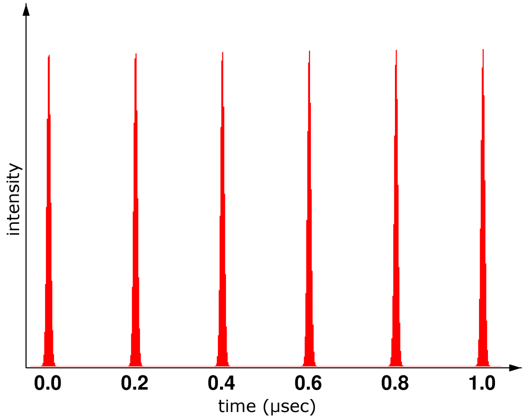
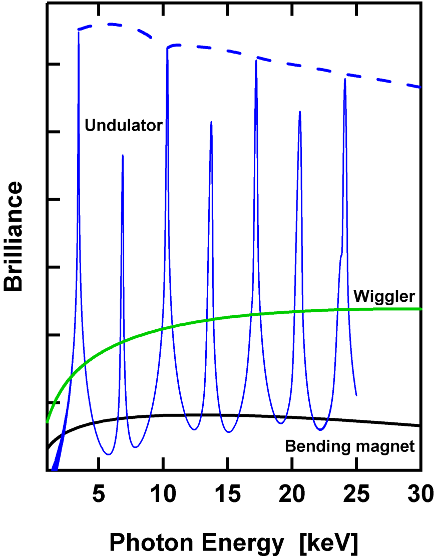


There are two important time scales for a storage ring such as the APS: pulse length and interpulse spacing

The APS pulse length in 24-bunch mode is 90 ps while the pulses come every 154 ns

Other modes include single-bunch mode for timing experiments and 324-bunch mode (inter pulse timing of 11.7 ns) for a more constant x-ray flux

Spectral comparison



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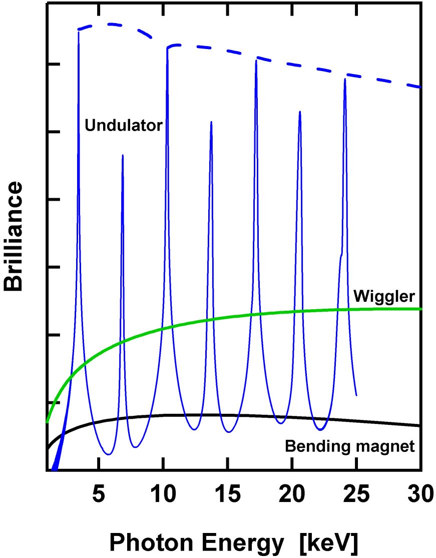
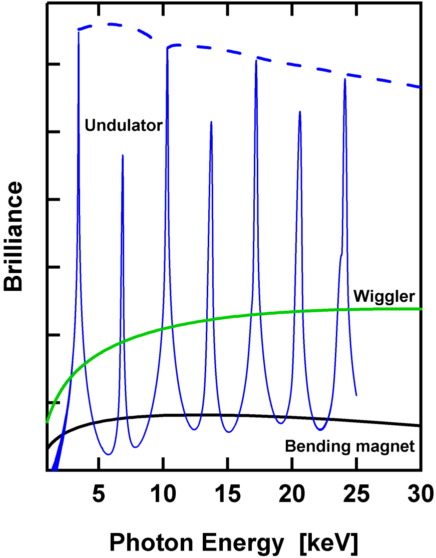


- Bending magnet

Spectral comparison



- Bending magnet
  - Broad, nearly white spectrum

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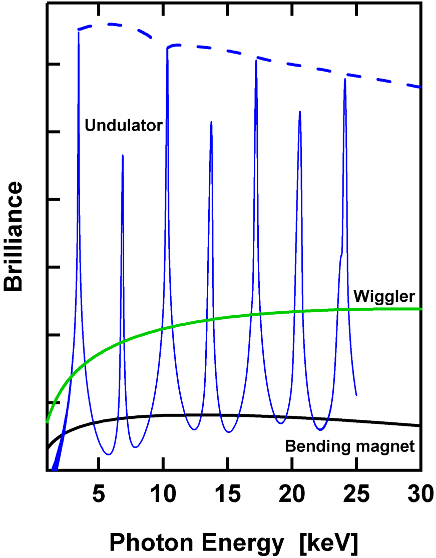

- Bending magnet
  - Broad, nearly white spectrum
  - Energies extend to 100's of keV

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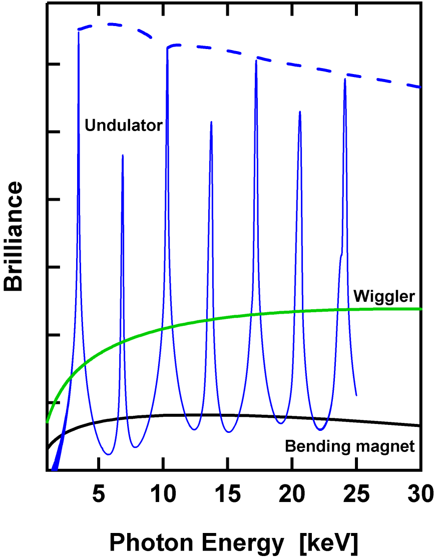

- Bending magnet
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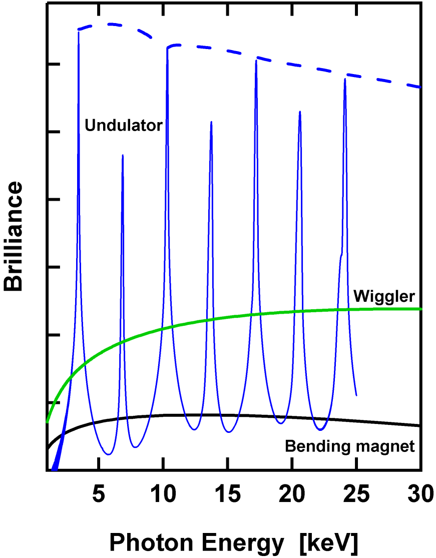
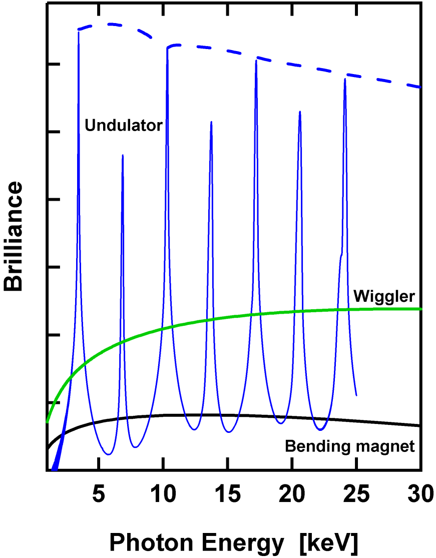
- Wiggler

Spectral comparison



- Bending magnet
  - Broad, nearly white spectrum
  - Energies extend to 100's of keV
- Wiggler
  - Shifts critical energy higher than bending magnet

Spectral comparison



- Bending magnet
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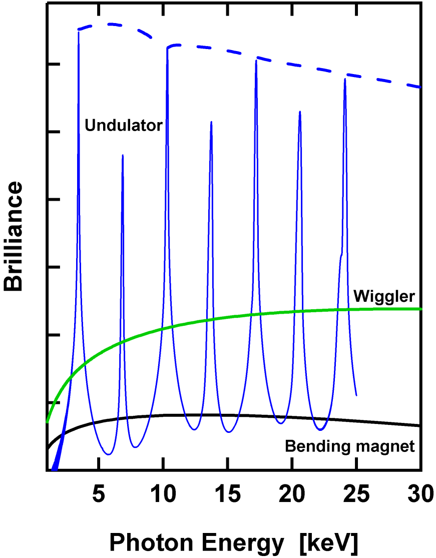
  - Shifts critical energy higher than bending magnet
  - Brilliance is more than an order of magnitude greater than a bending magnet

Spectral comparison



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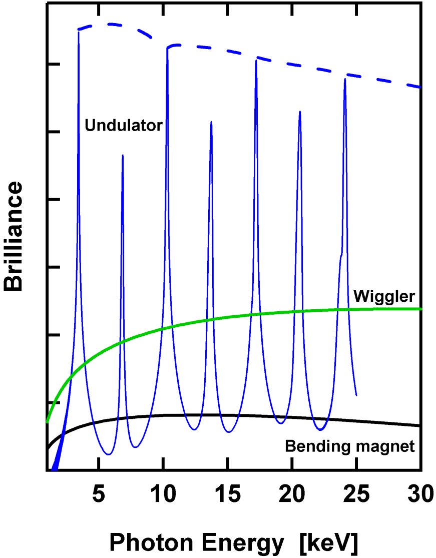

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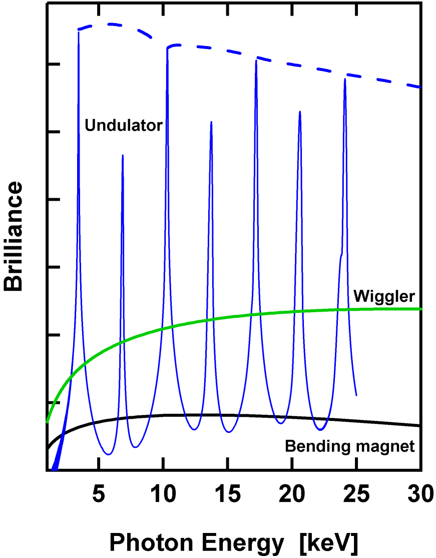

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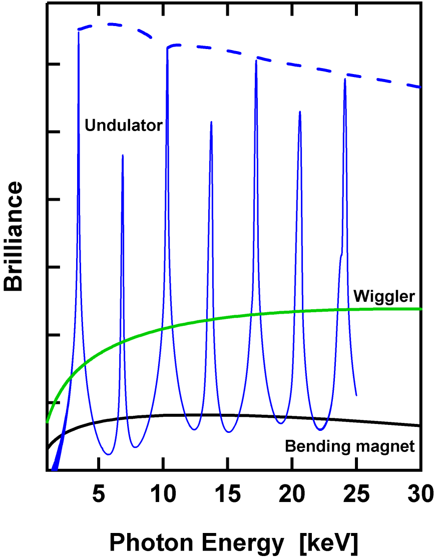

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    - Harmonics can be tuned in energy (dashed lines)

Emittance

Is there a limit to the brightness of an undulator source at a synchrotron?

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the brightness is inversely proportional to the square of the product of the linear source size and the angular divergence

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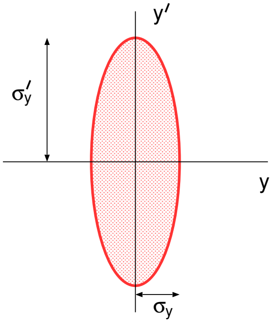

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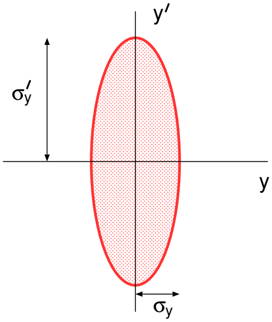

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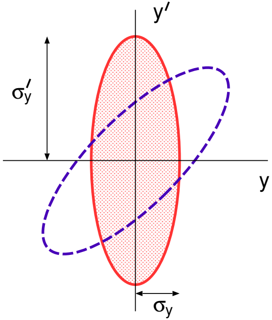

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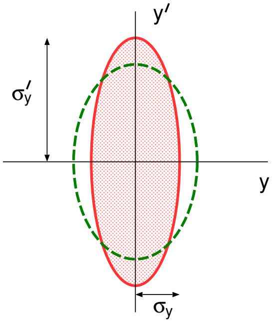

this emittance cannot be changed but it can be rotated or deformed by magnetic fields as the electron beam travels around the storage ring as long as the area is kept constant

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For photon emission from a single electron in a 2m undulator at 1Å

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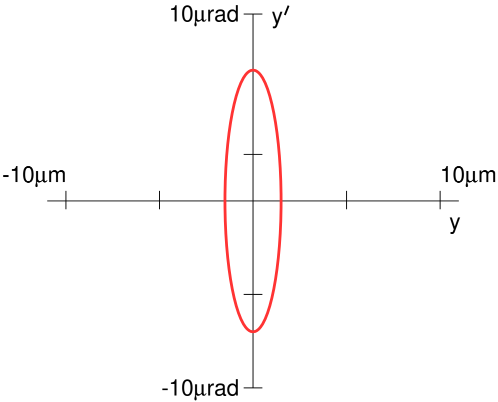

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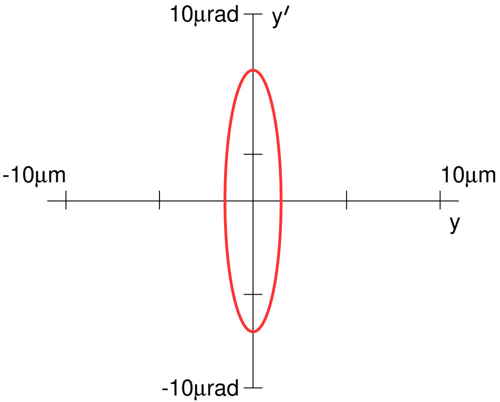

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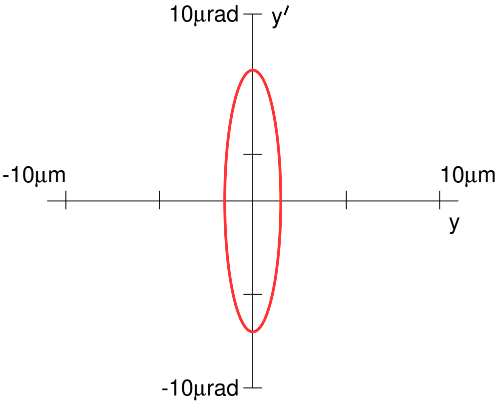

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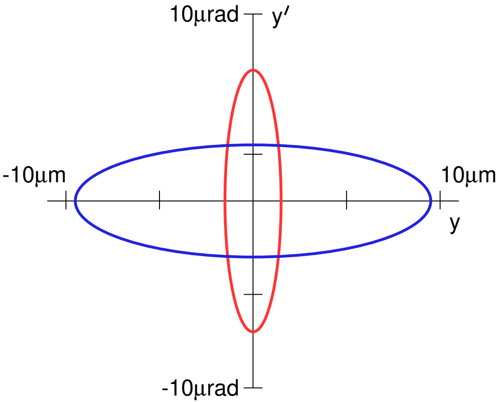

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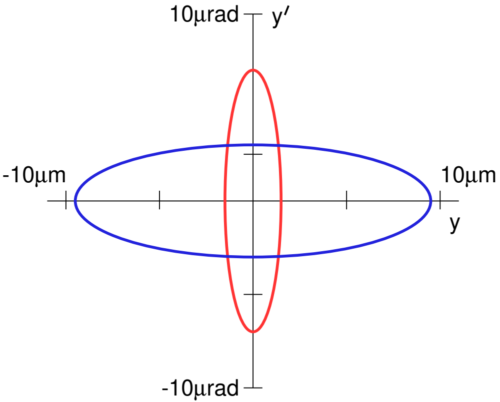

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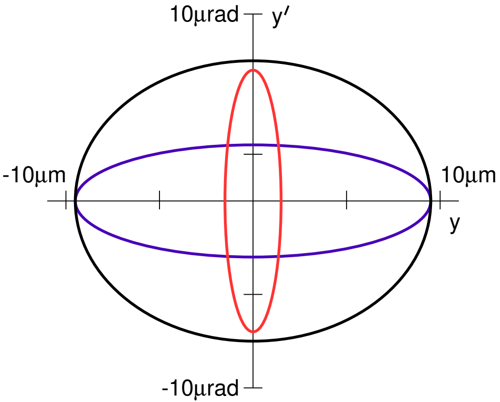

$$\sigma_{radiation} = 9.1\mu\text{m}$$
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Evolution of APS parameters

Parameter	APS 1995	2001	2005
Bunches		24 & 324	
σ_x	334 μm	352 μm	280 μm
σ'_x	24 μrad	22 μrad	11.6 μrad
σ_y	89 μm	18.4 μm	9.1 μm
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Bunches		24 & 324		48	324
σ_x	334 μm	352 μm	280 μm	18.1 μm	21.8 μm
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σ_y	89 μm	18.4 μm	9.1 μm	10.6 μm	4.1 μm
σ'_y	8.9 μrad	4.2 μrad	3.0 μrad	4.2 μrad	1.7 μrad

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The APS-U will make the beam smaller and more square in space making for higher performance insertion device beam lines.

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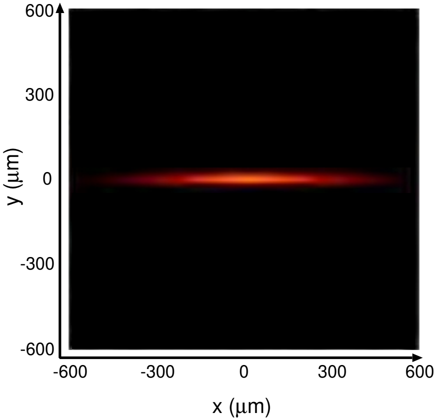

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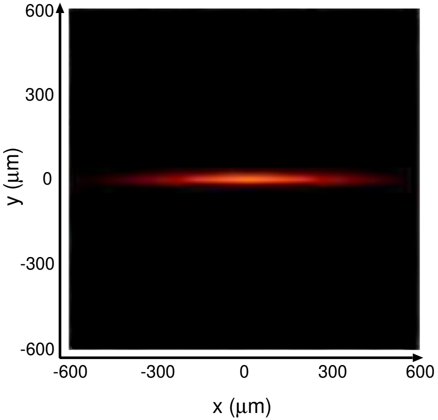

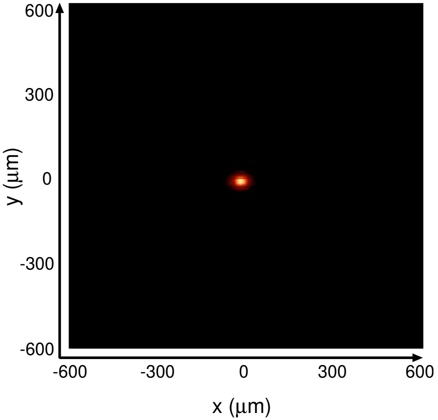

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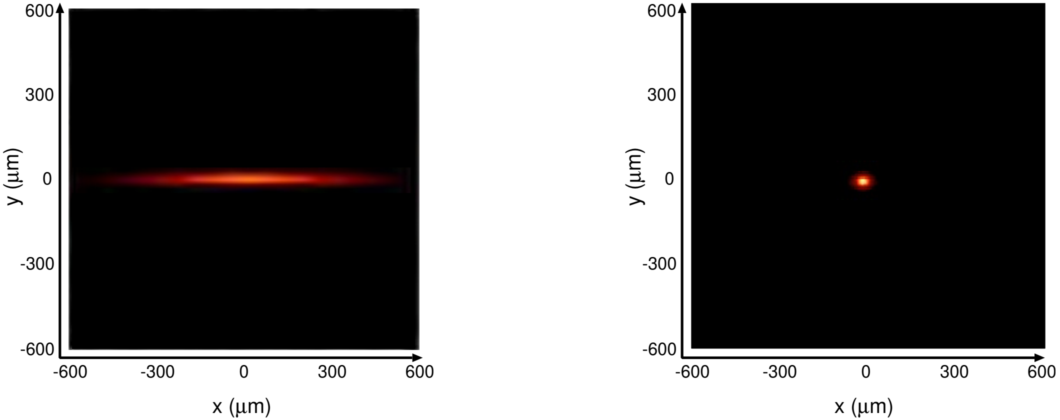

The beam will be nearly square and there will be much more coherence from the undulators

APS-U magnet layout

The APS upgrade will install a multi-bend achromat instead of the two bending magnets.

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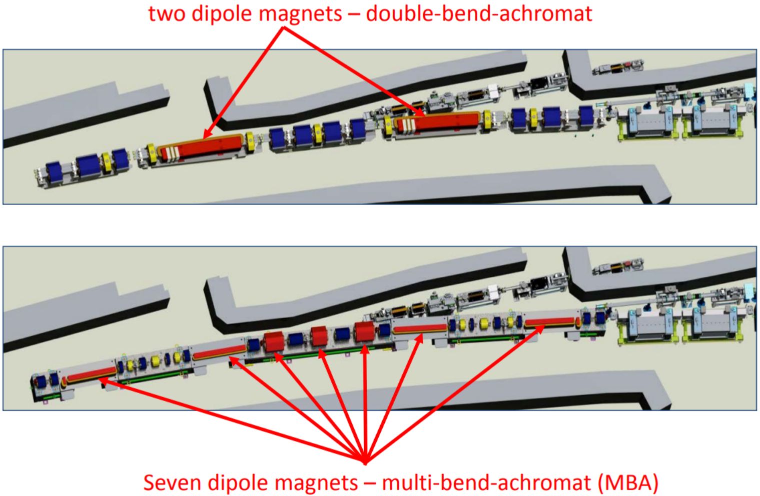

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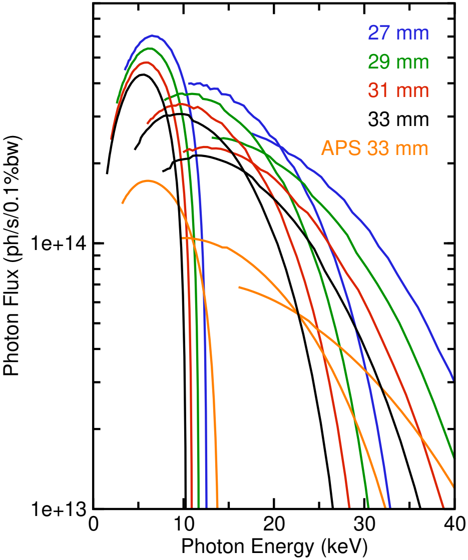

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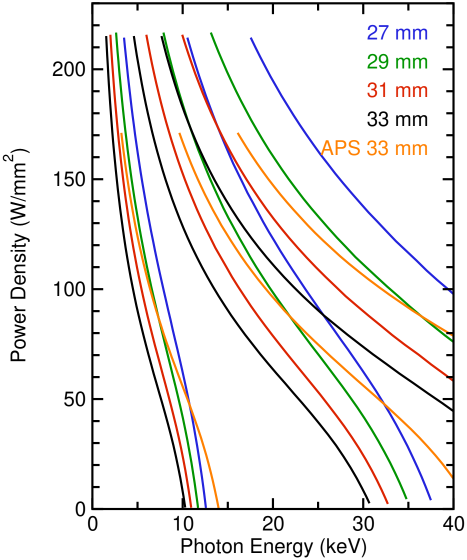
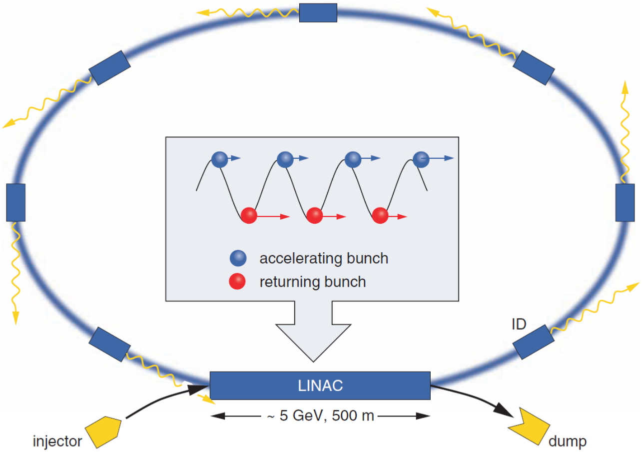
The APS-U is an example of a "4^{th}" generation synchrotron source

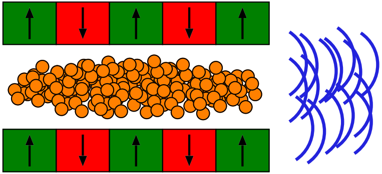


Energy recovery linacs

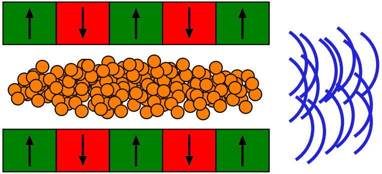
Another way to imcrease the undulator peak brilliance is the energy recovery linac which overcomes the fundamental limitation of a synchrotron by passing the beam through only once.



Free electron laser



Free electron laser



Initial electron cloud, each electron emits coherently but independently

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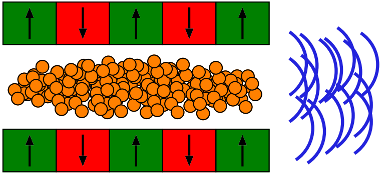

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Over course of 100 m, electric field of photons, feeds back on the electron bunch

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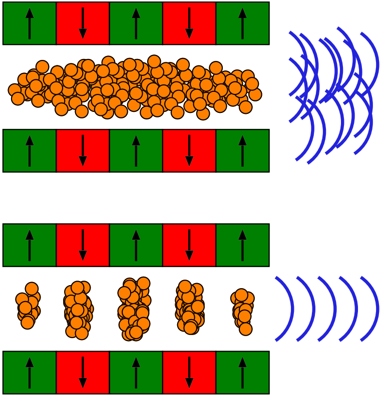

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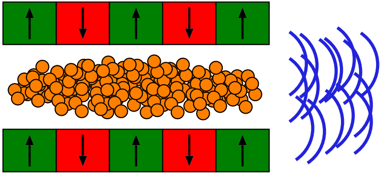

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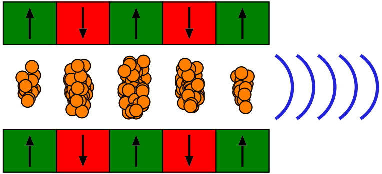
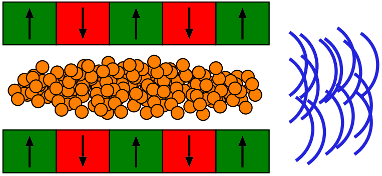


Microbunches form with period of FEL (and radiation in electron frame)

Free electron laser



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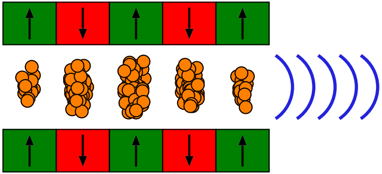

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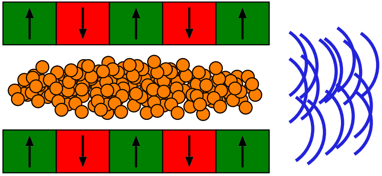

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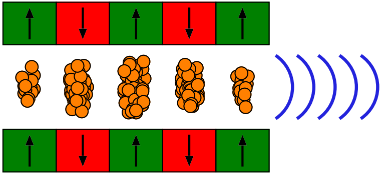

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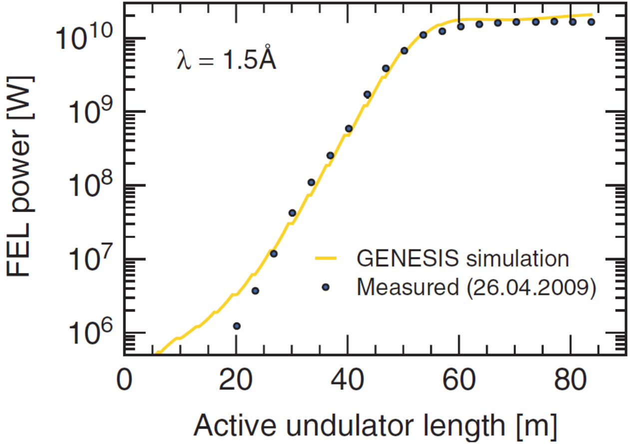
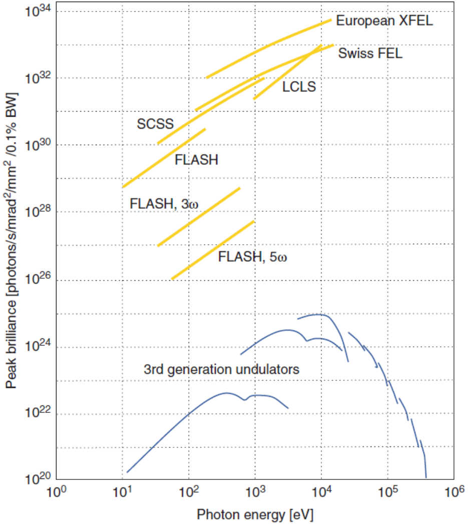
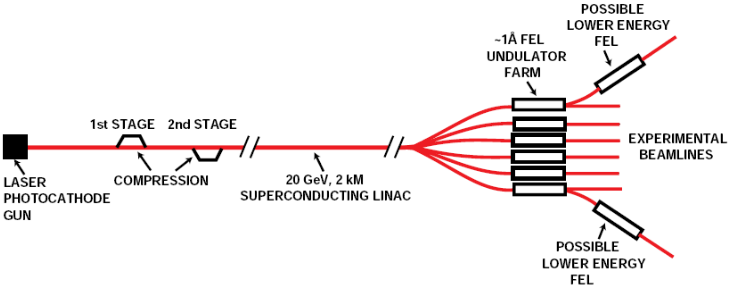
Again, an alternative way to view this is that the pulse train from a 100m long undulator is long enough in time to produce a monochromatic and coherent frequency distribution when Fourier Transformed

FEL performance





FEL layout



POSSIBLE
LOWER ENERGY
FEL
~1Å FEL
UNDULATOR
FARM
1st STAGE
2nd STAGE
EXPERIMENTAL
BEAMLINES
LASER
PHOTOCATHODE
GUN
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20 GeV, 2 kM
SUPERCONDUCTING LINAC
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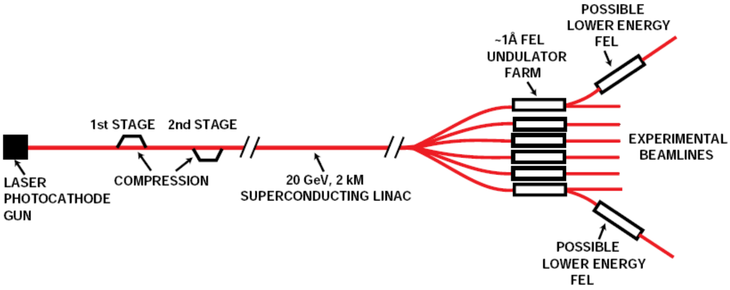

An FEL has a single accelerator whose electron beam is shunted sequentially through different undulators and end stations

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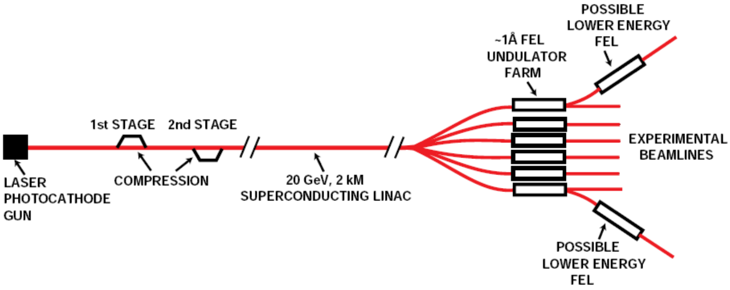

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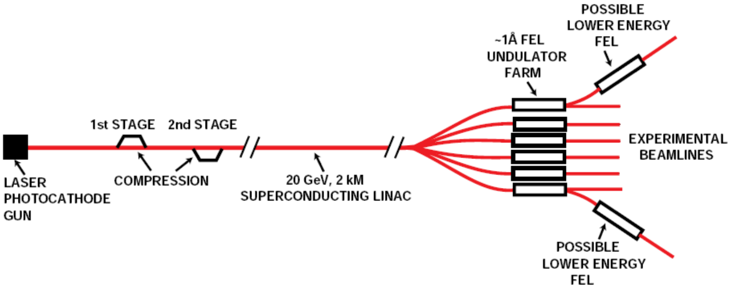

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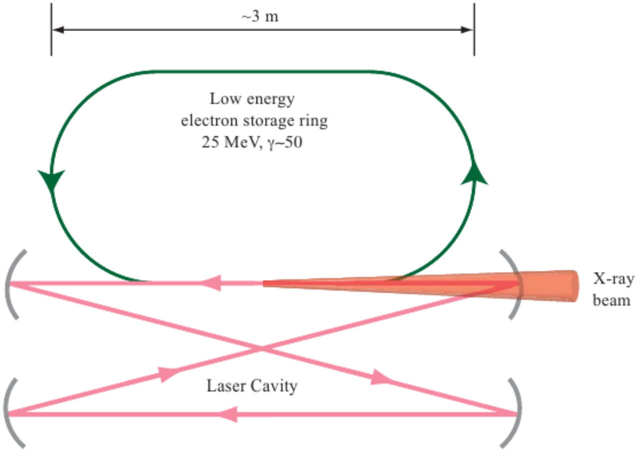
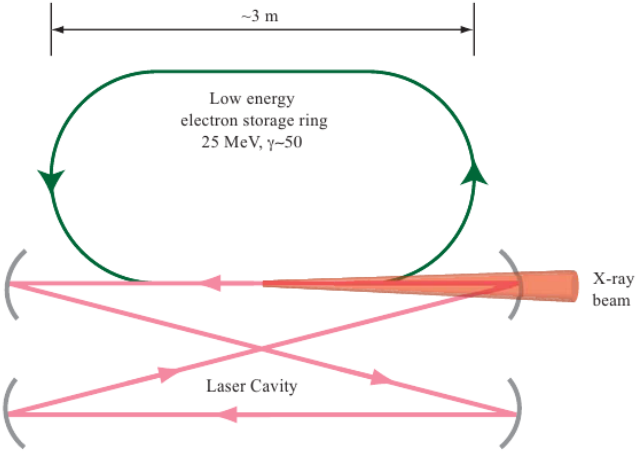
The high brightness usually results in destruction of the sample during the illumination, thus the need for multiple samples and multiple shot experiments

Compact sources



Small low energy, high current electron ring

Compact sources



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Straight section intersects a laser cavity

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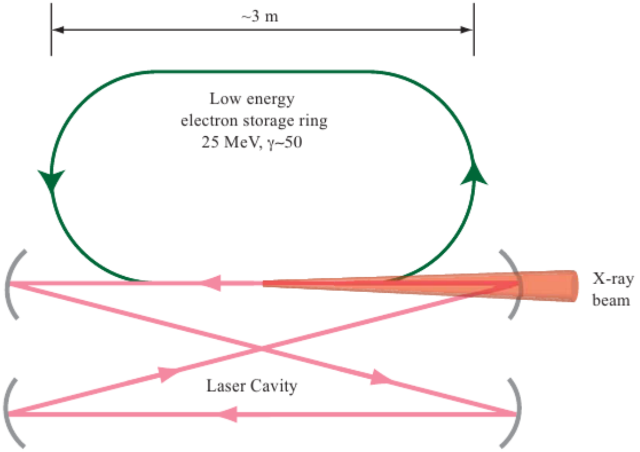

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Undulator is the standing wave of the laser, alternatively can consider this an inverse Compton effect

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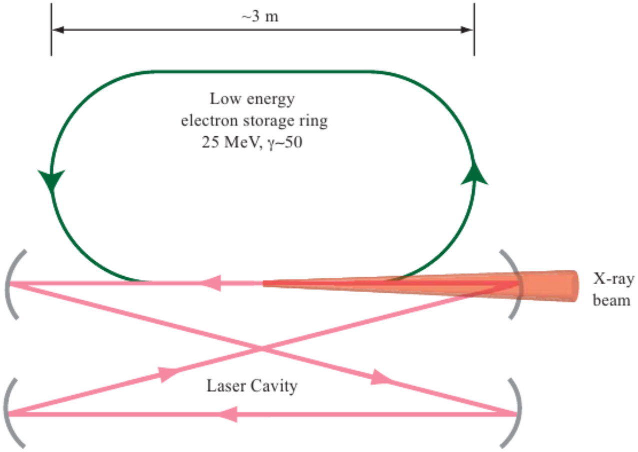

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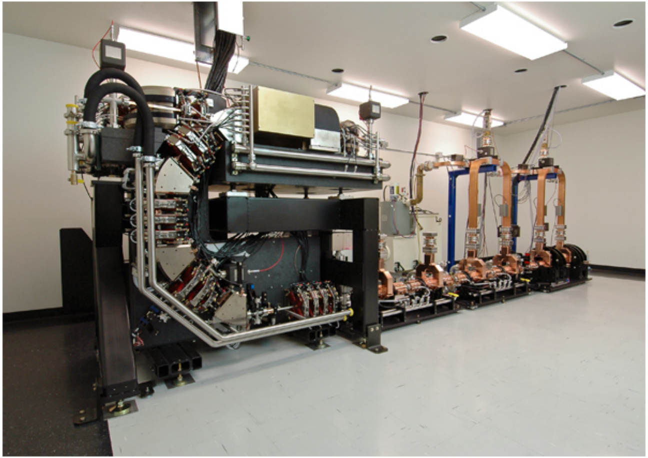

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Cost ~\$5 M plus ~\$1 M per year service contract

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Gas detectors

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- Ionization chamber

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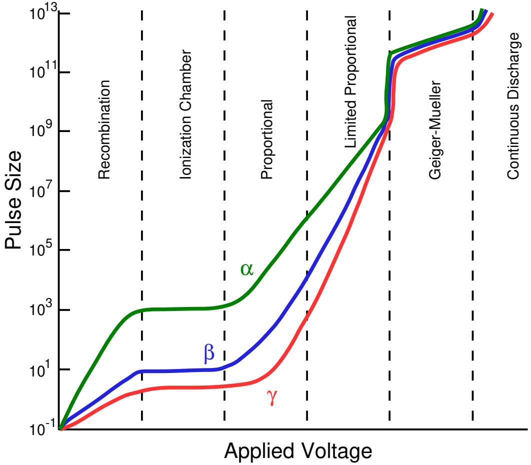
Gas detectors operate in several modes depending on the particle type, gas composition and pressure and voltage applied



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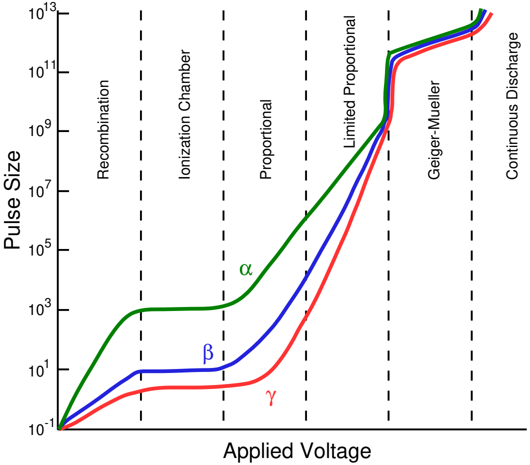

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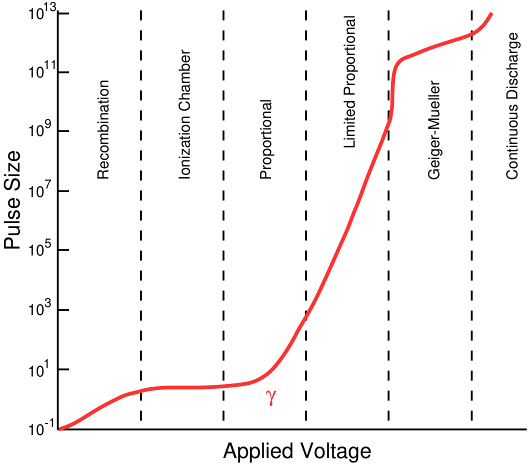

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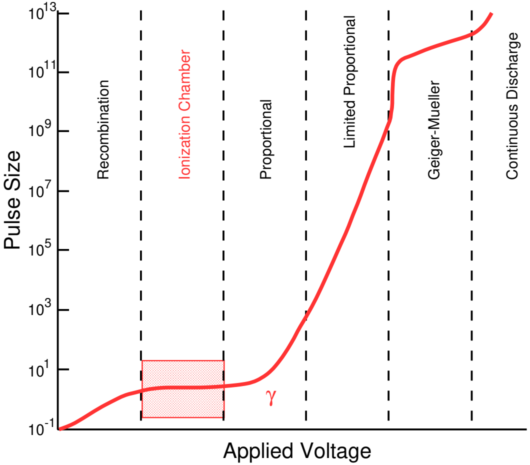
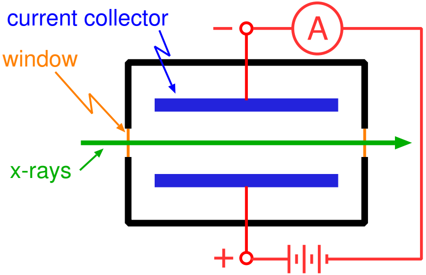
At a synchrotron, the particle being detected is most often a photon (γ)

The most useful regime is the ionization region where the output pulse is independent of the applied voltage over a wide range



Ionization Chamber

Useful for beam monitoring, flux measurement, fluorescence measurement, spectroscopy.



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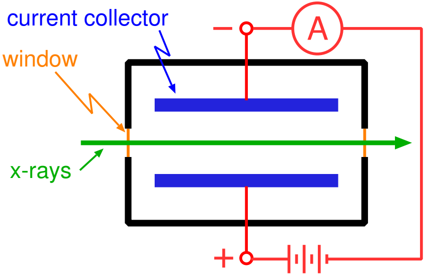

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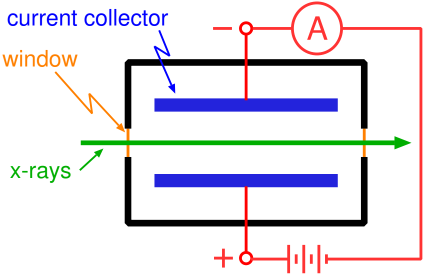

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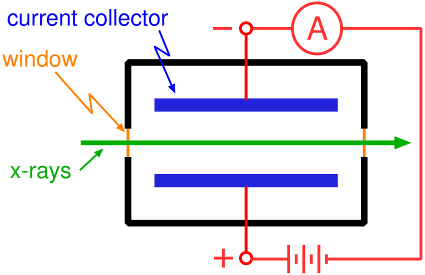

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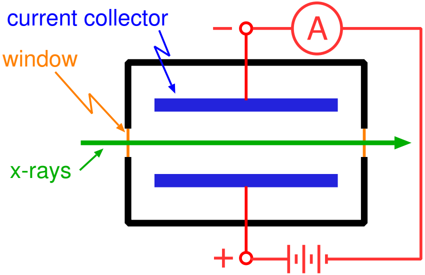

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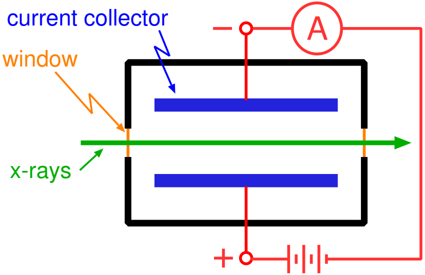

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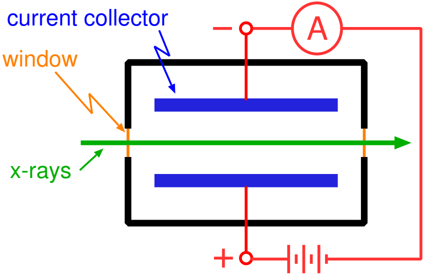

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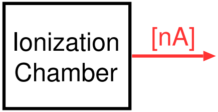
- Count rates up to 10^{11} photons/s/cm^3
- 22-41 eV per electron-ion pair (depending on the gas) makes this useful for quantitative measurements.

Getting a reading

The ionization chamber puts out a current in the nA range, this needs to be converted into a useful measurement



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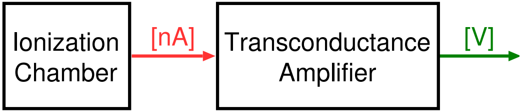

the tiny current is fed into an sensitive amplifier with gains of up to 10^{10} which outputs a voltage signal of 1-10 V that tracks the input with an adjustable time constant

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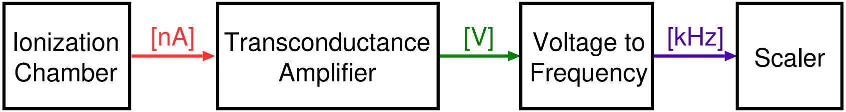

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the digital pulse train is counted by a scaler for a user-definable length of time