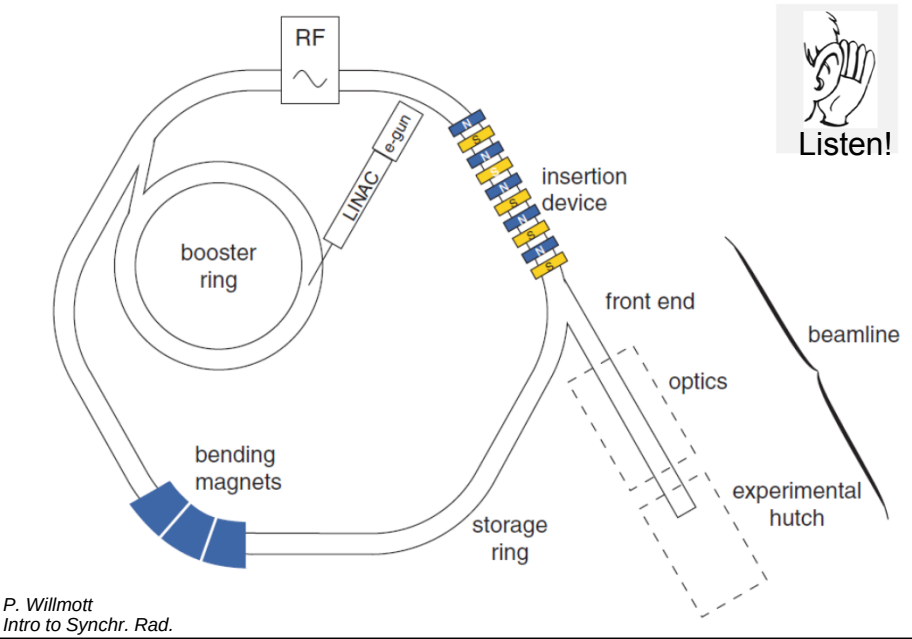
3. Synchrotrons

Synchrotron Basics

What you will learn about…

- Overview of a Synchrotron Source
- Losing & Replenishing Electrons
- Storage Ring and Magnetic Lattice
- Synchrotron Radiation
  Flux, Brilliance and Emittance
- Bending Magnets, Insertion Devices

Overview



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Overview

- Electron source: Hot filament, thermionic emission
- LINAC: accelerate to ~ 100 MeV & inject into booster ring
- Booster ring
  - Accelerates electrons to storage ring energy
  - Inject into storage ring to maintain storage ring current
- Storage ring
  - Energy in GeV range
  - Contains:
    - RF cavity
    - Bending magnets
    - Insertion devices
    - Focusing magnets

Line-by-line... Radiation from Relativistic Electrons

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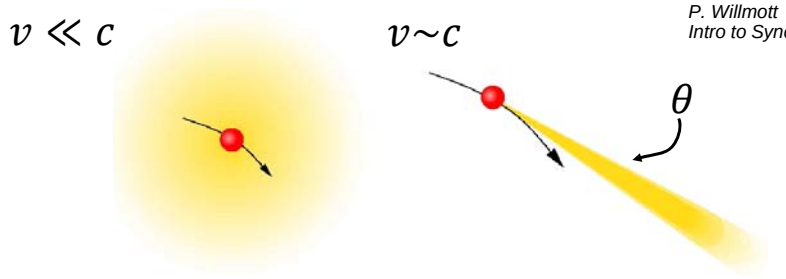


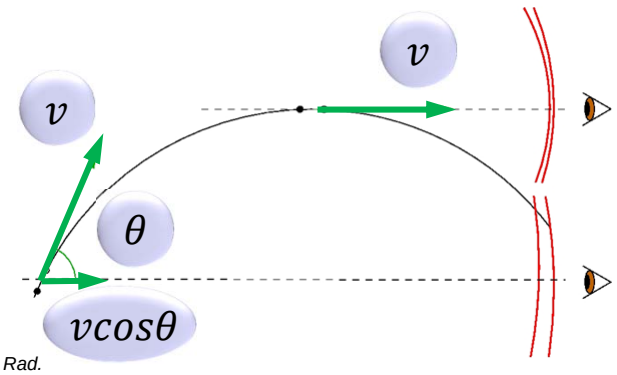
- Sweeping searchlight: narrow light beam radiating in same direction as electron motion, tangential to electron path
- Angular frequency (rad/sec) $\omega_0 = 2\pi\,(v/2\pi r) = v/r \approx c/r$
- NB: 300 m storage ring with 50 m straight sections $2\pi r \rightarrow$ 250 m
- Electron kinetic energy $\varepsilon = \gamma mc^2$ where γ is the Lorentz Factor
- Electron rest-mass energy: $mc^2 \approx 511\ keV \rightarrow \gamma = 1957\varepsilon\ [GeV]$
- Divergence $\theta \sim \gamma^{-1} \rightarrow$ 0.5-0.06 mrad for 1-8 GeV
  1 mrad ~ 0.057°, so θ = 0.03-0.003°

ETH PSI Pencil Beam & Doppler Effect

Doppler effect

- Observer sees electron move along observation axis with a velocity _____
- Wavelength hugely relativistically compressed as $\theta \rightarrow$ _
- In observers frame of reference: large Doppler shift ≡

_____



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The Lorentz Force, A Reminder…

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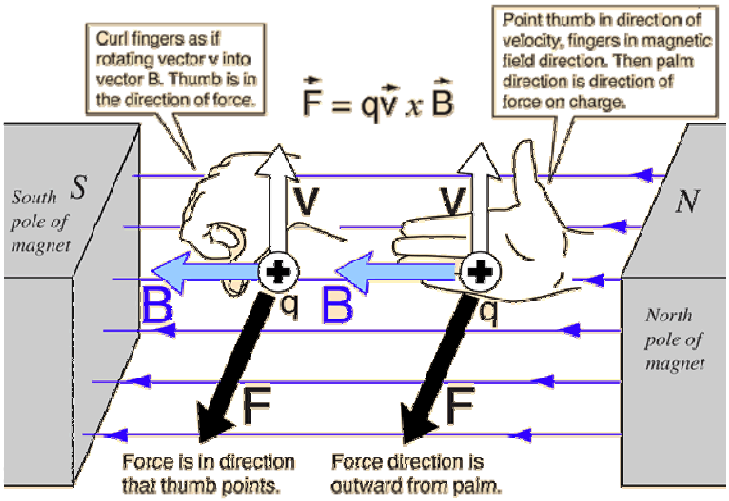

http://hyperphysics.phy-astr.gsu.edu

Storage Ring – Magnetic Lattice

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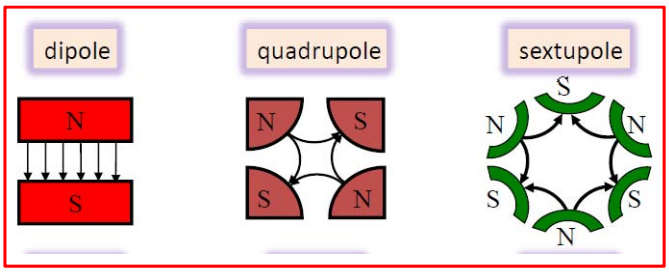


Listen!

Storage Ring – Magnetic Lattice

Magnet Lattice is an array of magnets that maintain electrons on closed path via the Lorentz force: F = e ***v*** x ***B***

1. Bending magnets

→ *Dipole magnets*

- Closed path
- Emit synchrotron radiation

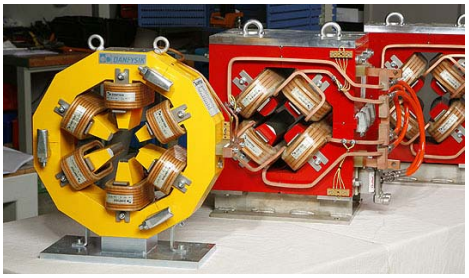
2. Focusing optics

- *Quadrupole magnets*
  focus & compensate for Coulomb repulsion
- *Sextapole magnets*
  correct chromatic aberration from quadrupoles

3. Insertion devices

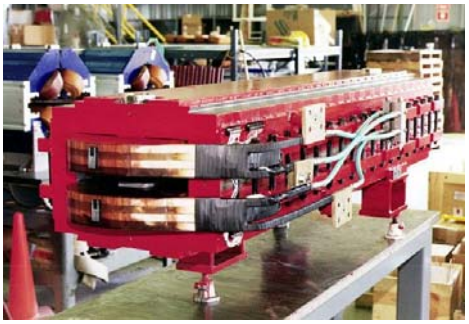
- *Wigglers*
- *Undulators*

Storage Ring – Magnetic Lattice



Quadrupole, sextapole and dipole magnets

ELETTRA Storage Ring
http://www.danfysik.com



APS Bending Magnet
http://en.wikipedia.org

Radiated Power Loss

Stated without derivation:

circular arc length

$$P[\mathrm{kW}] = 1.266\,\mathcal{E}^2[\mathrm{GeV}]\,B^2[\mathrm{T}]\,L[\mathrm{m}]\,I[\mathrm{A}]$$

Radiated power from a circular arc of length L	Storage Ring Energy	Magnetic Field Strength	Current

- Power loss ~ 1 MW (10^6 W) @ 400 mA storage current
- For each circuit:

  Energy drop ~ 2.5 MeV

  ~ 0.1% of electrons' kinetic energy

Radiated Power Loss

Line-by-line...

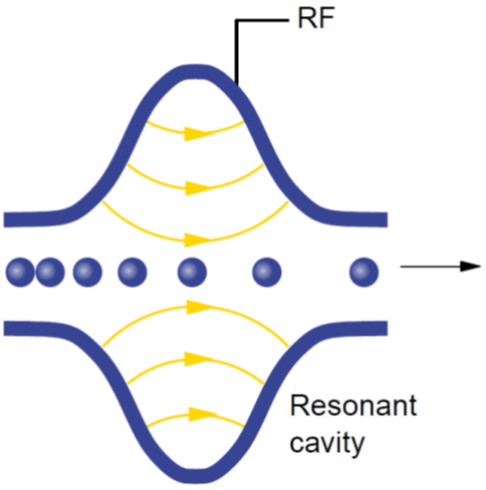
- In order to maintain path of electrons, balance of Lorentz & Centripetal Force:

  $F_L = e\,\mathbf{v} \times \mathbf{B}$ and $F_c = mv^2/r$

- Without help, electron will spiral in and collide into inside wall of vacuum storage ring
- Therefore need to compensate for power loss (due to energy lost by electrons) by pumping energy back into the electrons…..
- Use an RF ("klystron") cavity supplies electrons with energy each time it goes round

RF Power Supply and Bunching

- Restock electron KE using a “klystron”
- Electric field across cavity
- If electrons enter cavity at right moment in RF cycle, they are accelerated



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RF Power Supply and Bunching

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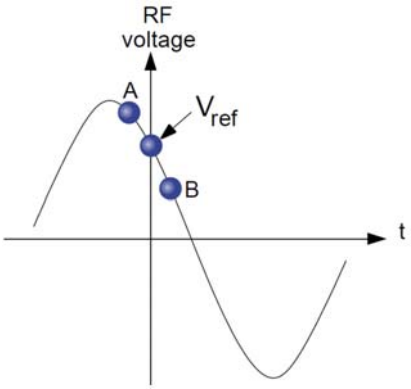
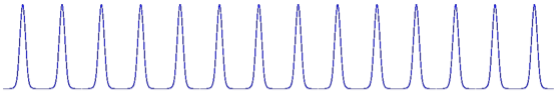
- On average, electron needs eV_{ref} energy boost for each circuit
- If electron dissipates
  - more energy, enters klystron at later point “A” → gets extra kick
  - less energy, too fast & enters at “B” in → gets less accelerated
- Outside certain range → lost to system
- Self-correcting → electron bunches associated with cycle of RF cavity



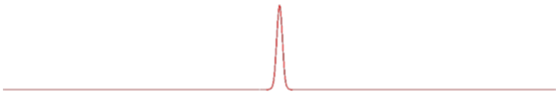
Filling Modes

→ **Time resolved studies using electron bunches:**

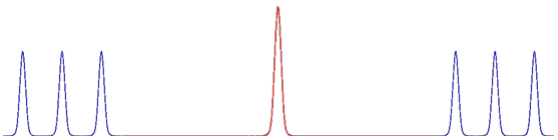
Normal bunch mode



Single bunch mode



Hybrid mode



→ Allows other beamlines to run at reasonable average photon fluxes

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Flux and Brilliance

Flux & Brilliance indicate quality of beamline facility:

$$Flux = \frac{photons}{second.\,0.1\%\ bandwidth}$$

Flux: number of photons per second per unit bandwidth passing through a defined area.

Important measure for experiments where the entire, unfocussed beam is used, e.g tomography

$$Brilliance = \frac{photons}{second.\,unit\ area\ source\ size.\,mrad^2.0.1\%\ bandwidth}$$

Brilliance: how flux is distributed in space and angular range (phase-space).

Note: Emittance = source size x beam divergence (in the same plane)

Want emittance as low as possible, with very small source size and x-rays as parallel as possible.

Dependent on x-ray optics and important for experiments where tight and parallel focusing is needed, e.g., protein crystallography, STXM, XRF mapping, …

Synchrotrons & Brilliance

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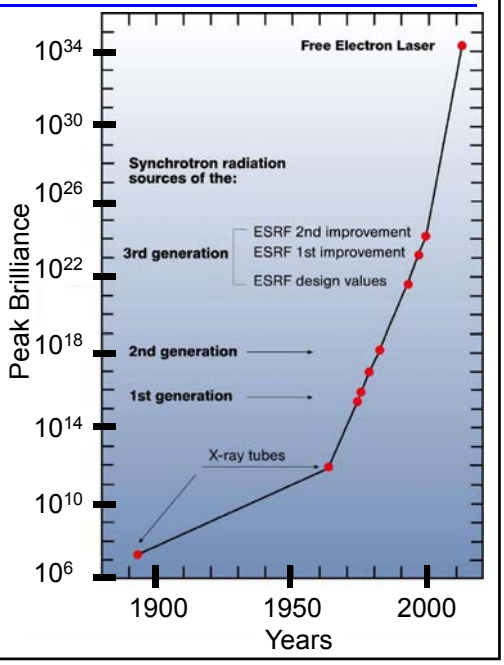

Source: DESY

Emittance

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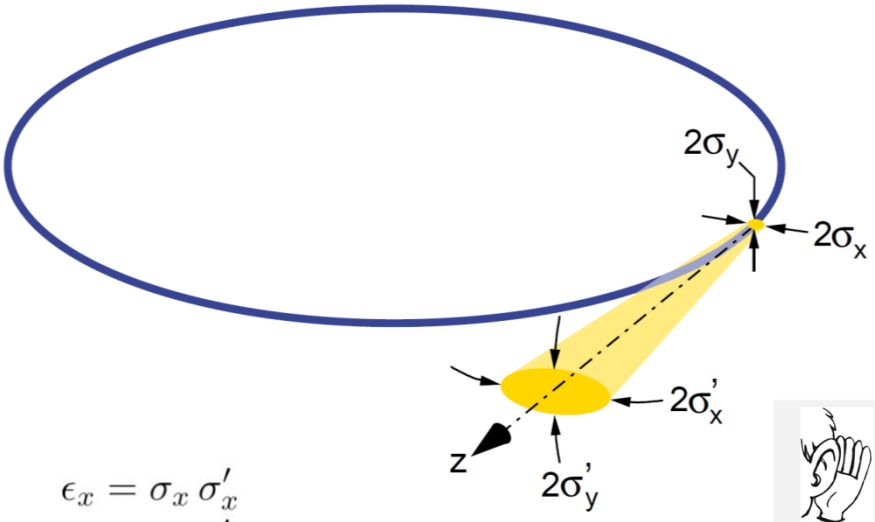

$$\epsilon_x = \sigma_x \, \sigma'_x$$
$$\epsilon_y = \sigma_y \, \sigma'_y$$

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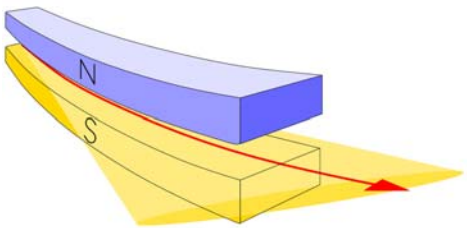
Emittance

Emittance = source size x beam divergence

- Want emittance as low as possible → small source size and x-rays almost parallel
- σ_x and σ_y are the standard deviations of Gaussians describing the beam profile
- $\epsilon_x > \epsilon_y$ because magnet lattice acts on x → spread of energies
- Pairs of alternating vertical and horizontal quadrupole magnets refocus e's and bring to ideal orbit, so that σ'_x is small

Bending Magnets

Line-by-line...



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- Mainly to keep electrons on a closed path
- B ~ 1 Tesla
- Radiation fan
  - Vertical divergence: $1/\gamma$
  - Horizontal: angular change in path of e's ~ 10^o
- Superconducting "superbend" ~ 5 Tesla
  - Flux $\propto B^2 \Rightarrow$ 25 x more flux
- Bending magnets produce broadband radiation

Insertion Devices

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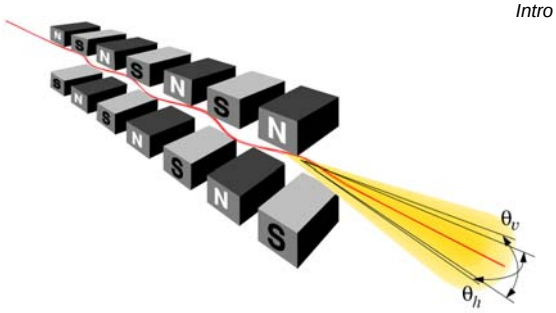
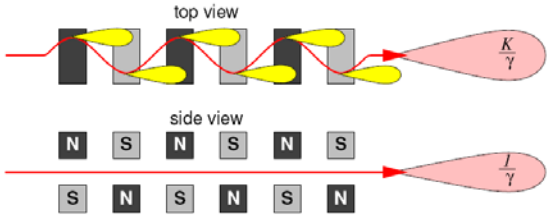


- Array of alternating N-S/S-N magnets → electrons oscillate
- Wigglers: large angular deviations (>1/γ)
- Undulators: smaller angular deviations (≤ 1/γ)

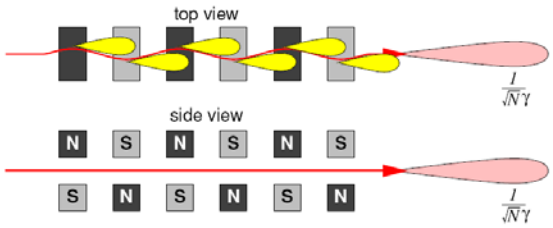
Insertion Devices

Wiggler



Radiation cones do not overlap and intensities are added

Undulator



Radiation cones overlap and interfere and amplitude peaks where interference is constructive

Features of Undulator Spectra

Relativistic energy parameter: γ

Undulator spatial period: λ_u

$K = \phi_{max}\gamma$, where ϕ_{max} is the maximum angular deviation of electron oscillations

The condition for constructive interference:

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

→ Peaks equally spaced in energy ΔE, where:

$$\Delta E = \frac{2hc\gamma^2}{\lambda_u\left(1 + \frac{K^2}{2}\right)}$$

Features of Undulator Spectra

Undulator spectrum:

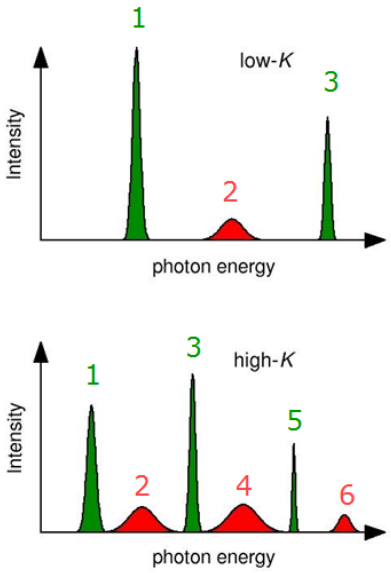
Peaks (energy bands) referred to as _____, which result from _____ _____ of amplitudes (_____ interference) of radiation created at each bend.

Spectrum tuned by changing __, i.e. changing the ____ between the two set of magnetic poles and therefore the _____ _____ _____.

K ↑ as undulator gap is _____.

Line-by-line...

Features of Undulator Spectra



- Odd harmonics dominate
- Low K undulator:
  even harmonics are suppressed, low harmonics strongest and dominated by n = 1
- High K undulator (closing undulator gap): higher harmonics start to dominate, even harmonics become more prevalent
- Width of peaks proportional to
  - 1/N (N = number of periods)
  - 1/n (n = harmonic number)

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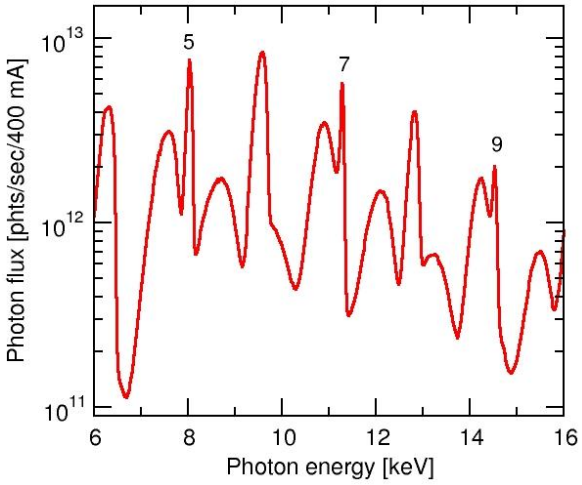
ETH PSI

A real undulator spectrum

Protein crystallography beamline, SLS with λ_u = 19 mm



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Tuning Undulators

$$K = \frac{eB_0}{mck_u} = 0.934\ \lambda_u[\mathrm{cm}]\ B_0[\mathrm{T}]$$

Close undulator gap:

- Increases B_0
- Increases K
- Increases A, the electron oscillation amplitude

$$A = \frac{K\lambda_u}{2\pi\gamma}$$

Optimizing Undulator Parameters

K = 1.5, N = 70 periods, 3 GeV and 200 mA
→ on axis peak intensity for 5th harmonic of

4.05×10^{17} photon.s^{-1}.0.1%BW^{-1}

For a typical undulator source size (150 x 20 mm^2), brilliance:
→ brilliance:

1.35×10^{20} photons.s^{-1}.mrad^{-2}.mm^{-2}.0.1%BW^{-1}

Different harmonics used in different energy ranges:

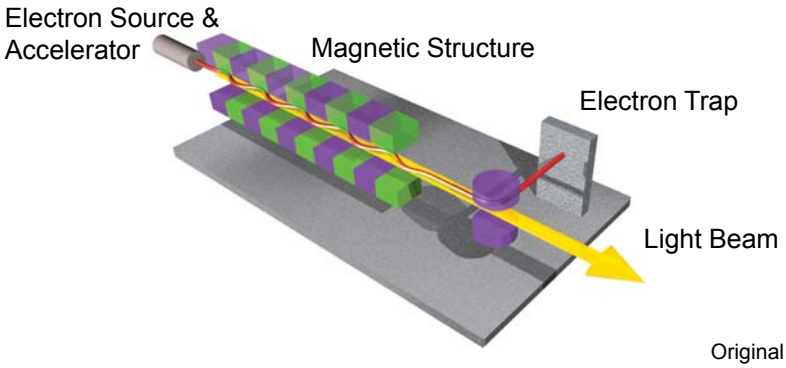
Access high harmonics with small λ_u, high K…
…(using small undulator gap).

Soft x-rays with large λ_u, low K (using large gap).

SASE

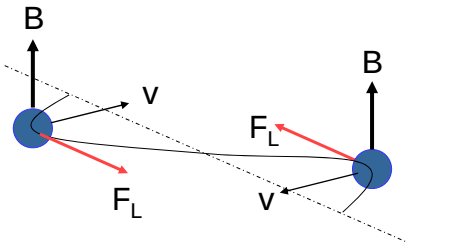
Self **A**mplified **S**timulated **E**mission

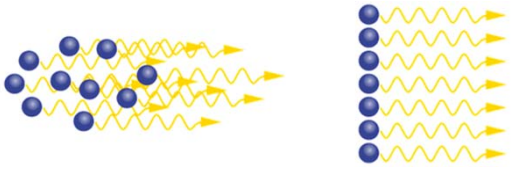
- Requires
  - Super-low emittance electron beam
  - Very long undulator: few 100 m
- Electrons in beam begin to interact with the EM radiation they have produced themselves



Original source: DESY

SASE





Non-Coherent Bunch

Coherent Bunch

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SASE

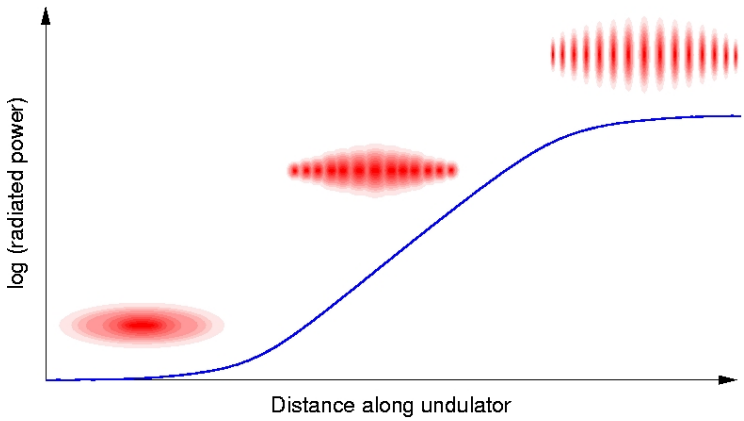
Electron beam modulated longitudinally with a period = λ

- Light beam generated is parallel & overlapping with electron beam
- B-field of EM radiation couples with transverse component of electron motion
  → Lorentz force acting on e⁻s in axial direction producing bunching

$$\frac{\lambda_{magnet\ periodicity}}{\gamma} = \lambda_{emitted}$$

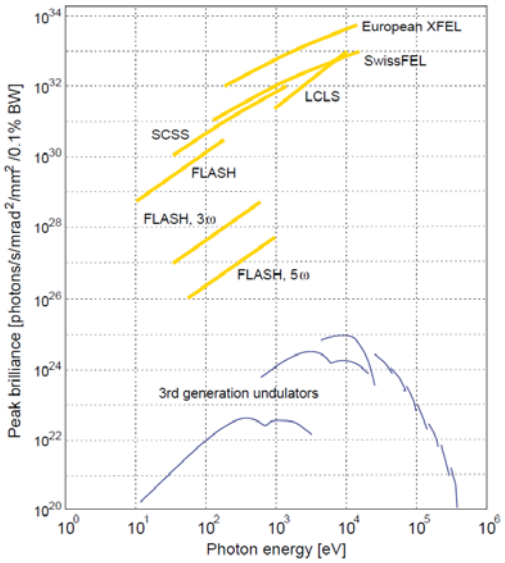
- Microbunches (containing 10^8-10^9 electrons) emit coherently → intense & fully coherent radiation
- N electrons contained in a region shorter than the wavelength of the radiation emit coherently and intensity, $I \propto N^2$
  (for incoherent emission, $I \propto N$)
- Increasing light intensity increases bunch density modulation
  → Increases coherence even more → runaway effect !!!

SASE



- ~9 orders of magnitude greater radiated power than in conventional 3rd generation synchrotron sources
- Microbunch duration: few fsec to few 10's fsec → track ultrafast processes such as atomic vibrations

Brilliance



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