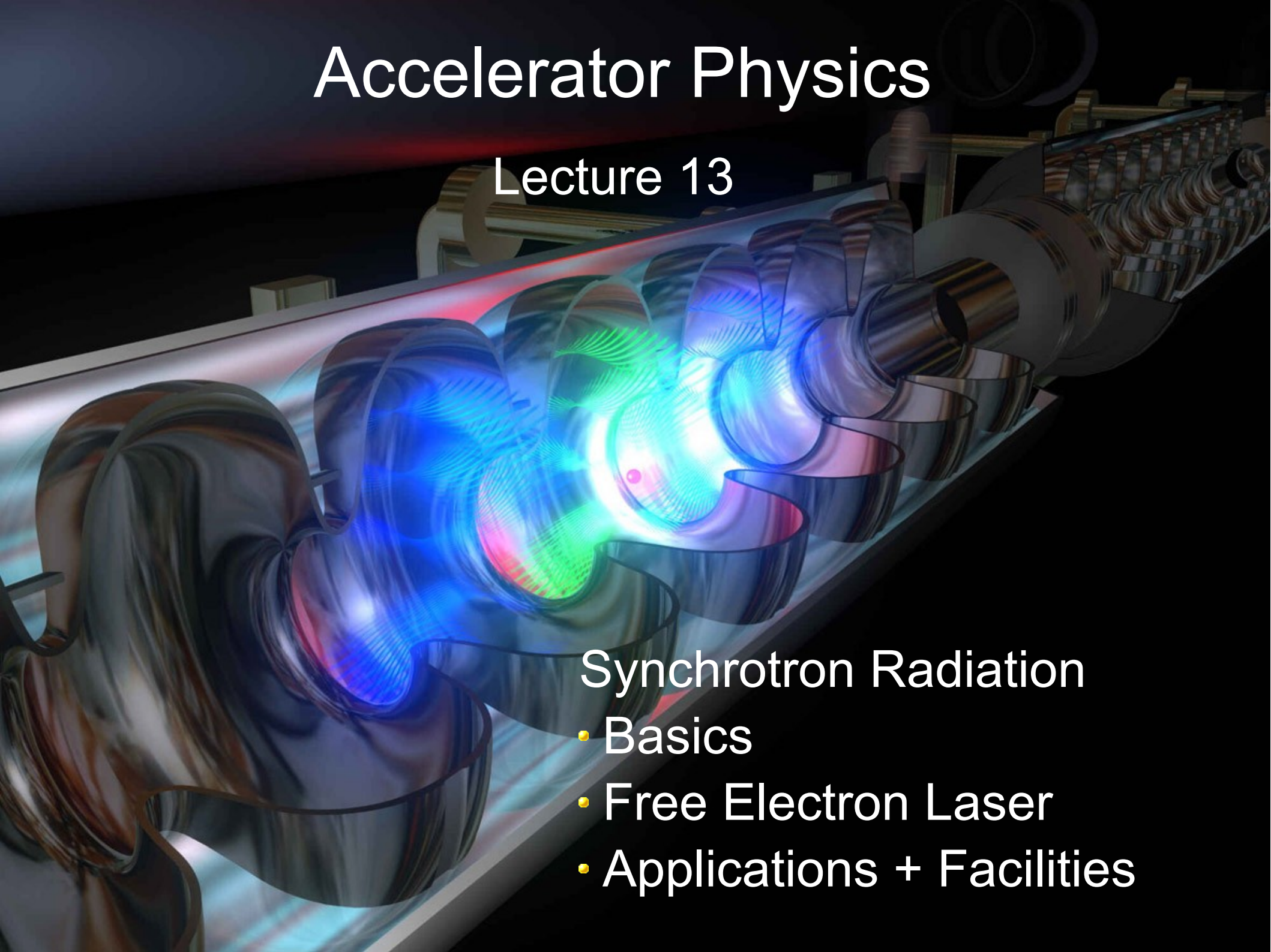


# Accelerator Physics

## Lecture 13



### Synchrotron Radiation

- Basics
- Free Electron Laser
- Applications + Facilities

# Synchrotron Radiation

- Atomic Physics
- Chemistry
- (Micro-)Biology
- Solid State Physics
- Medical Research

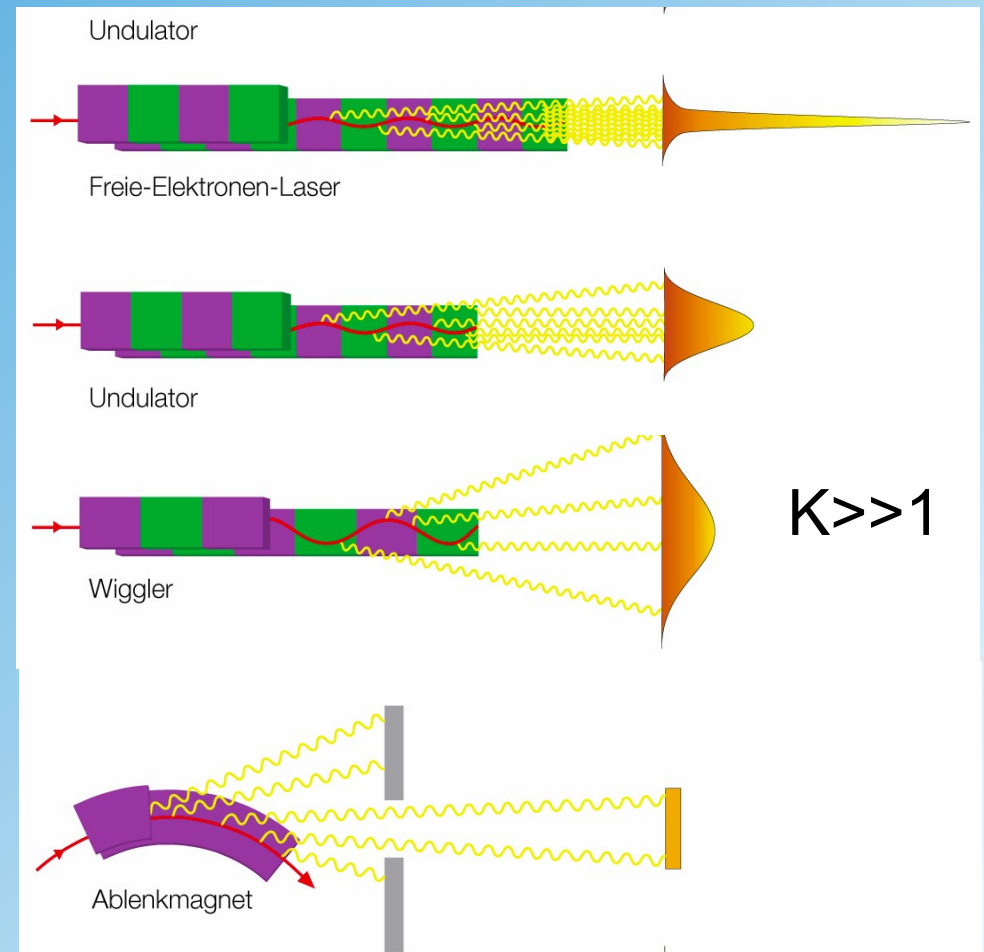
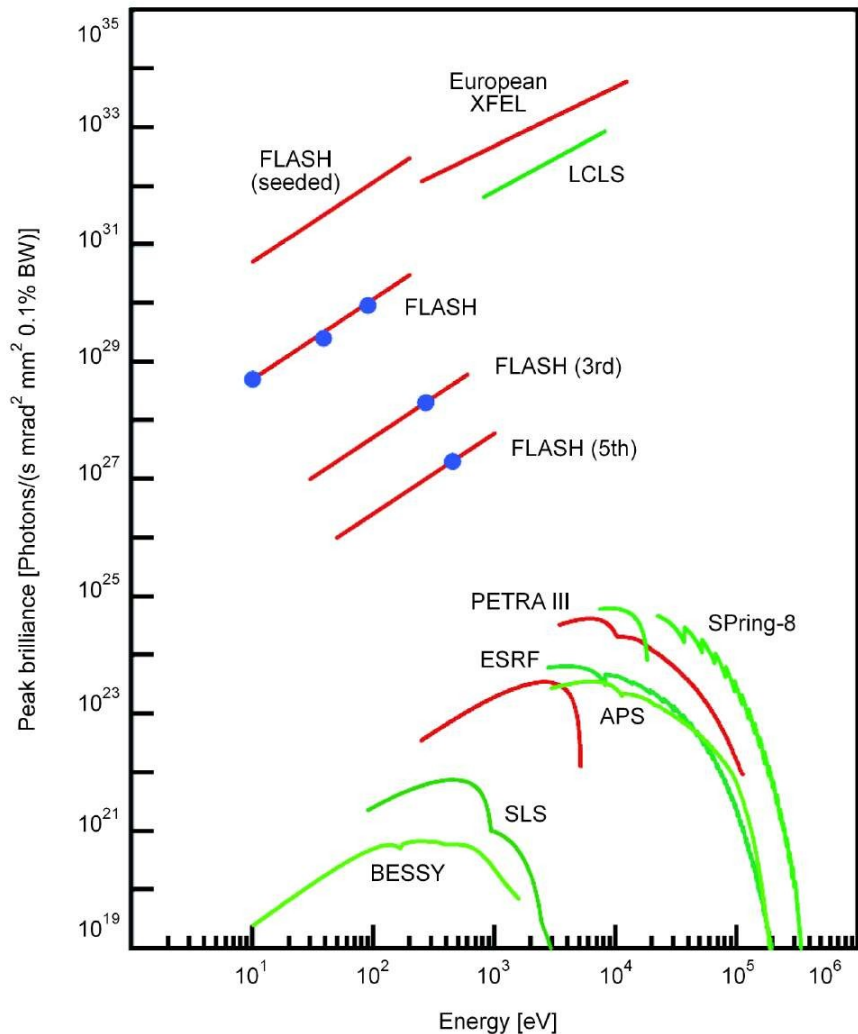


Wavelengths: Infrared to X-ray

# “Generations” of Synchrotrons

## Brilliance

$$[B] = \frac{\text{Photonen}}{\text{sec} \cdot \text{mm}^2 \cdot \text{mrad}^2 \cdot 0,1\text{BW}}$$



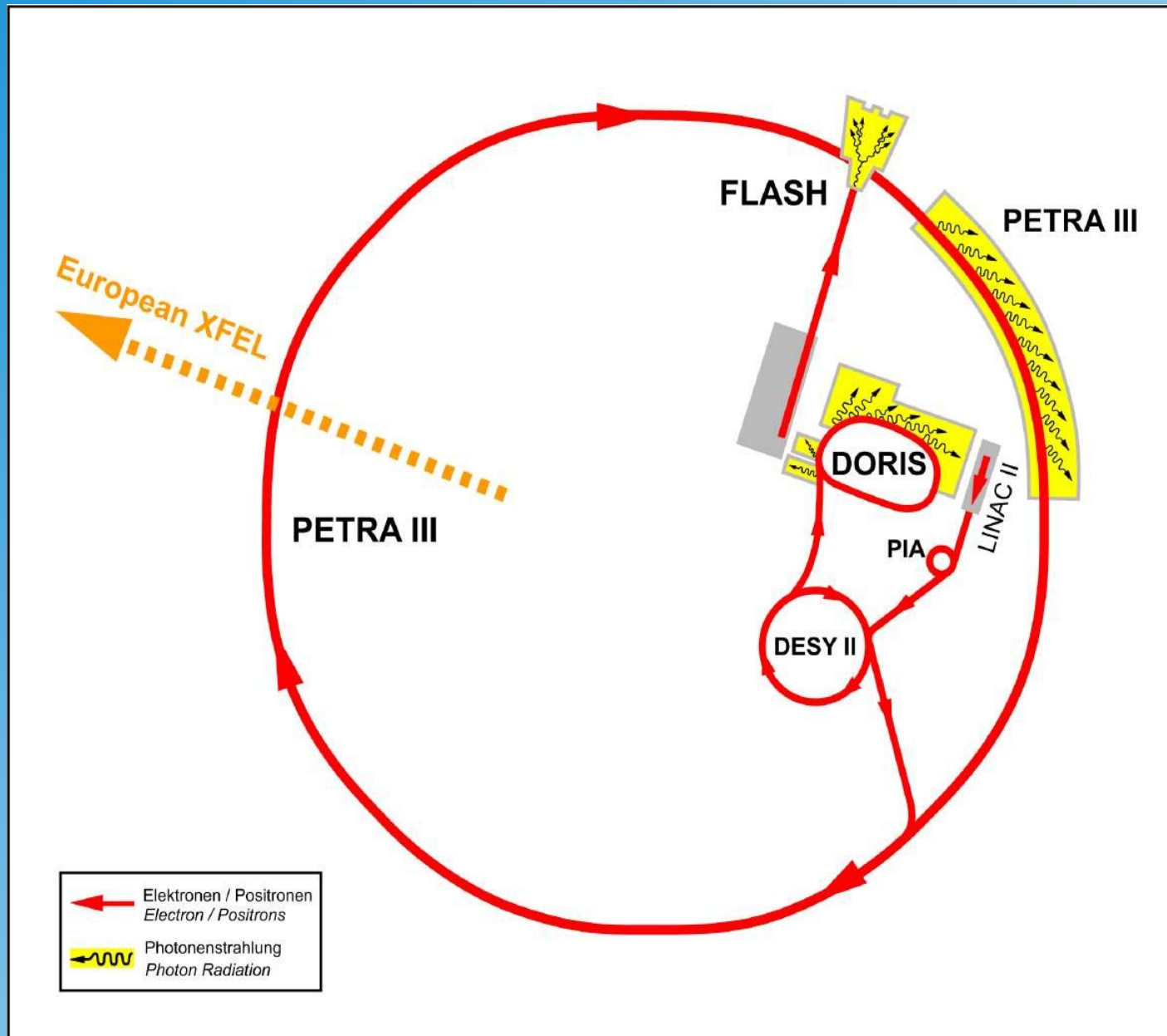
# European Synchrotron Radiation Facility (Grenoble)



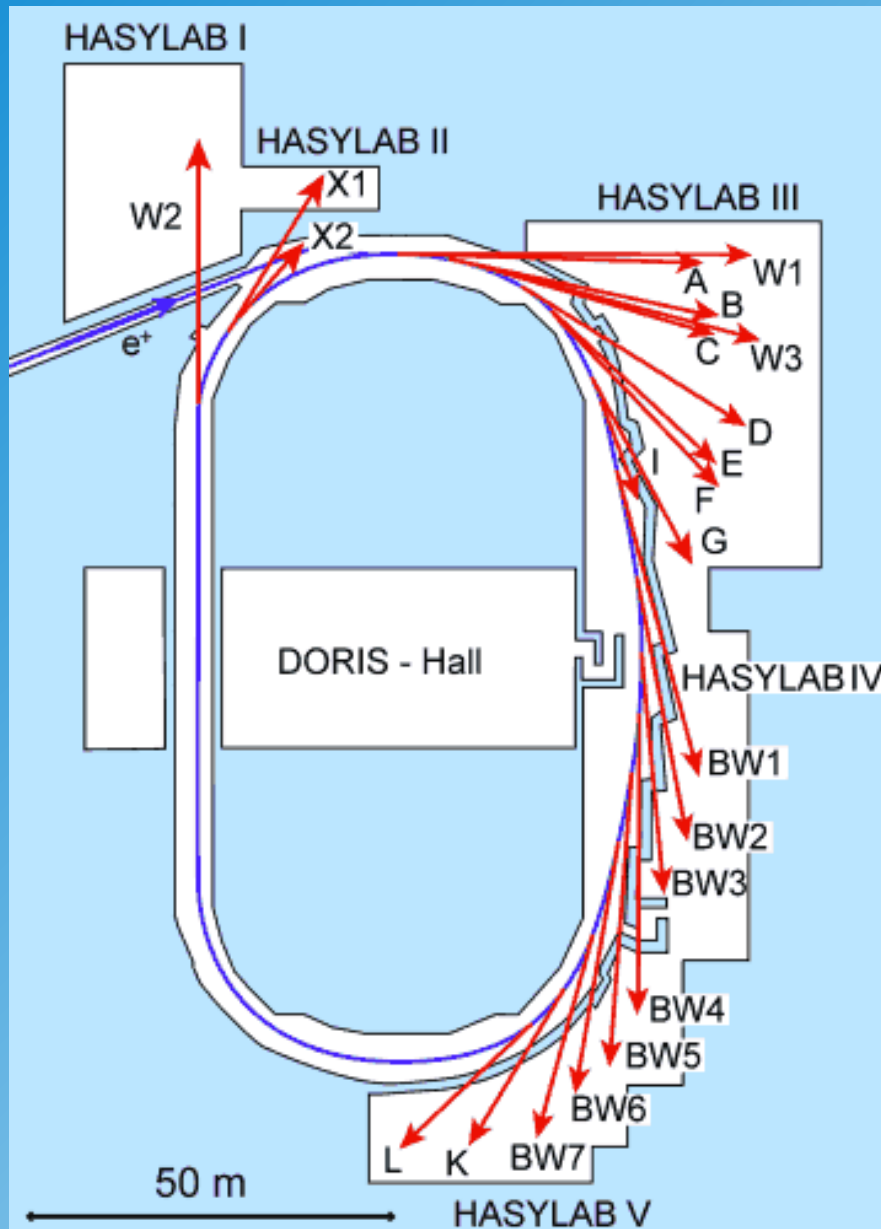
# Swiss Light Source (Schweiz)



# DESY Synchrotron Complex



# DESY HASYLAB



Beamlines for experiments

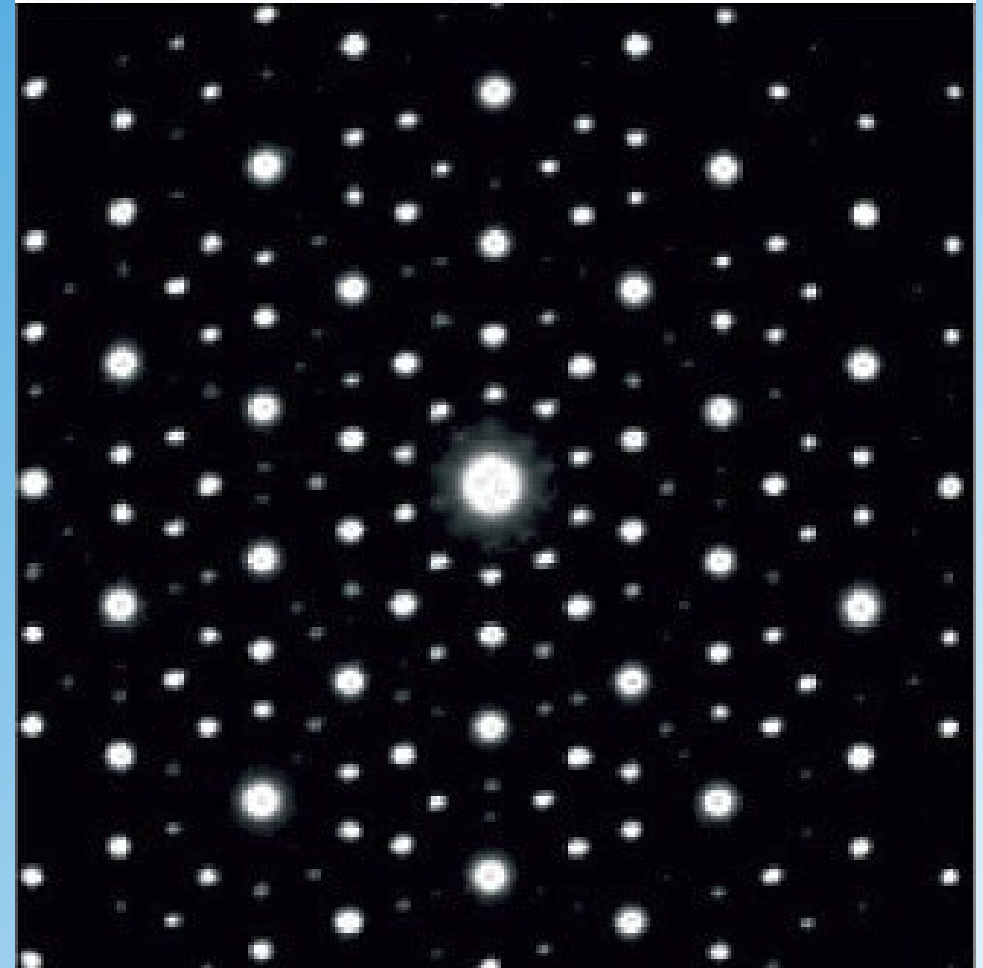
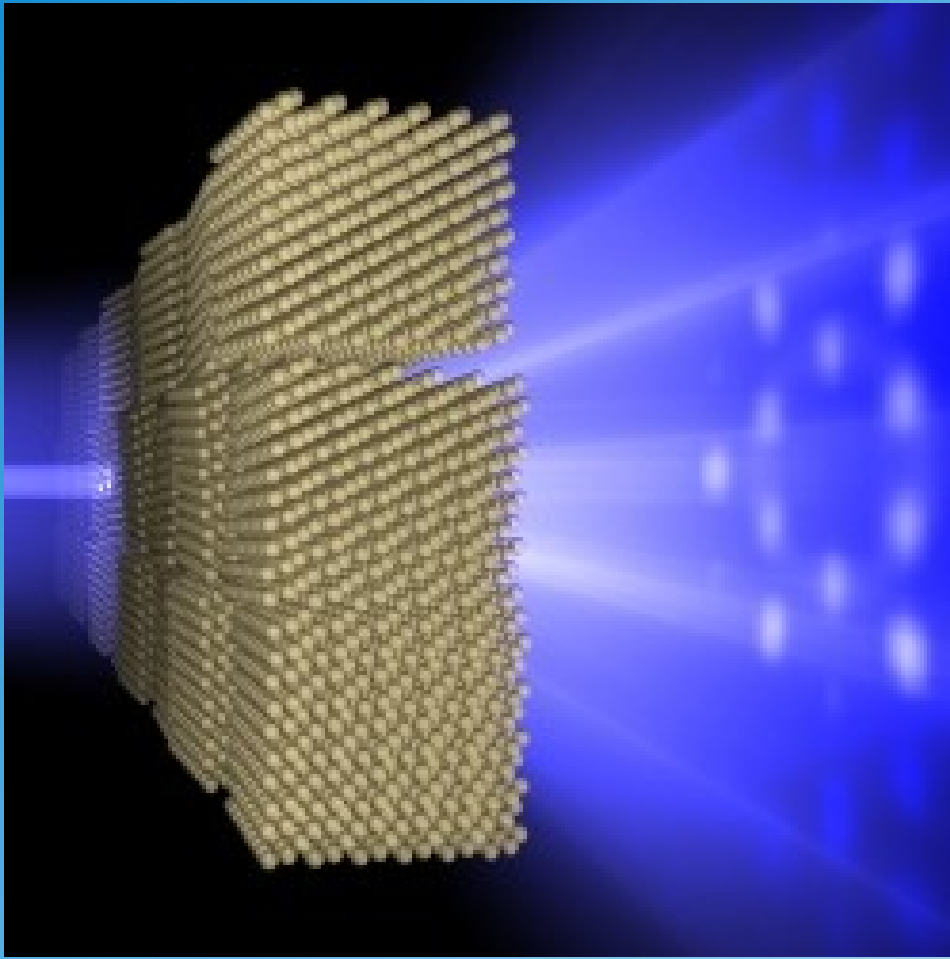
# DESY PETRA 3

Biggest monolithic concrete plate in the world





# Bragg Scattering in Crystals



- Regular structure (crystal)
- Monochromatic light

→ Diffractive Pattern

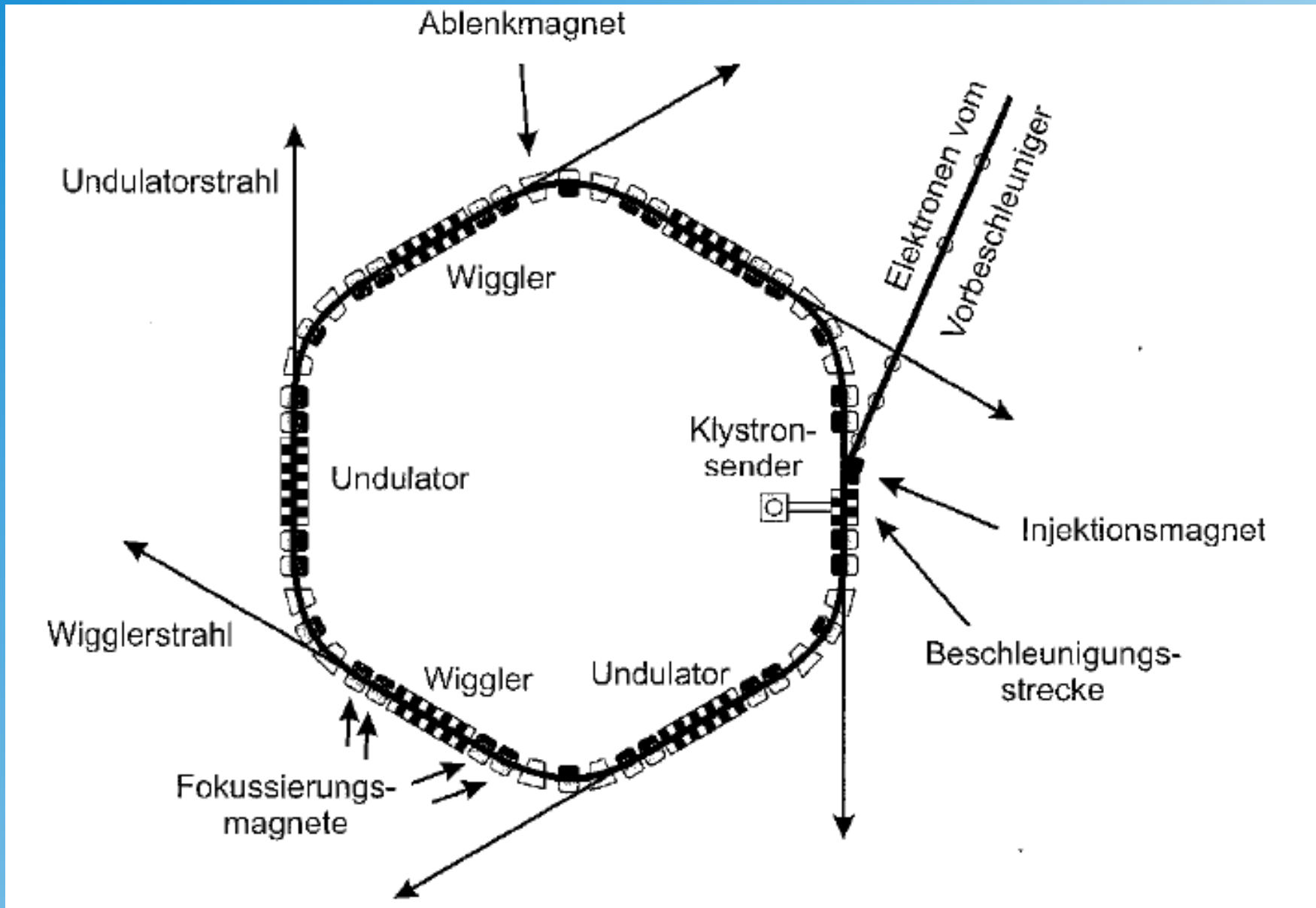
# Summary of Facilities

- ANKA (Angströmquelle Karlsruhe)
- Advanced Photon Source in den USA
- NSLS (National Synchrotron Light Source) am Brookhaven National Laboratory, Long Island, USA
- OPTIVUS (Loma Linda University Medical Center in Californien)[1][2] USA
- DESY (Forschungszentrum Deutsches Elektronen-Synchrotron)
- Diamond (Diamond Light Source) South Oxfordshire, UK
- Elektronen-Stretcher-Anlage (ELSA) Universität Bonn [3]
- CERN (frz. Conseil Européen pour la Recherche Nucléaire, das Europäische Kernforschungslabor)
- GSI (Gesellschaft für Schwerionenforschung mbH, Darmstadt)
- HIT (Heidelberger Ionenstrahl Therapie, Universitätskliniken Heidelberg)
- COSY (Cooler Synchrotron im Forschungszentrum Jülich)
- BESSY (Berliner ElektronenSpeicherringgesellschaft für SYNchrotronstrahlung)
- DELTA (Dortmunder Elektronen Speicherring Anlage)
- ESRF (European Synchrotron Radiation Facility) in Grenoble
- ELETTRA (ELETTRA Synchrotron Light Laboratory) in Triest, Italien
- MAMI (Mainzer Microtron [4]) Johannes Gutenberg-Universität, Mainz
- SOLEIL (Synchrotron SOLEIL) in GIF-sur-YVETTE, bei Paris, Frankreich
- SPring-8 (Super Photon ring-8 GeV) in Japan
- SLS (Swiss Light Source) am Paul-Scherrer-Institut in der Schweiz
- CLS (Canadian Light Source)
- SSLS (Singapore Synchrotron Light Source an der National University of Singapore)
- SESAME (Synchrotron-light for Experimental Science and Applications in the Middle East) in Allaan, Jordanien

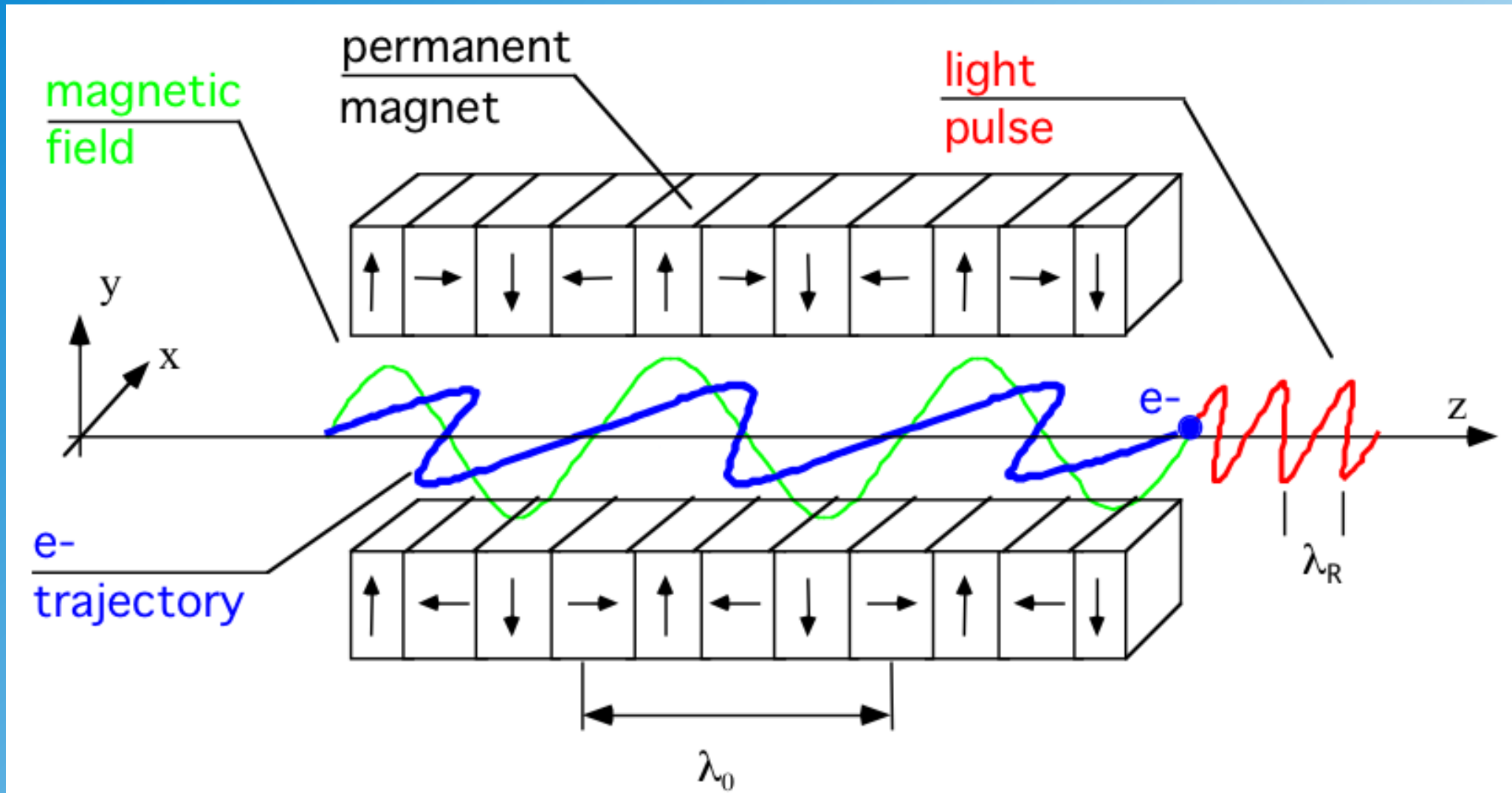
# Soleil, France



# Main Principle



# Wiggler / Undulator



# Synchrotron Radiation Calculation

From Maxwell Equations:

$$\partial_\nu \partial^\nu A^\mu = \frac{-1}{c} j^\mu$$

Solved using retarded Green-Functions

Lienard-Wiechert potential:

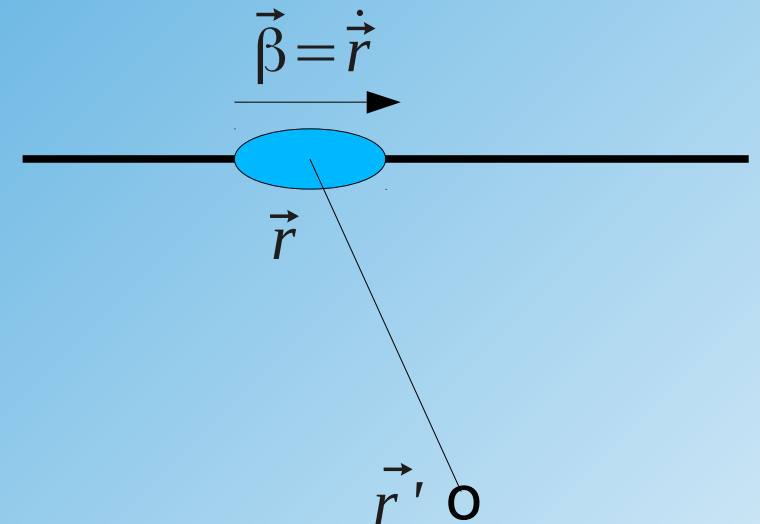
$$\Phi = \frac{q}{|\vec{r} - \vec{r}'| - (\vec{r} - \vec{r}') \cdot \vec{\beta}}$$

E.M. Fields:

$$\vec{E} = -\frac{\partial}{\partial t} \vec{A} - \nabla \Phi$$

$$\vec{B} = \nabla \times \vec{A}$$

Moving electron bunch:



$$\vec{A} = \vec{\beta} \Phi$$

# Synchrotron Power

Poynting Vector

$$\vec{S}_{far} = c \vec{E} \times \vec{B}$$

Radiated power per solid angle

$$dP = |\vec{r} - \vec{r}'| (\vec{r} - \vec{r}') \vec{S}_{far} d\Omega$$

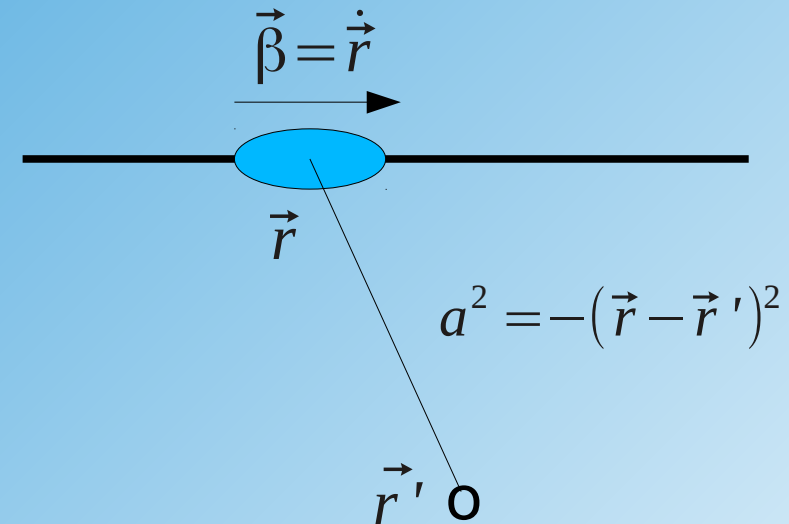
→ integration

$$P = \frac{2q}{3c(1-\beta)^3} (\dot{\vec{\beta}}^2 - |\vec{\beta} \times \dot{\vec{\beta}}|^2)$$

Radiation power in ring accelerator:

$$P = \frac{2qE^4}{3(mc^2)^4 R^2} \quad R = \text{radius}$$

Moving electron bunch:



in magnetic field:  $\vec{\beta} \perp \dot{\vec{\beta}}$

# Synchrotron Energy Spectrum

via Fourier Transformation of time dependence:

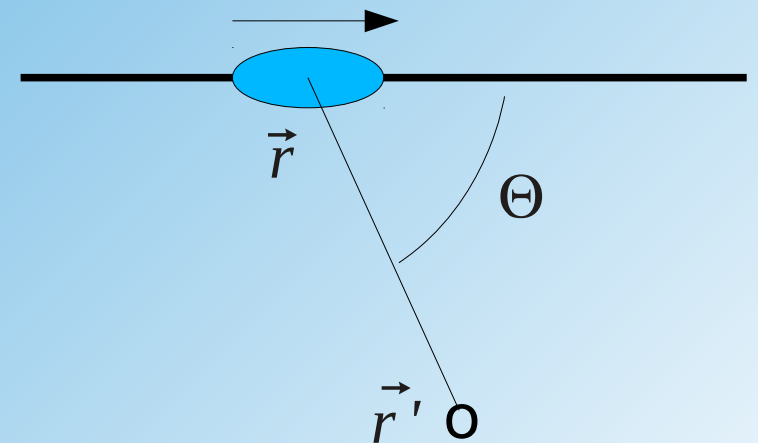
$$\frac{dE}{d\omega d\Omega} = \frac{q^2 a^2 \omega^2}{3\pi^2 c^3} \left( \frac{1}{\gamma^2} + \Theta^2 \right)^2 \left[ K_{2/3}^2(\xi) + \frac{(\gamma^2 \Theta^2)}{1 + \gamma^2 \Theta^2} K_{1/3}^2(\xi) \right]$$

$\omega = \text{frequency}$

$\Theta = \text{radiation angle}$

$K_\nu = \text{modified Bessel function}$

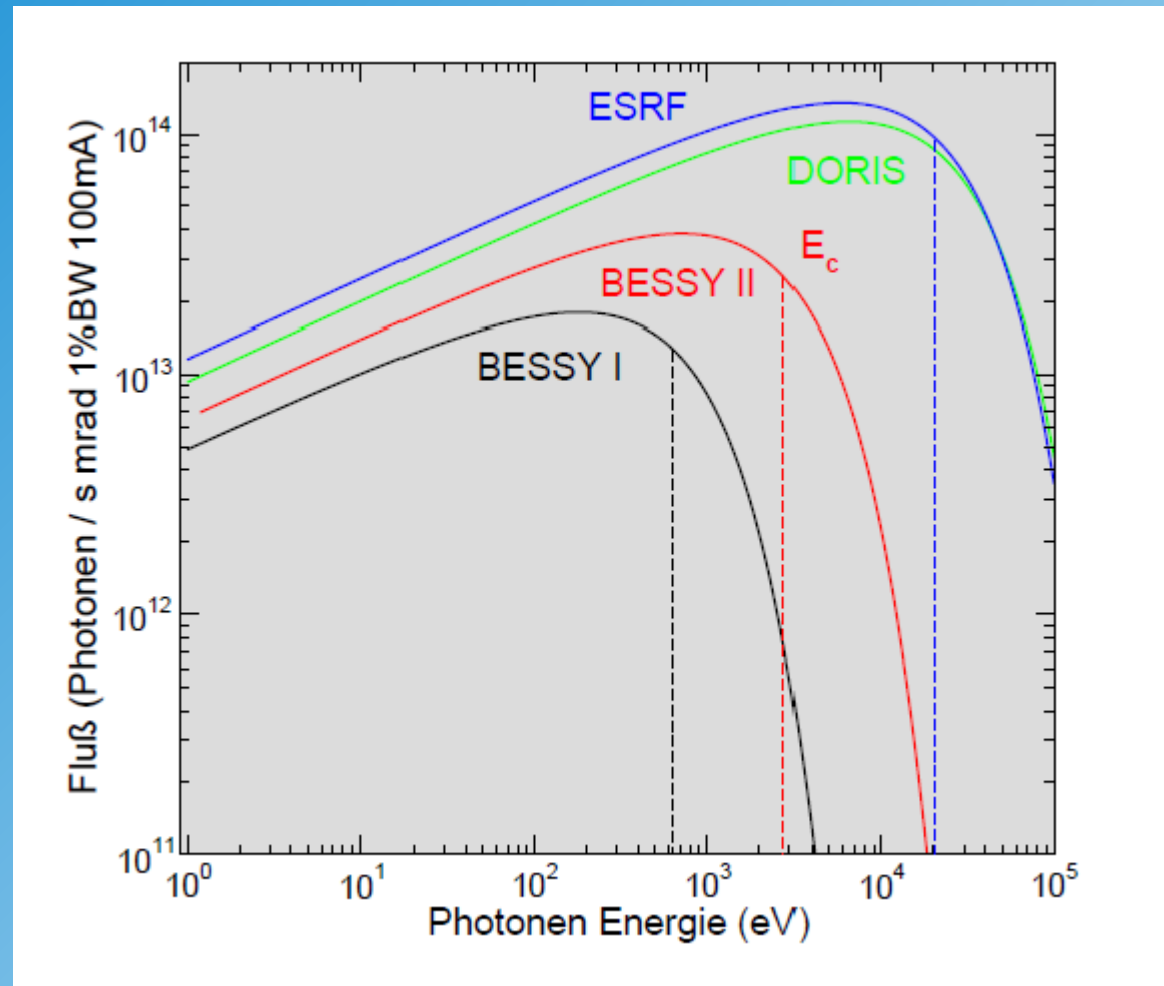
$$\xi = \frac{\omega a}{3c} \left( \frac{1}{\gamma^2} + \Theta^2 \right)^{3/2}$$





# Energyspectrum

Power law

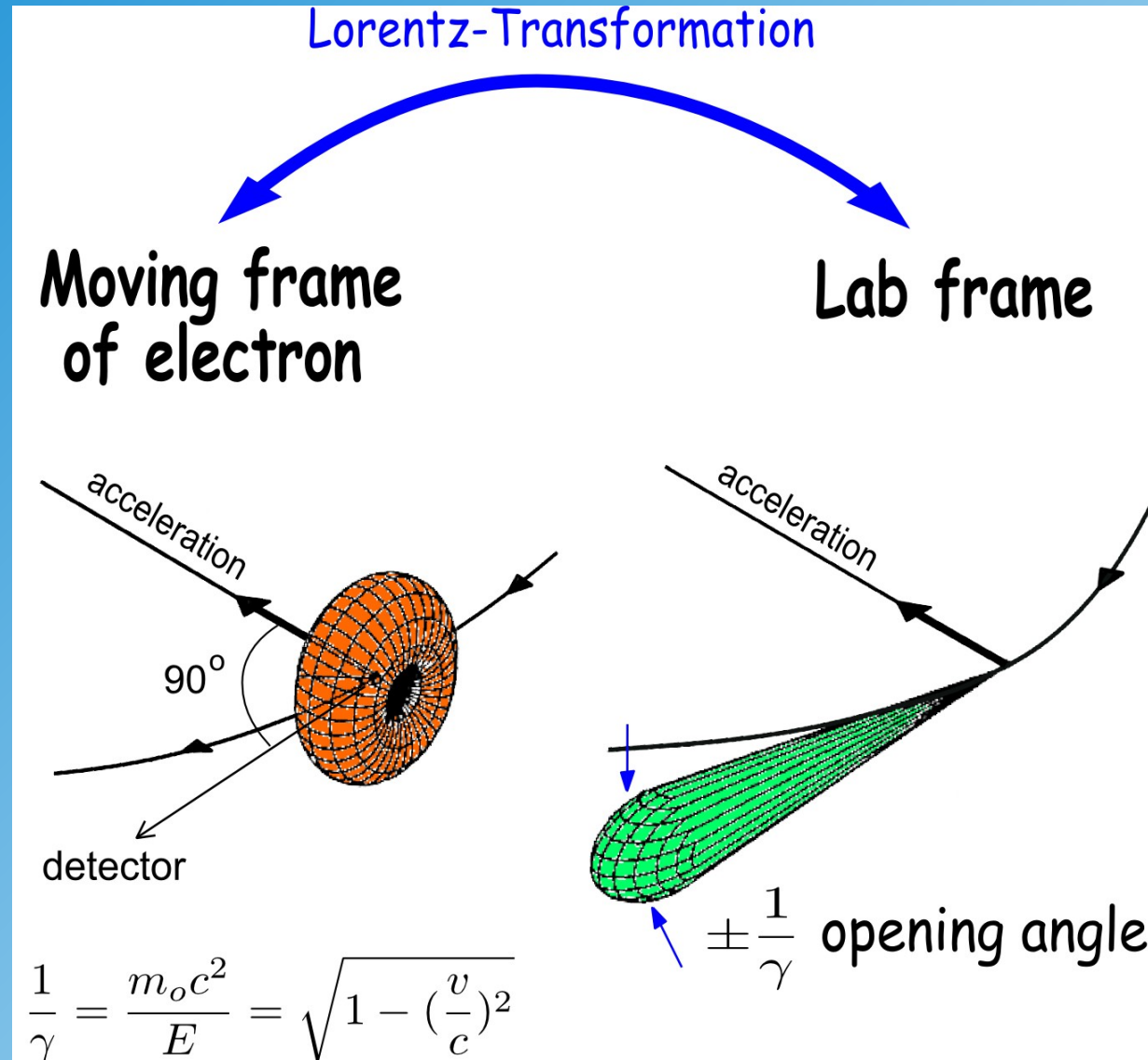


Exponential fall

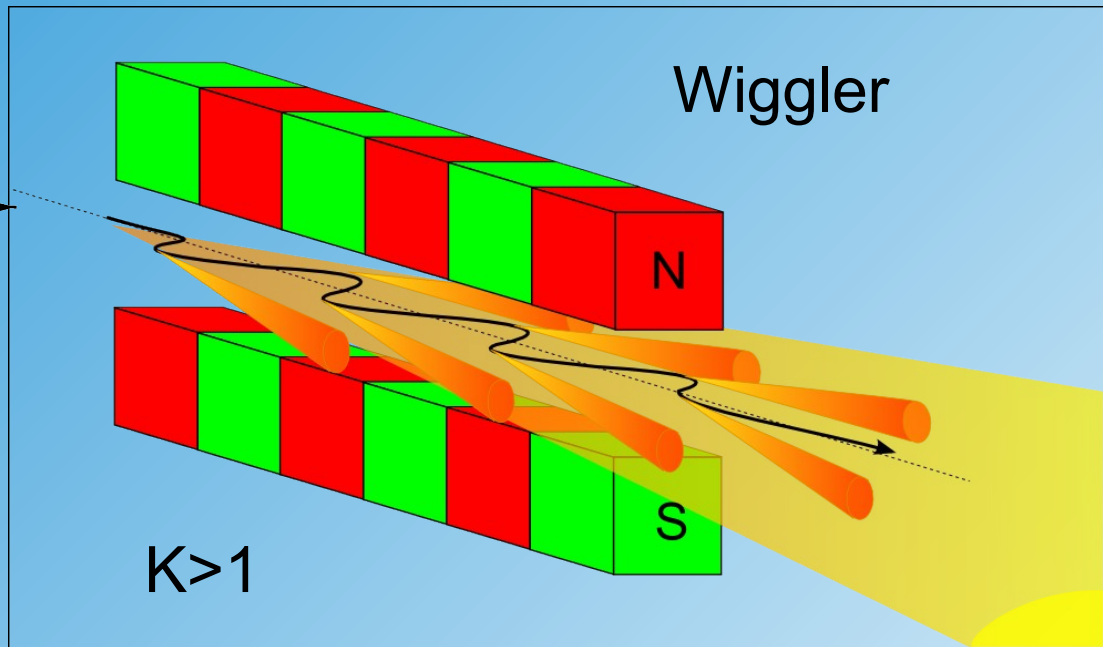
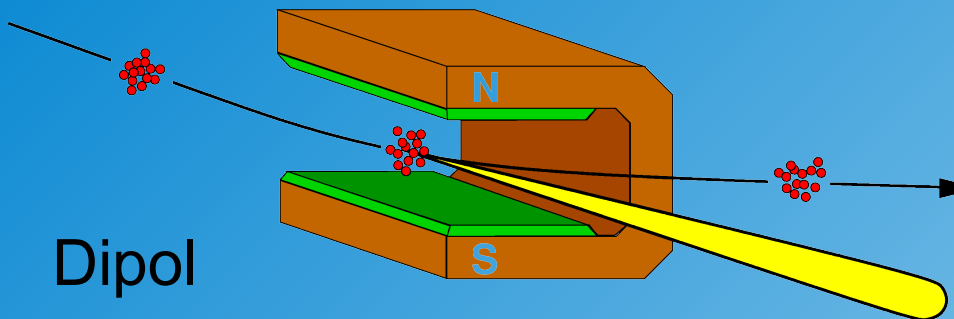
Energy distribution  
described by mod. Bessel Function

$$\omega_c = \frac{1}{2} \frac{3c\gamma^3}{R}$$

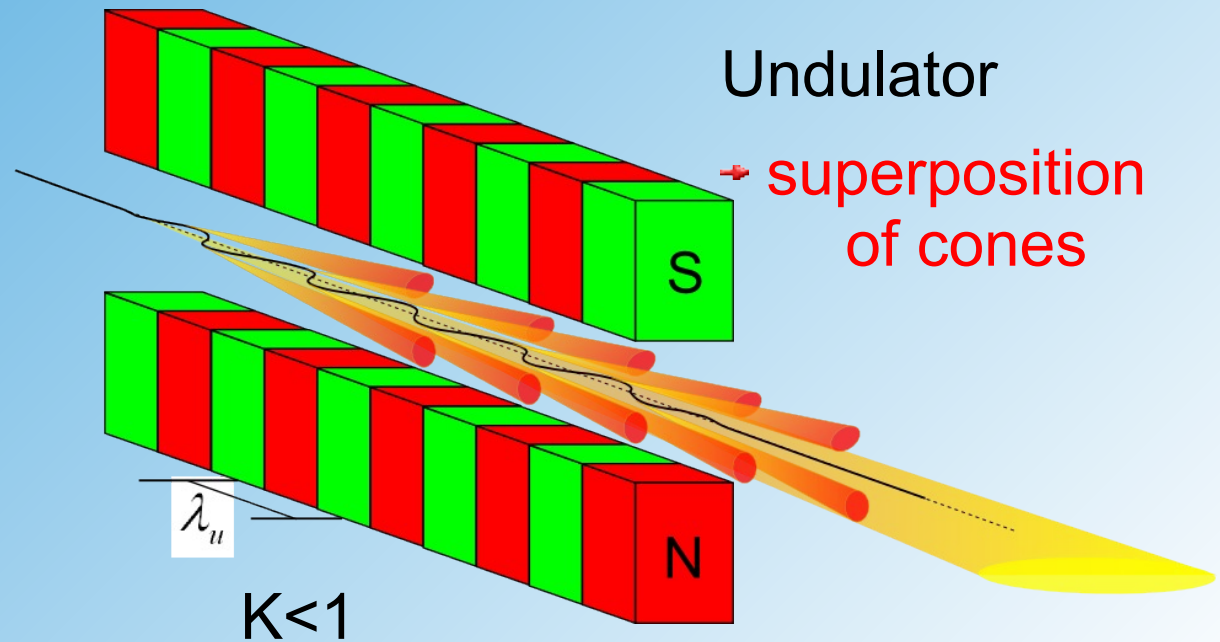
# Synchrotron Radiation Cone



# Undulator versus Wiggler I



$$K = \frac{e}{m_e c} \lambda_u B$$



# Undulator Parameter

Characteristic Parameter

$$K = \frac{e}{m_e c} \lambda_u B$$

Relation to radiation angle

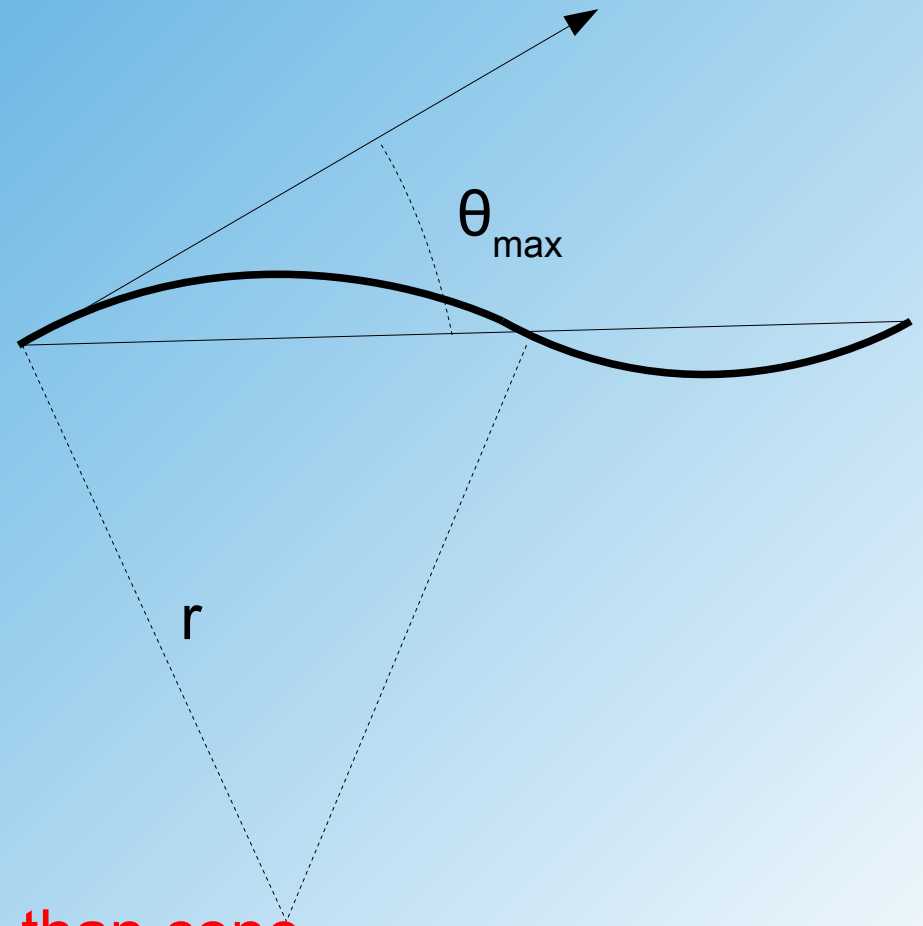
$$p = e R B$$

$$2\theta_{max} = \frac{\lambda_u}{2R}$$

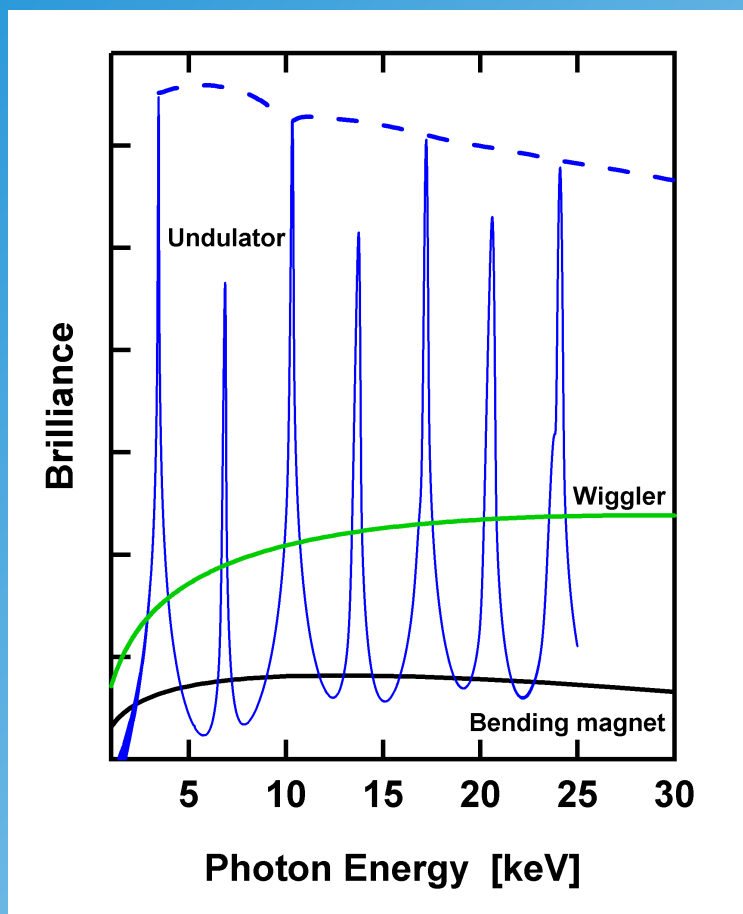
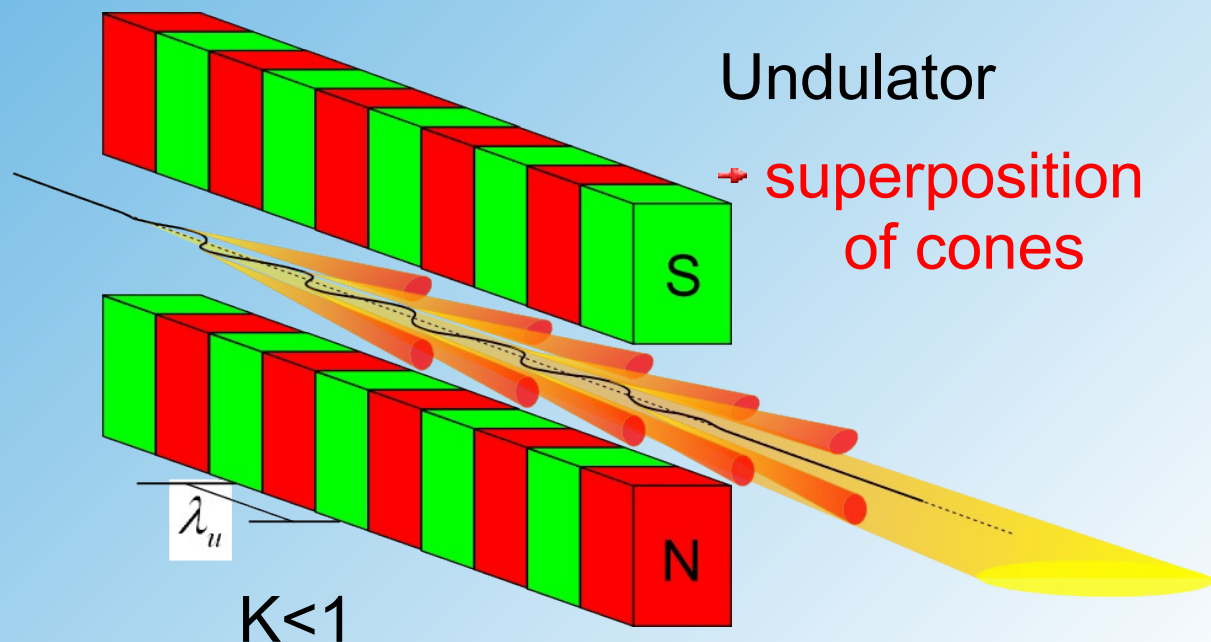
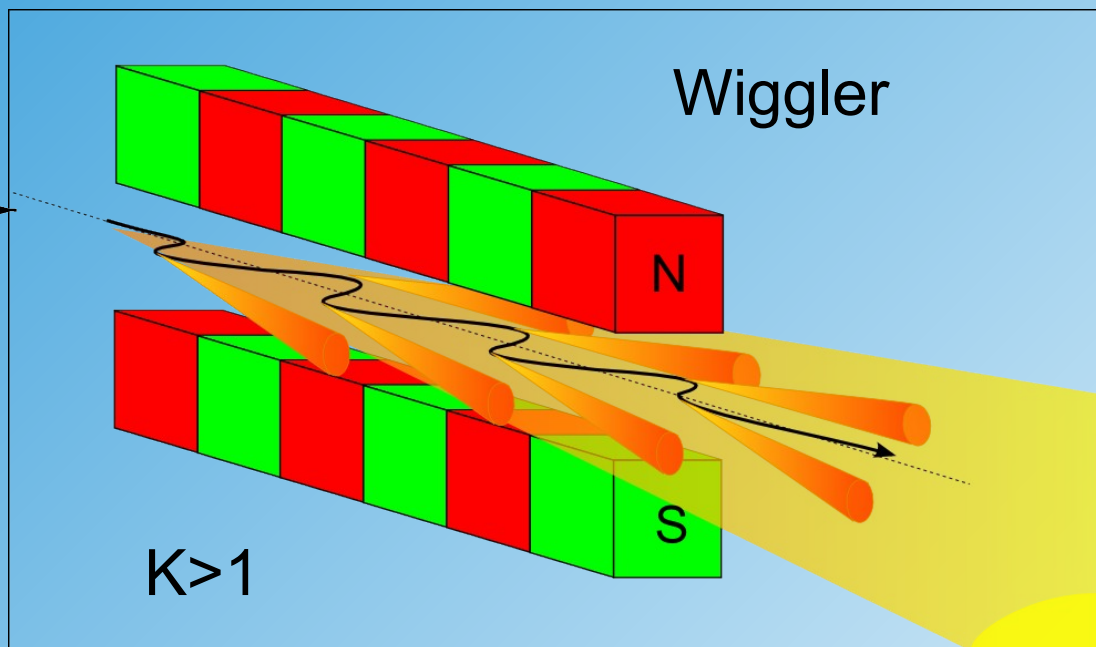
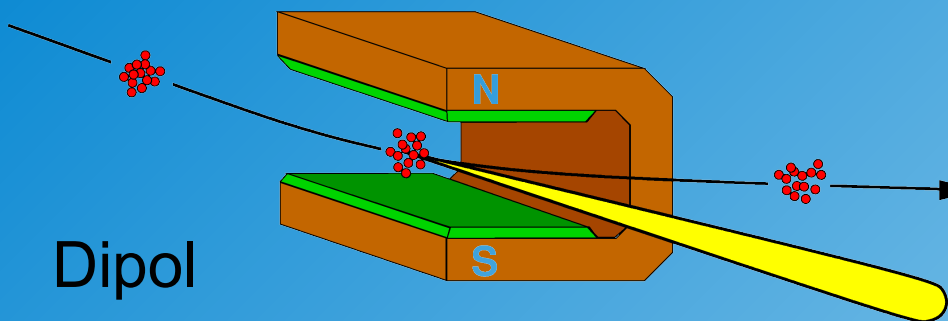
Insertion

$$K = 4\theta_{max} \gamma$$

If  $K > 1$ , synchr. Radiation fan large than cone



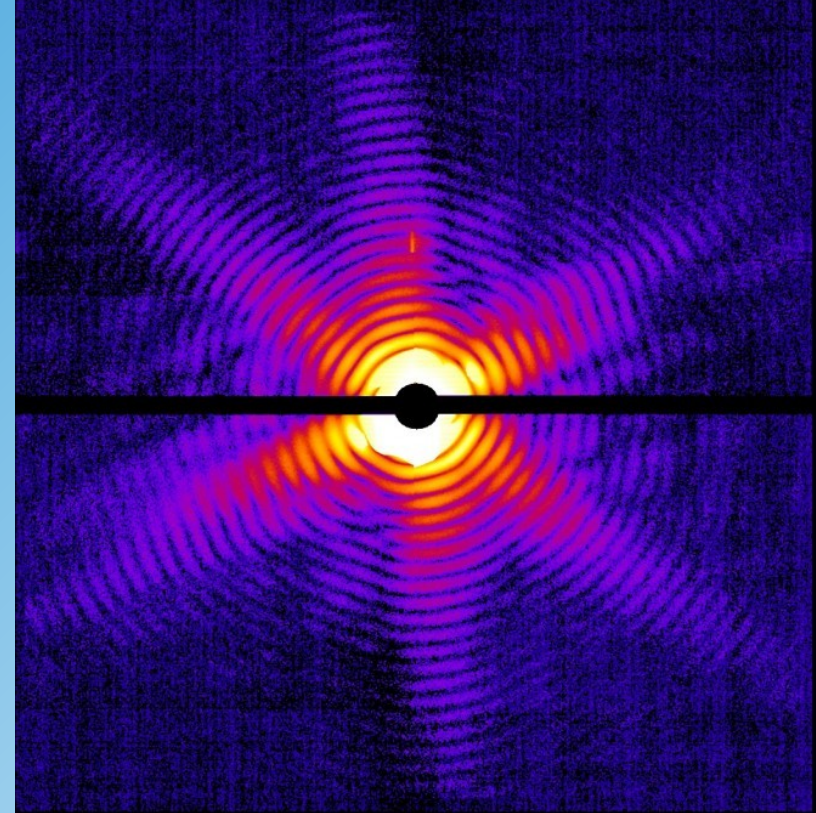
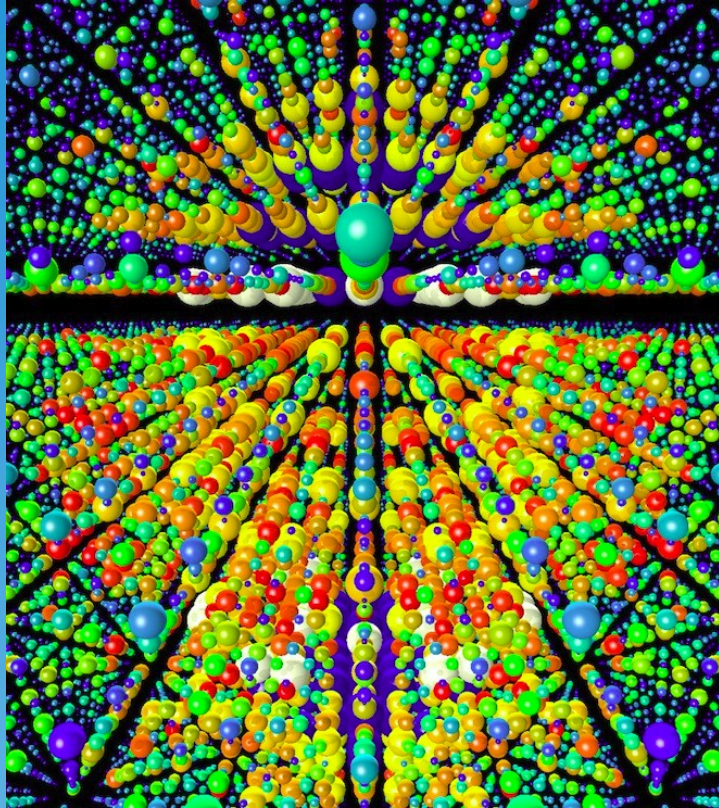
# Undulator versus Wiggler I



# Free Electron Lasers (FEL)

- SASE – FEL = Self Amplified Stimulated Emission
  - Very short, and intense light pulses
  - Monochromatic and adjustable in a wide energy range
  - light is coherent!
  - Light is polarised (spin polarised)
- Produced in long undulators

# Virus studied in X-FEL



Possible to study irregular structures (virus)

By Marvin Seibert, Janos Hajdu et al. Nature, Vol. 470, No. 7332, February 3, 2011.

# Equation of Motions in Undulator

From Lorentz Force

$$\gamma m_e \dot{\vec{v}} = -e \vec{v} \times \vec{B}$$

Equation of Motion

$$\ddot{x} = \frac{e}{\gamma m_e} B_y \dot{z} \quad \ddot{z} = \frac{-e}{\gamma m_e} B_y \dot{x}$$

Usual approximations:

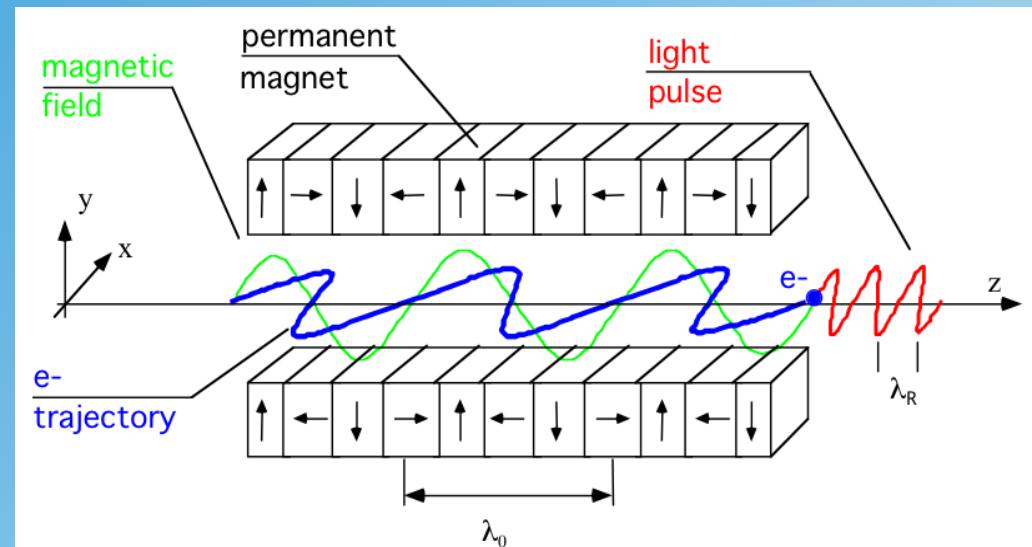
$$v_x \ll v_z$$

$$v_z \approx v$$

Solution:

$$x = \frac{K}{\beta \gamma k_u} \sin(k_u z)$$

$$K = \frac{eB}{m_e c k_u}$$





# Electron Velocities

Total velocity

$$v = \beta c$$

x-projection

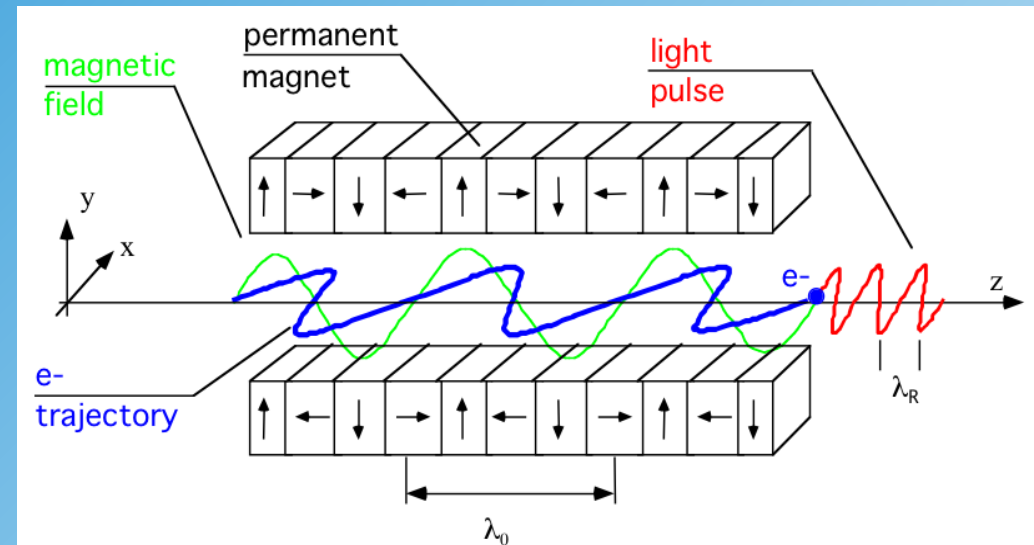
$$v_x = \frac{Kc}{\gamma} \cos(k_u c t)$$

z-projection

$$v_z = \sqrt{v^2 - v_x^2} \quad \bar{v}_z = \sqrt{v^2 - \bar{v}_x^2}$$

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

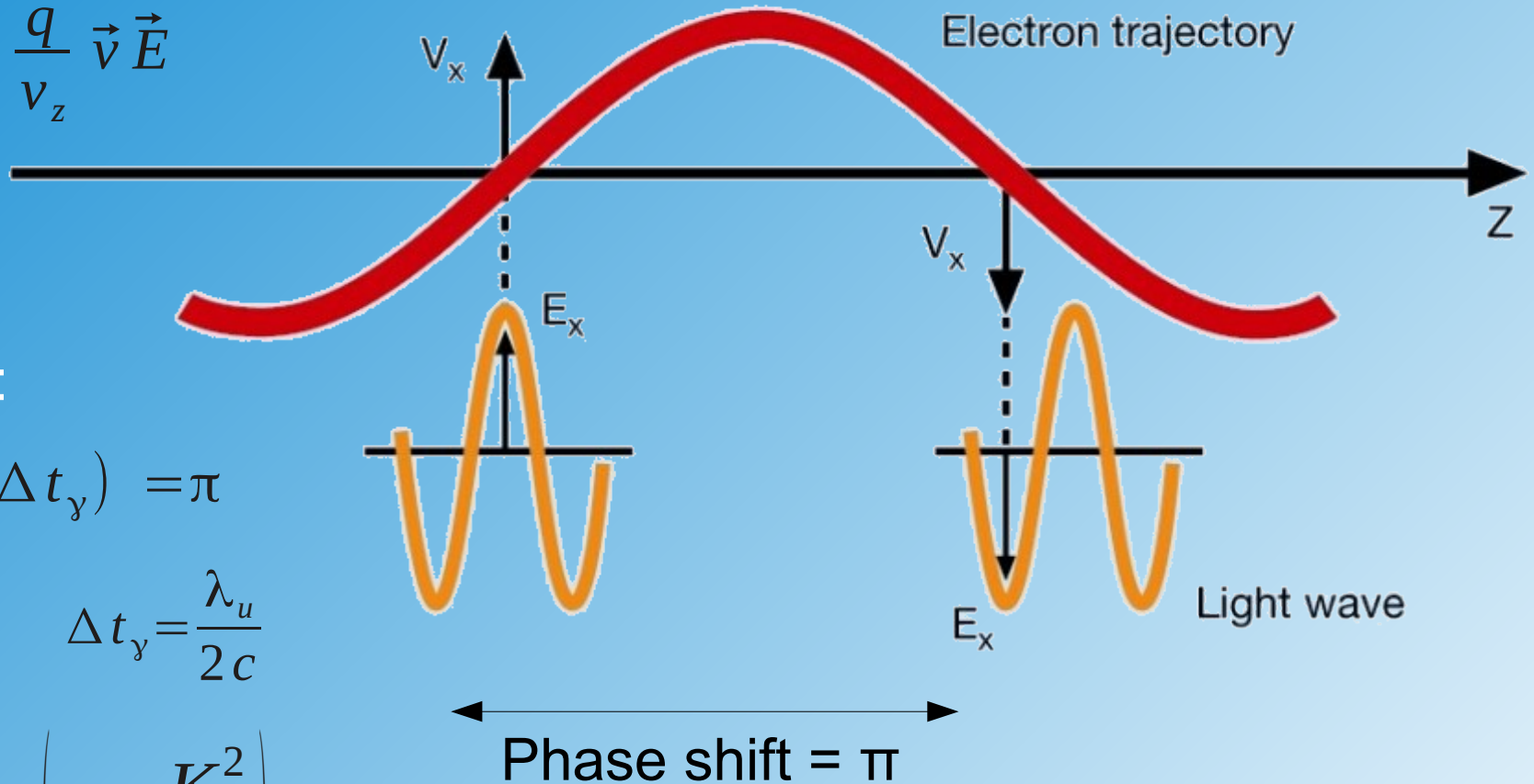
Large K value reduces longitudinal velocity



# Energy Transfer

Energy transfer:

$$\frac{dW}{dz} = \frac{q}{v_z} \vec{v} \vec{E}$$



Condition:

$$\omega_y (\Delta t_e - \Delta t_y) = \pi$$

$$\Delta t_e = \frac{\lambda_u}{2v_z} \quad \Delta t_y = \frac{\lambda_u}{2c}$$

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

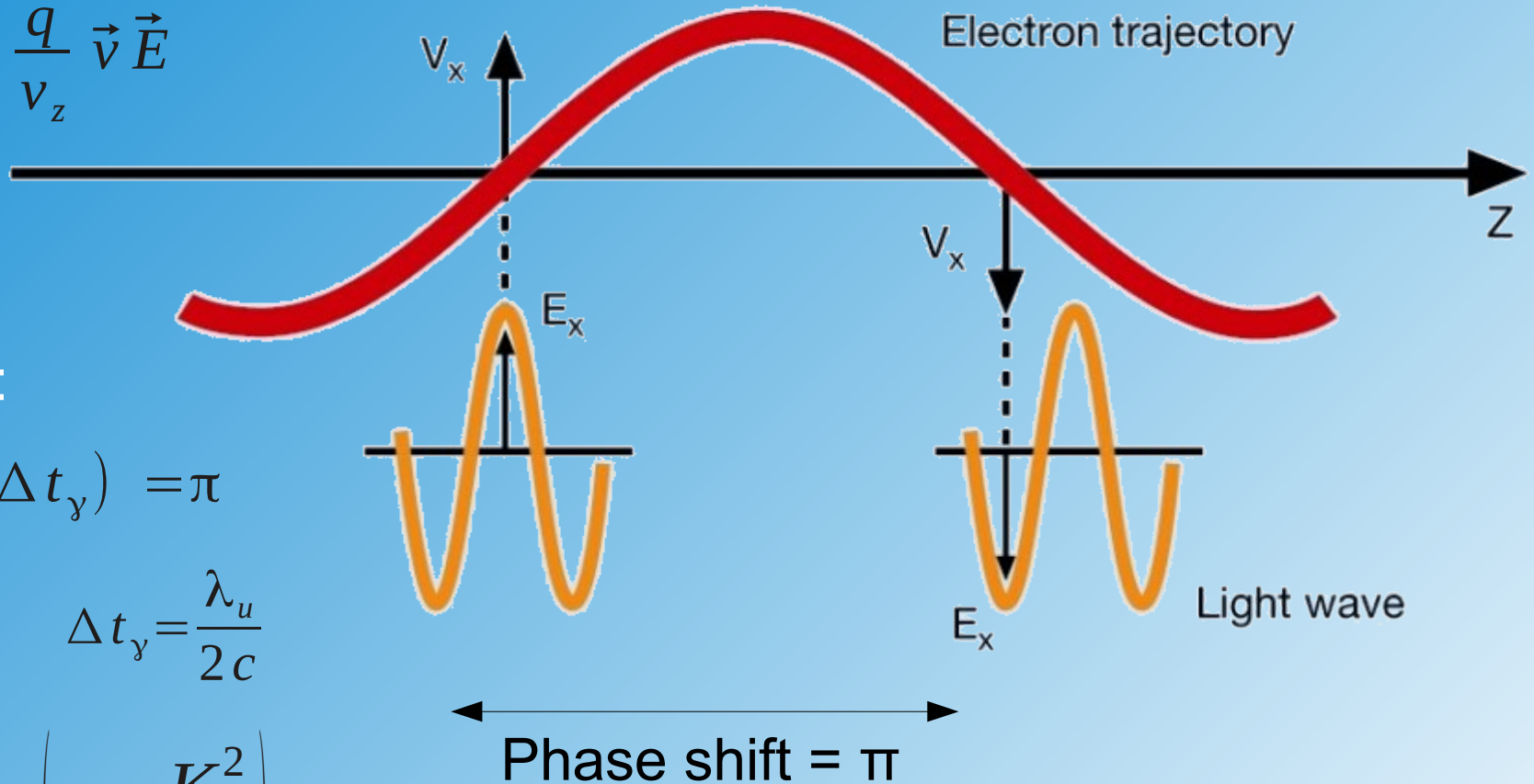
# Superposition



# Energy Transfer

Energy transfer:

$$\frac{dW}{dz} = \frac{q}{v_z} \vec{v} \vec{E}$$



Condition:

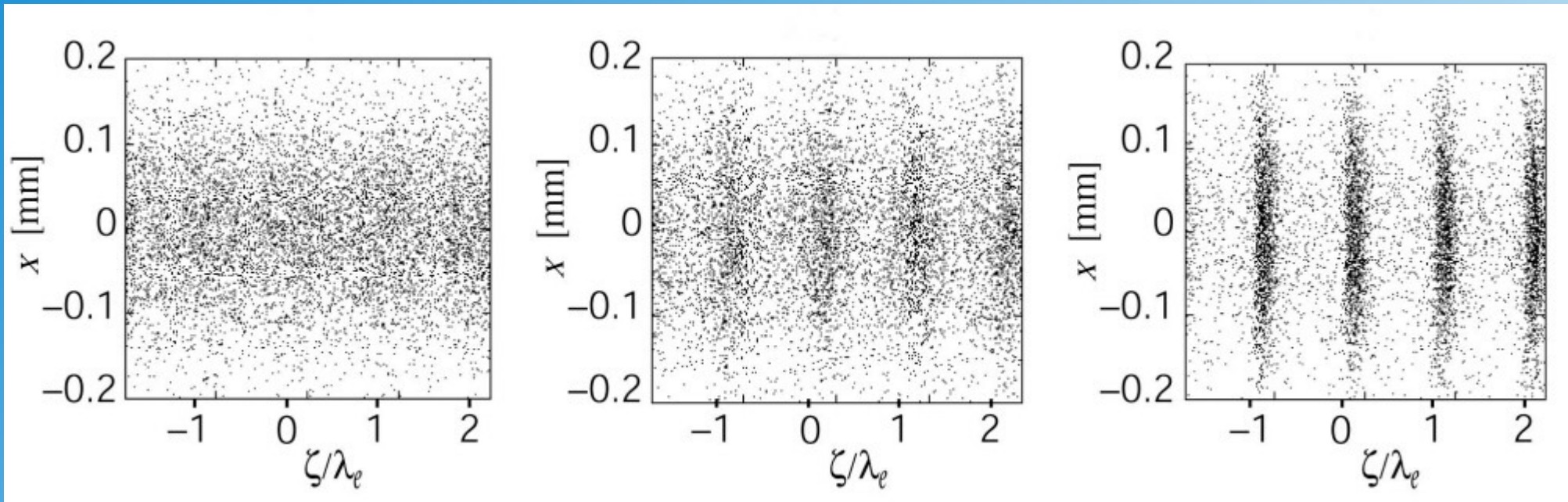
$$\omega_y (\Delta t_e - \Delta t_y) = \pi$$

$$\Delta t_e = \frac{\lambda_u}{2v_z} \quad \Delta t_y = \frac{\lambda_u}{2c}$$

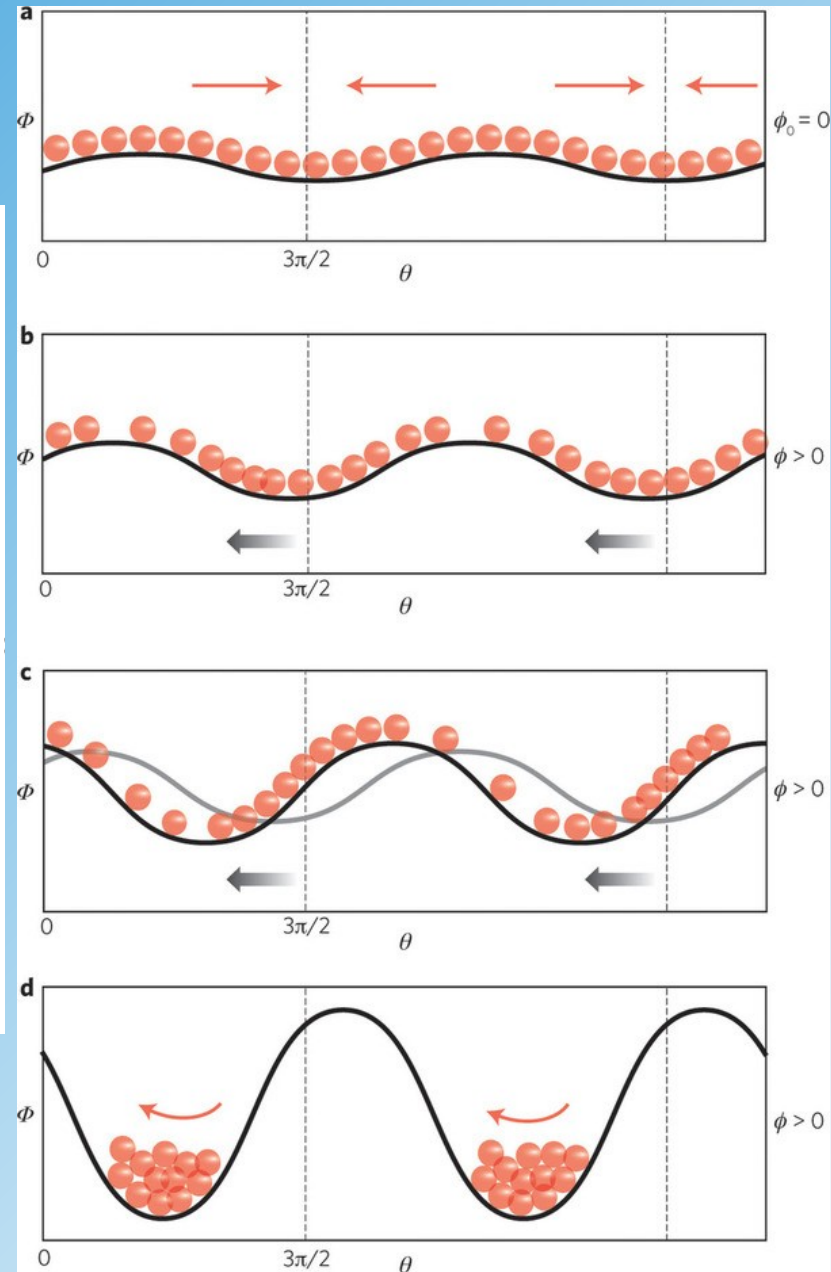
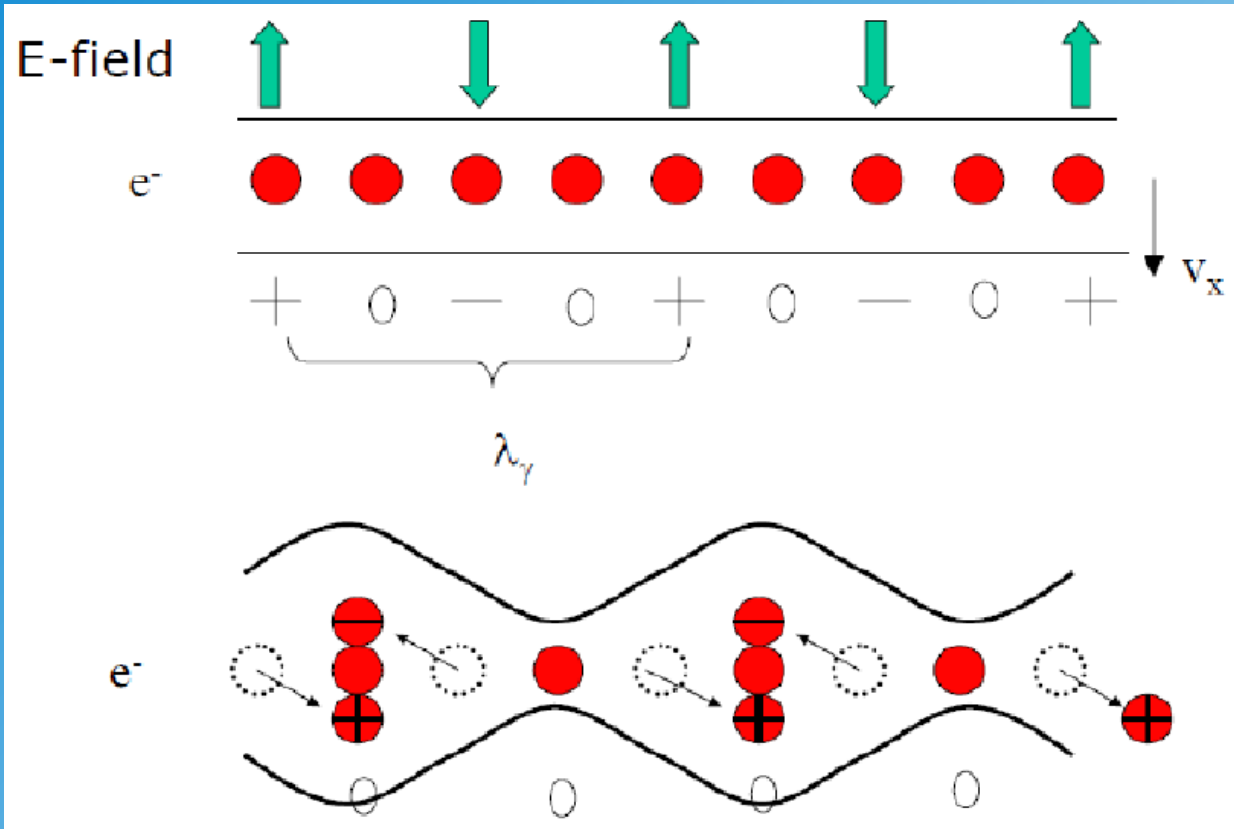
$$\lambda_y = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right)$$

- problem: bunch length  $\sim 50 \mu\text{m} \gg$  photon wave length
- cancellation

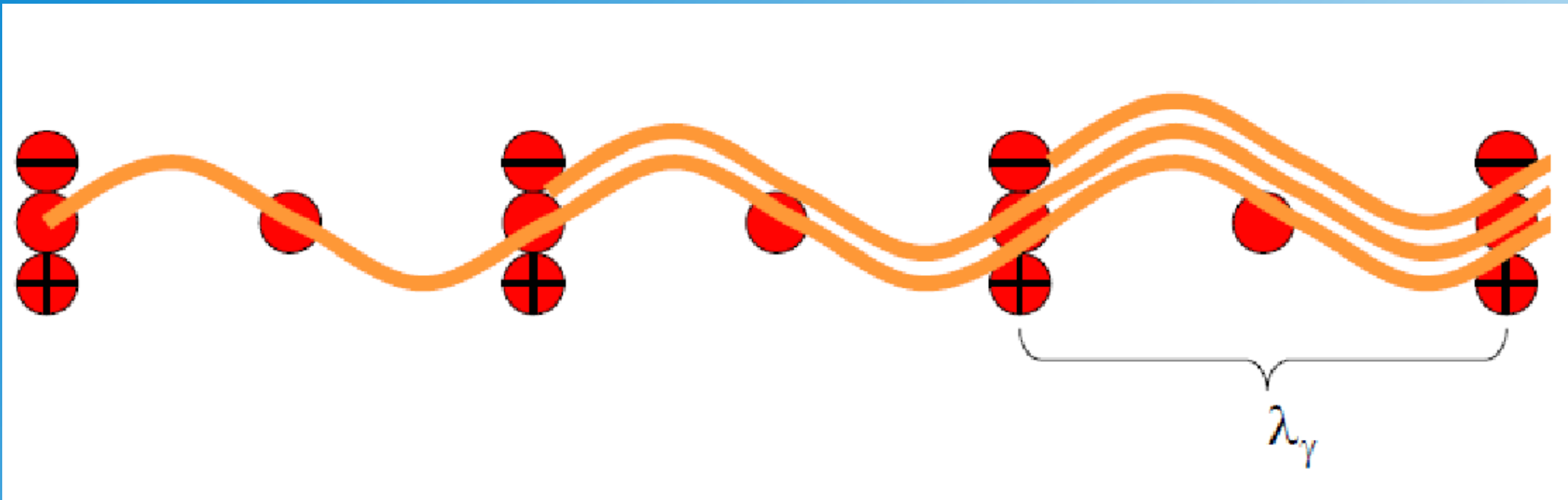
# Microbunching + Self Modulation



# Microbunching Principle



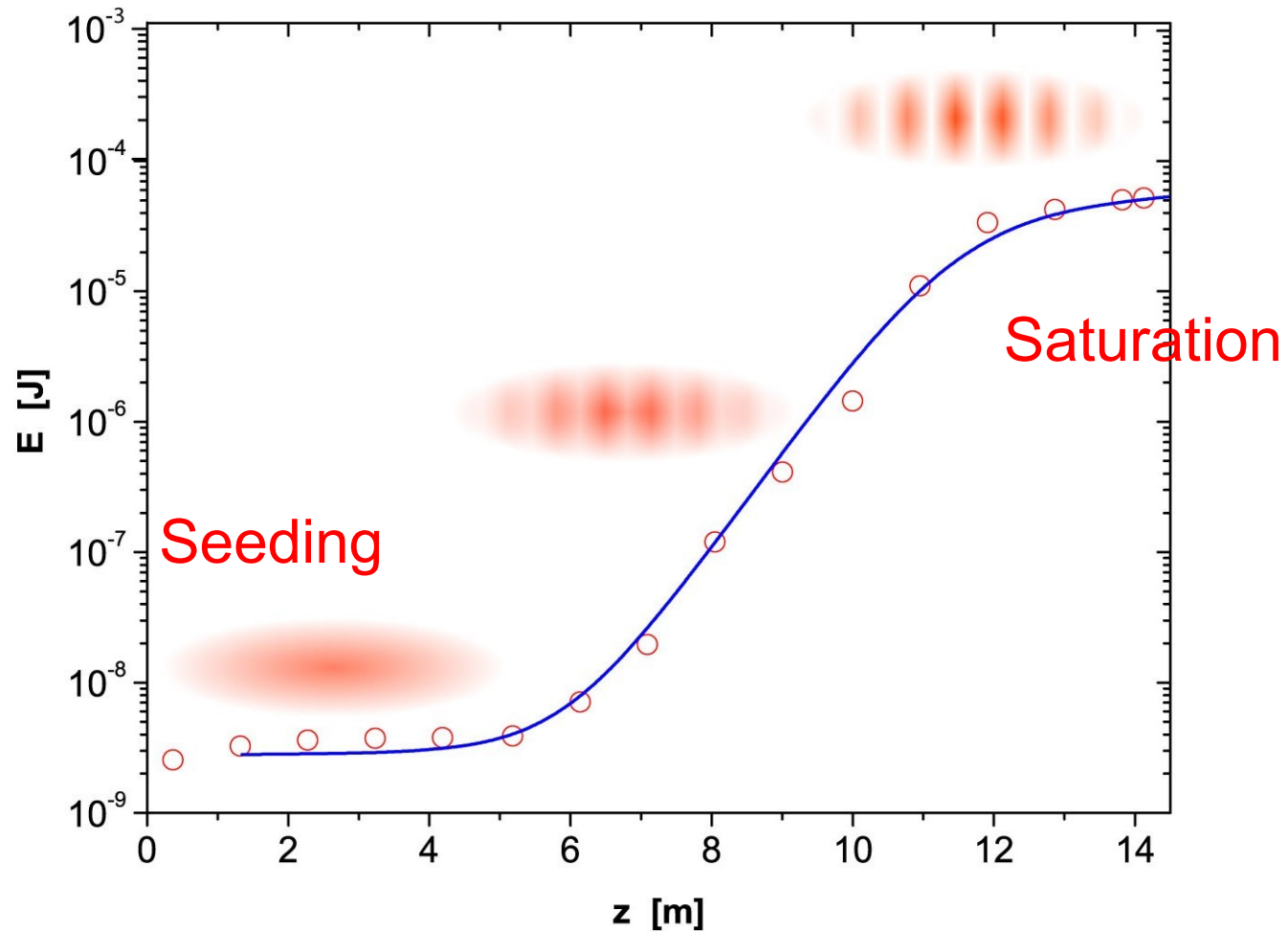
# Superposition



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

Power scales quadratically with number of particles in microbunch

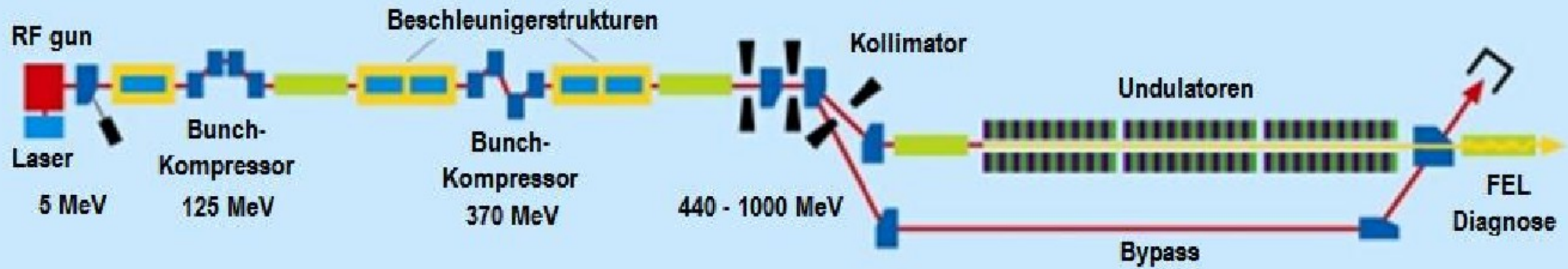
# Self Amplification



Photon Power: 
$$P(z) = A \cdot P_0 \cdot \exp\left(\frac{2z}{L_g}\right)$$



# DESY FLASH (Tesla Test Facility)



FEL:

Energy  $\sim 1$  GeV

Bunchlength  $50 \mu\text{m}$



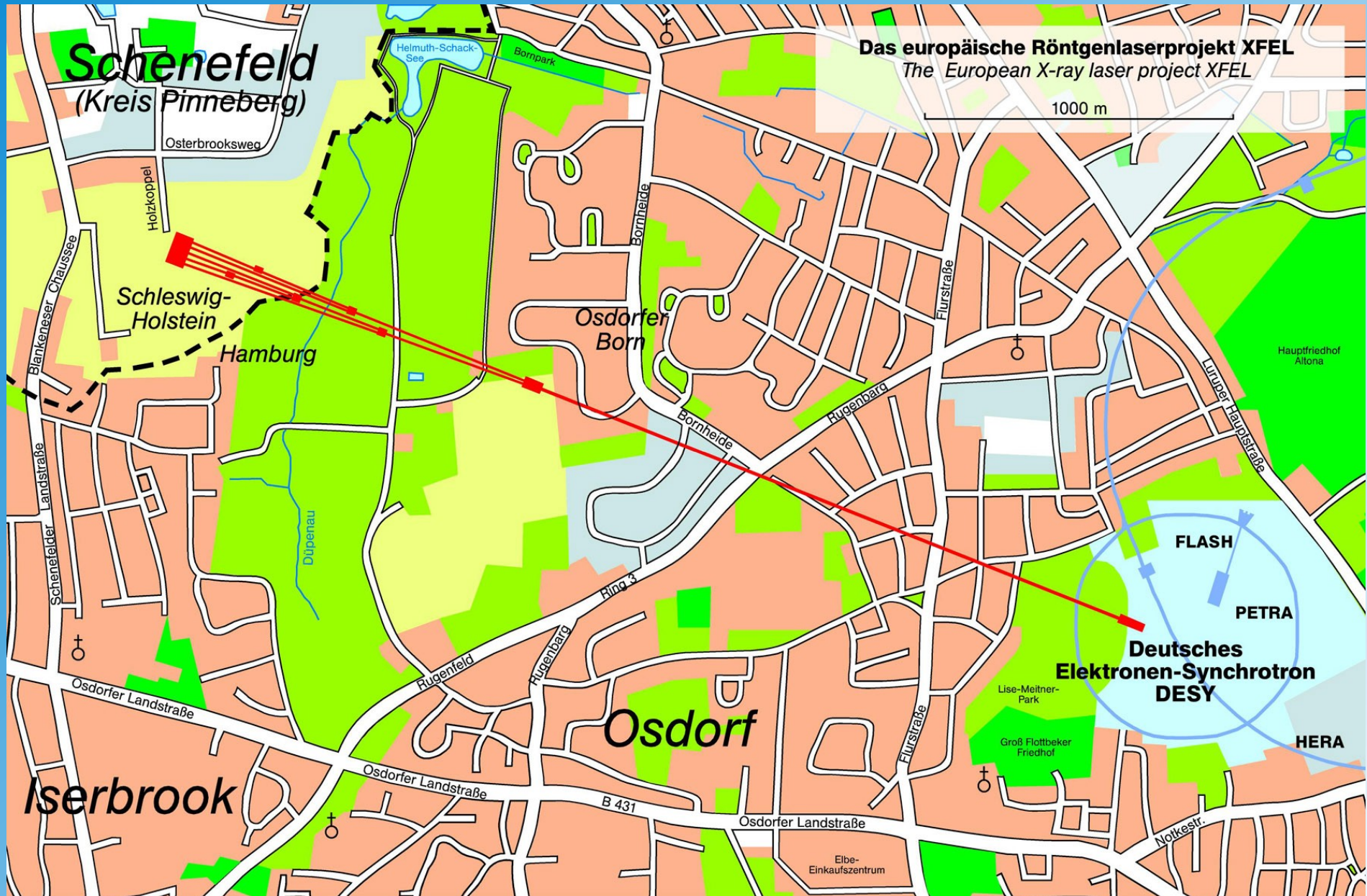
Tesla Cavities



# DESY XFEL (in construction)



# DESY XFEL (20 GeV)



# Comparision XFEL - FLASH

	European XFEL	FLASH	
<b>Abkürzung für</b>	European X-ray Free-Electron Laser (Freie-Elektronen-Laser für Röntgenlicht)	Freie-Elektronen-Laser in Hamburg	
<b>Start der Inbetriebnahme</b>	2014	2004	
<b>Länge des Beschleunigers</b>	1,7 Kilometer	0,15 Kilometer	x11
<b>Länge der Anlage</b>	3,4 Kilometer	0,3 Kilometer	x11
<b>Anzahl der Beschleunigermodule</b>	100	7	x14
<b>Maximale Elektronenenergie</b>	17,5 Milliarden Elektronenvolt	1 Milliarde Elektronenvolt	x17,5
<b>Minimale Wellenlänge des Laserlichts</b>	0,1 Nanometer (Größenordnung eines Atoms)	4,1 Nanometer (Größenordnung eines Moleküls)	x1/41
<b>Zahl der Undulatoren (Magnetstrukturen zur Lichterzeugung)</b>	5	1	
<b>Anzahl der Experimentierplätze</b>	10 vollständig instrumentiert	5	x2
<b>Standort</b>	Hamburg und Schenefeld	Hamburg	
<b>Betreiber</b>	European XFEL GmbH	DESY	

# XFEL Accelerator + Experiments

