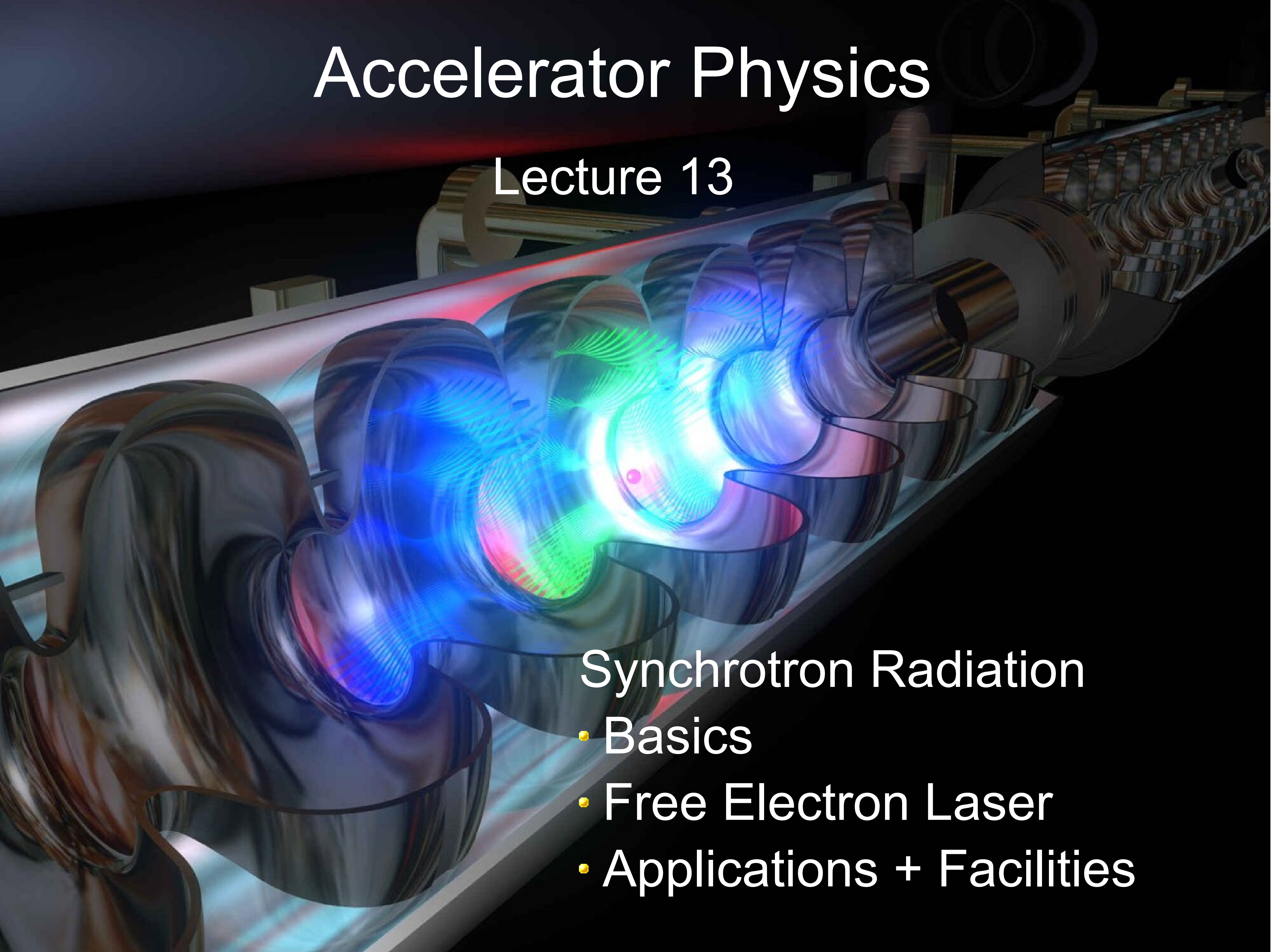


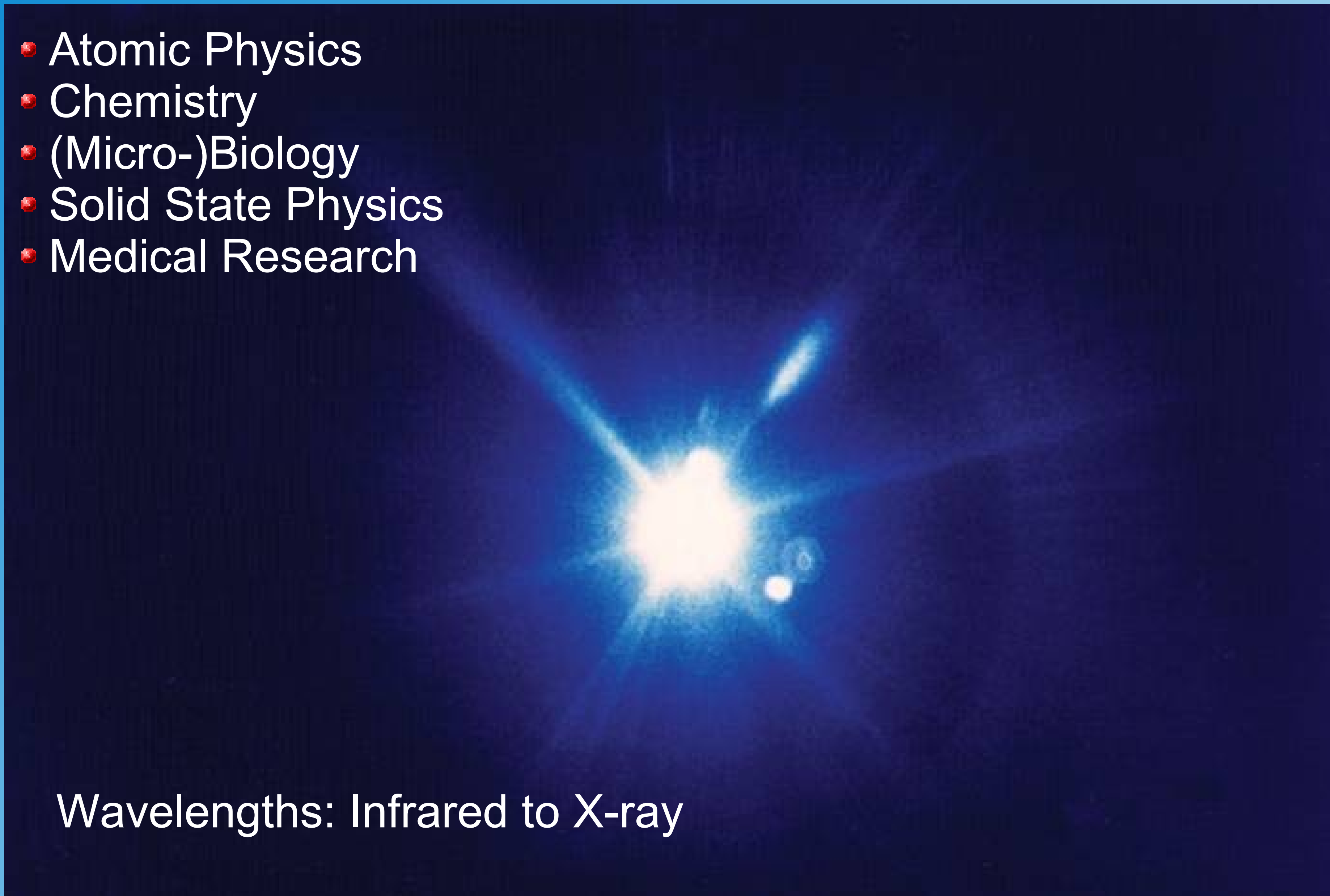
Accelerator Physics

Lecture 13

Synchrotron Radiation

- Basics
- Free Electron Laser
- Applications + Facilities

Synchrotron Radiation



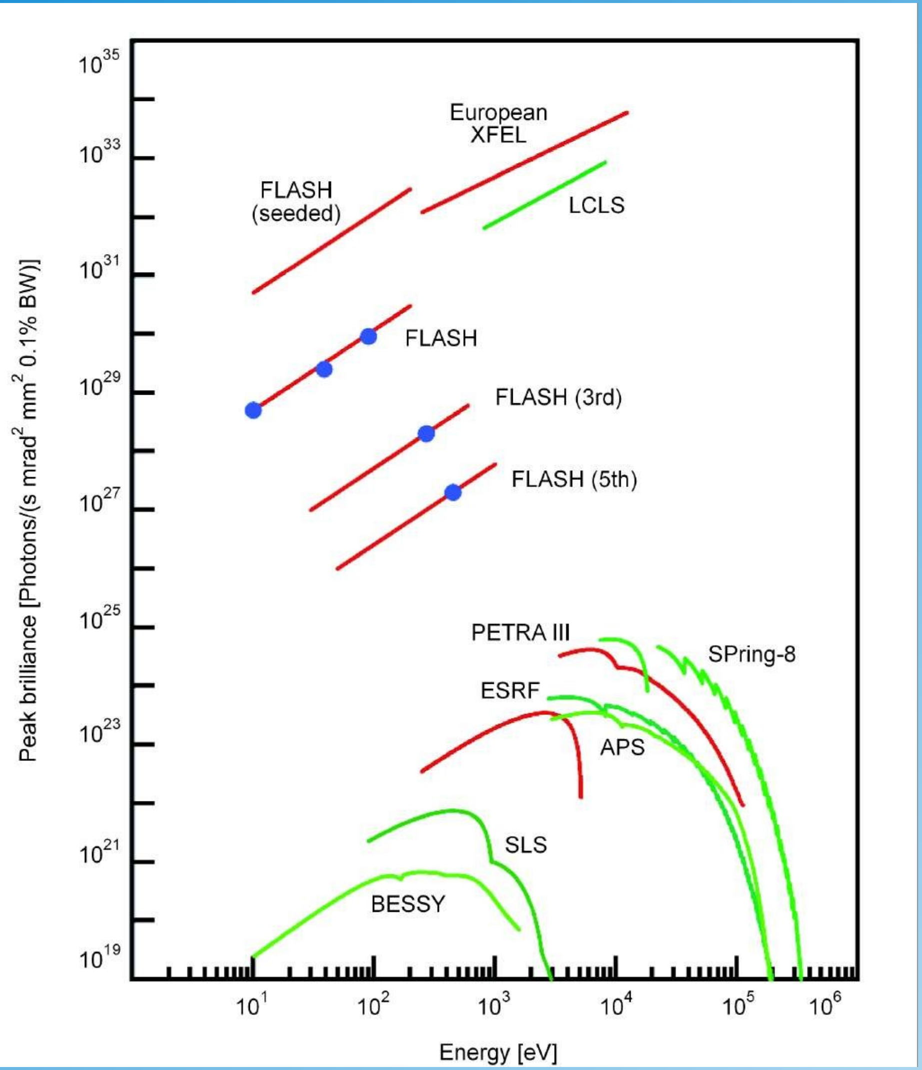
- Atomic Physics
- Chemistry
- (Micro-)Biology
- Solid State Physics
- Medical Research

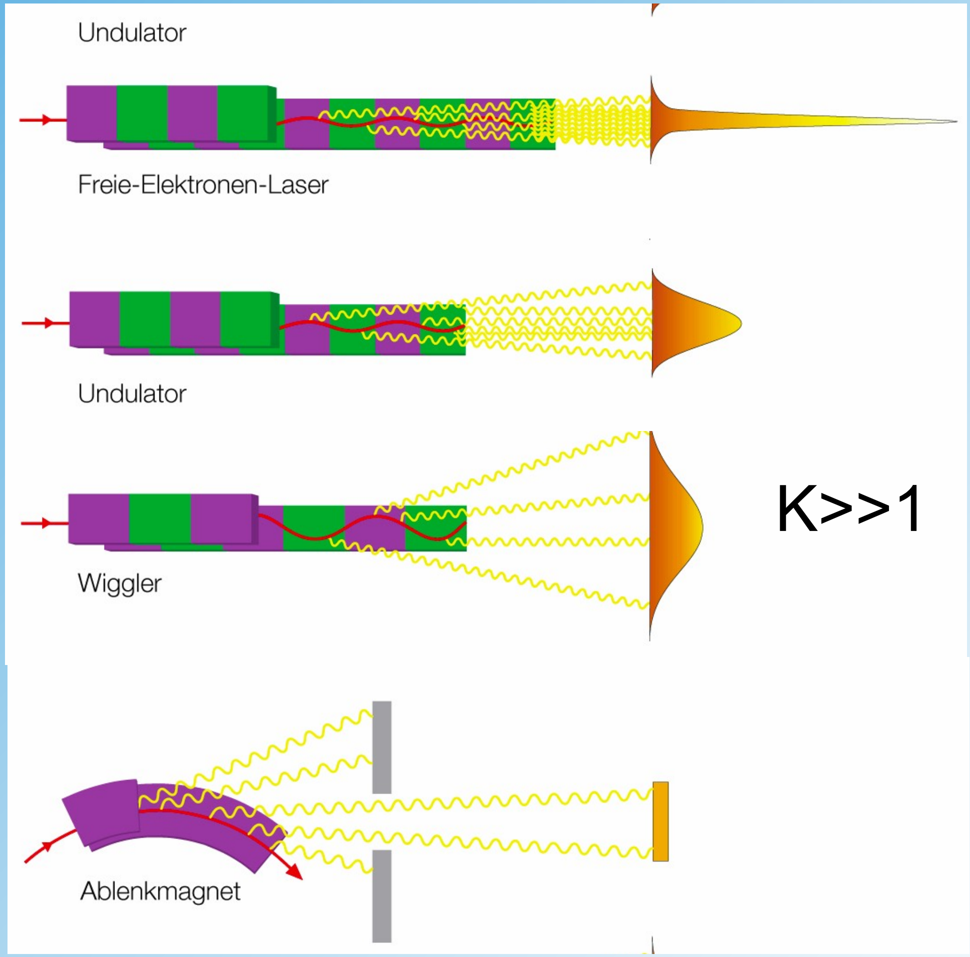
Wavelengths: Infrared to X-ray

“Generations” of Synchrotrons

Brilliance

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



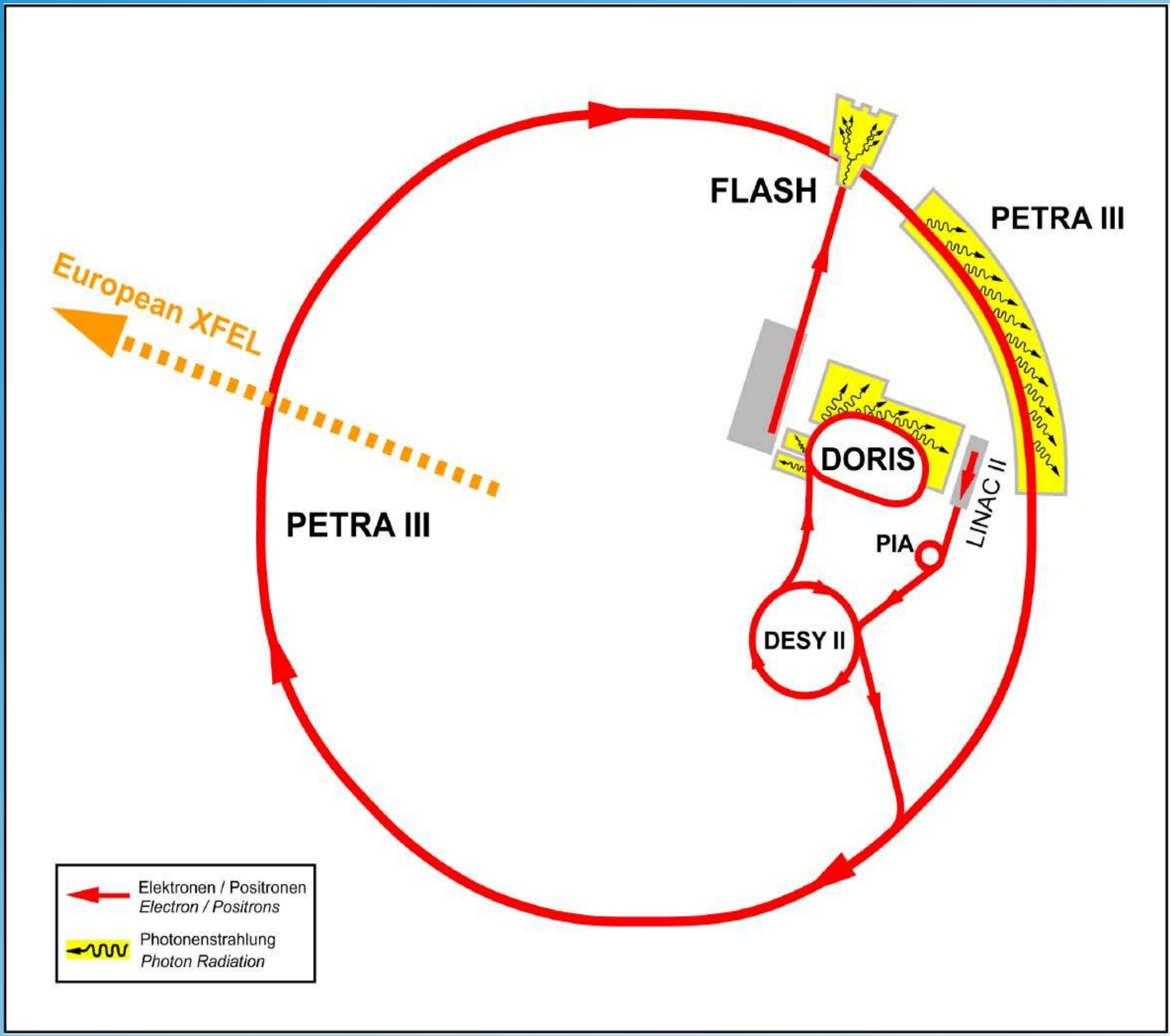


K>>1

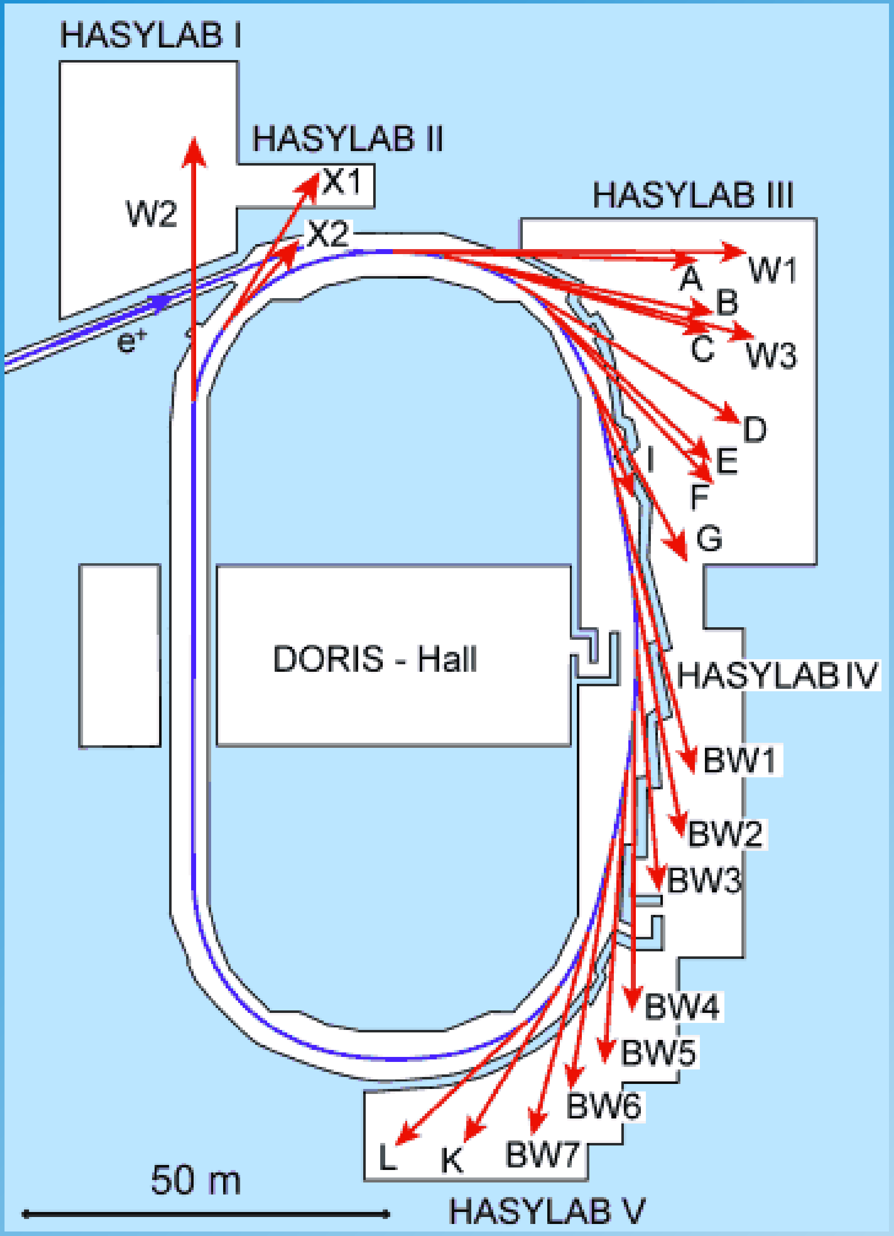
European Synchrotron Radiation Facility (Grenoble)

Swiss Light Source (Schweiz)

DESY Synchrotron Complex



DESY HASYLAB

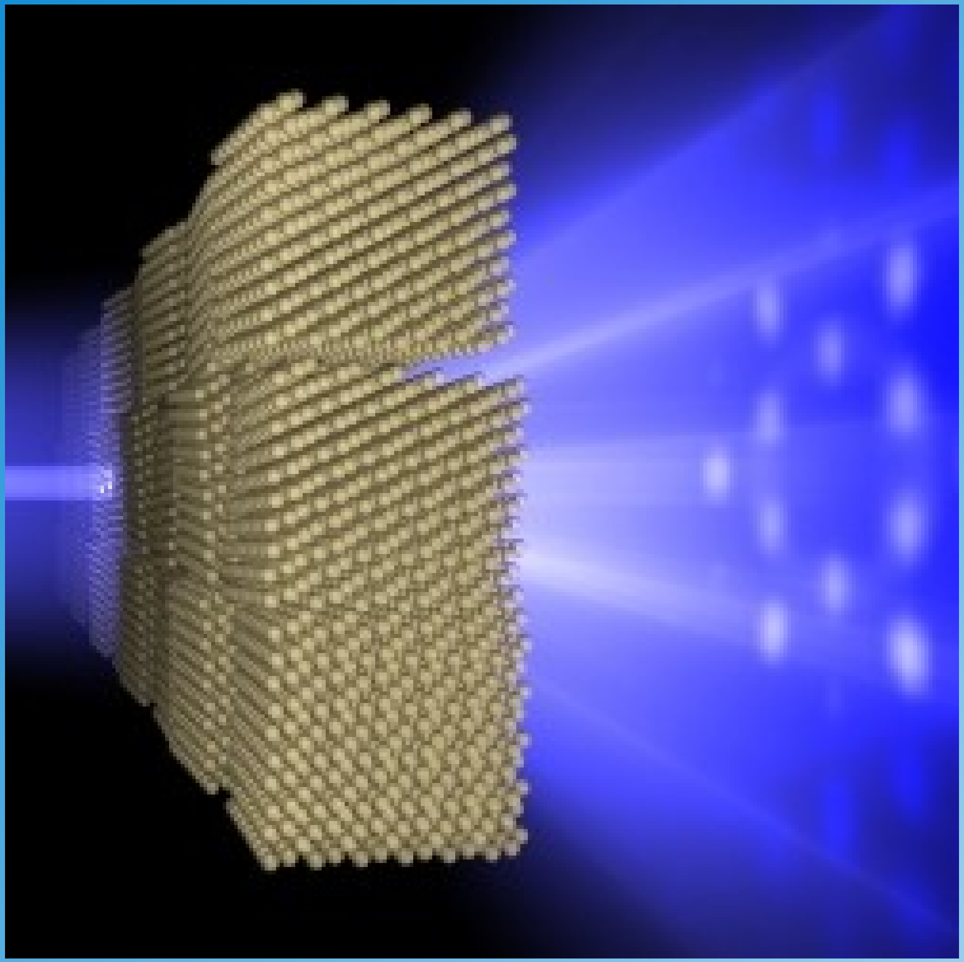


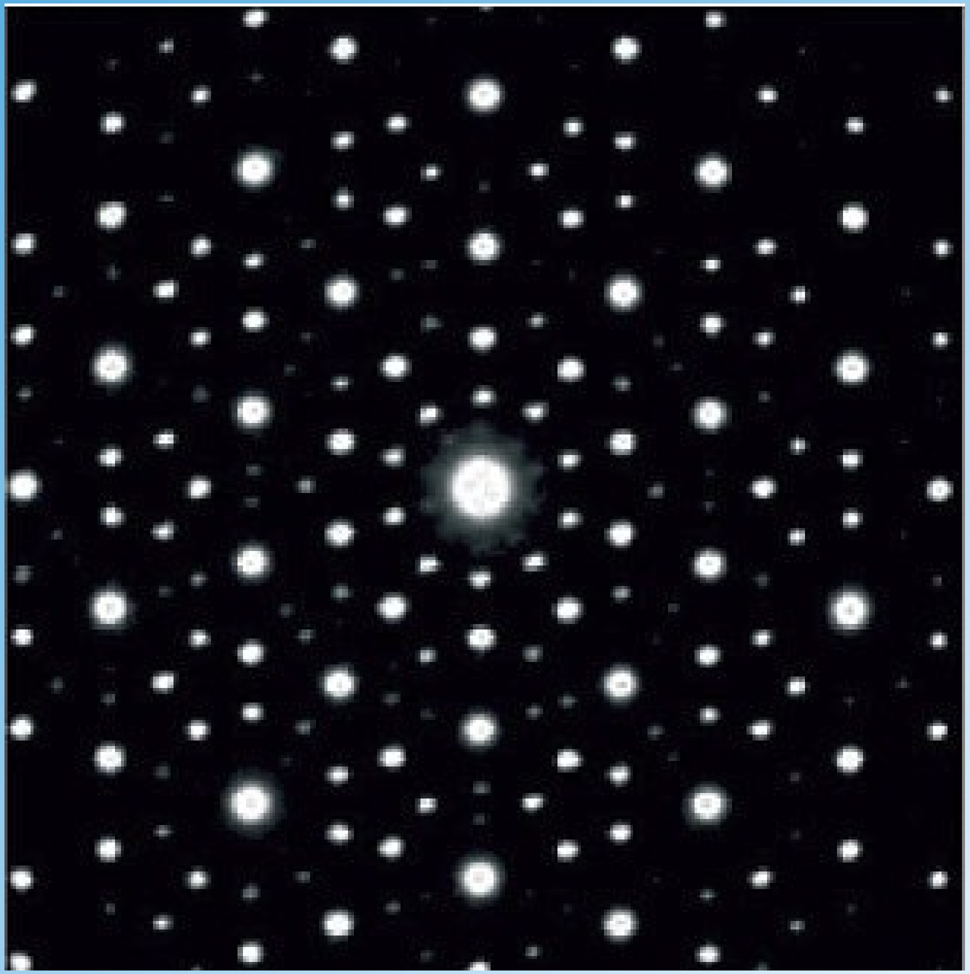
Beamlines for experiments

shutdown 2012


DESY PETRA 3
Biggest monolithic concrete plate in the world

Bragg Scattering in Crystals





- Regular structure (crystal)
- Monchromatic light

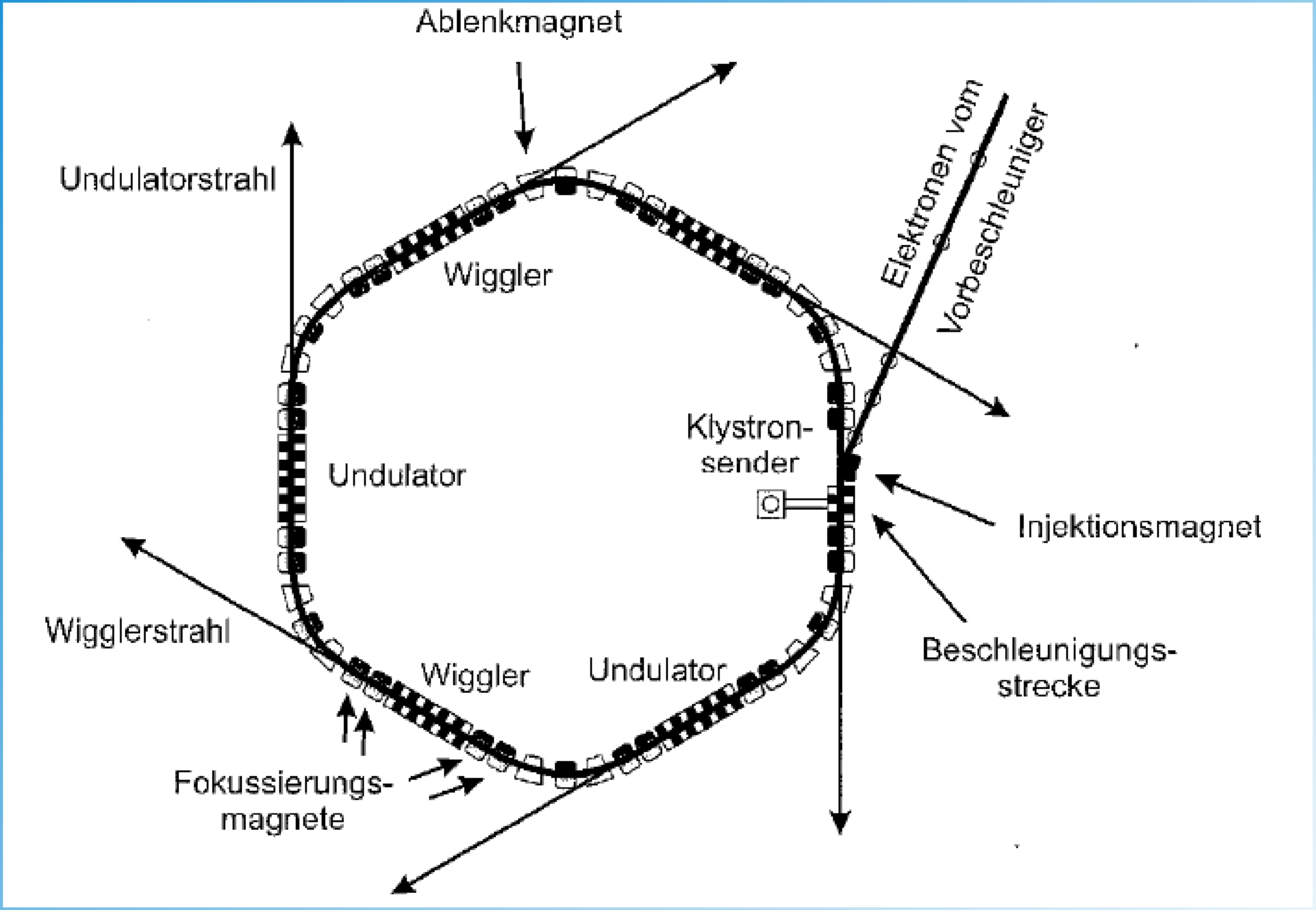
→ Diffractive Pattern

Summary of Facilities

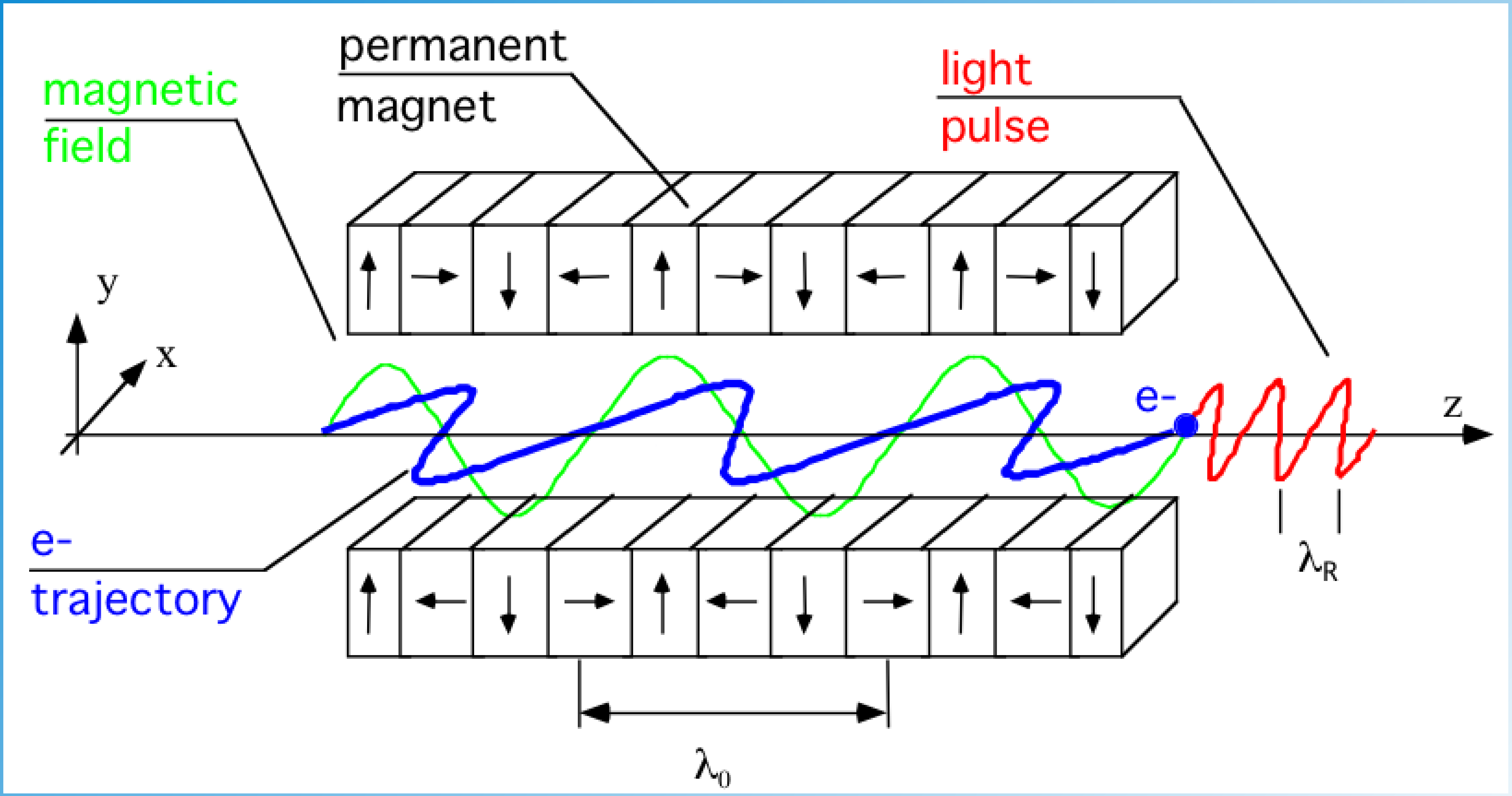
- ANKA (Angströmquelle Karlsruhe)
- Advanced Photon Source in den USA
- NSLS (National Synchrotron Light Source) am Brookhaven National Laboratory, Long Island, USA
- OPTIVUS (Loma Linda University Medical Center in Californien)[1][2] USA
- DESY (Forschungszentrum Deutsches Elektronen-Synchrotron)
- 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

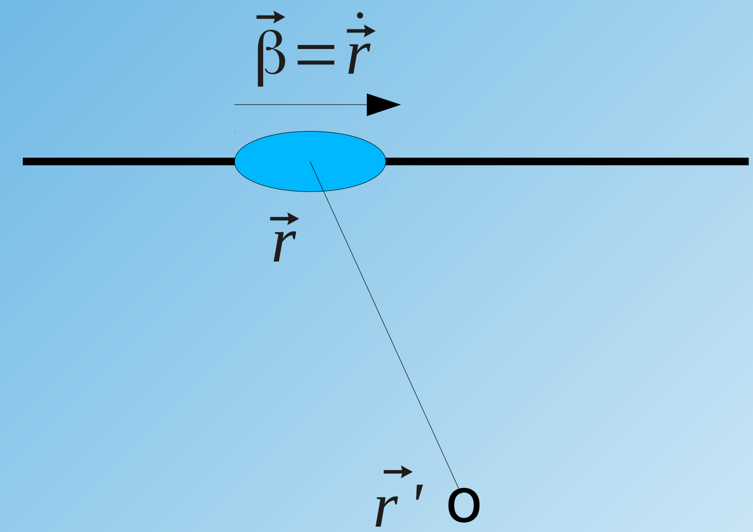


Wiggler / Undulator



Synchrotron Radition Calculation

Moving electron bunch:



From Maxwell Equations:

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

Solved using retarded Green-Functions

Lienard-Wiechert potential:

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

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

E.M. Fields:

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

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

Synchrotron Power

Poynting Vector

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

Radiated power per solid angle

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

- integration

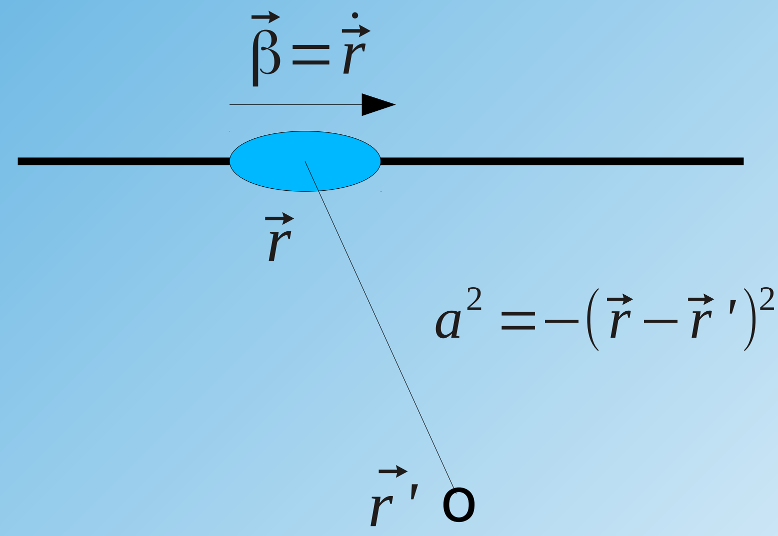
$$P = \frac{2\,q}{3\,c\,(1-\beta)^3}\,(\dot{\vec{\beta}}^2 - |\vec{\beta}\times\dot{\vec{\beta}}^2|)$$

Radiation power in ring accelerator:

$$P = \frac{2\,q\,E^4}{3\,(m\,c^2)^4\,R^2}$$

R = *radius*

Moving electron bunch:



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

Synchrotron Energy Spectrum

via Fourier Transformation of time dependece:

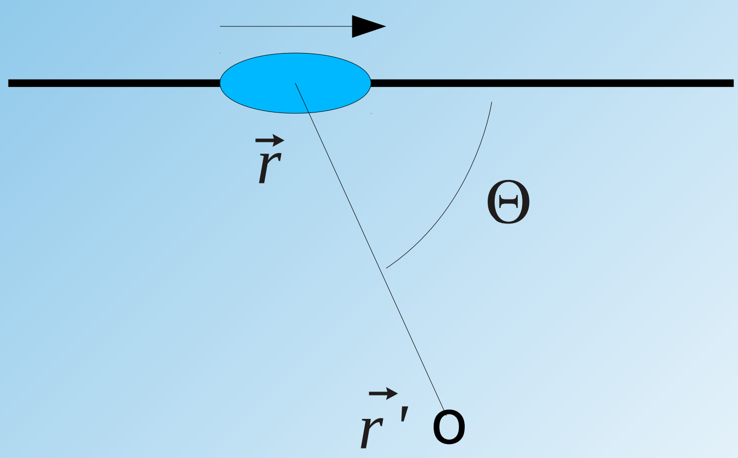
$$\frac{dE}{d\omega\, d\Omega} = \frac{q^2 a^2 \omega^2}{3\pi^2 c^3} \left(\frac{1}{\gamma^2} + \Theta^2\right)^2 \left[K^2_{2/3}(\xi) + \frac{(\gamma^2\Theta^2)}{1+\gamma^2\Theta^2} K^2_{1/3}(\xi)\right]$$

$\omega = frequency$

$\Theta = radiation\ angle$

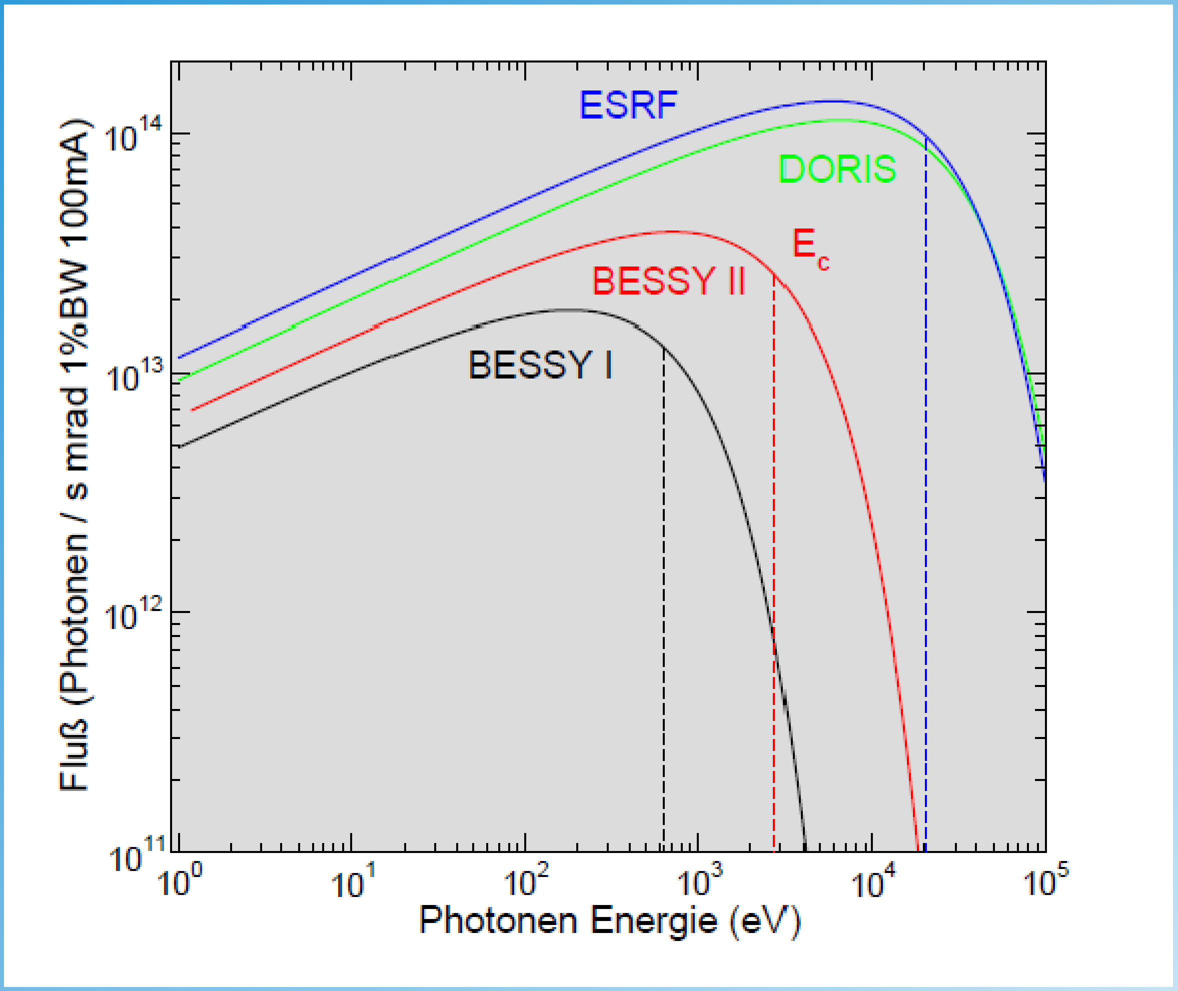
$K_\nu = modified\ Bessel\ function$

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



Energyspectrum

Power law

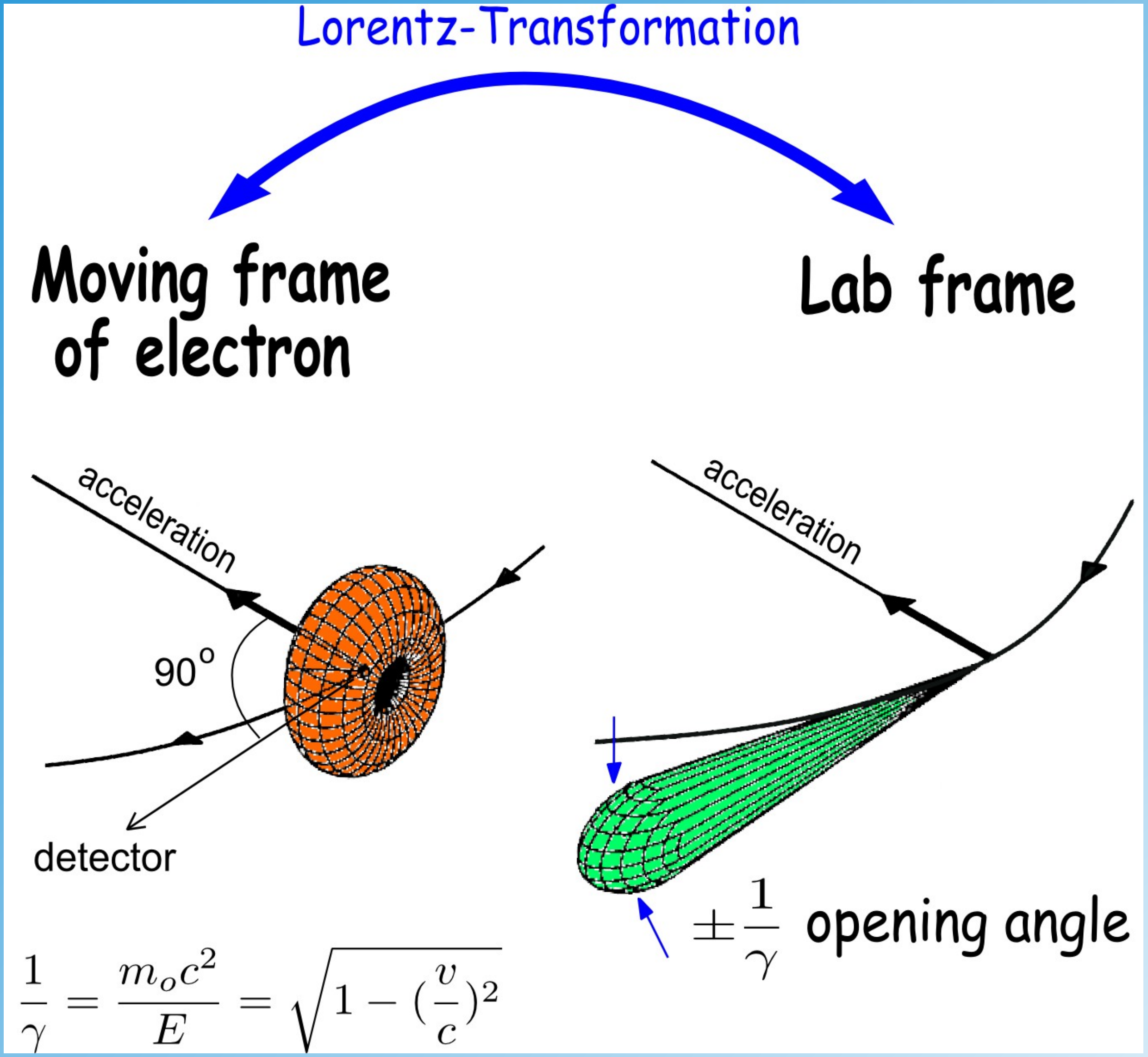


Exponential fall

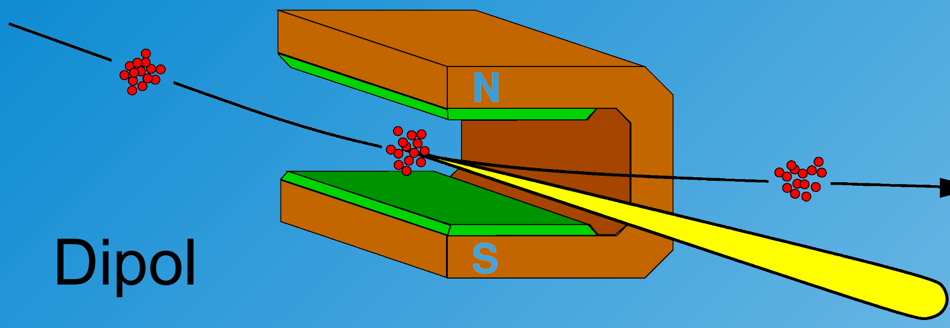
Energy distribution
described by mod. Bessel Function

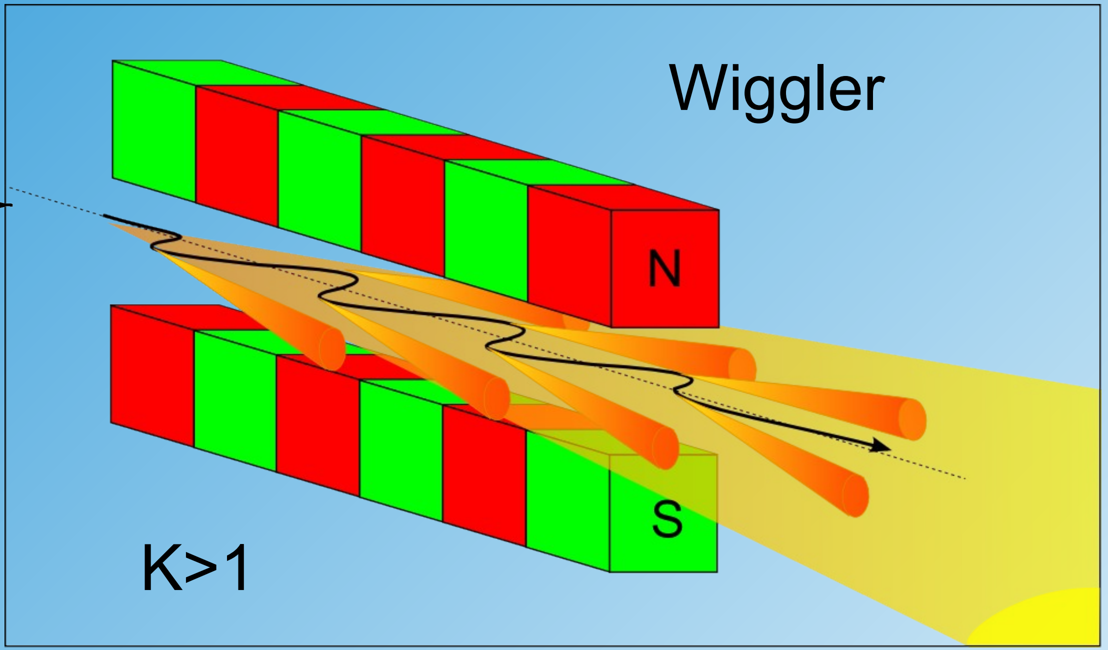
$$\omega_c = \frac{1}{2}\frac{3c\gamma^3}{R}$$

Syncrotron Radiation Cone

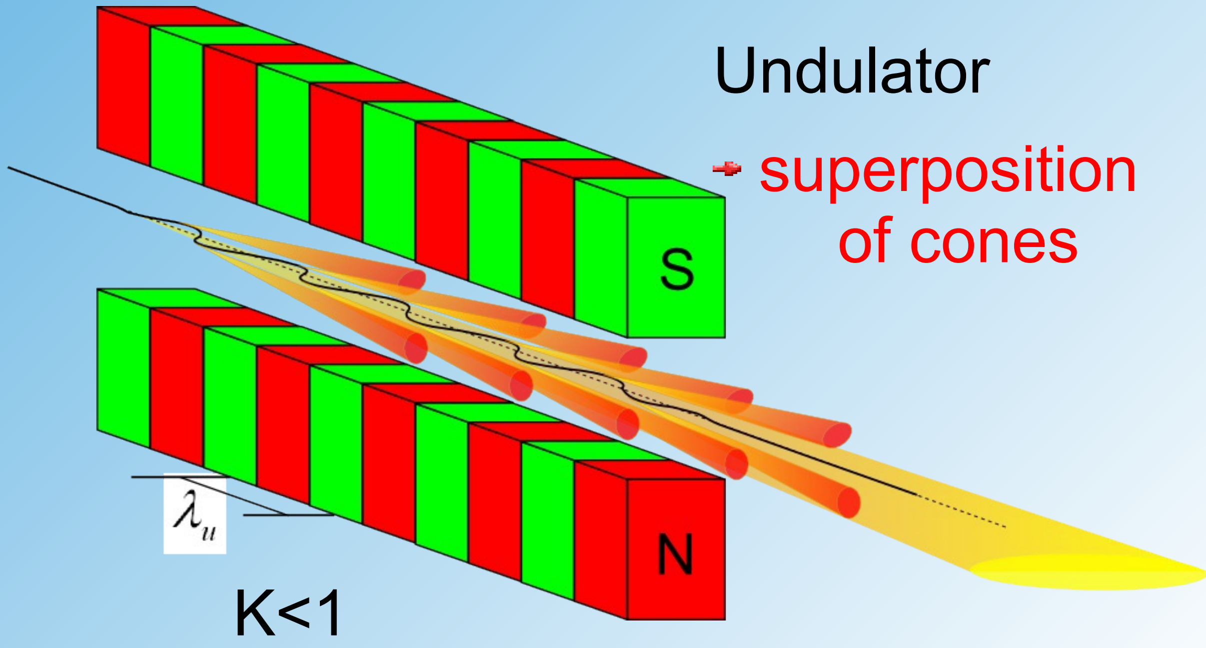


Undulator versus Wiggler I





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



Undulator Parameter

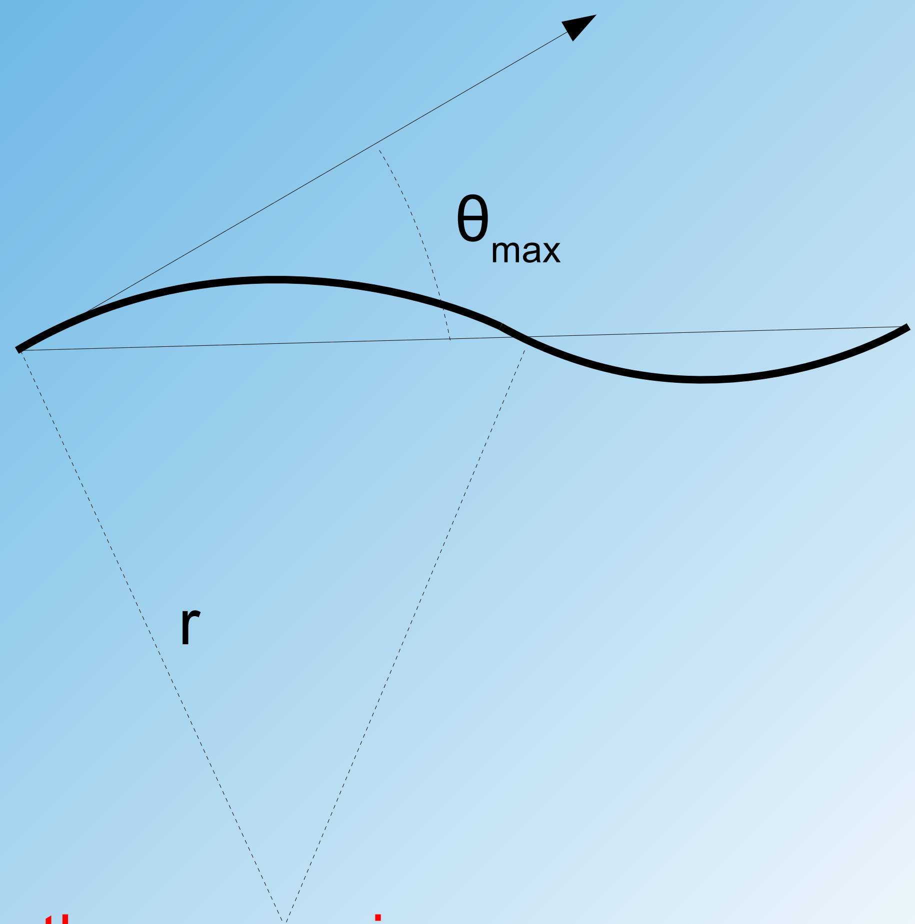
Characteristic Parameter

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

Relation to radiation angle

$$p = e R B$$

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

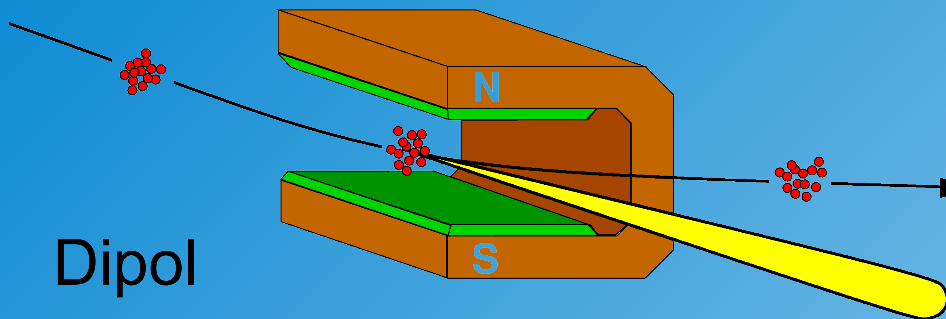


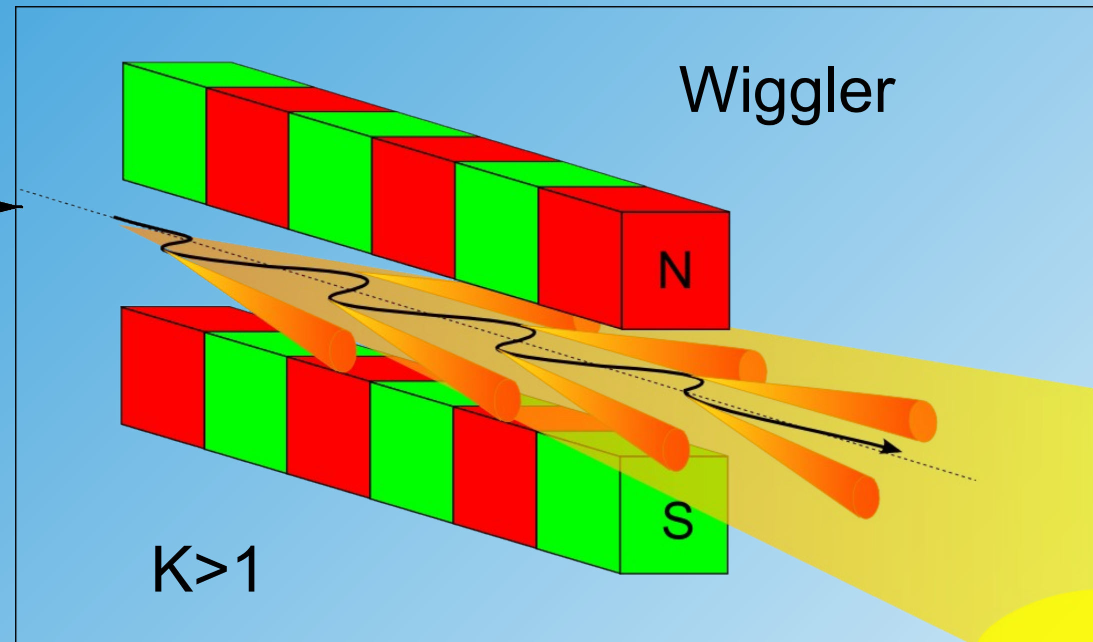
Insertion

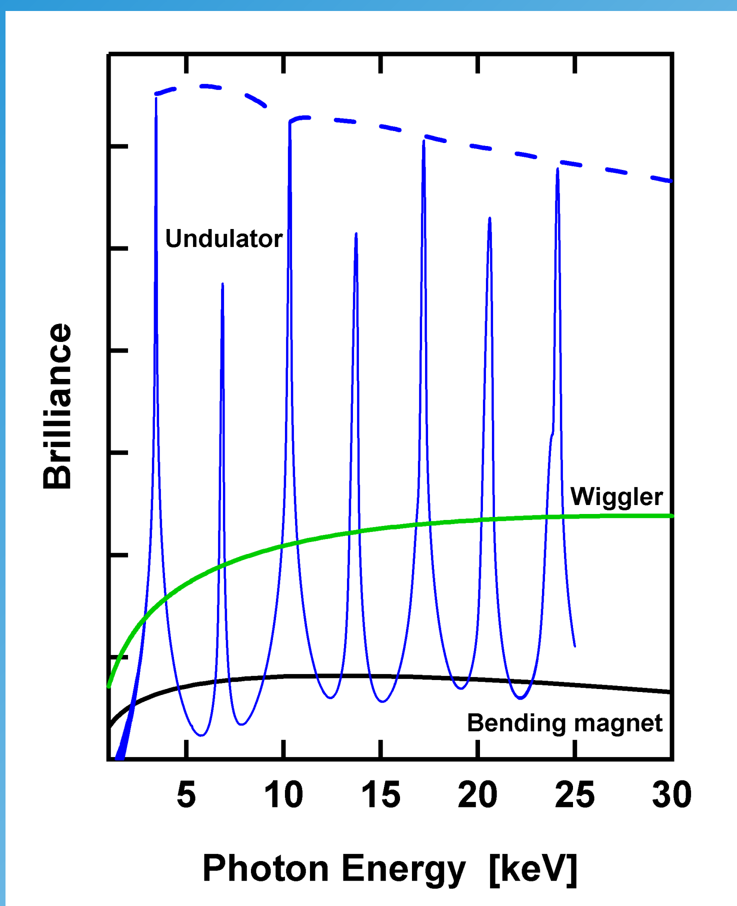
$$K = 4\theta_{max}\gamma$$

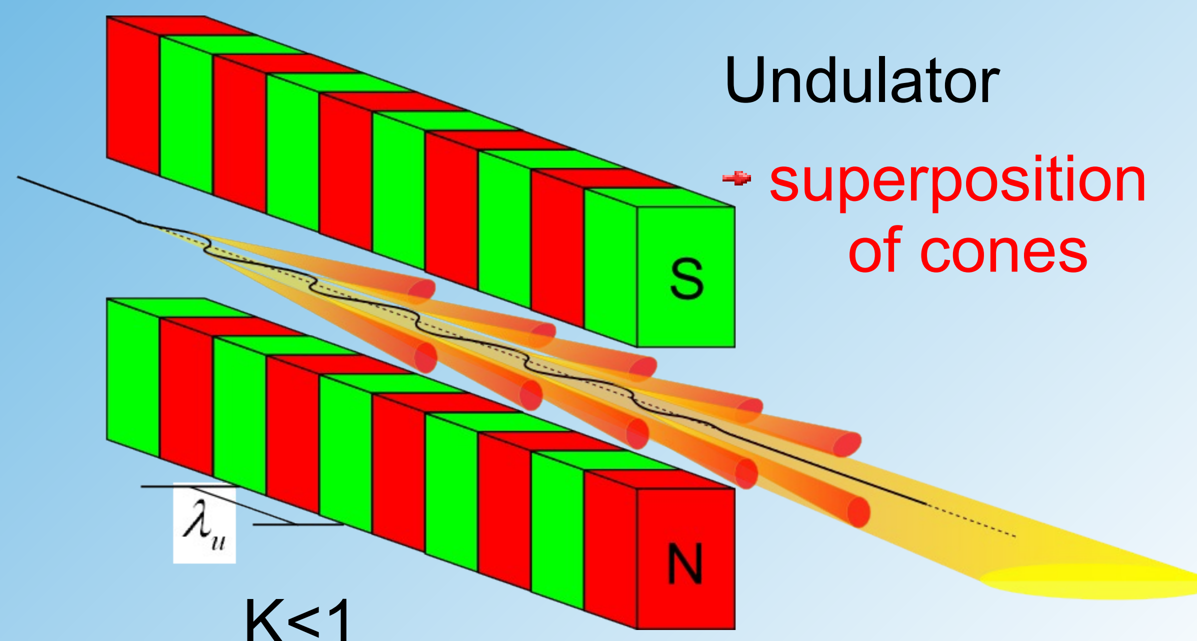
If K>1, synchr. Radiation fan larger than cone size

Undulator versus Wiggler I







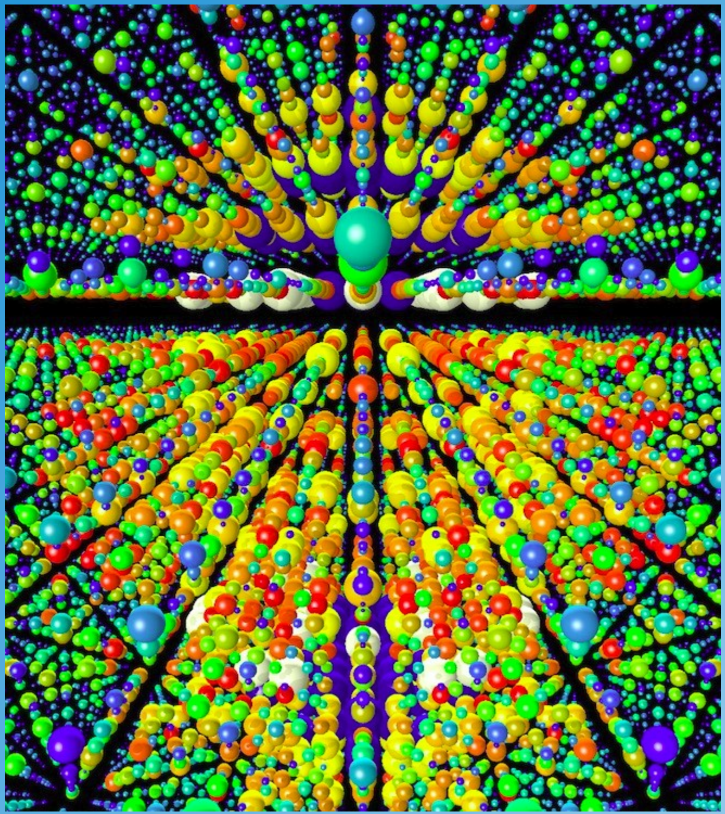


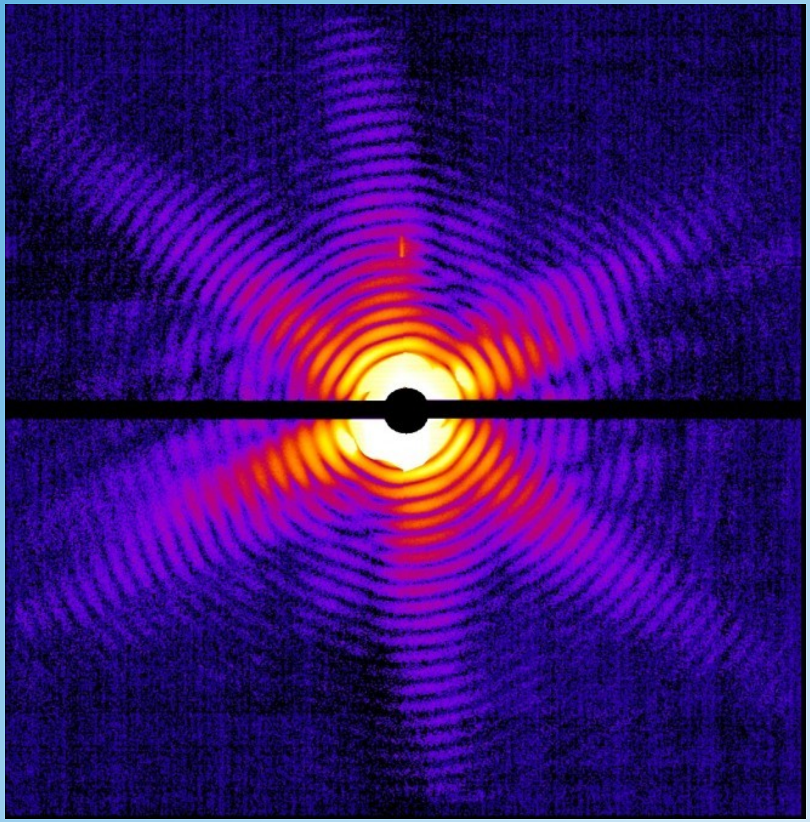
Free Electron Lasers (FEL)

- 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

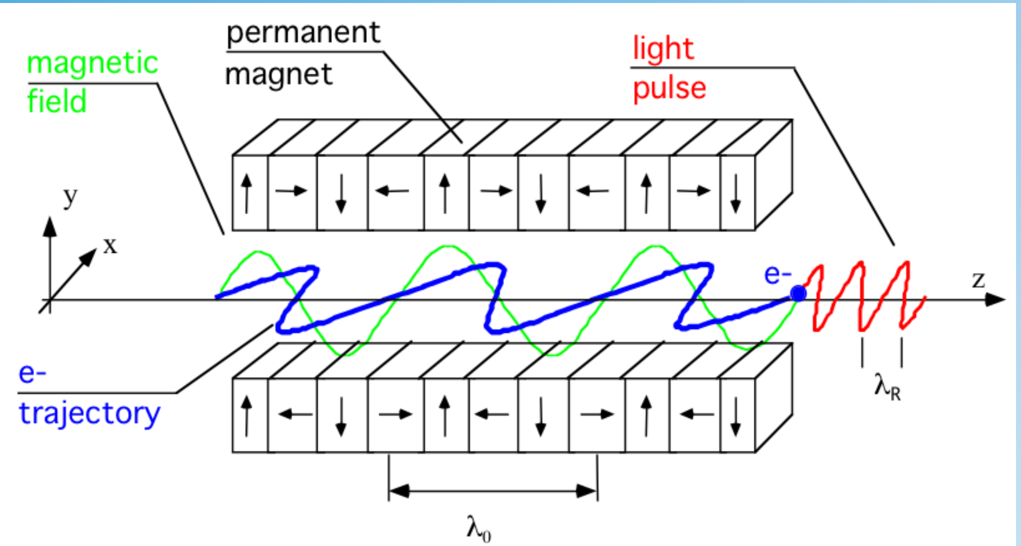




Possible to study irregular structures (virus)

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

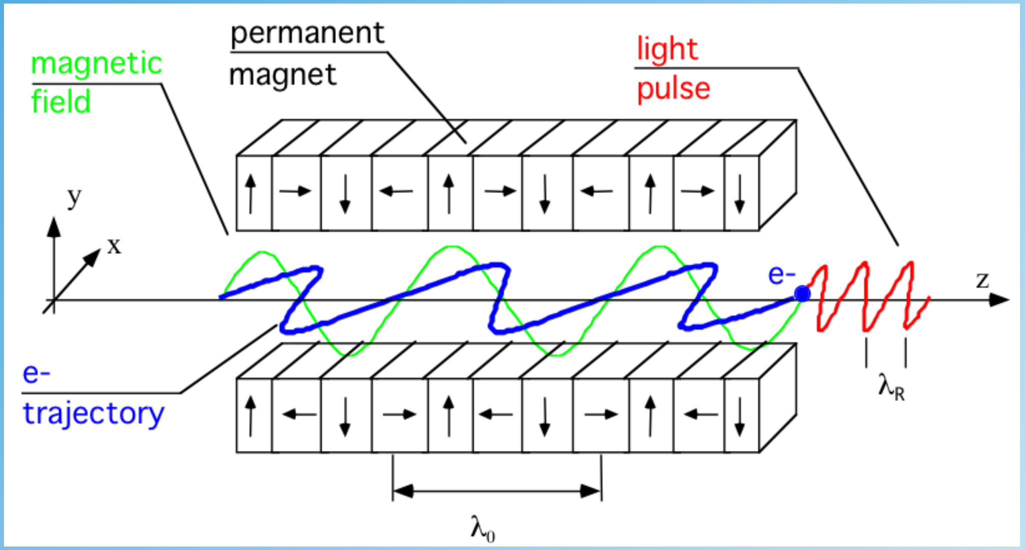
$$\ddot{x} = \frac{e}{\gamma m_e} B_y \dot{z} \qquad \ddot{z} = \frac{-e}{\gamma m_e} B_y \dot{x}$$

Usual approximations: $v_x \ll v_z$ $\quad v_z \approx v$

Solution:

$$x = \frac{K}{\beta \gamma k_u} \sin(k_u z) \qquad K = \frac{eB}{m_e c k_u}$$

Electron Velocities



Total velocity

$$v = \beta c$$

x-projection

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

z-projection

$$v_z = \sqrt{v^2 - v_x^2} \qquad \bar{v}_z = \sqrt{v^2 - \overline{v_x^2}}$$

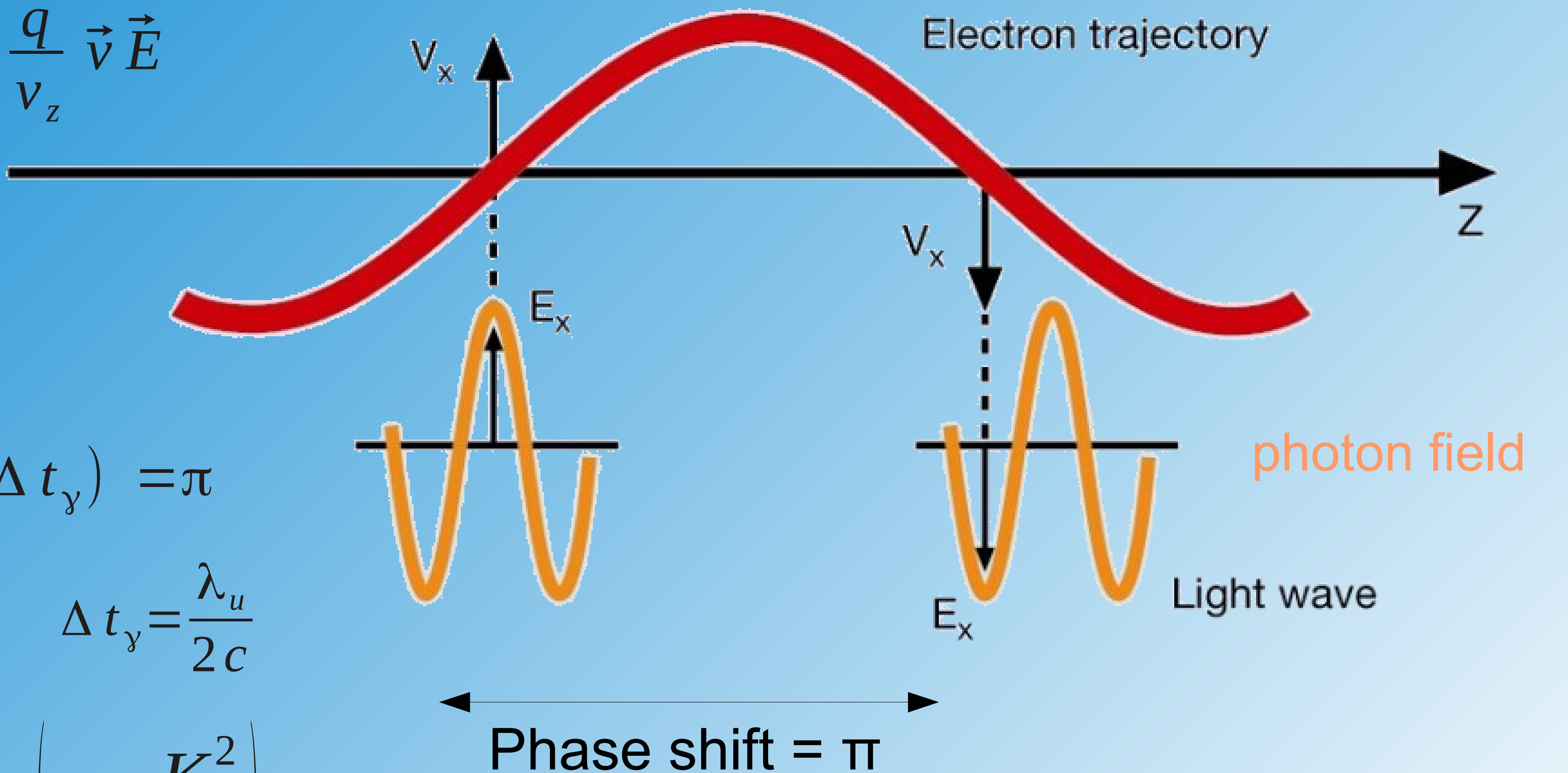
$$\rightarrow \quad \bar{v}_z \approx c\left[1 - \frac{1}{\gamma^2}\left(1 + \frac{K^2}{2}\right)\right]$$

Large K value reduces longitudinal velocity

Energy Transfer between Electrons and Photons

Energy transfer:

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



Condition:

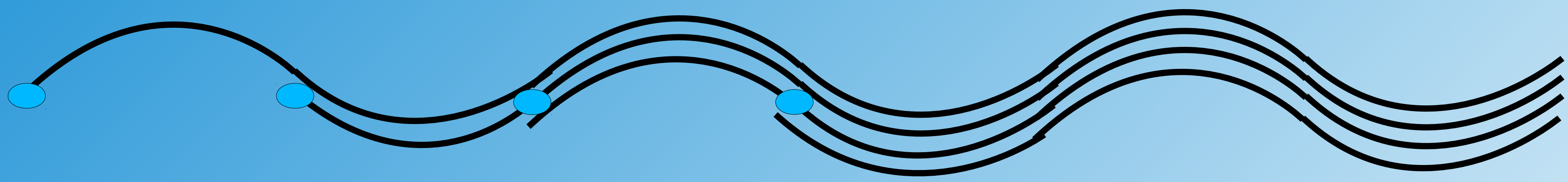
$$\omega_\gamma(\Delta t_e - \Delta t_\gamma) = \pi$$

$$\Delta t_e = \frac{\lambda_u}{2\overline{v_z}} \qquad \Delta t_\gamma = \frac{\lambda_u}{2c}$$

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

elecrons gain speed!

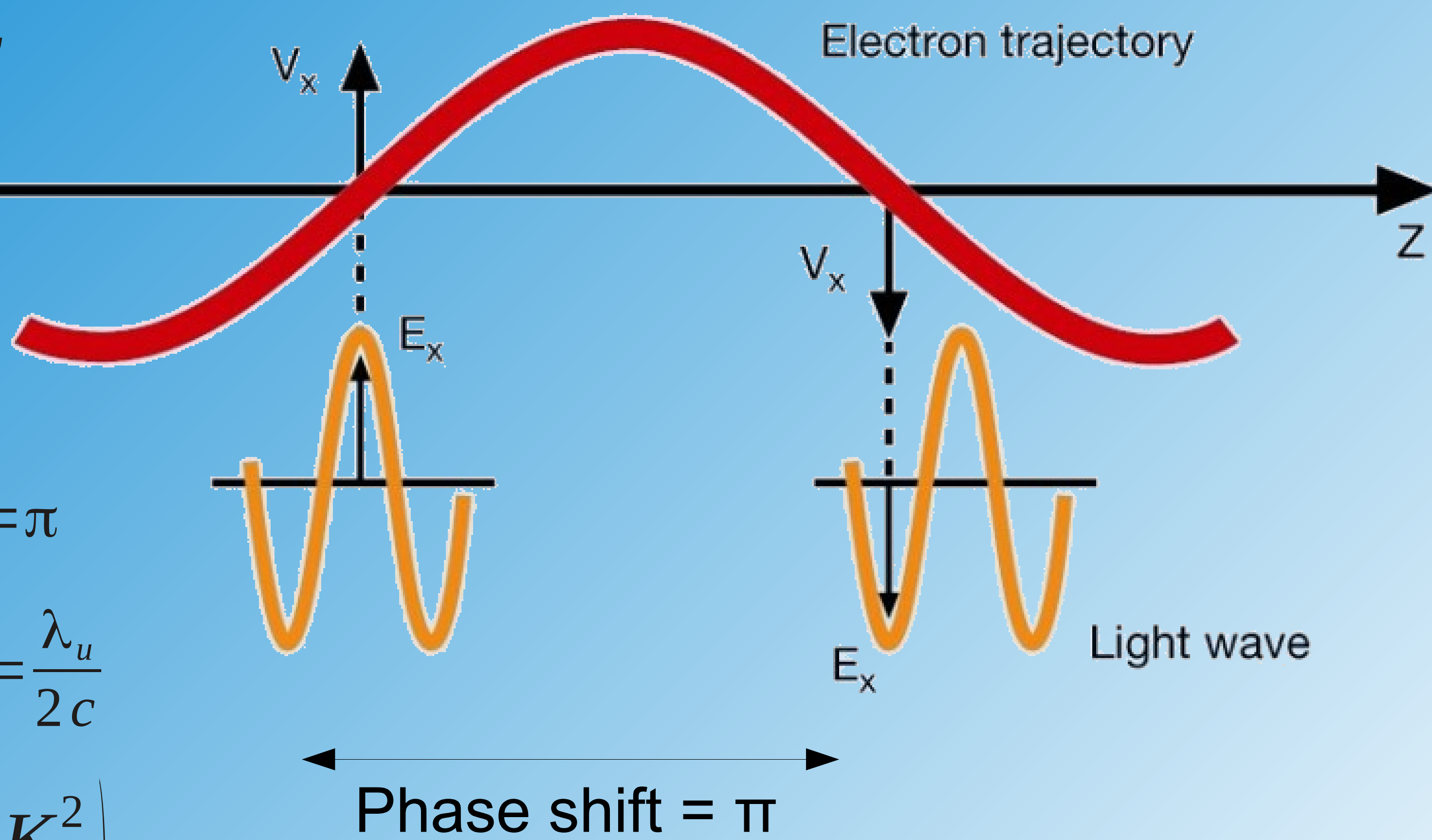
Superposition



Energy Transfer

Energy transfer:

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



Condition:

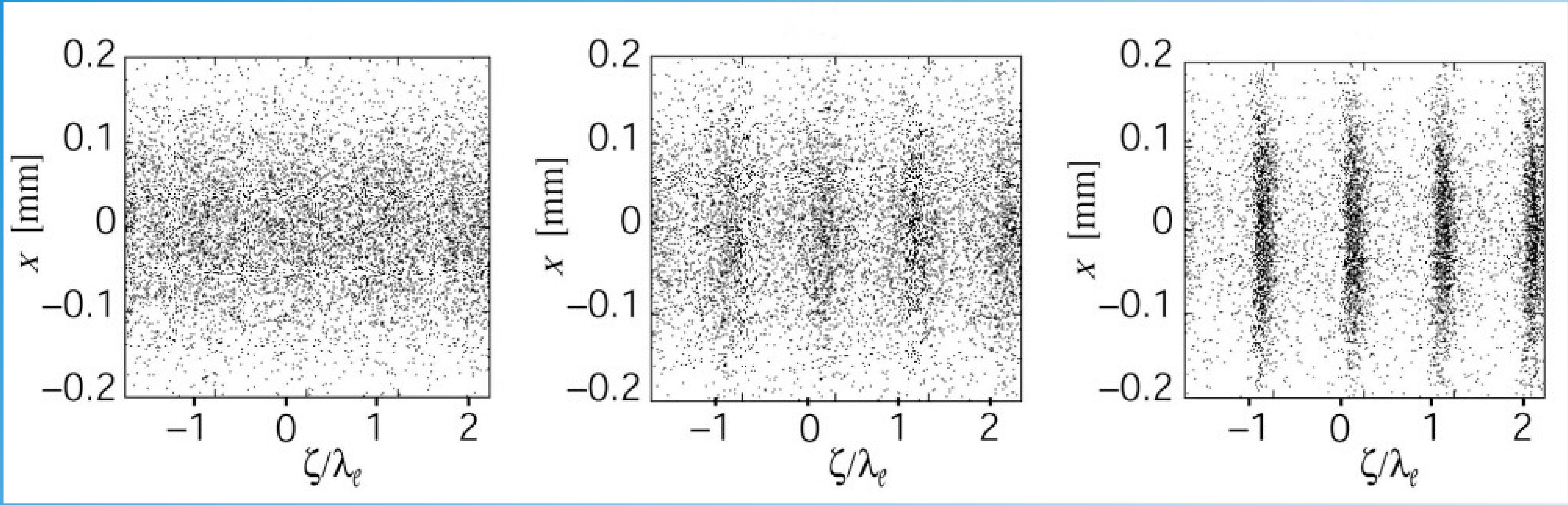
$$\omega_\gamma(\Delta t_e - \Delta t_\gamma) = \pi$$

$$\Delta t_e = \frac{\lambda_u}{2\overline{v_z}} \qquad \Delta t_\gamma = \frac{\lambda_u}{2c}$$

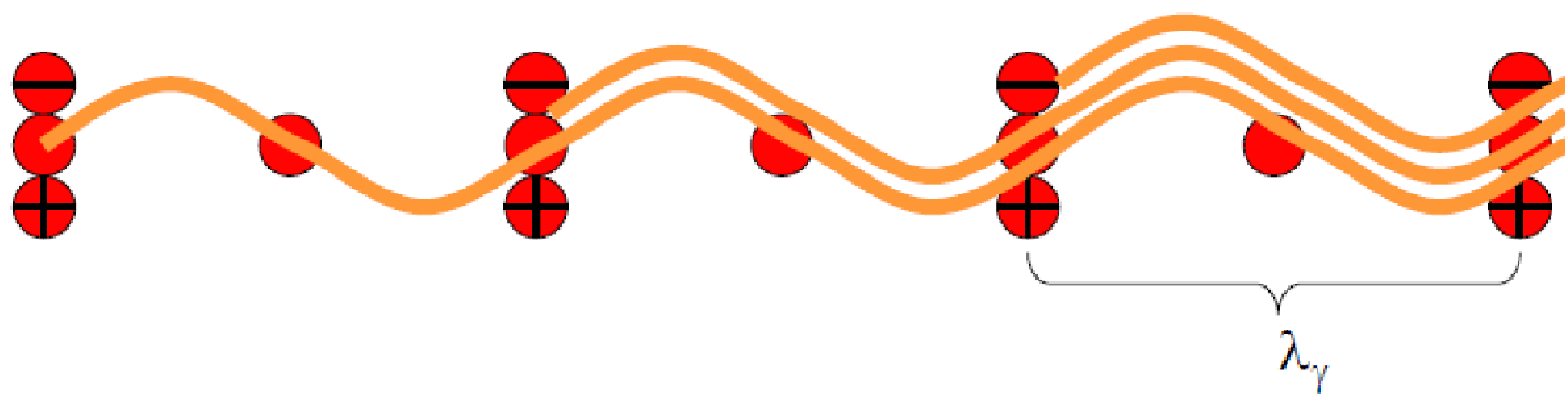
$$\lambda_\gamma = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

- problem: bunch length ~ 50 µm >> photon wave length
- → no effective superposition

Microbunching + Self Modulation



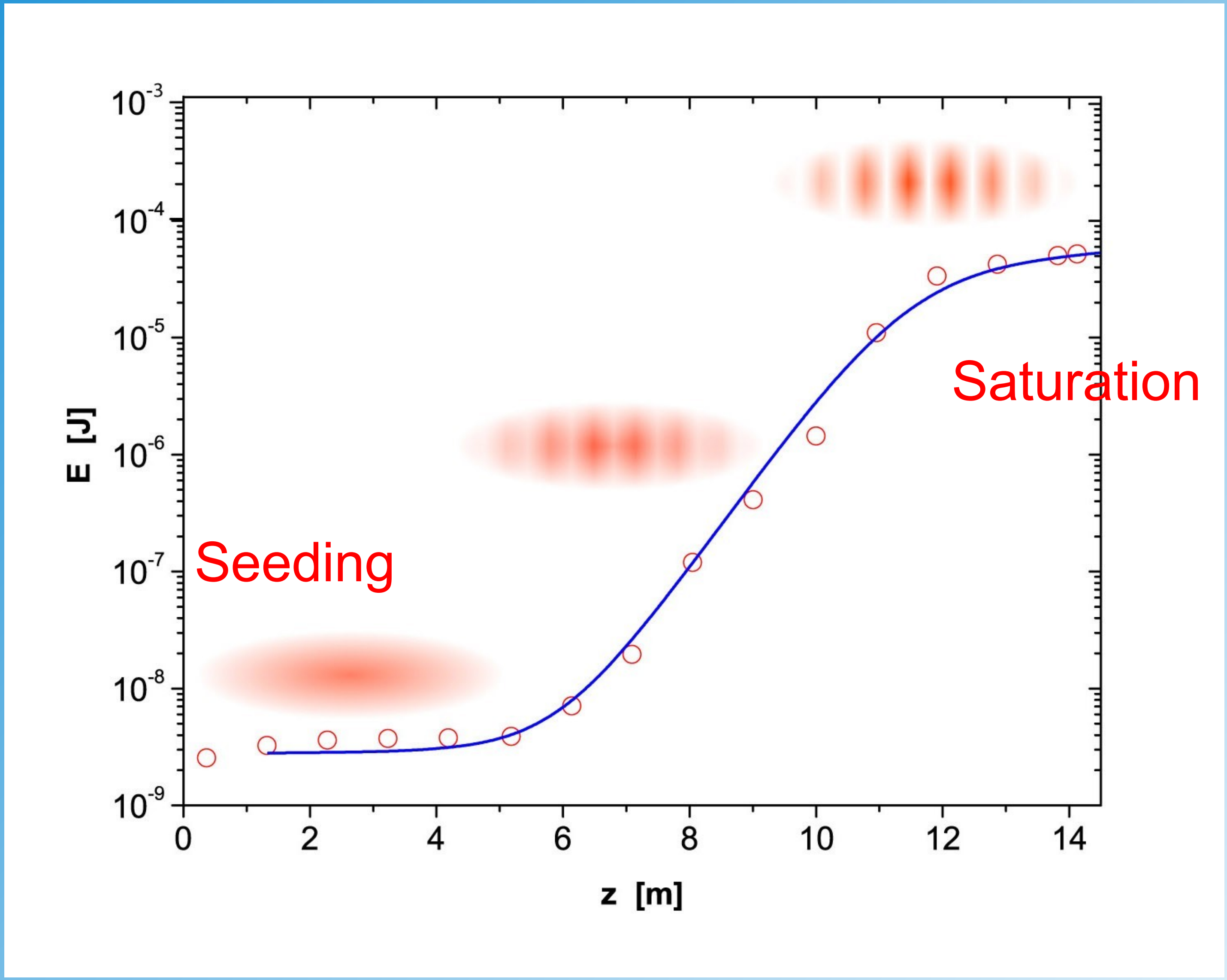
Superposition



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

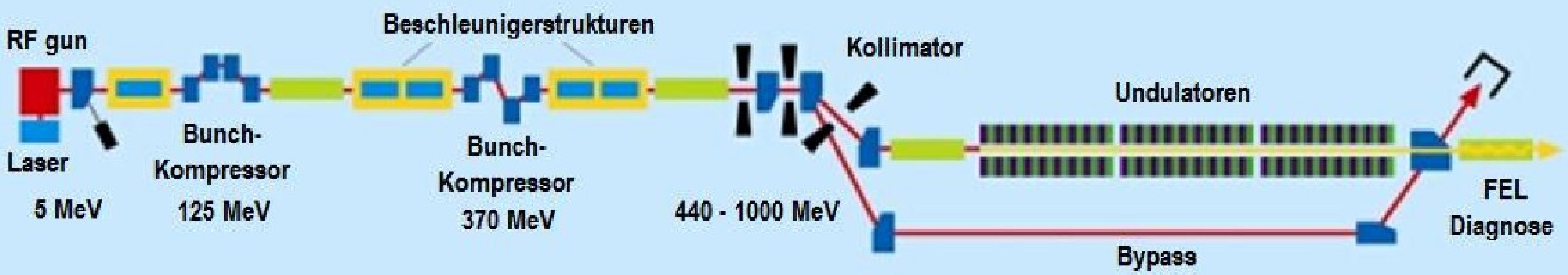
Power scales quadratically with number of particles in microbunch

Self Amplification



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

DESY FLASH (Tesla Test Facility)



FEL:

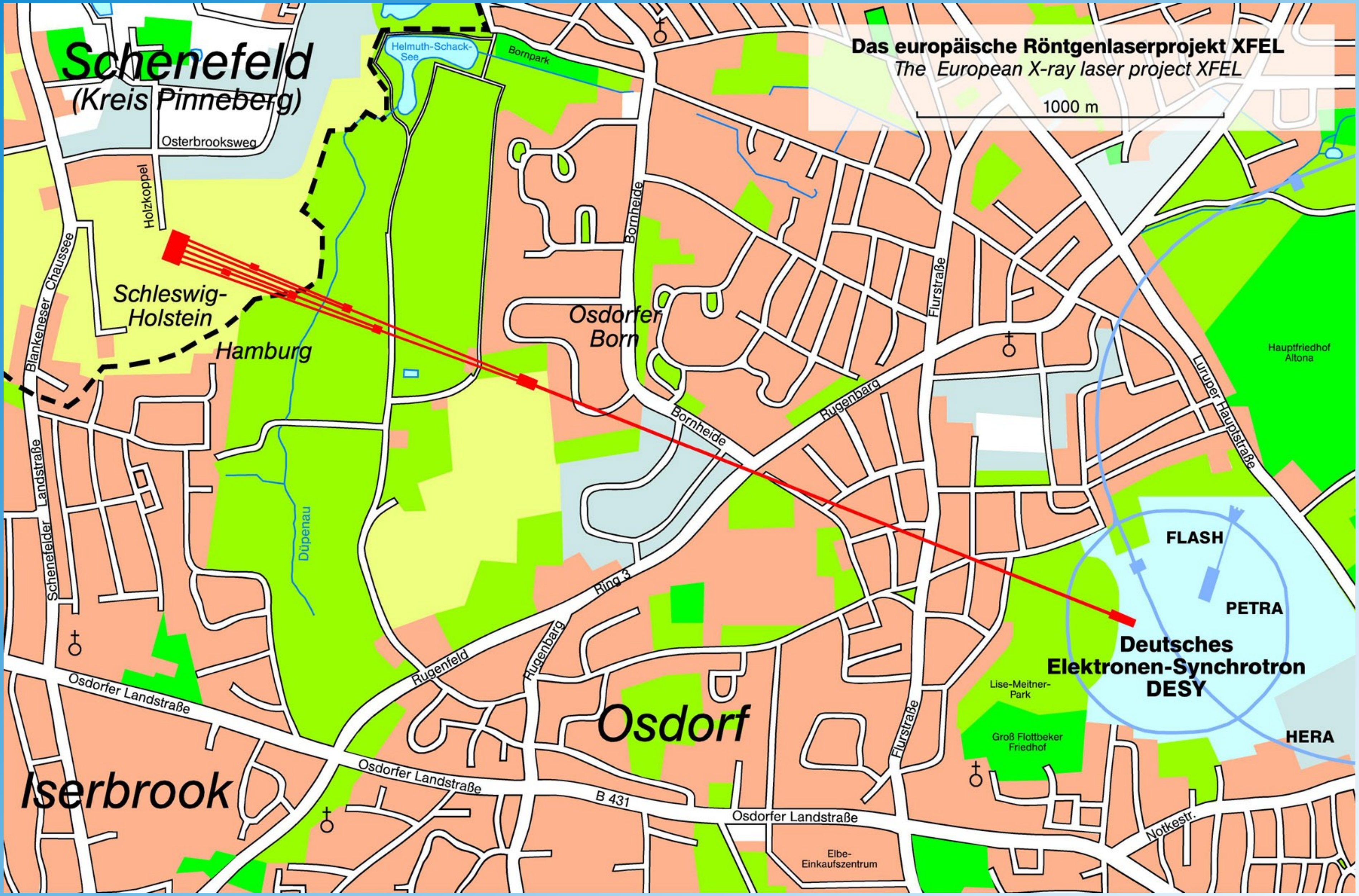
Energy ~1 GeV

Bunchlength 50 µm

Tesla Cavities

DESY XFEL (in construction)

DESY XFEL (20 GeV)



Comparision XFEL - FLASH

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

XFEL Accelerator + Experiments