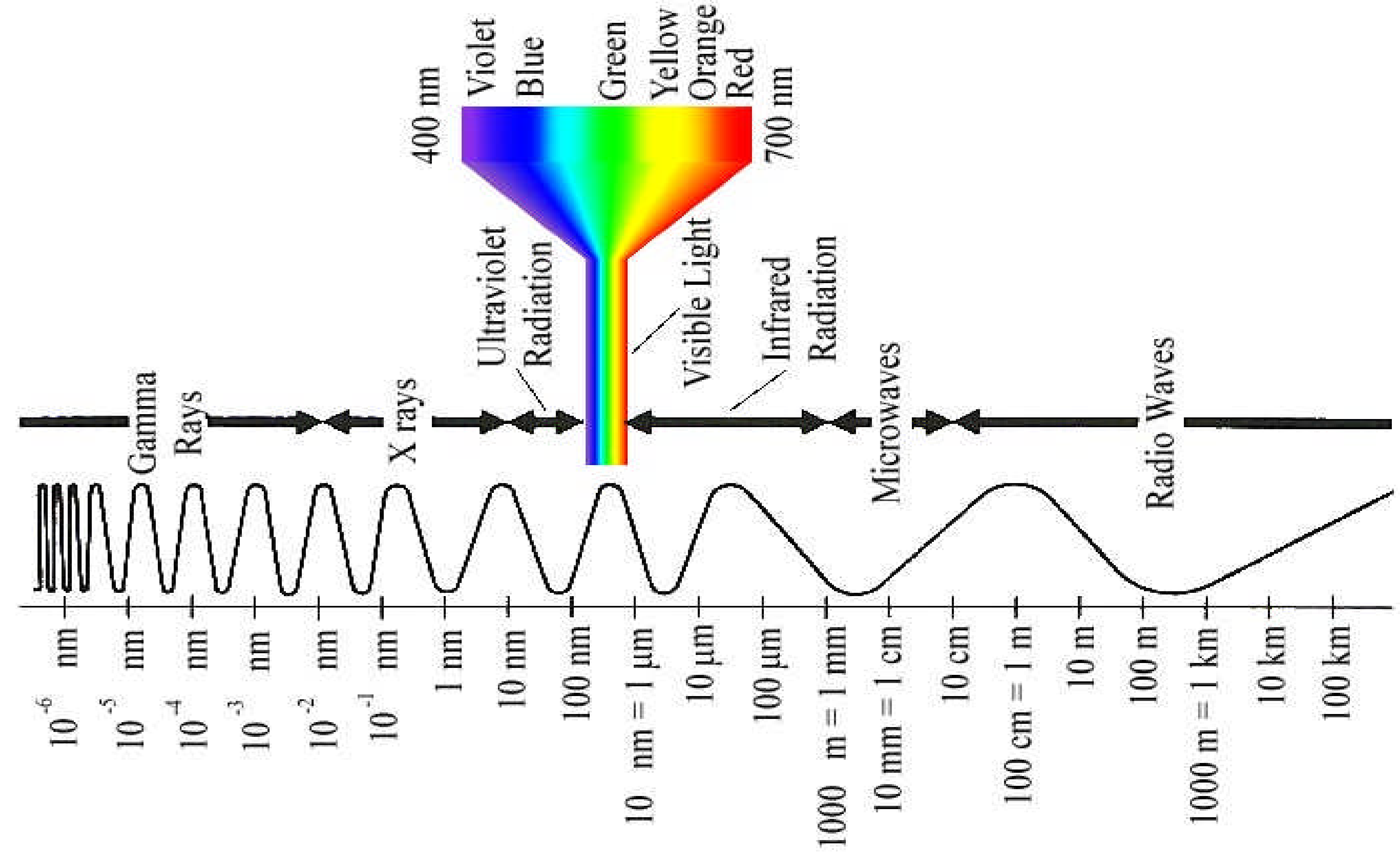
Synchrotrons: Some basics

R. Schlögl, Axel Knop-Gericke
www: fhi-berlin.mpg.de

BESSY, ALS, SLAC, SSRL

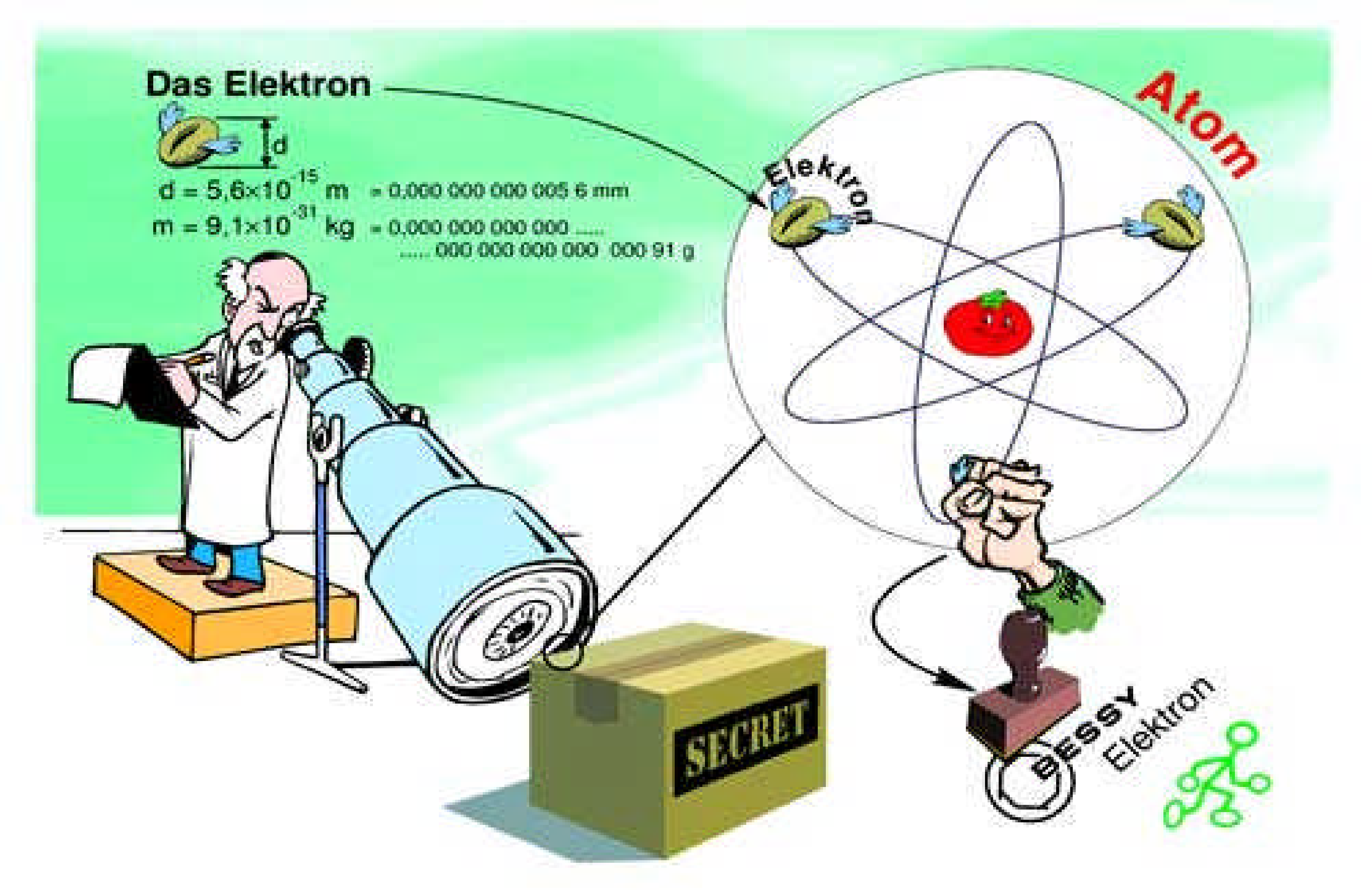
Spectrum of electromagnetic radiation



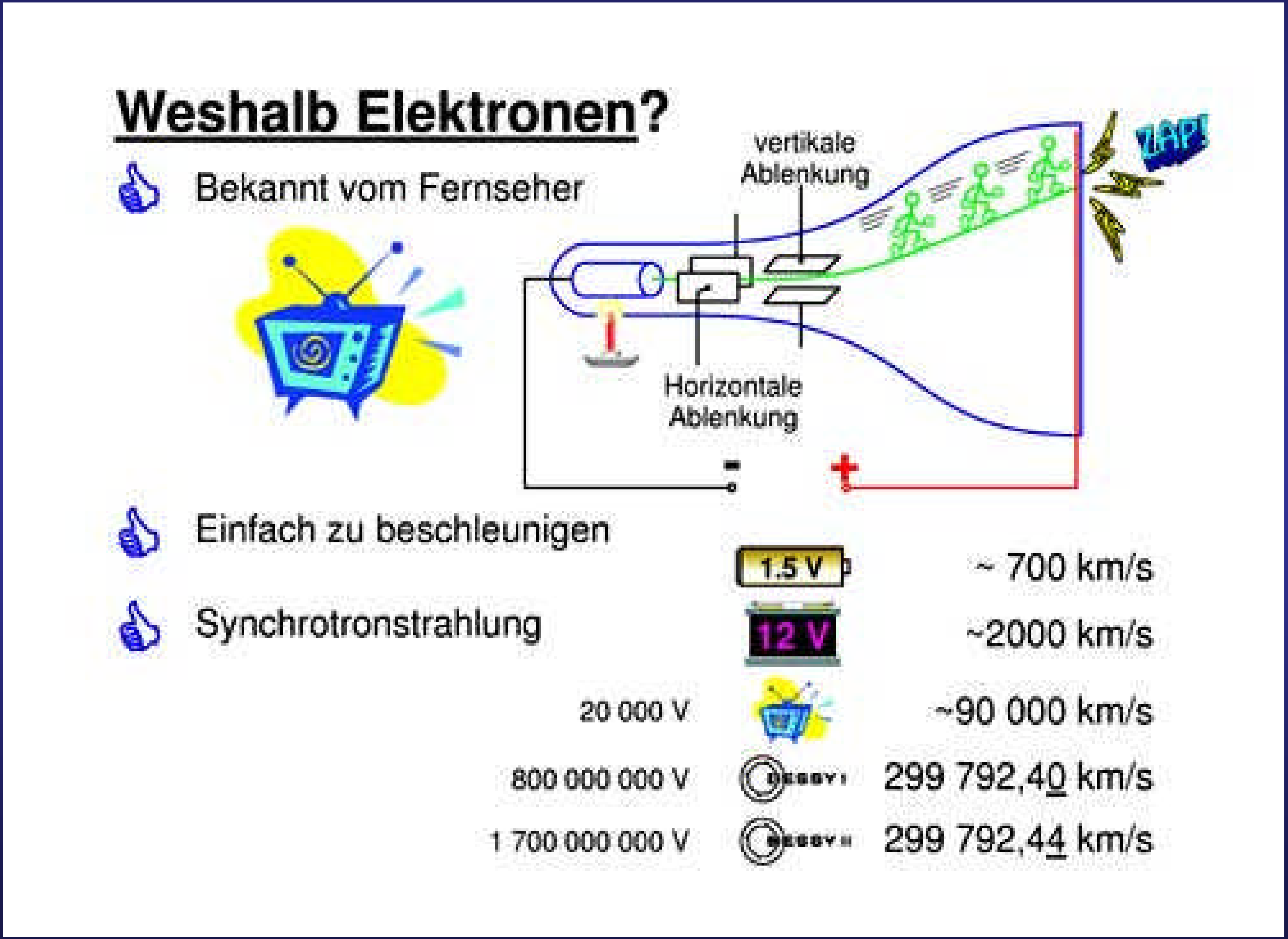
Special Characteristics of SR

- High brightness and high intensity, many orders of magnitude more than with x-rays produced in conventional x-ray tubes
- High brilliance, exceeding other natural and artificial light sources by many orders of magnitude: 3rd generation sources typically have a brilliance larger than 10^{18} photons / s / mm^2 / mrad^2 / 0.1%BW, where 0.1%BW denotes a bandwidth 10^{-3}w centered around the frequency w.
- High collimation, i.e. small angular divergence of the beam
- Low emittance, i.e. the product of source cross section and solid angle of emission is small
- Widely tunable in energy/wavelength by monochromatization (sub eV to tens of keV)
- High level of polarization (linear or elliptical)
- Pulsed light emission (pulse durations at or below one nanosecond, or a billionth of a second);

Synchrotron radiation



Synchrotron radiation



Weshalb Elektronen?

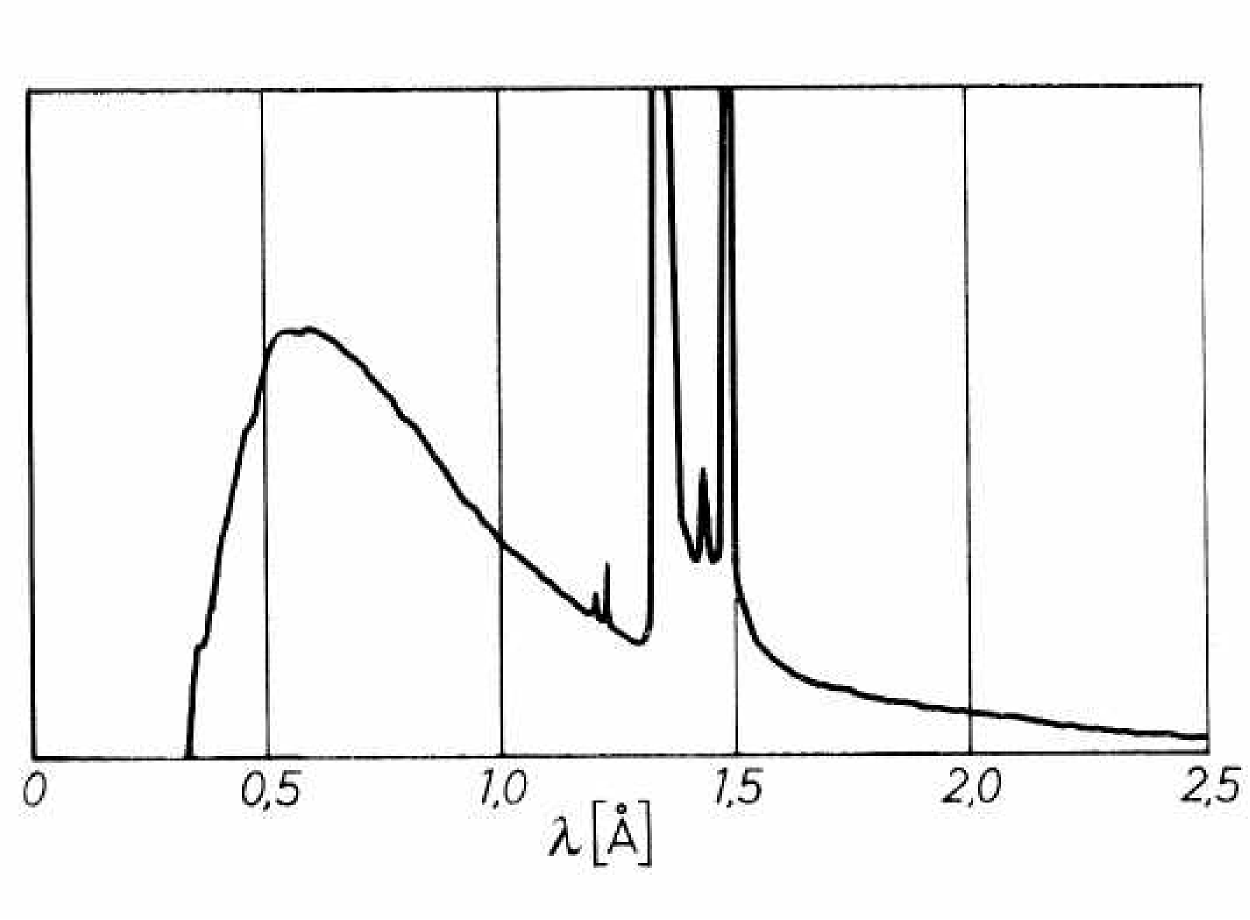
- Bekannt vom Fernseher

- Einfach zu beschleunigen
- Synchrotronstrahlung

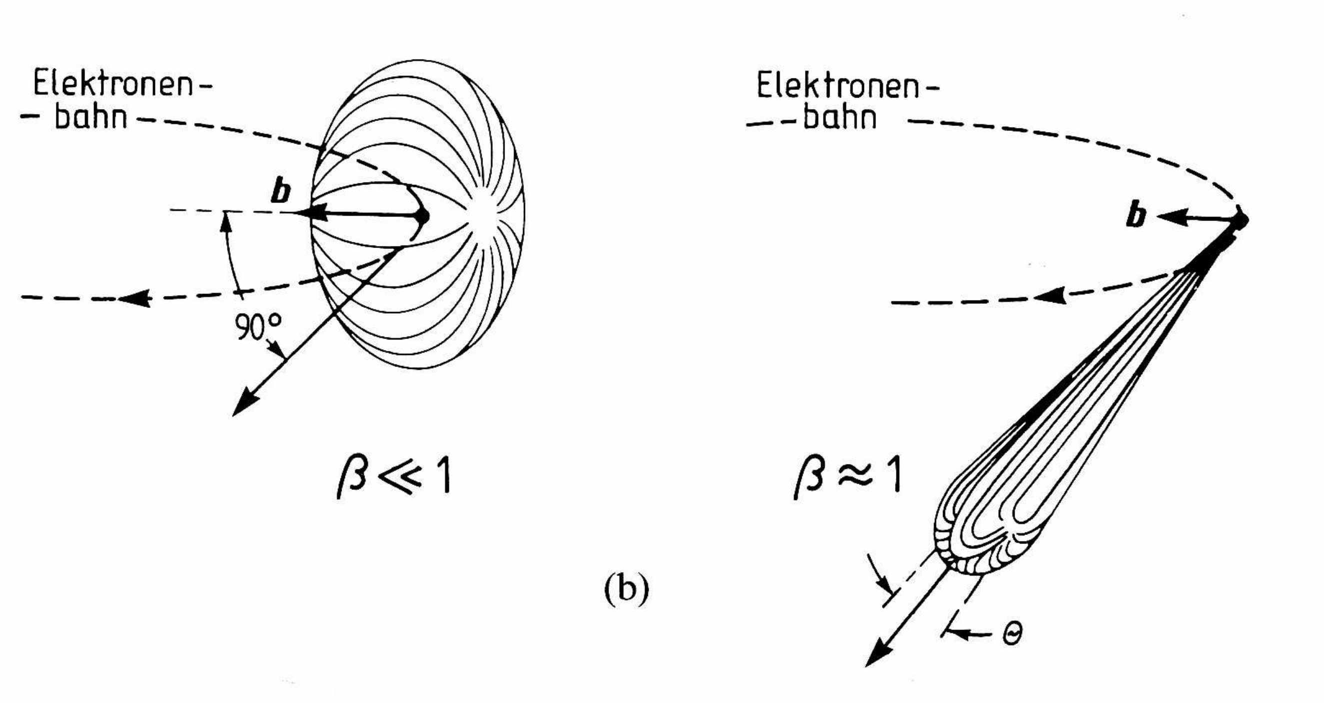
	1.5 V	~ 700 km/s
	12 V	~2000 km/s
20 000 V		~90 000 km/s
800 000 000 V	BESSY I	299 792,40 km/s
1 700 000 000 V	BESSY II	299 792,44 km/s

Bremsstrahlung: the basic principle

- el … the
  a … as
  a
- h
  m
- B … rum

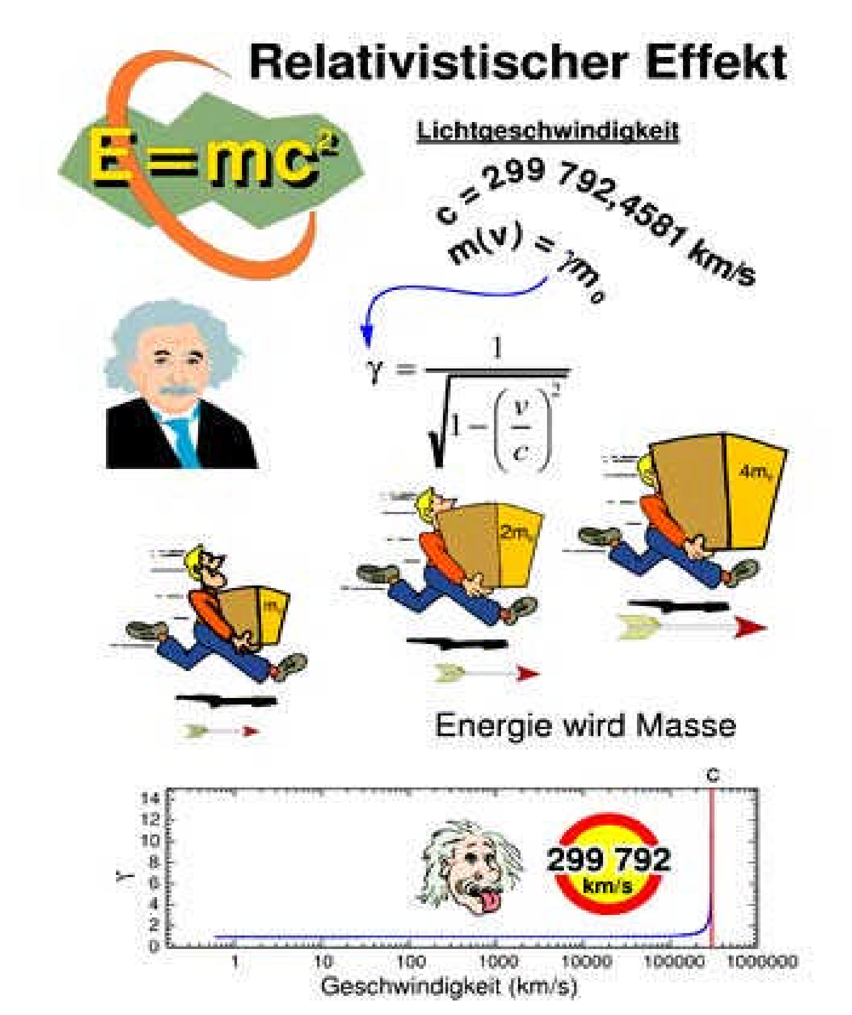


Why relativistic electrons

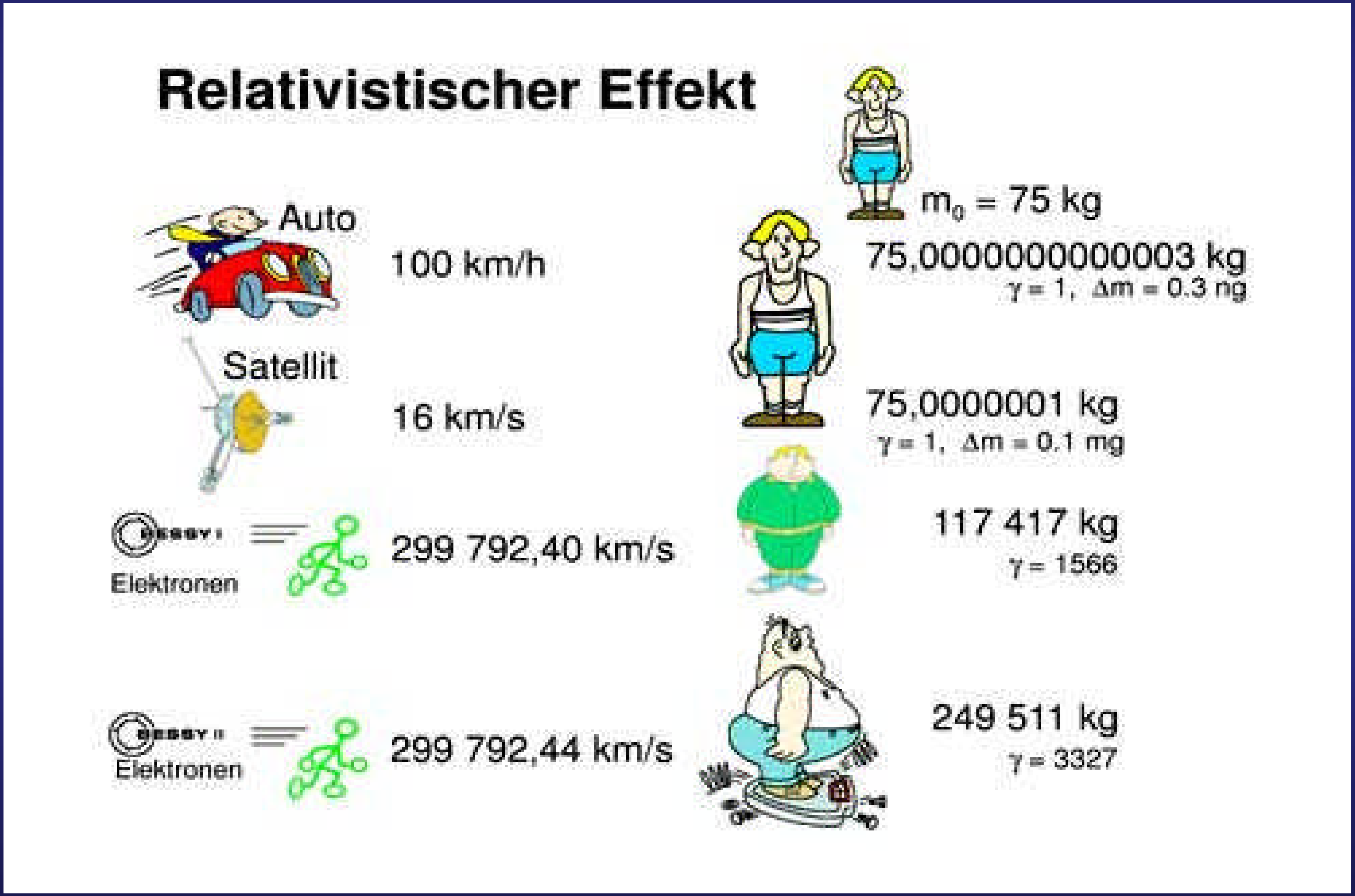


Beta =c/v: only then directed dipole radiation
otherwise omnidirctional and thus weak

Synchrotron radiation



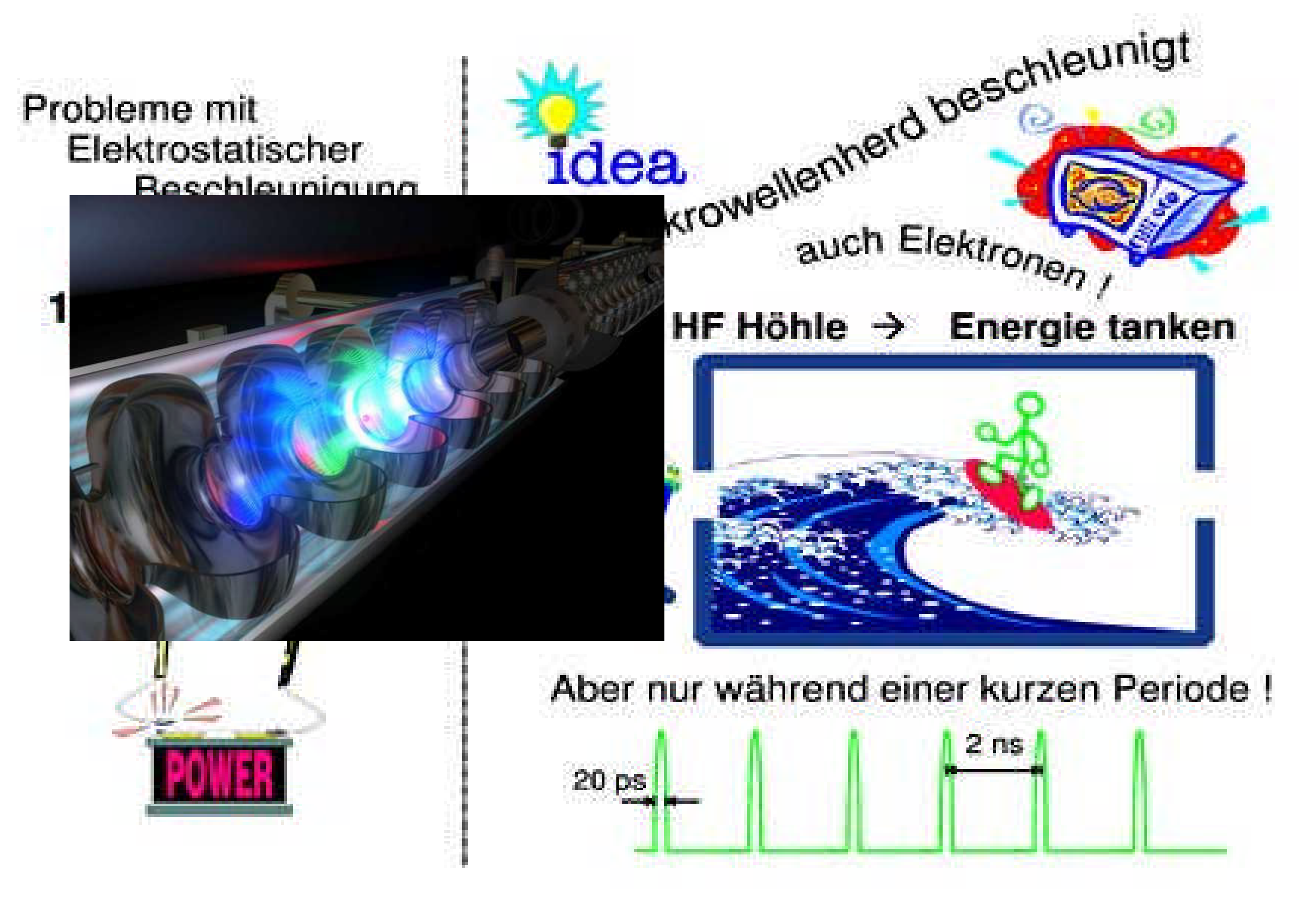
Synchrotron radiation



Relativistischer Effekt

		$m_0 = 75$ kg
Auto	100 km/h	75,0000000000003 kg $\gamma = 1$, $\Delta m = 0.3$ ng
Satellit	16 km/s	75,0000001 kg $\gamma = 1$, $\Delta m = 0.1$ mg
BESSY I Elektronen	299 792,40 km/s	117 417 kg $\gamma = 1566$
BESSY II Elektronen	299 792,44 km/s	249 511 kg $\gamma = 3327$

Synchrotron radiation



Probleme mit Elektrostatischer Beschleunigung

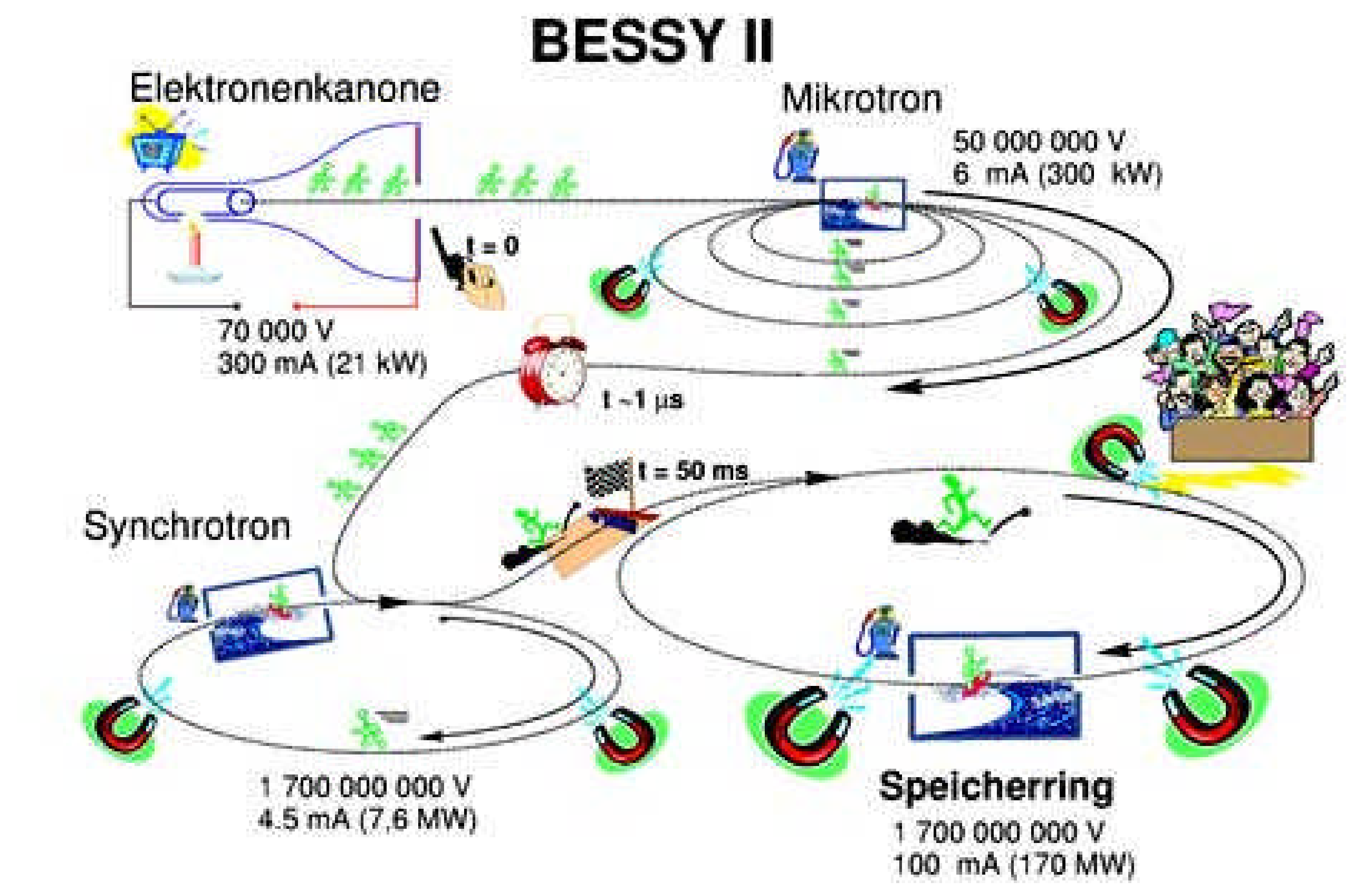
krowellenherd beschleunigt

auch Elektronen !

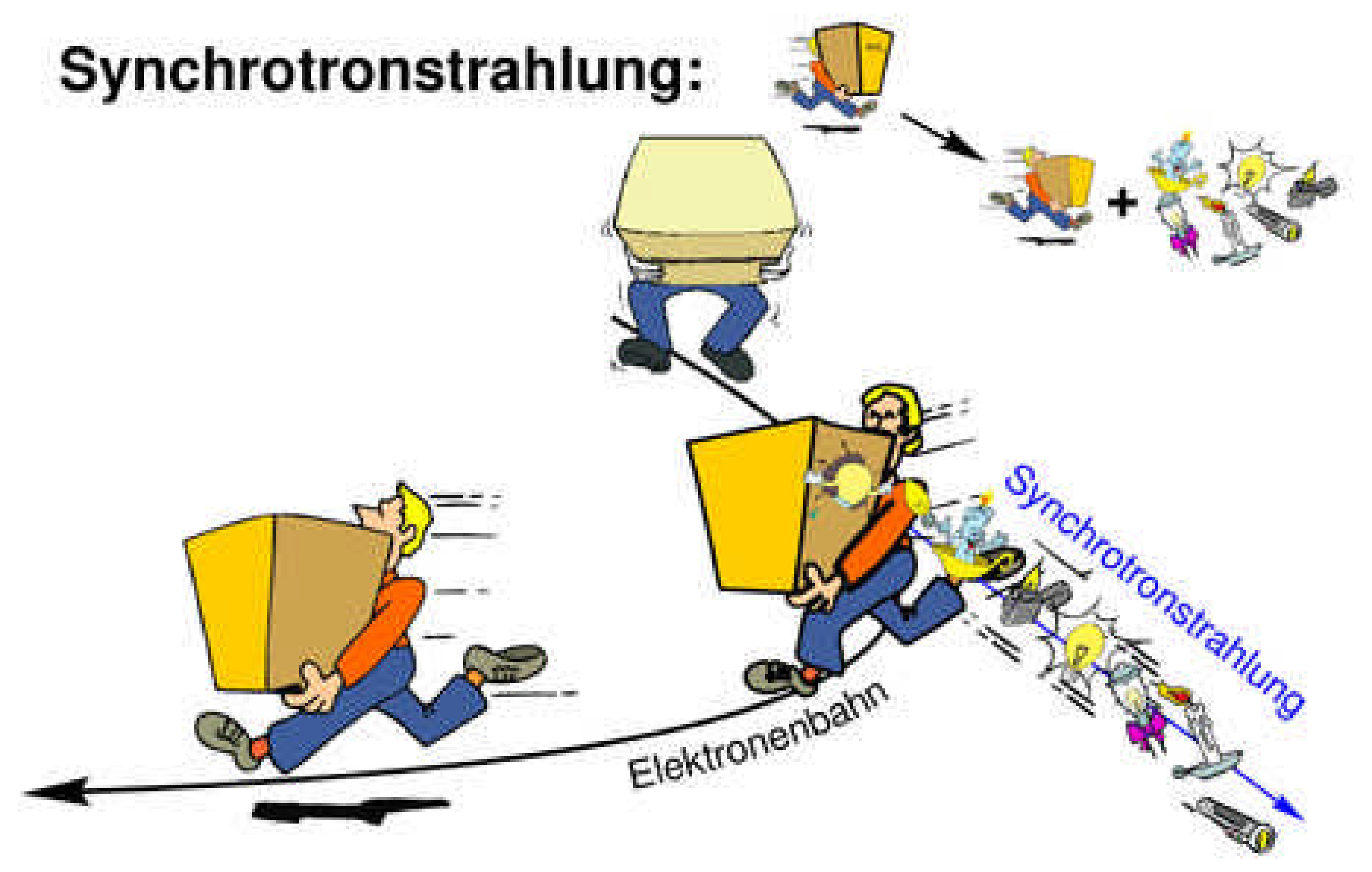
HF Höhle → Energie tanken

Aber nur während einer kurzen Periode !

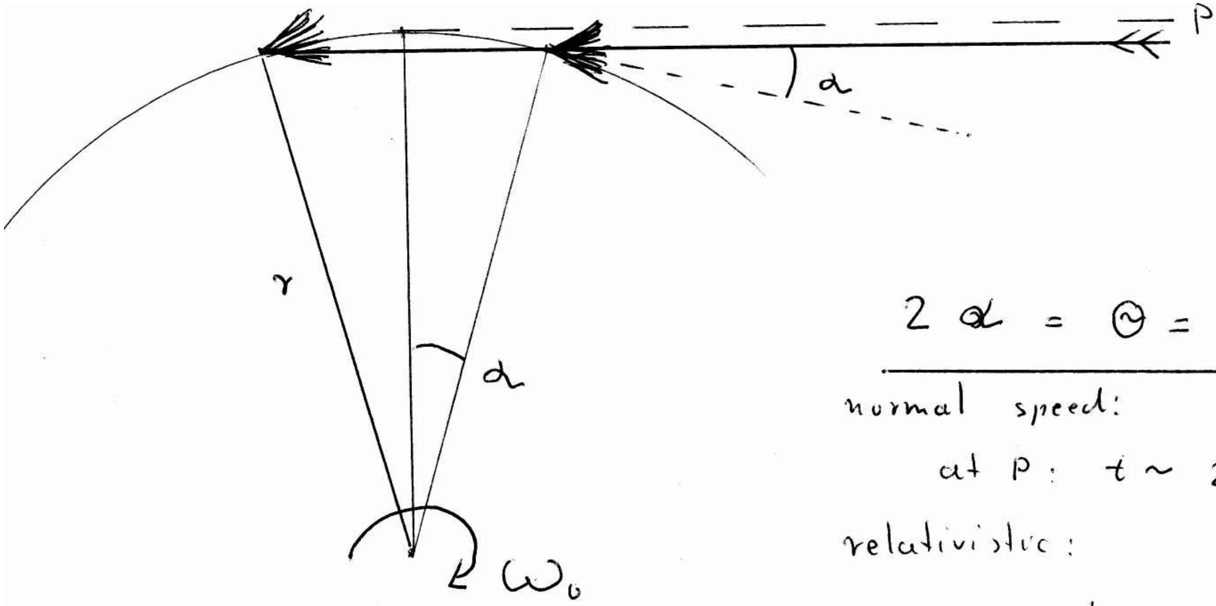
Synchrotron radiation



Synchrotron radiation



At which energy do we see light?



The light house effect

$$2\alpha = \Theta = 2 m_0 c^2 / E_{kin}$$

normal speed:

at P: $t \sim 2\alpha\,\omega_0$

relativistic:

$$t \sim \frac{r \cdot \alpha^3}{3c}$$

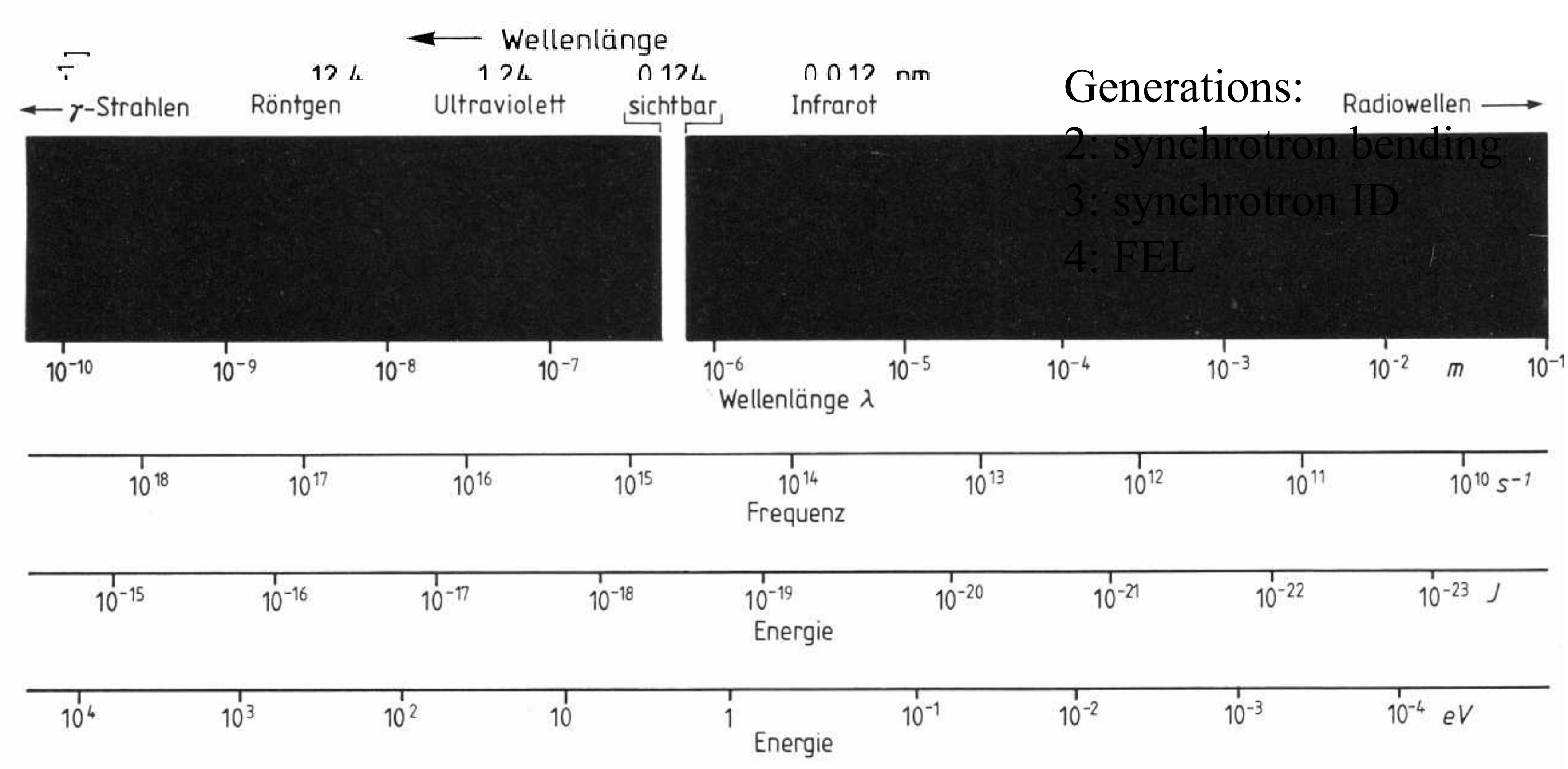
$$\Rightarrow \omega_{light} \sim \frac{3c}{r \cdot \alpha^3}$$

at 5 GeV: $\omega = \omega_0 \cdot 10^{12}$ x-ray!

Why are synchrotrons so large?

-
-
- n)

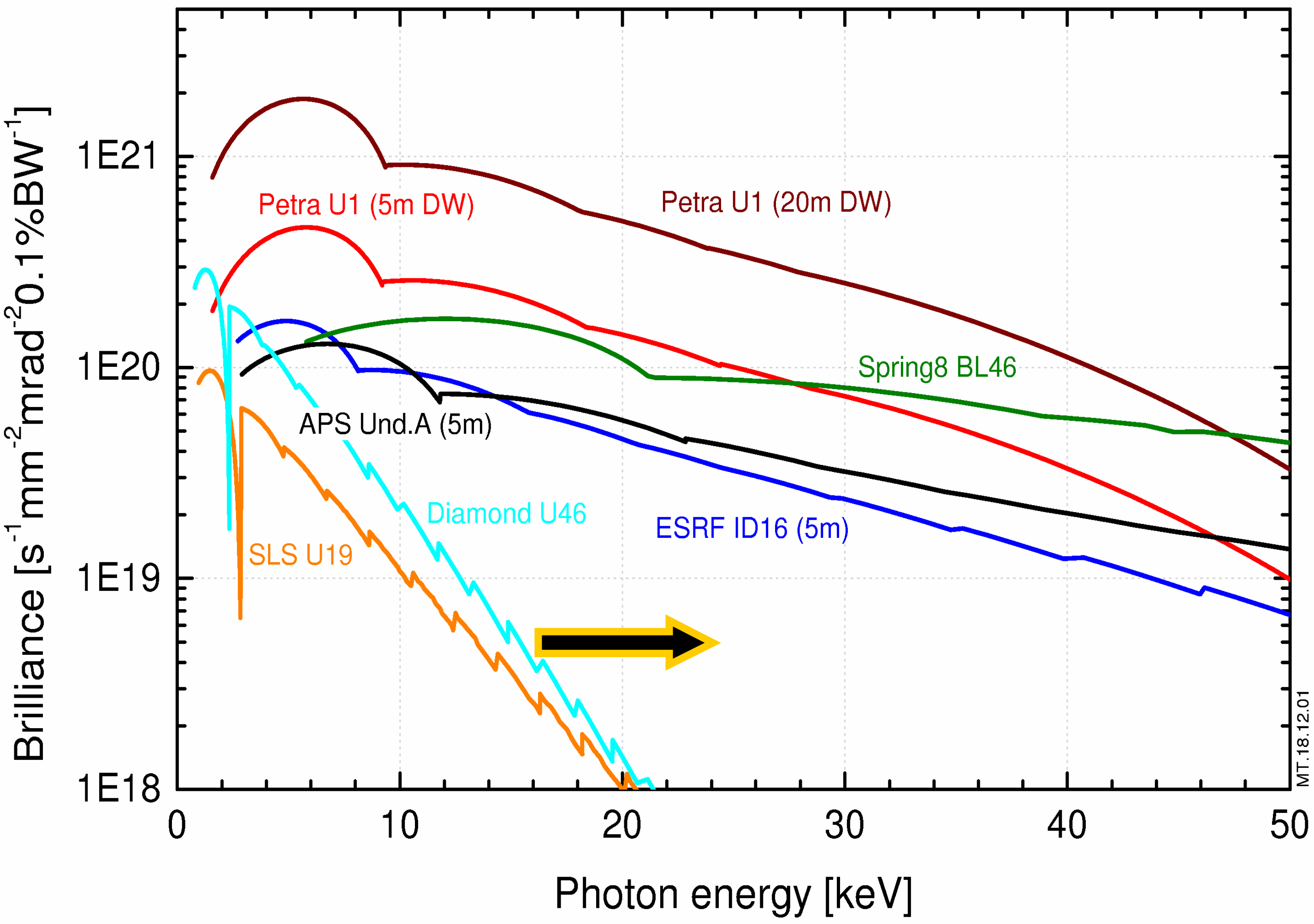
Energy distribution of SR



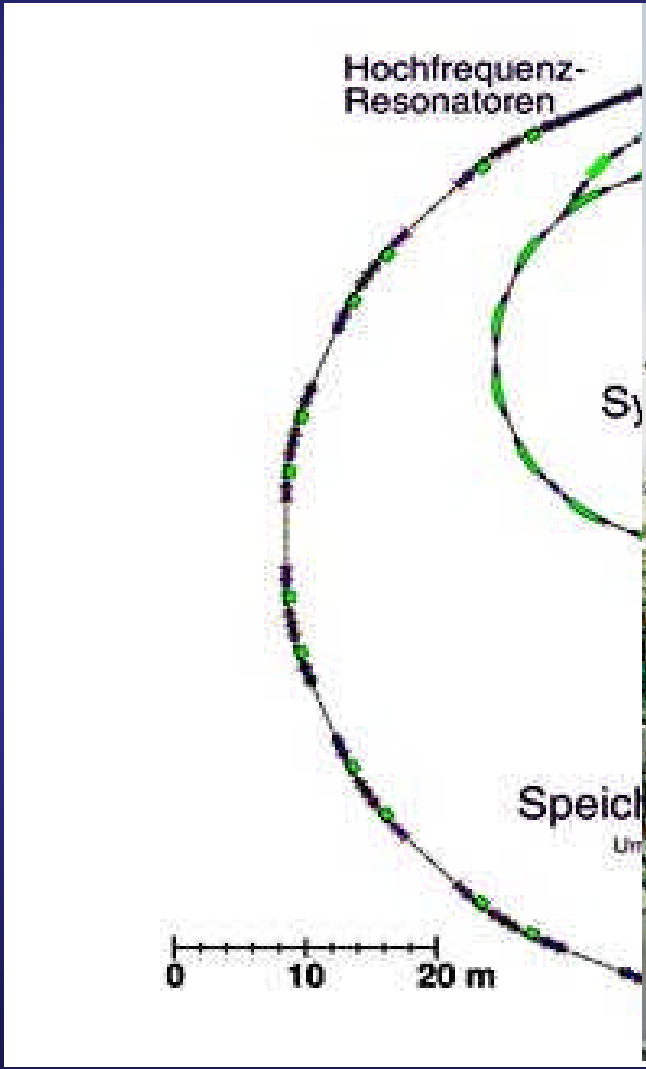
Generations:
2: synchrotron bending
3: synchrotron ID
4: FEL

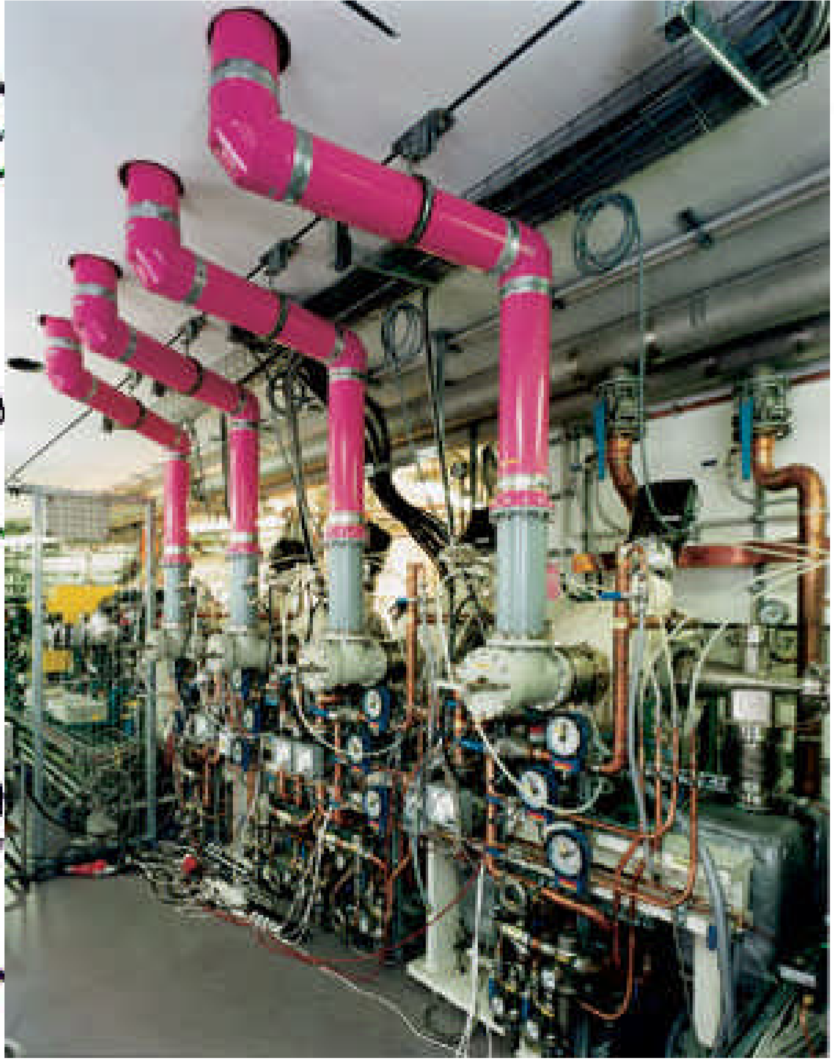
Second generation light sources: note the large range of useable energies!

Energy today and tomorrow

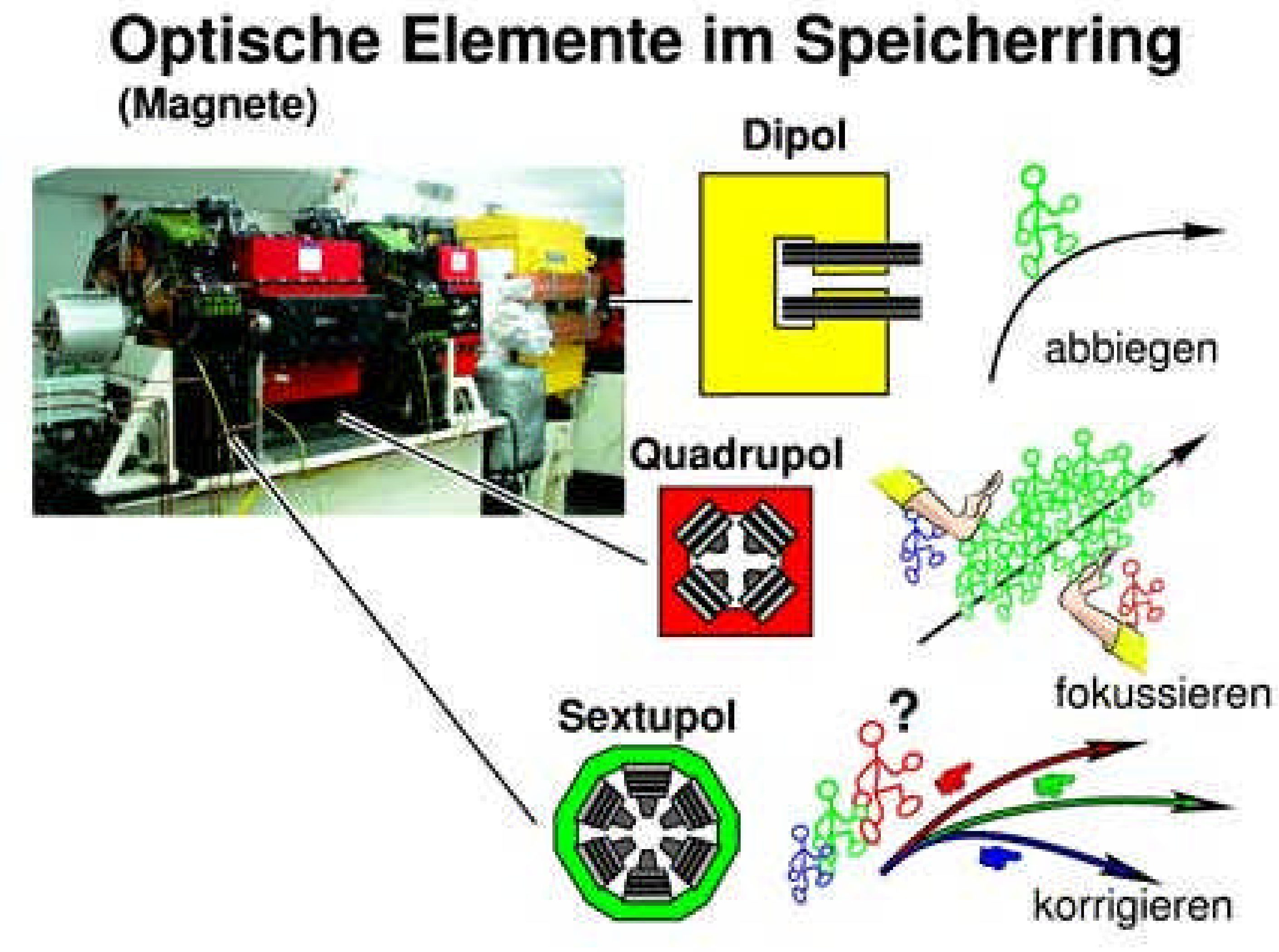


Synchrotron radiation

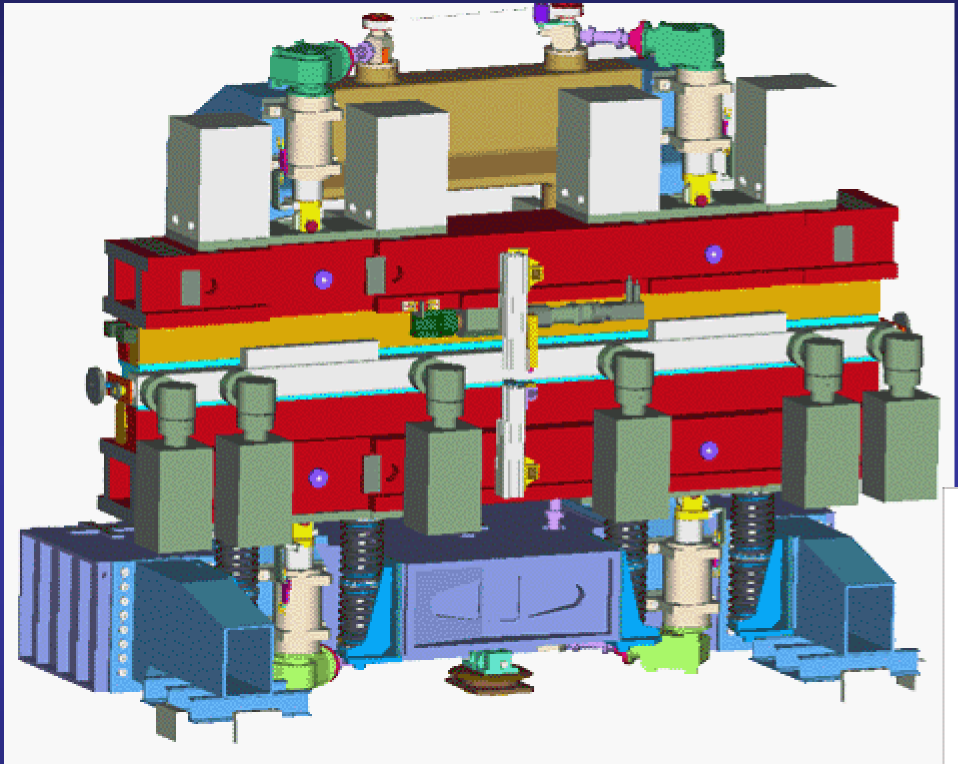


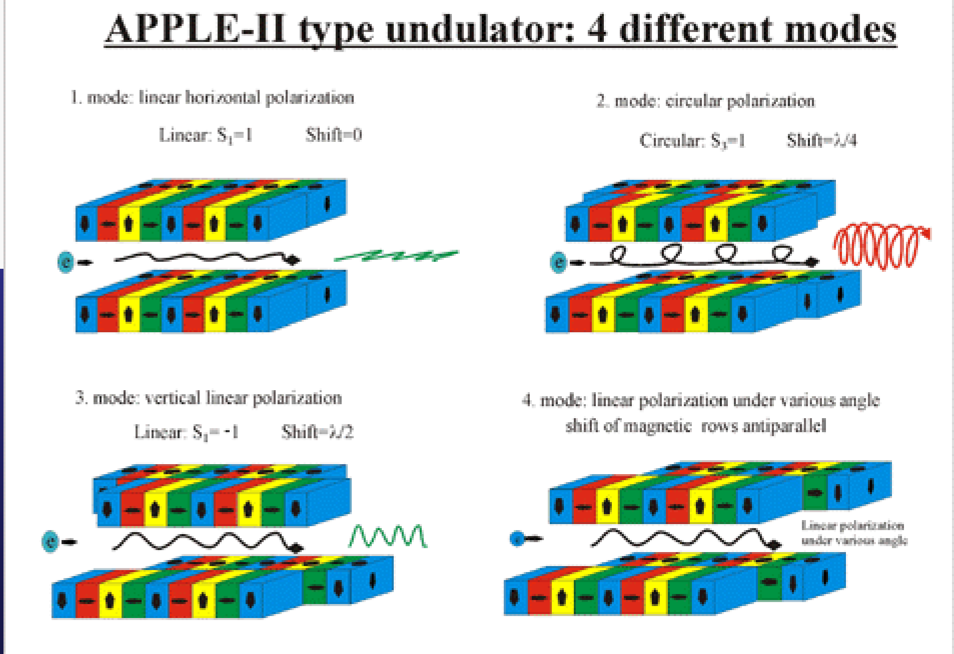


Synchrotron radiation



Undulator





APPLE-II type undulator: 4 different modes

1. mode: linear horizontal polarization

Linear: $S_1=1$ Shift=0

2. mode: circular polarization

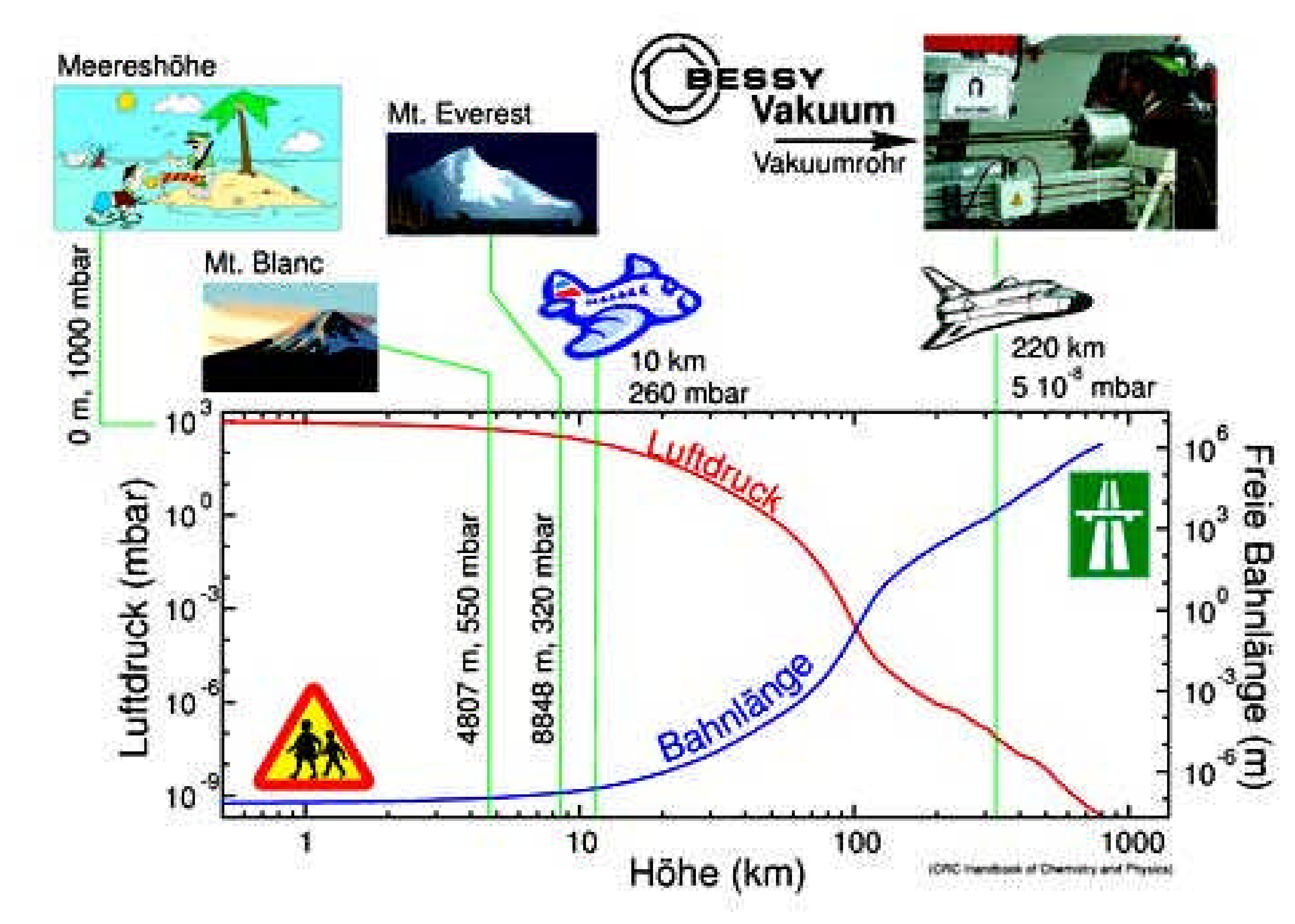
Circular: $S_3=1$ Shift=$\lambda/4$

3. mode: vertical linear polarization

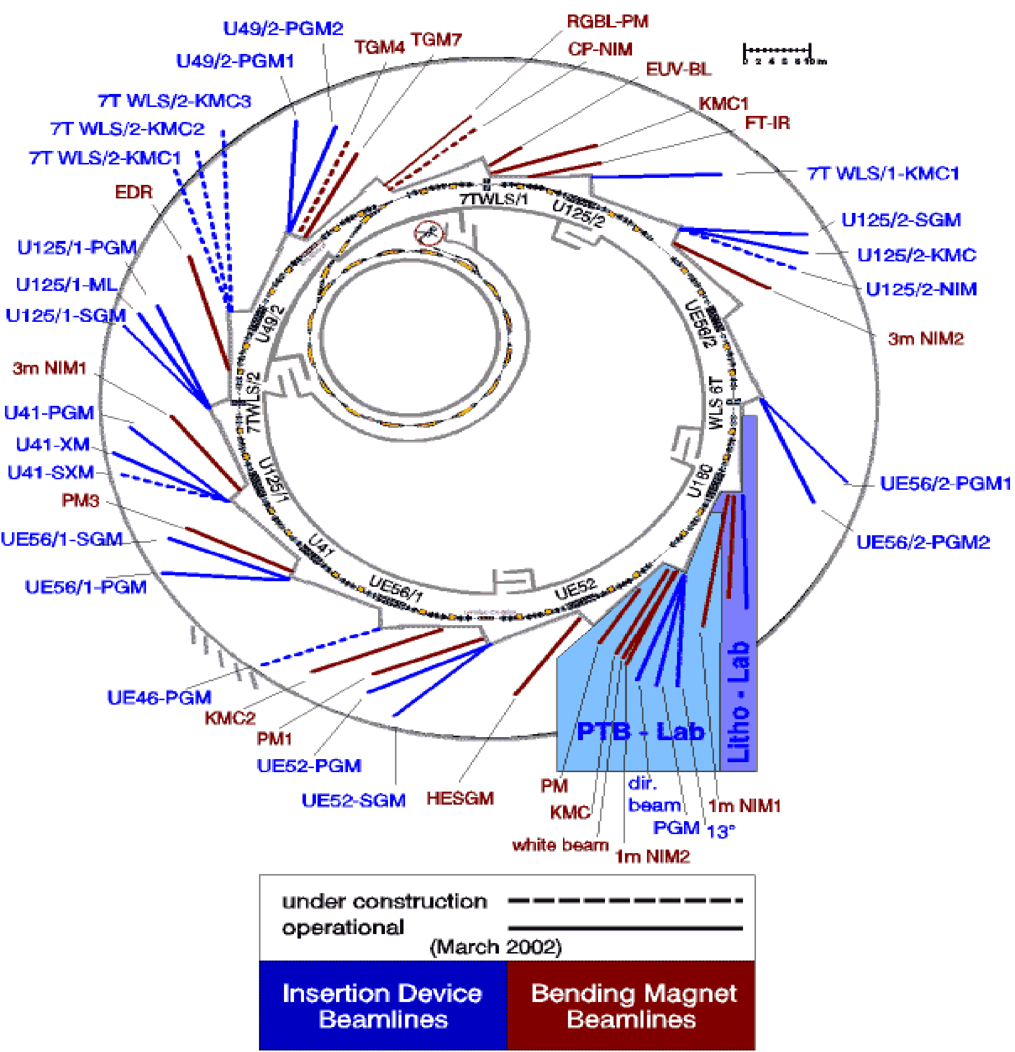
Linear: $S_1=-1$ Shift=$\lambda/2$

4. mode: linear polarization under various angle shift of magnetic rows antiparallel

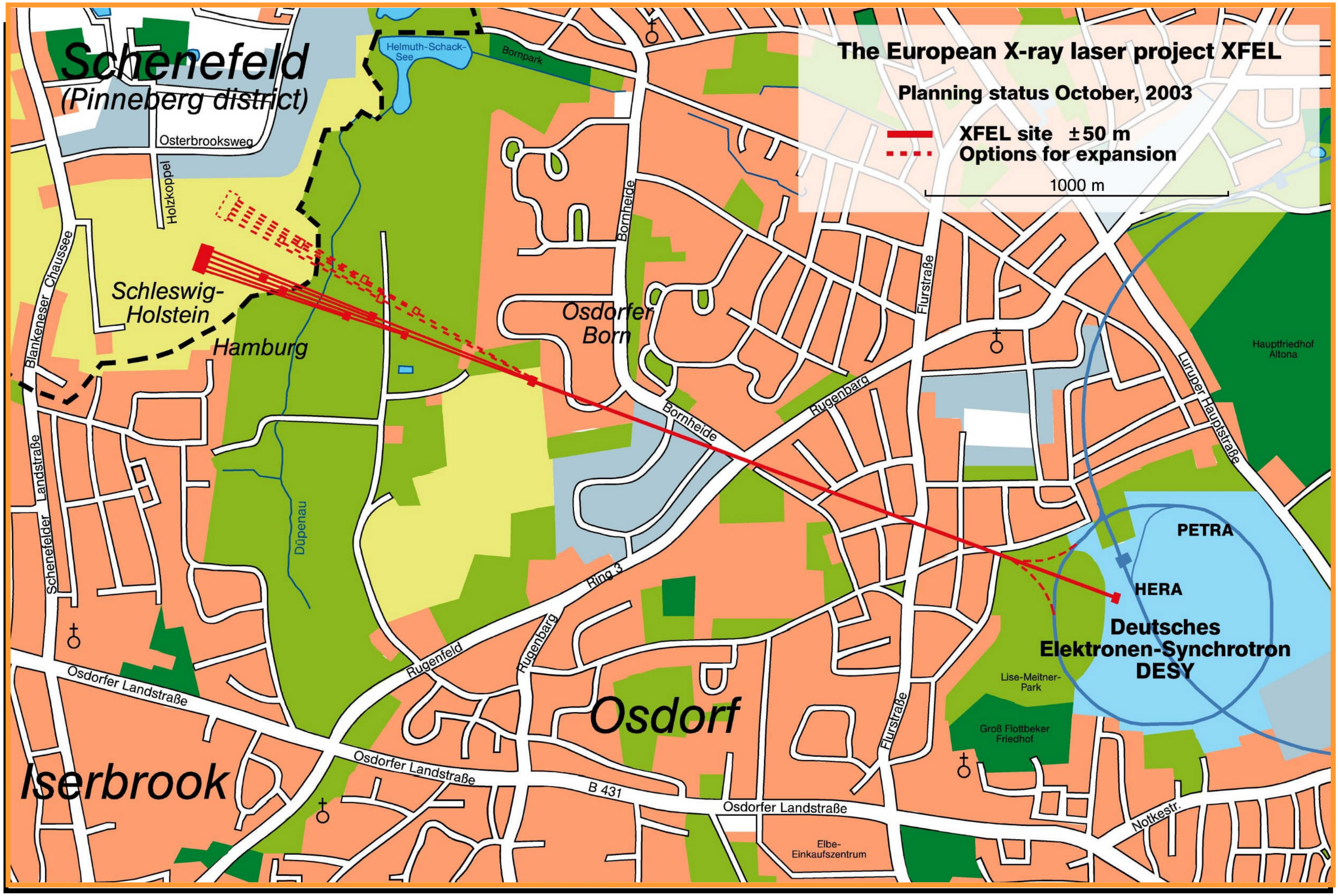
Synchrotron radiation: vaccum



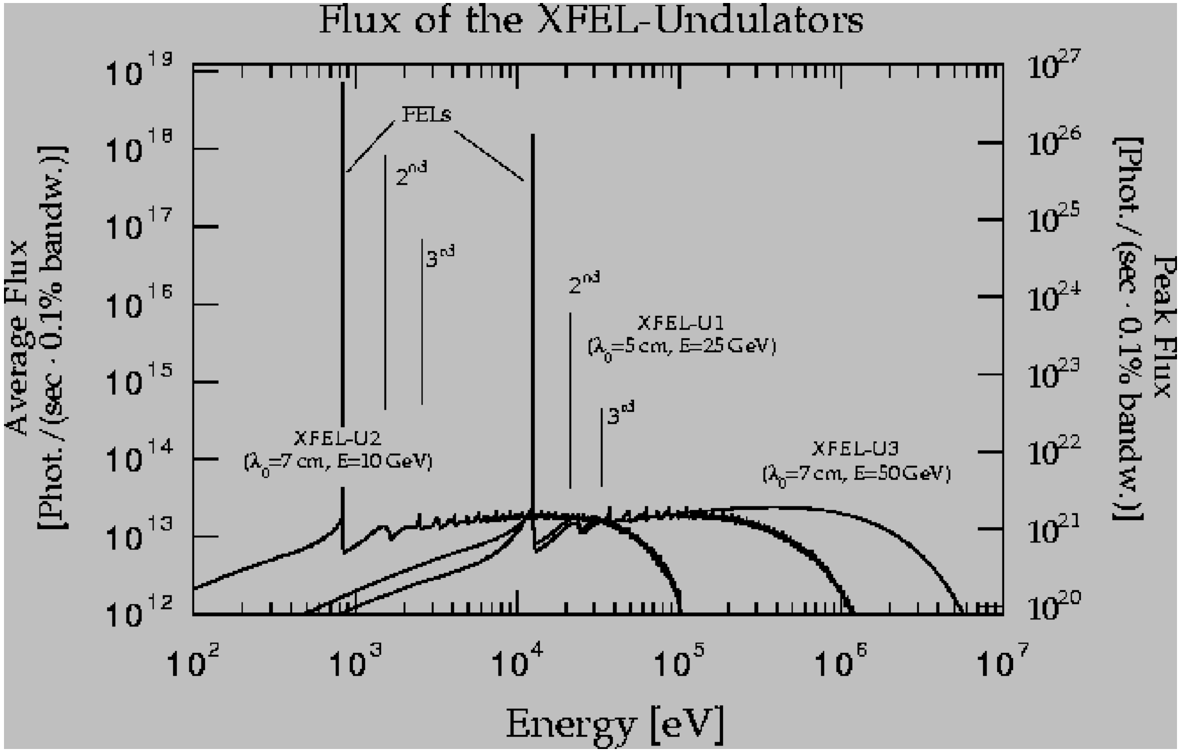
Synchrotron radiation



The Free-electron laser

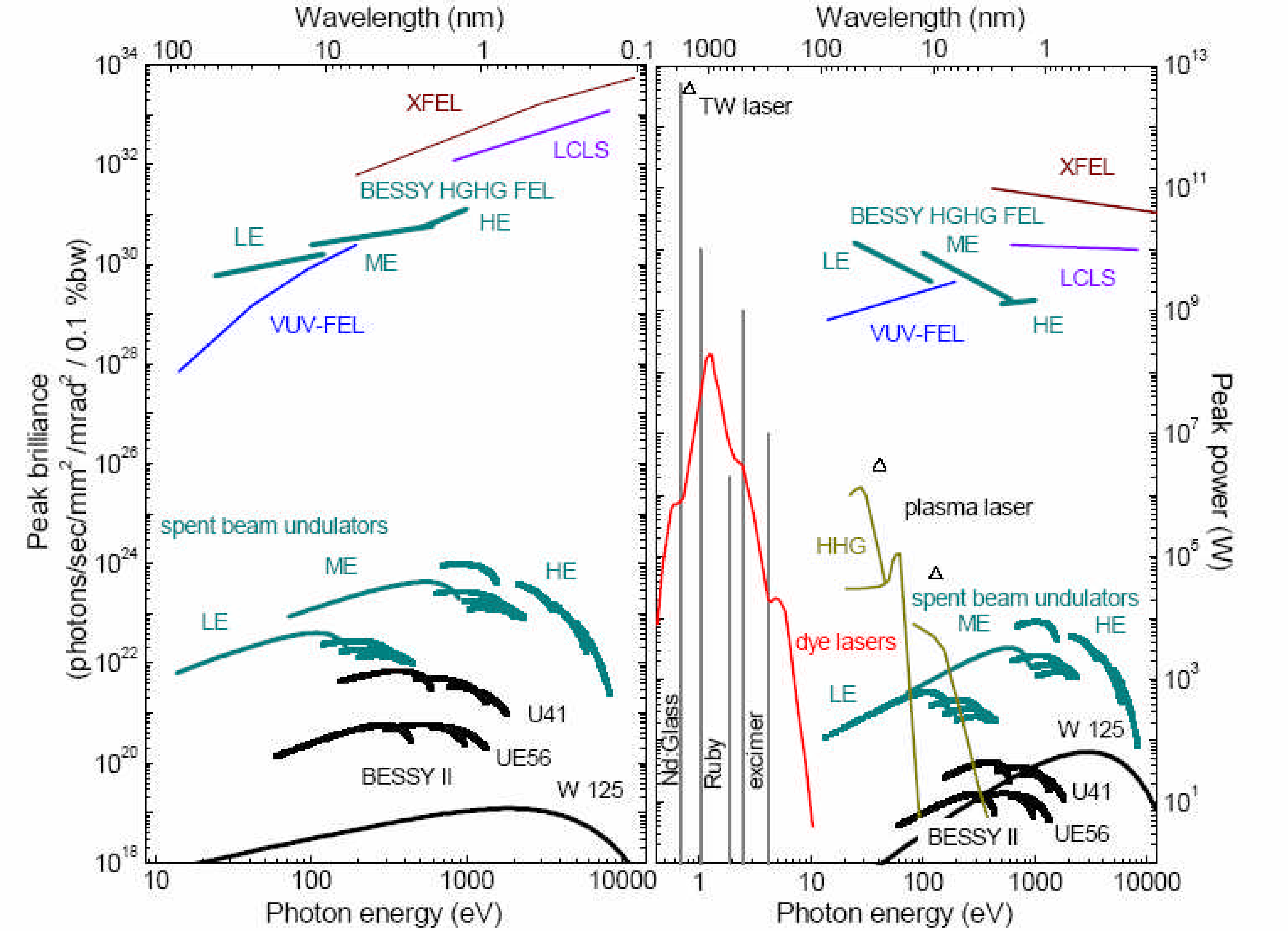


Spectral Distribution



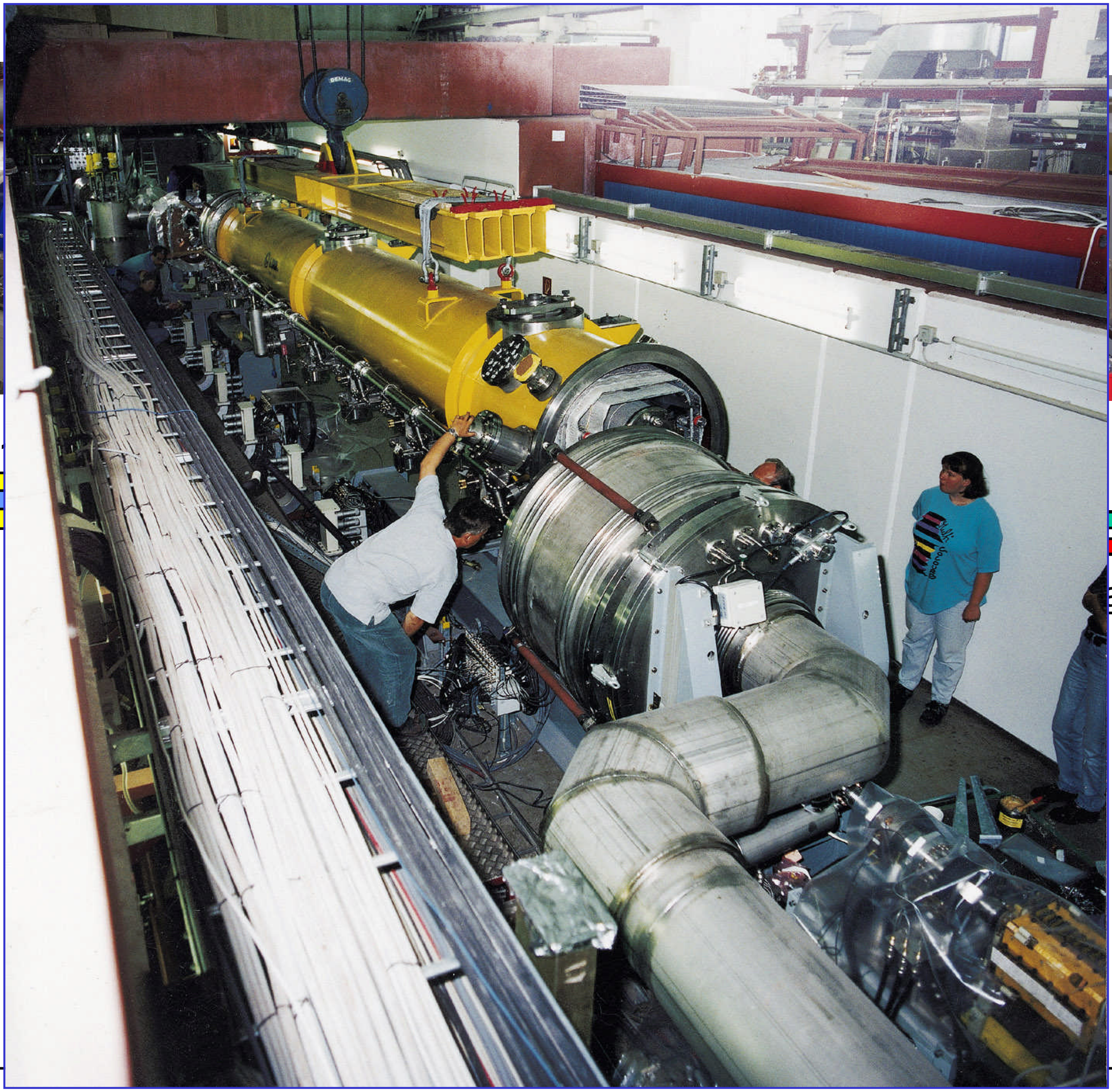
A close co-operation of experiment and light source is needed to exploit a useful range of energies with the FEL instruments in the X-ray range

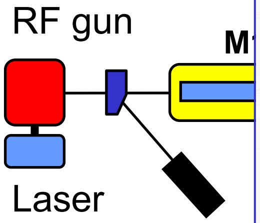
The BESSY Soft X-Ray FEL
Peak Power and Brilliance



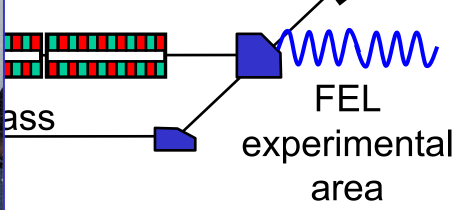
Experiments can be more readily extrapolated by the LASER community than by the synchrotron radiation community

VUV-FEL: Status of beamline installations

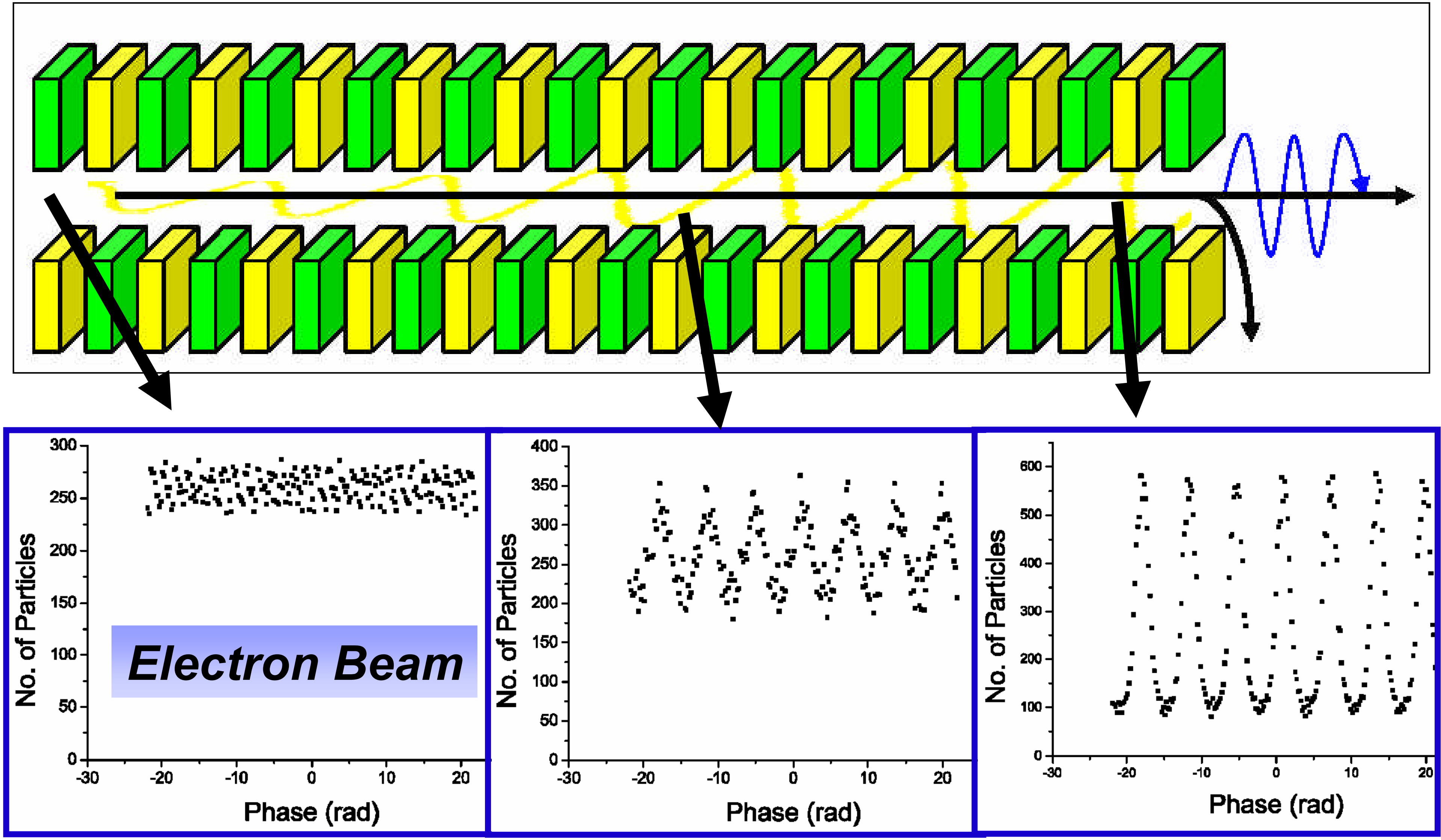




4 MeV

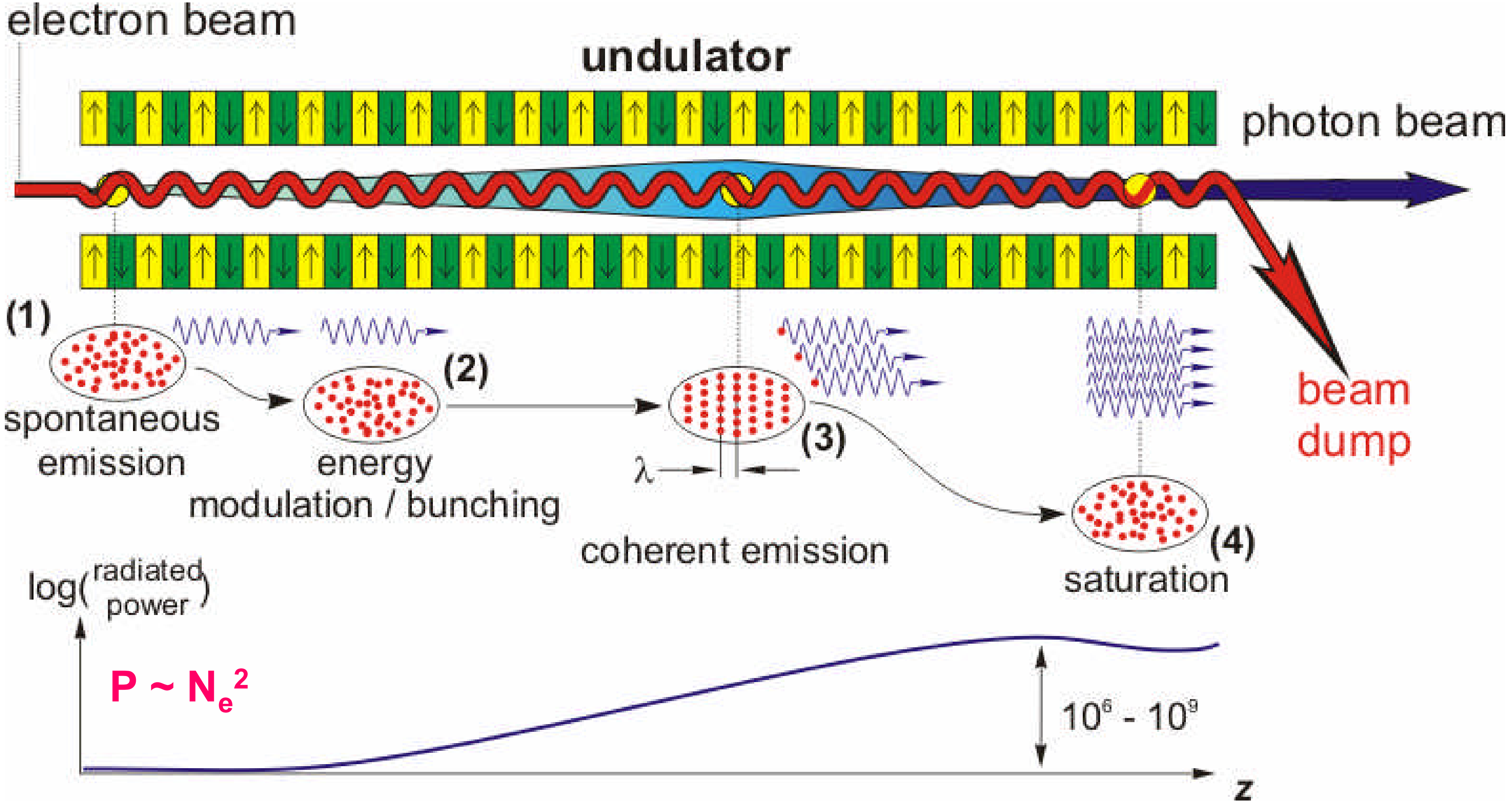


Funktion eines FEL

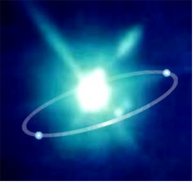


BESSY TDR

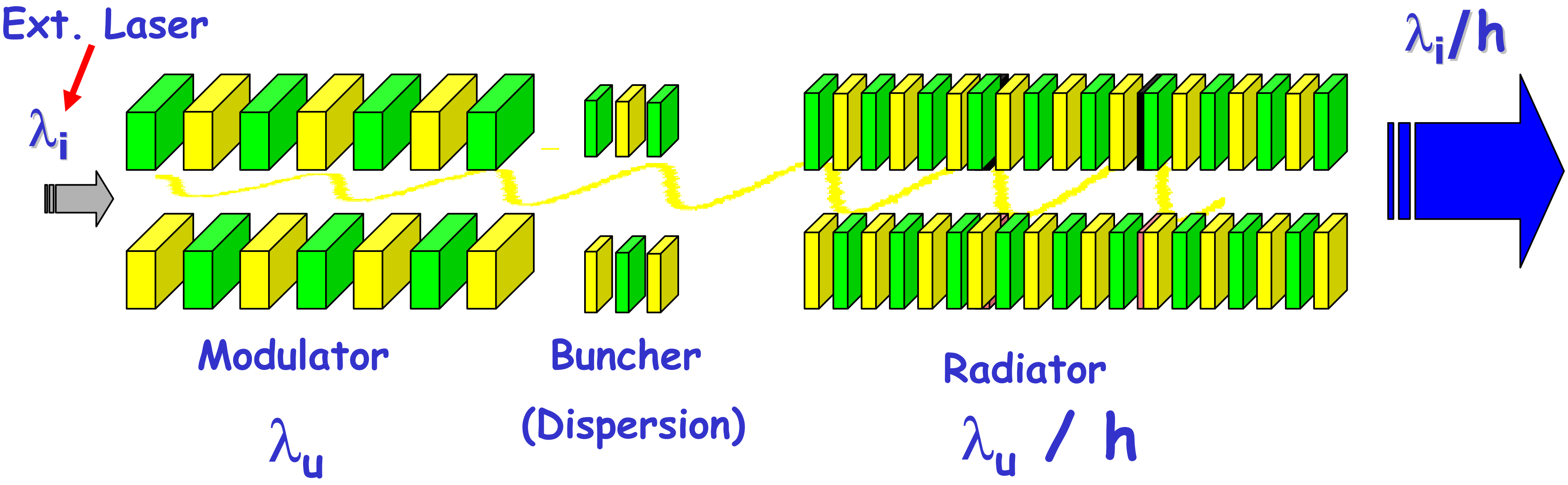
SELF AMPLIFIED SPONTANEOUS EMISSION „SASE“



Kondratenko, Saldin 1980



High Gain Harmonic Generation (HGHG)



Ext. Laser

λ_i

λ_i/h

Modulator

λ_u

Buncher

(Dispersion)

Radiator

λ_u / h

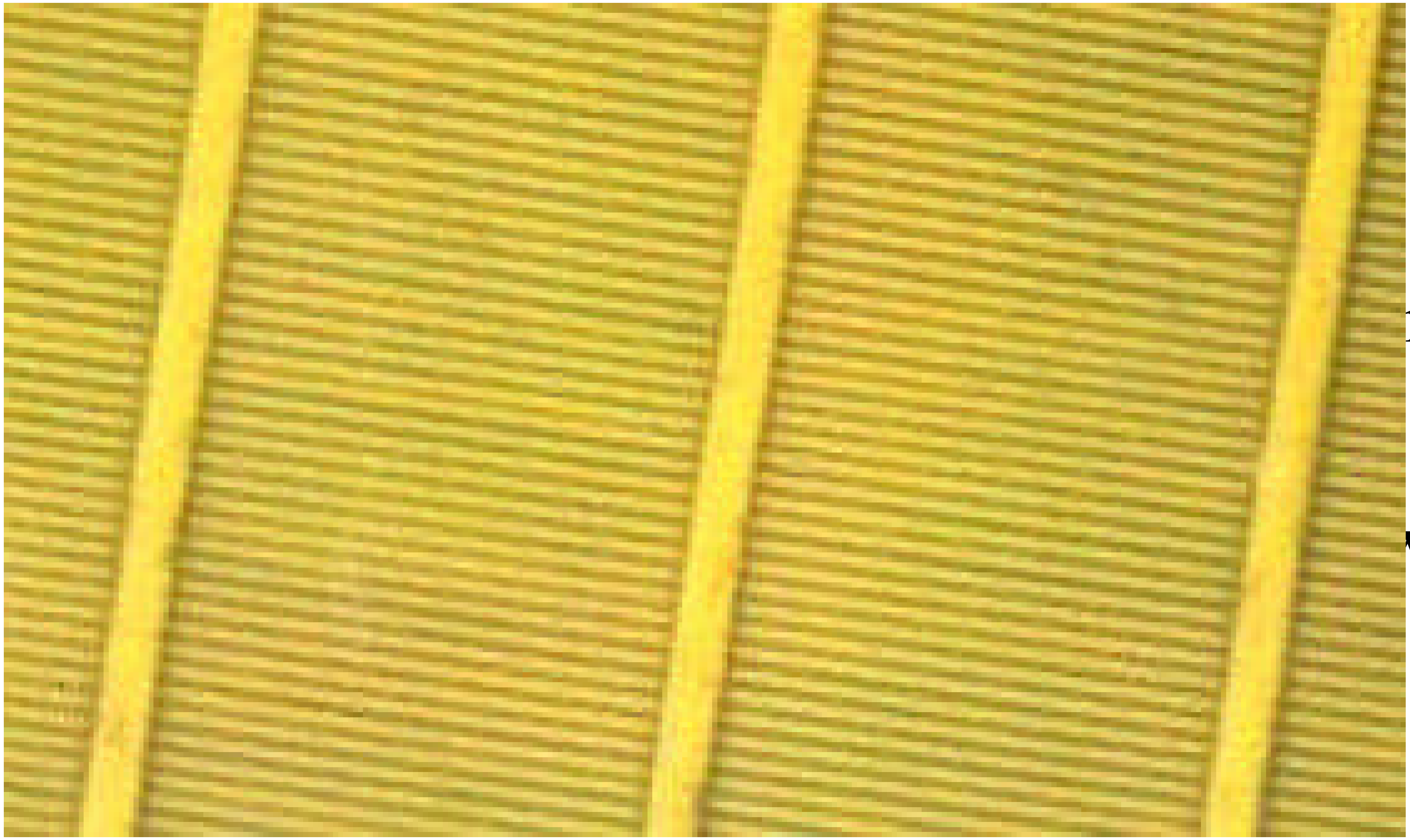
- Longitudinal coherence
- Ultra-fast pulses < 20 fs
- Reproducible pulse shape
- Non „chaotic“ light
- Intrinsic synchronization
- Attosecond HHG option

$$\lambda_w = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\Theta_0^2\right)$$

L.H. Yu, et. al. BNL

FEL Prize 2003

Energy selection



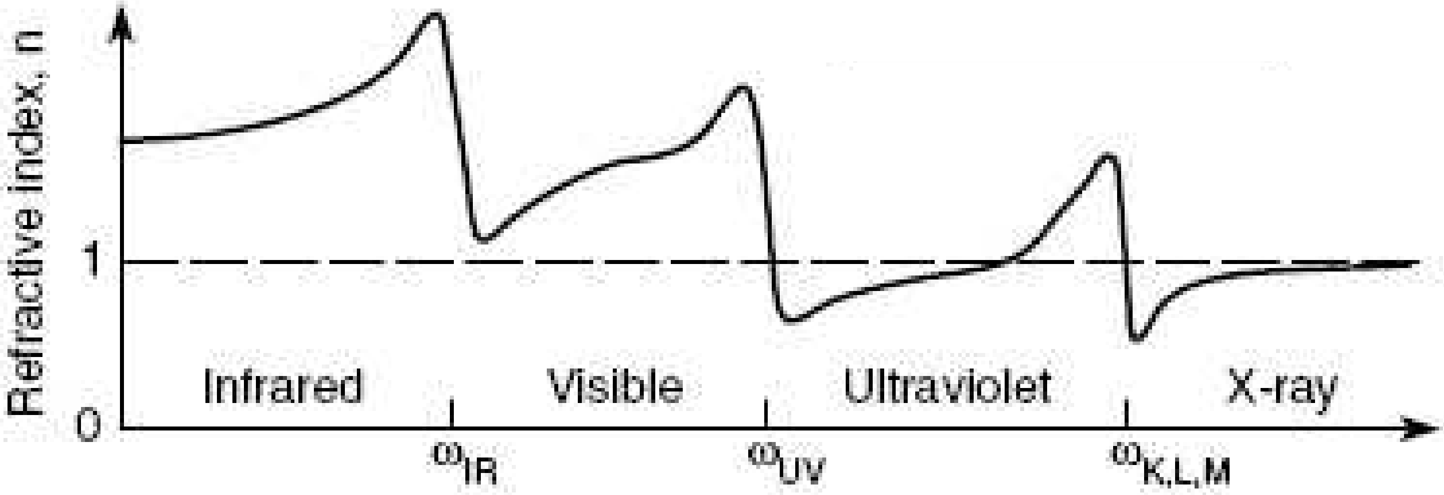
itiy

with

Energy selection

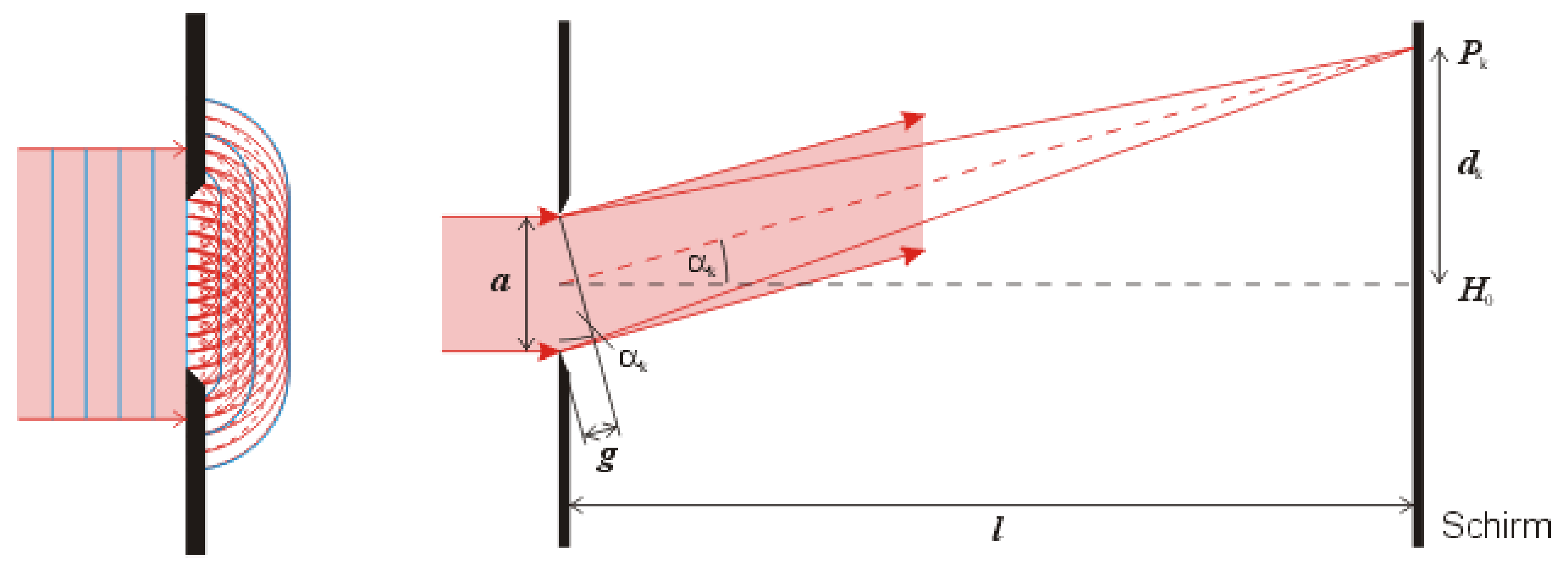
- The broad energy range of SR is usually unsuitable for experiments
- Energy selection by monochromatization by dispersive or grating systems (local discontinuitiy on optical properties with well-defined geometries)
- No suitable materials for dispersive elements with positive refractive index for high energies:
  - Gratings
  - Lattice planes of (Si)

Energy-dependence of refractive index



Single Slit Diffraction

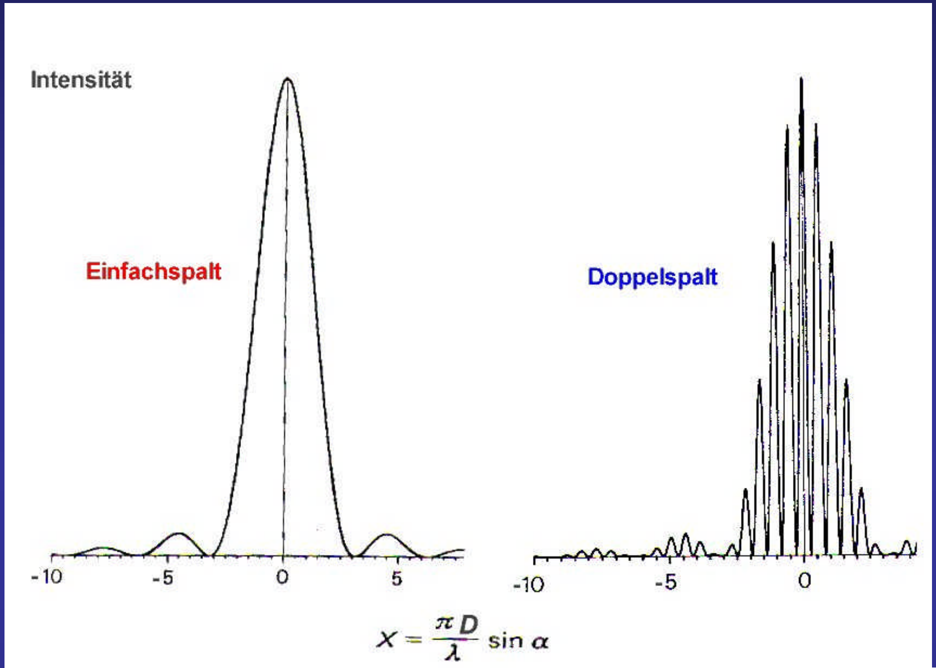
Princip of Huygens

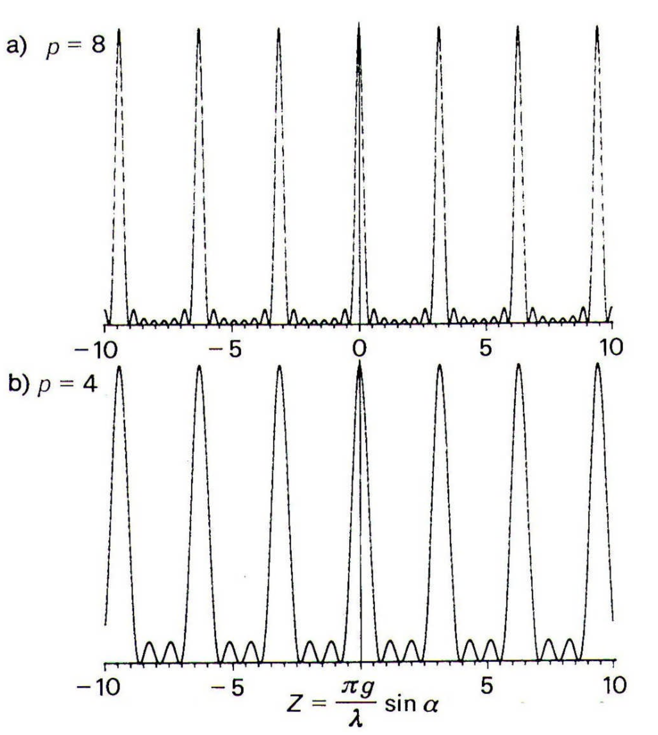


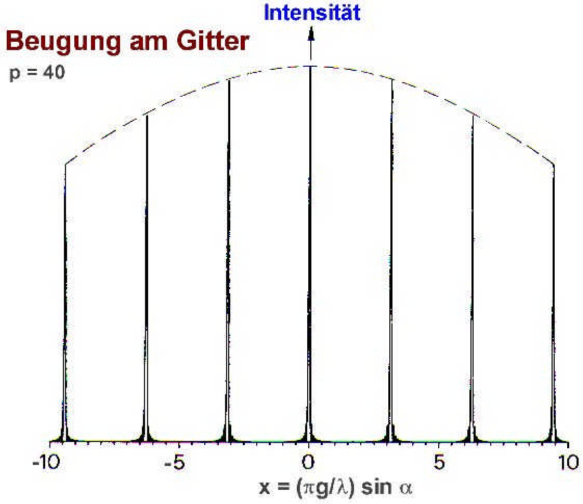
Minimum: g= k● k=1,2,3,...<a/●

sin ♋$_k$= g/a ; tan ♋$_k$ =d$_k$/l

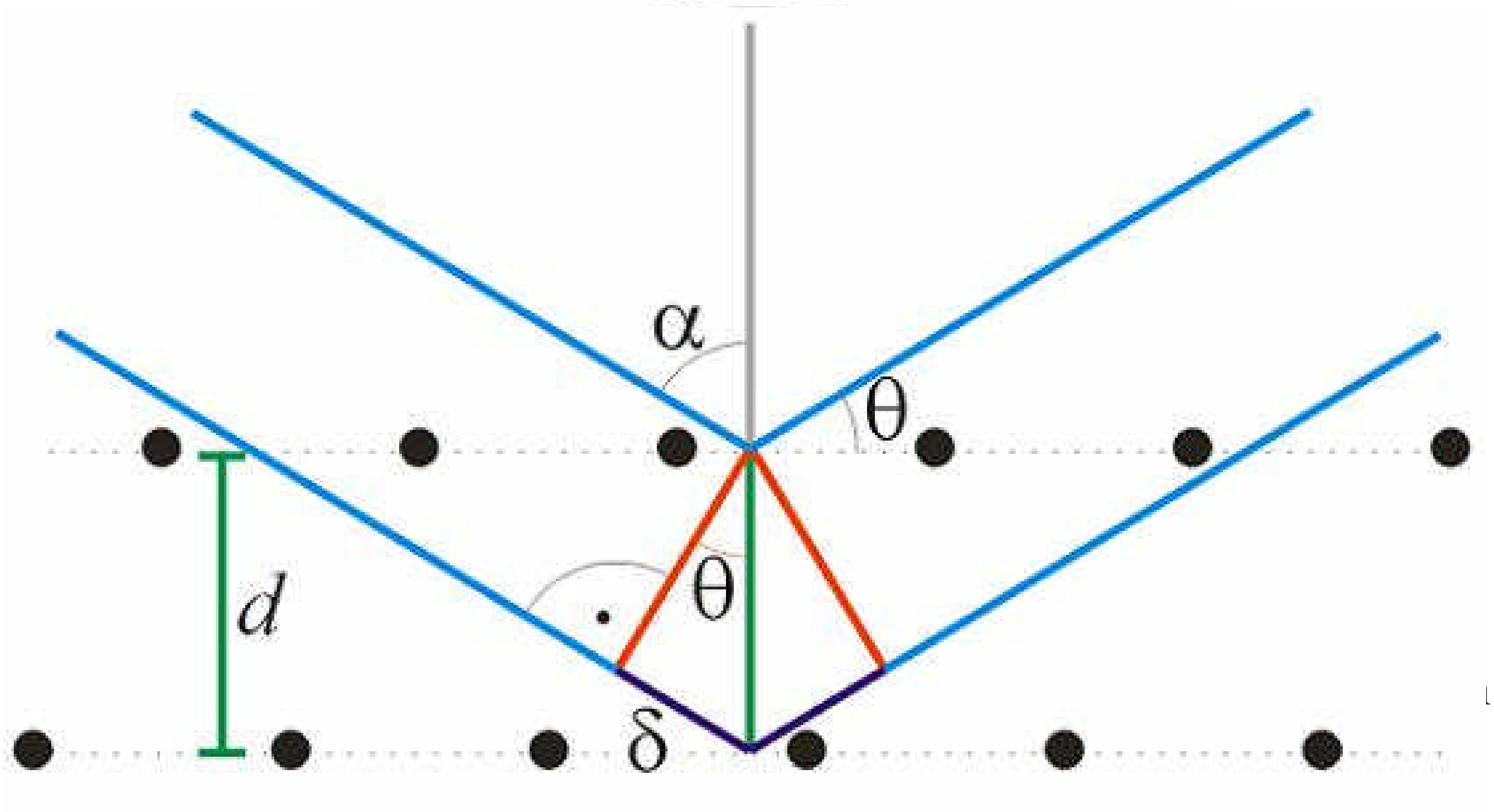
From single slit to grating: Diffraction pattern



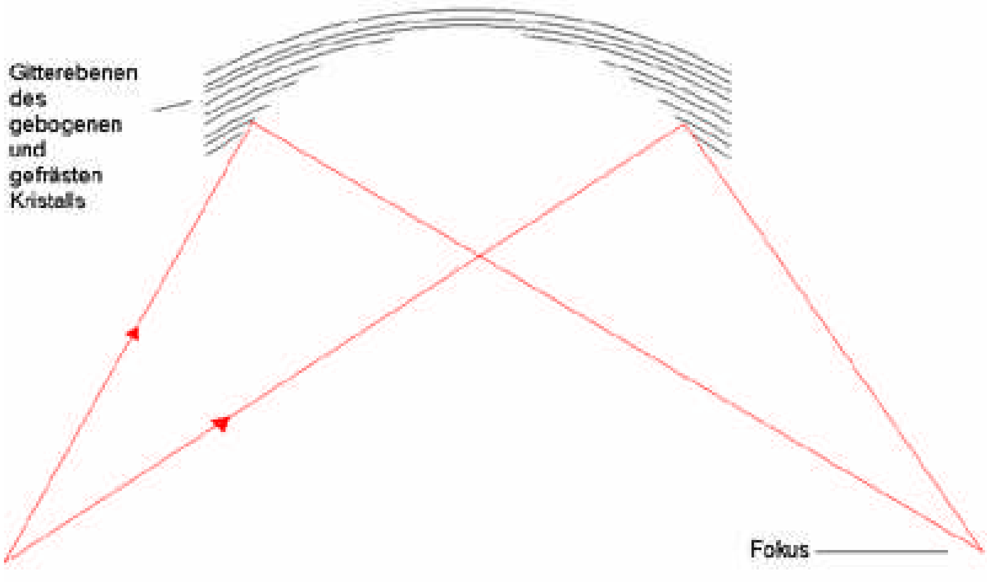




Crystal monochromator

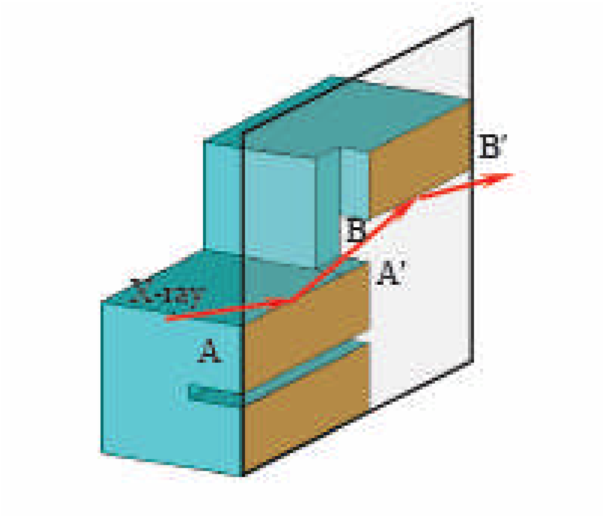


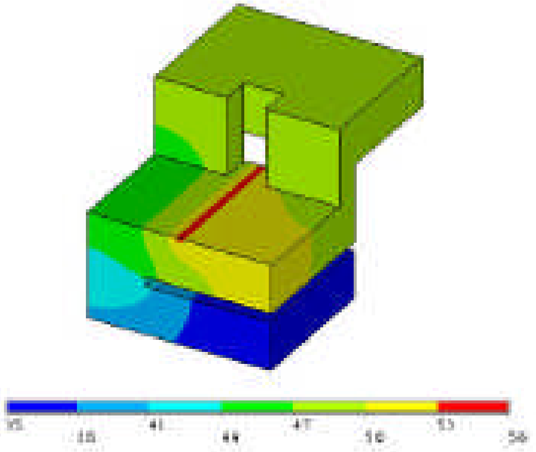
Crystal monochromator



Strongly exaggerated bending of a (Si) single crystal with subμ precision
Carving: energy selection by mechanical bending of the crystal

A practical double monochromator





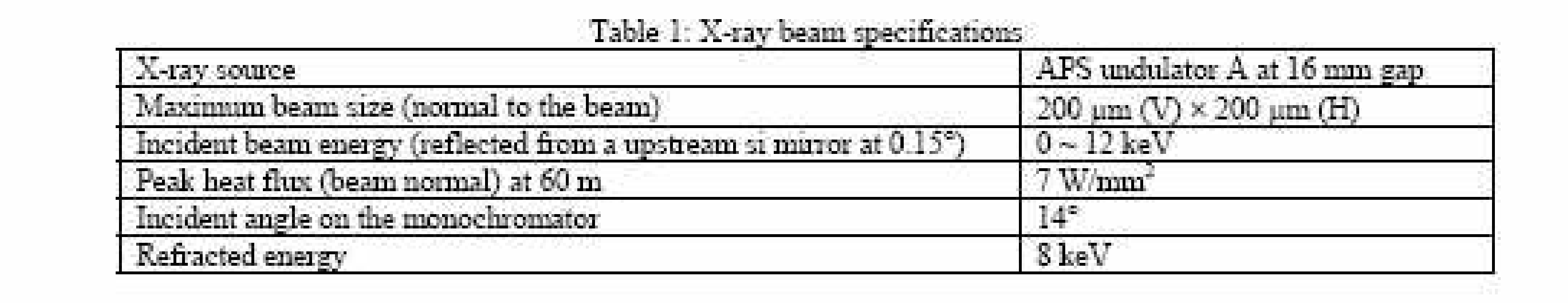
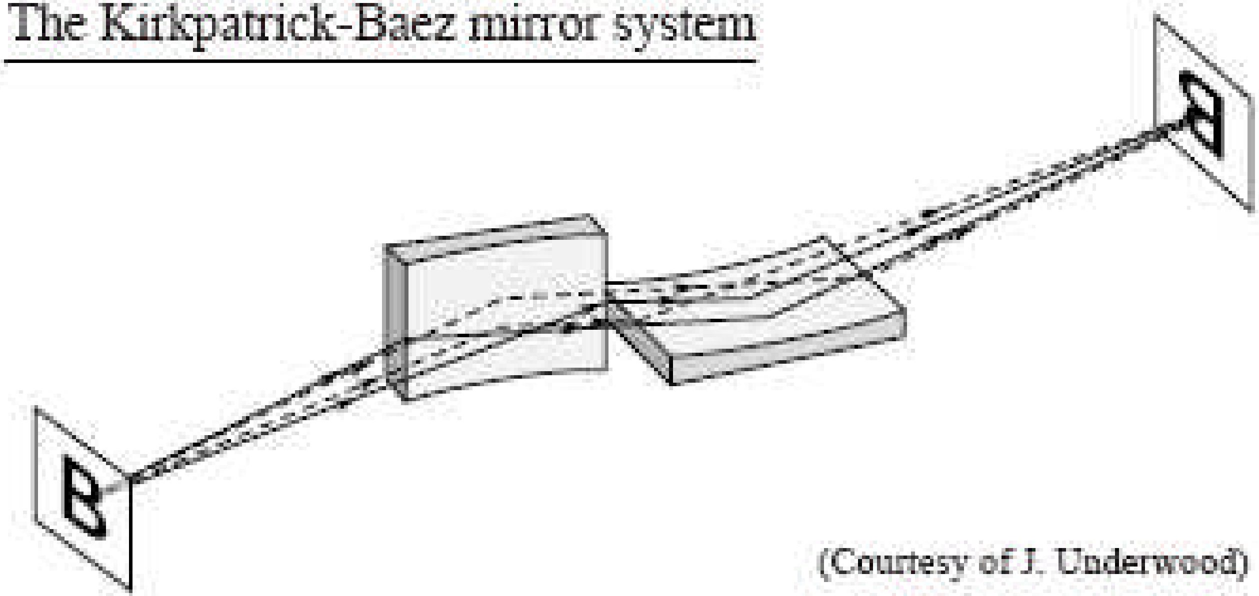


Table 1: X-ray beam specifications

X-ray source	APS undulator A at 16 mm gap
Maximum beam size (normal to the beam)	200 µm (V) × 200 µm (H)
Incident beam energy (reflected from a upstream si mirror at 0.15°)	0 ~ 12 keV
Peak heat flux (beam normal) at 60 m	7 W/mm^2
Incident angle on the monochromator	14°
Refracted energy	8 keV

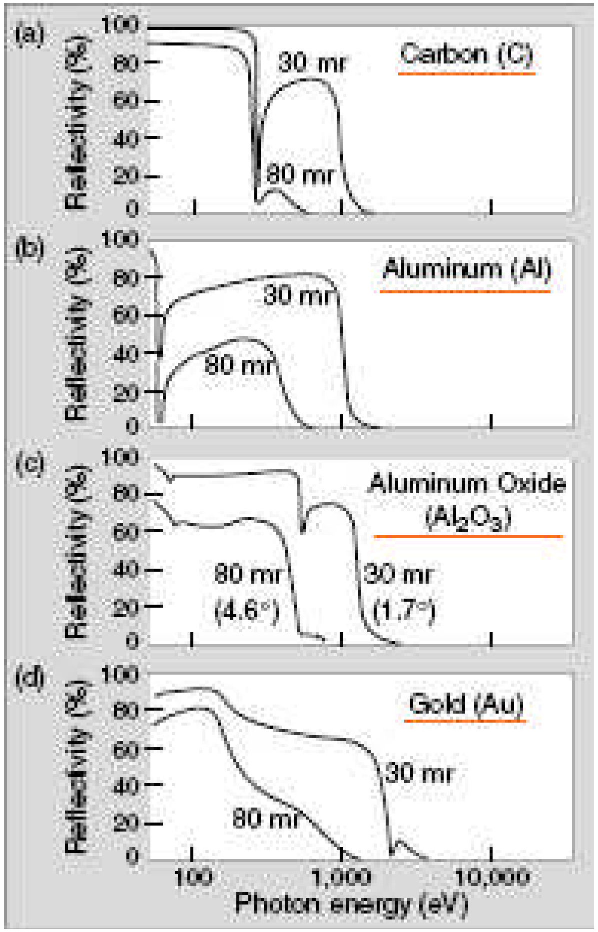
X-ray mirrors guiding SR light

The Kirkpatrick-Baez mirror system



(Courtesy of J. Underwood)

Materials for mirrors



Despite its poor reflectivity, Si is widely used for wide-energy applications

Synchrotron radiation: uses

- High-energy: X-rays for scattering techniques
  - X-ray, EXAFS (see following lecture)
- Low-energy: VUV or soft X-rays
  - Spectroscopy
  - Energy-dependent photoemission
  - X-ray absorption spectroscopy (like NEXAFS in high-energy range)