Accelerator-based photon sources

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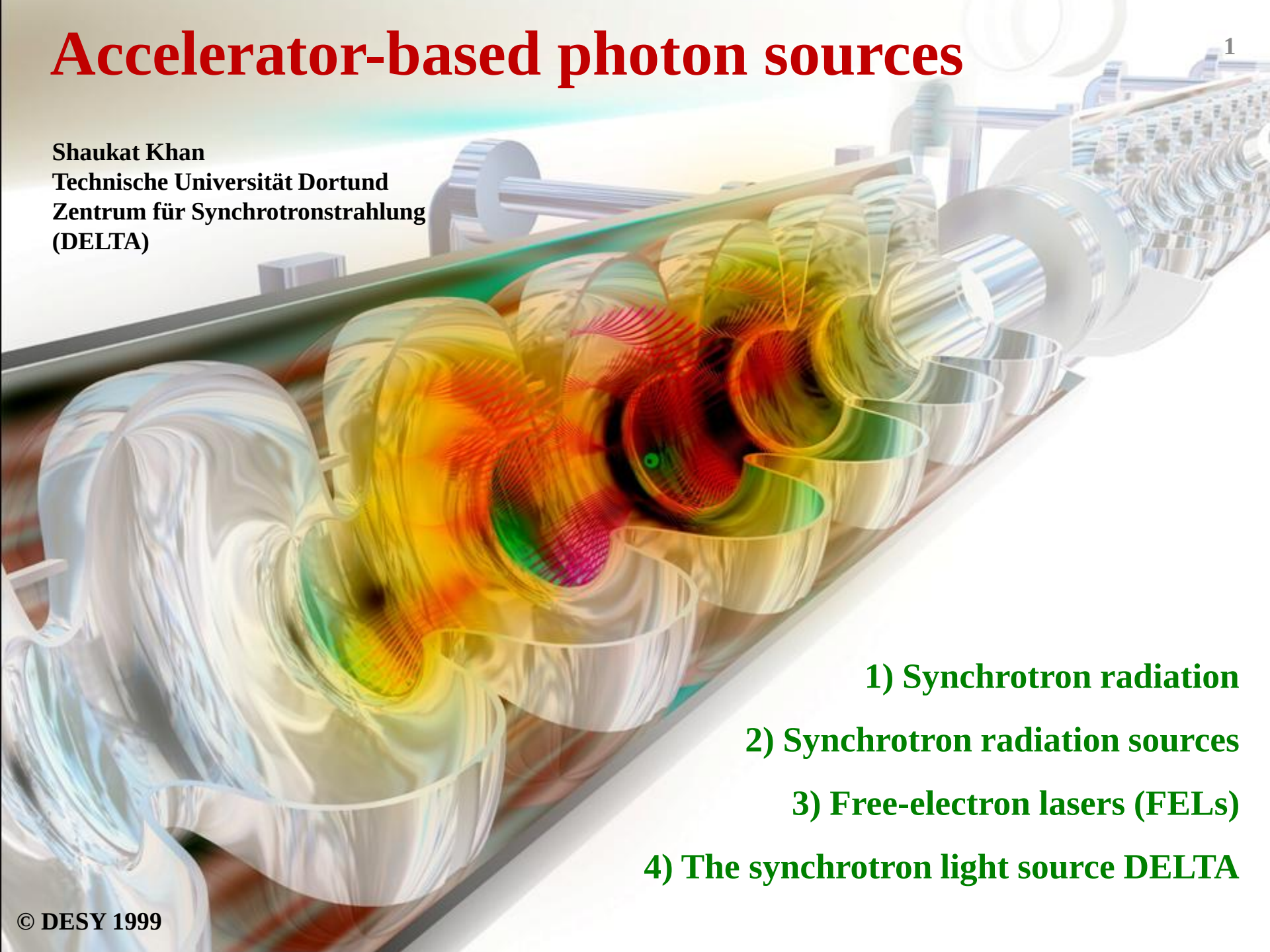

1) Synchrotron radiation

2) Synchrotron radiation sources

3) Free-electron lasers (FELs)

4) The synchrotron light source DELTA

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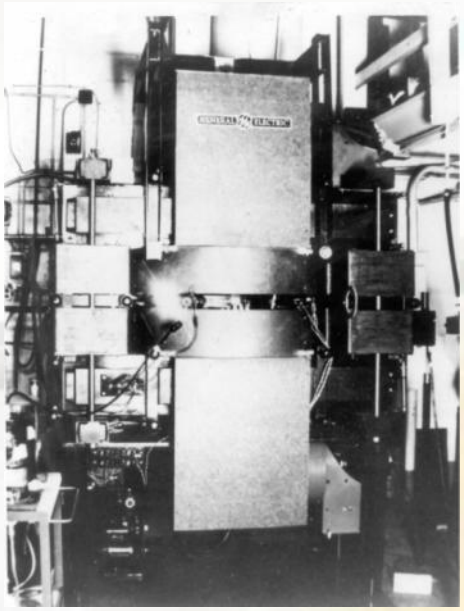
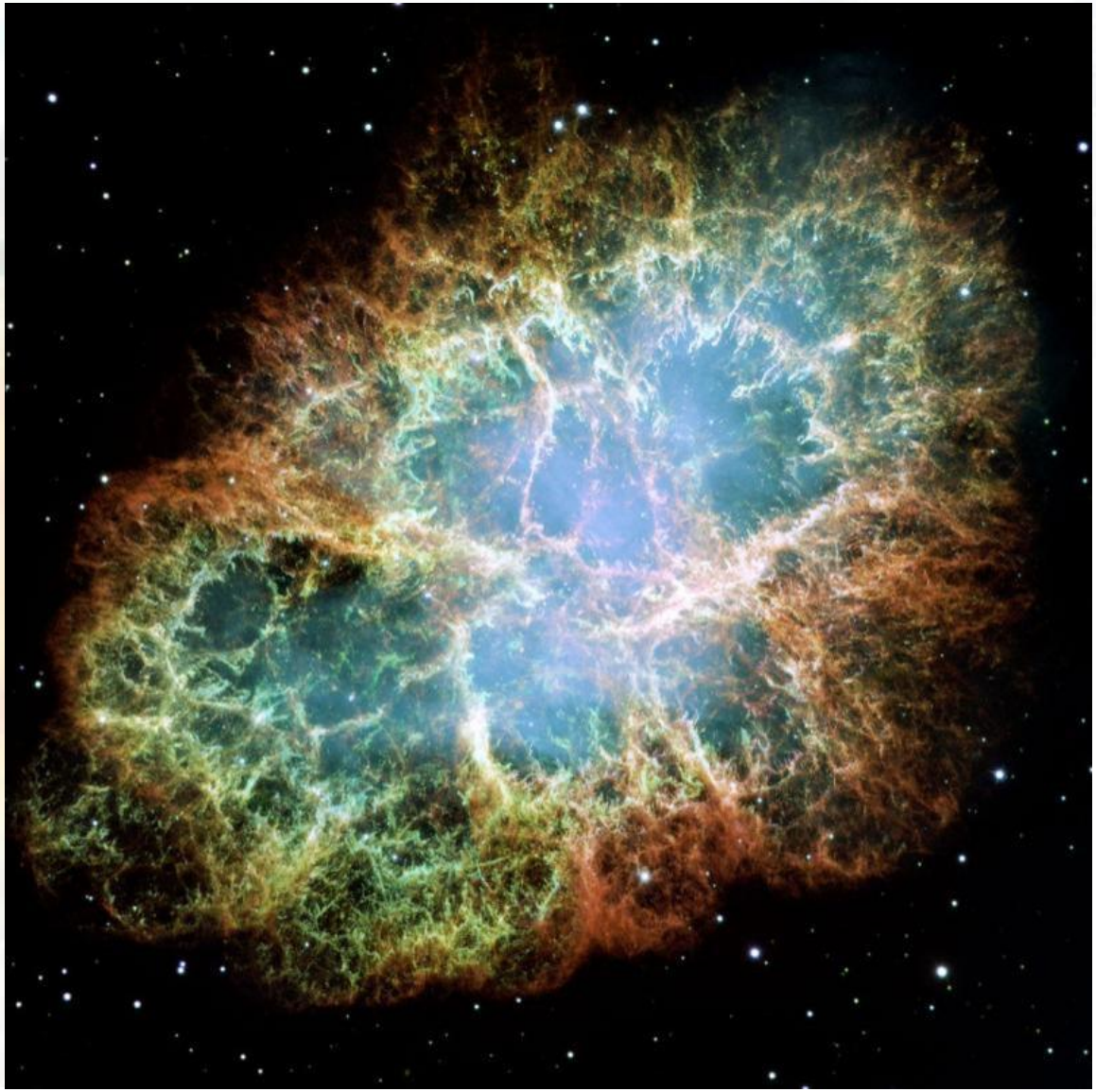
1) Synchrotron radiation



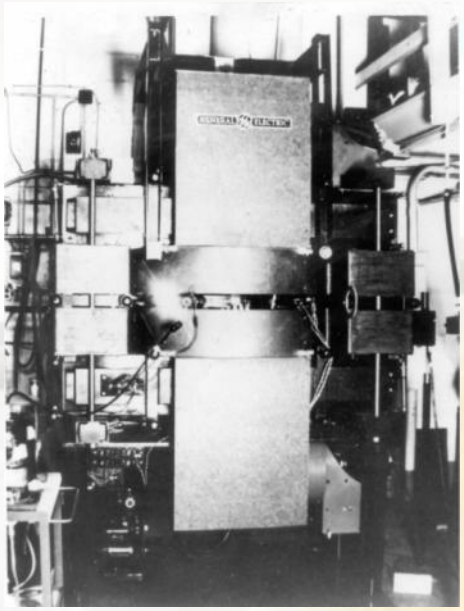


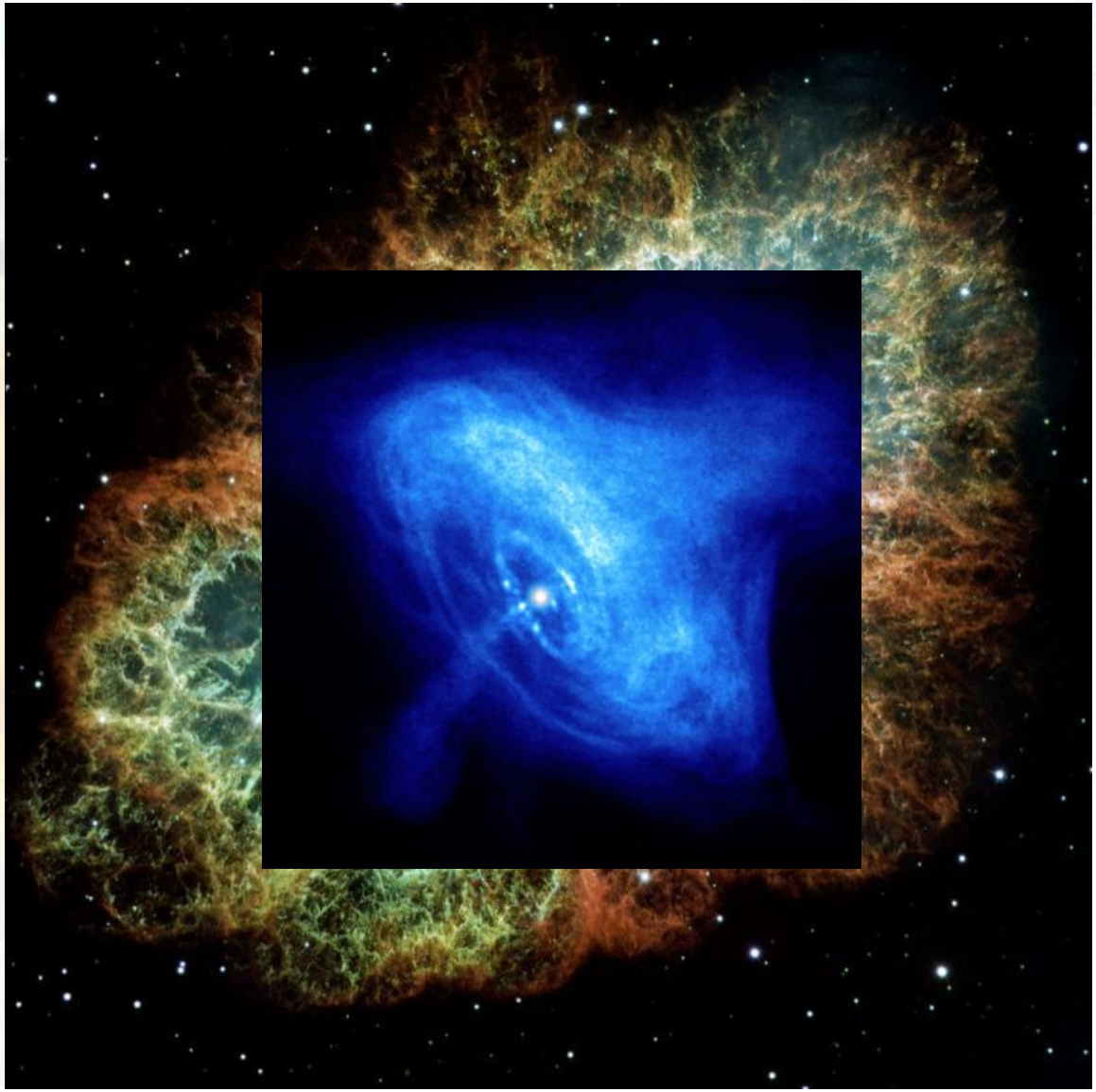
1947: Some intermittent sparking had occurred, ...

... but it soon became clearer that we were seeing Ivanenko and Pomeranchuk radiation.

(H. C. Pollock)

1) Synchrotron radiation



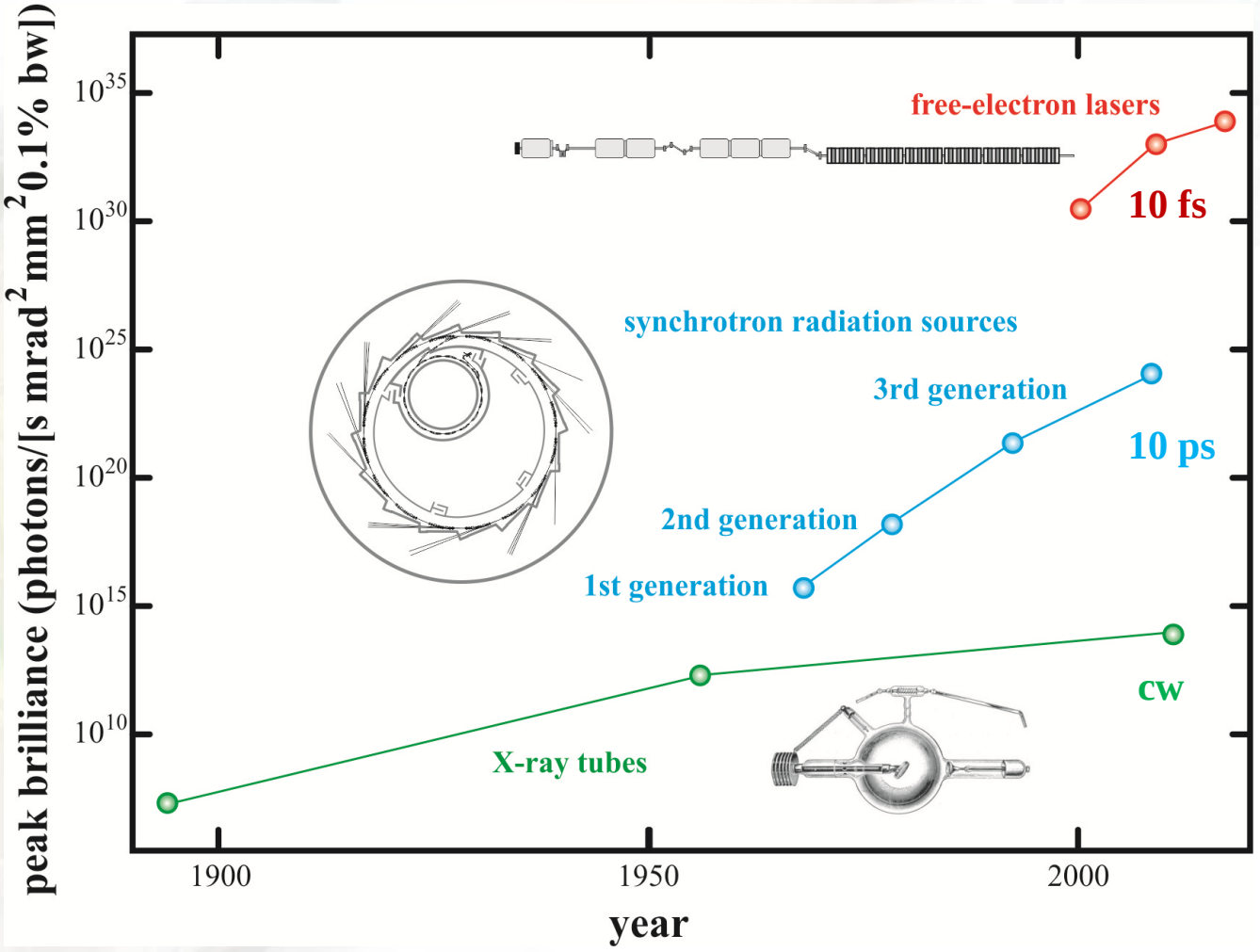


1947: Some intermittent sparking had occurred, ...

... but it soon became clearer that we were seeing Ivanenko and Pomeranchuk radiation.

(H. C. Pollock)

Brilliance $= \dfrac{\text{photons / time [s]}}{\text{source area [mm}^2\text{]} \cdot \text{solid angle [mrad}^2\text{]} \cdot \text{bandwidth [0.1\%]}}$



History

1947 first direct observation of synchrotron light (Schenectady, USA)

1953 first undulator by H. Motz (Stanford, USA)

1960s 1. generation of synchrotron light sources (SURF, DESY ...)

1970s 2. generation of synchrotron light sources (SRS, NSLS, BESSY ...)

1971 invention of the free-electron laser by J. Madey (Stanford, USA)

1977 first free-electron laser (FEL) at 3.7 μm (Stanford, USA)

1990s 3. generation of synchrotron light sources (ESRF, ALS, BESSY II ...)

2000 first sub-visible FEL (TTF, DESY, Hamburg, Germany)

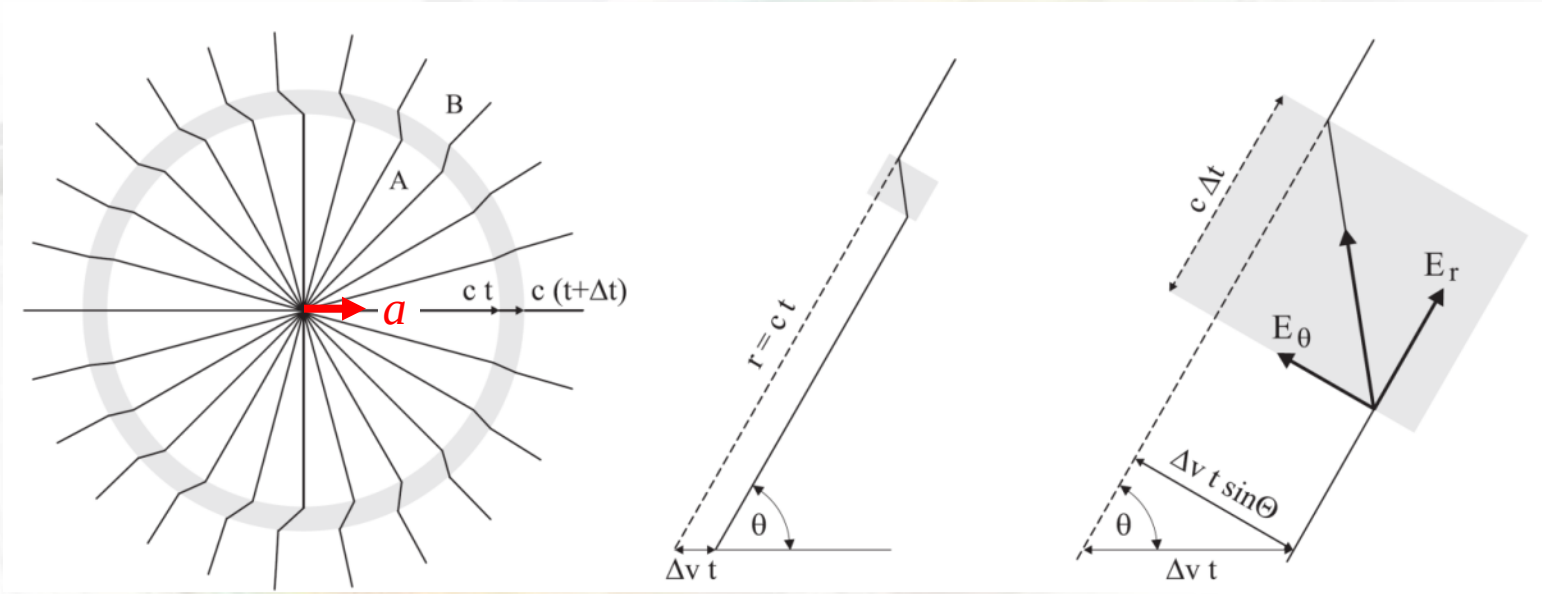
2009 first hard-X-ray FEL (LCLS, SLAC, Menlo Park, USA)

2010s 4. generation of synchrotron light sources (PETRA III, MAX IV, ...)

Radiation from accelerated electric charge

A simple example

Joseph J. Thomson



Power into solid angle $d\Omega$ is $P(\theta)\cdot d\Omega = \frac{e^2}{16\pi^2\varepsilon_0 c^3}\cdot a^2\cdot\sin^2\theta\cdot d\Omega$

depends on acceleration $a = \Delta v/\Delta t$

and emission angle θ

Radiation from accelerated electric charge

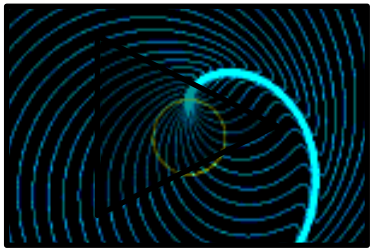
Retarded (Liénard-Wiechert) potentials describe distortions of the electric field:

Alfred-Marie Lienard

Emil Wiechert

$$\vec{E}(t) = \frac{e}{4\pi\varepsilon_0\left(1-\vec{n}\cdot\vec{\beta}\right)^3}\left(\frac{1-\beta^2}{R^2}\left(\vec{n}-\vec{\beta}\right)+\frac{1}{cR}\left(\vec{n}\times\left[\left(\vec{n}+\vec{n}\vec{\beta}\right)\times\frac{d\vec{\beta}}{dt}\right]\right)\right)_{\text{ret}}$$

Coulomb term ~ $1/R^2$ **radiation term ~ $1/R$**

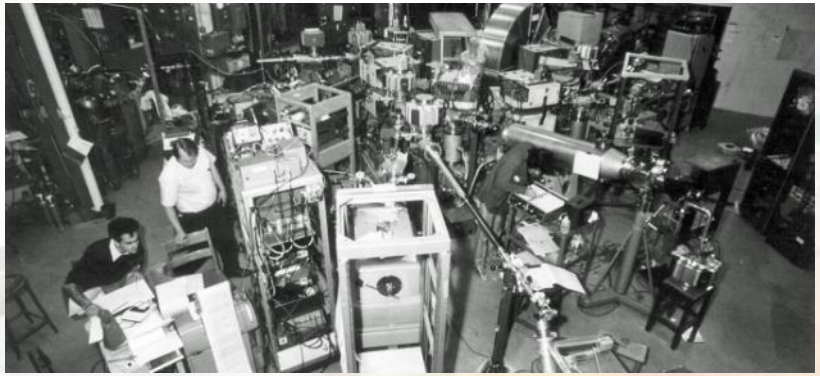


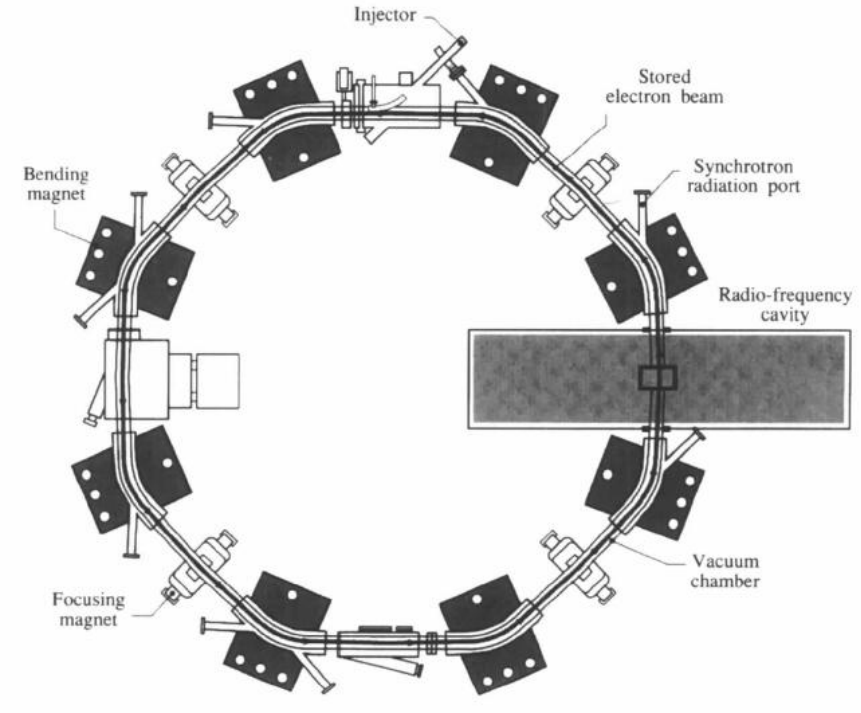
Program Radiation 2D
by T. Shintake, OIST

2) Synchrotron Radiation Sources

Synchrotron light sources: 1. generation

Example: Tantalus, University of Wisconsin, USA





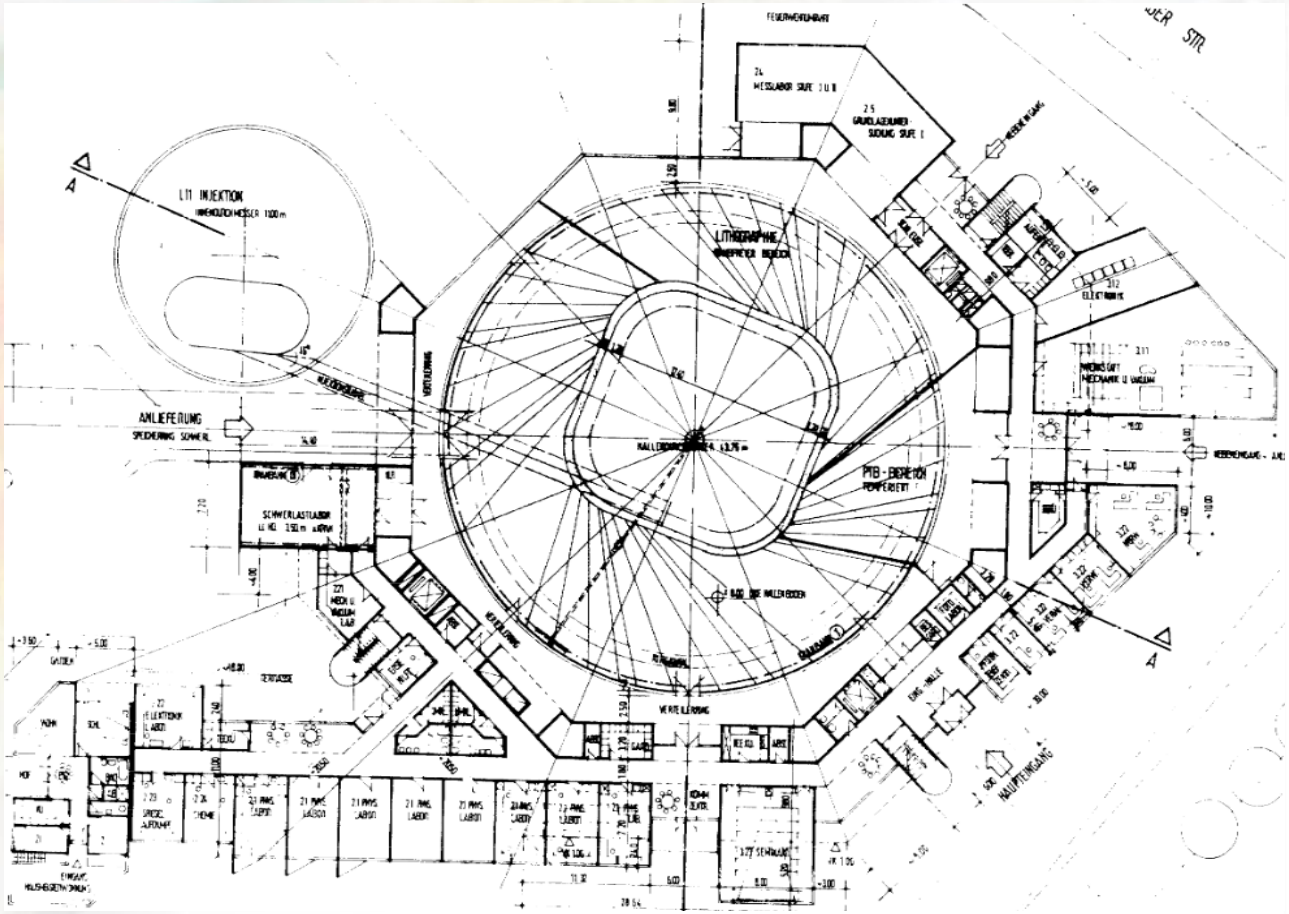
- **FFAG**
- **storage ring 40 to 240 MeV**

D. W. Lynch, J. Sync. Rad. 4 (1997), 334

Synchrotron light sources: 2. generation

Example: BESSY, Berlin, Germany

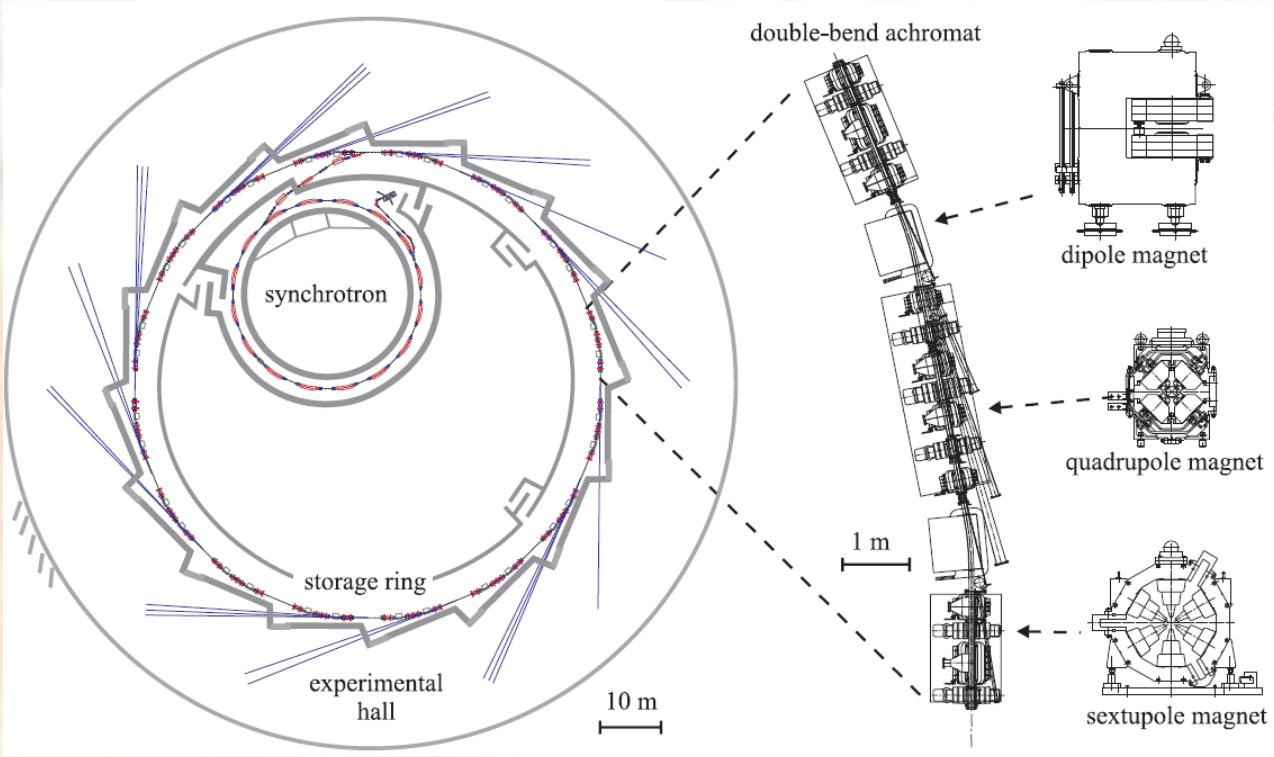
- **microtron**
- **synchrotron**
- **800-MeV storage ring**



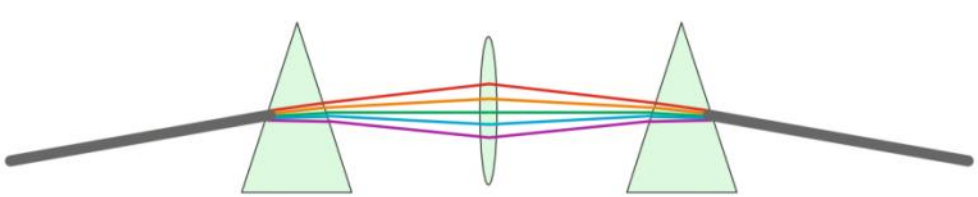
Synchrotron light sources: 3. generation

Example: BESSY in Berlin

- linac
- synchrotron
- 1.7-GeV storage ring



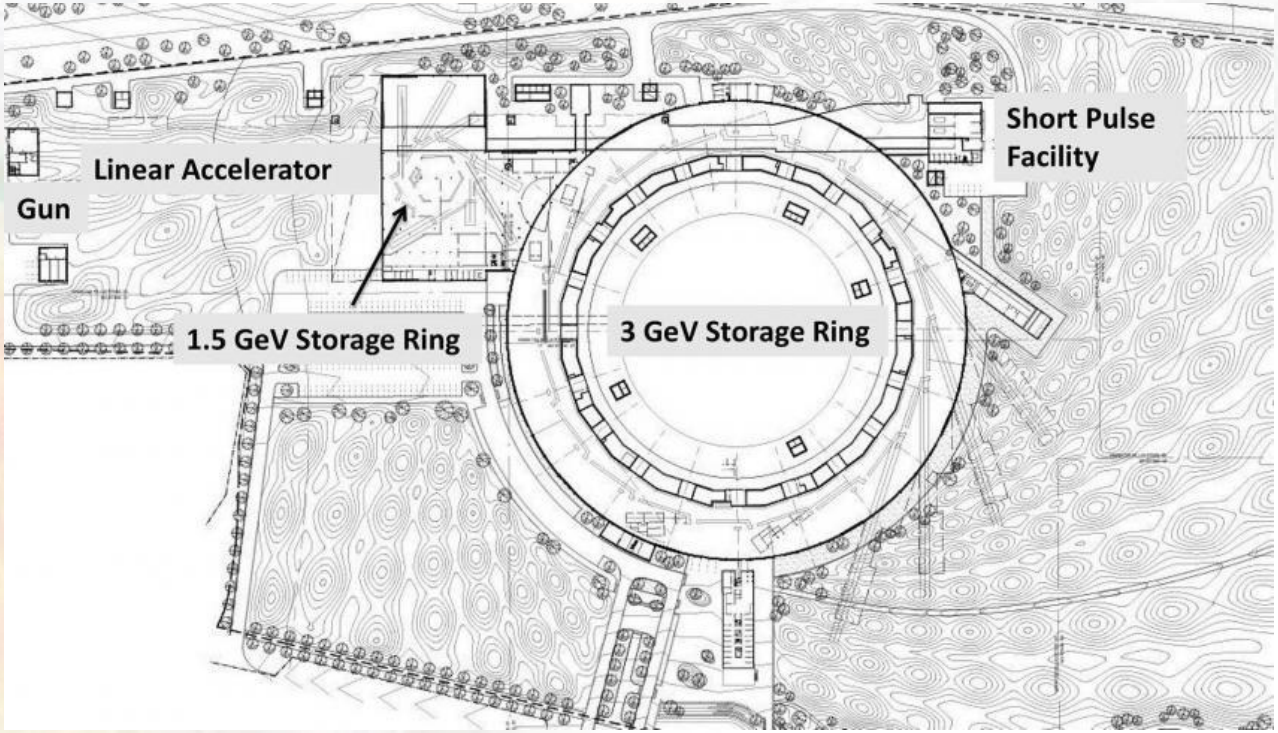
Lattice type: double-bend achromat



Synchrotron light sources: 4. generation

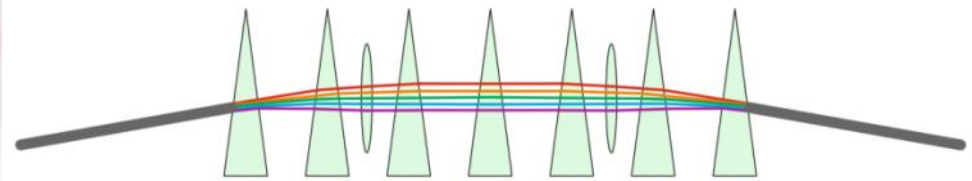
Example: MAX IV in Lund

P. Tavares et al., J. Sync. Rad. 21 (2014), 862



- full-energy linac
- 1.5-GeV storage ring
- 3.0-GeV storage ring

Lattice type: 7-bend achromat



Synchrotron light sources

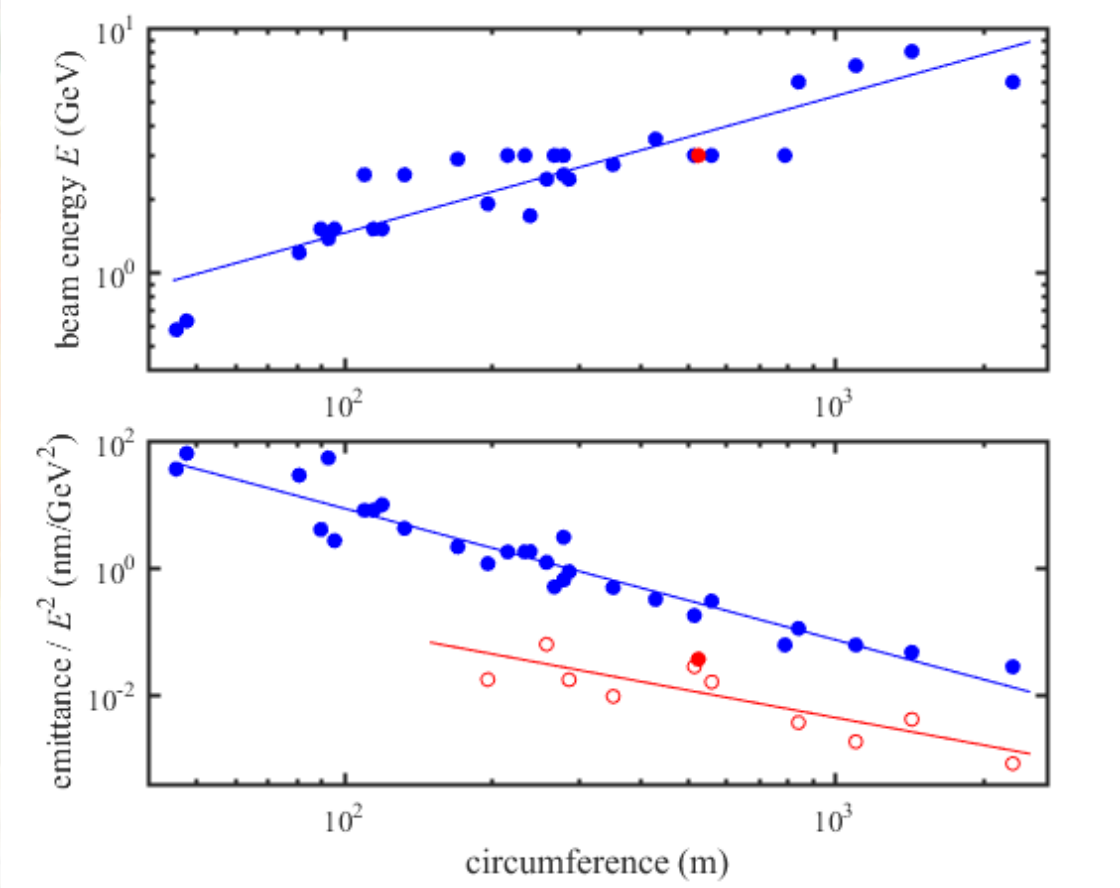
Horizontal emittance = horizontal source size · divergence $\varepsilon_x \propto E^2 / N_D^3$

Vertical emittance = fraction of ε_x (1% or less) depending on magnet errors

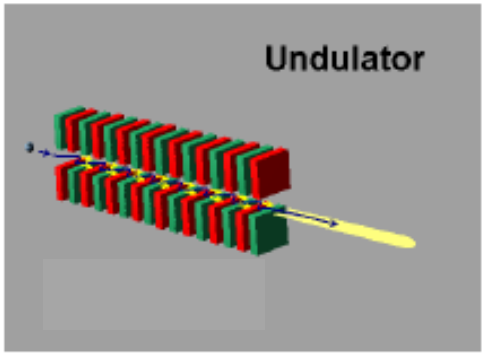
Blue: 3rd-generation light sources since 1992

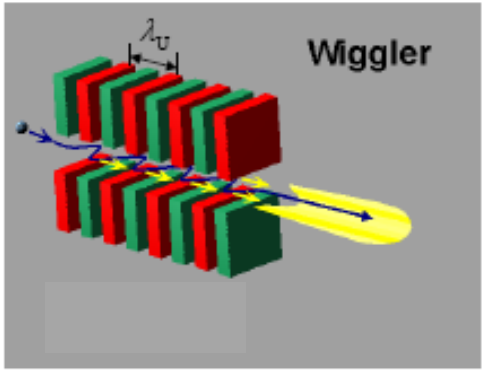
Red dot: MAX IV

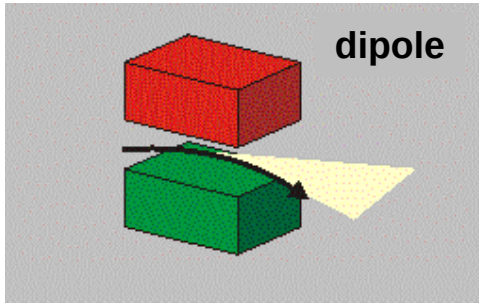
Red circles: upgrade of other light sources with multibend lattice

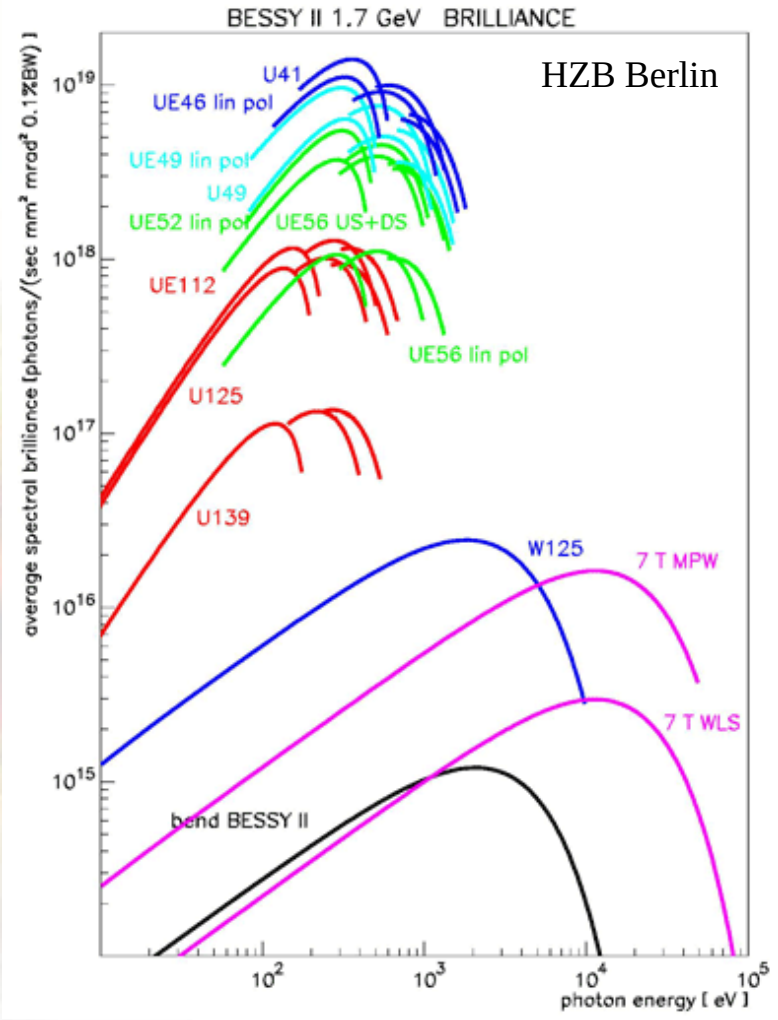


Synchrotron light sources









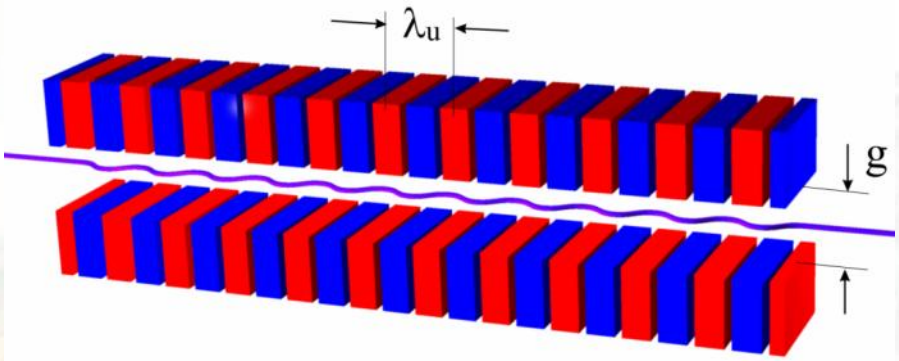
broad spectrum

critical energy

$$E_c\left[\text{keV}\right] = 0.665 \cdot E^2\left[\text{GeV}^2\right] \cdot B[\text{T}]$$

Synchrotron light sources

Undulators



planar or helical, outside or in vacuum, electromagnets or permanent magnets

λ_U : **period length**
N_U : **number of periods**
***K*: undulator parameter**

$$K \equiv \frac{\lambda_U e\hat{B}}{2\pi m_e c} = 93.4 \cdot \lambda_U\,[\mathrm{m}] \cdot \hat{B}[\mathrm{T}]$$

γ: **Lorentz factor**

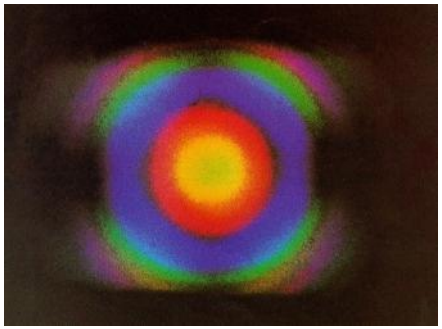
$$\gamma = E / 0.511\ \mathrm{MeV}$$

Line spectrum: fundamental + harmonics

$$\lambda = \frac{\lambda_U}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) + \frac{\lambda_U}{2}\theta^2$$

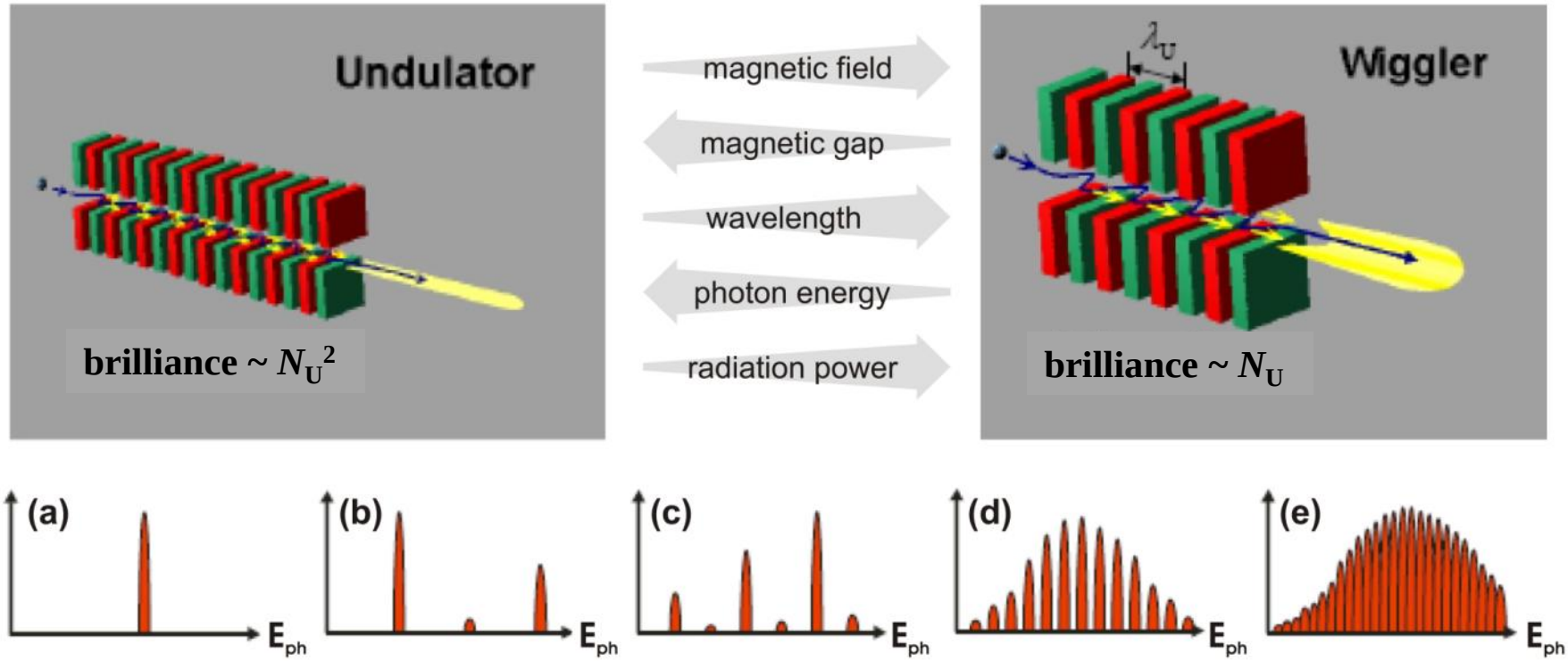
line width

$$\frac{\Delta\lambda}{\lambda} \approx \frac{0.9}{N_U} \quad (\mathrm{FWHM})$$



Synchrotron light sources

Undulators and wigglers – summary



Synchrotron light sources

Incoherent and coherent emission

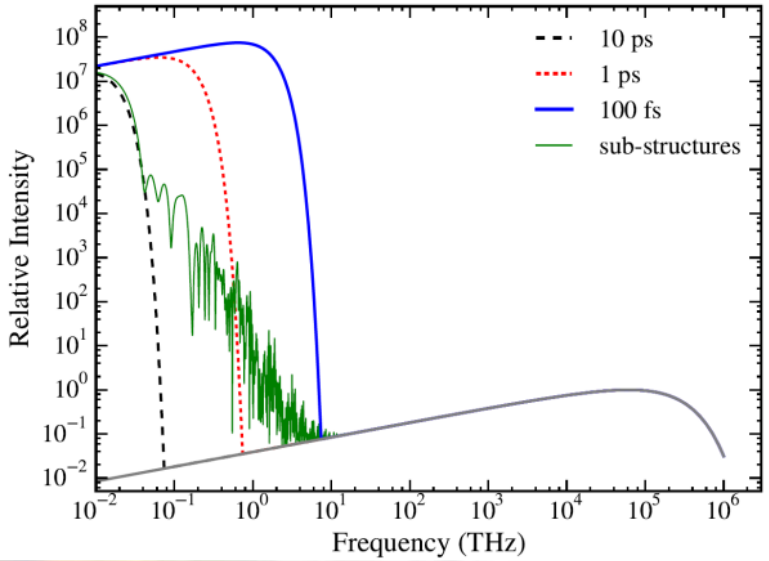
Radiation power

$$P(\omega) = N_e \cdot P_e(\omega) + N_e^2 \cdot g^2(\omega) \cdot P_e(\omega)$$

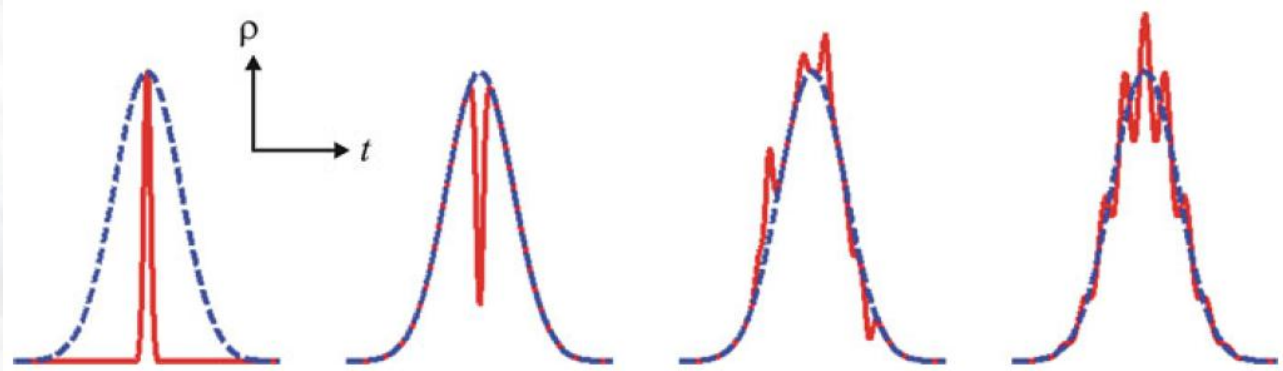
Gaussian bunch with rms length σ:

form factor $\quad g^2(\omega) = e^{-(\omega \cdot \sigma / c)^2 / 2}$

A.-S. Müller, M. Schwarz (KIT)



Generally: coherent emission for

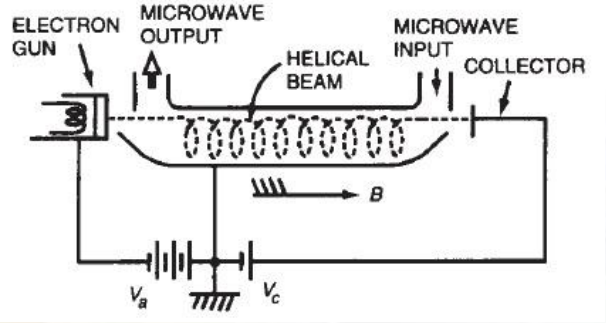


short bunch **short dip** **fluctuations** **microbunching**

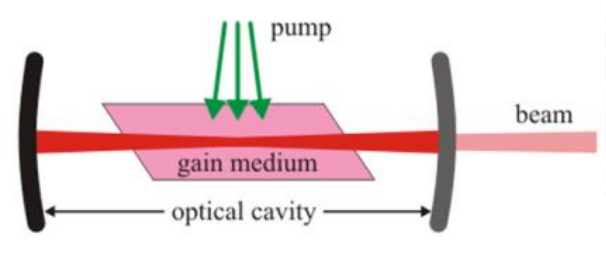
3) Free-electron lasers

What is a free-electron laser (FEL)?

Electrical engineer:
amplifier tube like the klystron

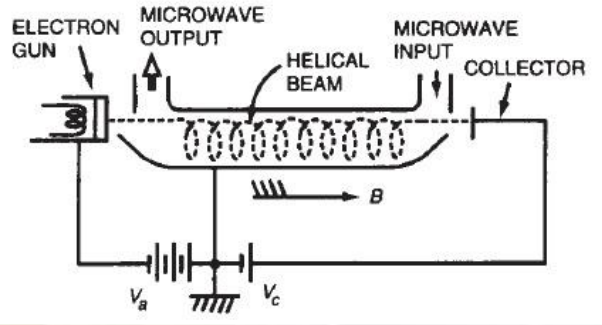


Laser physicist:
stimulated emission with free electrons

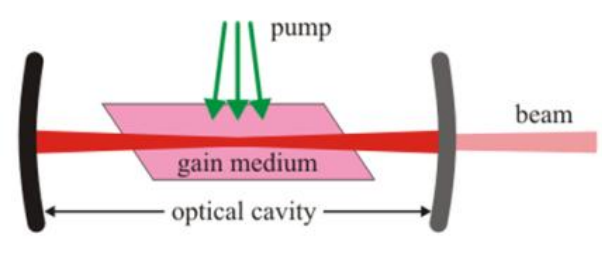


Accelerator physicist:
special type of synchrotron light source

What is a free-electron laser (FEL)?



Electrical engineer:
amplifier tube like the klystron

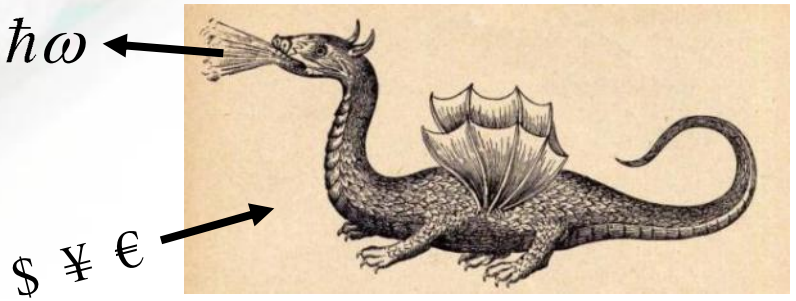


Laser physicist:
stimulated emission with free electrons

Accelerator physicist:
special type of synchrotron light source

User:
magic creature producing intense light when well-fed

... tunable wavelength in different regimes (THz to X-ray)
... high pulse energy (mJ)
... short pulse duration (fs)
... high degree of coherence
... limited repetition rate (kHz)
... limited pulse-to-pulse stability

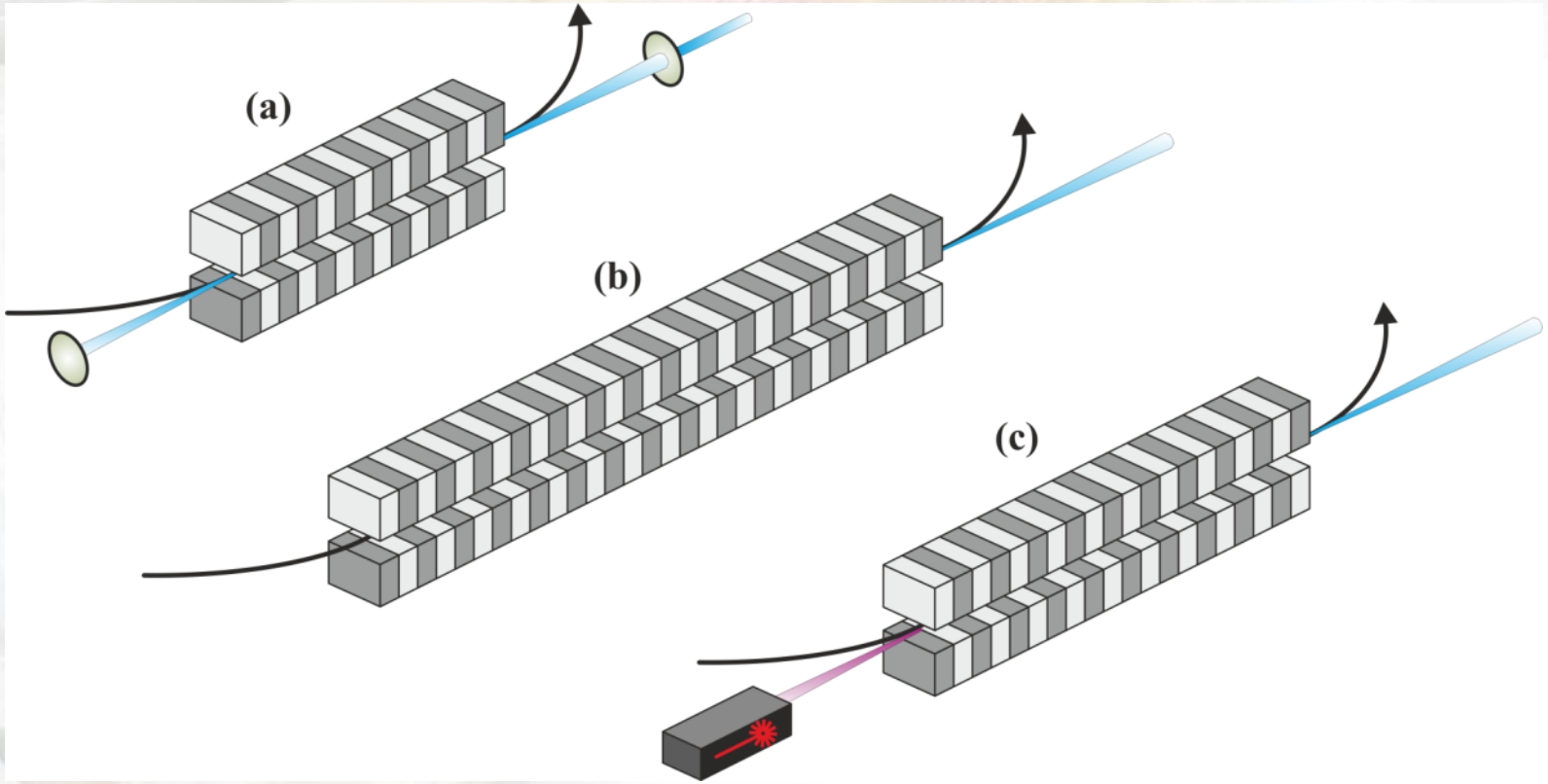


FEL types

(a) FEL oscillator: low-gain FEL, often used as far-infrared source

(b) SASE FEL: high-gain FEL starting from noise, soft and hard X-ray source

(c) Seeded FEL: high-gain FEL with external pulses, usually soft X-rays source



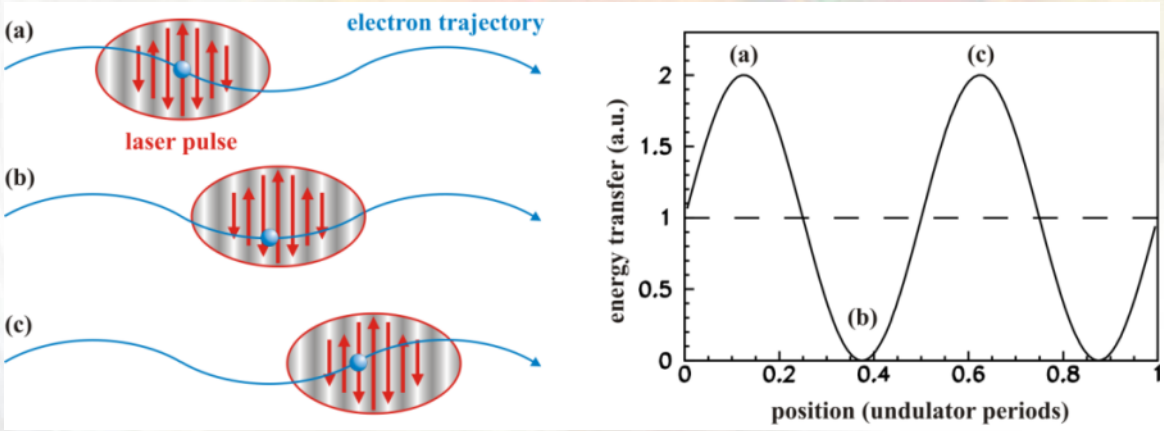
Basic process

Exchange of energy between electron and radiation in an undulator

$$\frac{dW}{dt} = \frac{\vec{F} \cdot d\vec{s}}{dt} = -e \cdot \vec{E}_L(t) \cdot \vec{v}(t) = -e \cdot E_L(t) \cdot v_\perp(t)$$

Assume plane light wave, same sign of dW over the whole undulator requires

$$\lambda = \frac{\lambda_U}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$ **i.e., radiation wavelength = undulator wavelength**



Electron lags behind the light field by one wavelength per undulator period ("slippage")

Basic process

Two coupled equation describe the electron motion of low-gain FELs (E_0 constant)

Define relative energy offset $\eta \equiv \frac{\Delta\gamma}{\gamma}$ and longitudinal phase offset Ψ

$$\frac{d\eta}{dt} = -\frac{eE_0K}{2m_ec\gamma^2}\cdot\sin\Psi$$

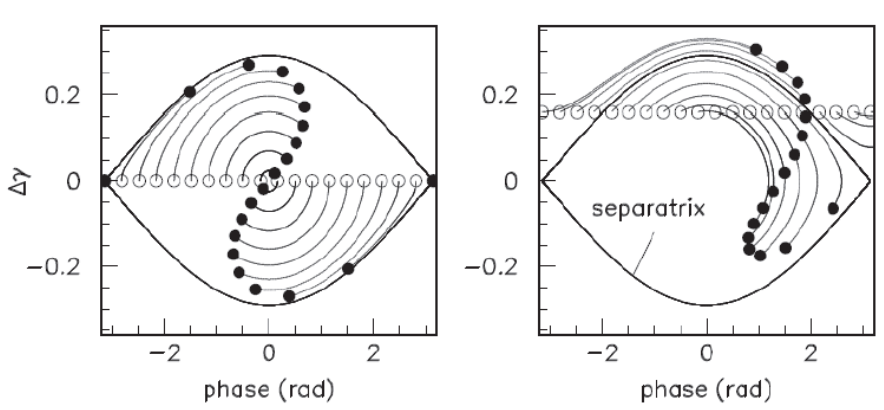
energy gained or lost depends on the phase offset

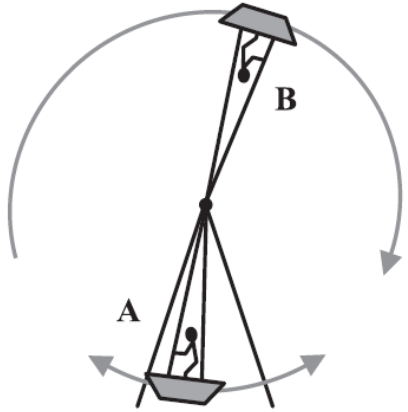
$$\frac{d\Psi}{dt} = 2k_Uc\cdot\eta$$

change of phase depends on the energy offset

$$\rightarrow \ddot{\Psi} + \Omega^2\sin\Psi = 0 \qquad \Omega^2 \equiv \frac{eE_0k_UK}{m_e\gamma^2}$$

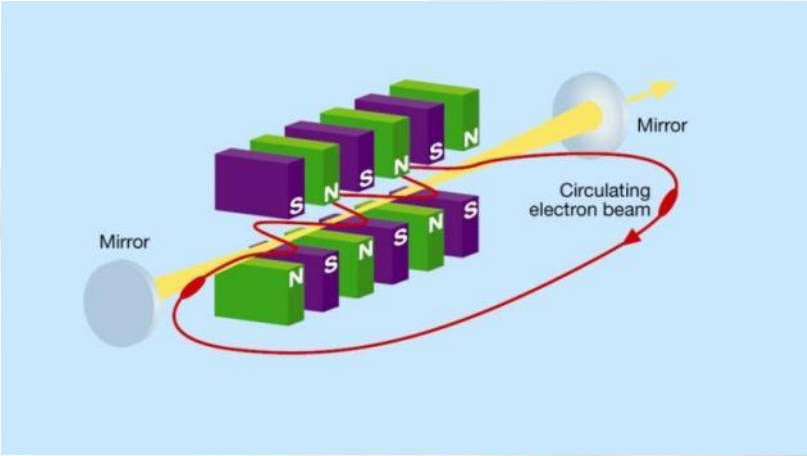
pendulum equation

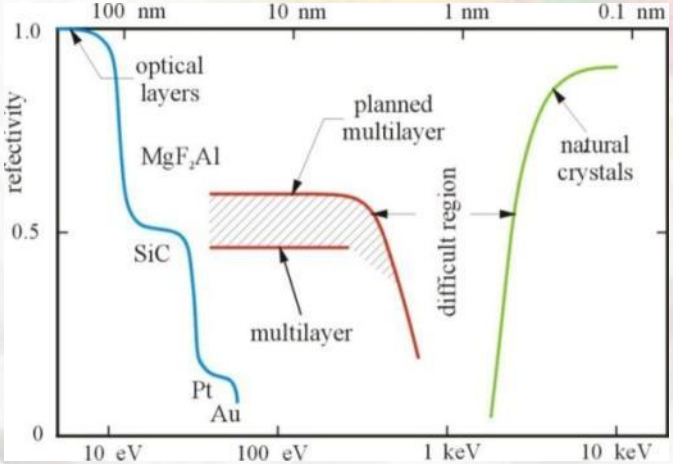




Low-gain FEL

FEL oscillator: slow increase of radiation field in an optical cavity, driven by electrons from a storage ring or linac; typically far-infrared FEL.





However, no good mirrors below 200 nm

→ full amplification in single pass
→ high-gain FEL

Basic process

Three coupled equation describe the electron motion of high-gain FELs

Define relative energy offset $\eta \equiv \frac{\Delta\gamma}{\gamma}$ and longitudinal phase offset Ψ

$$\frac{d\eta}{dt} = -\frac{eE_0 K}{2m_e c\gamma^2}\cdot\sin\Psi$$

energy gained or lost depends on the phase offset

$$\frac{d\Psi}{dt} = 2k_U c\cdot\eta$$

change of phase depends on the energy offset

$$\frac{dE_0}{ds} = -\frac{K}{2\varepsilon_0 c\gamma}\cdot\frac{1}{N_e}\sum_{k=1}^{N_e}\exp\left(-i\psi_k\right)$$

increase of the electric field given by the bunching factor (collective quantity!)

Radiation power in simple 1-d theory

$$P(s) \propto \exp\left(\frac{s}{L_g}\right) \qquad L_g = \frac{1}{\sqrt{3}}\left(\frac{4\varepsilon_0 c^2 m_e}{e^2}\frac{\gamma^3}{K^2 k_U n_e}\right)^{1/3}$$

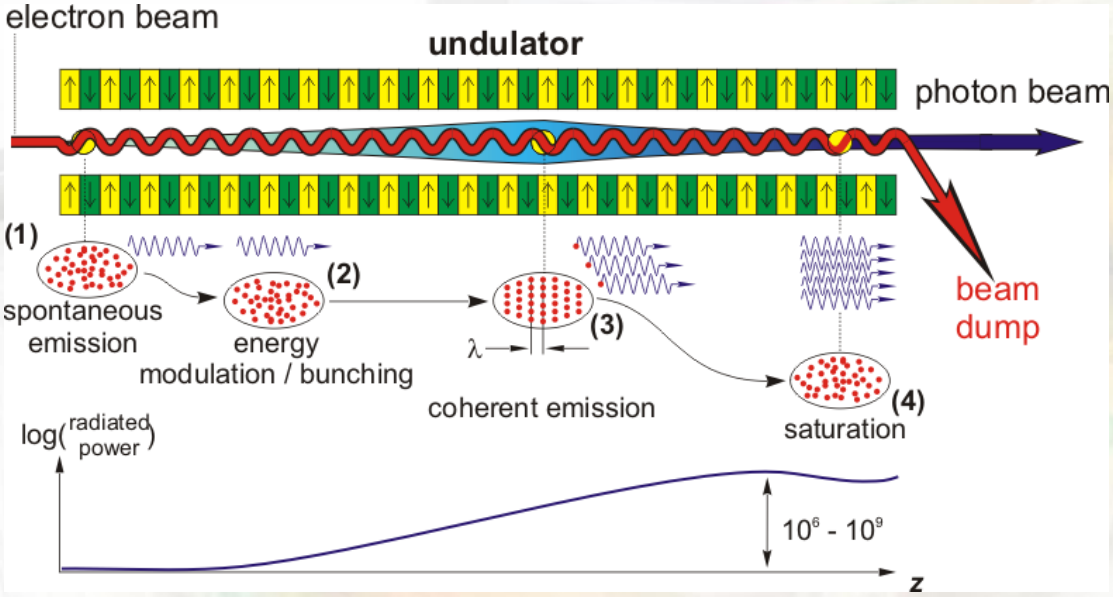
gain length $\propto n_e^{-1/3}$

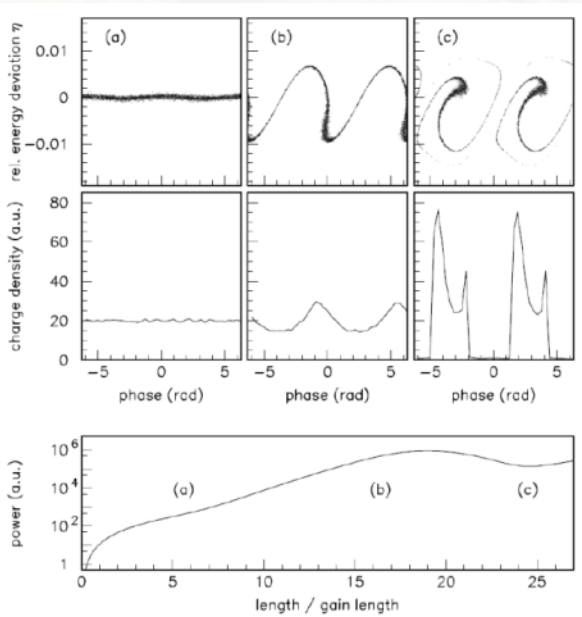
High-gain FEL

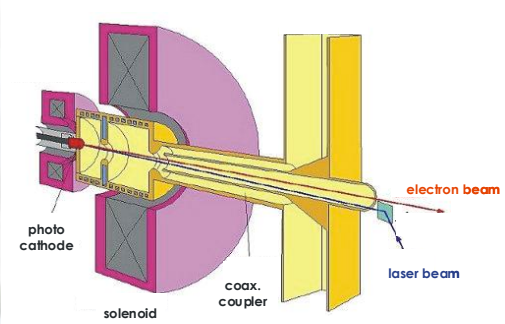
requires low emittance and short bunches

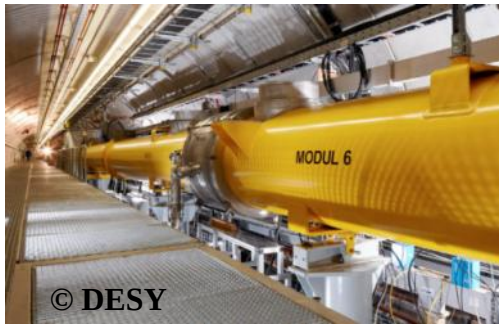
→ linear accelerator, photocathode gun + other tricks, long undulator

→ low repeption rate compared to storage rings









saturation after ~20 gain lengths

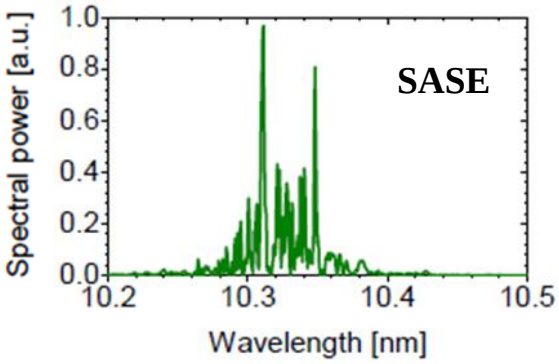
High-gain FEL

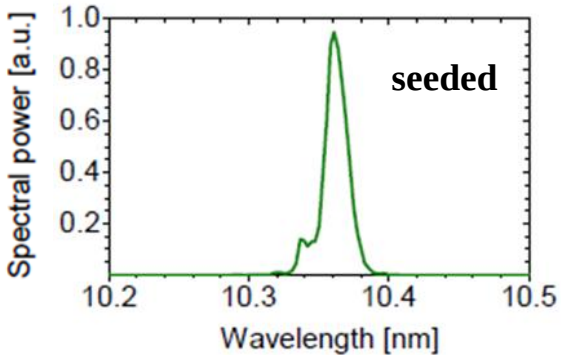
SASE (self-amplified spontaneous emission):
starting from noisy undulator radiation

Seeding with external source:
better control over spectrotemporal properties

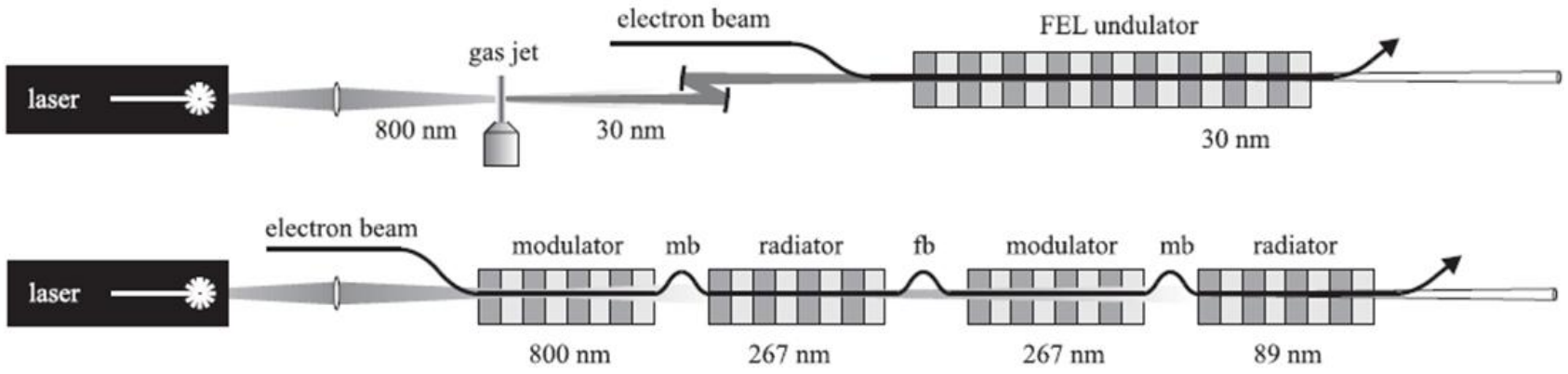
Seeding schemes

- **direct seeding with high-harmonic generation**
- **harmonics of microbunching (HGHG, EEHG)**
- **self-seeding**



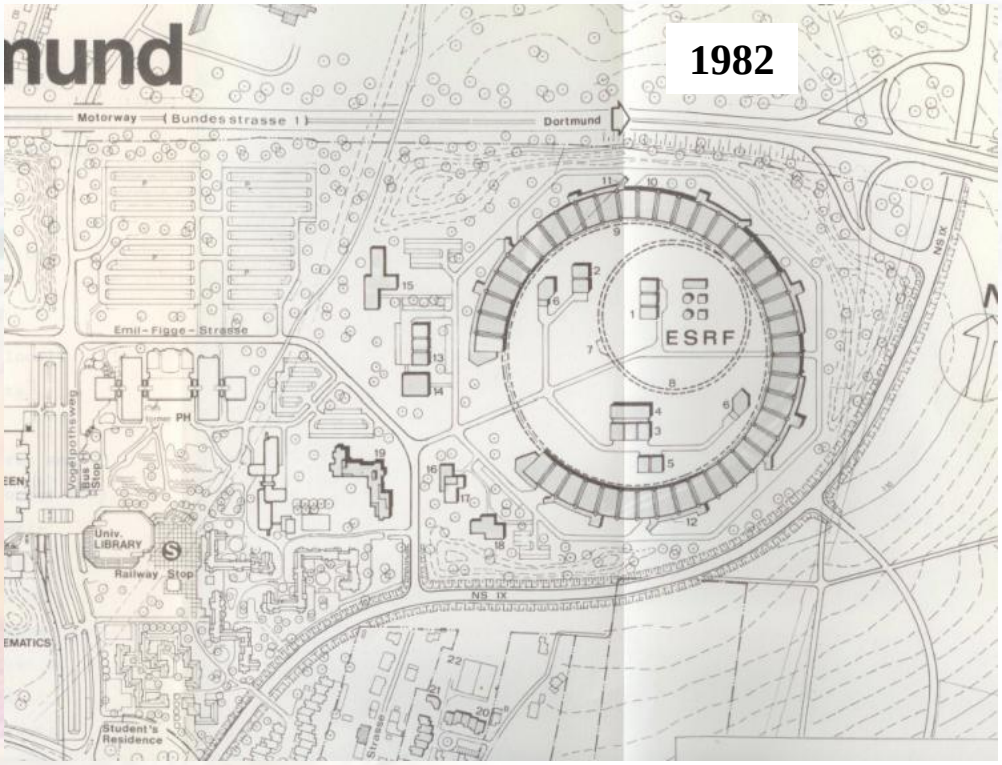


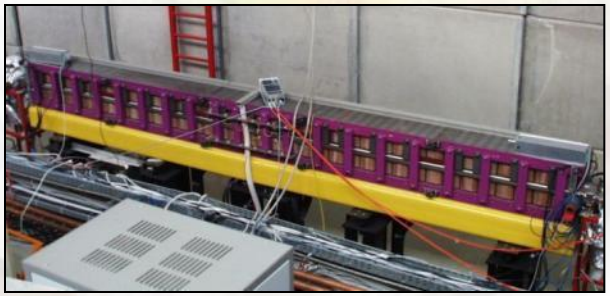
BESSY FEL TDR, Eds.: D. Krämer, E. Jaeschke, W. Eberhardt (2014)



A brief history of DELTA

1992 building completed
1994 first linac beam
1995 first beam in BoDo
1996 beam in storage ring
1998 SAW and U55 installed
1999 U250, first FEL lasing
2011 stort-pulse facility



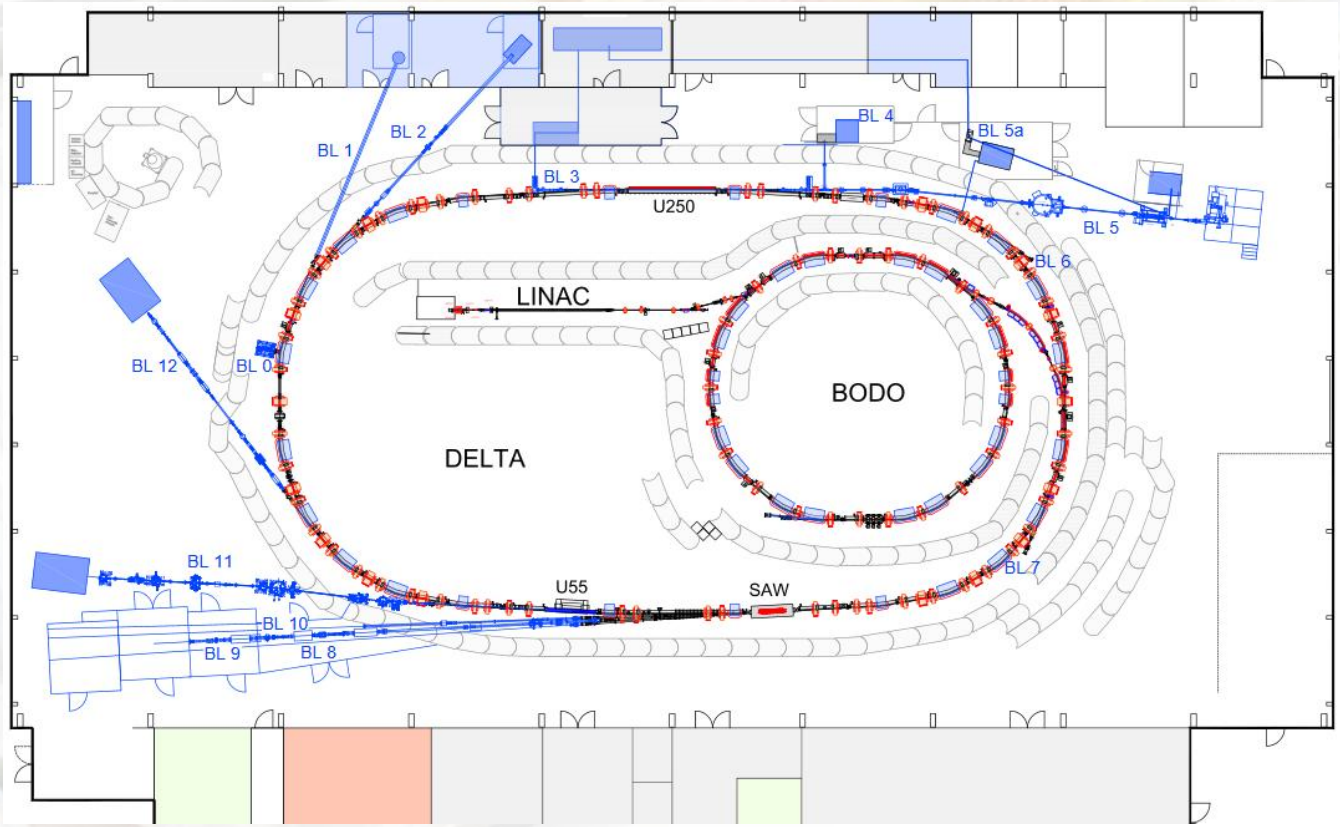


Klaus Wille

The synchrotron radiation source DELTA

circumference	**115.2 m**
beam energy	**1.5 GeV**
beam current (multibunch)	**130 mA**
beam current (single bunch)	**< 20 mA**
beam lifetime (100 mA)	**> 16 hrs**
pulse duration (FWHM)	**100 ps**

user operation (20 weeks)	**2000 h/year**
machine studies (10 weeks)	**1000 h/year**



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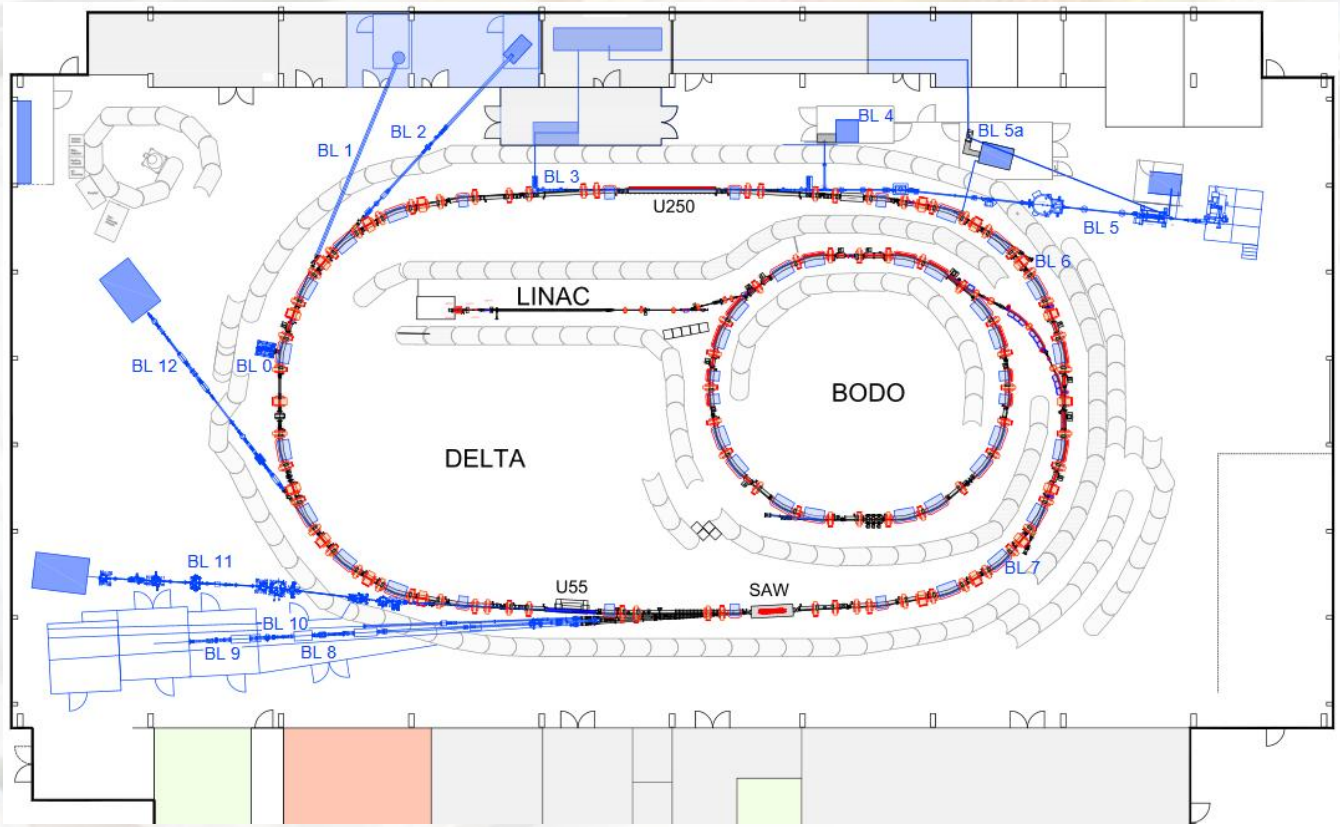

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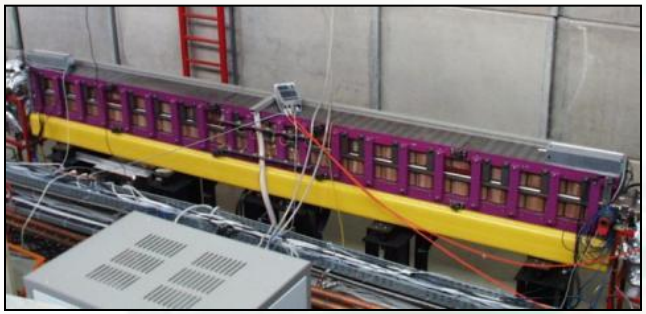
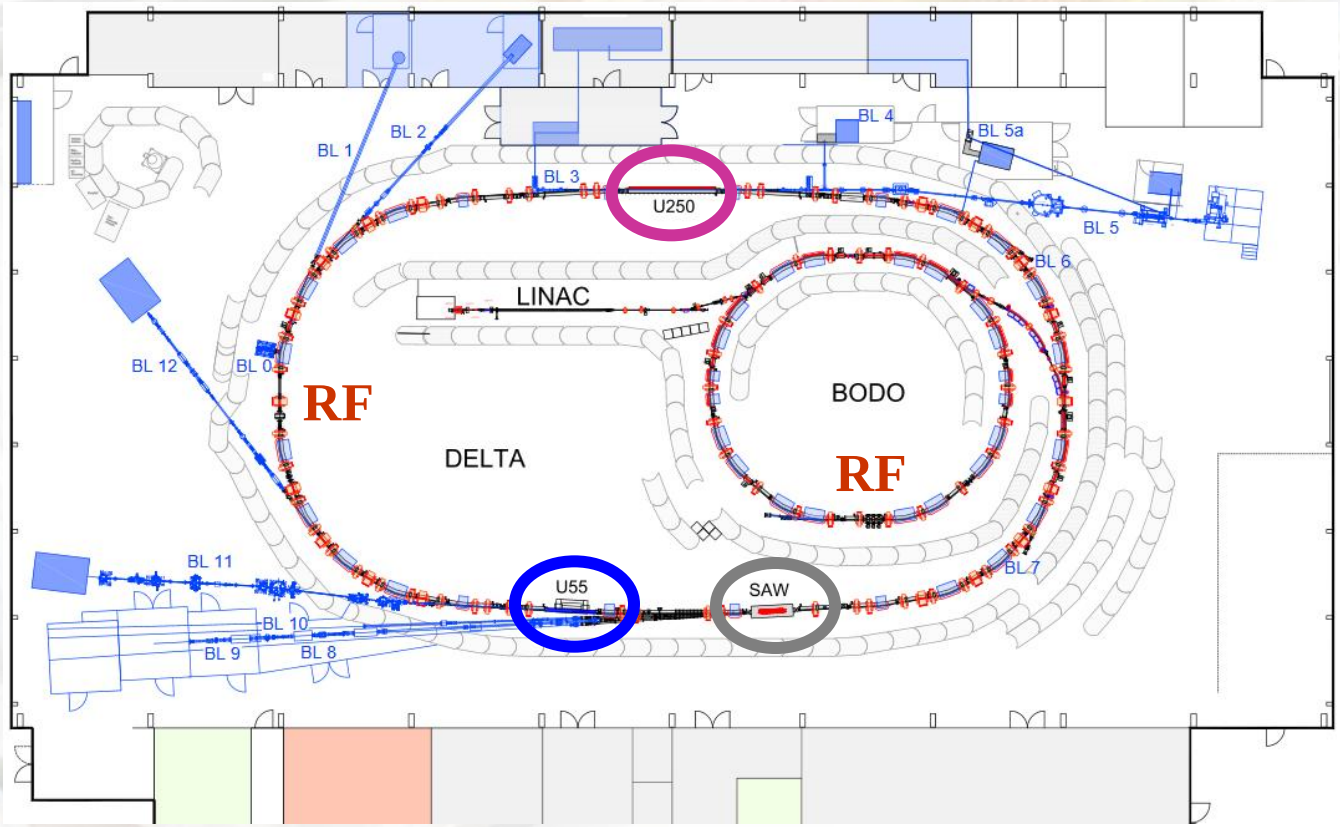
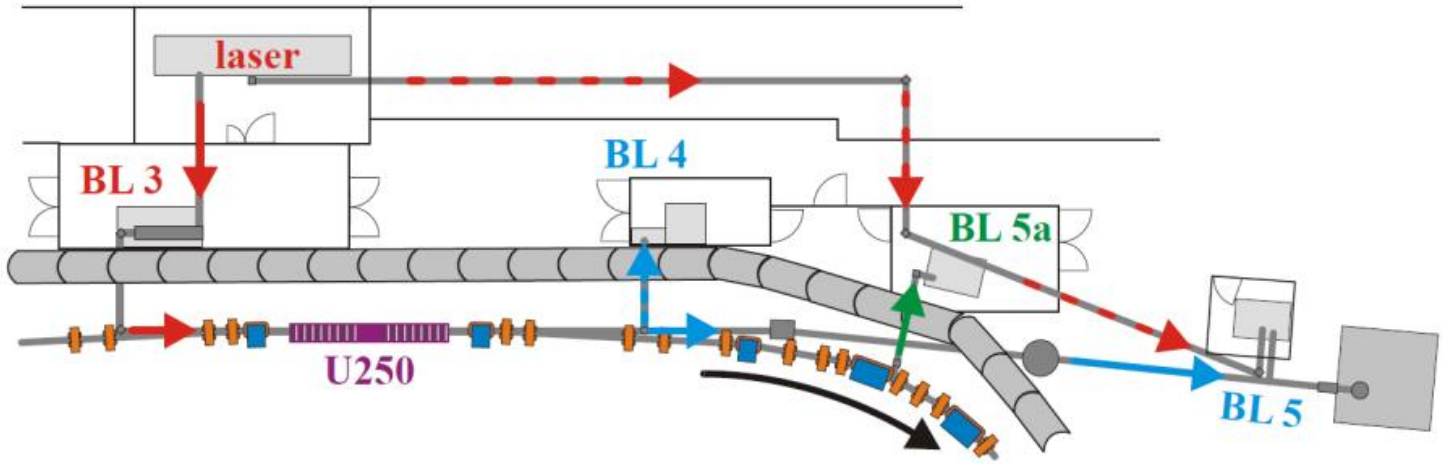
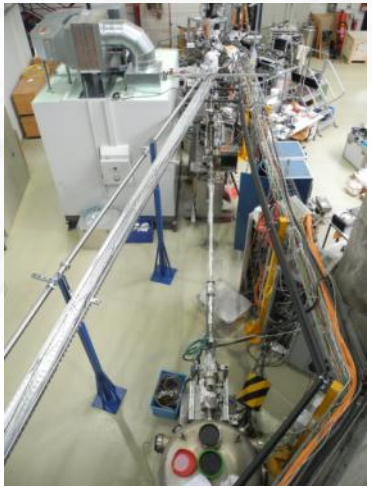


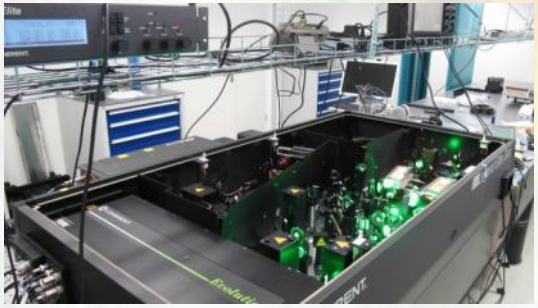


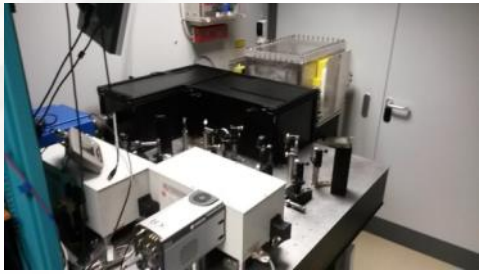
Facility for ultrashort VUV and THz pulses

- since 2011
- using undulator U250 (previous storage ring FEL)
- new: fs laser system, diagnostics, THz beamline, instrumentation, ...









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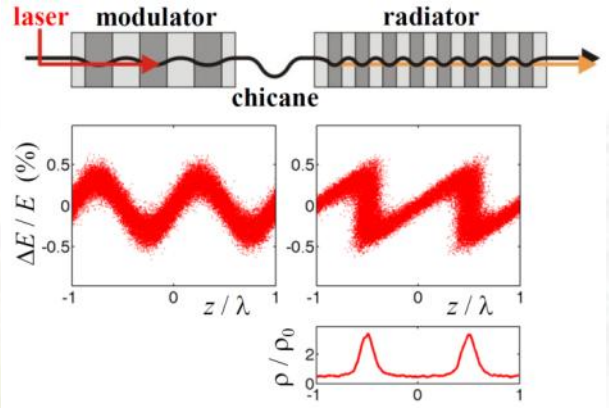
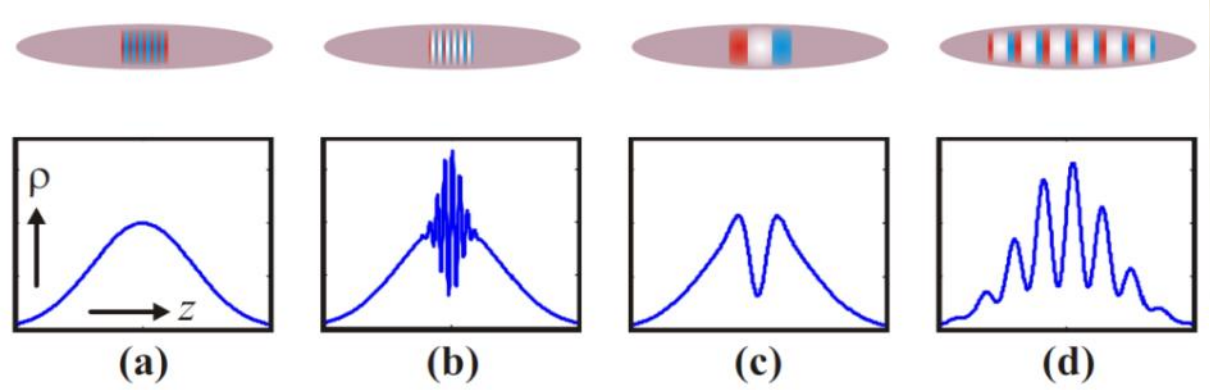


Coherent harmonic generation (CHG)

- laser-induced energy modulation in a bunch "slice"
- density modulation in a magnetic chicane
- coherent radiation at harmonics

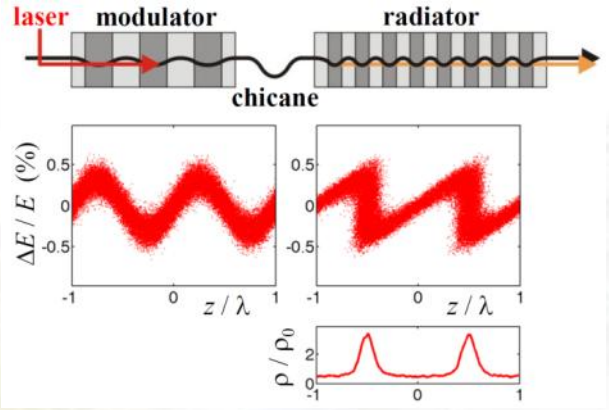
Coherent terahertz (THz) radiation

- short "dip" due to energy-dependent path length
- broadband THz radiation over several turns
- or: narrowband THz radiation from multiple dips



energy modulation | density modulation → vacuum-UV | single dip → broadband THz | multiple dips → narrowband THz

Facility for ultrashort VUV and THz pulses



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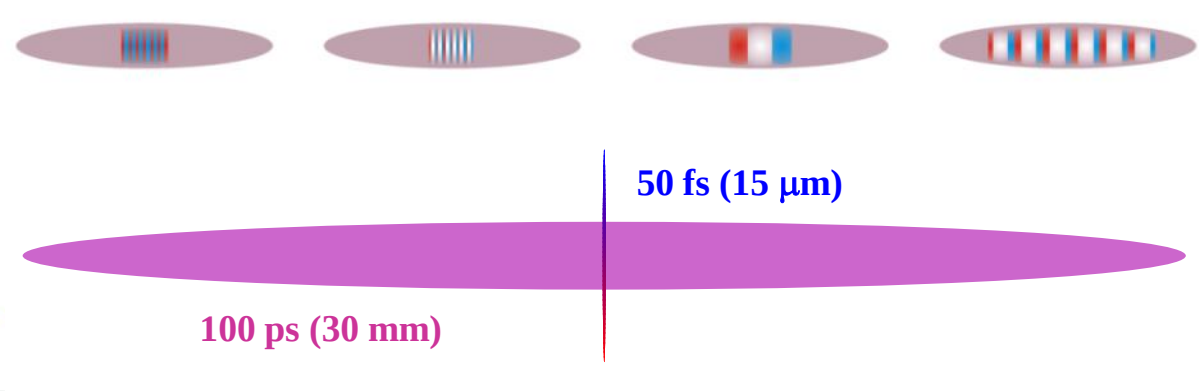
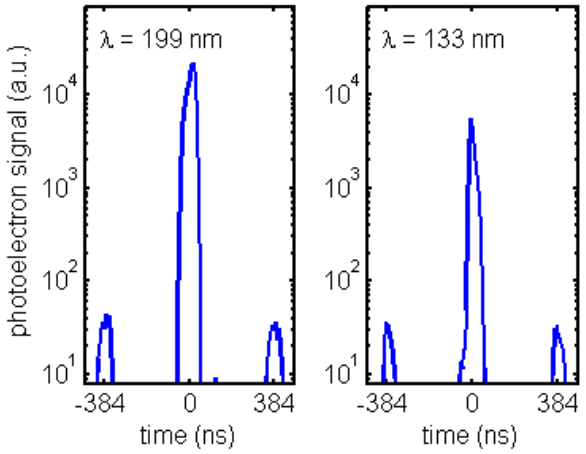




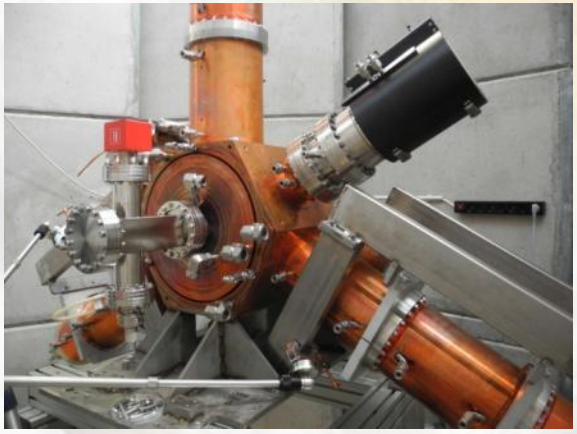
Near-future projects

New superconducting wiggler delivered

- magnetic field 5.3 T → 7 T
- number of periods 5 → 9
- He losses 130 l/week → none

RF upgrade

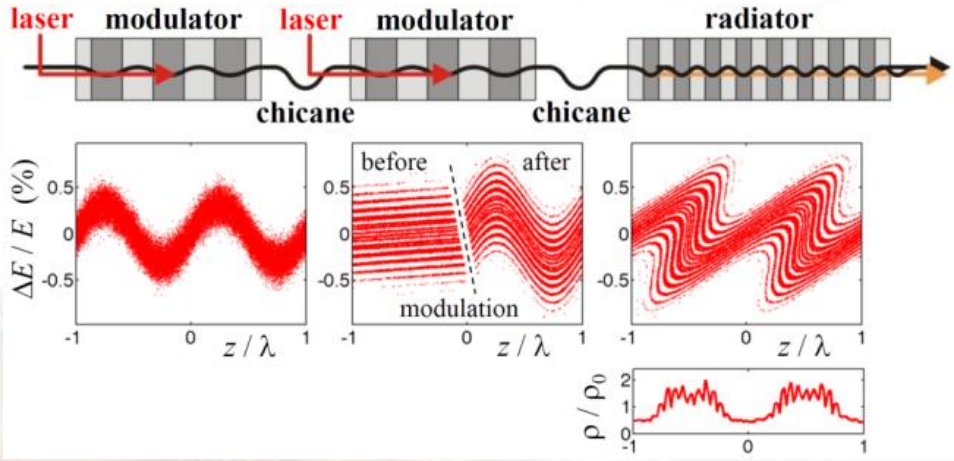
- second 500-MHz resonator
- 70-kW solid-state amplifier

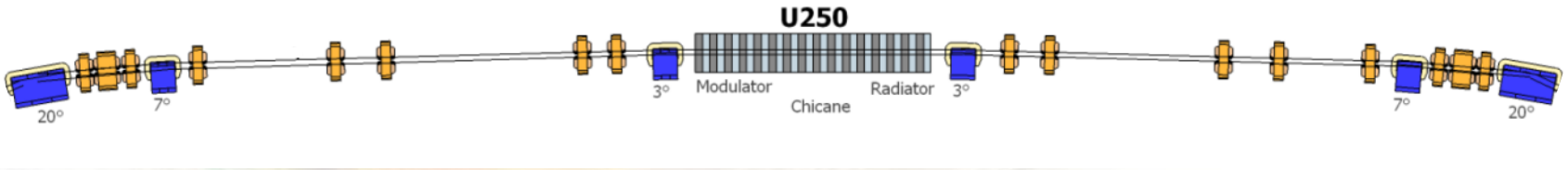


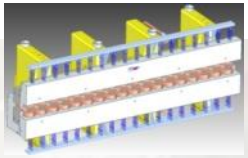
Near-future projects

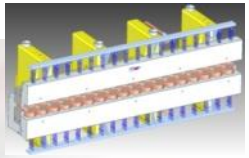
Echo-enabled harmonic generation

- FEL seeding scheme (G. Stupakov 2009)
- access to higher harmonics
- unique at storage rings
- two undulators U200 in house









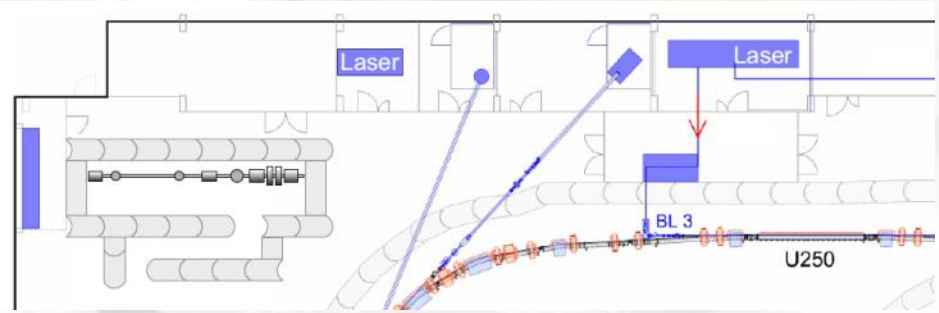
Not-so-near-future project

Ultrafast electron diffraction

- 5-MeV source of ultrashort bunches
  (like UED@ASTA, REGAE)
- pump-probe experiments

Design study

- two doctorate positions funded
- space and infrastructure available



Thank you for your attention

Bundesministerium
für Bildung
und Forschung

DFG Deutsche Forschungsgemeinschaft

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Ministerium für
Kultur und Wissenschaft
des Landes Nordrhein-Westfalen