Synchrotron Radiation Light Sources

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Paul Scherrer Institute

Instruments development:

400 years of discoveries with “telescopes” and “microscopes”

Galileo Galilei

Zacharias Janssen

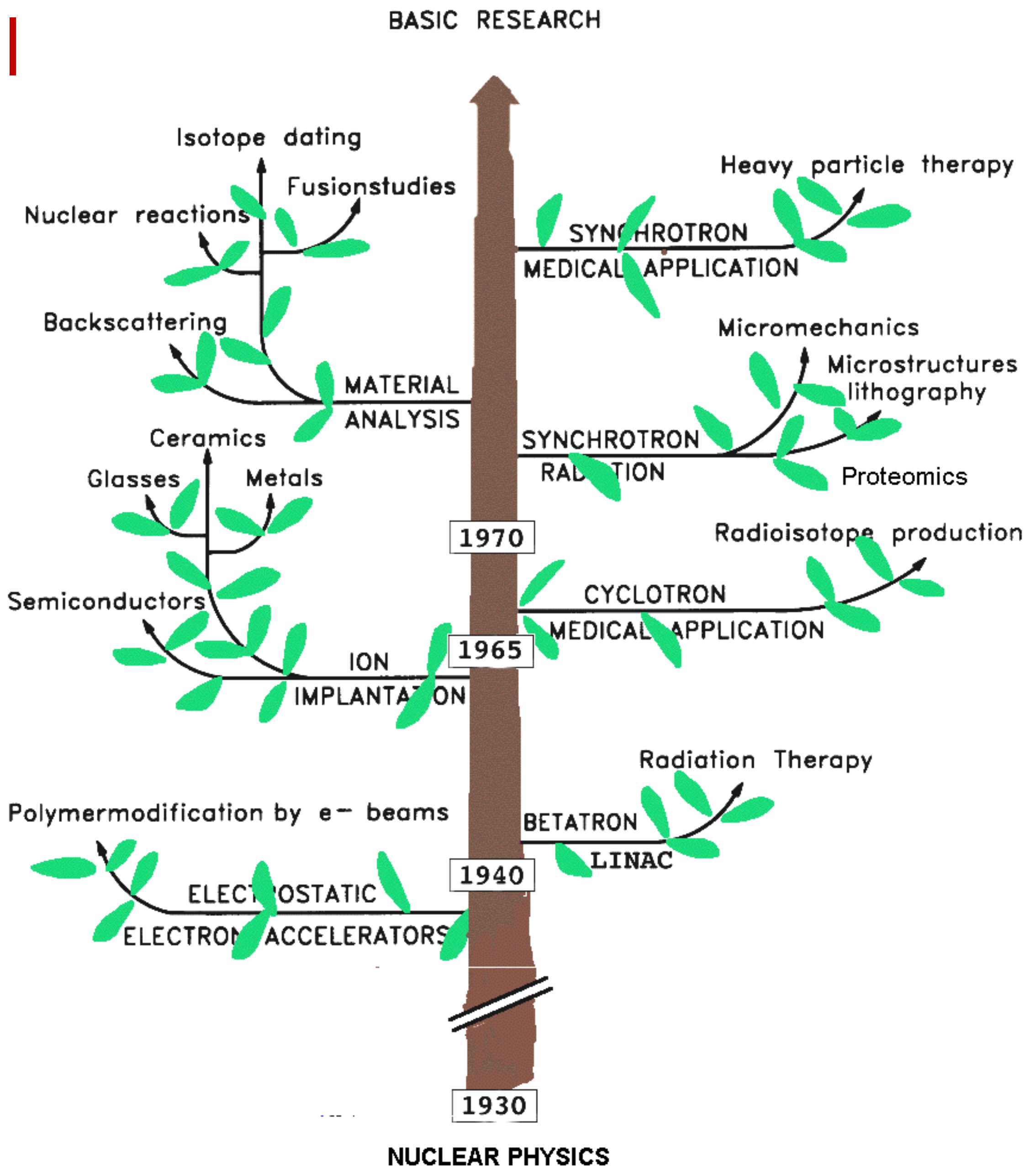
Accelerator driven applications to meet the needs of society

- Advanced instruments for basic and applied science
- Analysis of physical, chemical and biological materials
- Modification of physical, chemical and biological properties of matter
- Medical: diagnostics, treatment and targeted drug design
- Security: cargo scanning, IT hardware
- Environment
- Energy

The role of accelerators in Physical and Life Sciences

"Instruments have a life of their own.
They do not merely follow theory; often they determine theory, because instruments determine
what is possible, and what is possible determines to a large extent what can be thought. The telescope, the microscope, the chronograph, the photograph: all gave rise to a blossoming of theoretical understanding
not possible before their invention"

Hankins & Silverman,
Instruments and the Imagination



24 Nobel Prizes in Physics that had direct contribution from accelerators

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

2013: François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

20 Nobels with X-rays

Chemistry

1936 Peter Debye

1962 Max Perutz and Sir John Kendrew

1976 William Lipscomb

1985 Herbert Hauptman and Jerome Karle

1988 Johann Deisenhofer, Robert Huber and Hartmut Michel

1997 Paul D. Boyer and John E. Walker

2003 Peter Agre and Roderick Mackinnon

2009 V. Ramakrishnan, Th. A. Steitz, A. E. Yonath

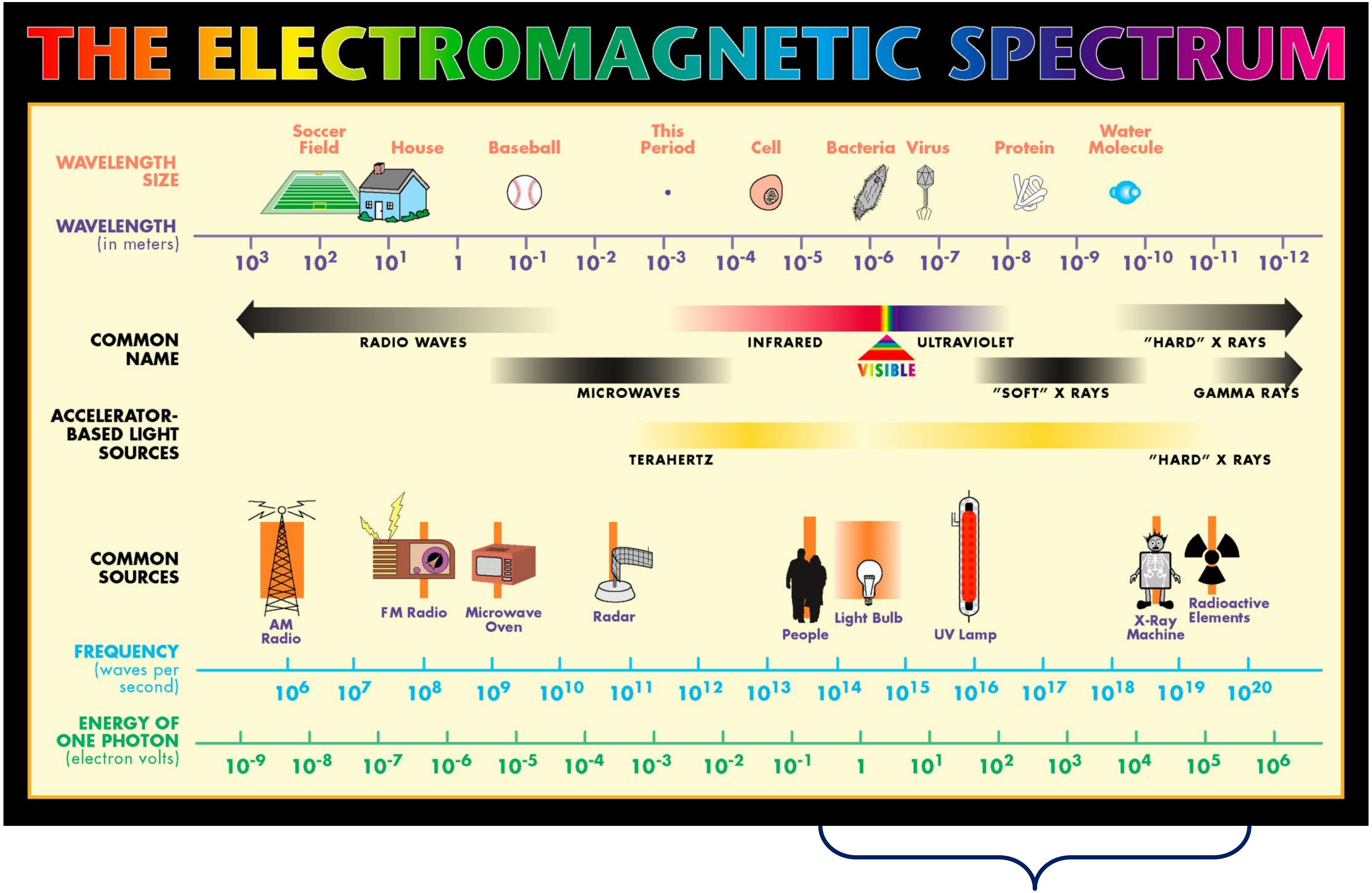
2012 Robert J. Lefkowitz and Brian K. Kobilka

Physics

1901 Wilhelm Rontgen
1914 Max von Laue
1915 Sir William Bragg and son
1917 C. G. Barkla
1924 Manne Siegbahn
1927 A. H. Compton
1981 Kai Siegbahn

Medicine

1946 Hermann Muller
1962 Frances Crick, James Watson and Maurice Wilkins
1979 Alan Cormack and Godfrey Hounsfield

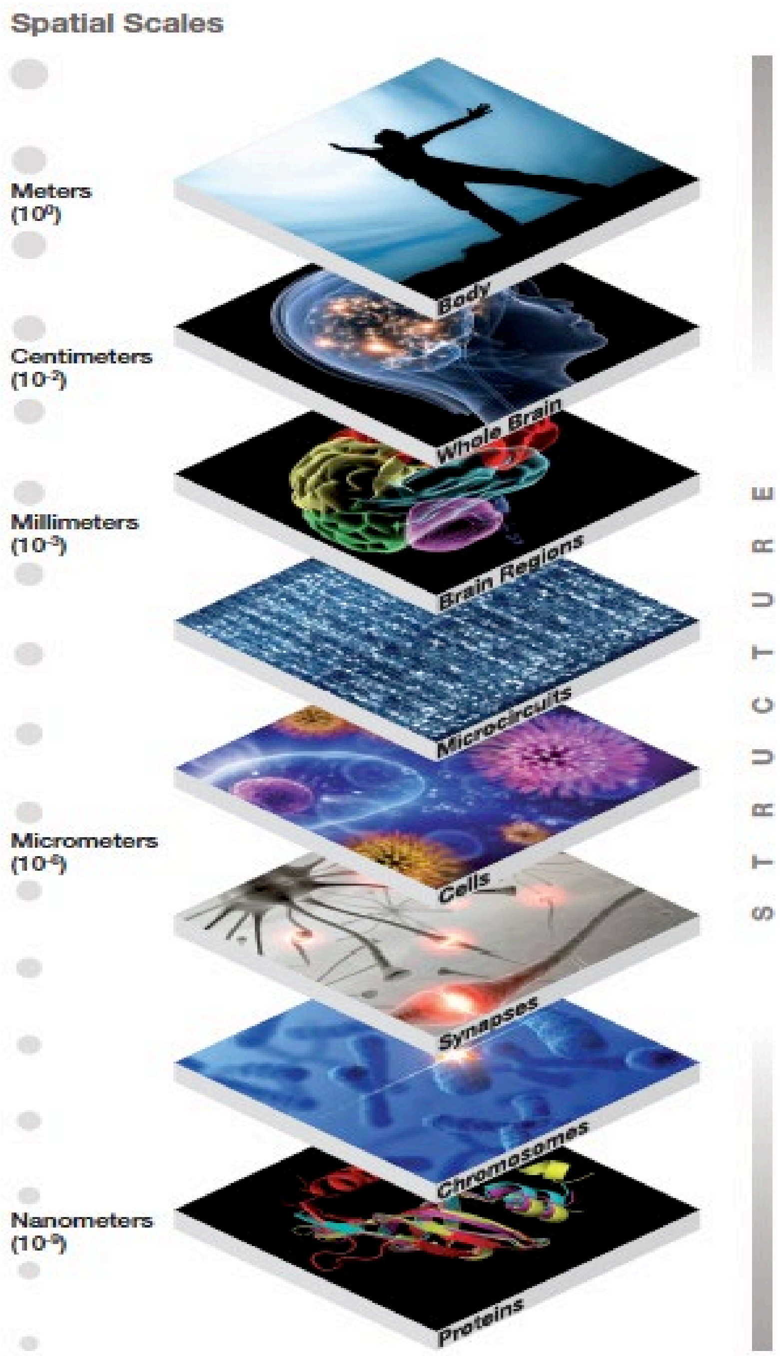


Wavelength continuously tunable !

Imaging things

on all length and time scales
using accelerators,

e.g. latest X-Ray and
computational technologies
(developed at accelerators)

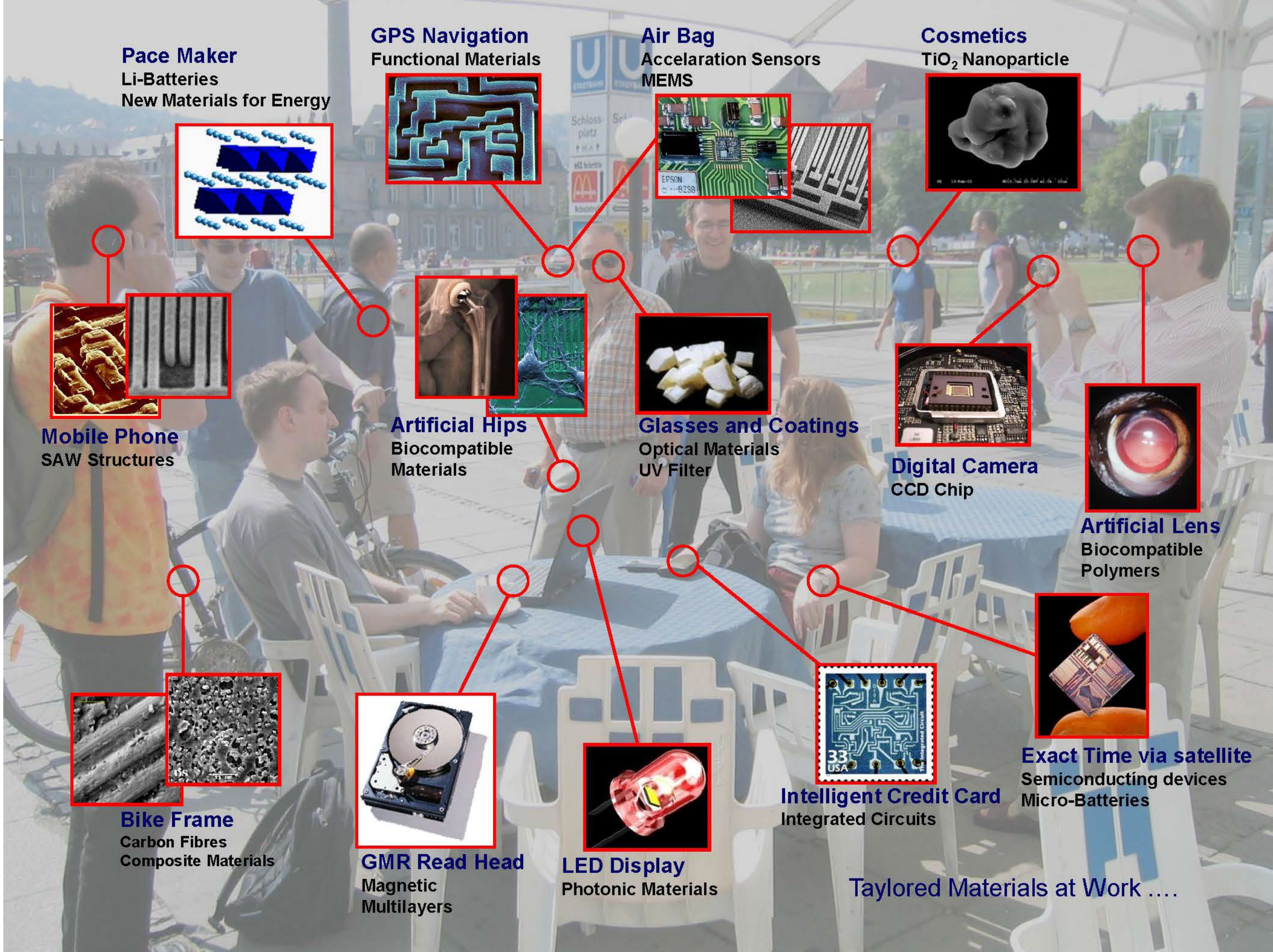


Materials

Modern day materials

Accelerators had an impact on a wide range of materials

Modern day materials



Synchrotron Light Sources: about 50 storage ring based

60‘000 users world-wide

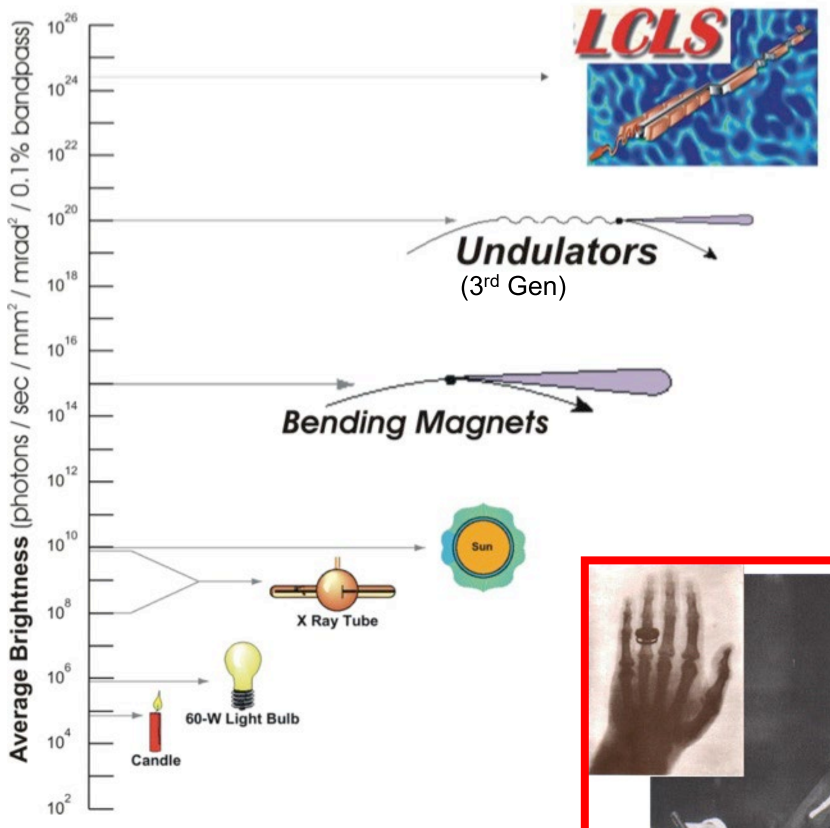
Established, mature technology

The «brightness» of a light source

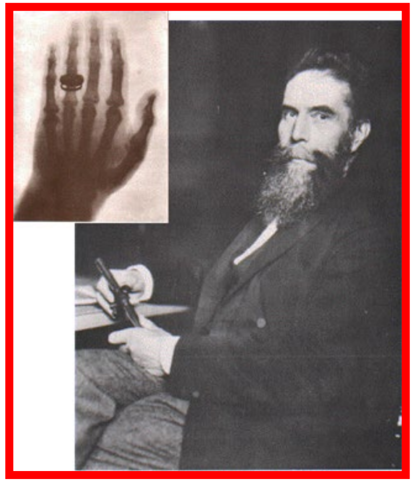
$$\text{Brightness} = \text{constant} \times \frac{F}{S \times \Omega}$$

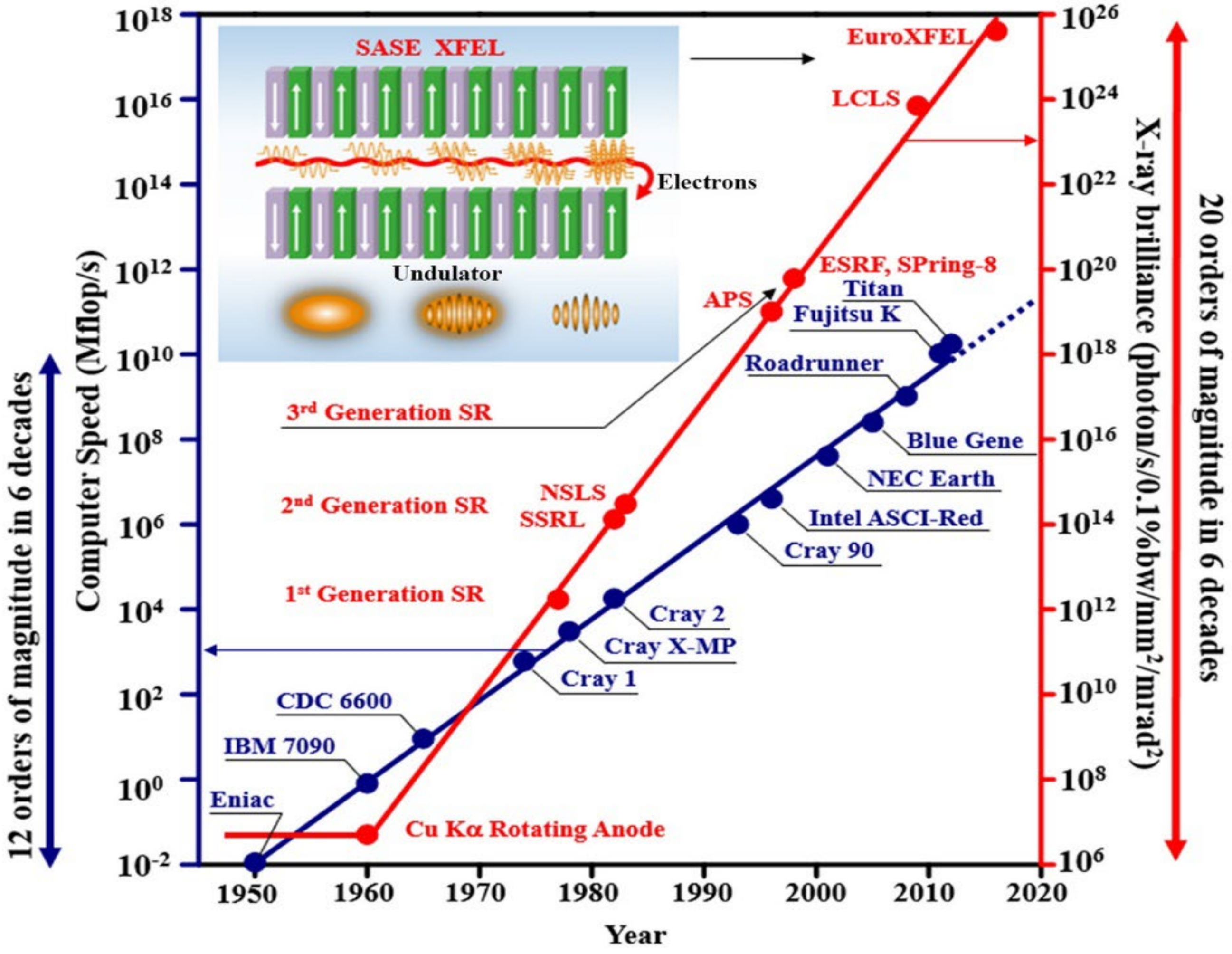
X – Rays Brightness

Average Brightness



Bertha Roentgen's hand
(exposure: 20 min)



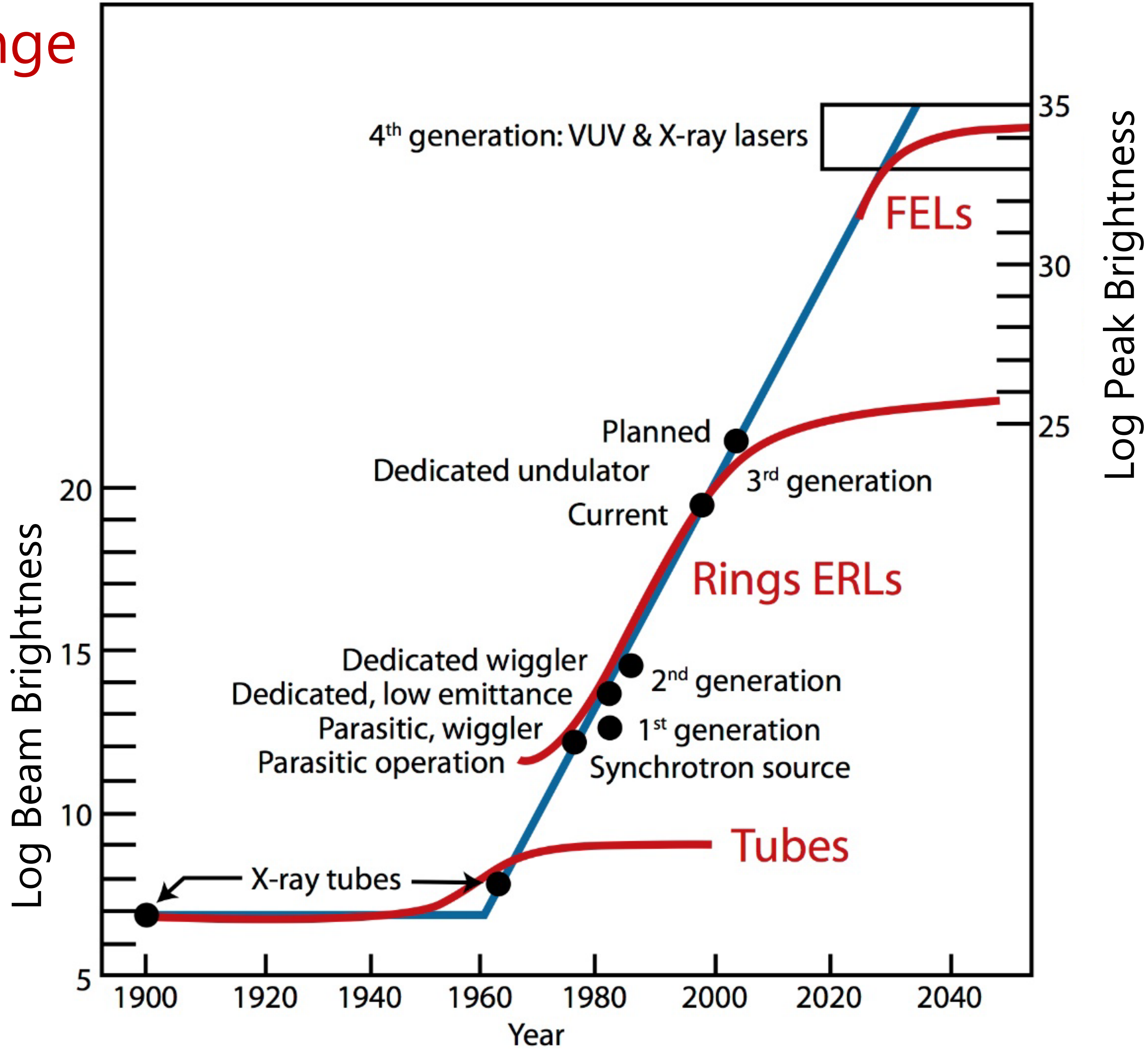


Easter morning 1900: 5th
the automobile.

Easter morning 1913: 5th Ave, New York City.
Spot the horse.

Brightness: disruptive change

- X-ray Tubes
- Storage Rings
- FELs
- ? Compact sources ?



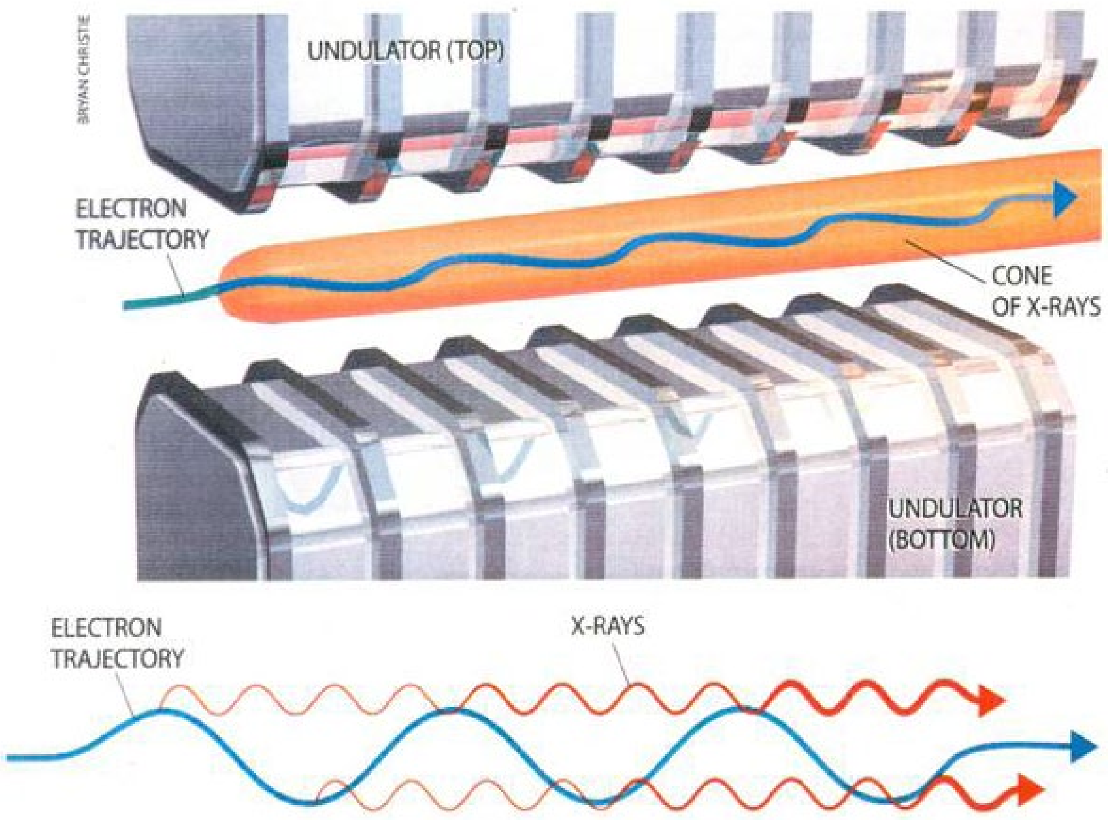
Sources of Synchrotron Radiation

Bright beams of particles: phase space density

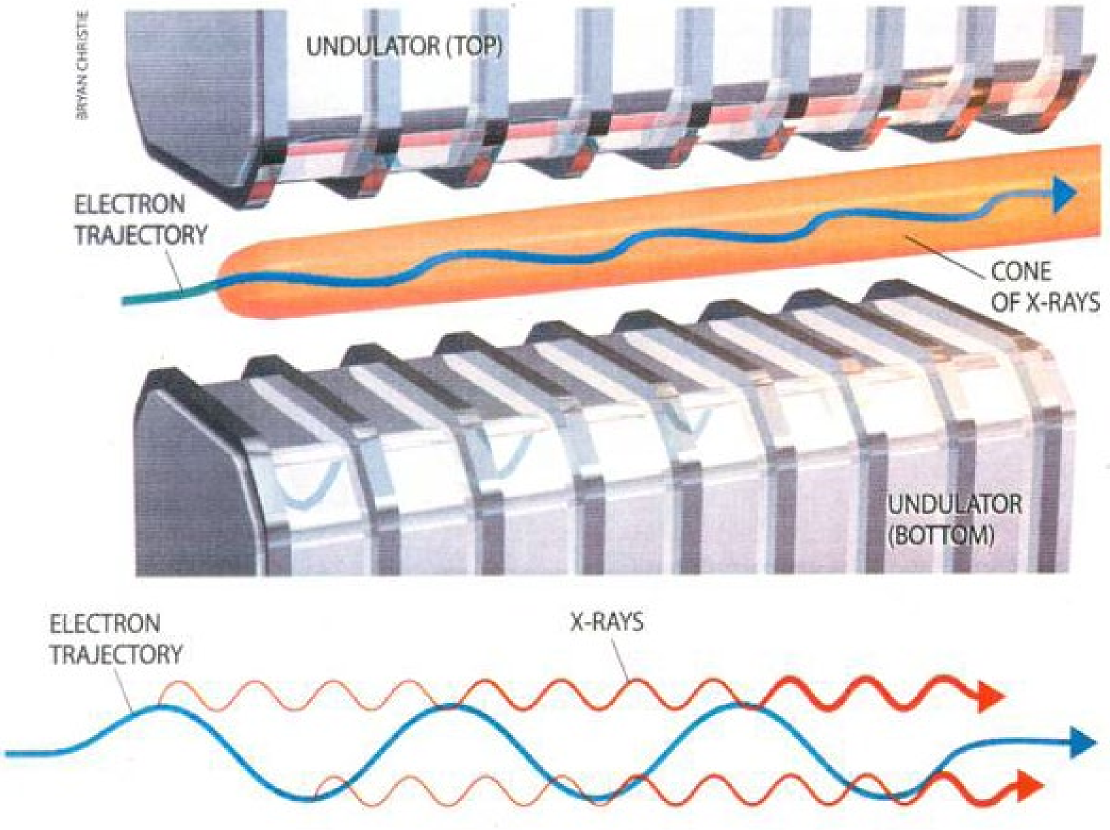
Incoherent, spontaneous emission of light:

Large phase space

Coherent, stimulated emission of light



Undulators

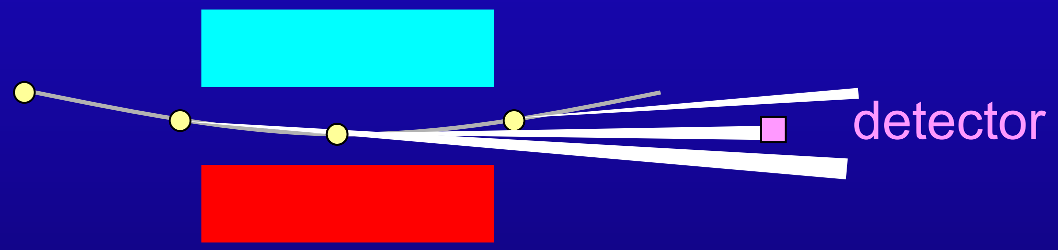


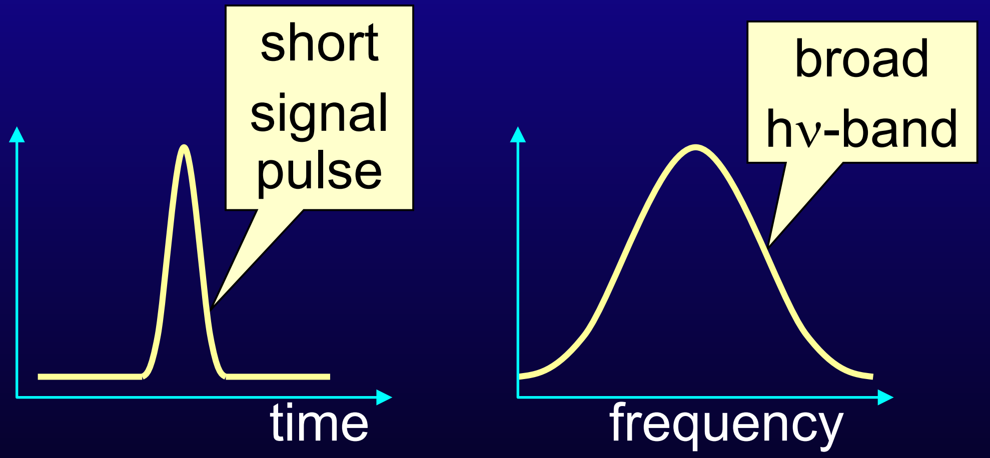
$$T_{obs} = T_{emit}(1-\beta)$$

$$\lambda_{light} \approx \frac{\lambda_u}{2\gamma^2}$$

3 types of storage ring sources:

1. Bending magnets: $\mathbf{B \sim N_e}$

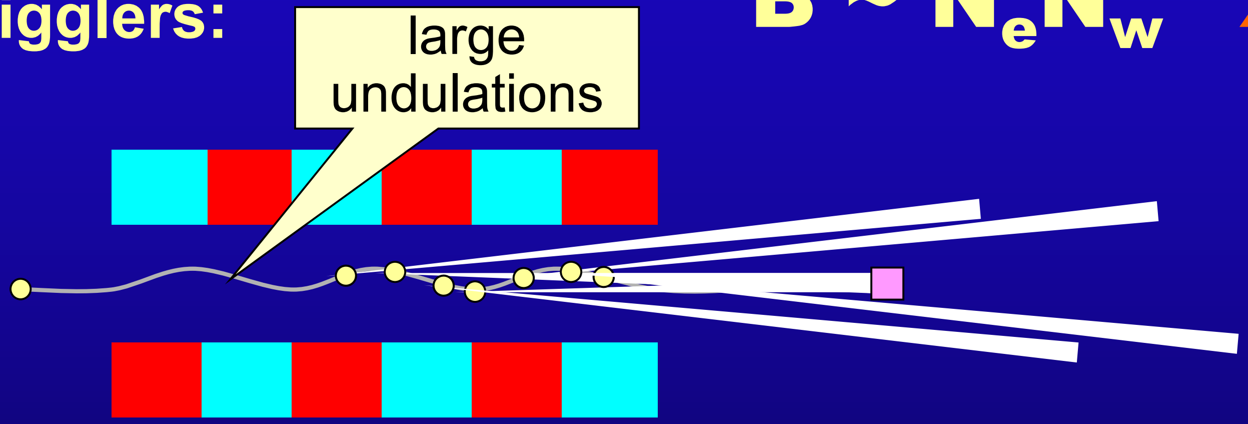


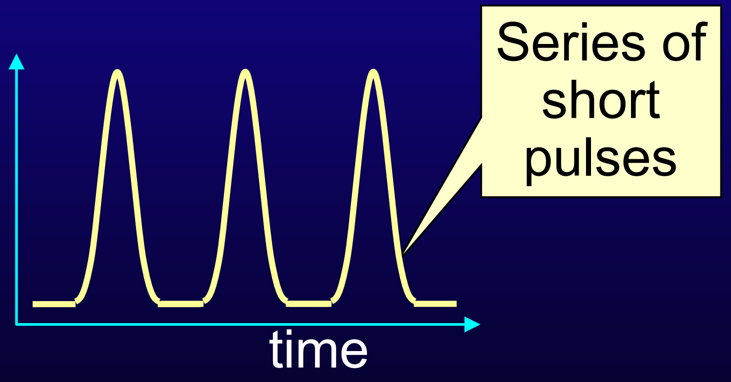


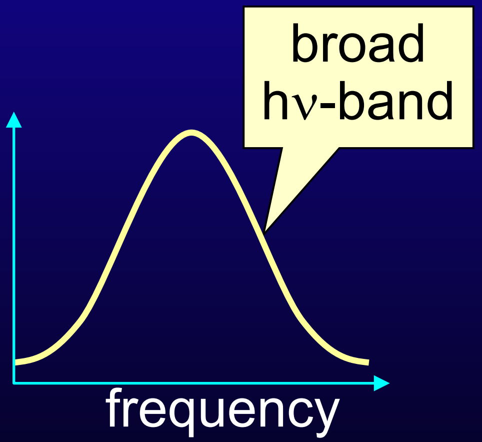
3 types of storage ring sources:

2. Wigglers:

$B \sim N_e N_w$ **x10**

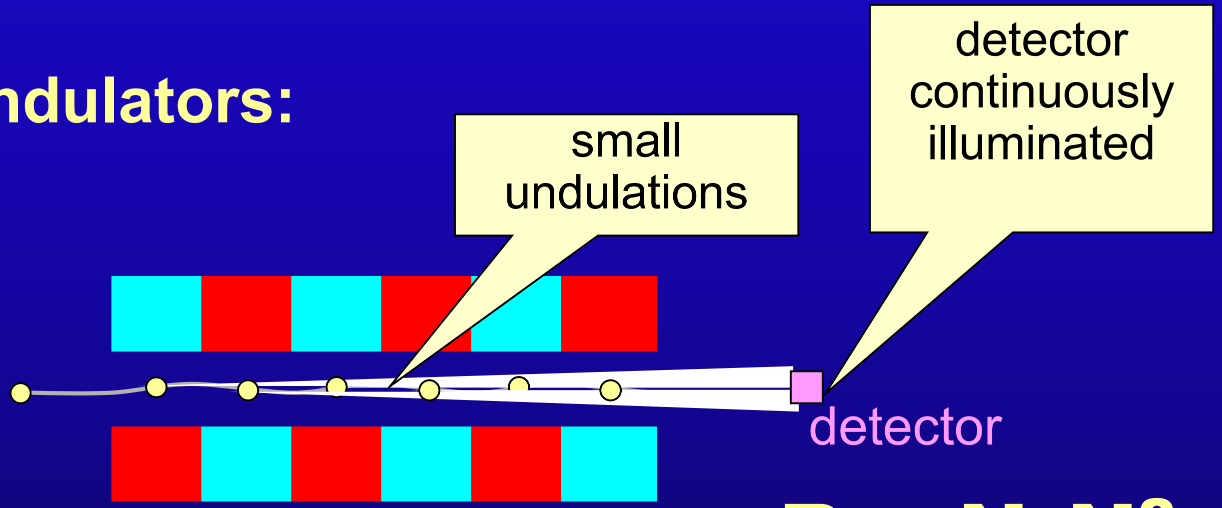




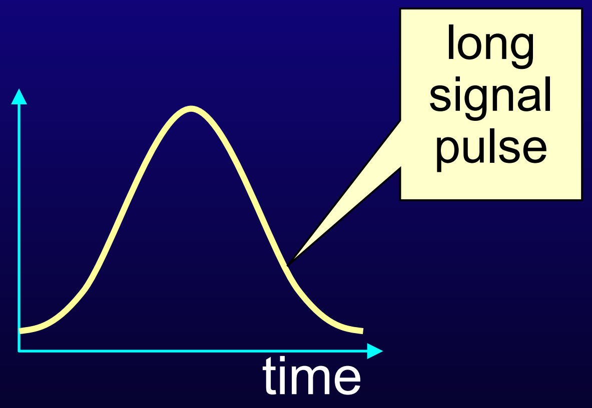


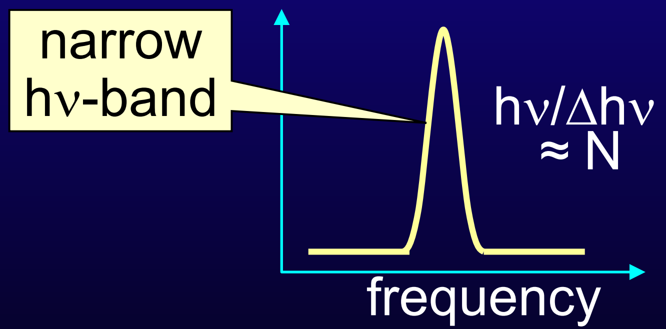
3 types of storage ring sources:

3. Undulators:

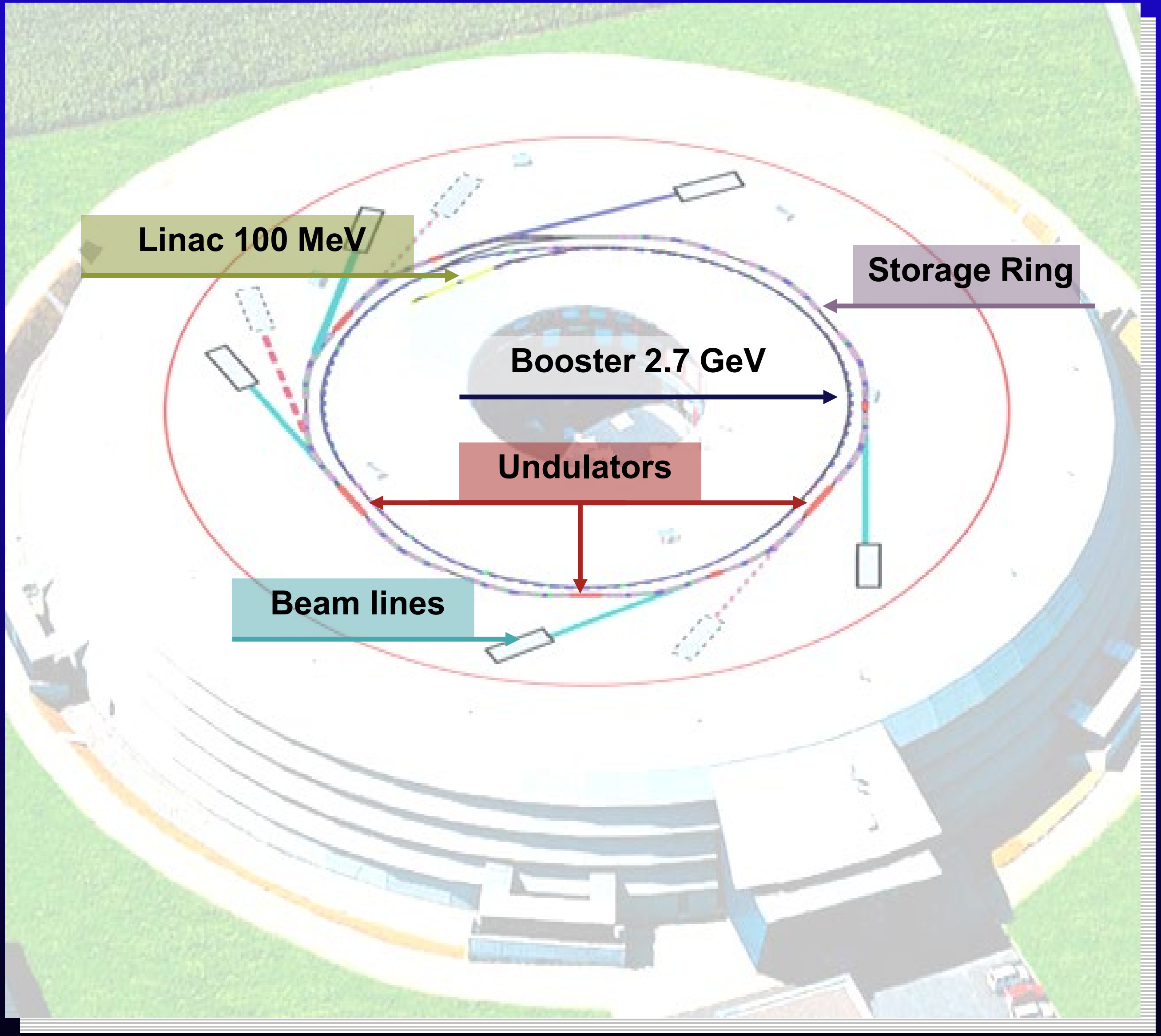


$$B \sim N_e N_u^2 \quad x10^3$$

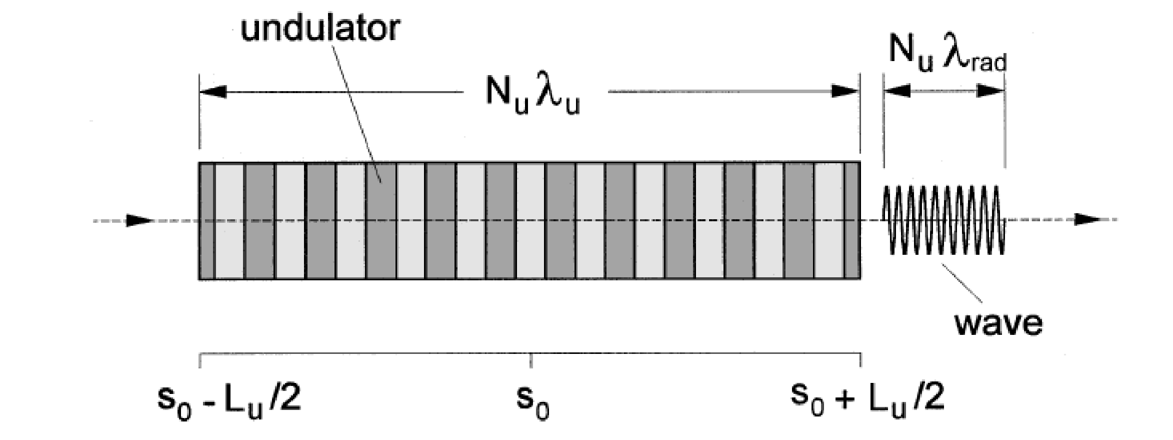




Anatomy of a light source



Undulator line width



Undulator of infinite length

$$N_u = \infty \quad \Rightarrow \quad \frac{\Delta\lambda}{\lambda} = 0$$

Finite length undulator

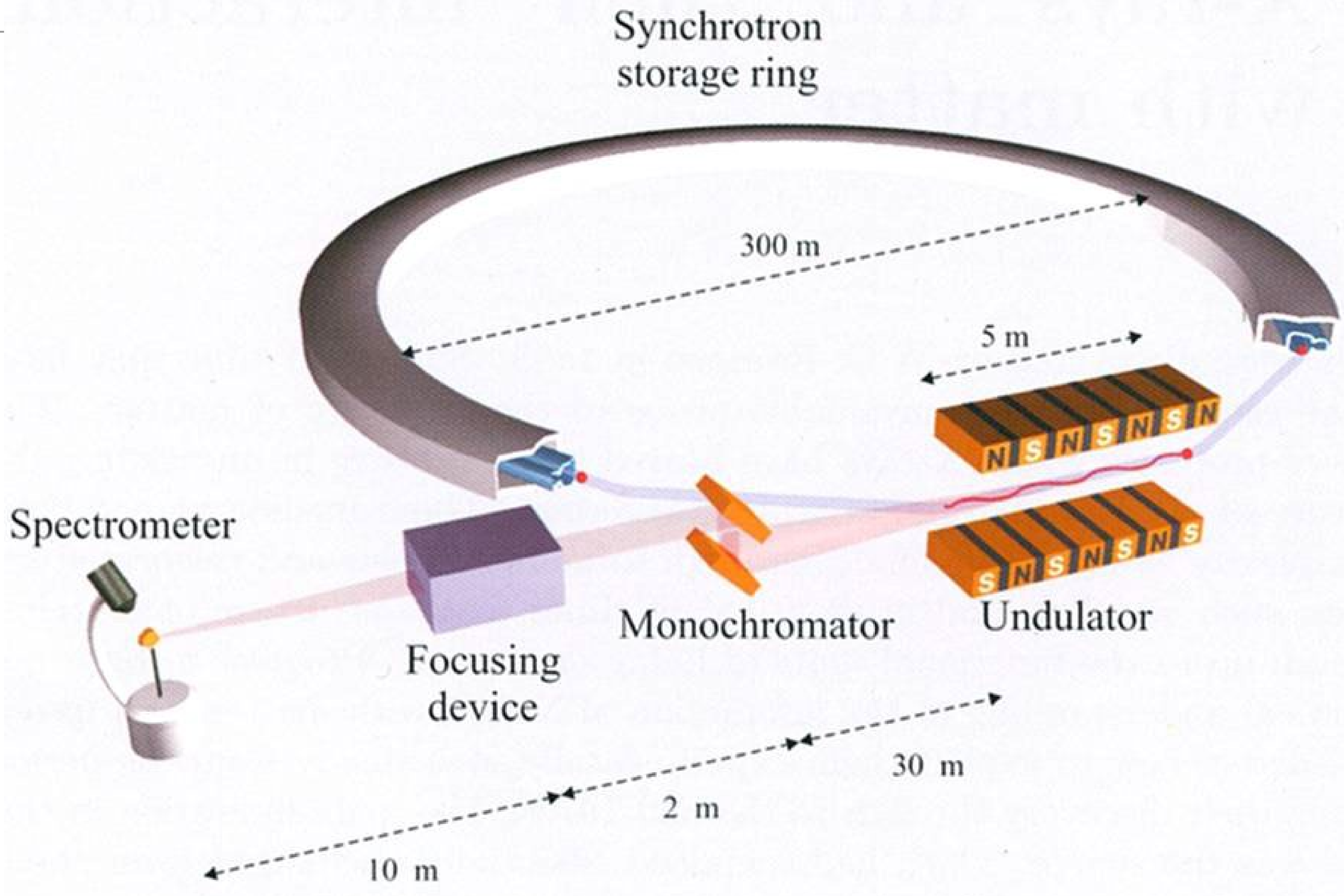
- radiation pulse has as many periods as the undulator
- the line width is

$$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{N_u}$$

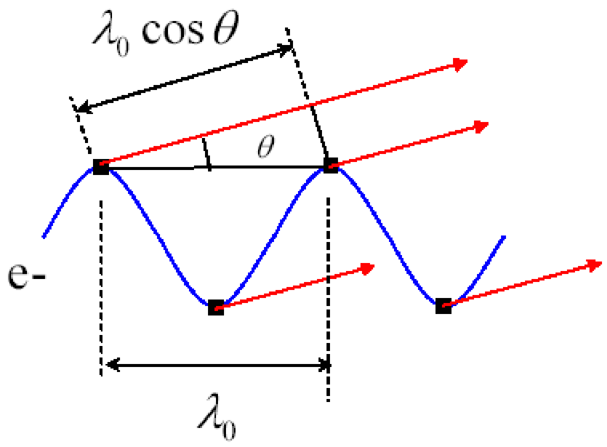
Due to the electron energy spread

$$\frac{\Delta\lambda}{\lambda} = 2\frac{\sigma_E}{E}$$

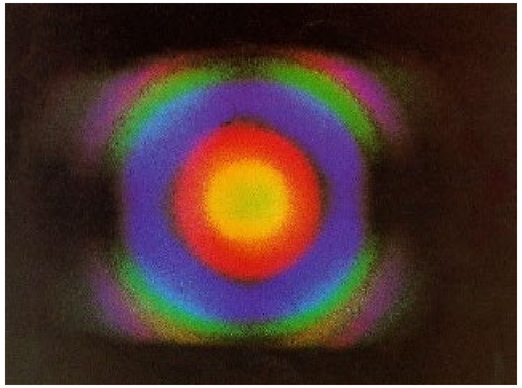
Undulator based beamline

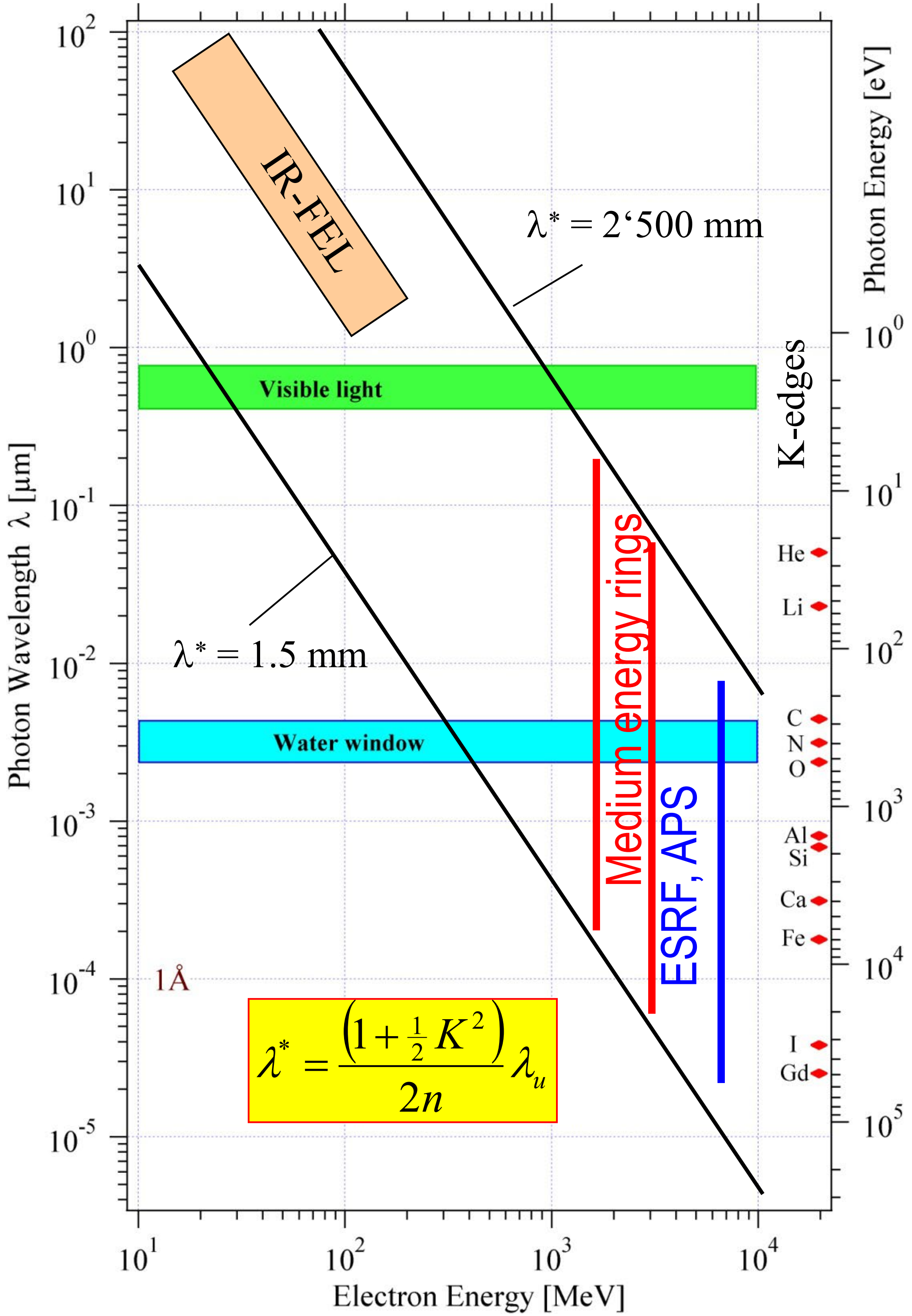


Undulator radiation



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





Particle beam emittance

Emittance = S x Ω

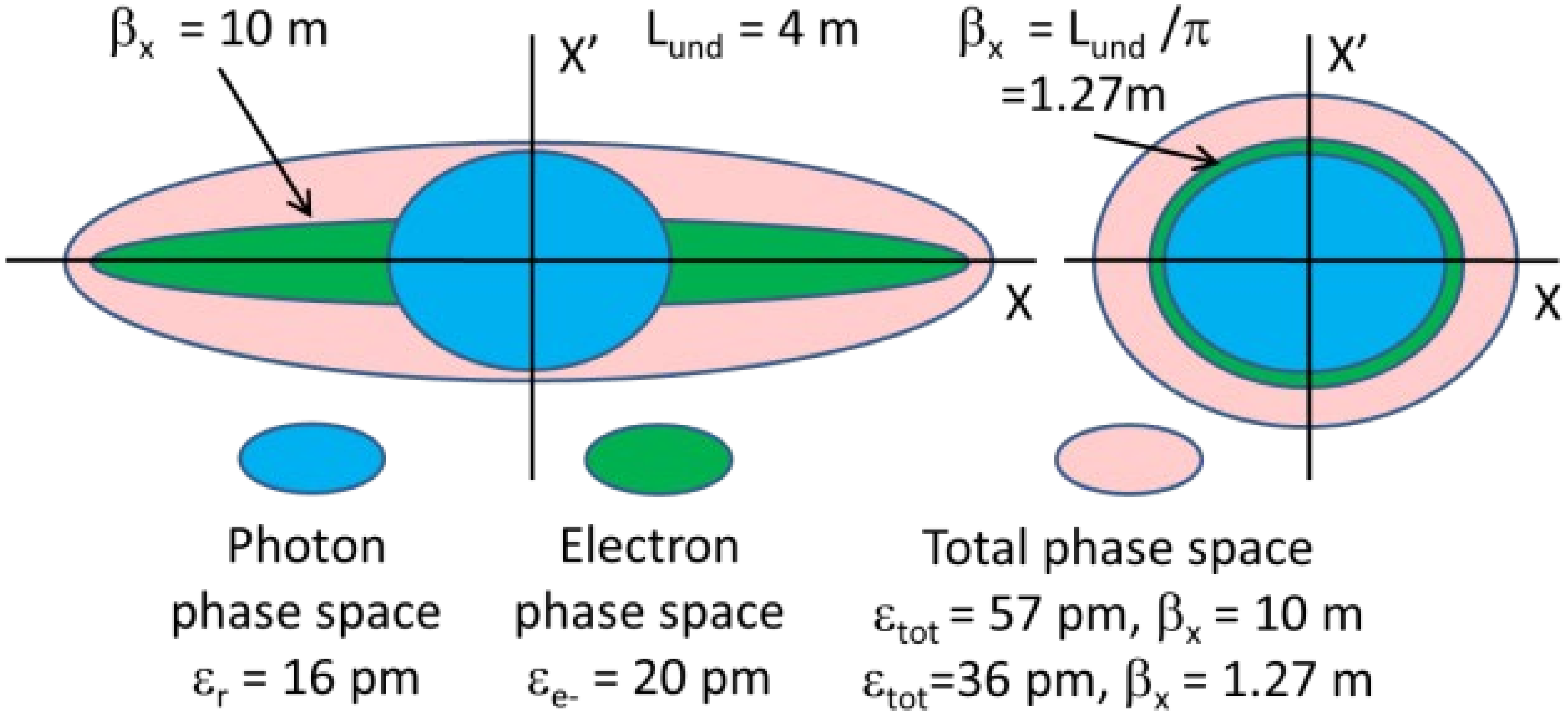
X-ray emittance from electron source:
a convolution of electron and photon phase space

$$\text{Brightness} = \frac{\Phi}{(2\pi)^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

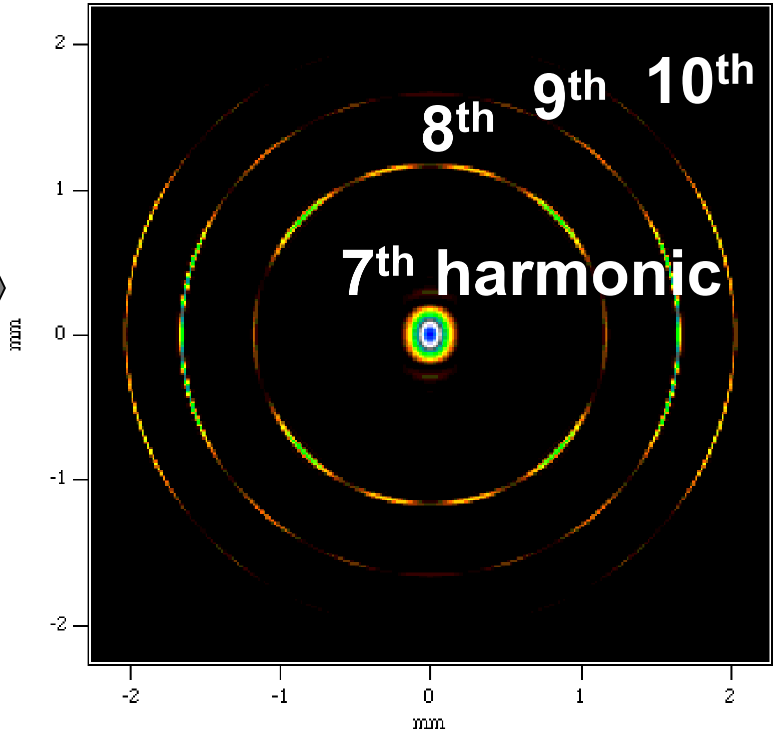
$$\Sigma^2 = \sigma_e^2 + \sigma_\gamma^2$$

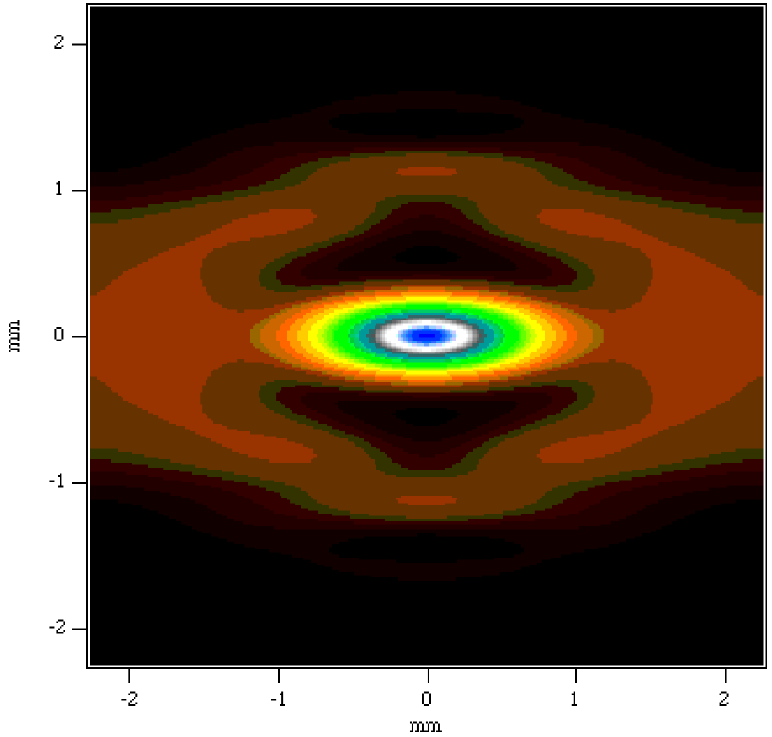
$$\sigma_\gamma' = \sqrt{\frac{\lambda}{L}}$$

$$\sigma_\gamma = \frac{\sqrt{\lambda L}}{4\pi}$$



Undulator radiation from 6 GeV beam with zero emittance, energy spread (example ESRF)

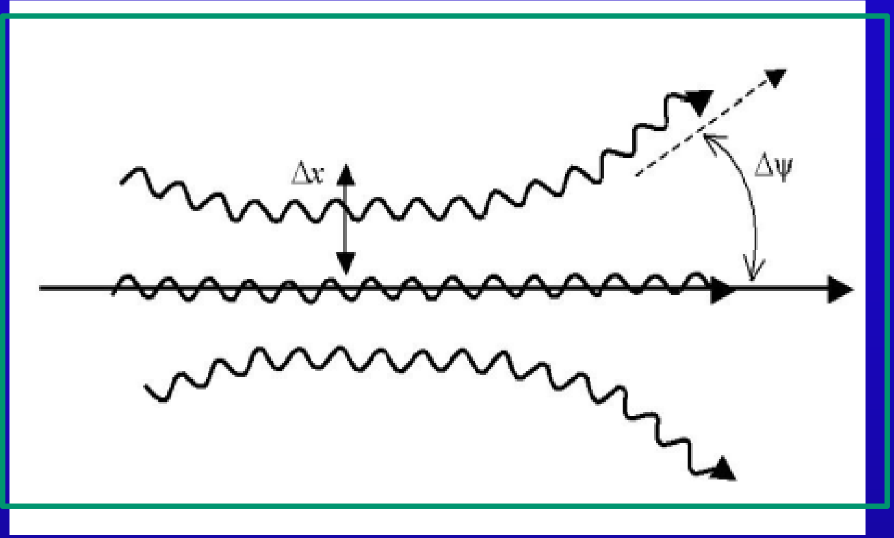




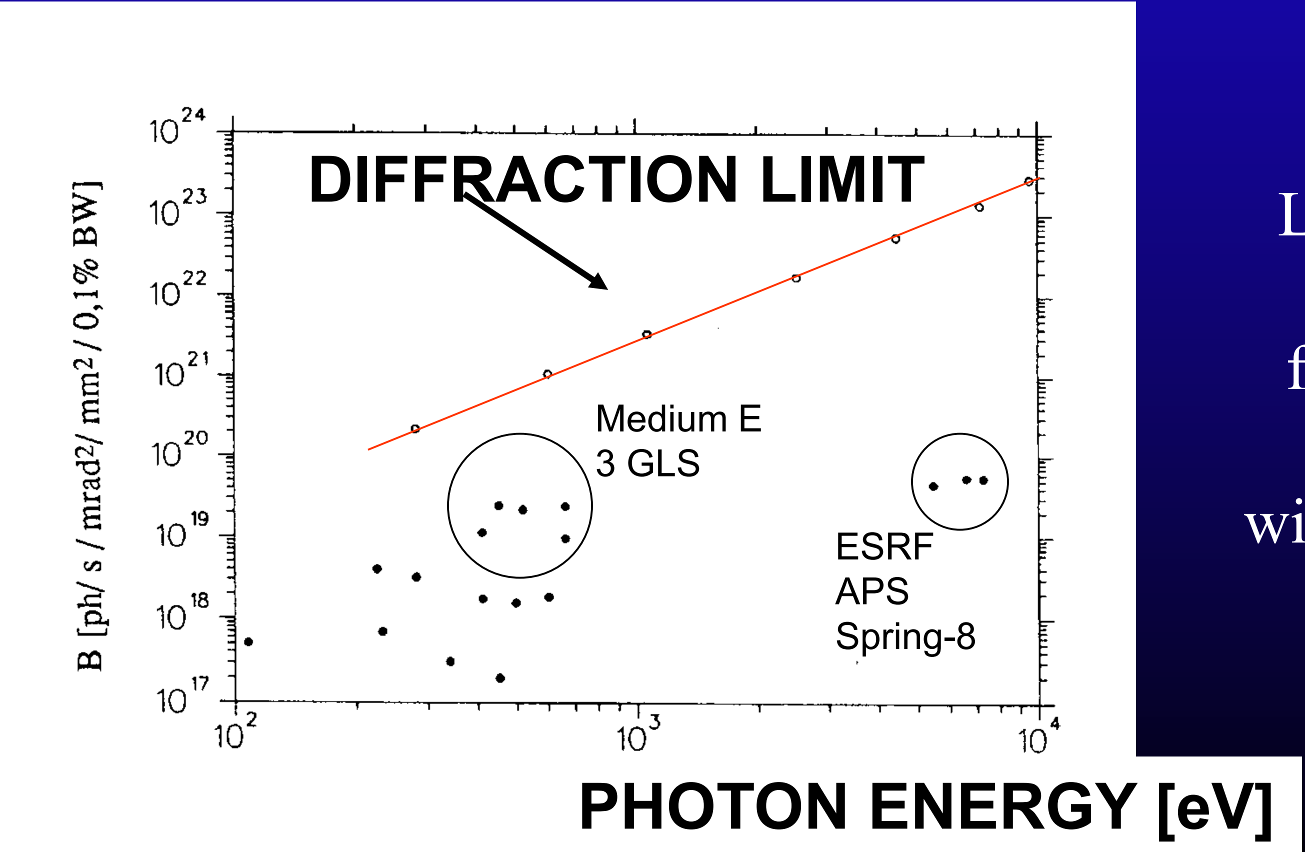
Emittance 4 nm·rad, 1% coupling, finite energy spread

Diffraction limited storage rings

HITTING THE DIFFRACTION LIMIT

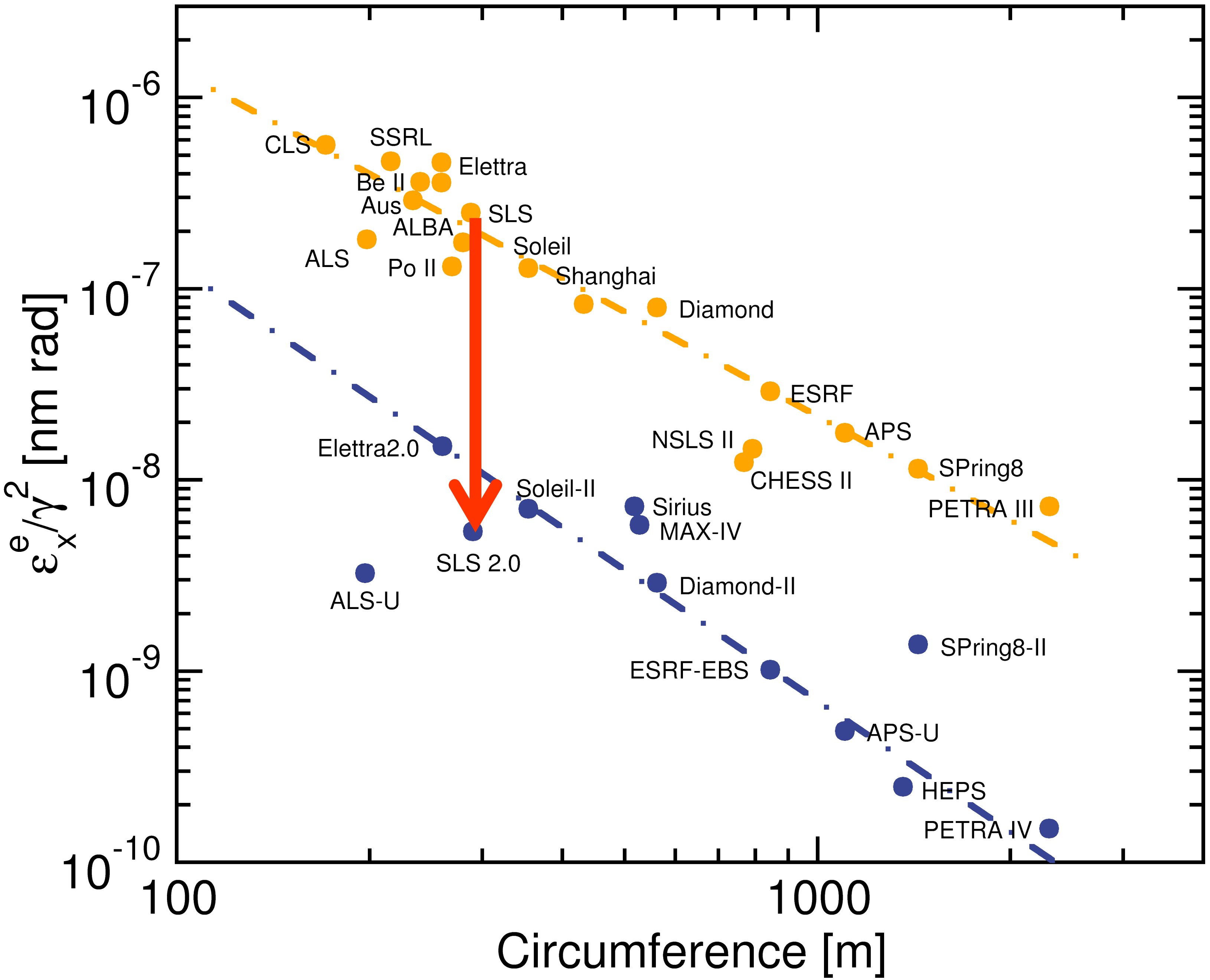


BRIGHTNESS:



Light of wavelength
λ
focused to spot size
Δx
will diffract with angle
$\Delta\psi = \sim \lambda/\Delta x$

Diffraction limited light sources



LEAPS League of European Accelerator-based Photon Sources

at a glance

LEAPS is the largest consortium of analytical facilities world-wide and further expanding its service to an interdisciplinary European user community

19 facilities - **16** institutions - **10** countries

> **300** operating End Stations

> **1.000.000** h beamtime /year

> **7’000** publications/year

> **15** spin off companies

> **35.000** users from all EU & beyond
researchers from all research areas

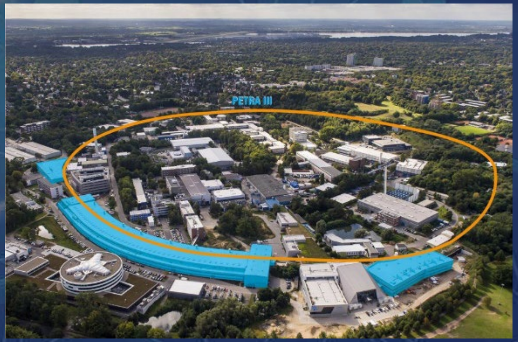
Construction and Operation (~ 800 M€/year) through national funding
Investment: 1.6 B€; 1.5 B€ upgrade programs

LEAPS League of European Accelerator-based Photon Sources

LEAPS League of European Accelerator-based Photon Sources

Synchrotrons

ESRF & PETRA III
6 GeV



Alba, Diamond, Elettra, Max IV, SLS, Soleil
2-3 GeV

ASTRID, BESSY II, DAFNE, Max IV, PTB, Solaris **< 2 GeV**

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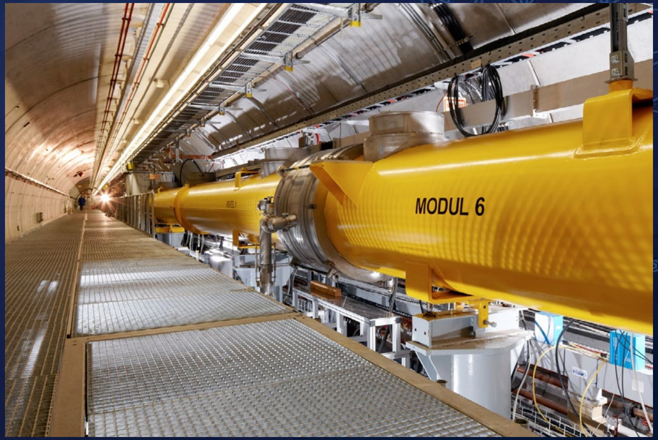
FELs from Hard X rays to IR

European XFEL

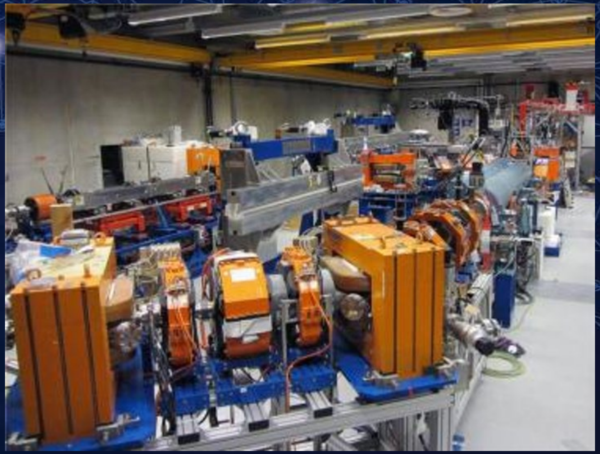
SwissFEL

FERMI

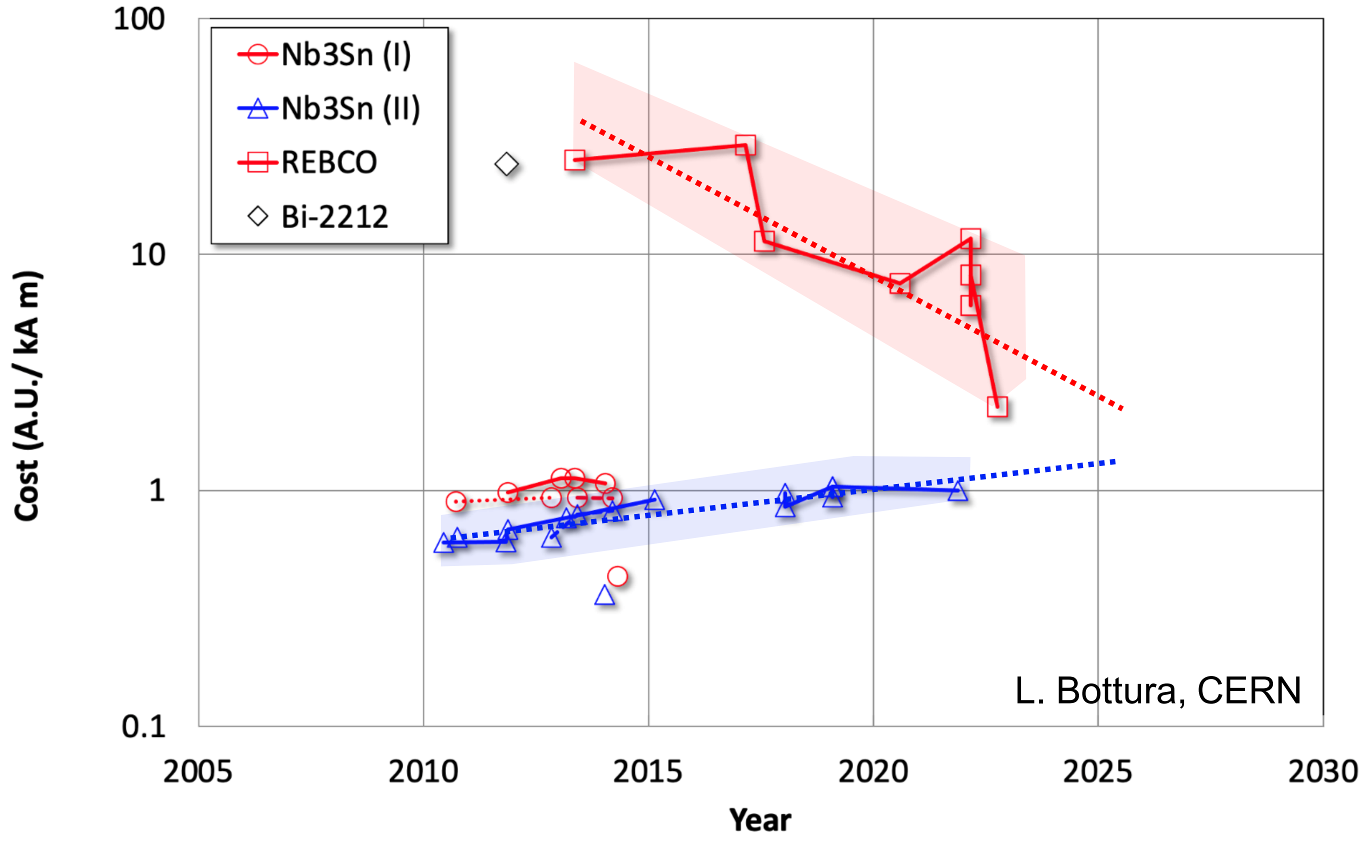
FELBE

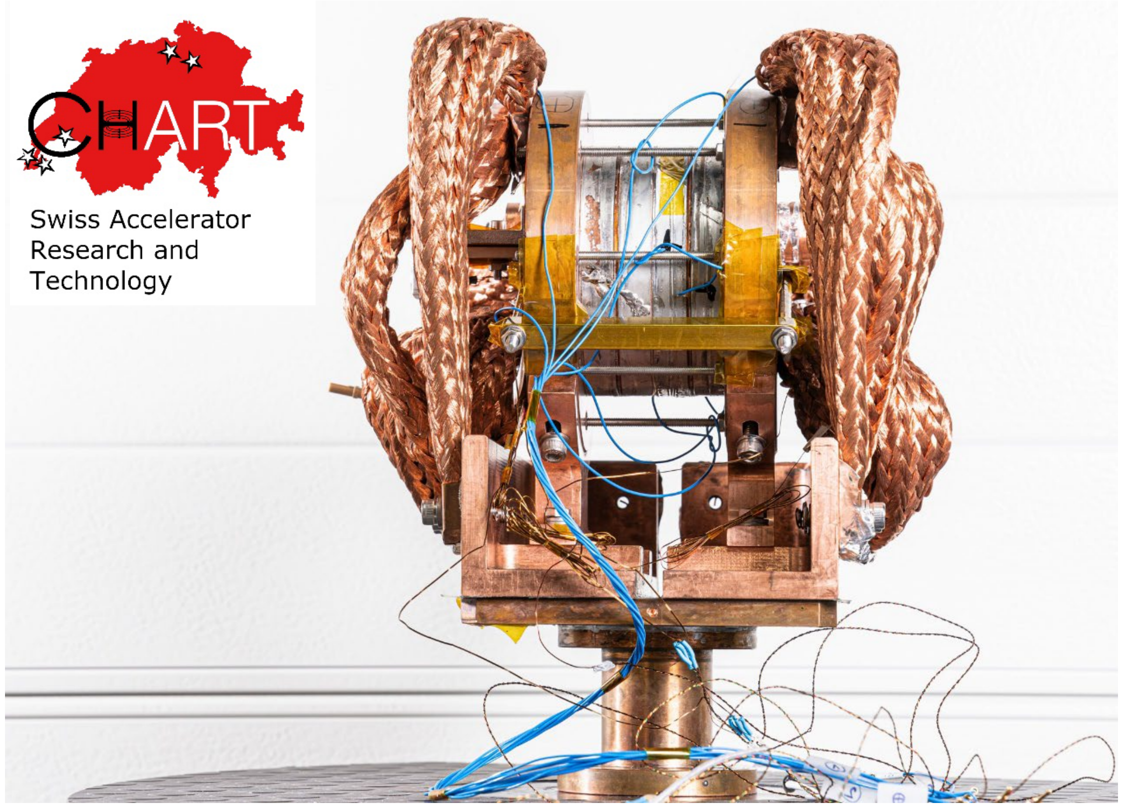


FLASH



FELIX





High Temperature Superconductors (HTS) example of technology development for fusion and accelerators

HTS superconducting magnet technology: developments for fusion (Tokamak Energy Ltd., UK)

Using non-insulated HTS tapes:

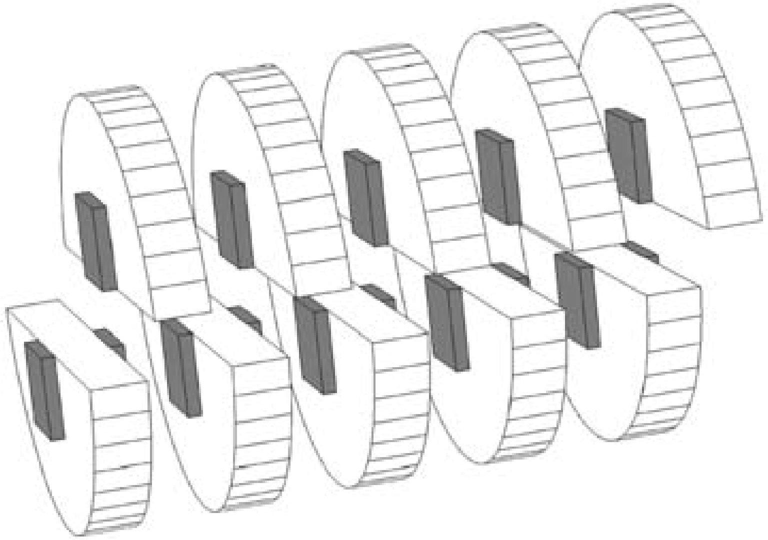
18.2 Tesla @ 12 K field reached recently

Recent claims from Korea of ambient temperature and pressure LK-99 superconductor...
(many claims of room temperature, high pressure s.c.)

HTS superconducting magnet technology undulators

Using bulk HTS material: can reach 2 Tesla for very short period magnets

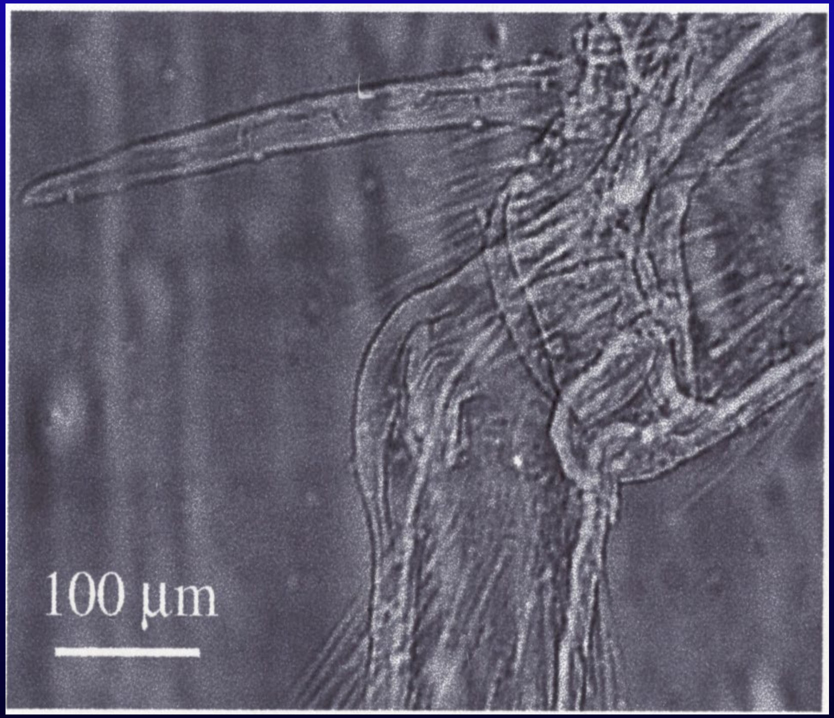
Put the structure into a solenoid magnet, cool it and trap the field



Transverse coherence

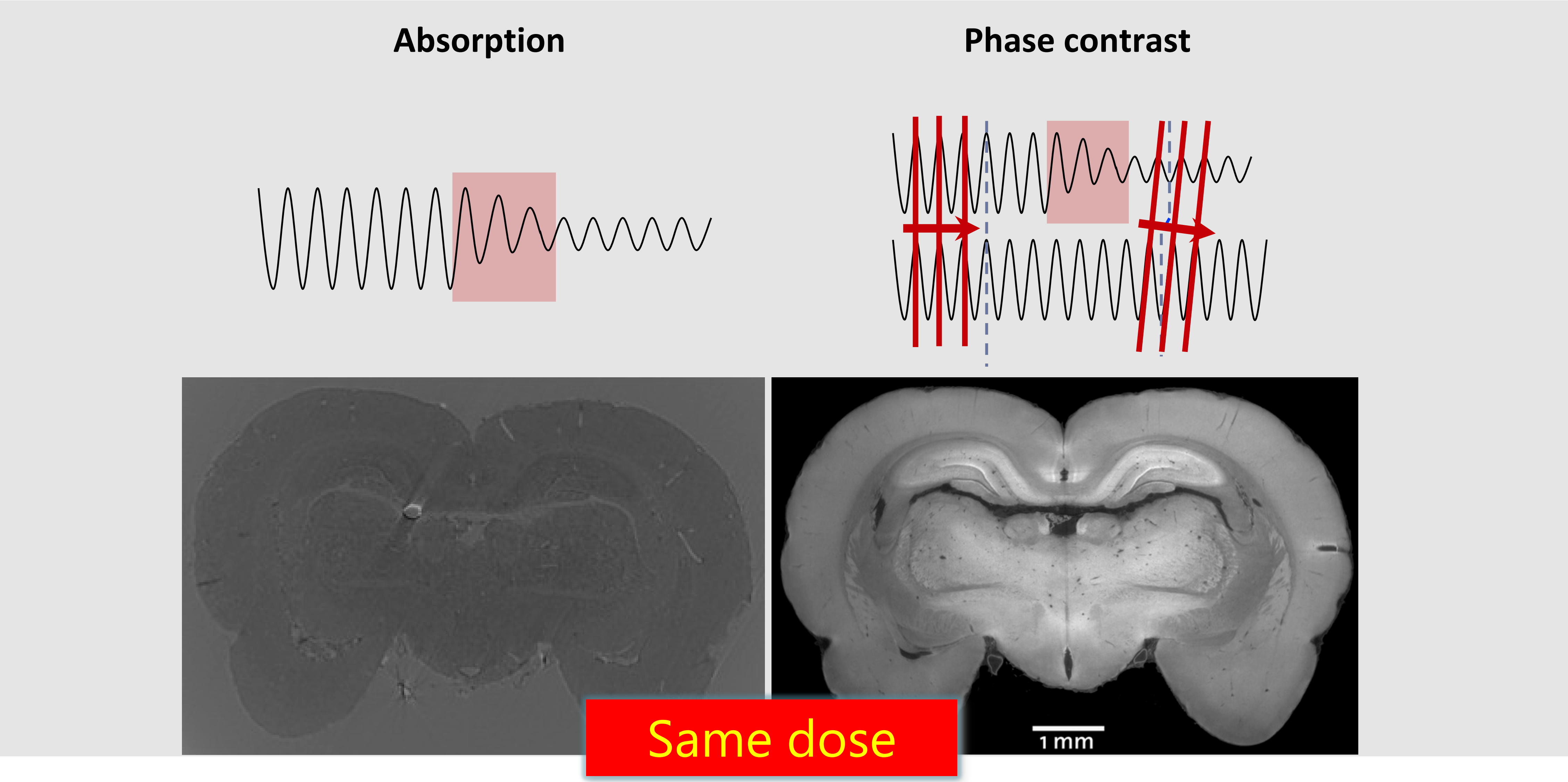
- High brightness gives coherence
- Wave optics methods for X-rays (all chapters in Born & Wolf)
- Holography

The knee of a spider



phase contrast imaging

Phase contrast X-Ray imaging: improved soft tissue contrast

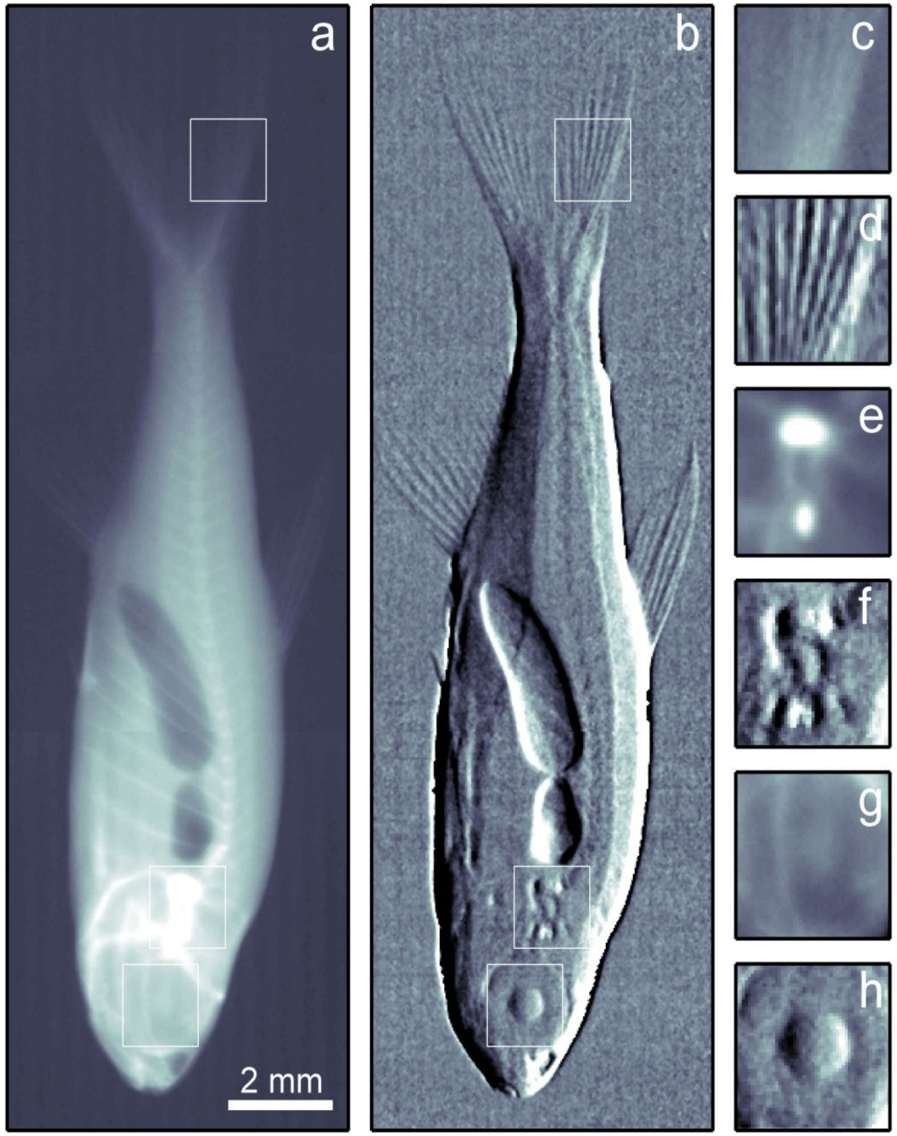


X-ray Radiography of a fish

conventional Absorption

a

(+ details c , e, g)

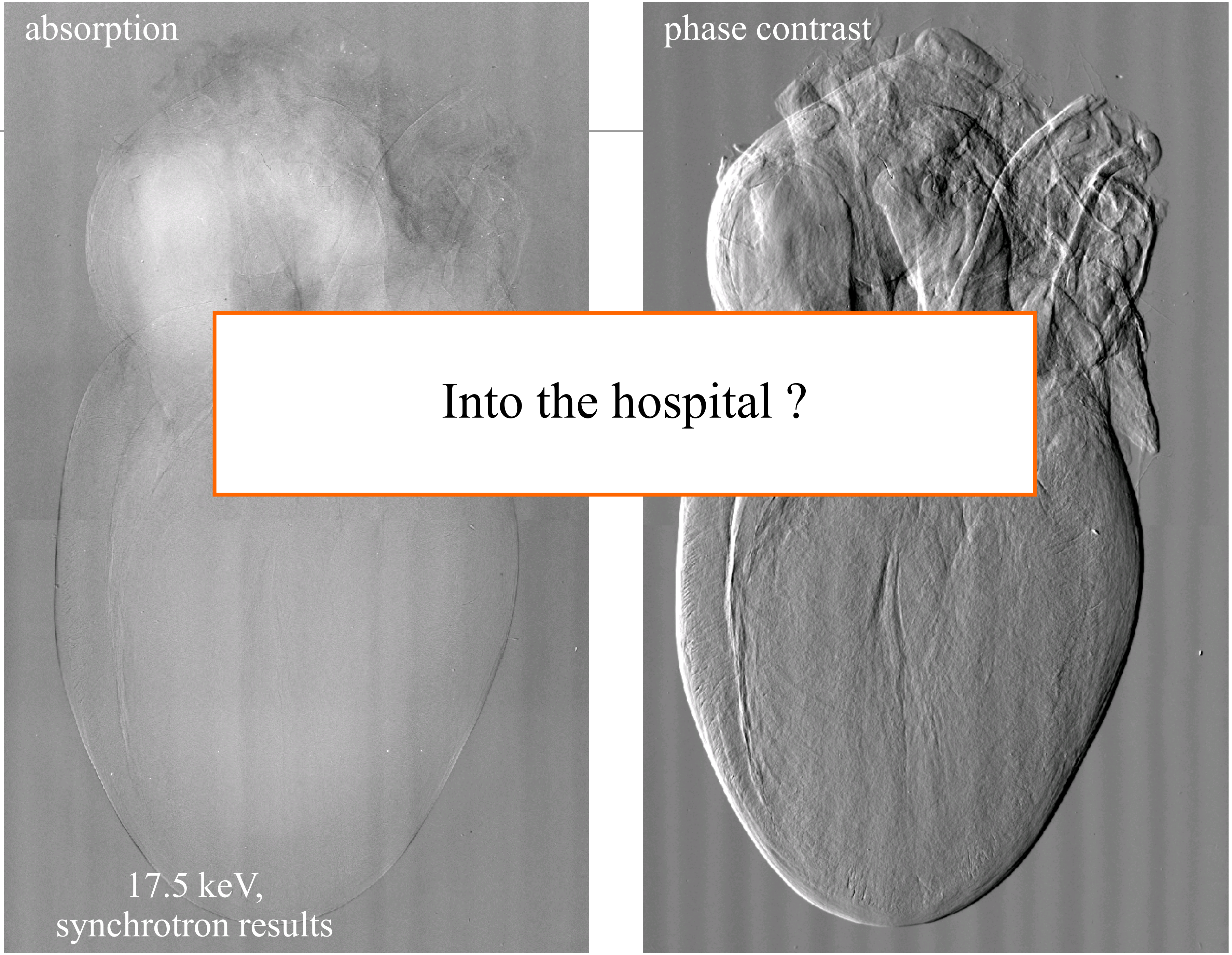


Phase contrast Microscopy

b

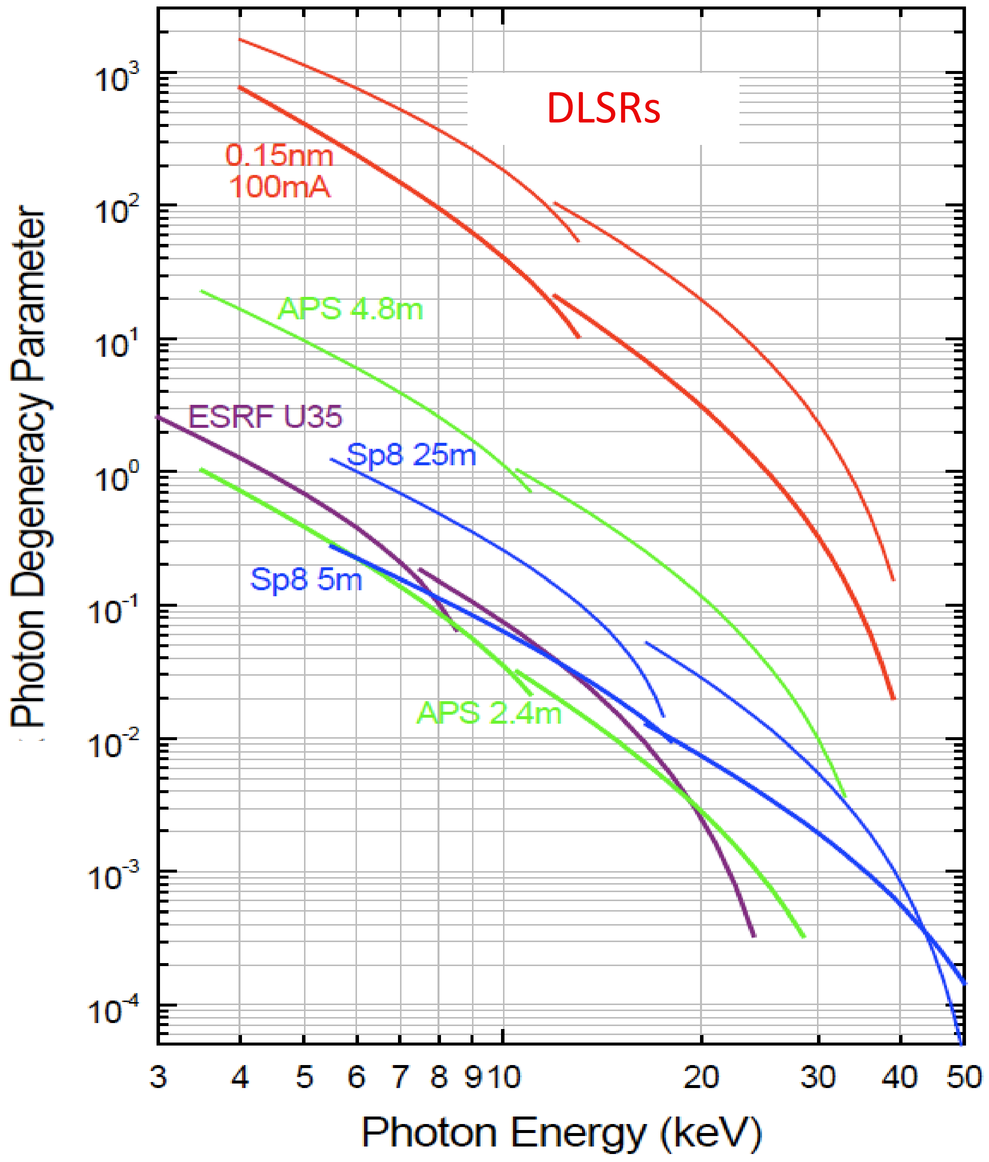
(+ details d, f, h)

Imaging for Life Science Applications



Into the hospital ?

Source photon degeneracy parameter



Photons per spatial and temporal mode

$$\delta = B\,\lambda^3/4c = F_c\tau_c$$

Muscles and tracheal network *during* flight

R. Mokso *et al.*, Scientific Reports 5 8727 (2015)

Fake news?

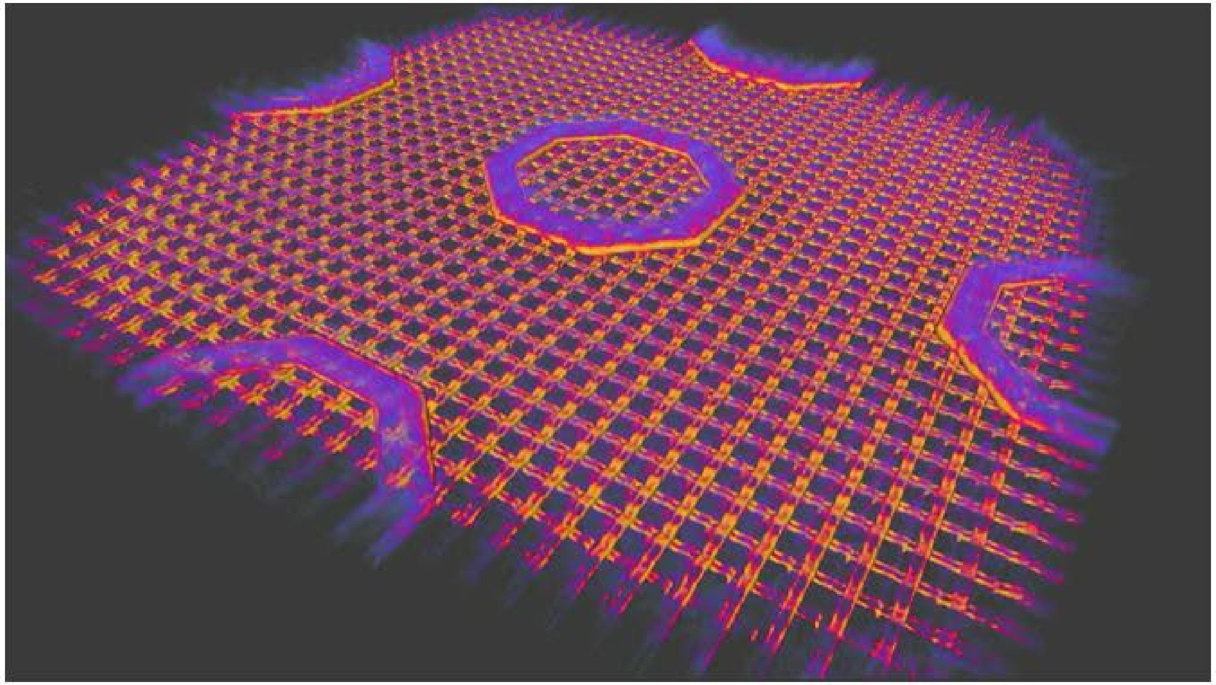
Intel Core Pentium G3260 (3300) Dual Core, 22 nm

Holler et al., Nature 543, 402–406 (16 March 2017)

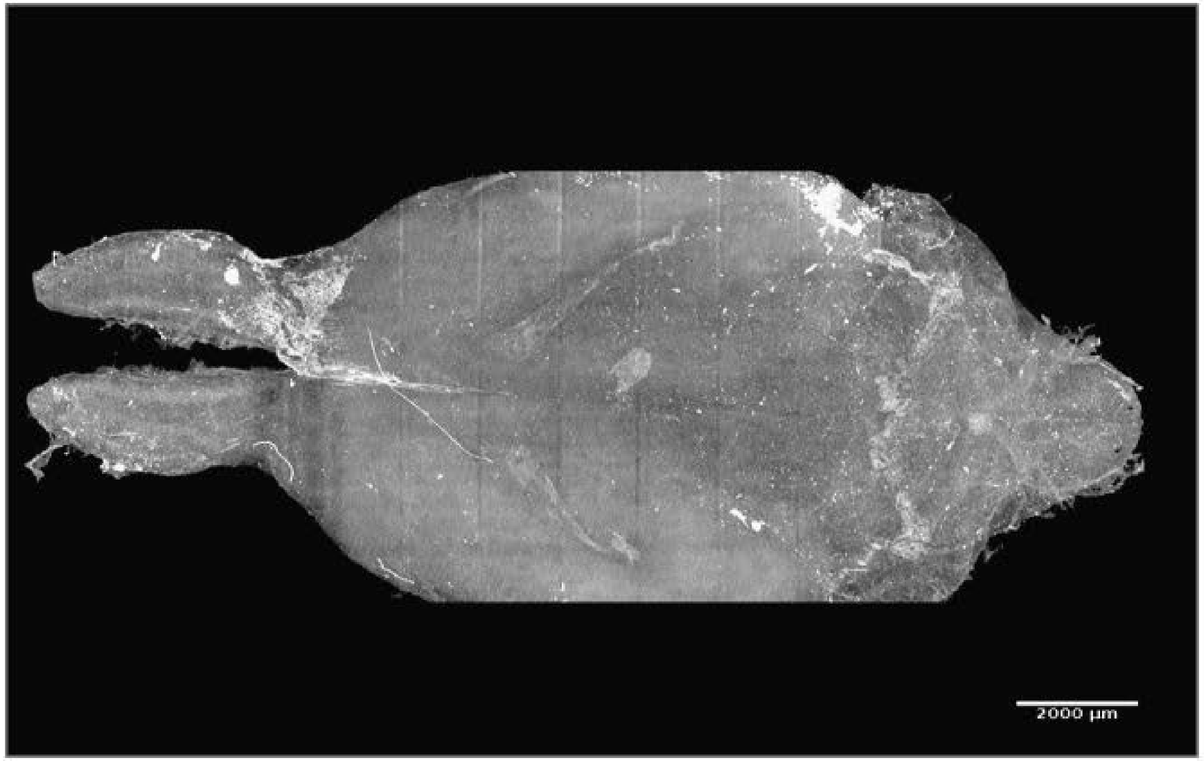
X-Ray tomography

Architecture of artificial and natural intelligence on all scales

Nature Electronics 2, 464-470 (2019)



Brain of a mouse in 3-D
Miettinen *et al.*

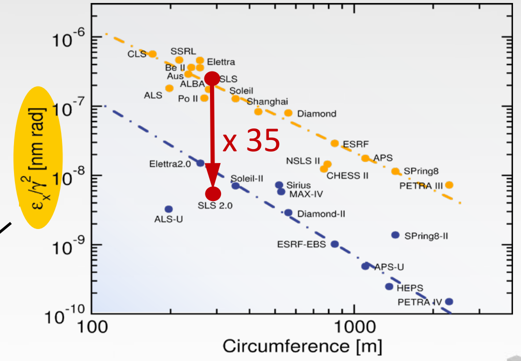


PAUL SCHERRER INSTITUT PSI

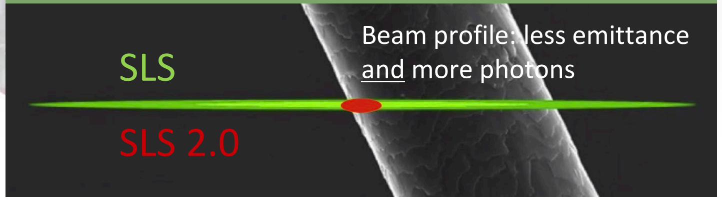
SLS 2.0: upscaling Swiss Light Source

$$\mathcal{B} = \frac{\text{flux}}{\text{emittance}}$$

Brilliance



HUMAN HAIR (0.017 millimeters)



2021 2022 2023 2024 2025 2026

DECEMBER 2020

Swiss Parliament agrees on the Swiss Dispatch on Promotion of ERI.

OCTOBER 2023

Start of construction. Dark period 15 months

JULY 2025

Restart of User Operation

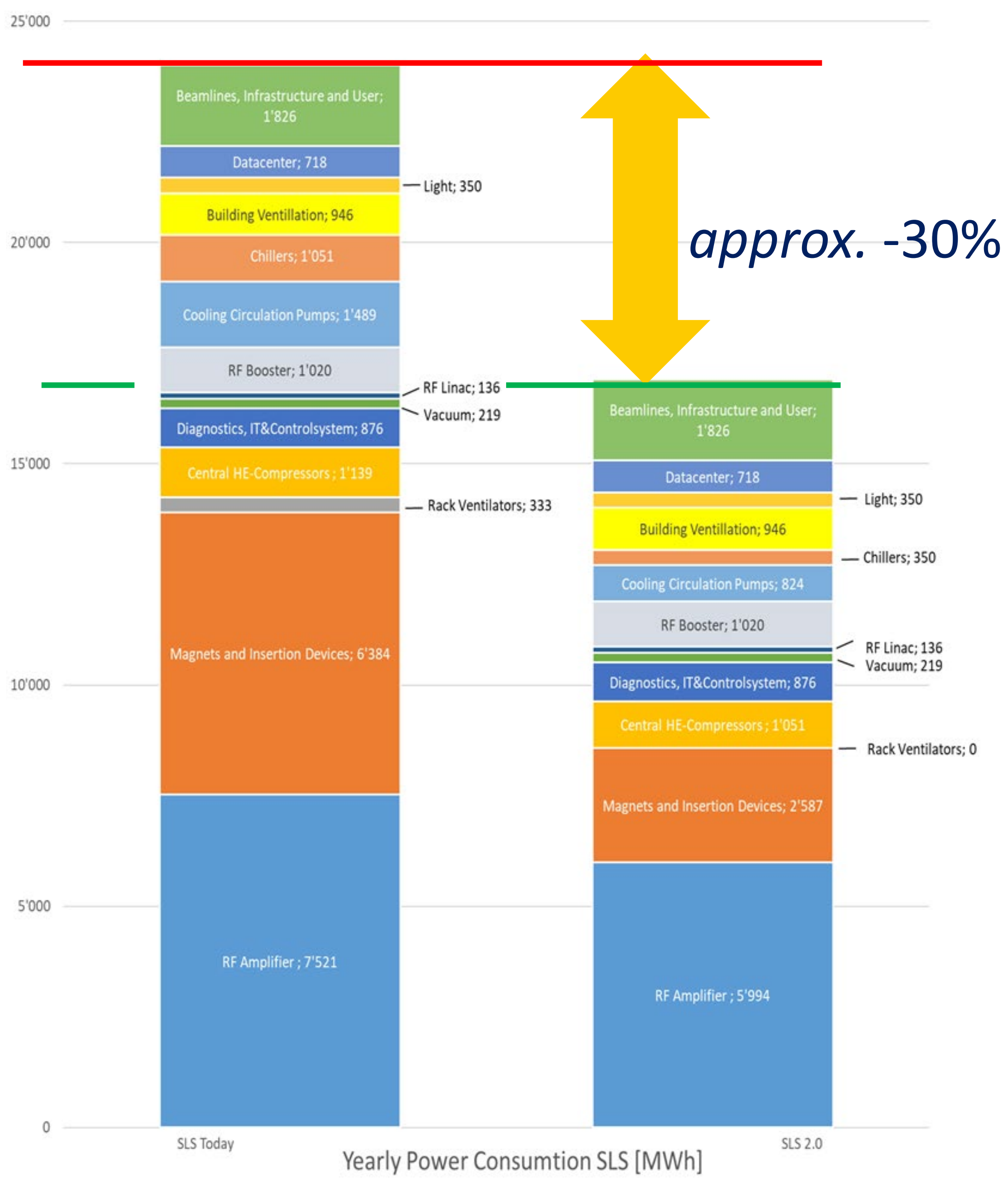
Power economy SLS2.0 vs. SLS

More radiated X-ray power for users
Less electricity consumption

	SLS → SLS2.0
E_{e^-}	2.4 GeV → 2.7 GeV
P_{SR}	310 GeV → 365 kW
W_{elec}/y	24 GWh → 17 GWh

Key savings:

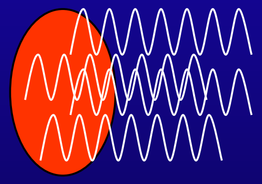
Electromagnets → Permanent magnets
Klystrons → Solid state amplifiers
standard pumps → modern pumps for cooling



Free Electron Lasers

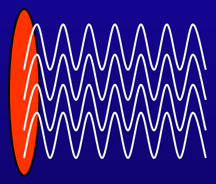
COHERENT EMISSION BY THE ELECTRONS

Intensity $\propto N$



INCOHERENT EMISSION

Intensity $\propto N^{2}$



COHERENT EMISSION

FIRST DEMONSTRATIONS OF COHERENT EMISSION (1989-1990)

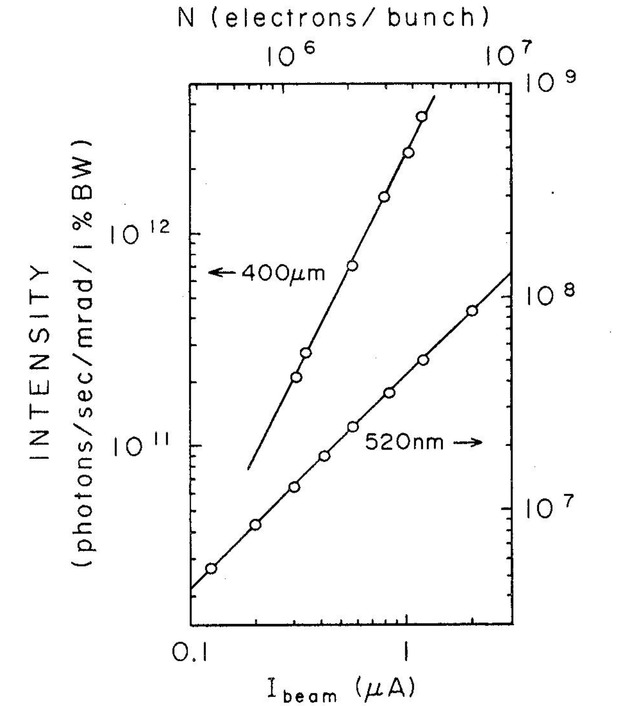


Fig. 4. Dependence of SR intensity on the beam current at $\lambda = 400$ μm and $\lambda = 520$ nm for the long pulse/short bunch beam. The ordinate is given on the left-hand side for $\lambda = 400$ μm and on the right for $\lambda = 520$ nm. The two lines show the linear and quadratic relations to the beam current. The beam current is converted to the average number of electrons in a bunch on the upper side.

180 MeV electrons

T. Nakazato et al., Tohoku University, Japan

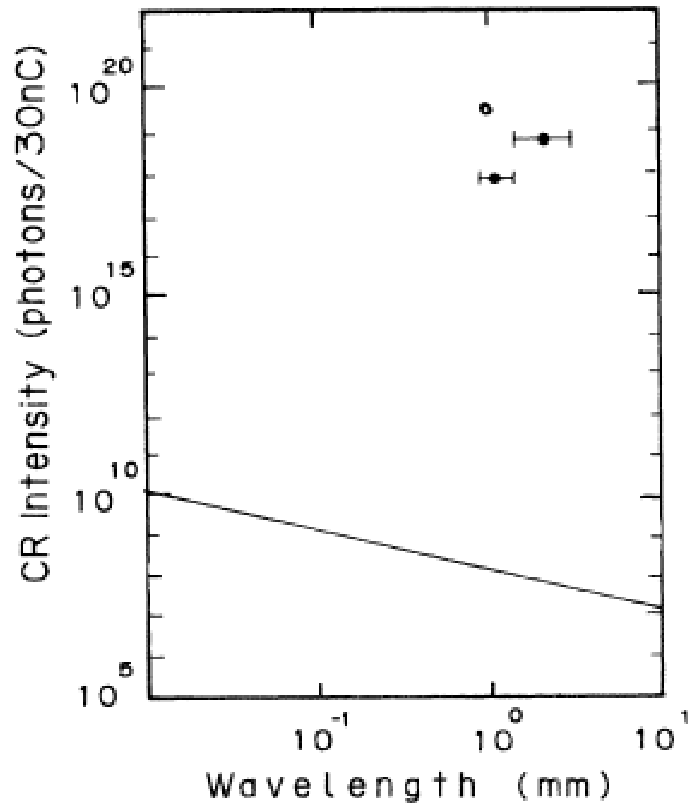
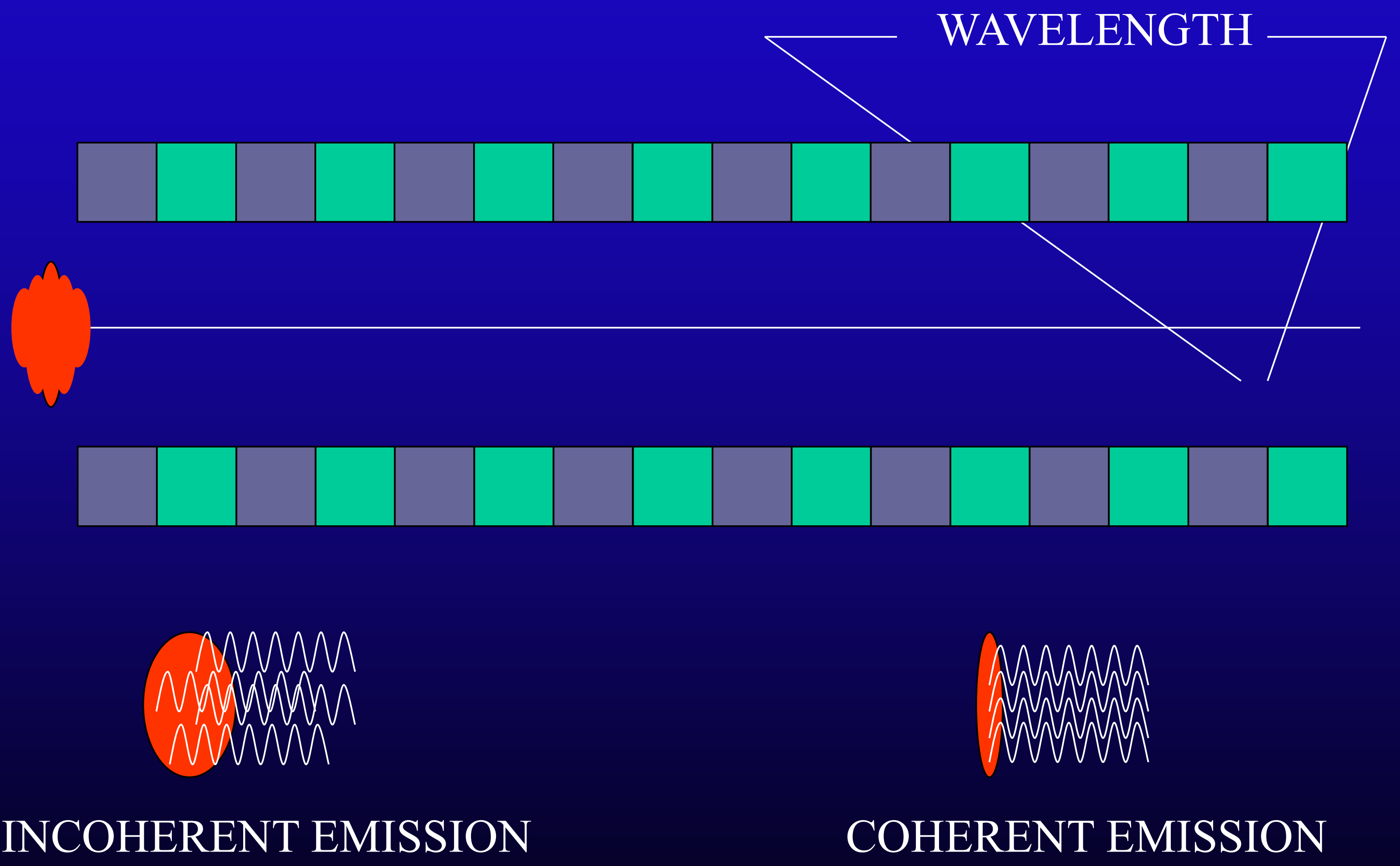


FIG. 3. The intensity of the CR measured for the bandwidths indicated with horizontal bars, the spectrum calculated according to Eq. (1) for 10% bandwidth (solid line), and the intensity expected for the complete coherence over the bunch for 10% bandwidth (open circle).

30 MeV electrons

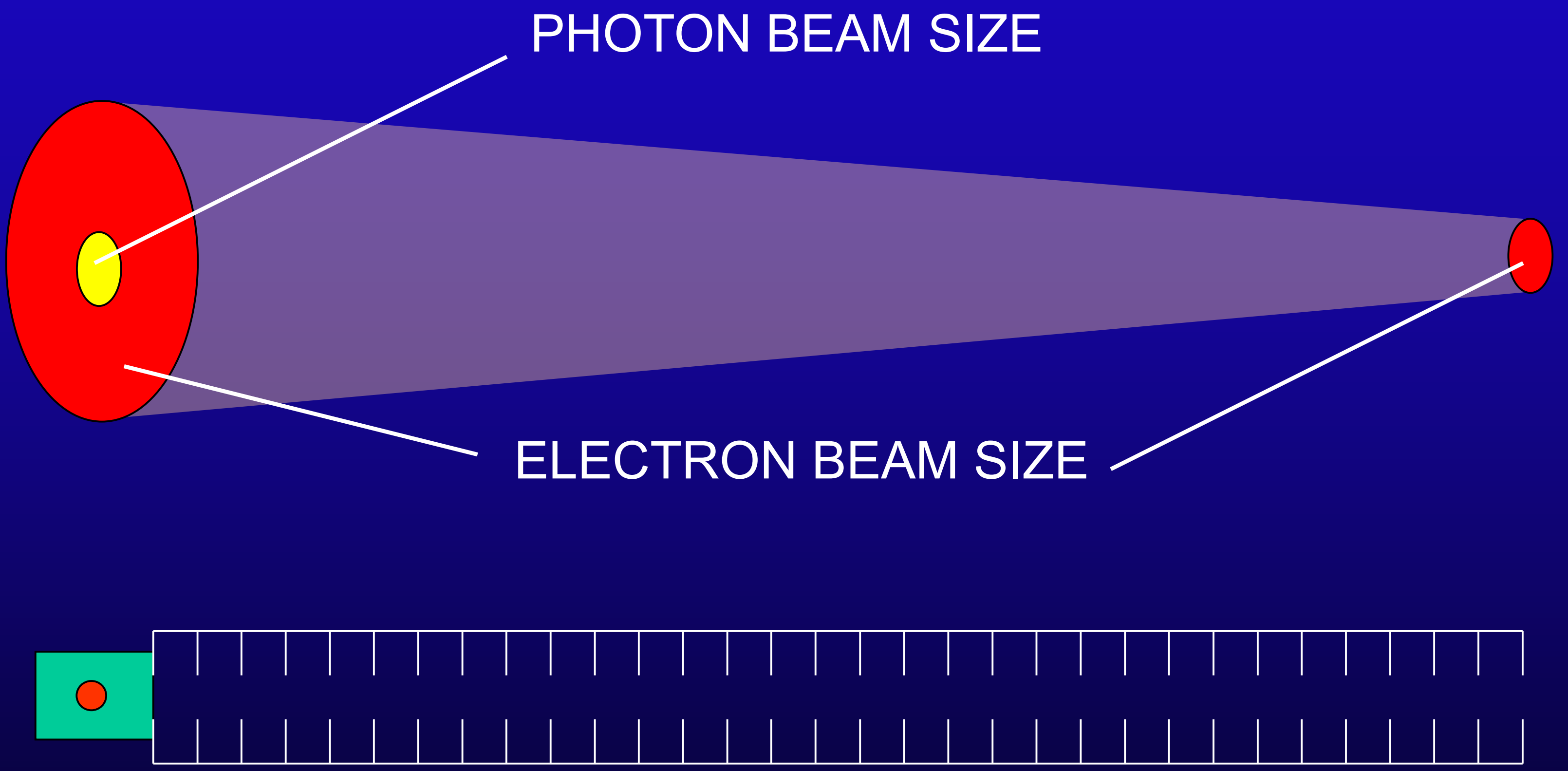
J. Ohkuma et al., Osaka University, Japan

MUCH HIGHER BRIGHTNESS CAN BE REACHED WHEN THE ELECTRONS COOPERATE



THE ELECTRON BEAM SHOULD BE ~ 1 Å

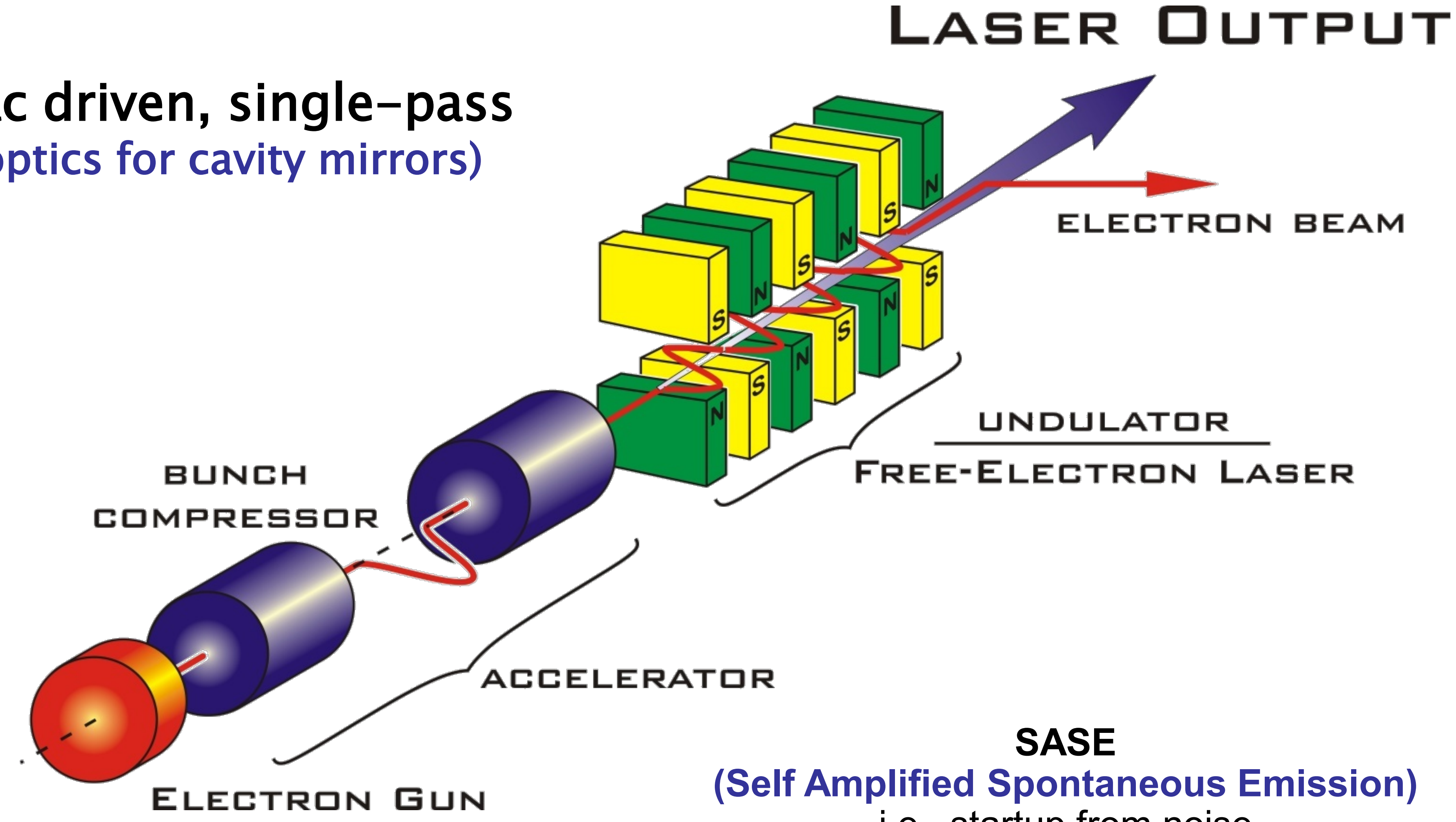
AS SMALL AS THE X-RAY WAVELENGTH!



Paul Scherrer Institute

Free Electron Laser Keywords:

- **Linac driven, single-pass**
  (no optics for cavity mirrors)

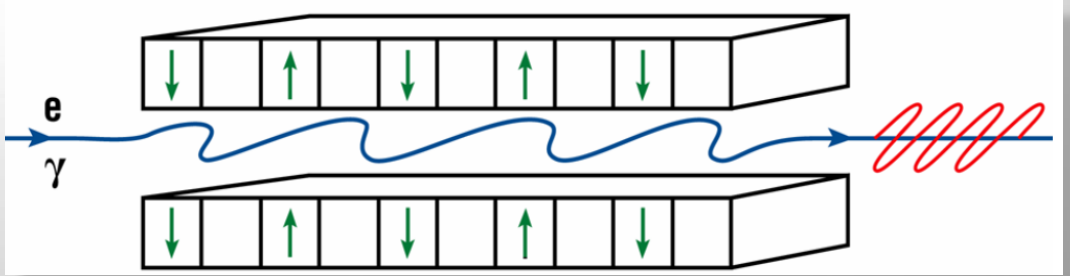


SASE
(Self Amplified Spontaneous Emission)
i.e., startup from noise

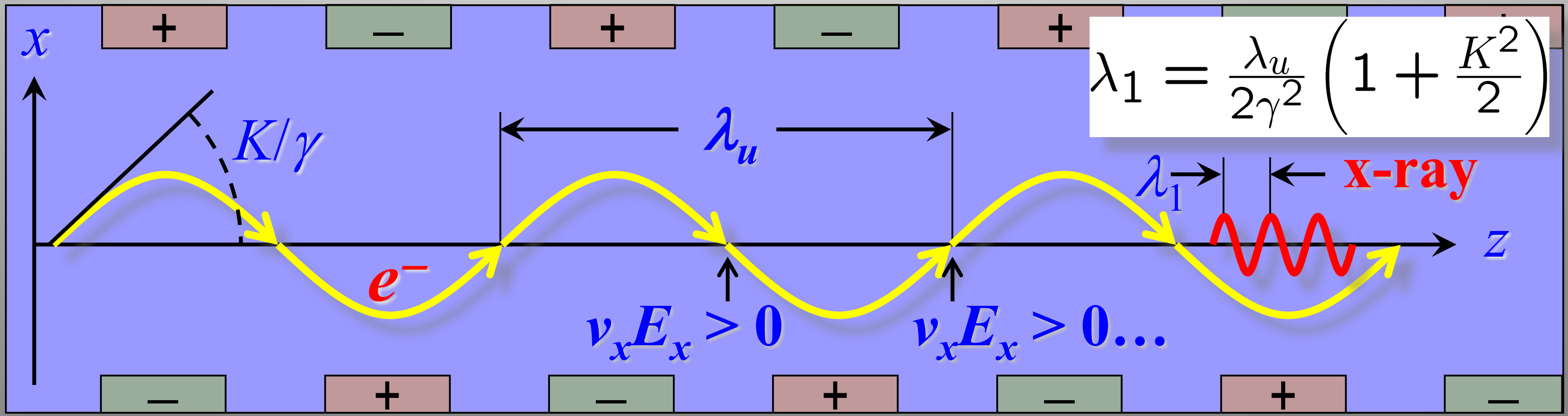
R. Bakker

FEL Principles

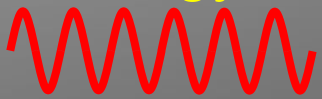
Z. Huang



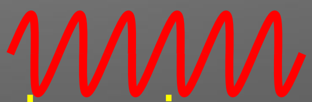
- Electrons **slip** behind EM wave by λ_1 per undulator period (λ_u)



- Due to sustained interaction, some electrons lose energy, while others gain ➔ **energy modulation at λ_1**



- e^- losing energy slow down, and e^- gaining energy catch up ➔ **density modulation at λ_1 (microbunching)**



- Microbunched beam radiates coherently at λ_1, enhancing the process ➔ **exponential growth of radiation power**

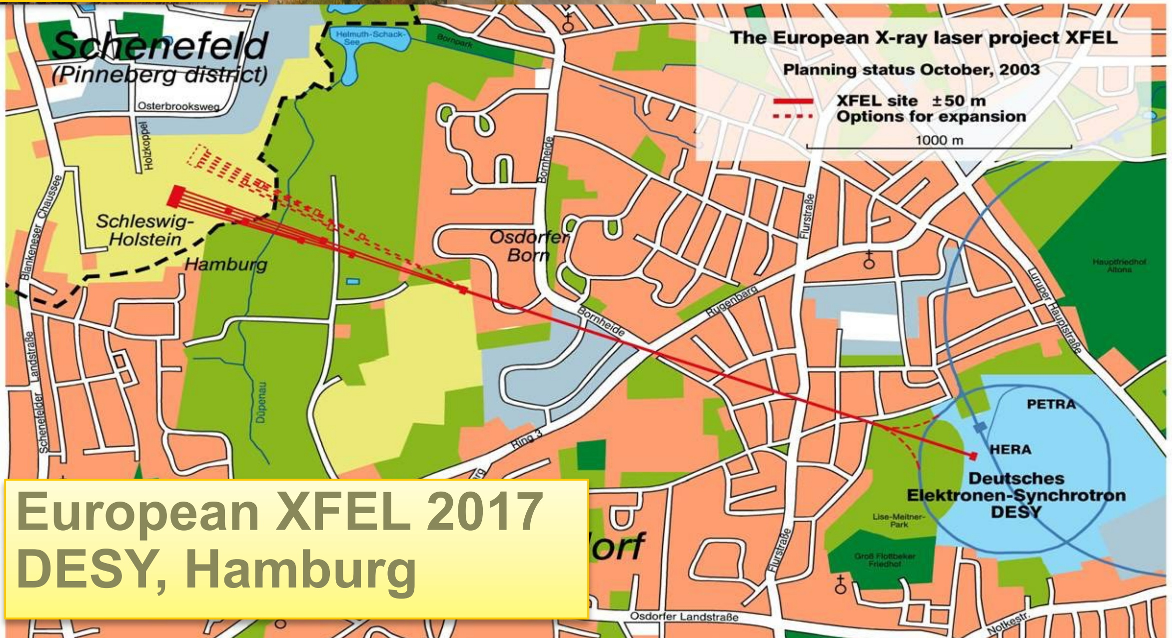
X-Ray Free Electron Lasers

PAL XFEL 2016

SACLA 2011
8.5 GeV, 60 Hz NC

SwissFEL 2017

LCLS I, II 2009, 2022



European XFEL 2017
DESY, Hamburg

Spin-off product from basic research

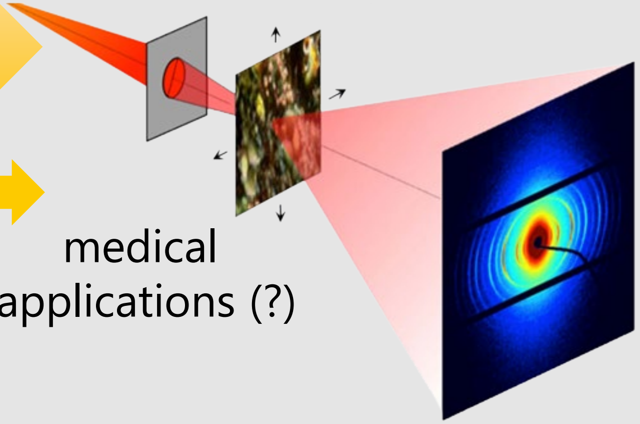
15 years

pixel detector for particle physics

CMS detector at CERN, Geneva

spin-off

medical applications (?)

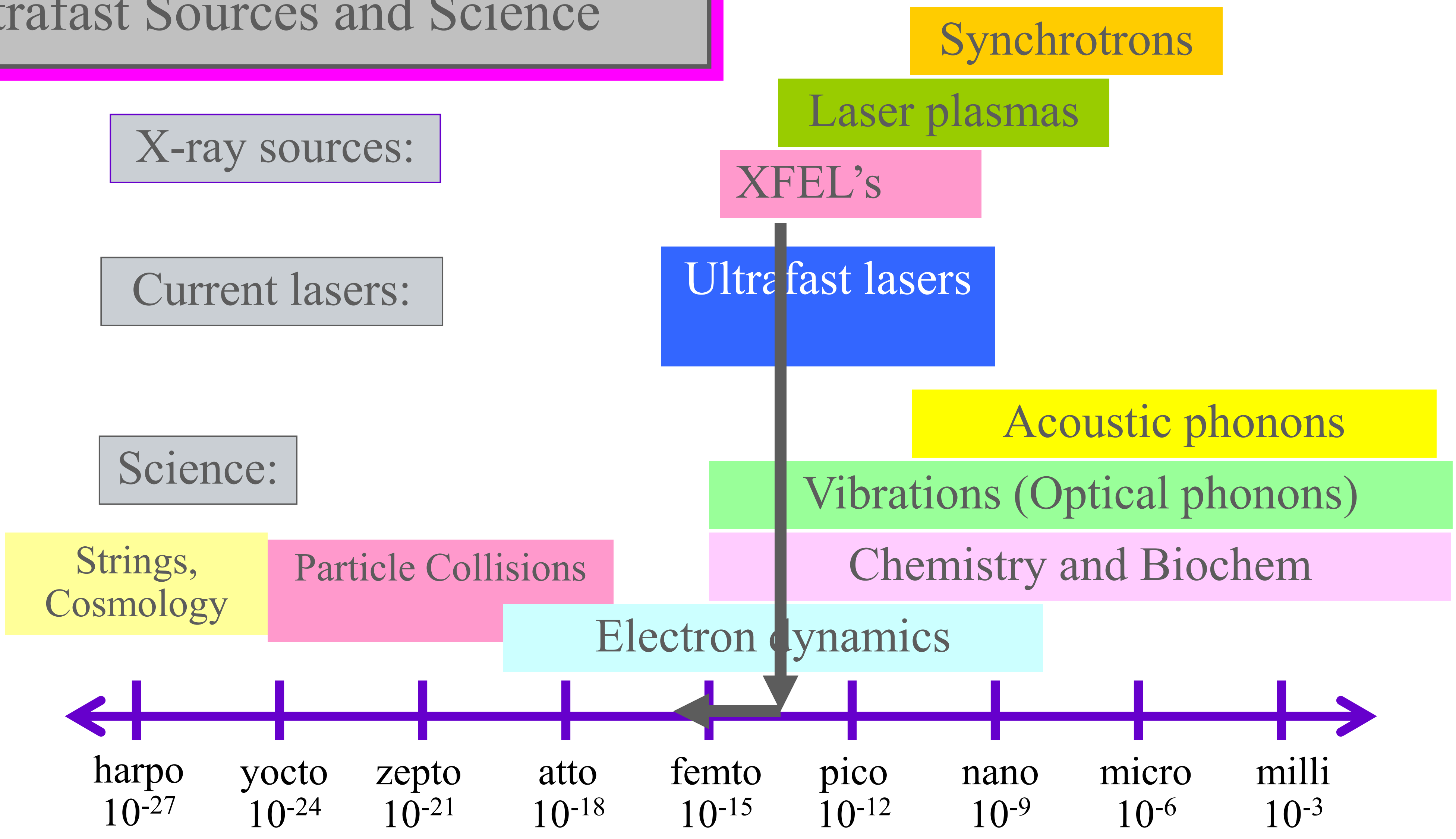


synchrotron sources worldwide

applications in materials research

PILATUS 6M Pixel-Detector (Dectris Ltd., Switzerland)

Ultrafast Sources and Science



J. Hastings

1878: E. Muybridge at Stanford

Tracing motion of animals by spark photography

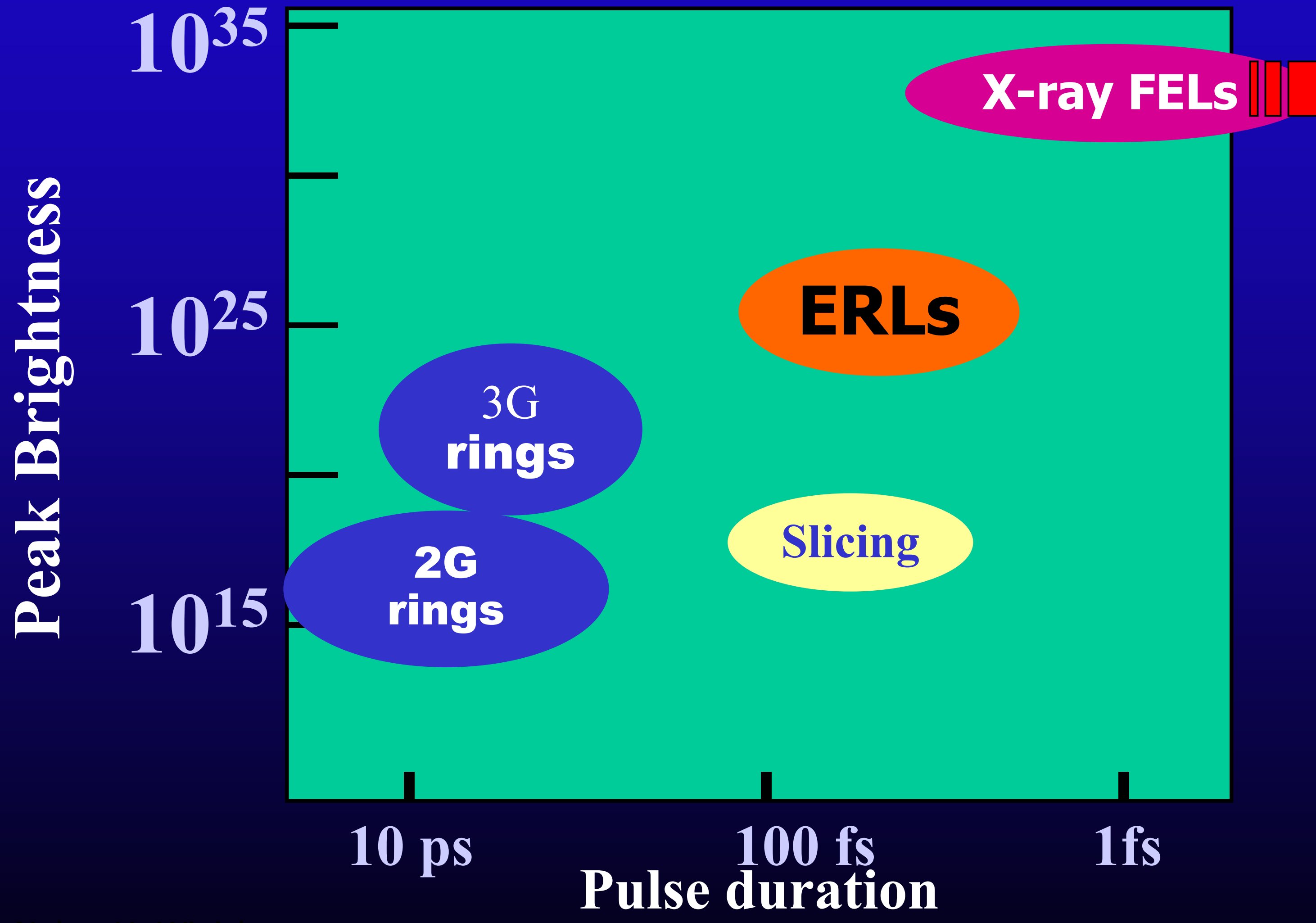
E. Muybridge

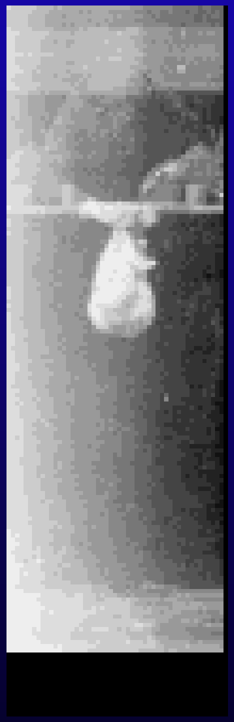
L. Stanford

Muybridge and Stanford disagree whether all feet leave the ground at one time during the gallop…

E. Muybridge, *Animals in Motion*, ed. by L. S. Brown (Dover Pub. Co., New York 1957).

FELs and ERLs COMPLEMENT the Ring sources





H.-D. Nuhn, H. Winick

After H.-D. Nuhn, H. Winick

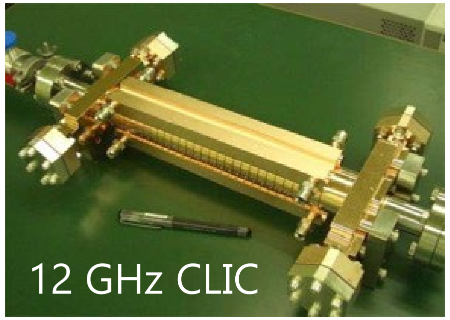
Compact accelerators:
sources of photons, neutrons, electrons etc.

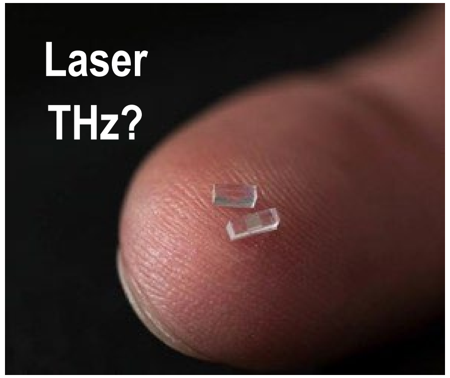
Compact accelerators

GORDON AND BETTY MOORE FOUNDATION

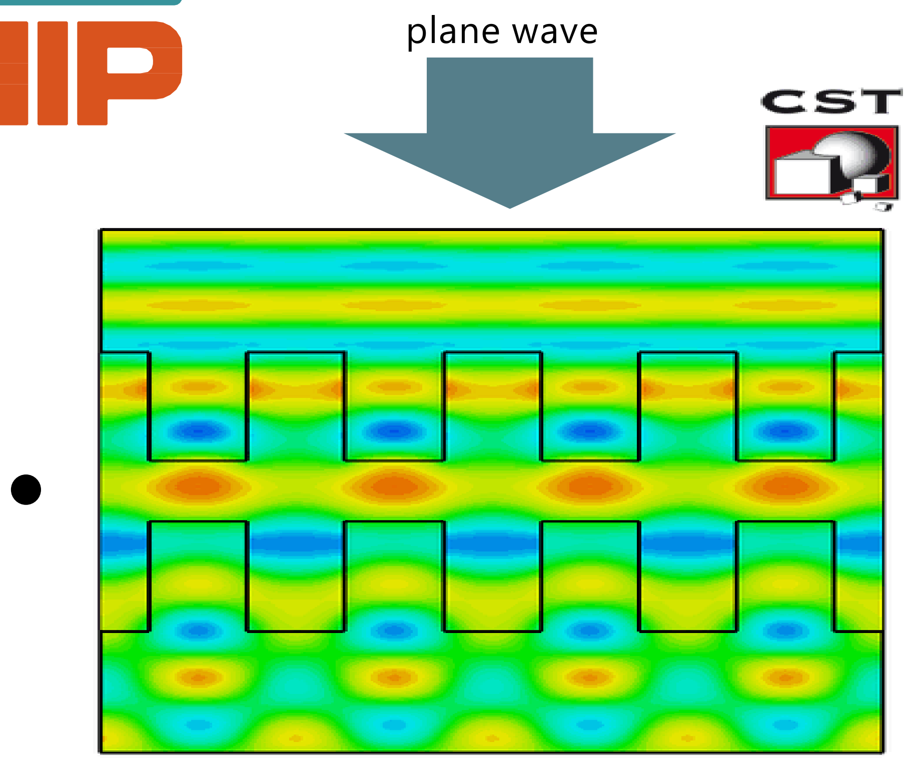
DESY · EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE · FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG · PAUL SCHERRER INSTITUT PSI · SLAC NATIONAL ACCELERATOR LABORATORY

STANFORD UNIVERSITY · TECH-X · TECHNISCHE UNIVERSITÄT DARMSTADT · UH Universität Hamburg





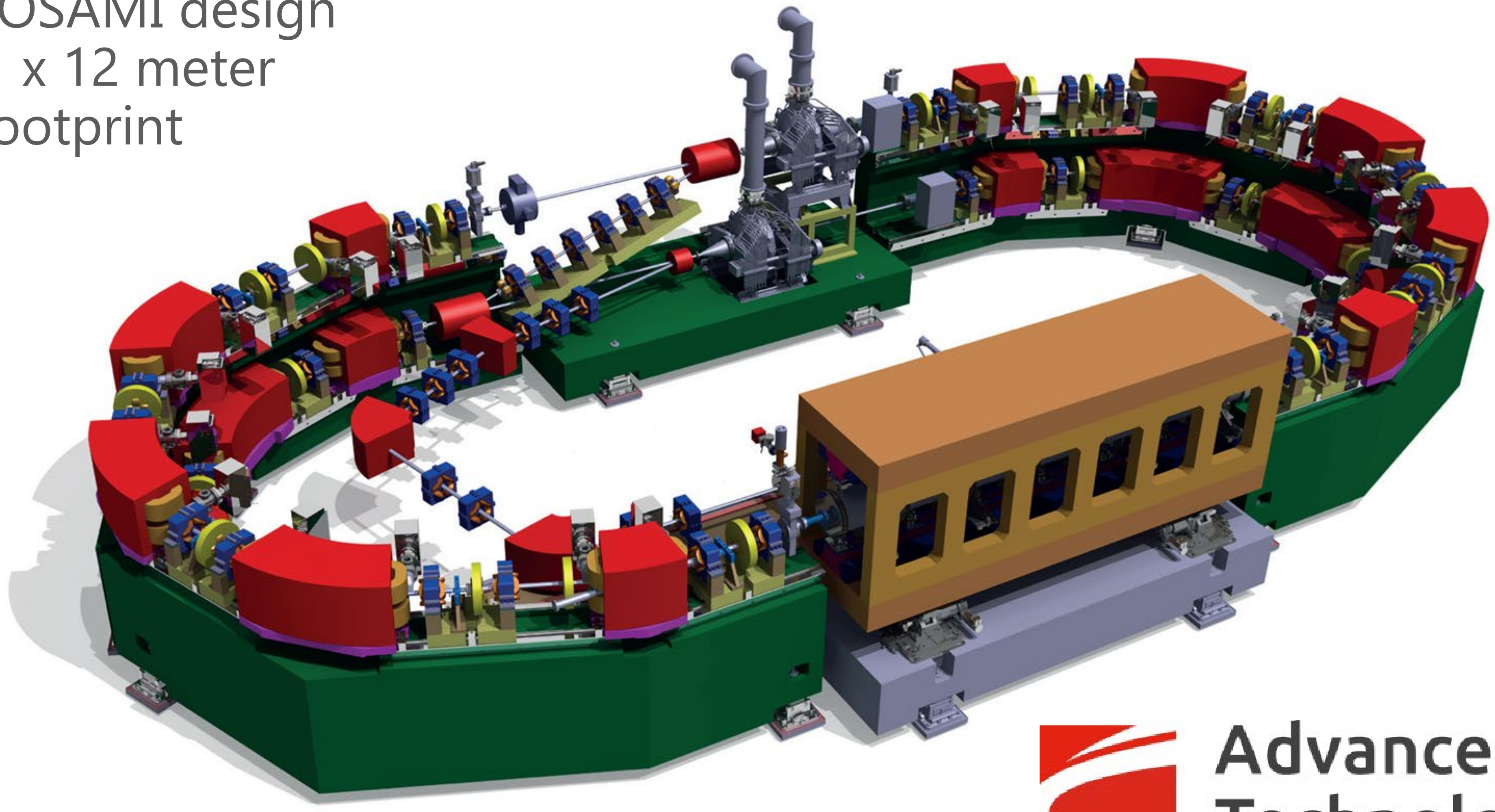
ACHIP



CST

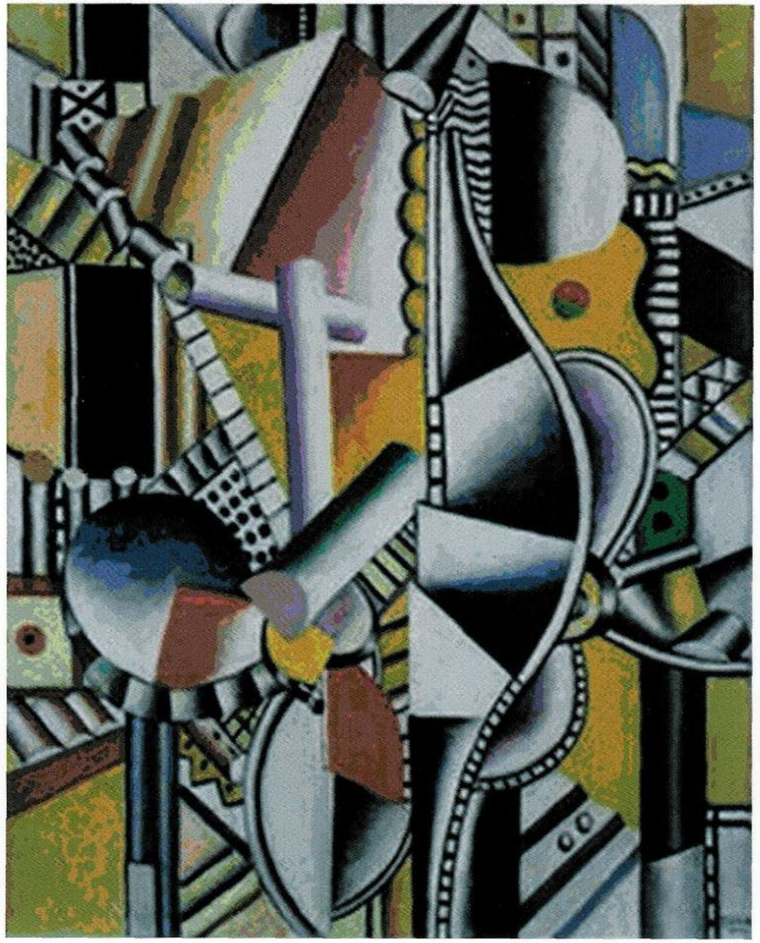
Disruptive storage rings technology change: a much brighter compact sources e.g. for shorter wavelength lithography

COSAMI design
5 x 12 meter
Footprint



Advanced Accelerator Technologies

ENGINES OF DISCOVERY



A Century of Particle Accelerators

Andrew Sessler · Edmund Wilson

« Le seul véritable voyage … ce ne serait pas d'aller vers de nouveaux paysages, mais d'avoir d'autres yeux, de voir l'univers avec les yeux d'un autre, de cent autres, de voir les cent univers que chacun d'eux voit, que chacun d'eux est. »

(Marcel Proust, La Prisonnière, 1923)

"The real voyage of discovery consists not in seeking new landscapes but in having new eyes"

Marcel Proust