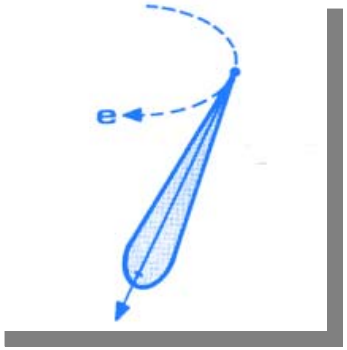
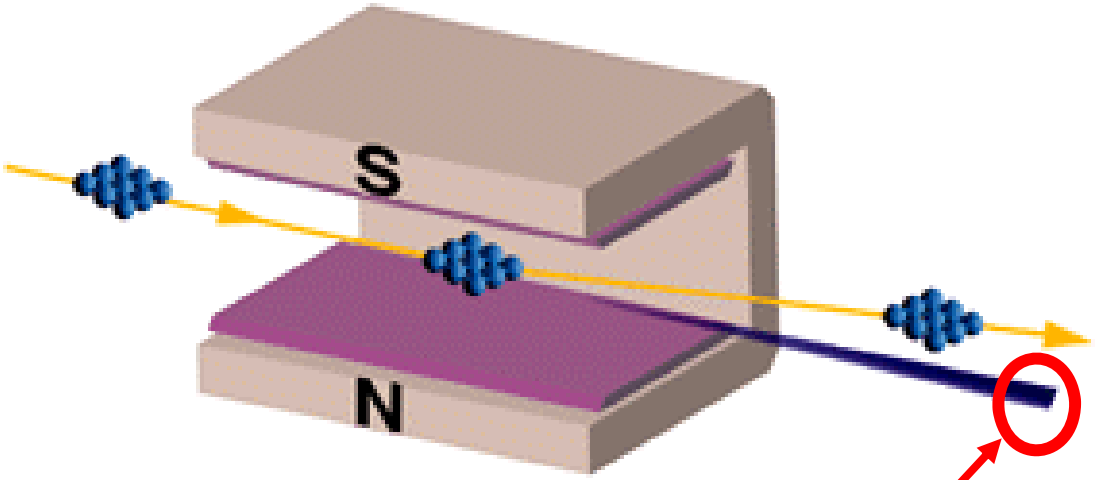


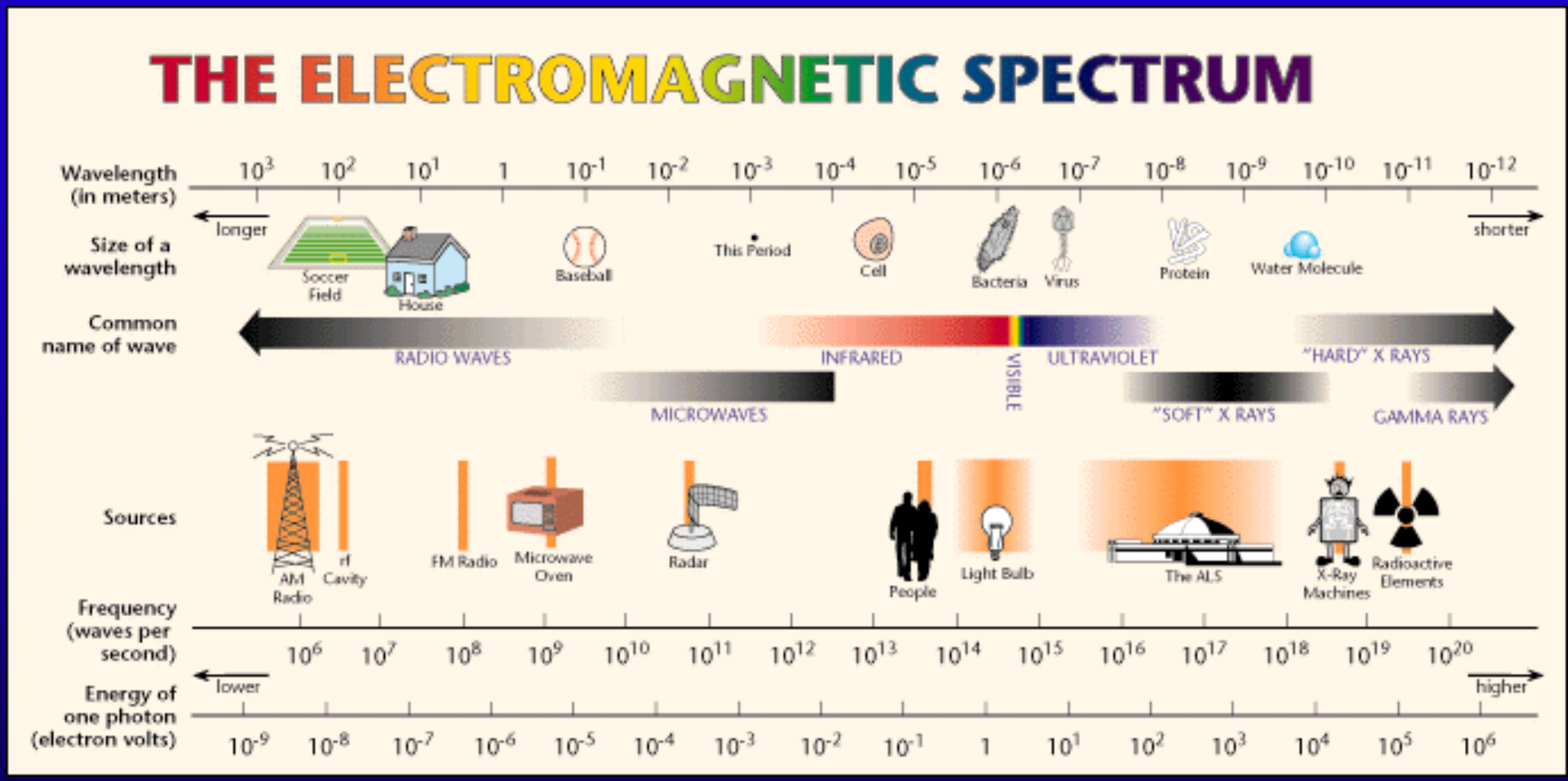
X-Ray sources

Lenny Rivkin, PSI & EPFL

Curved orbit of electrons in magnetic field

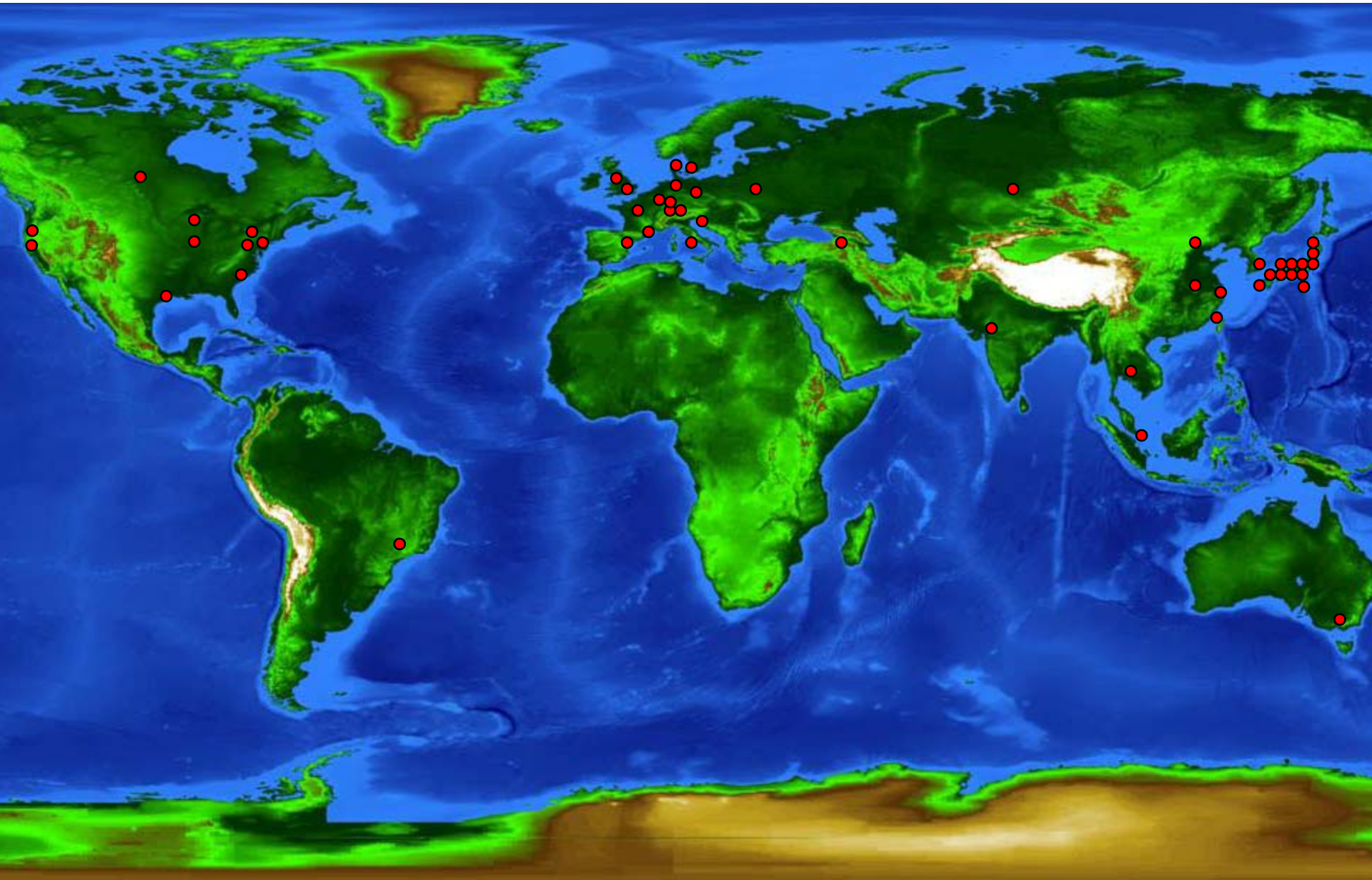


Accelerated charge → Electromagnetic radiation

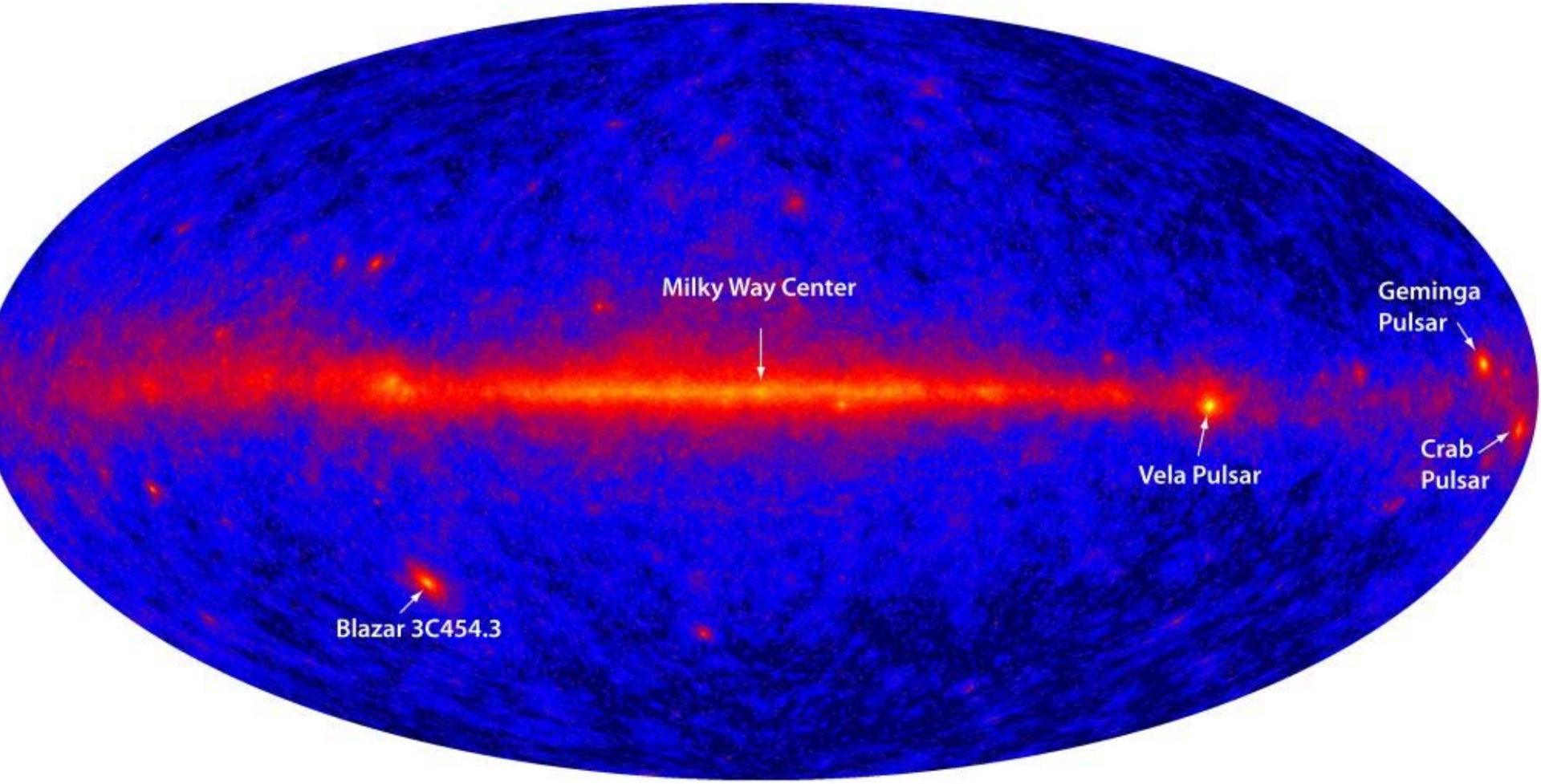


Wavelength continuously tunable !

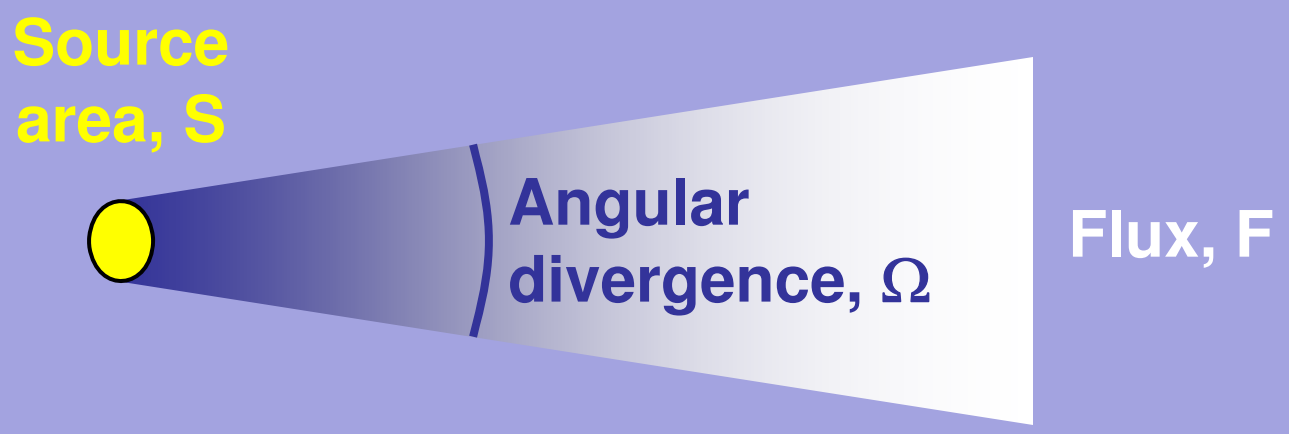
60‘000 users world-wide



A larger view



The "brightness" of a light source:

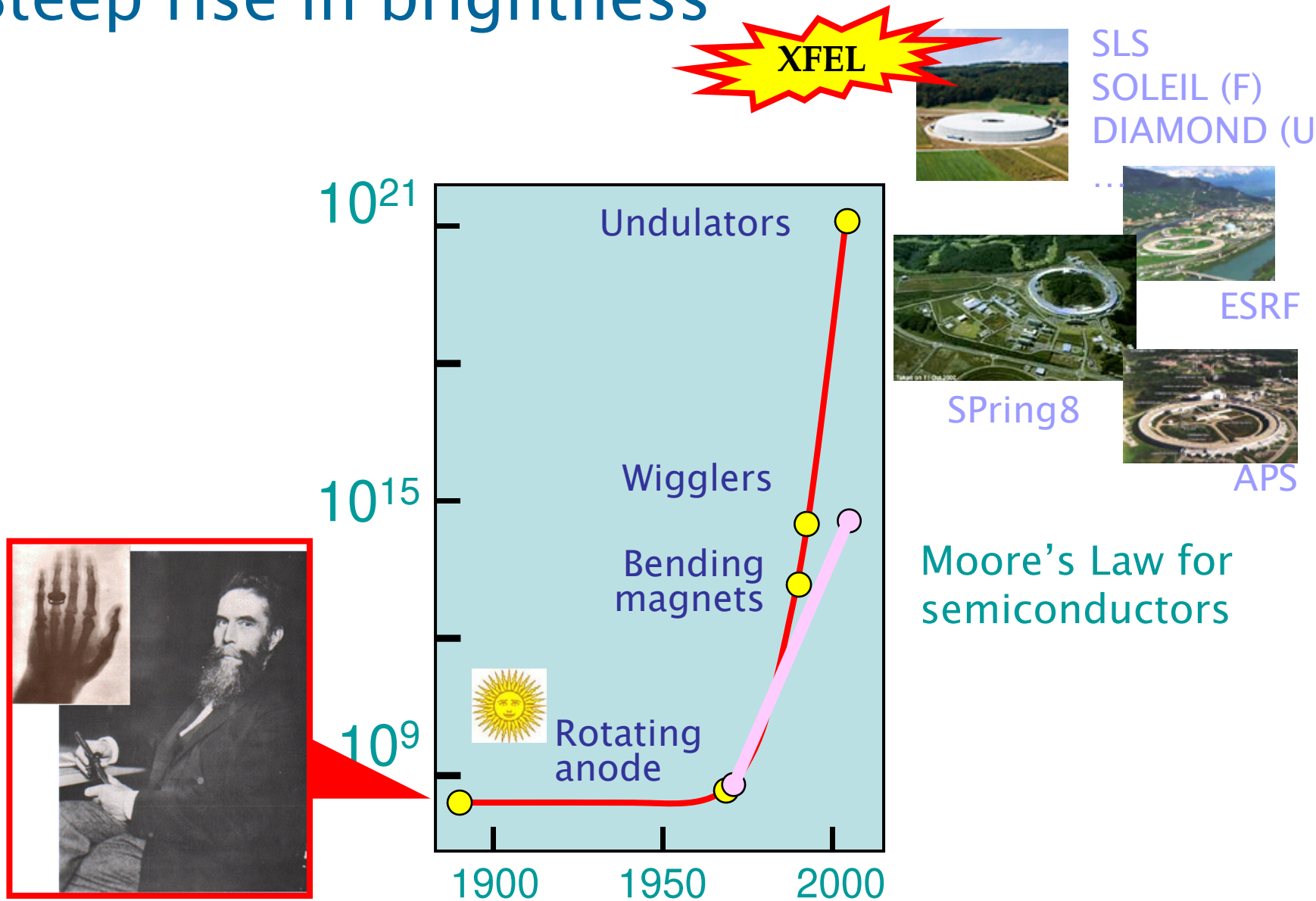


$$\text{Brightness} = \text{constant} \times \frac{F}{S \times \Omega}$$

G. Margaritondo

Steep rise in brightness

the second wave

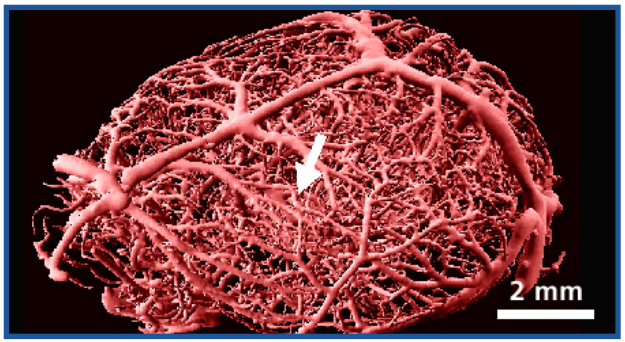


Bertha Roentgen's hand (exposure: 20 min)

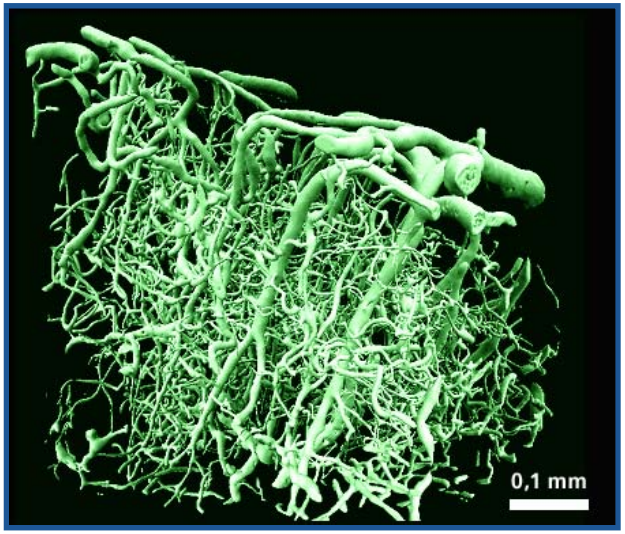
Higher brightness: more photons on small sample or through a pinhole of ~ λ: coherence

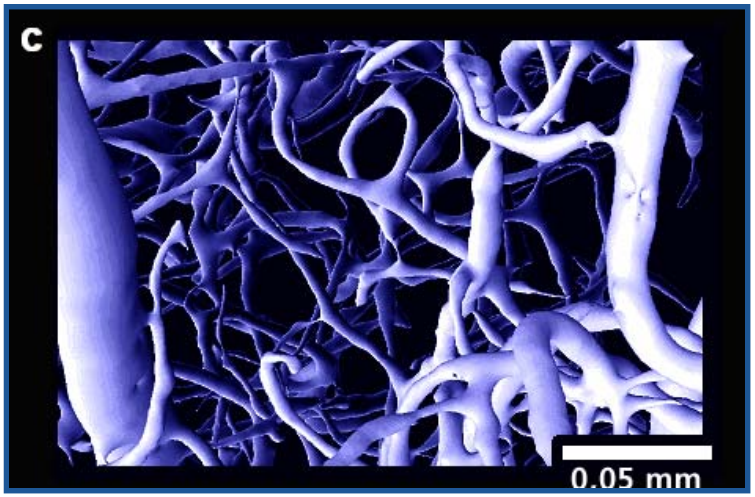
- measurements on very small probes (few μm crystals)
- small divergence:
  - compact mirrors, optics elements
  - minimized aberrations
- short measurement times
- high transverse coherence
  - phase contrast imaging

Microtomography



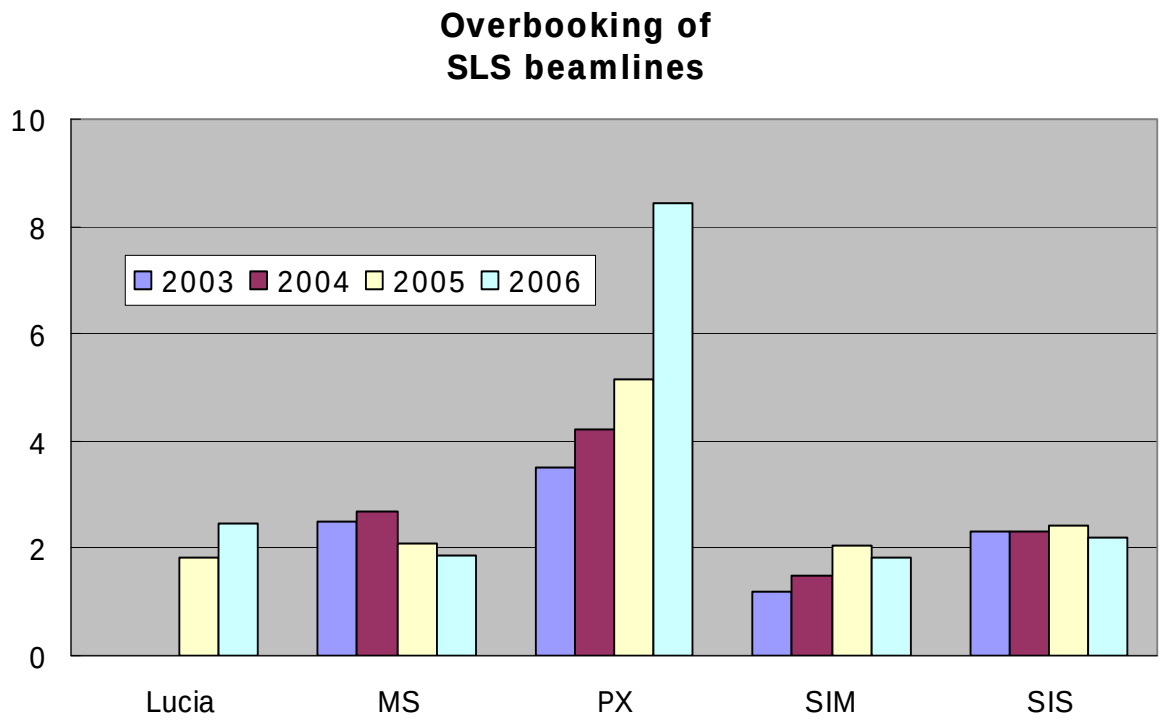
Brain blood vessels in a mouse with Alzheimer



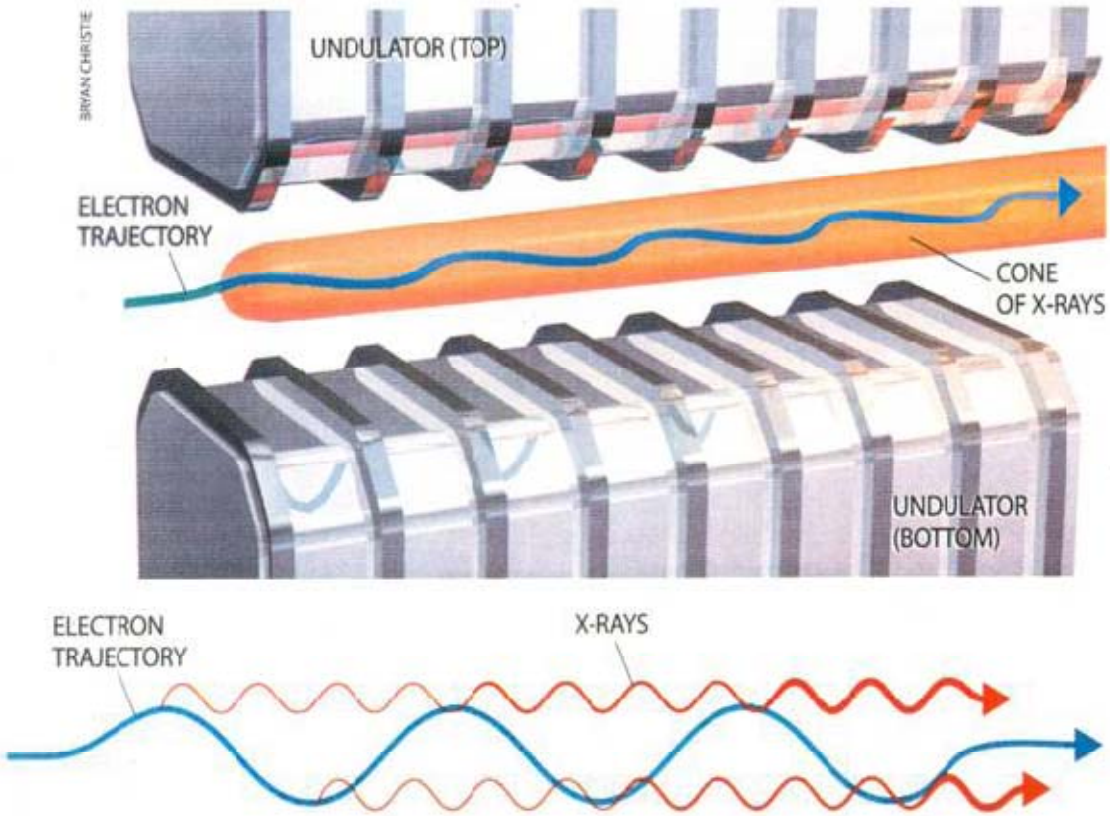


Demand for beam time remains high

Industrial use is growing



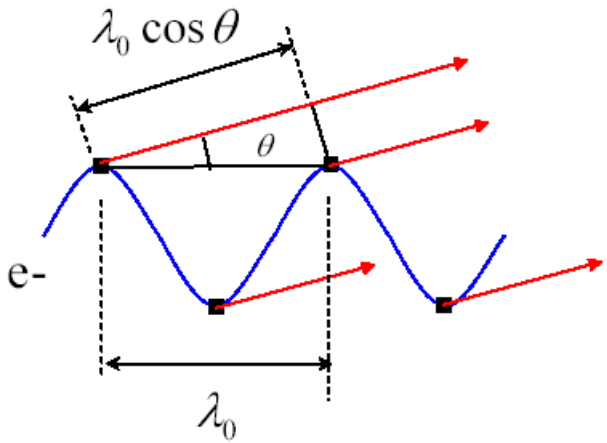
Undulators



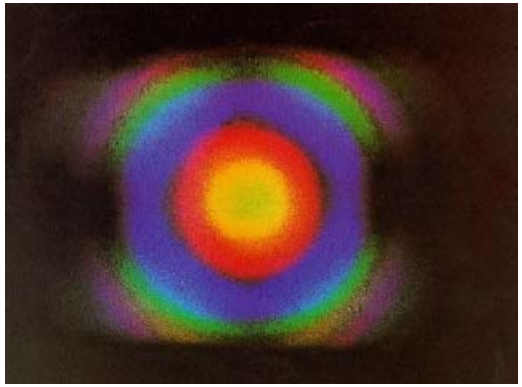
$$T_{obs} = T_{emit}(1-\beta)$$

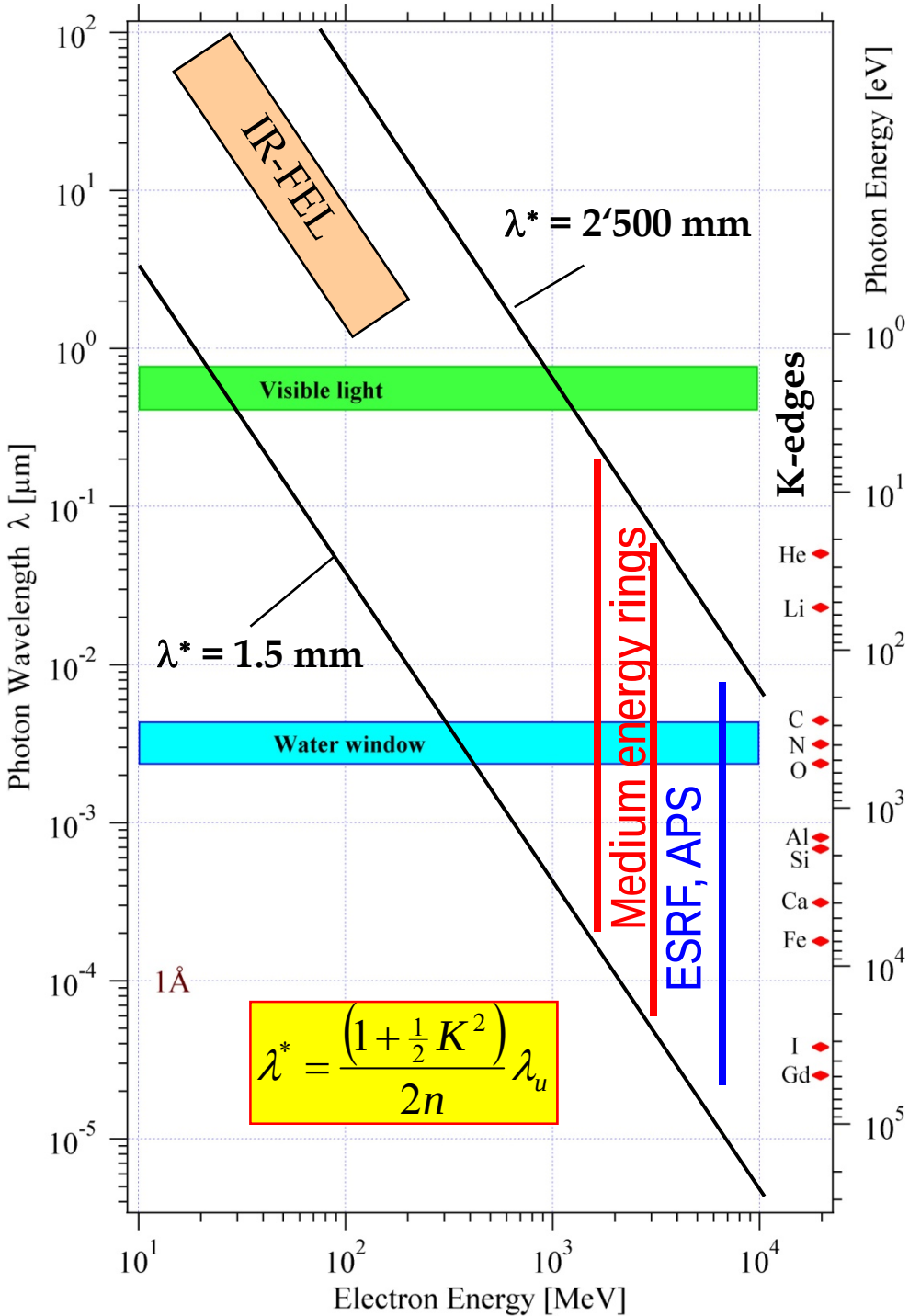
$$\lambda_{light} \approx \frac{\lambda_u}{2\gamma^2}$$

Undulator radiation



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

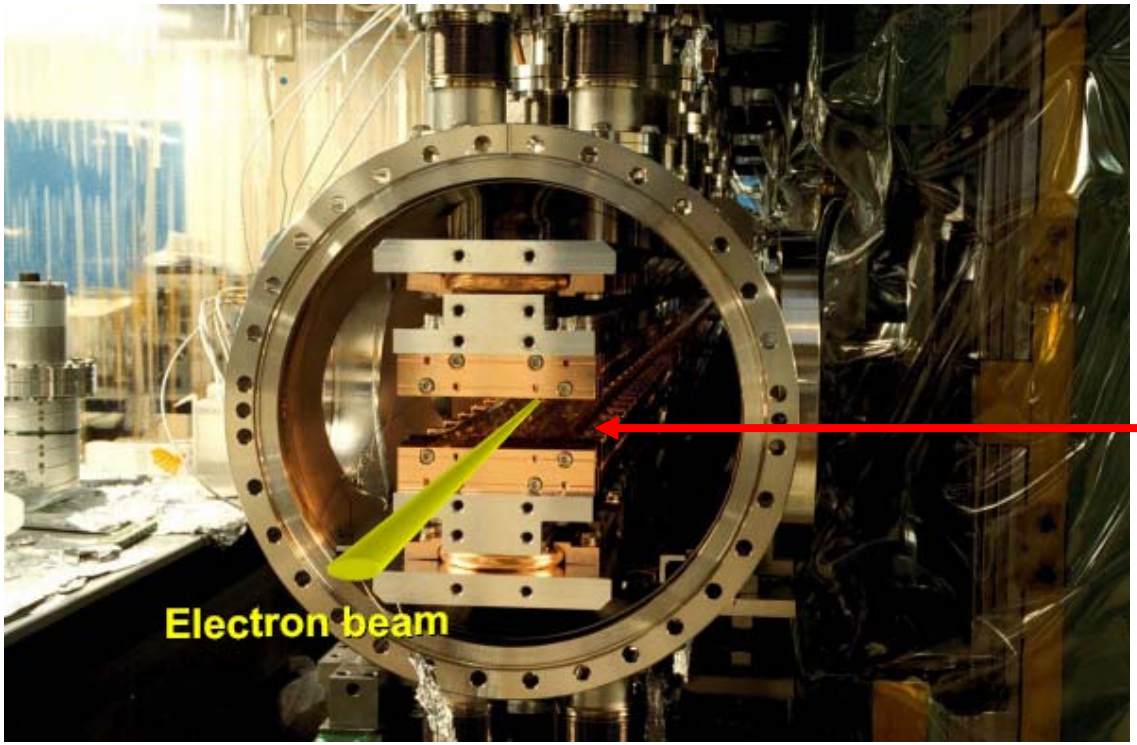




Main R&D directions

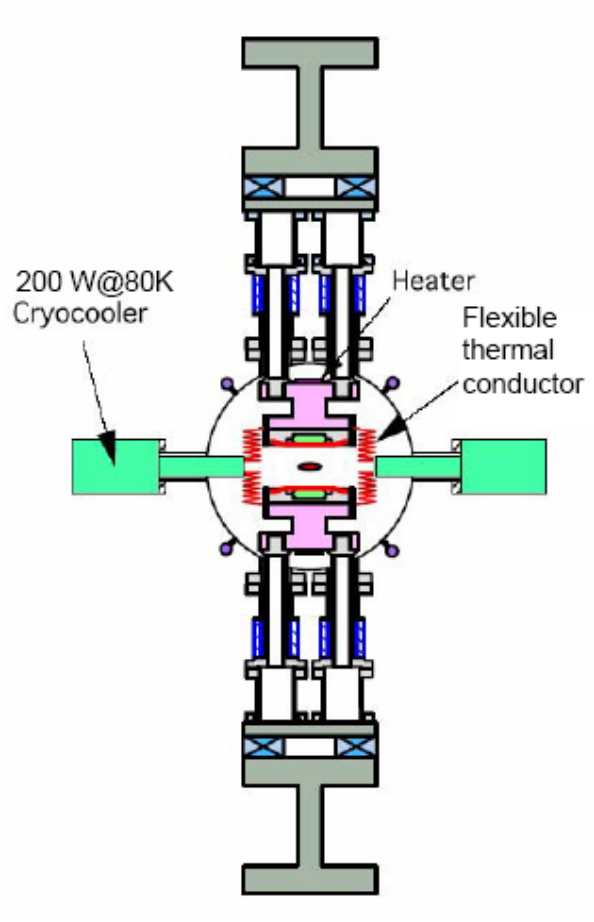
- Short period (small gap) undulator developments
- Approaching diffraction limit: very small equilibrium emittance with large rings and damping wigglers
- Detector development complementing source improvements
- Linac based light sources development: ERLs
- Free electron lasers developments

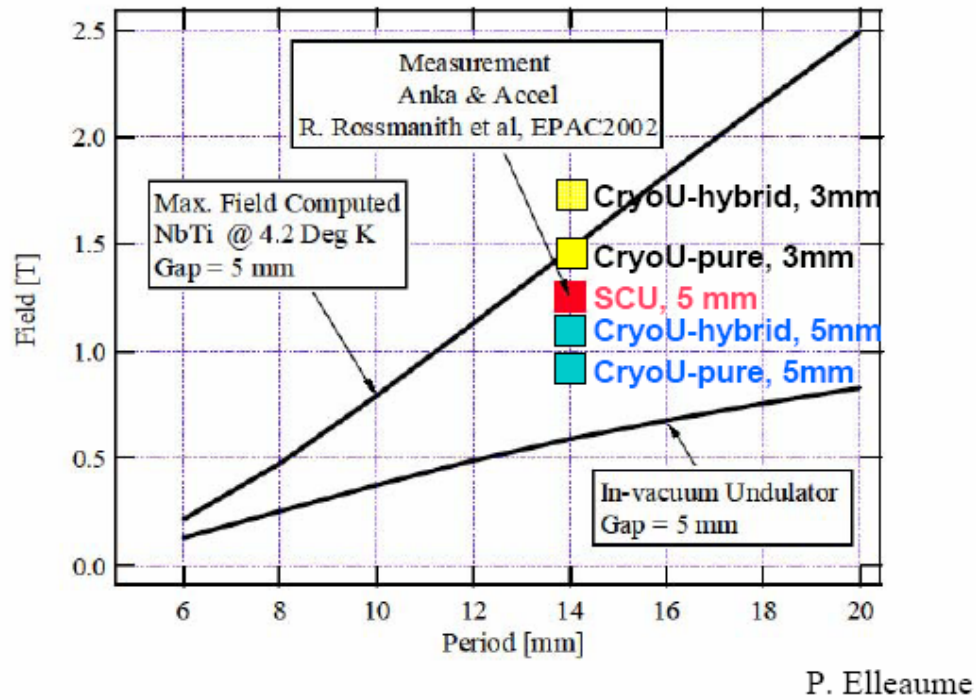
In-vacuum undulators / s.c. undulators



Gaps down to 3 mm

Cryo-cooled undulators





H. Kitamura, SPring-8

Third Generation Light Sources in Operation

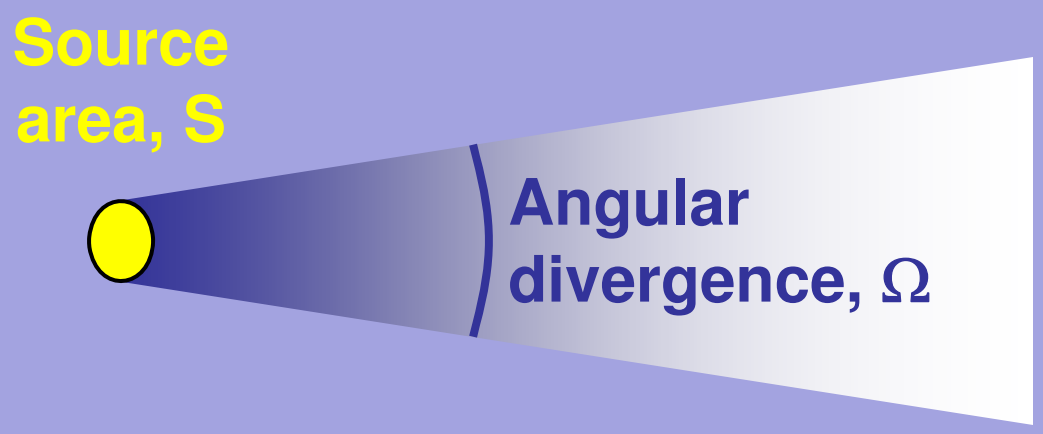
Third Generation Light Sources in Operation

Light Source	Energy (GeV)	Circumference (m)	Emittance (nm.rad)	Current (mA)	Straight Section	Status
ESRF	6.0	844.4	3.7	200	32×6.3m	Operational(1993)
APS	7.0	1104	3.0	100	40×6.7m	Operational(1996)
SPring-8	8.0	1436	2.8	100	44×6.6m, 4×30m	Operational(1997)
ALS	1.9	196.8	6.3	400	12×6.7m	Operational(1993)
TLS	1.5	120	25	240	6×6m	Operational(1993)
ELETTRA	2.0/2.4	259	7	300	12×6.1m	Operational(1994)
PLS	2.5	280.56	10.3	200	12×6.8m	Operational(1995)
LNLS	1.37	93.2	70	250	6×3m	Operational(1997)
MAX-II	1.5	90	9.0	200	10×3.2m	Operational(1997)
BESSY-II	1.7	240	6.1	200	8×5.7m, 8×4.9m	Operational(1999)
Siberia-II	2.5	124	65	200	12×3m	Operational(1999)
NewSUBARU	1.5	118.7	38	500	2×14m, 4×4m	Operational(2000)
SLS	2.4-2.7	288	5	400	3×11.7m, 3×7m, 6×4m	Operational(2001)
ANKA	2.5	110.4	50	200	4×5.6m, 4×2.2m	Operational(2002)
CLS	2.9	170.88	18.1	500	12×5.2m	Operational(2003)
SPEAR-3	3.0	234	12	500	2×7.6m,4×4.8m,12×3.1m	Operational(2004)
SAGA-LS	1.4	75.6	7.5	300	8×2.93m	Operational(2005)

Main R&D directions

- Short period (small gap) undulator developments
- Approaching diffraction limit: very small equilibrium emittance with large rings and damping wigglers
- Detector development complementing source improvements
- Linac based light sources development: ERLs
- Free electron lasers developments

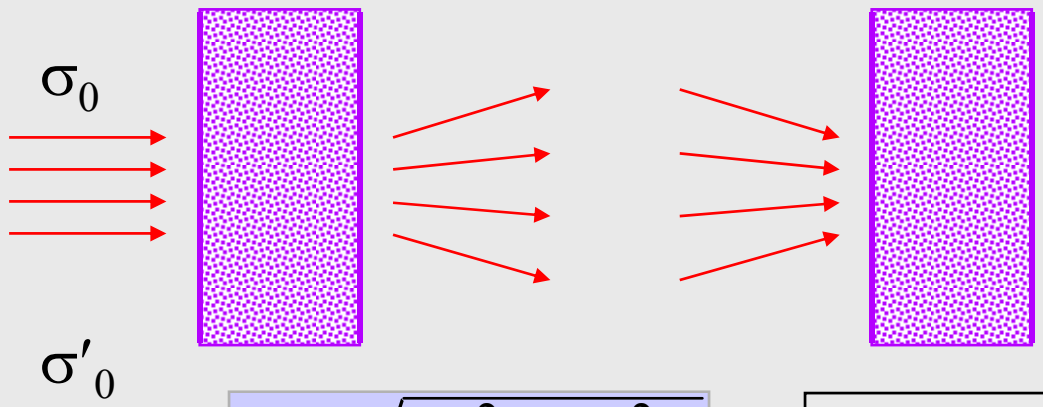
The electron beam "emittance":



The brightness depends on the geometry of the source, i.e., on the electron beam emittance

$$\text{Emittance} = S \times \Omega$$

Ring equilibrium emittance



$$\sigma' = \sqrt{\sigma'^2_0 + \sigma'^2_{MS}}$$

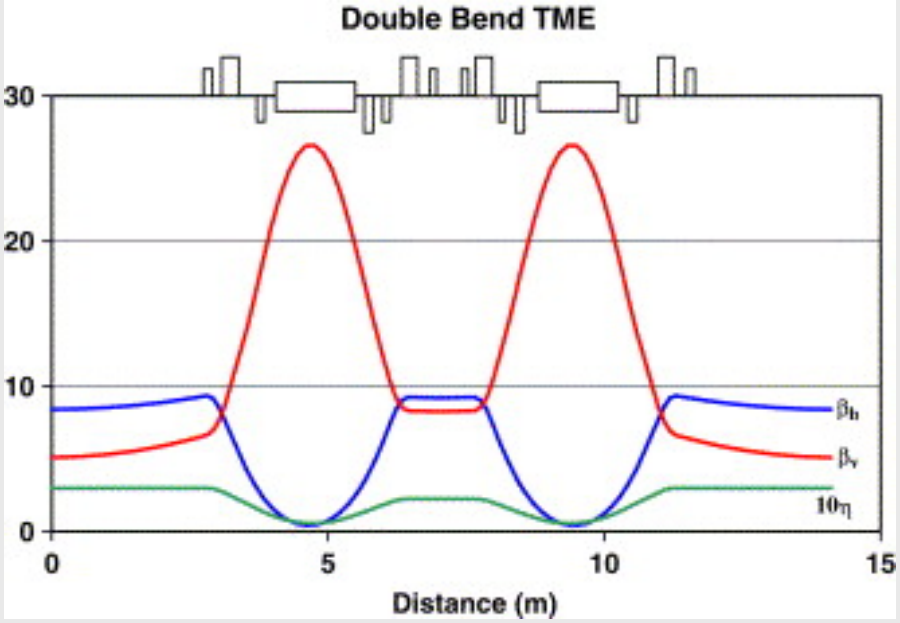
$$\sigma'_0 >> \sigma'_{MS}$$

to minimize the blow up due to multiple scattering in the absorber we can **focus** the beam

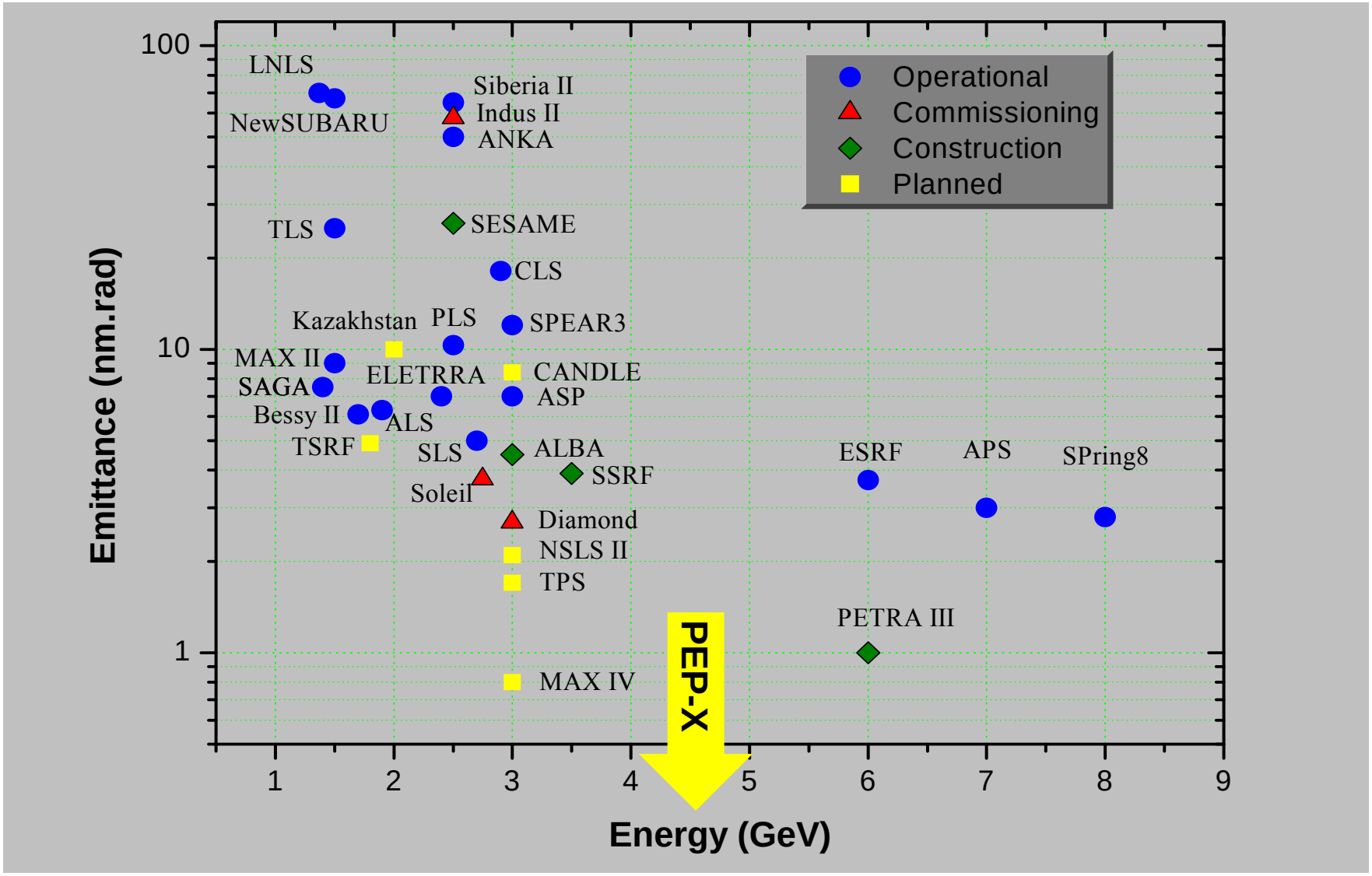
Theoretical **M**inimum **E**mittance lattice

$$\varepsilon_{x0} = \frac{C_q E^2}{J_x} \cdot \theta^3 \cdot F_{latt}$$

$$F_{min} = \frac{1}{12\sqrt{15}}$$

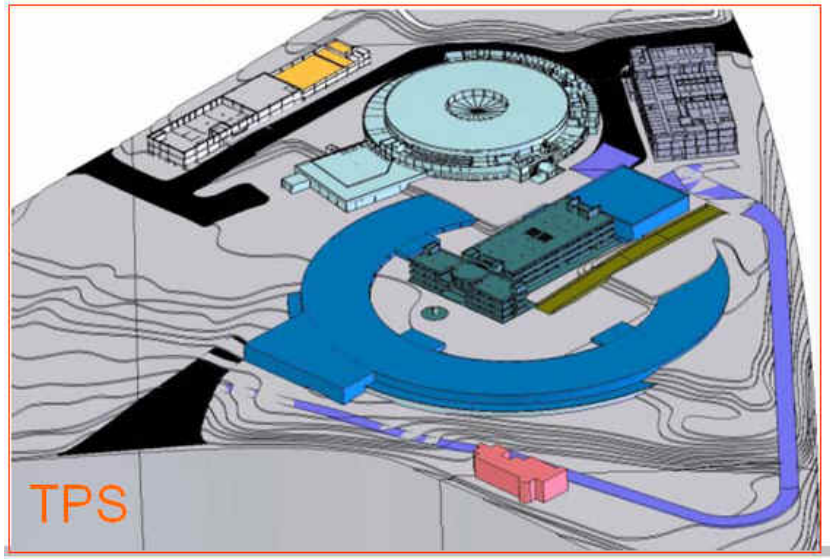


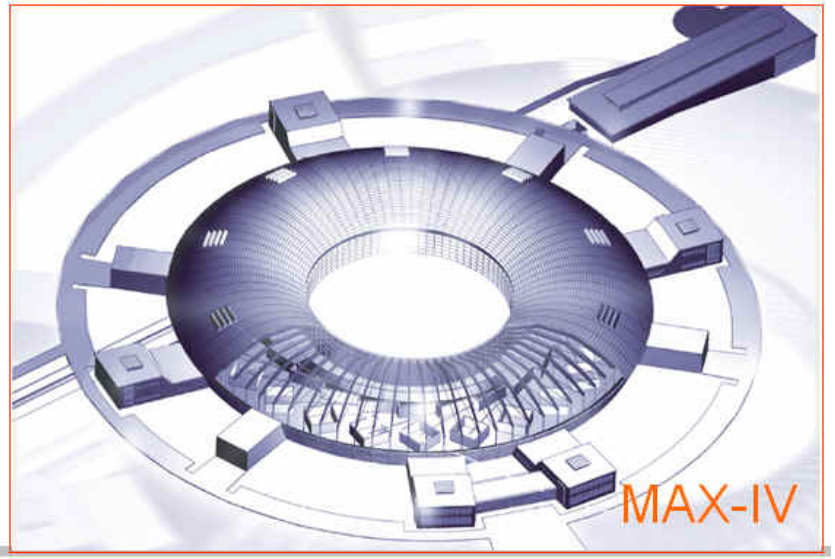
Third Generation Light Sources



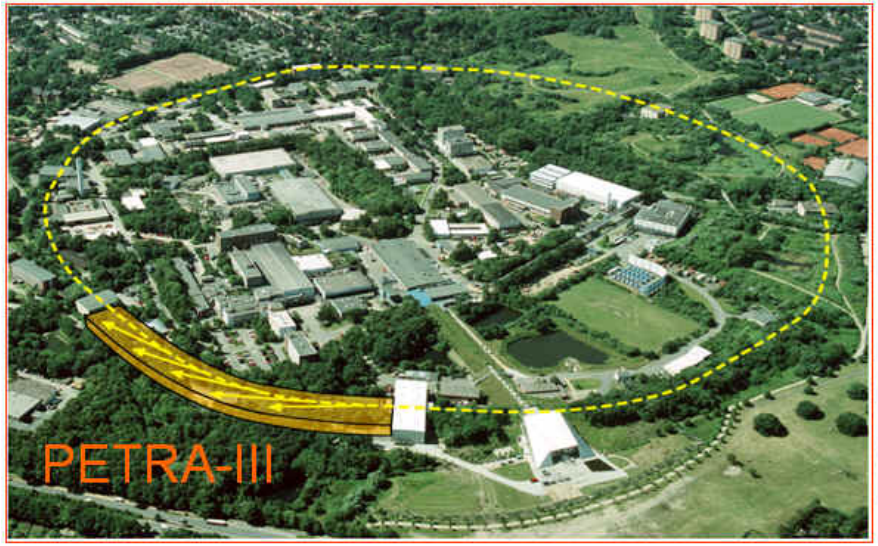
New Synchrotron Radiation Facilities

New Synchrotron Radiation Facilities

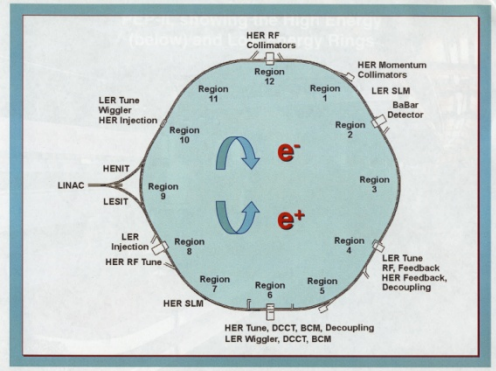




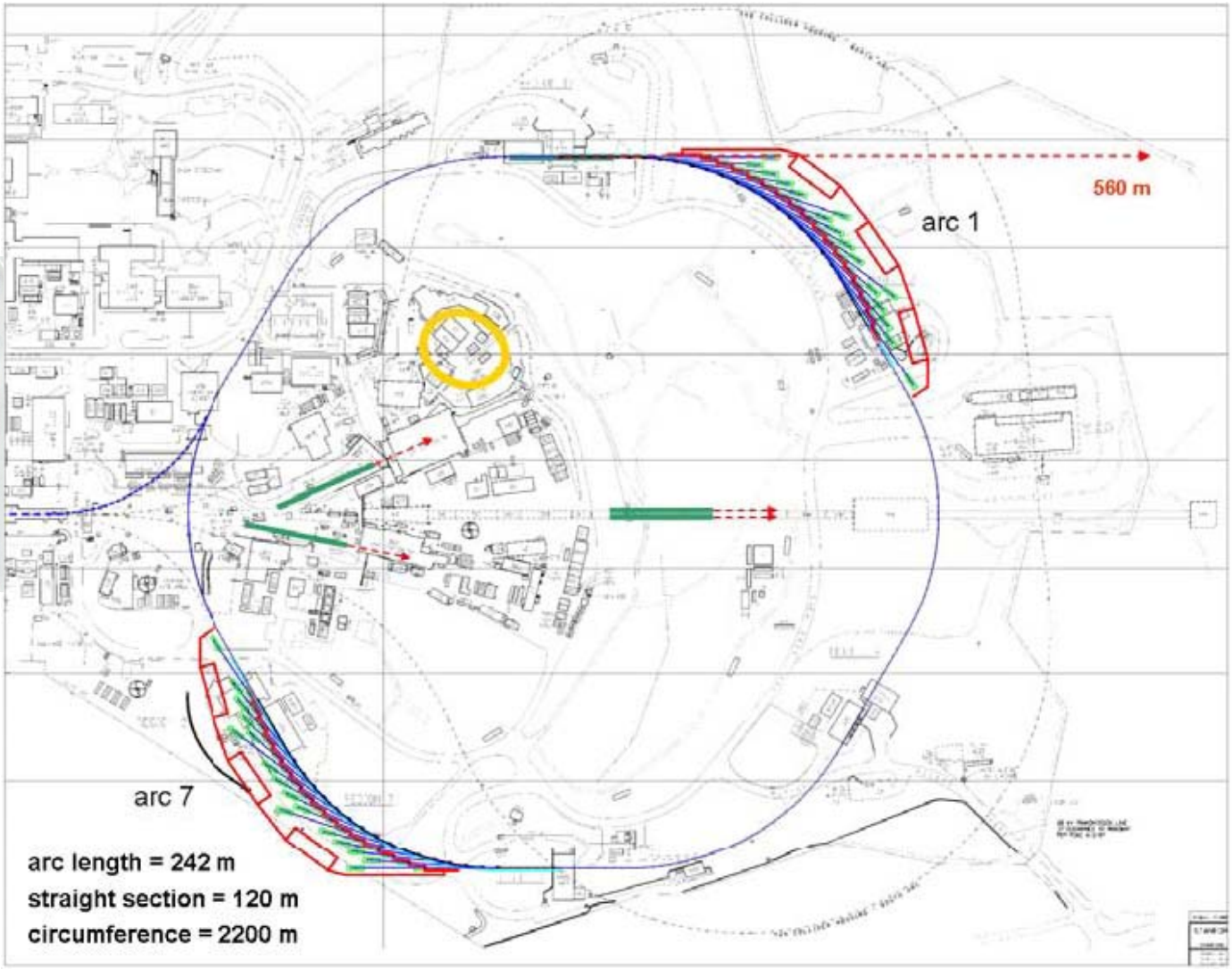
New Synchrotron Radiation Facilities



From PEP–II

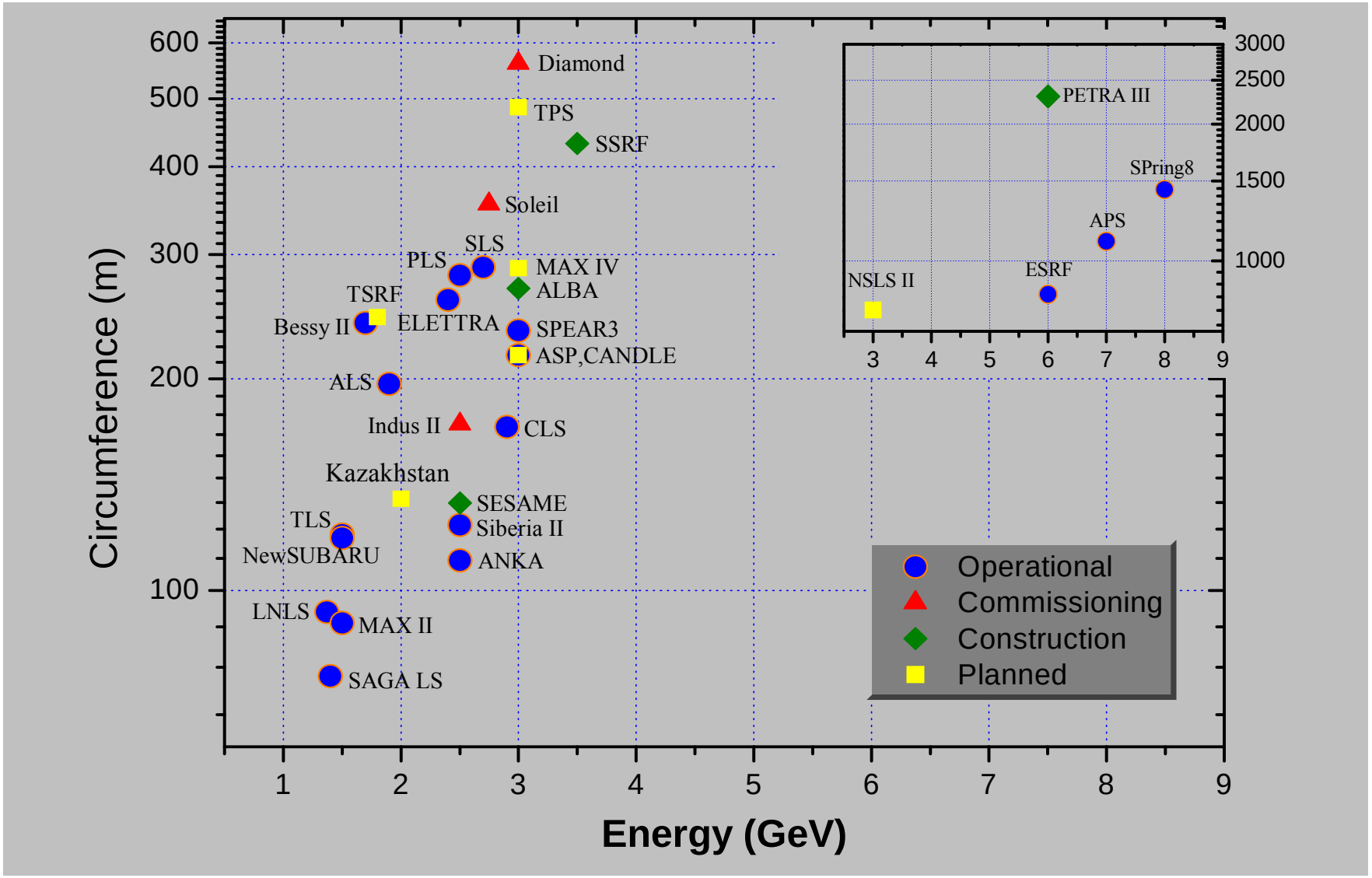


to PEP–X



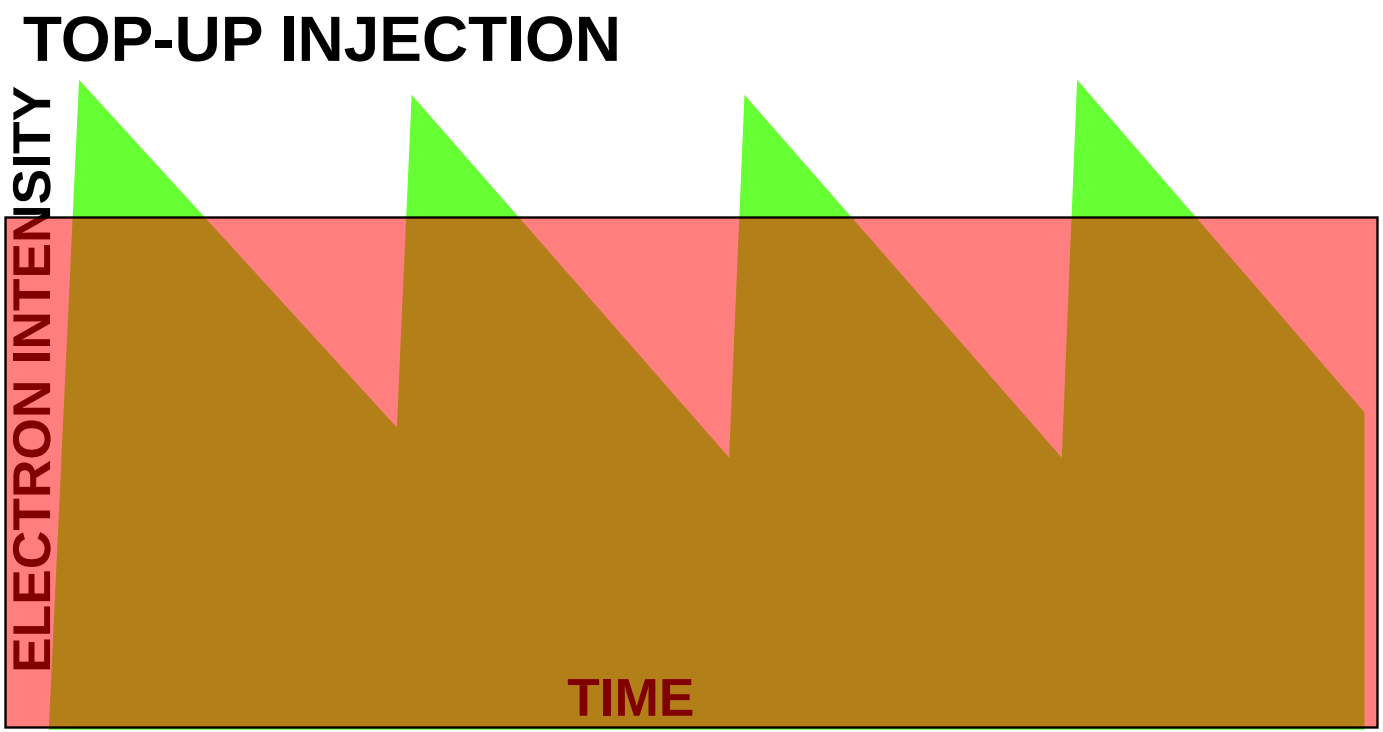
Use of damping wigglers as in PETRA III to reach 0.1 nm.rad

Third Generation Light Sources



CERN's 27 km 'tunnel with a future'

Top-up injection: key to stability



also Trickle Charge cont. Injection at PEP-II, KEKB

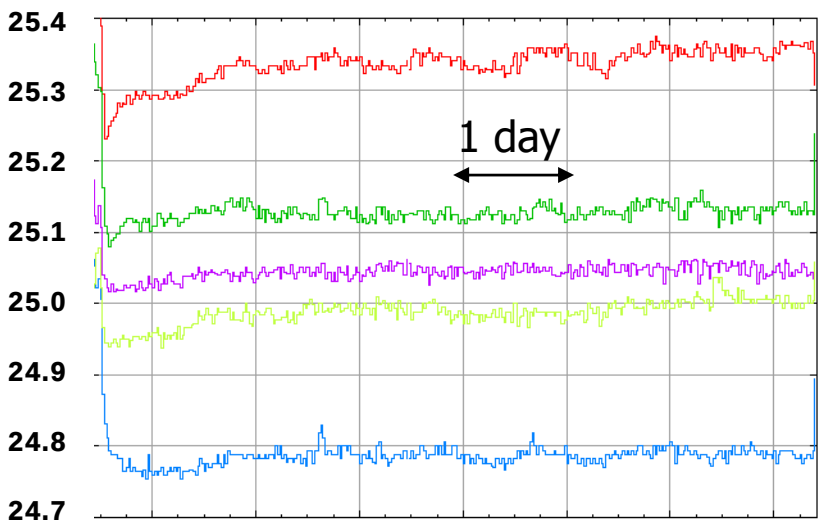
Top-up is key to the source stability

Constant thermal load on:

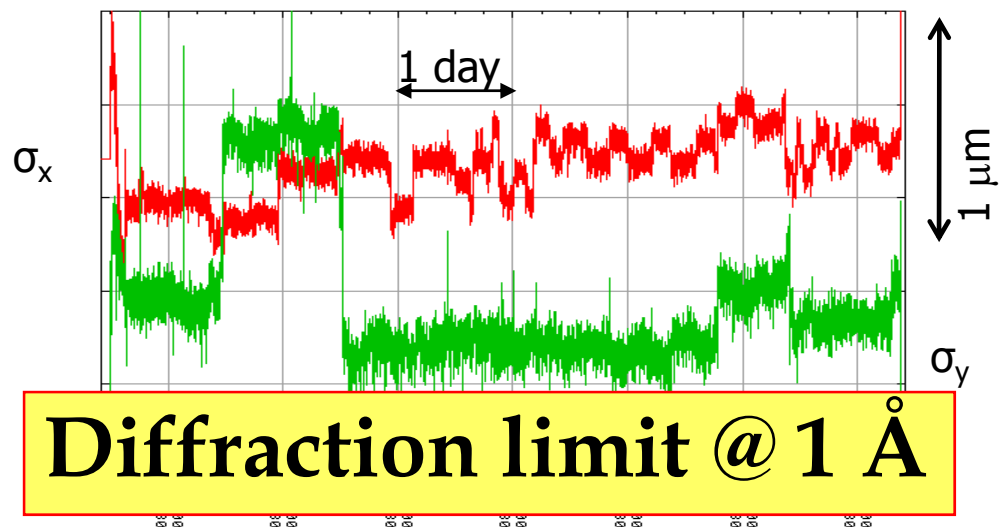
- Beam line optics
- Accelerator components (BPMs, vacuum chamber…)

Beam lifetime ~7h, not relevant! Injection every 1.5 min

Tunnel Temperature [^{0}C] 25 ± 0.03



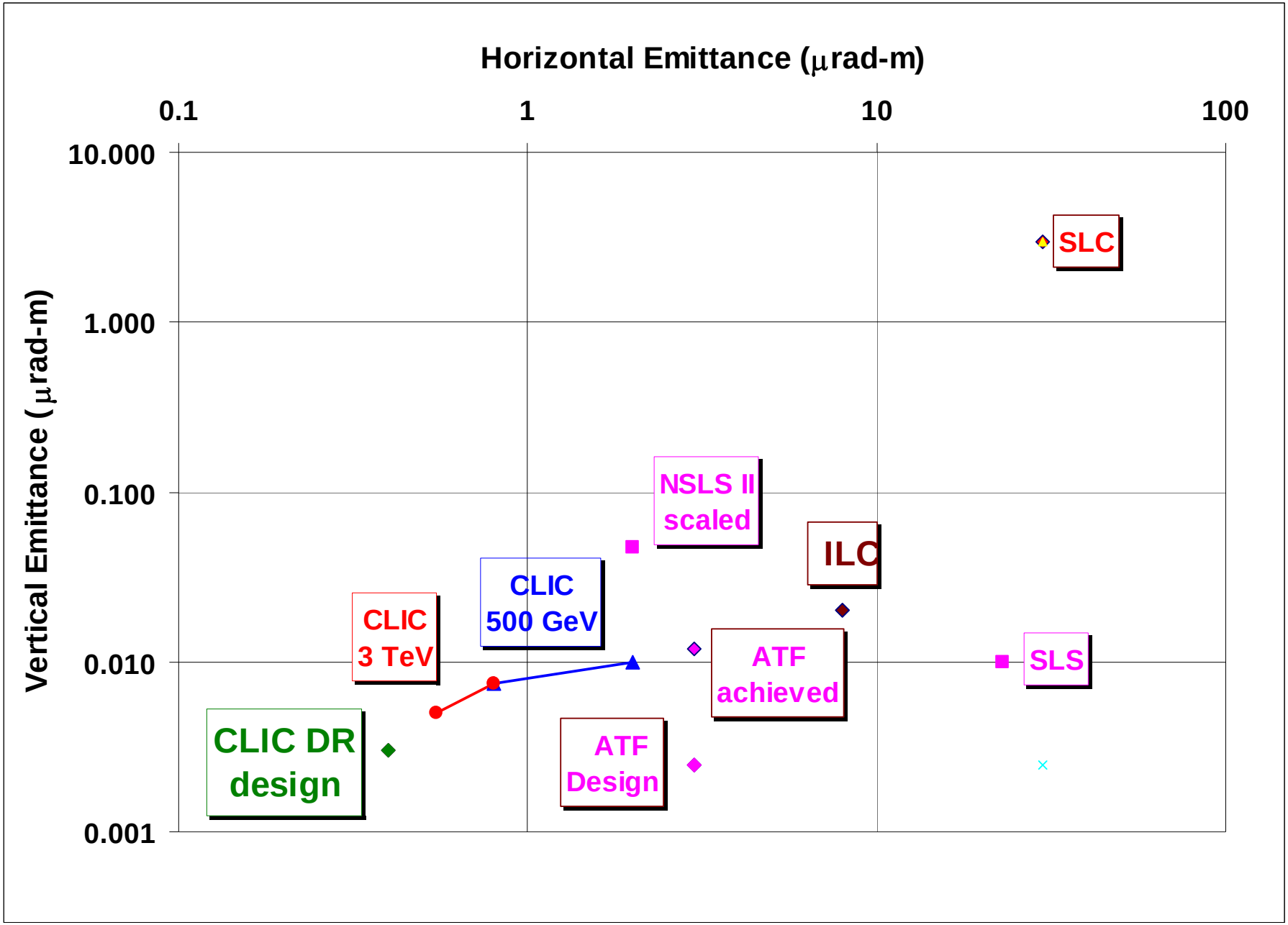
Beamsizes σ_x σ_y [μm]



Diffraction limit @ 1 Å

Vertical emittance $\varepsilon_y \rightarrow 4$ pm-rad; coupling $\varepsilon_y/\varepsilon_x \sim 0.08\%$

Damping Rings beam emittances



Top-up Status at routinely operated sources

Facilty	Energy [GeV]	Current [mA]	Emittance [nm.mrad]	Injector	Injection Efficiency	Current Stability	Operatinal Status	Top-up Status
APS	7	102	3	7GeV Boost.	80 - 100%	±0.4%	Oper. (1996)	Oper. (2001)
SLS	2.4 (2.7)	400	5	2.7GeV Boost.	90 - 100%	0.3%	Oper. (2001)	Oper. (2001)
New SUBARU	1 (1.5)	220 (350)	67	1GeV Li.	~80%	0.6%	Oper. (2000)	Oper. (2003)
SPring-8	8	99.8	3.2	8GeV Boost.	>80%	0.03%	Oper. (1997)	Oper. (2004)
TLS	1.5	300 (360)	25	1.5GeV Boost.	>70%	±0.2%	Oper. (1993)	Oper. (2005)

Top up vs. top off

Which definition?

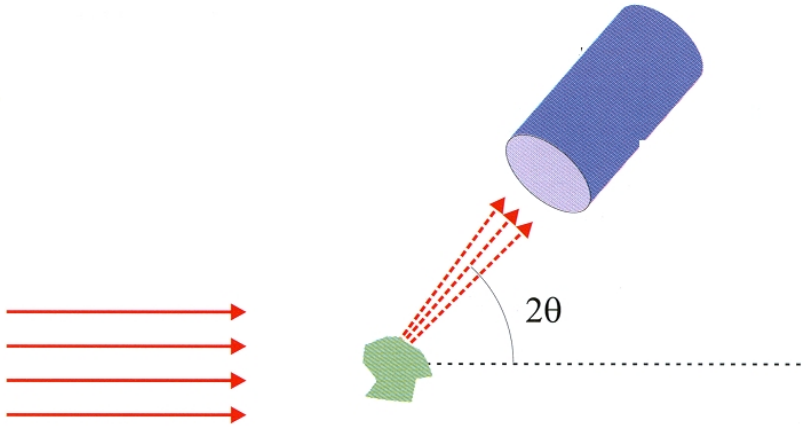
top up *vb.* (*tr.,adv.*) *Brit.*

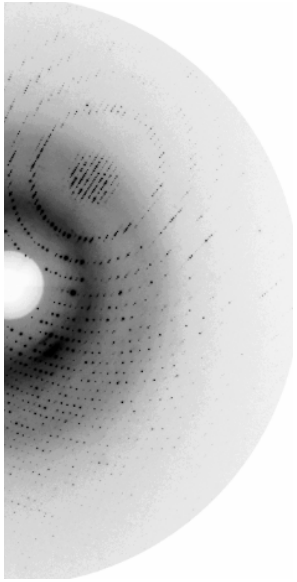
1. to raise the level of (a liquid, powder, etc.) in (a container), usually bringing it to the brim of the container:
top up the sugar in those bowls.

top off *vb.*

(*tr., adv,*) to finish or complete, esp. with some decisive action:
he topped off the affair by committing suicide.

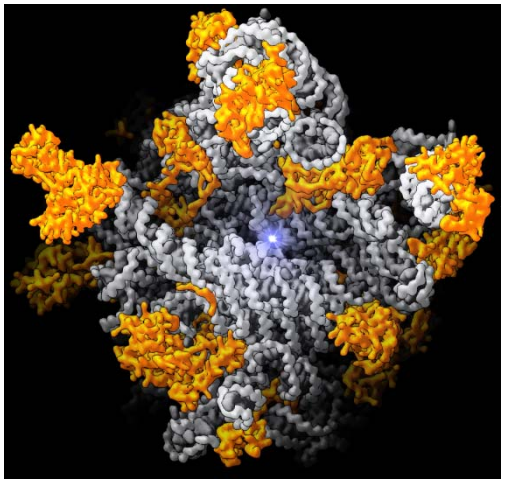
Protein structure





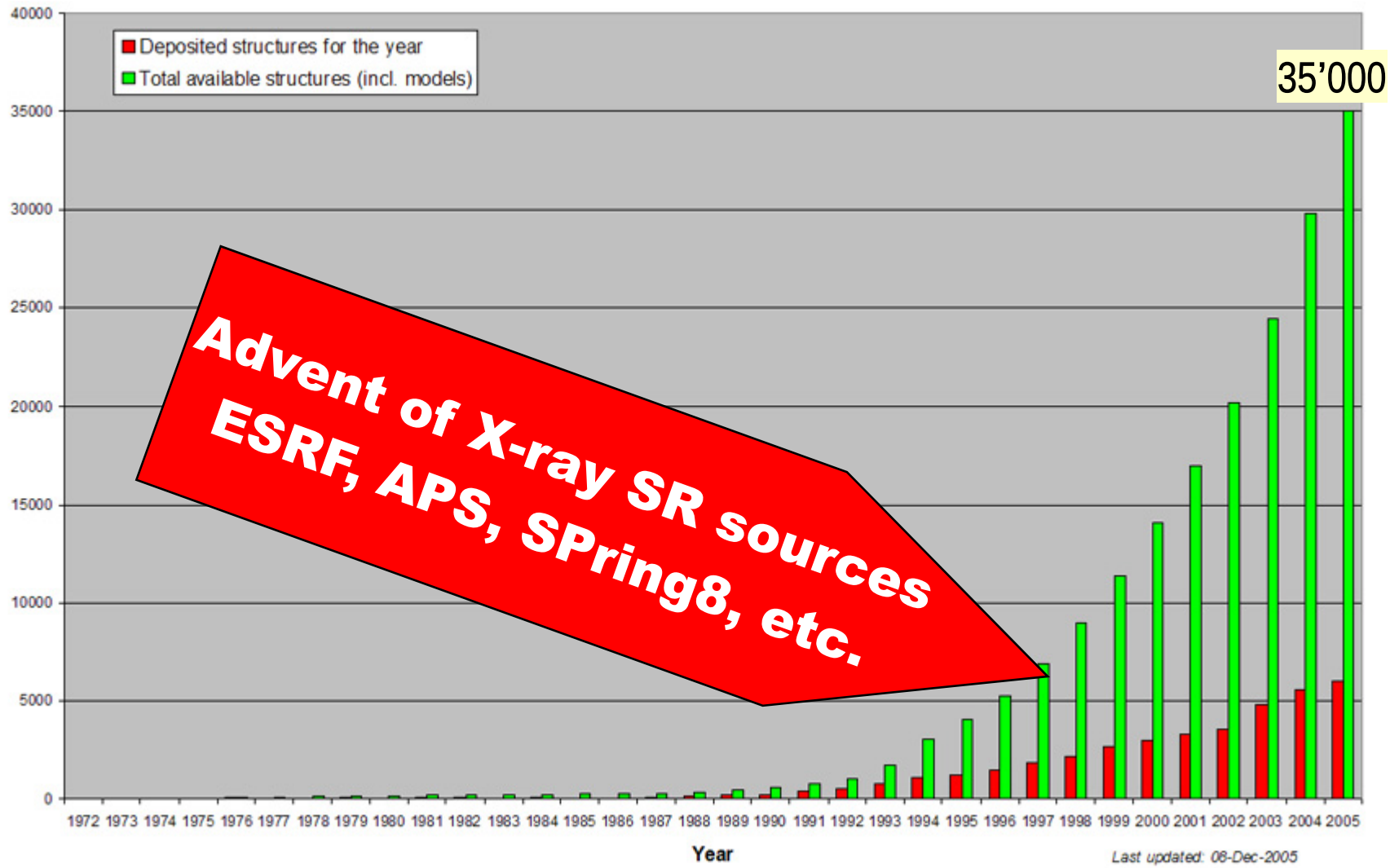
Diffraction pattern

Part of a Ribosome



N. Ban et. al.

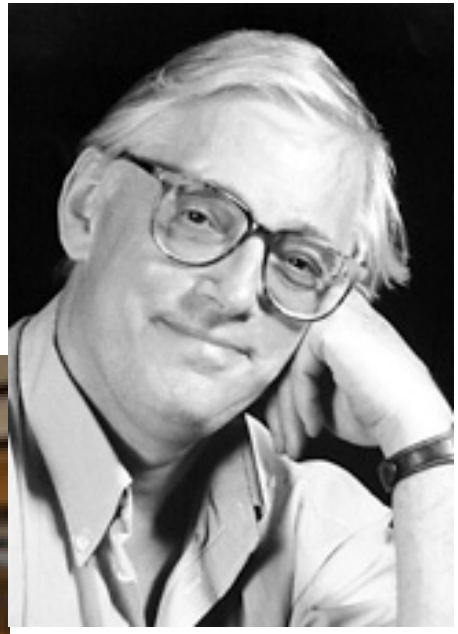
Spectacular growth of structural biology



Nobel Prizes in Chemistry to Synchrotron Radiation Work in Protein Crystallography

1997 John E. Walker

Structure of F1-ATPase



2003 Roderick McKinnon

Structure of Cellular Ion Channels

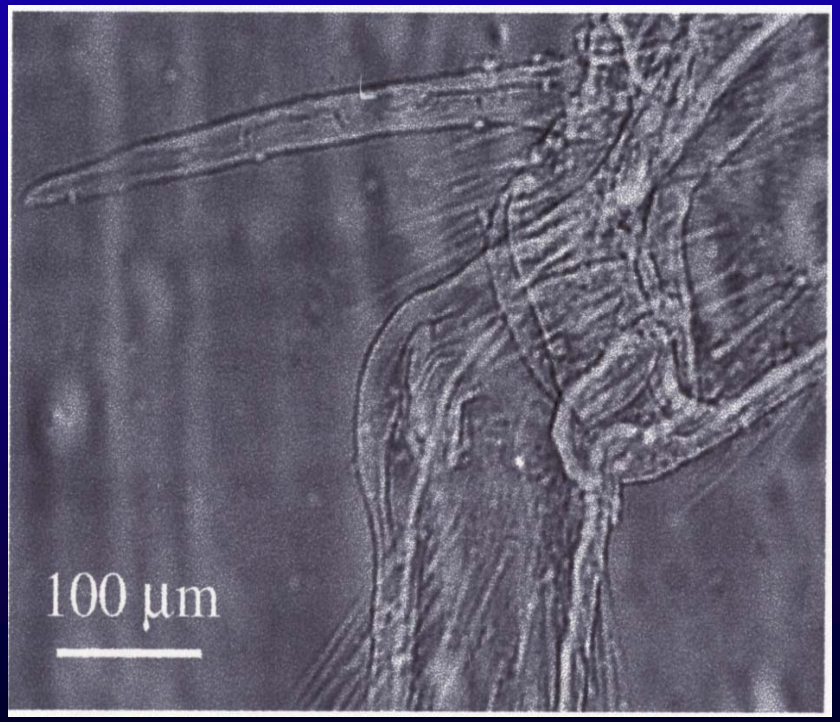
2006 Roger D. Kronberg

Structure of RNA polimerase

Transverse coherence

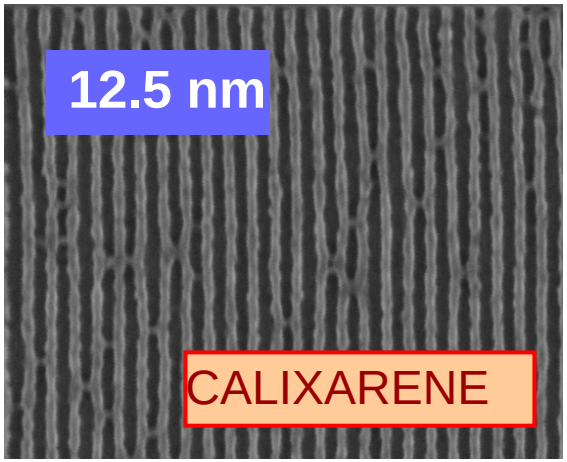
- High brightness gives coherence
- Wave optics methods for X-rays (all chapters in Born & Wolf)
- Holography

The knee of a spider



phase contrast imaging

Lithographic Performance

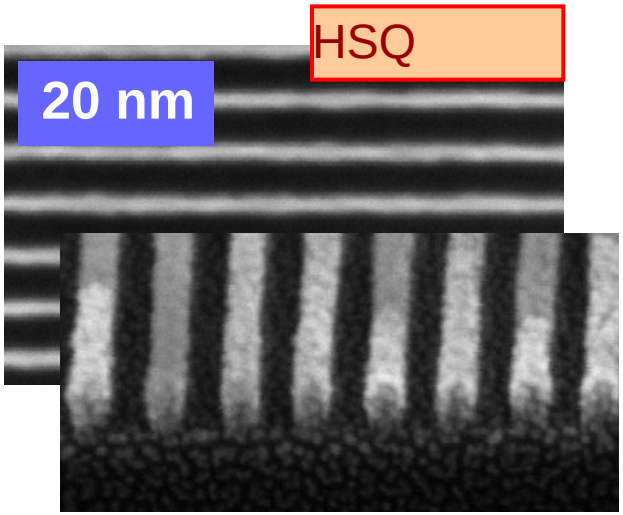


EIPBN 06, Solak *et al*

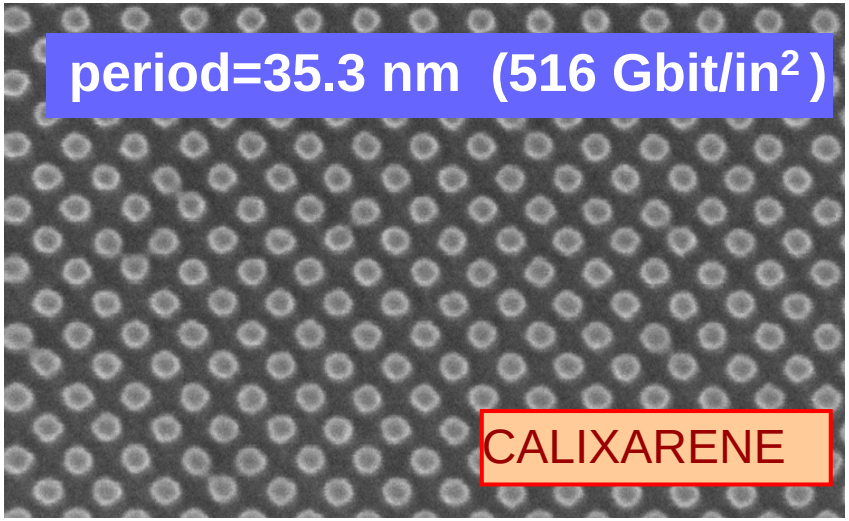
- Worldwide highest resolution in photon-based lithography
- Field size: up to 2x2 mm^2 (Achromatic Talbot)
- High throughput: ~10'000x e-beam
- Quality, reproducibility: enabling industrial operation

Fundamentals:

Stable, coherent source
Short wavelength (13.5 nm)
No proximity effect (electron mean free path <1 nm)



MNE 06, Ekinci *et al*



EIPBN 07, Solak *et al*

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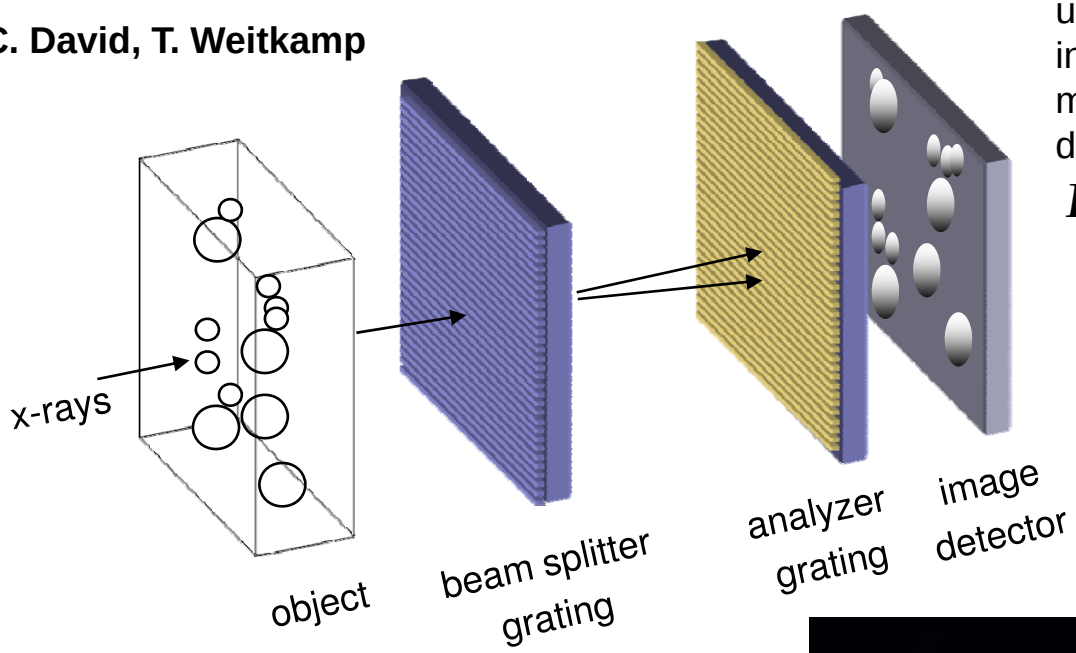
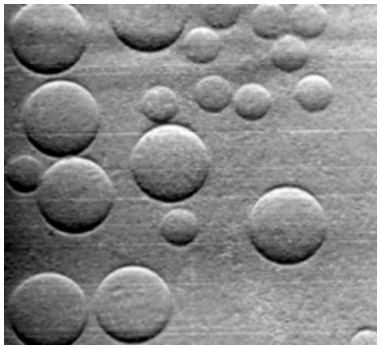
X-ray phase contrast imaging

C. David, T. Weitkamp



using a shearing interferometer based on microfabricated silicon diffraction gratings

F. Pfeiffer et al., PRL 94, April 2005

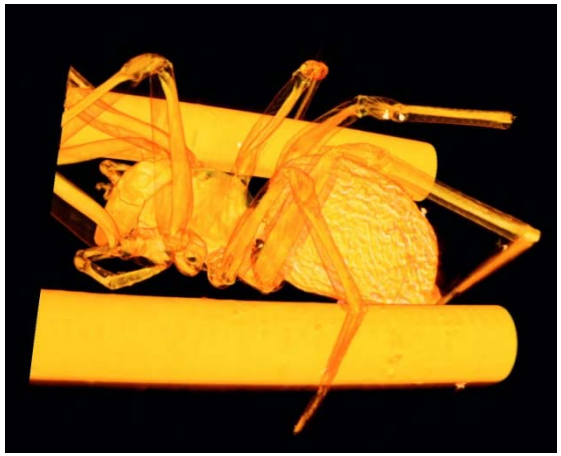


Phase-object example:

100µm and 200µm styrene beads

Advantages:

- significantly enhanced contrast compared to conventional "absorption-mode" for light materials
- High potential in medical diagnosis and research



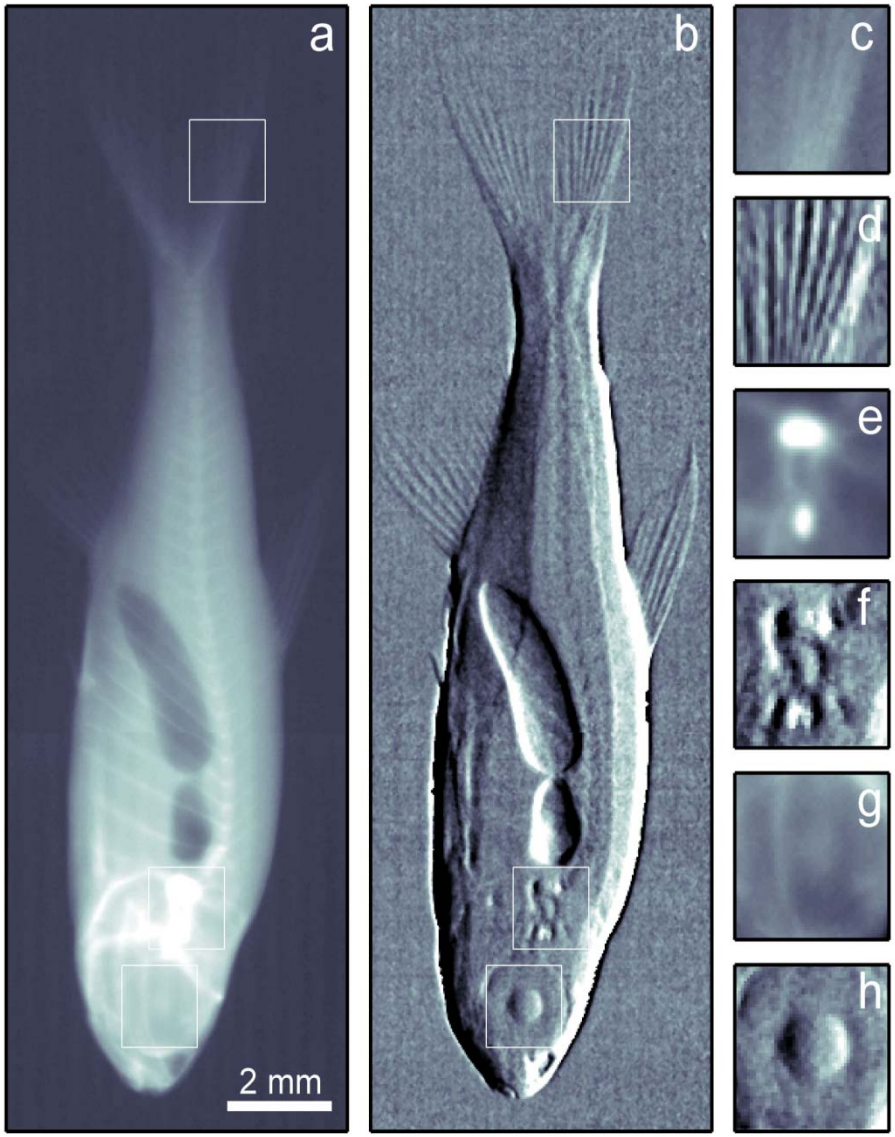
Tomographic phase reconstruction of a spider

X-ray Radiography of a fish

conventional

Absorption a

(+ details c , e, g)

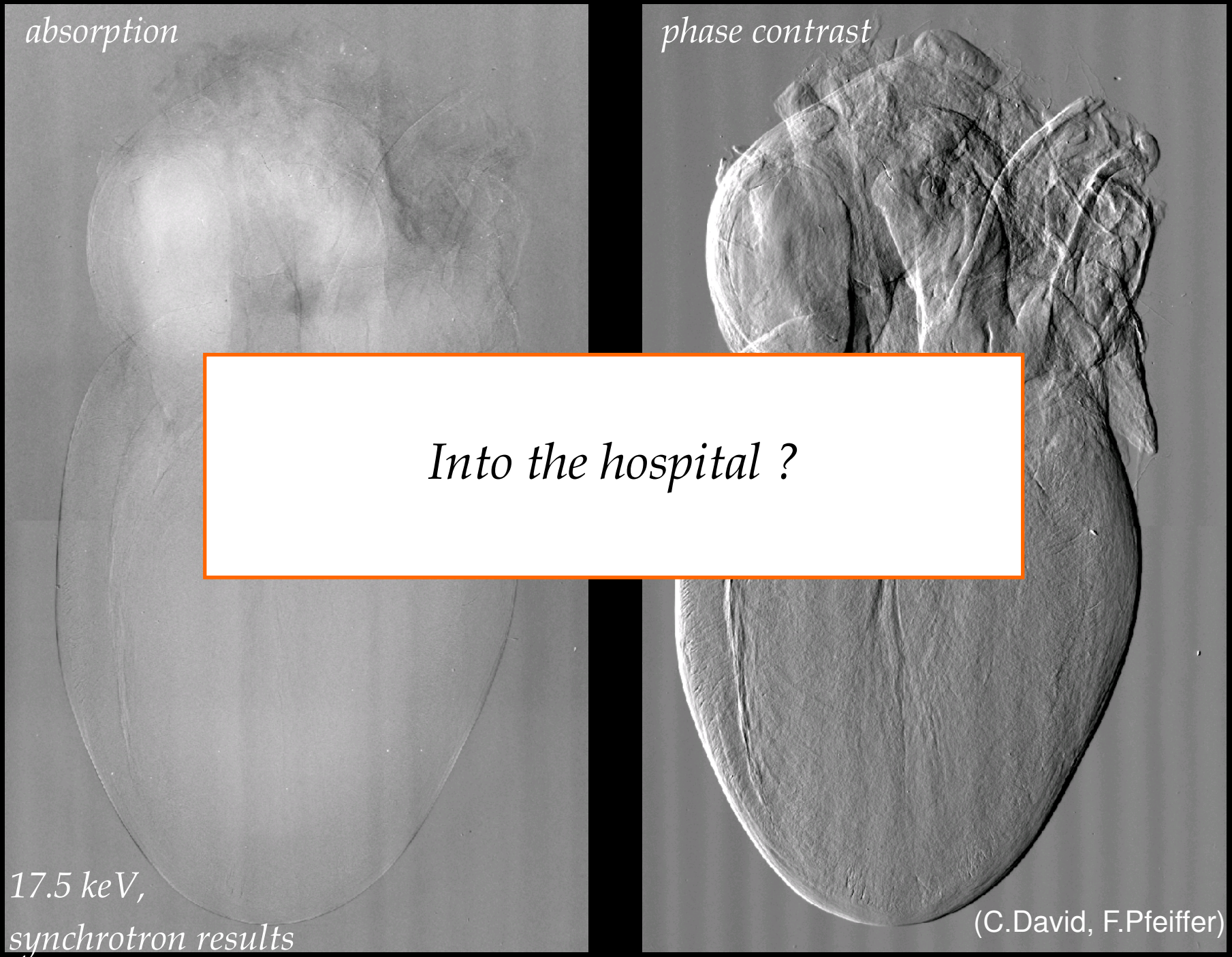


Phase contrast

Microscopy b

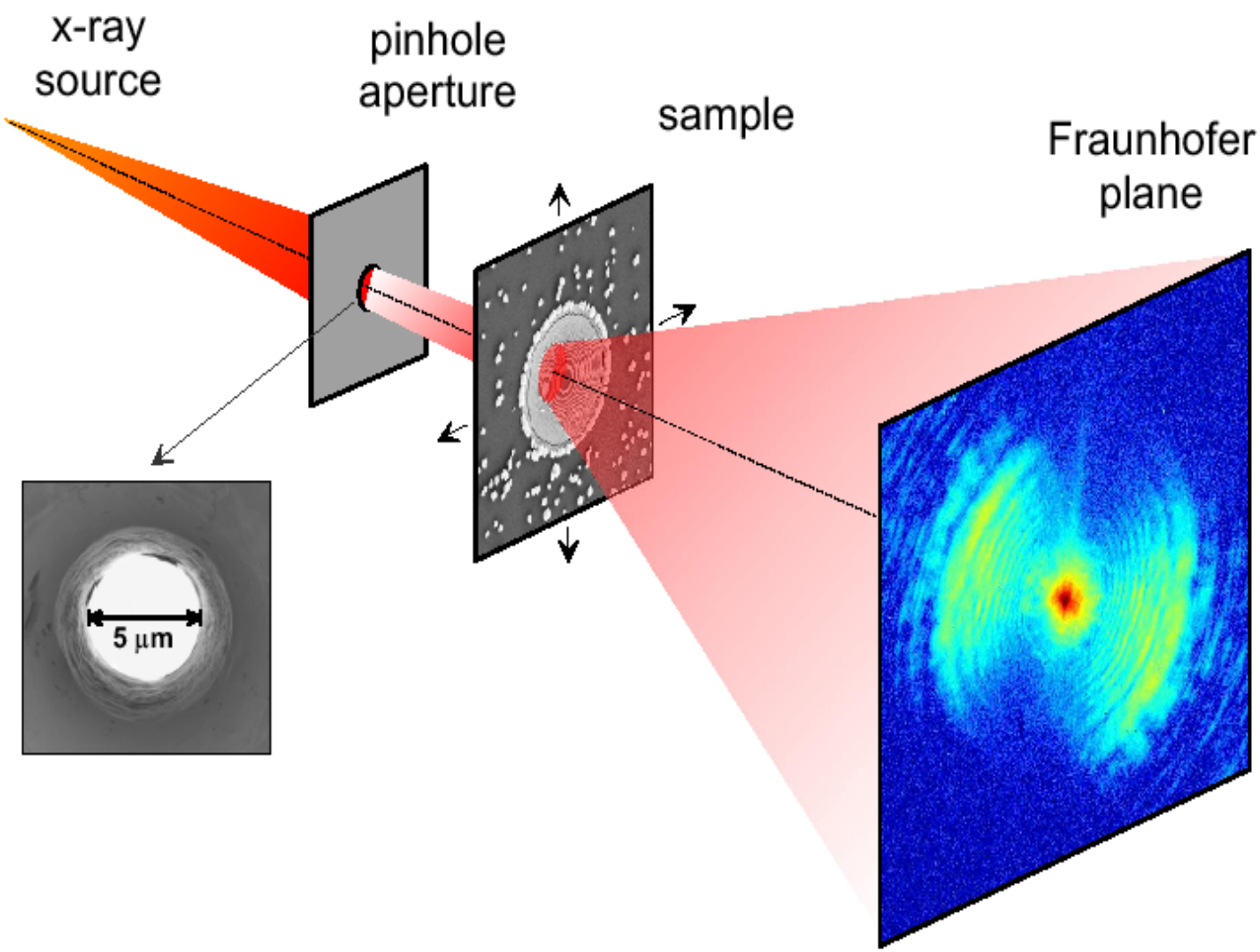
(+ details d, f, h)

(F.Pfeiffer)



Into the hospital ?

Lensless coherent Scanning Microscopy with hard X-rays



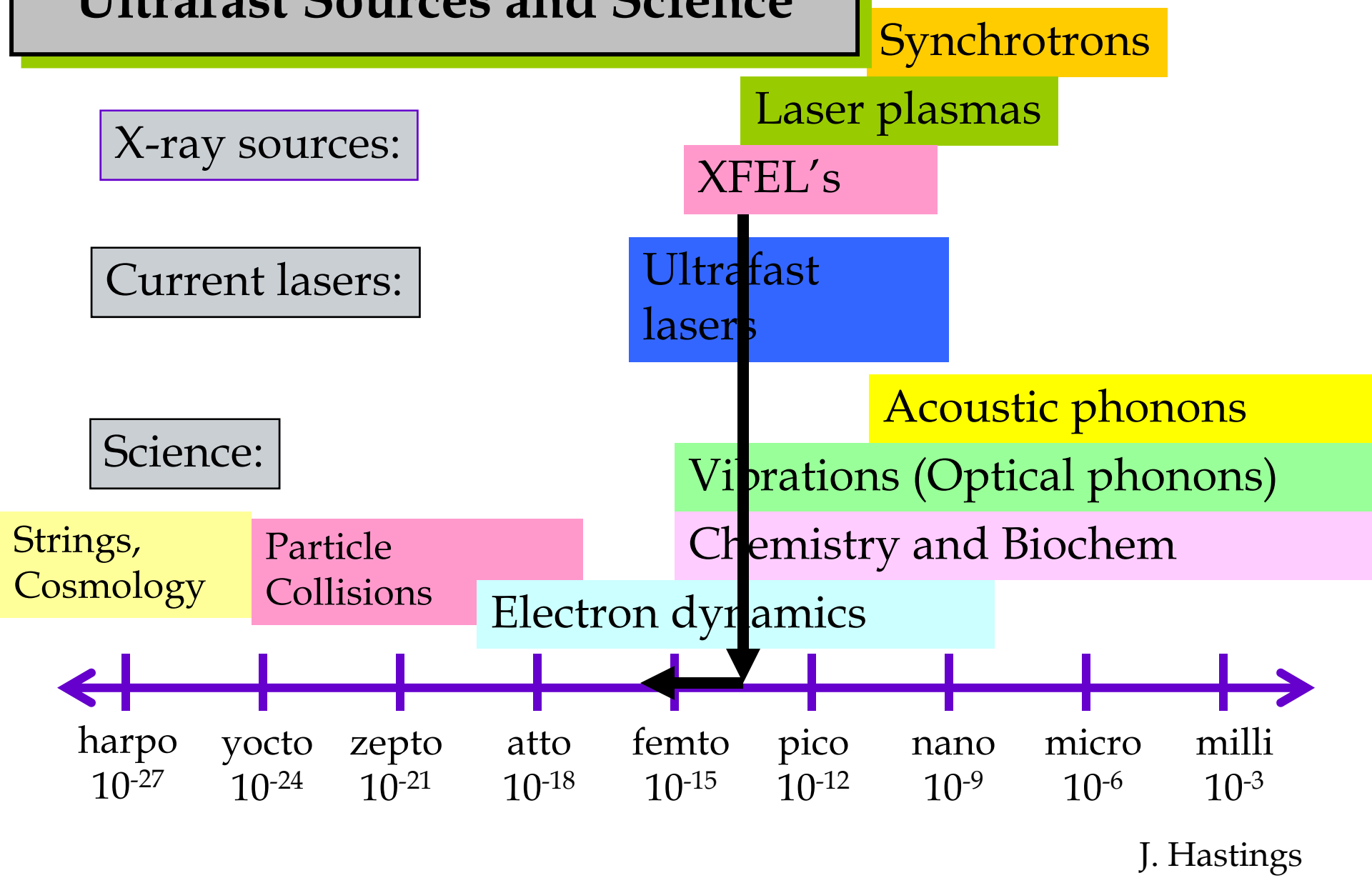
Ultrafast X-ray science

„If you want to understand function, study structure“

Francis Crick

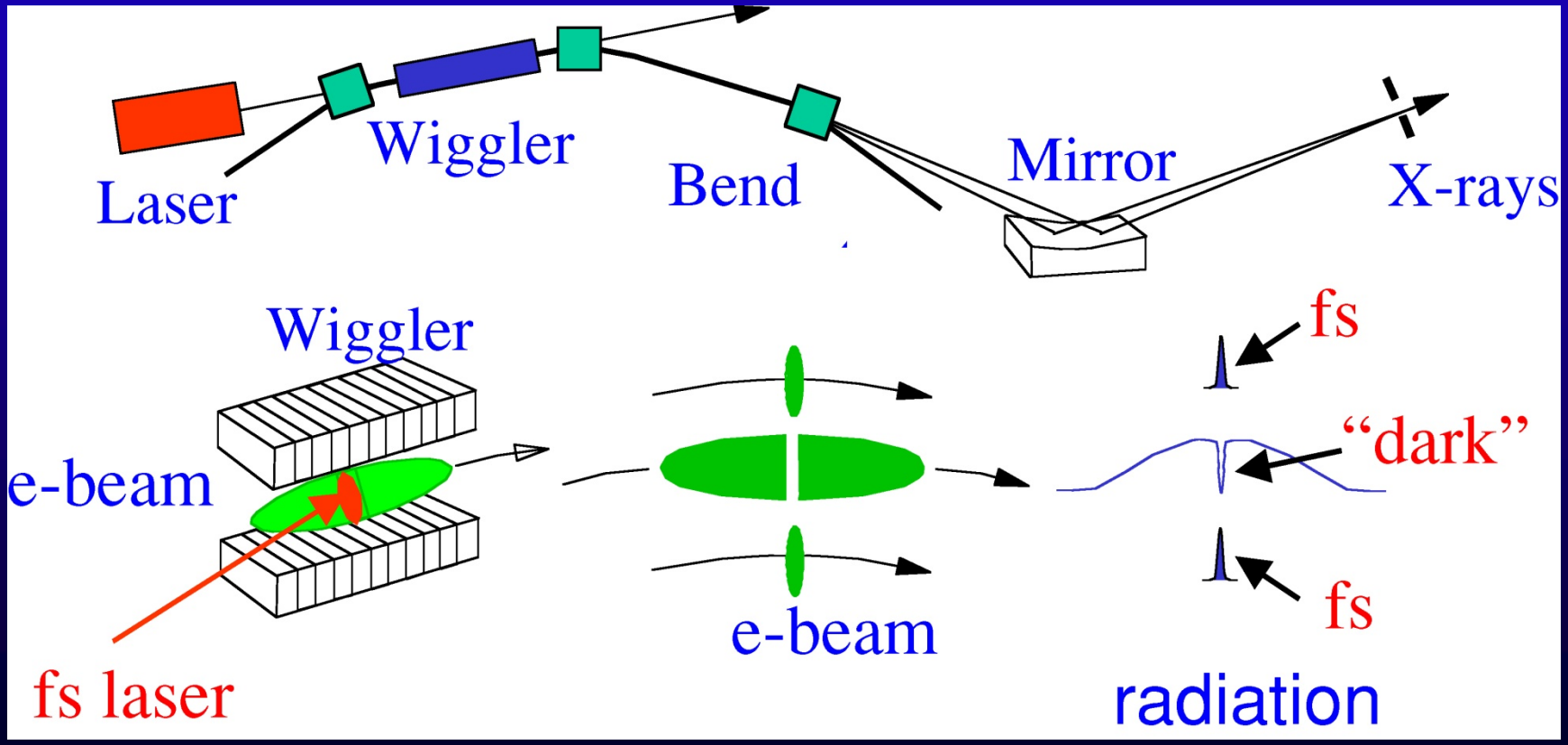
- X-ray Free Electron Lasers extend the ultrafast laser techniques to the X-ray domain
- „Seeing“ structures evolving with time as phenomena take place
- FEMTO: Slicing technique at synchrotrons
- Similar technique to reach < 1 fs with XFELs

Ultrafast Sources and Science



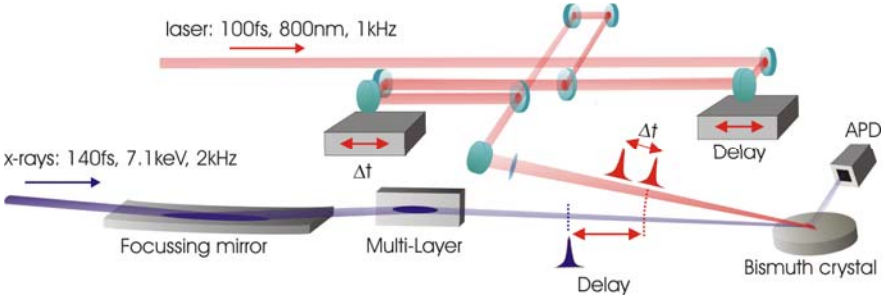
J. Hastings

Laser slicing
Pioneering ideas and experiments at ALS
Facilities at ALS, BESSYII, SLS



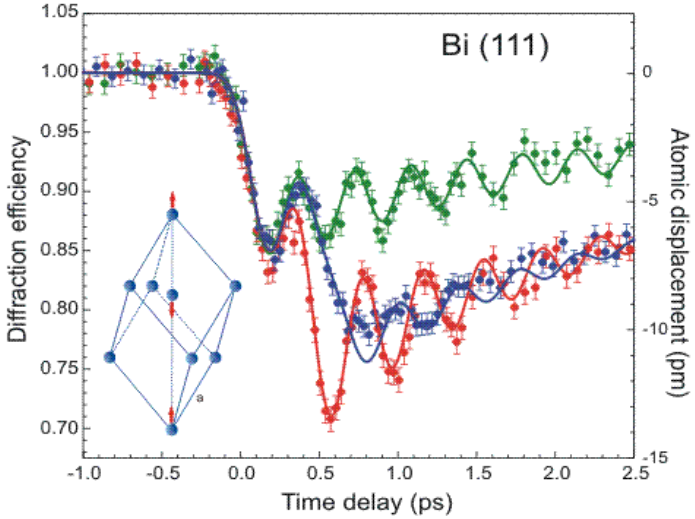
Dynamics on atomic scale visible with ultra-short X-ray pulses

FEMTO



First optical experiment with atomic resolution:

Amplification and damping of lattice vibrations



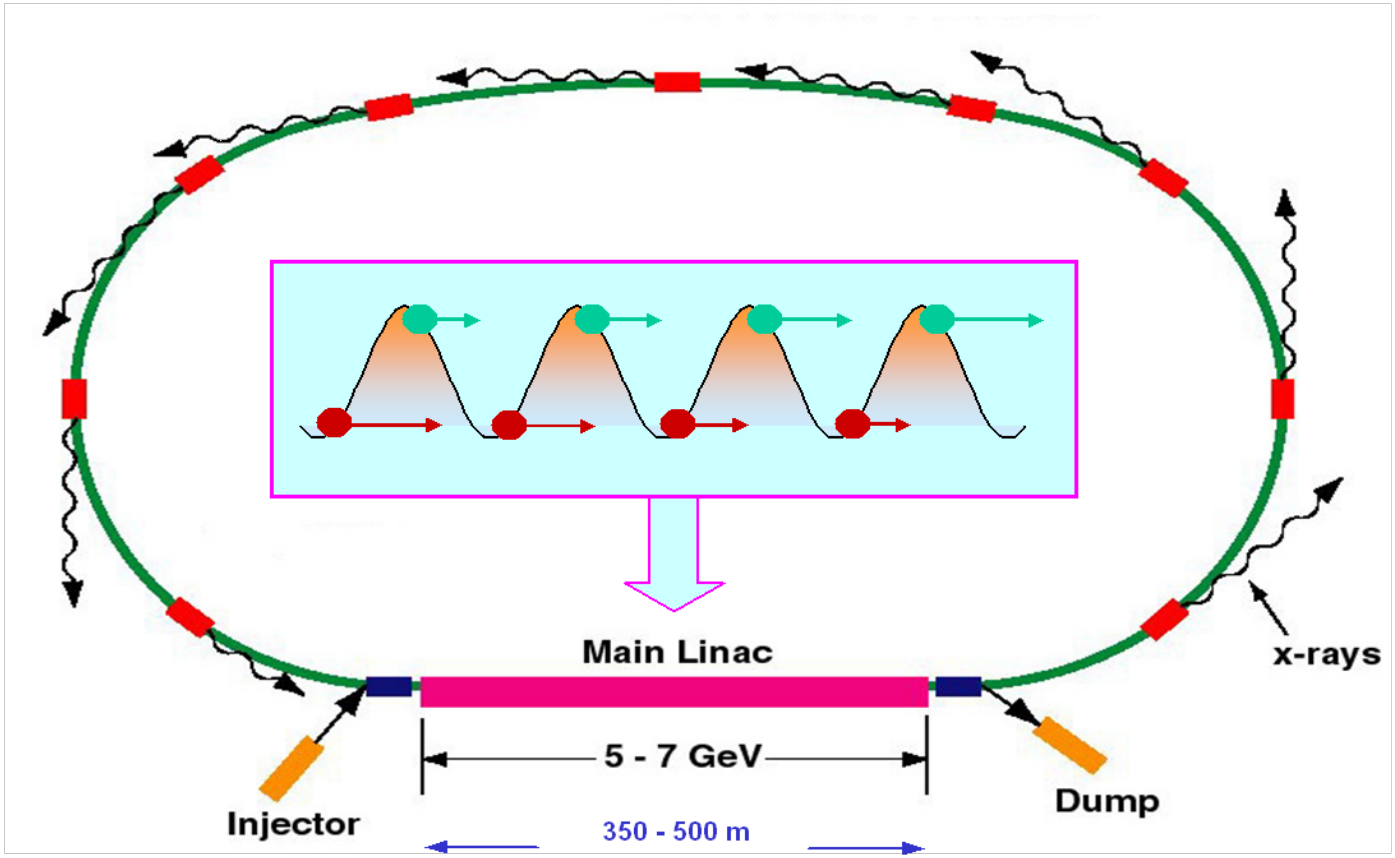
Phys. Rev. Lett. 99, 174801 (2007)

Main R&D directions

- Approaching diffraction limit: very small equilibrium emittance with large rings and damping wigglers
- Short period (small gap) undulator developments
- Detector development complementing source improvements
- Linac based light sources development: ERLs
- Free electron lasers developments

Energy Recovery Linac Schematic

Single pass: emittance and energy spread are determined by injector, can be much smaller than in storage ring



Ch. Sinclair, Cornell

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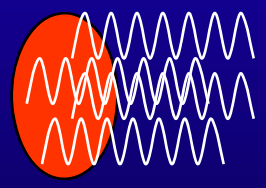
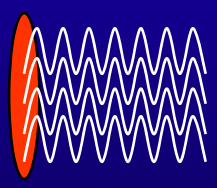
COHERENT EMISSION BY THE ELECTRONS

Intensity $\propto$ N



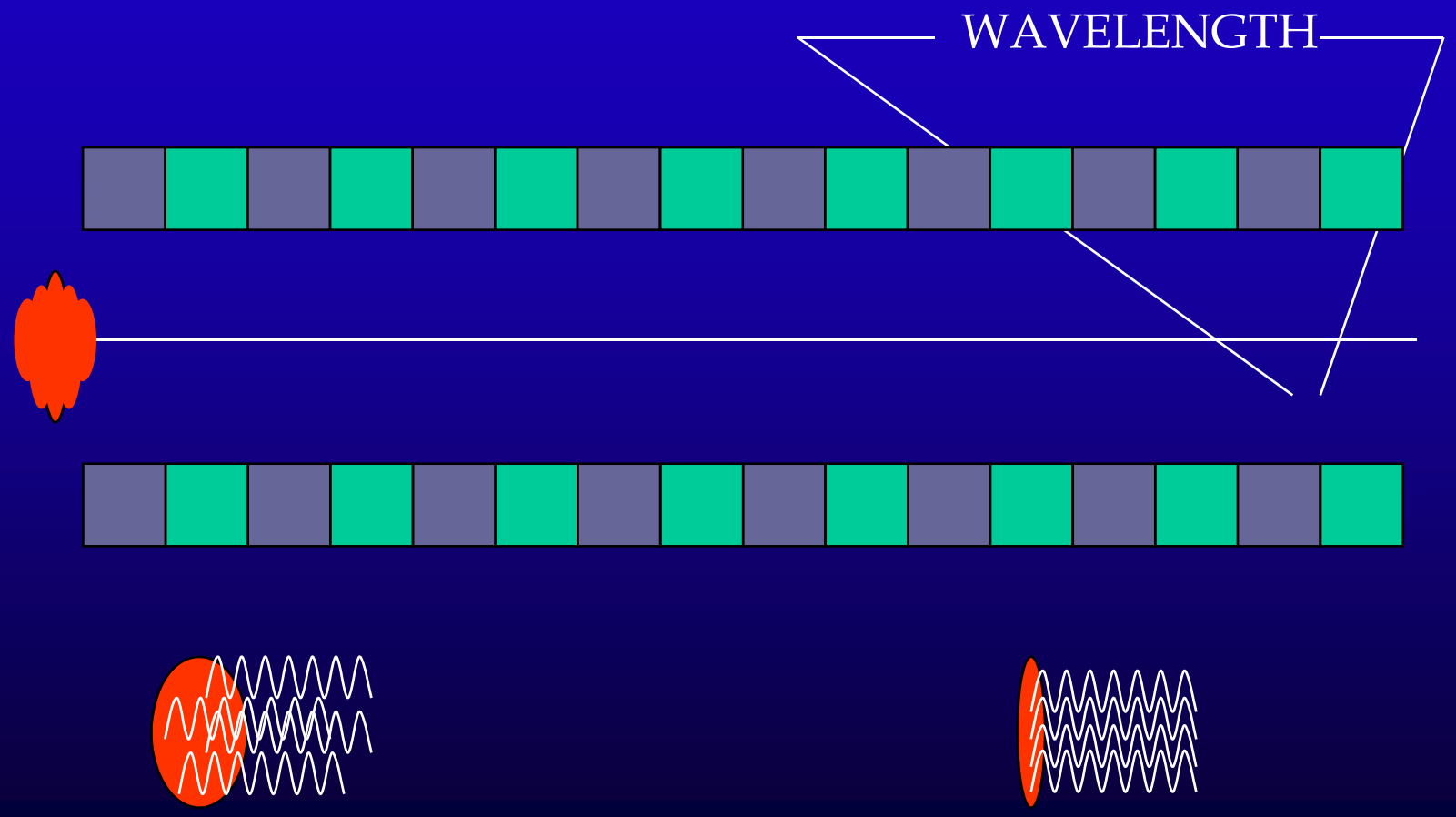
INCOHERENT EMISSION

Intensity $\propto$ N^2



COHERENT EMISSION

MUCH HIGHER BRIGHTNESS CAN BE REACHED WHEN THE ELECTRONS COOPERATE



From rings to linear accelerators

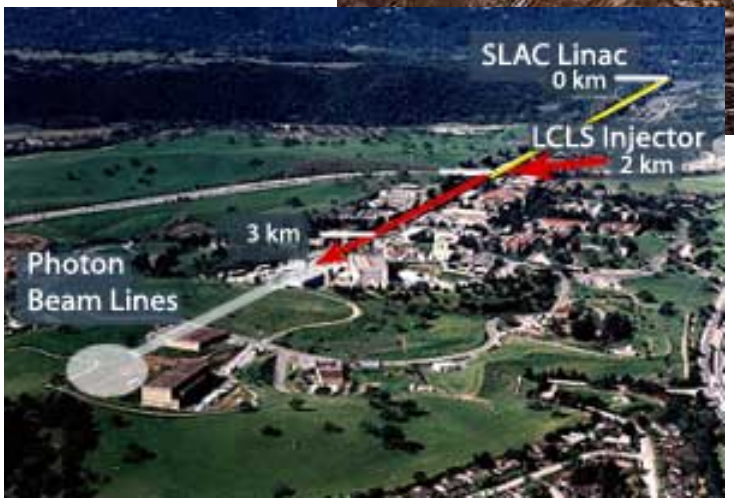
- The number of beamlines served simultaneously
- The stability of the rings based sources
- High average brightness

- Fewer beamlines
- Very short pulses, single shot measurements
- High peak brightness

X-FEL facilities

European XFEL
DESY 2013

Japan
SCSS – SPring8 2010



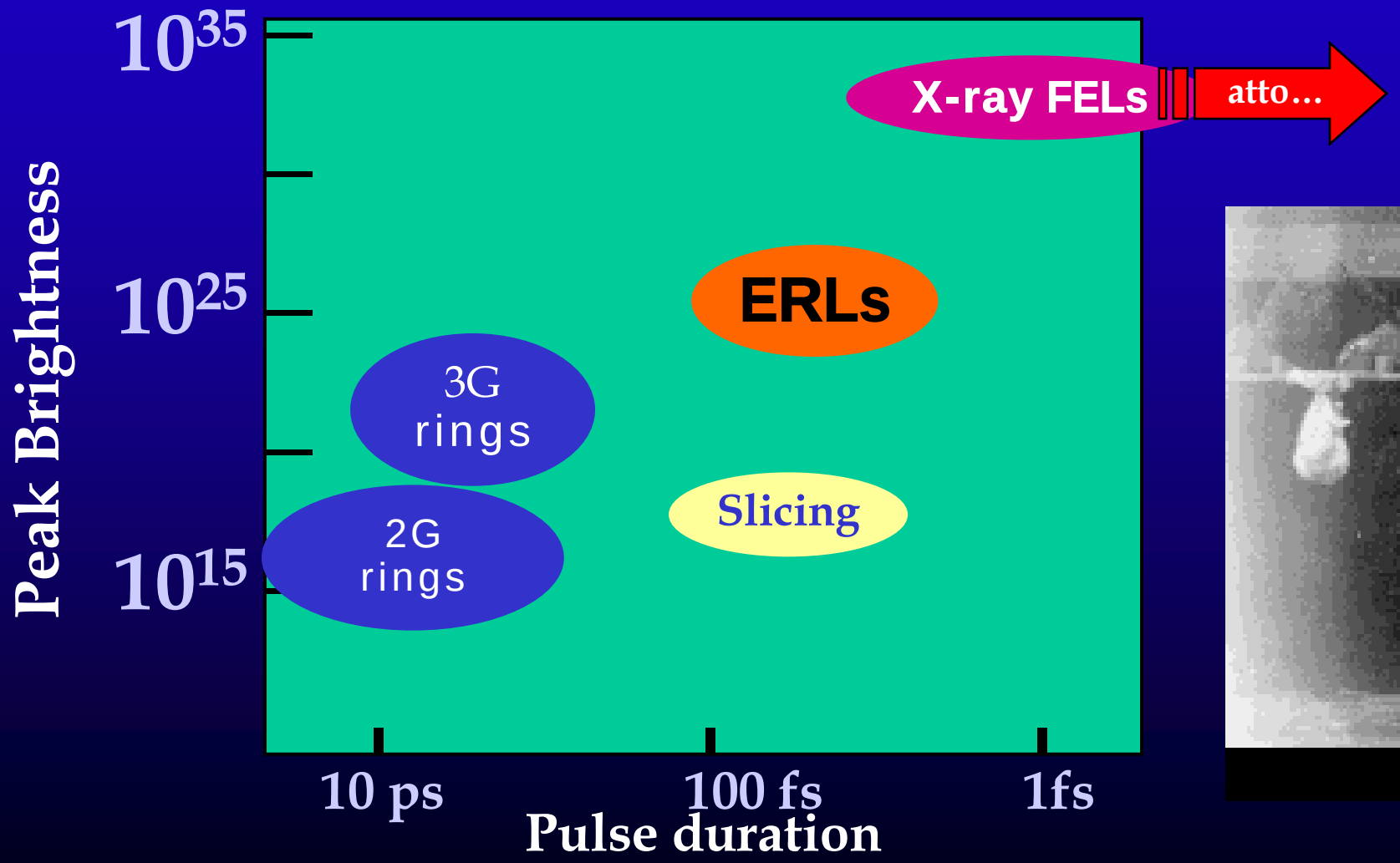
USA
LCLS – SLAC 2009

Expected Fluctuations of LCLS

Parameter	Value	Origin*
Pulse intensity fluctuation	~ 30 %	Varying # of FEL producing SASE spikes; 100% intensity fluctuation/per-spike; etc.
Position & pointing jitter (x, y, α, β)	~ 25 % of beam diameter ~ 25 % of beam divergence	Varying trajectory per pulse; Saturation at different locations of β-tron curvature
Source point jitter (z)	~ 5 m	SASE process reaching saturation at different z-points in undulator
X-ray pulse timing (arrival time) jitter	~ 1 ps FWHM	Timing jitter btw injection laser and RF; Varying e^-energy per-pulse
X-ray pulse width variation	~ 15 %	Varying e-energy leading to varying path (compression) in bunch compressors
Center wavelength variation	~ 0.2 % (comparable to FEL bandwidth)	Varying e-energy leading to varying FEL fundamental wavelength and higher order

David Fritz
dmfritz@slac.stanford.edu

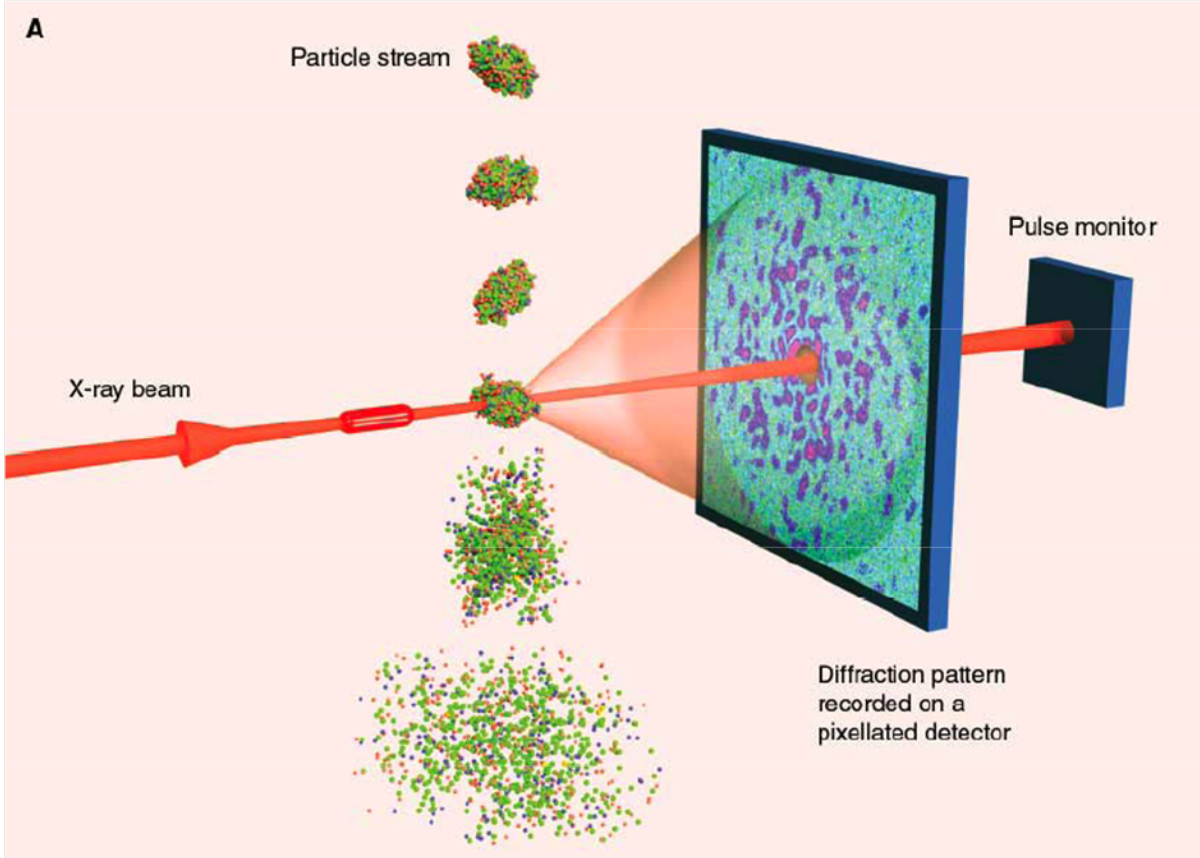
FELs and ERLs COMPLEMENT the Ring sources



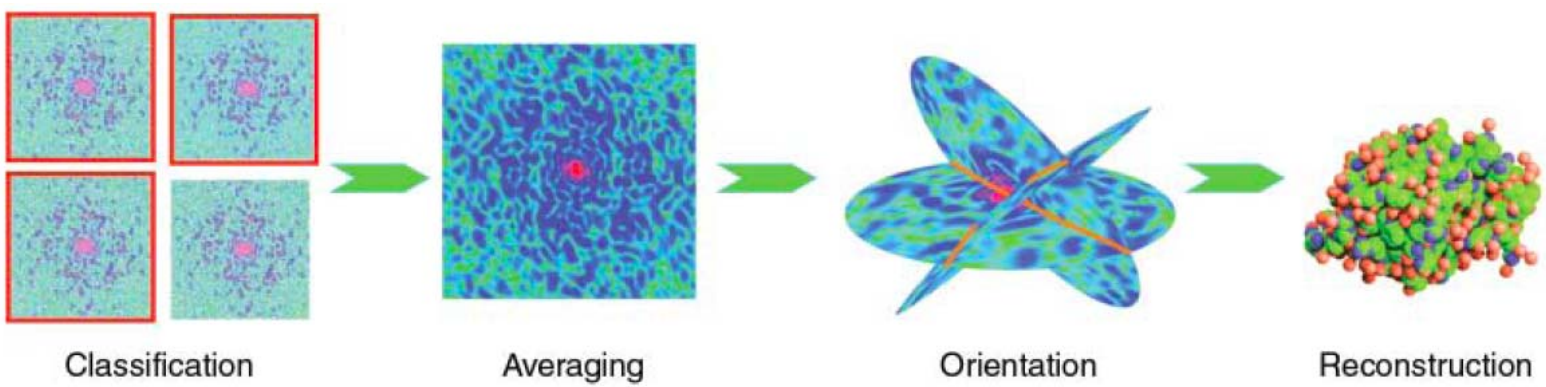
H.-D. Nuhn, H. Winick

After H.-D. Nuhn, H. Winick

Structure determination of single molecules before the Coulomb explosion

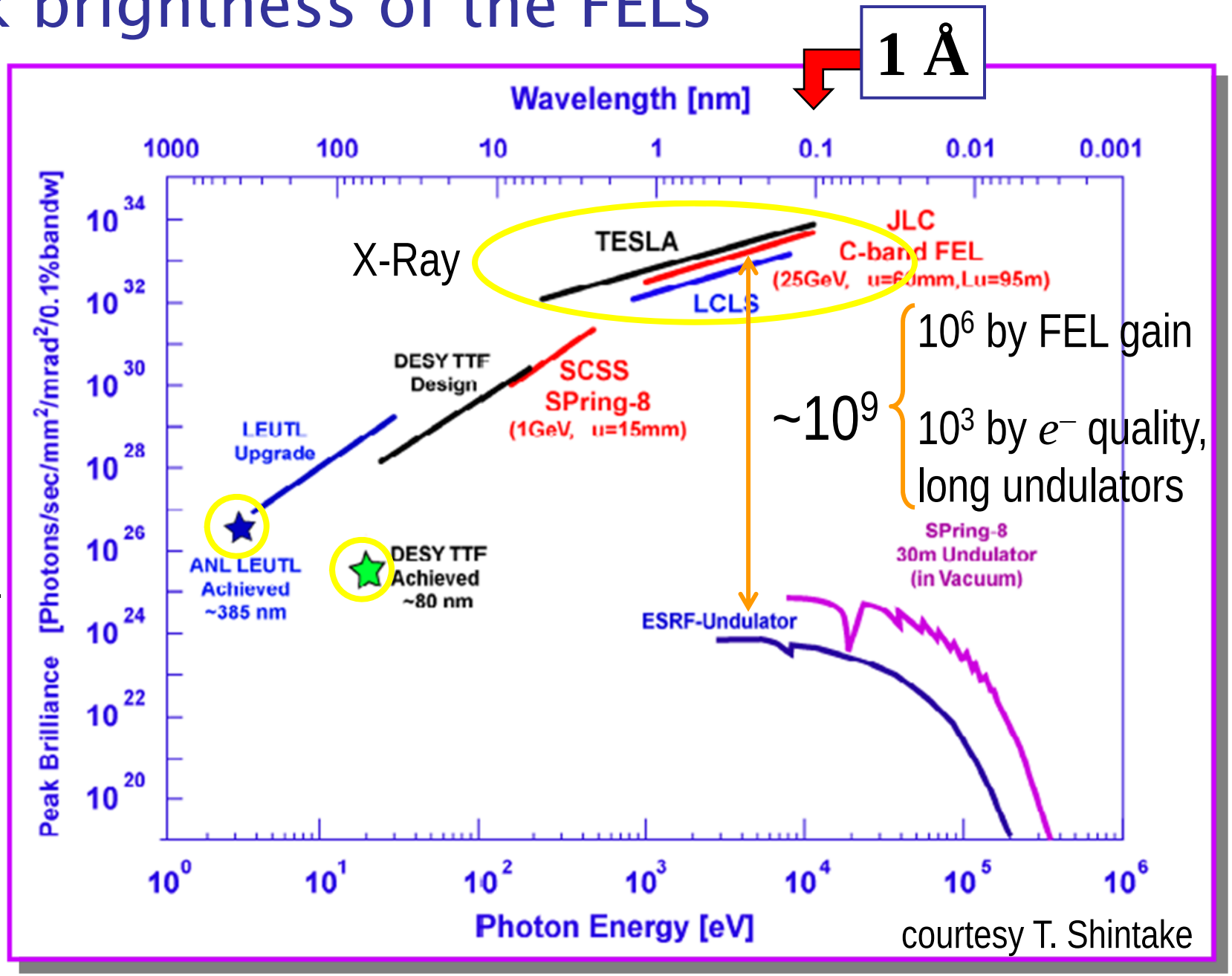


H. Chapman (2007)



Peak brightness of the FELs

photons per phase-space volume per band-width



courtesy T. Shintake

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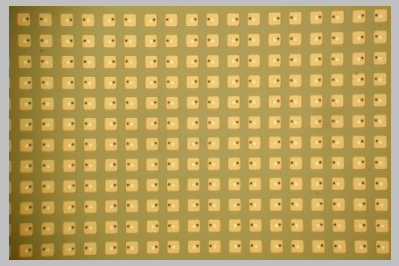
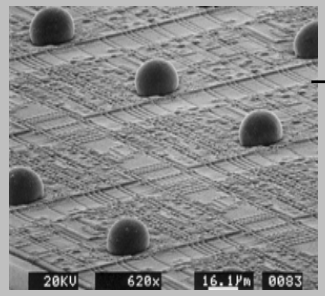
Hybrid-Pixel Technology

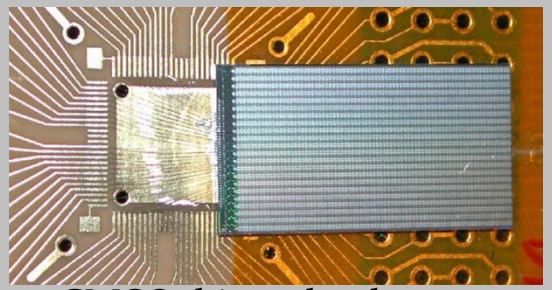
Si-sensor with pixelated pn-diode structure



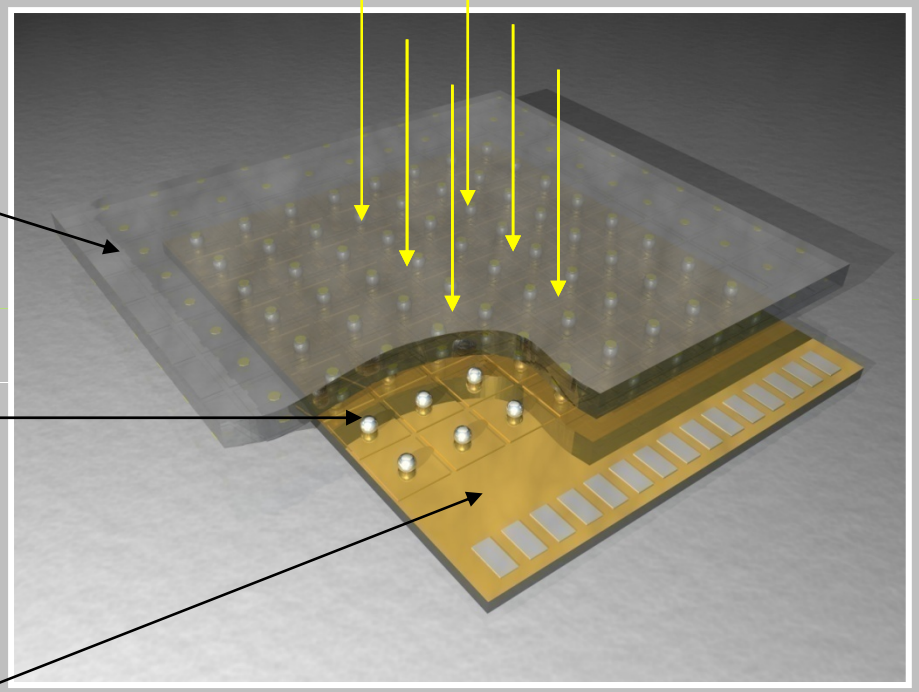
Indium bump-bonding technology

18um bumps





CMOS chip technology,



Direct Detection of X-rays

Single Photon Counting

Frame rate ~ 1 kHz

Advanced detectors: collaboration with HEP detector groups

Cutting-edge 2D pixel detectors

DECTRIS
Next Generation X-Ray Detectors

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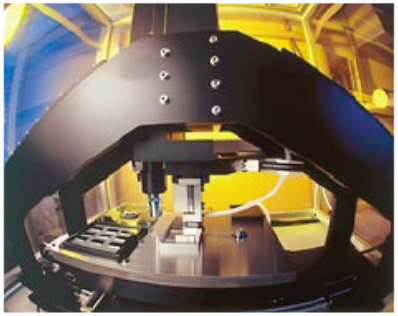
DECTRIS · Products · Applications · References · Technology · Support · Career



WELCOME TO DECTRIS

DECTRIS is the first company worldwide to sell novel hybrid-pixel X-ray detector systems which operate in single-photon counting mode. This new technology features a very high dynamic range, a short readout time and an excellent signal-noise ratio.

These properties improve measurement quality and throughput significantly in many areas such as basic research at synchrotron light sources, laboratory diffraction systems or industrial and medical applications.

DECTRIS offers a variety of detector systems scaled to meet the needs of different applications.

The DECTRIS technology was developed at the Paul Scherrer Institut (PSI) in Switzerland in a decade of scientific research. DECTRIS is proud to have the sole responsibility for the development, production, sales, application support and the maintenance of their detector systems.

DECTRIS provides solutions for challenging measurements.

Last modified: 02/23/07

Spin-off company from PSI

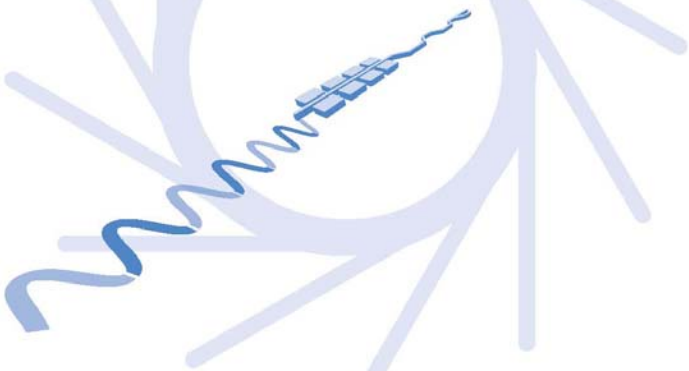
C. Brönnimann, et al

Further reading

SLAC-R- 910
LBNL-1090E

Scientific Needs for Future X-Ray Sources in the U.S.

A White Paper



Based on a study group co-chaired by Roger Falcone and Joachim Stöhr, and members: Uwe Bergmann, John Corlett, John Galayda, Jerry Hastings, Robert Hettel, Zahid Hussain, Janos Kirz, Bill McCurdy, Tor Raubenheimer, Fernando Sannibale, John Seeman, Z.-X. Shen, Robert Schoenlein, and Alexander Zholents.

Lawrence Berkeley National Laboratory

SLAC National Accelerator Laboratory

October 2008

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

Summary

- Strong growth in ring based supply continues
- Complementary laser-like X-ray sources for atomic resolution studies: lots of learning to do
- Linac based sources for ultra-fast X-ray science
- Detector development is crucial
- Sample damage: a problem looking for a solution