Australian Government

ansto
Nuclear-based science benefiting all Australians

Overview of Synchrotron Radiation Research and the AOFSRR

Richard Garrett

Senior Advisor, Synchrotron Science, ANSTO

2015 Cheiron School

AOF Synchrotron Radiation

Asia/Oceania Forum for Synchrotron Radiation Research

Founded - 2006

AOFSRR Objective

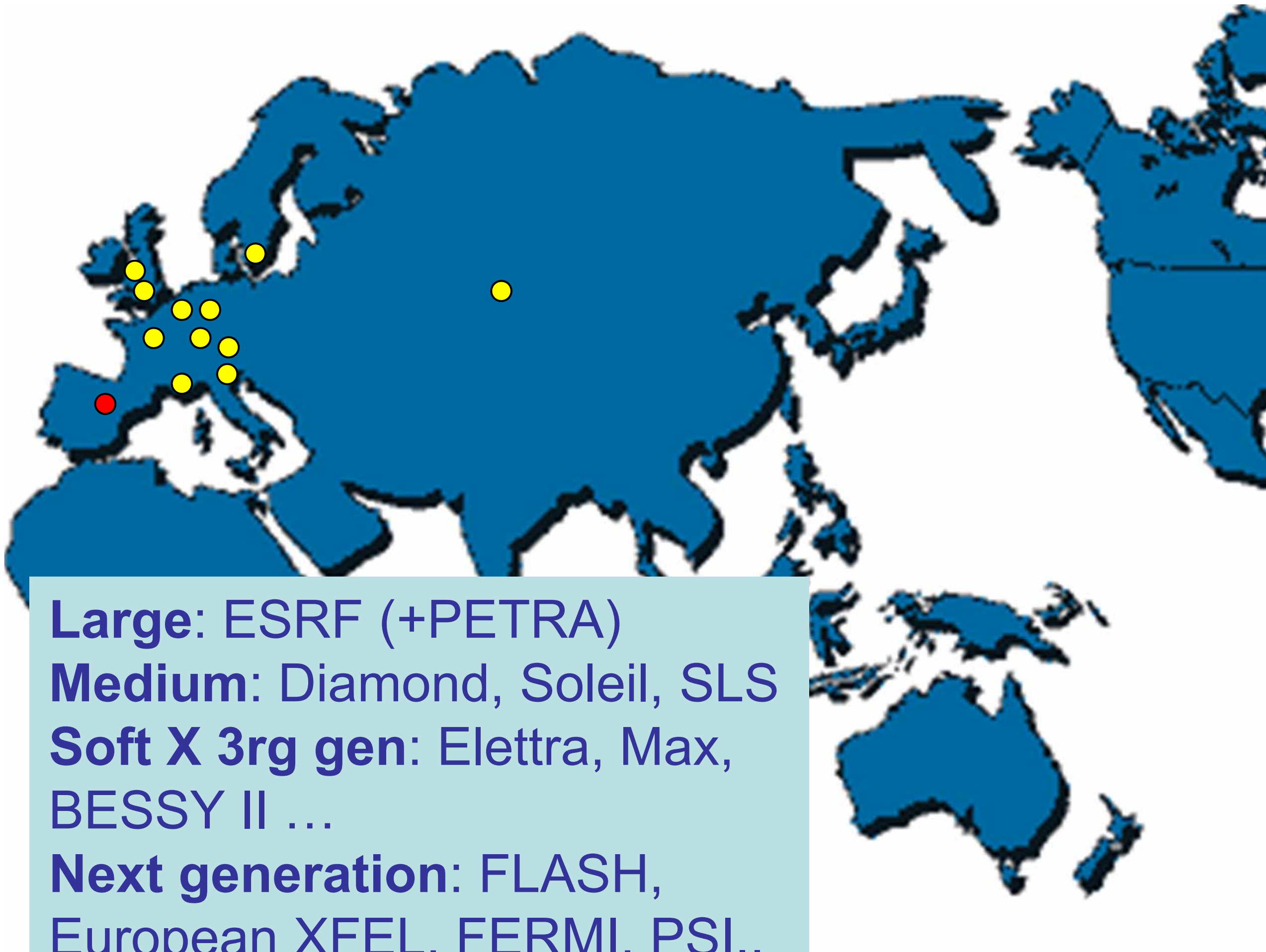
The objective of the AOFSRR is to encourage regional collaboration in, and to promote the advancement of, synchrotron radiation research and related subjects in Asia and Oceania.

Specific Activities:

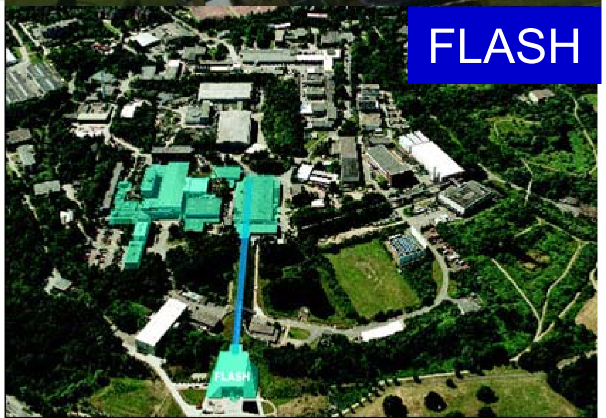
(1) The annual workshop and Cheiron School, and organization of other scientific collaboration meetings;
(2) Exchange of information of facilities and user groups;
(3) Provision of a framework for cooperative activities;
(4) Any activities that promote and expand the role of synchrotron light source facilities and synchrotron based research in the Asia – Oceania region.

AOF Synchrotron Radiation

European Union



Large: ESRF (+PETRA)
Medium: Diamond, Soleil, SLS
Soft X 3rg gen: Elettra, Max, BESSY II …
Next generation: FLASH, European XFEL, FERMI, PSI..



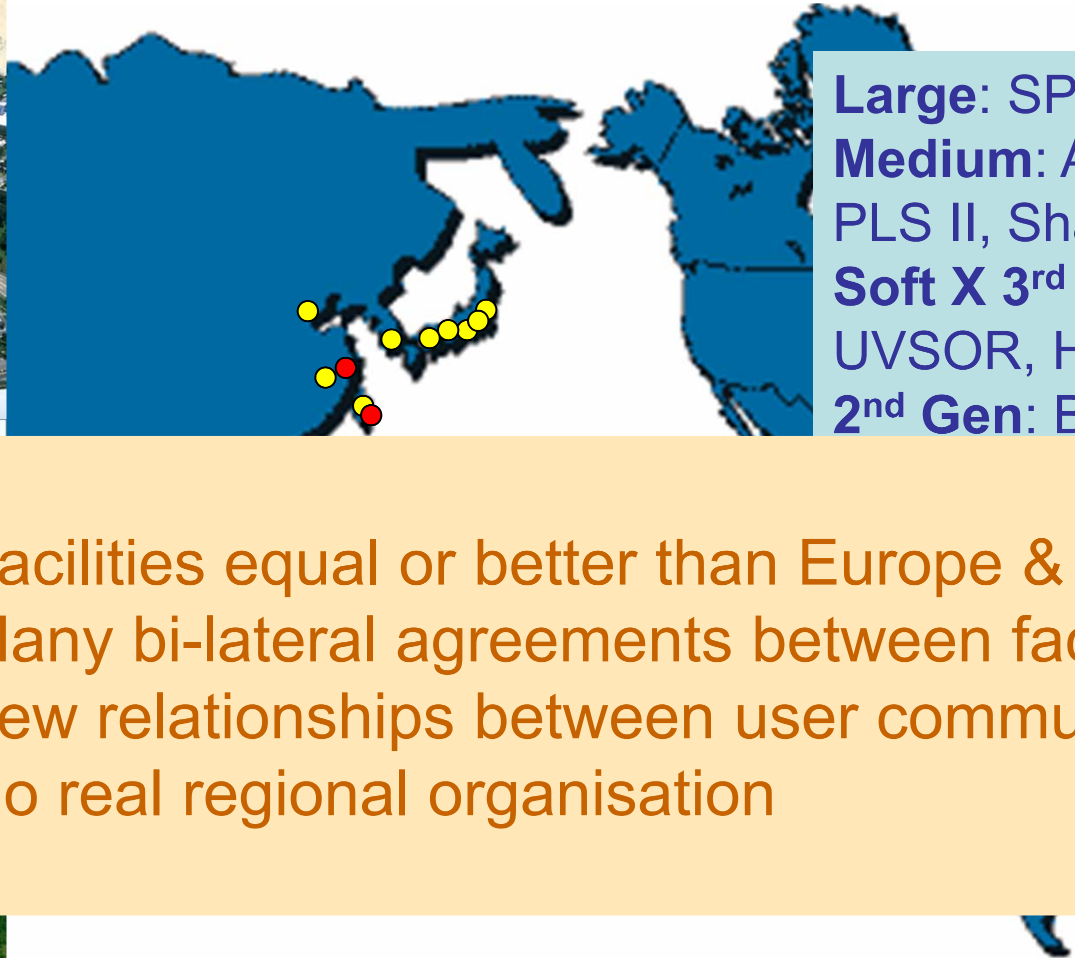
AOF
Synchrotron Radiation

The Americas

Large: APS
Medium: CLS, NSLS II, SSRL
Soft X 3rd Gen: ALS
2nd gen: NSLS, CHESS, Brazil, Alladin…
Next generation: LCLS, JLab, Cornell ERL(?)

AOF Synchrotron Radiation

Asia Oceania & the AOFSRR



Large: SPring-8
Medium: AS, Indus II, PLS II, Shanghai, TPS..
Soft X 3rd Gen: TLS, UVSOR, Heifei..
2nd Gen: Beijing, PF, ..

- Facilities equal or better than Europe & USA
- Many bi-lateral agreements between facilities
- Few relationships between user communities
- No real regional organisation

Members:

- Australia
- China
- India
- Japan
- South Korea
- Singapore
- Taiwan
- Thailand

Associate Members:

- Malaysia
- New Zealand
- Vietnam

AOFSRR Activities

Annual Workshop

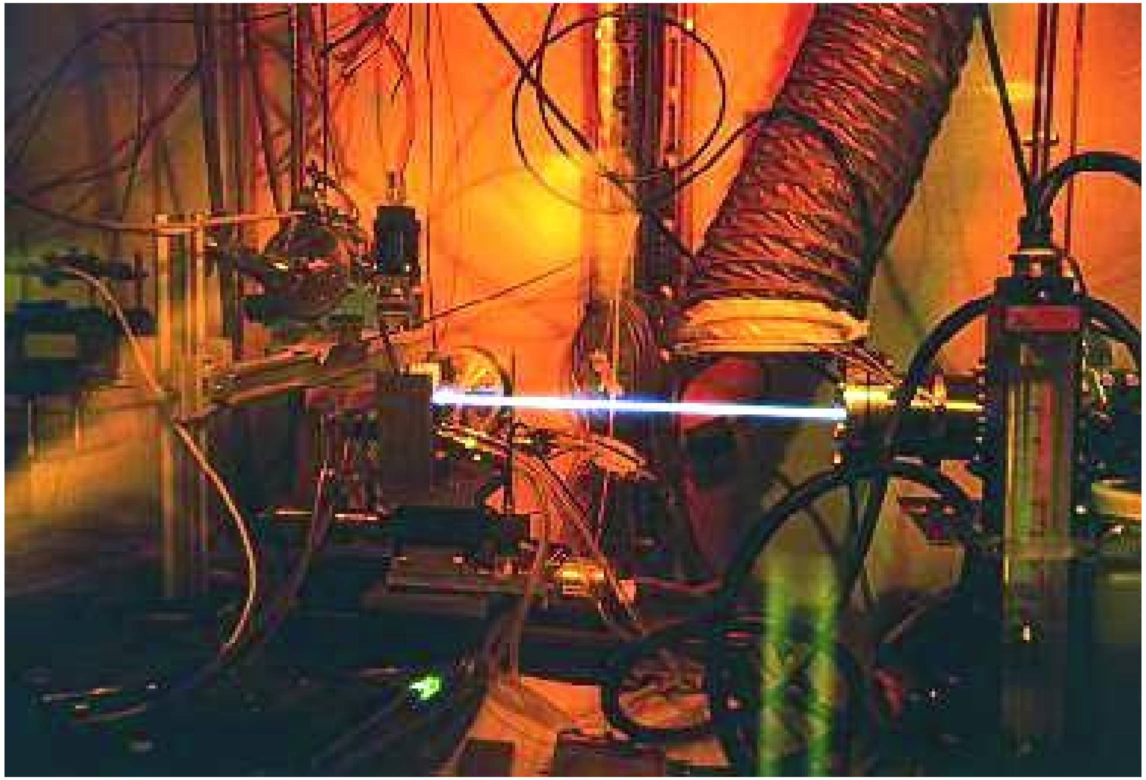
Year	Host
2006	Tsukuba, Japan
2007	Hsinchu, Taiwan
2008	Melbourne, Australia
2009	Shanghai, China
2010	Pohang, South Korea
2011/12	Bangkok, Thailand
2013	Himeji, Japan
2014	Hsinchu, Taiwan
2015	Melbourne, Australia

Cheiron School: Always SPring-8 !!

Promote Synchrotron Research

- Nations can build new communities at other facilities
  - Australian soft X-ray program at NSRRC and
  - NSRRC hard X-ray program at SPring-8
  - Indian beamline at the Photon Factory
- Promote SR research in non-member nations in the A-O region
- Assist SR science in developing nations
  - Cheiron School
  - Assistance to attend conferences
  - Work with other organisations (IUCr etc)

Synchrotron Radiation



X25 wiggler beam, NSLS

Outline

- What is a synchrotron?
- What are the Applications
- How is the light produced & what are its characteristics?
- Brief Basics of Synchrotron Beamlines
- The Future (is here already): “Next Generation Sources”
- A Cool Example

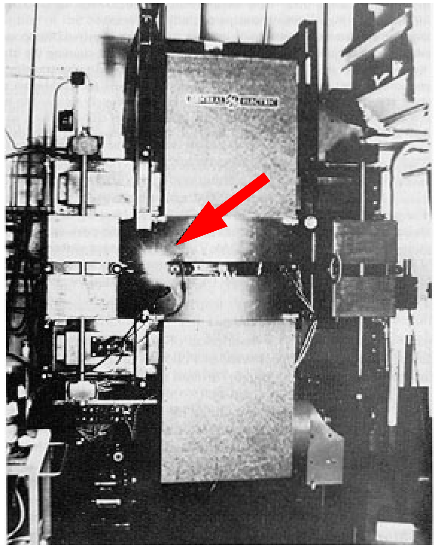
A brief history

- First observed:

  1947, General Electric, 70 MeV synchrotron
- First user experiments:

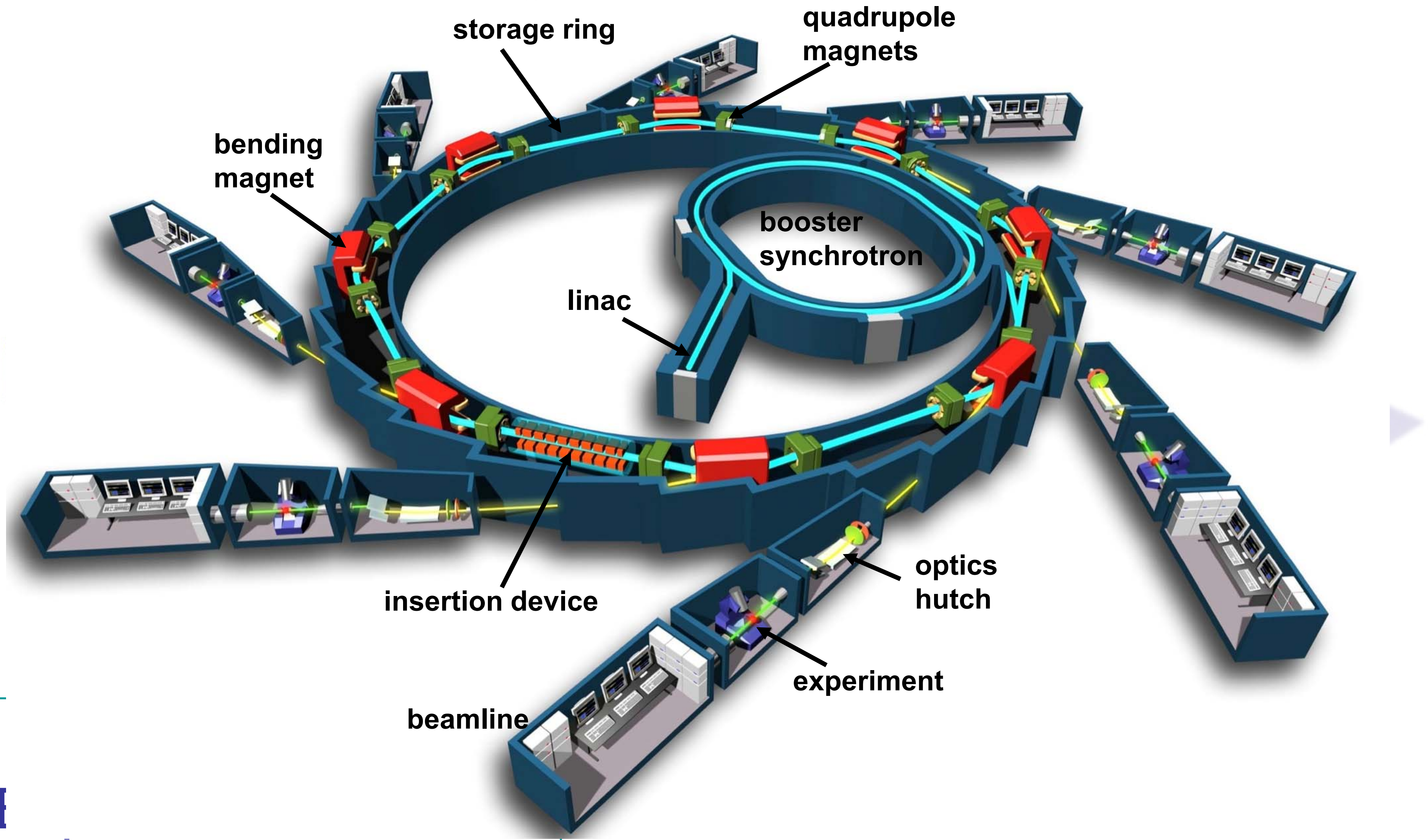
  1956, Cornell, 320 MeV synchrotron
- First insertion Device:

  1979, 7 pole wiggler, SSRL



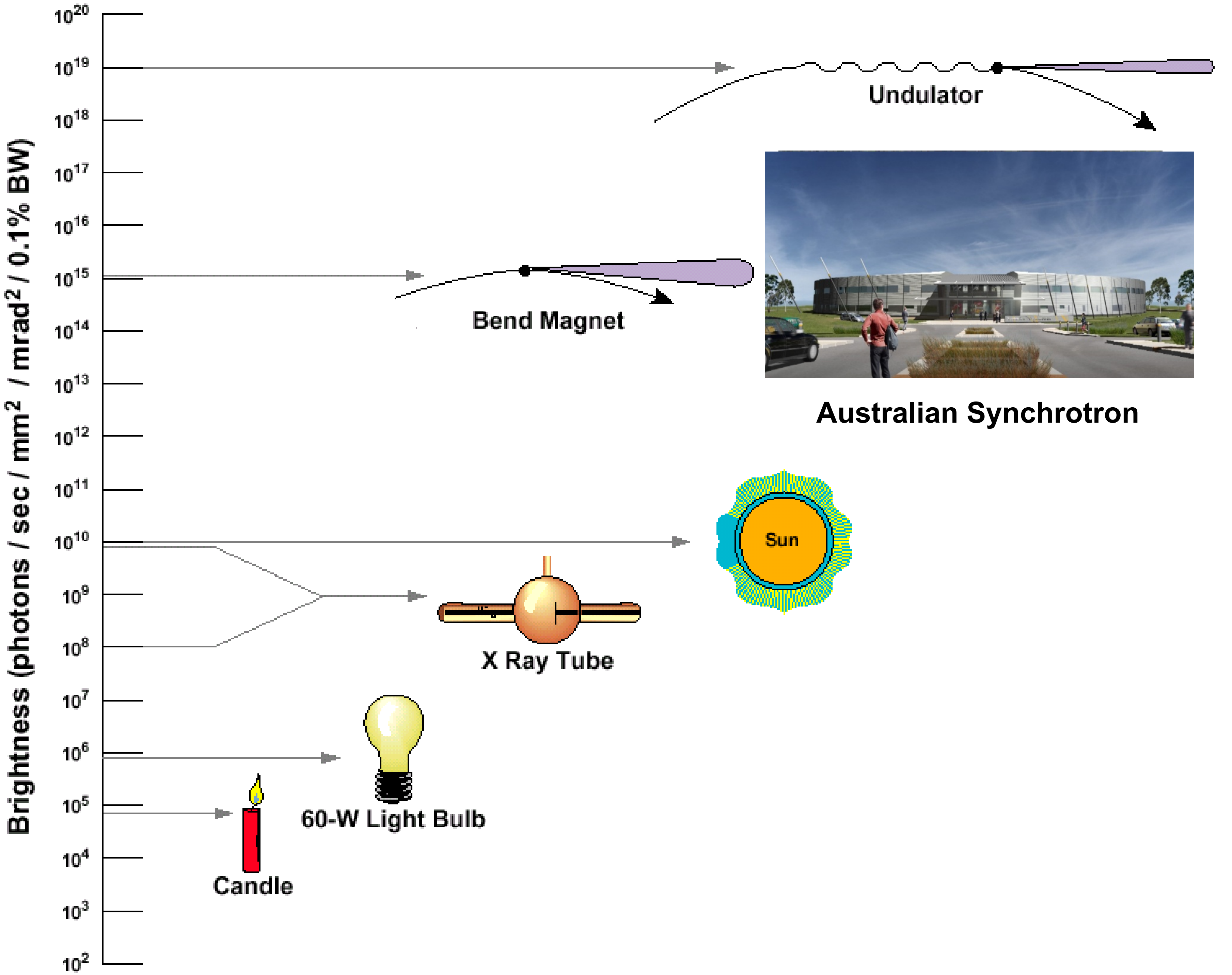
- 1st generation light sources: high energy physics synchrotrons and storage rings used parasitically for synchrotron radiation – eg DESY (Germany), INS-SOR (Tokyo), SPEAR (USA), (1960's, 1970's)
- 2nd generation light sources: purpose built synchrotron light sources, eg Photon Factory, NSLS, Daresbury (1980s onwards)
- 3rd generation light sources: optimised for high brilliance with low emittance and Insertion Devices; SPRing-8,ESRF, APS, Diamond, …(1990's onwards)
- Free Electron Laser sources: FLASH (Germany), LCLS (USA), SACLA (Japan), FERMI (Italy) … (2000's)
- Next??

A Synchrotron Step by Step



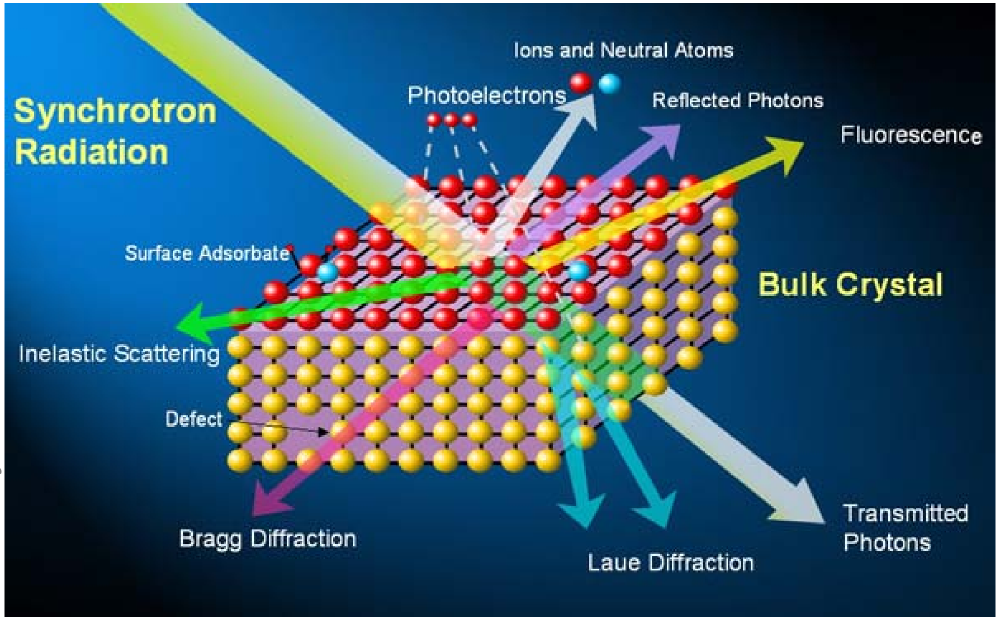
Unique Characteristics of Synchrotron Radiation

- Extremely high brightness. Modern synchrotron sources are about 10 billion times as intense as a laboratory X-ray generator: dilute samples; fast measurements; trace elements;
  - Low divergence: high intensity can be focussed onto tiny samples: Microscopies
- Wide X-ray energy spectrum:
  - the optimum X-ray energy to be chosen for each experiment;
  - X-ray spectroscopies are possible eg EXAFS
- Polarisation: various dichroisms; magnetic imaging; molecular orientation;
- Time structure: time of flight and very fast timing.


Brightness (photons / sec / mm^2 / mrad^2 / 0.1% BW)
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
Undulator
Bend Magnet
Australian Synchrotron
Sun
X Ray Tube
60-W Light Bulb
Candle

X-rays and their Interaction with Matter

Courtesy SRRC, Taiwan



X-ray Diffraction ➔ Structure

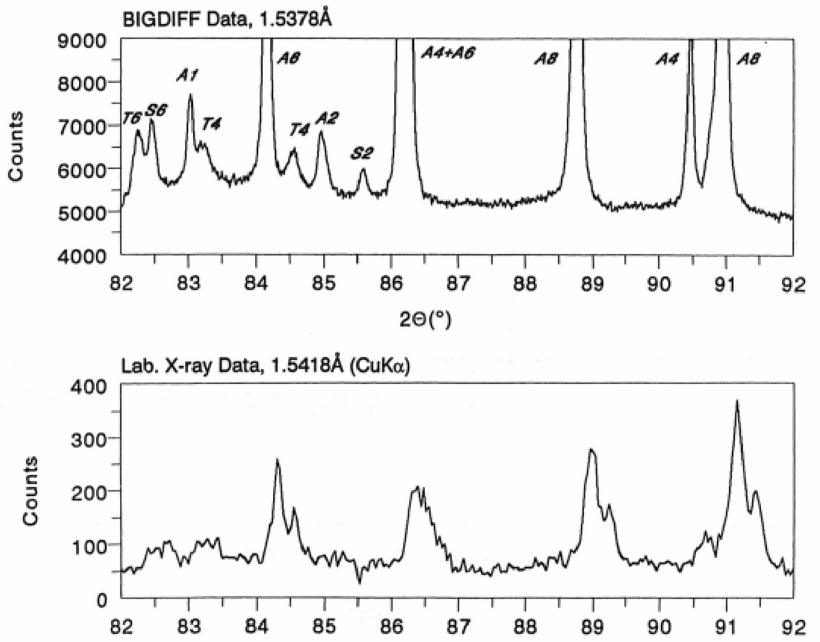
X-ray Fluorescence
➔ trace element analysis

Transmitted Photons:
➔ Imaging
Absorption Spectroscopy
➔ Chemical information

	Synchrotron	Proton	Electron Microscope	SIMS	Neutron
Sensitivity	✓	●	✗	✓	✗
Sub micron	✓	●	✓	✗	✗
Chemical Information	✓	✗	●	●	✗
In-situ	✓	●	✗	✗	✓
Atomic Structure	✓	✗	✓	✗	✓

AOF Synchrotron Radiation

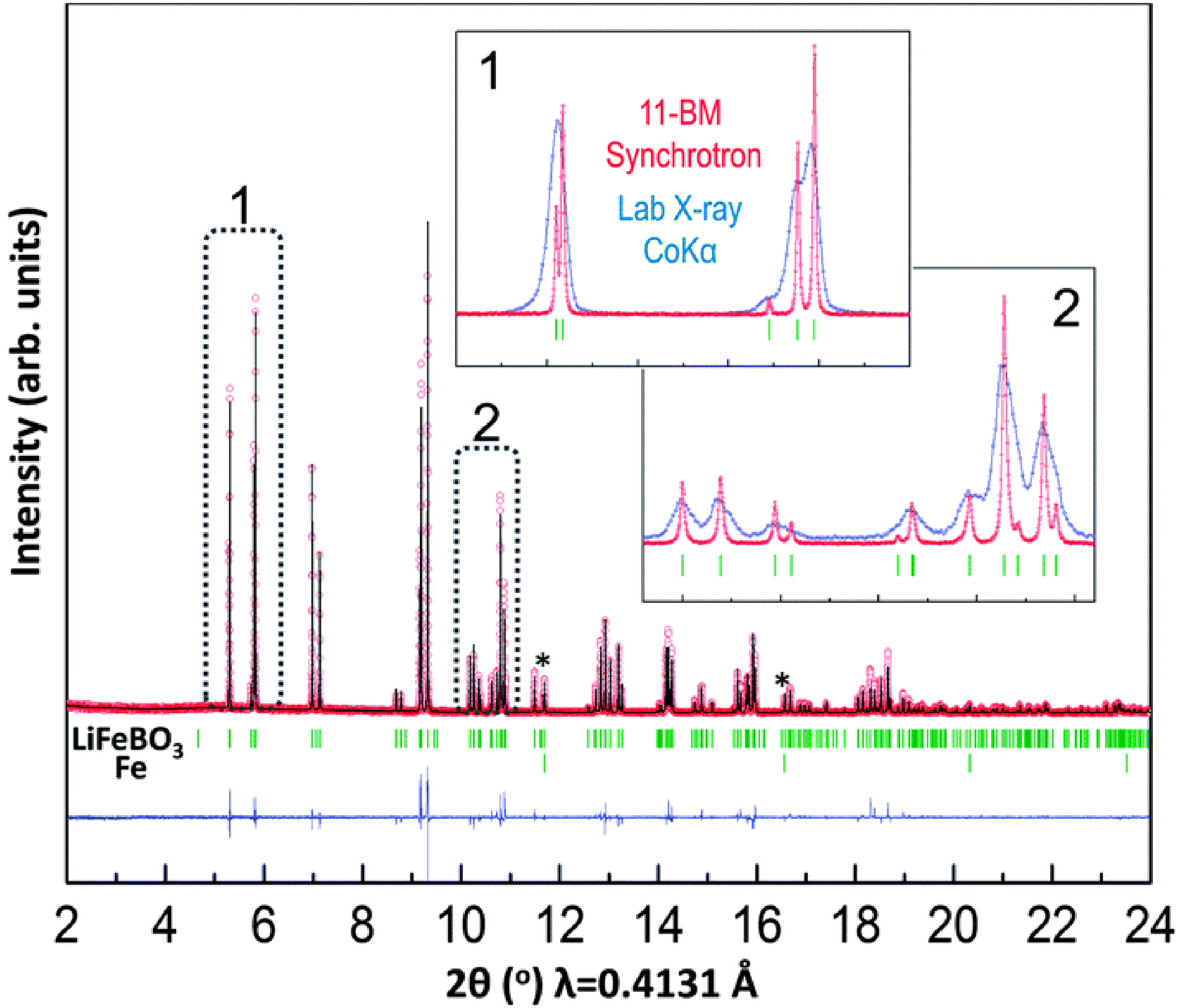
Sometimes High Intensity = Better Data
Synchrotron Powder XRD



Multi-phase ceramic: α Al_2O_3, ZrO_2, MgO-Al_2O_3 (spinel).
Top synchrotron data; Bottom: lab data.

B. H. Oconnor, A. van Riessen, J. Carter, G. Burton,
R. F. Garrett and D. J. Cookson,
J. American Chemical Soc. 80 (1997) 1373

Synchrotron Powder Diffraction



Preparation, structure and electrochemistry of $LiFeBO_3$: a cathode material for Li-ion batteries†

Cite this: J. Mater. Chem. A, 2014, 2, 2060

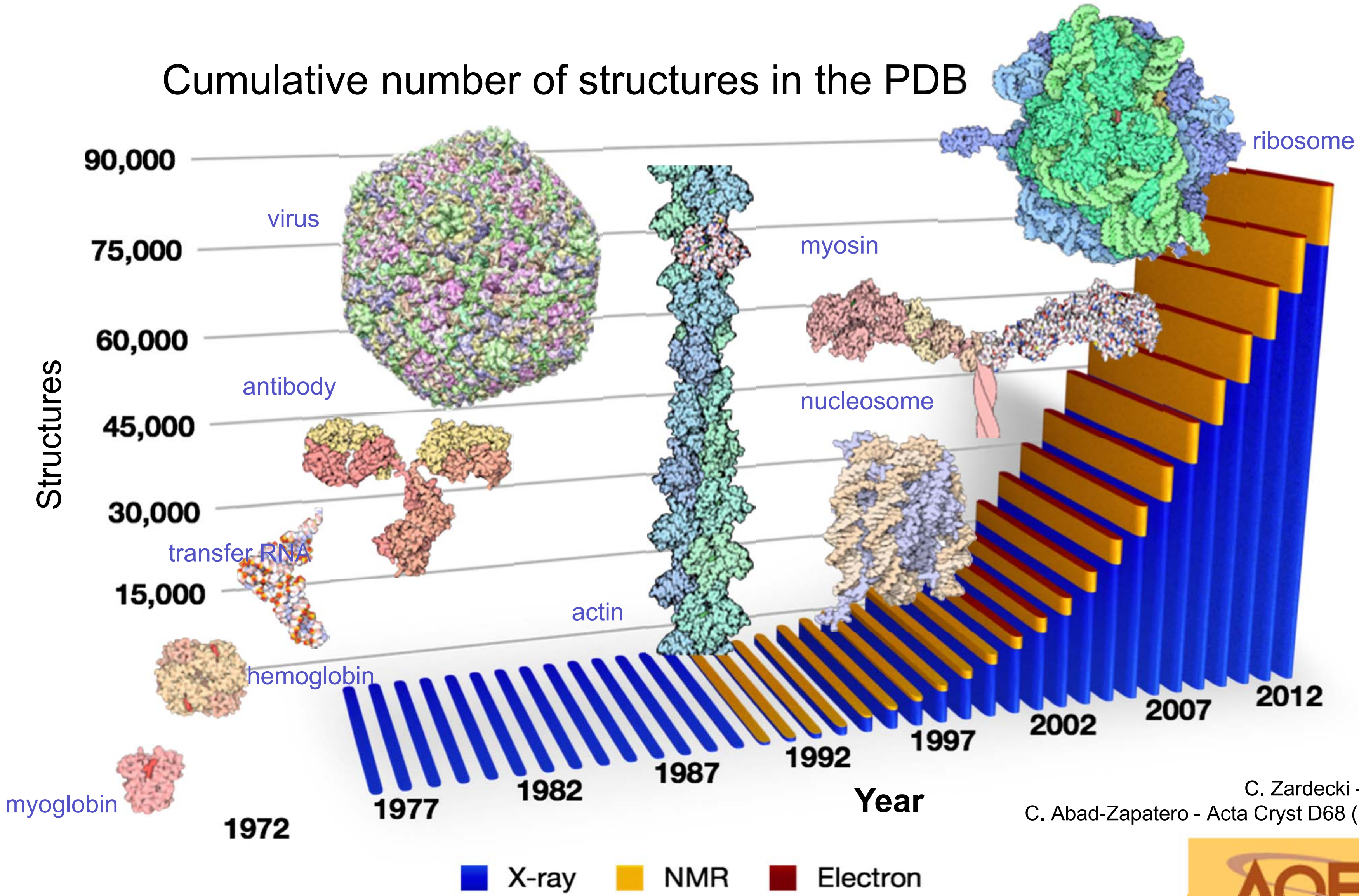
L. Tao,[a] G. Rousse,[b] J. N. Chotard,[a] L. Dupont,[a] S. Bruyère,[a] D. Hanžel,[c] G. Mali,[de] R. Dominko,[d] S. Levasseur[f] and C. Masquelier*[a]

- Higher Resolution – and single wavelength
- Enhanced Sensitivity
- Greater "Q" Range (more reflections)
- Variable energy/ wavelength

Synchrotron data from APS beamline 11-BM

AOF Synchrotron Radiation

Impact of Synchrotrons on Structural Biology



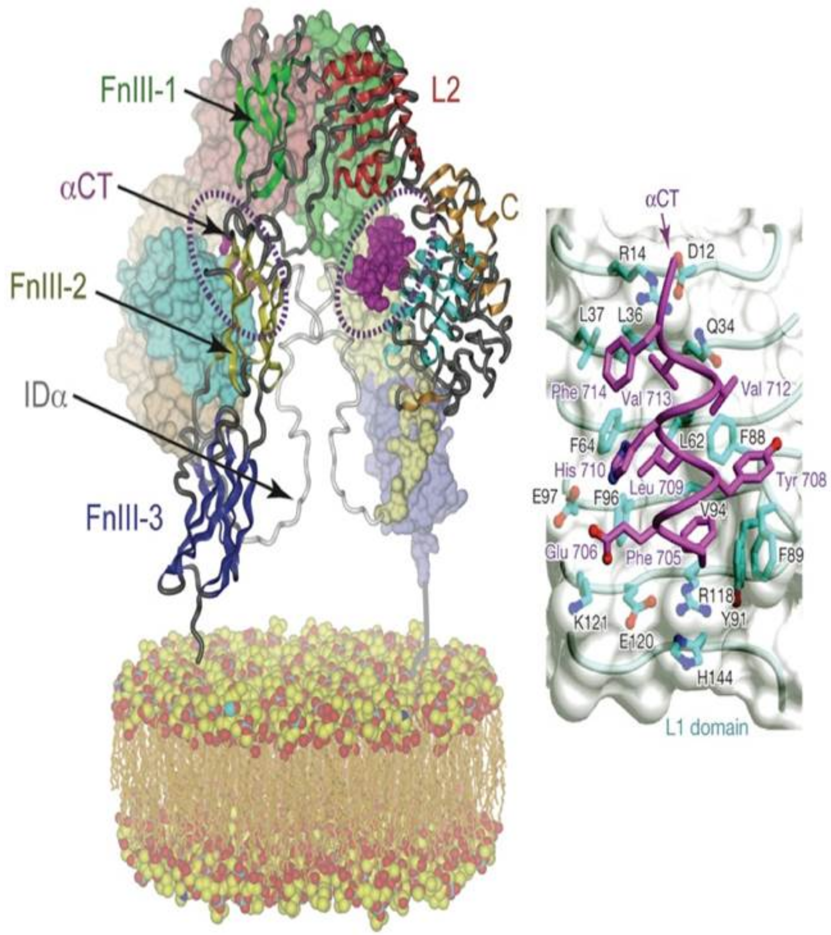
C. Zardecki - PDB
C. Abad-Zapatero - Acta Cryst D68 (2012)

AOF Synchrotron Radiation

Structure informs Function: Insulin bound to it's cell wall receptor

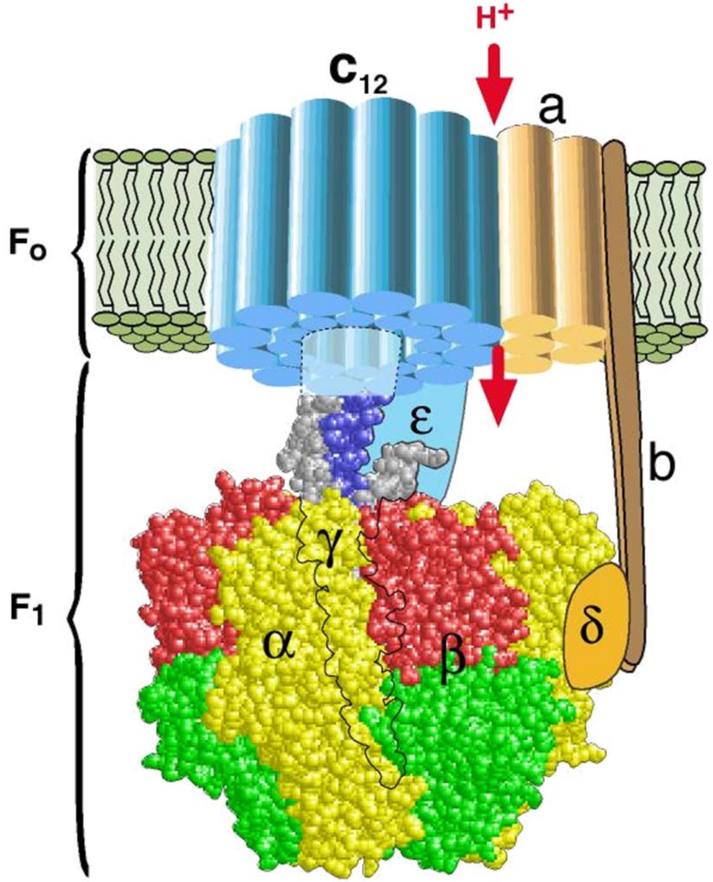
The 3D structure of the insulin molecule was solved by Dorothy Hodgkin in 1969 after an extraordinary 35 year effort!

The 3D structure of insulin bound to its target receptor is a huge milestone towards better diabetes treatment and could lead to the design of synthetic insulin compounds.

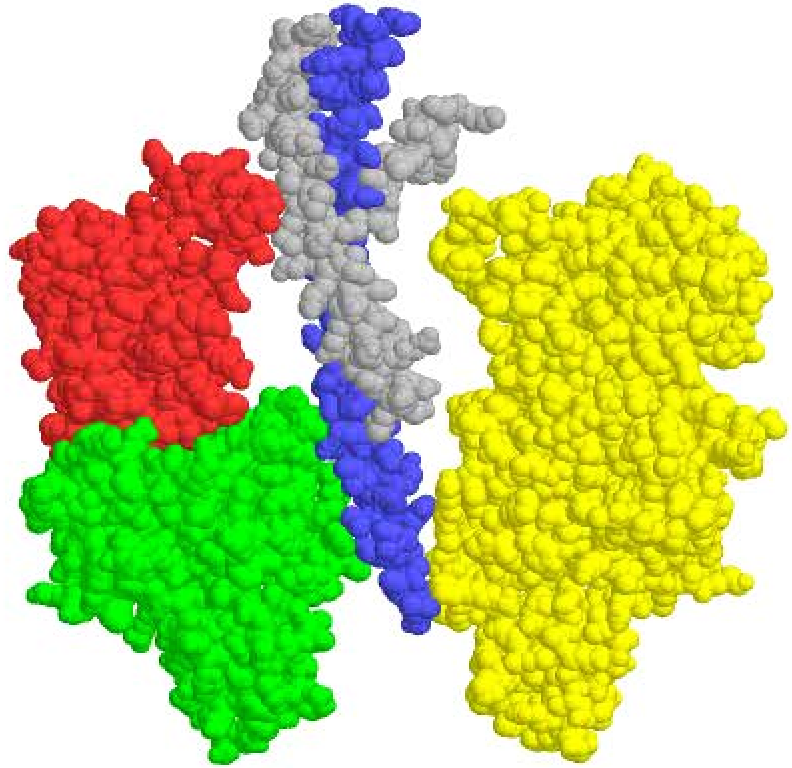


Menting et al. Nature (2013)
Protein crystallography at Australian Synchrotron

ATP Synthase: a Molecular Motor



H. Wang and G. Oster (1998). Nature 396:279-282.



Atomic structure informs biological function

John Walker won the 1997 Nobel Chemistry prize for solving the F1 catalytic domain using synchrotron radiation at Daresbury, UK.

AOF Synchrotron Radiation

Broad Energy Spectrum: <u>SR Only Spectroscopies</u>

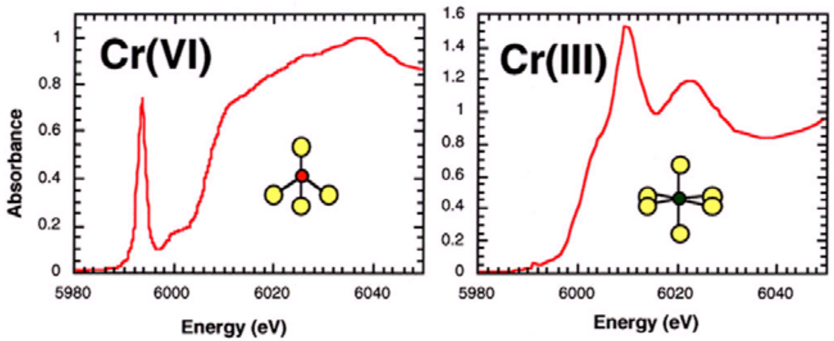
eg Xray Absorption Spectroscopy

XANES: near edge structure

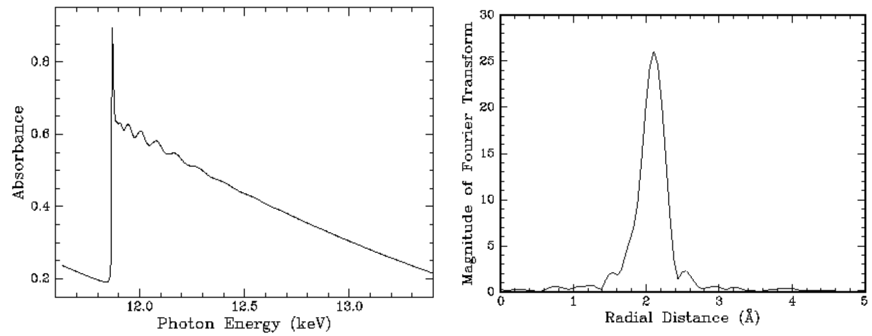
Sensitive to chemical environment of absorbing element.
Often different valence states have markedly different XANES spectra.

EXAFS: extended structure to ~1 keV above an absorption edge

Nearest neighbour atomic distances, coordination etc. Crystals not required: disordered systems like solution species can be measured.



XANES spectra of Cr III (relatively benign) and Cr VI, a known carcinogen.



Amorphous GaAs EXAFS and Fourier transform.

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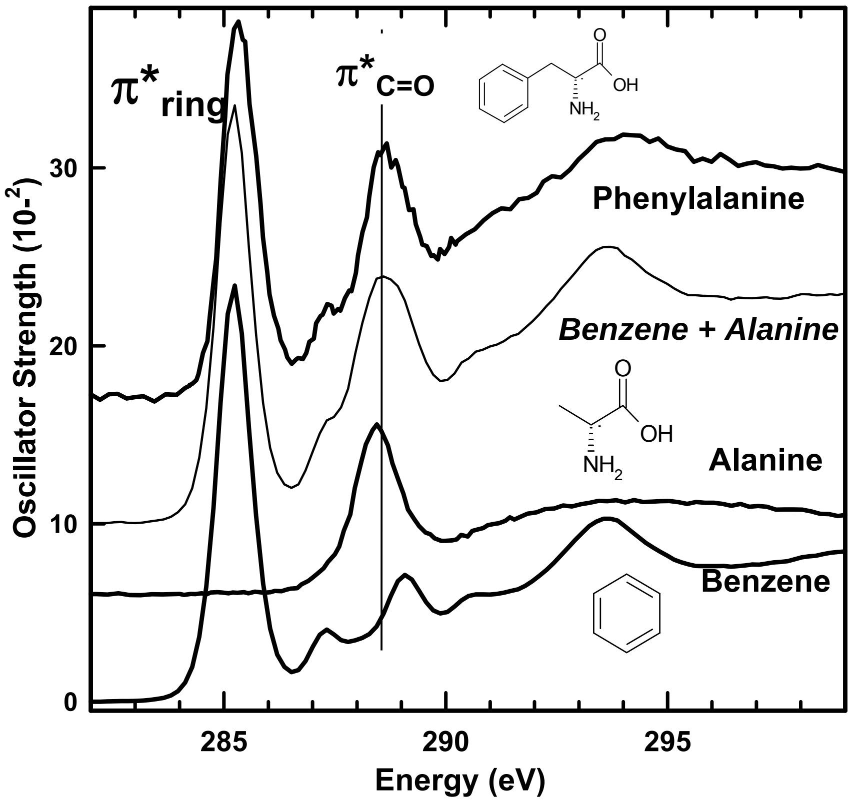
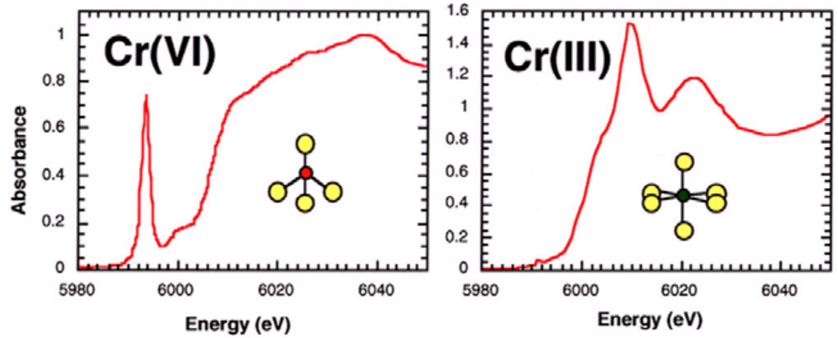
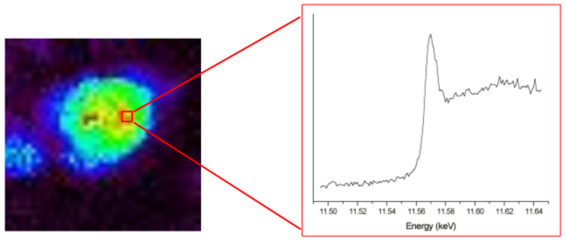
Near Edge Spectroscopy: Chemical Sensitivity



Carbon K-edge Spectra

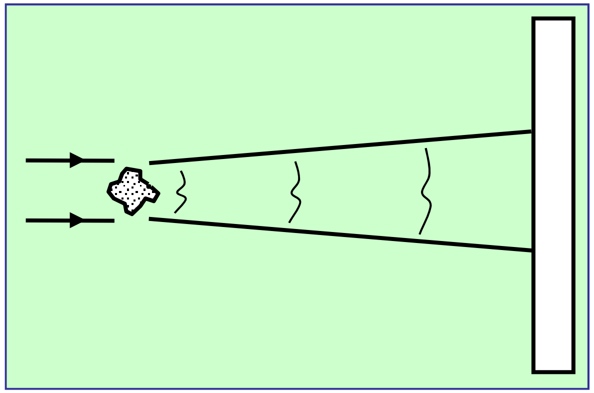




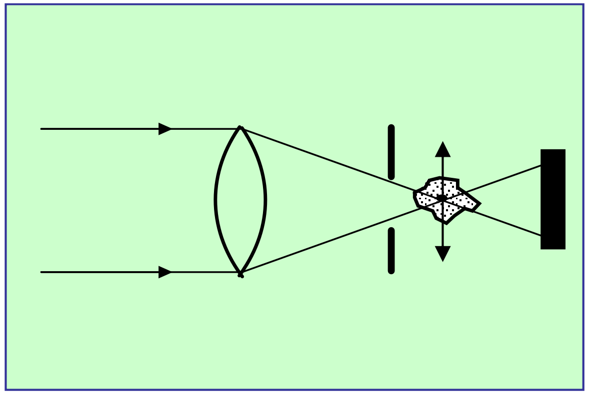
XANES of Pt located in a tumour cell Hambley, U Syd

Imaging

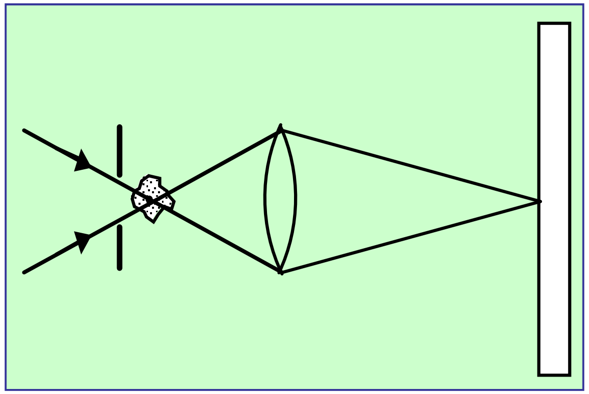
Mapping



Radiography



Scanning



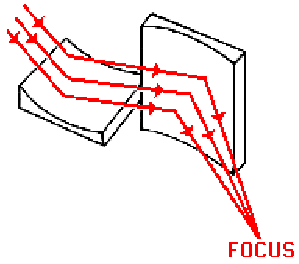
Imaging

Various Imaging Techniques have become more and more important in synchrotron research over the last 10 years

Some Imaging Needs Focusing optics

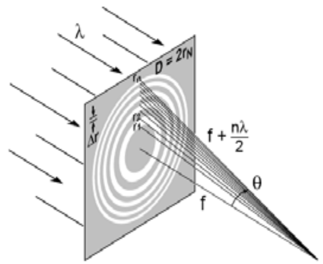
Reflective (Kirkpatrick-Baez mirrors) **typical ~1 µm**

High efficiency, achromatic, limited to ~10 nm



Diffractive (Fresnel zone plates) **typical ~ 100 nm**

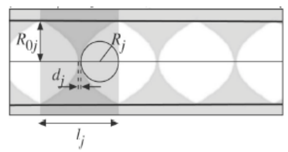
Moderate efficiency, limited to ~10 nm



Refractive (compound refractive lenses) **10s µm - ~ 50 nm**

Low efficiency, highly chromatic, aberrations

Works well with high energy X-rays



Contrast mechanisms in x-ray imaging

➢ **Absorption**	measure electron density; can be element specific
➢ **Fluorescence**	measure elemental distribution
➢ **Spectroscopy**	extract chemical state, spin state
➢ **Diffraction**	reveal structure, strain, magnetism, charge…
➢ **Phase**	measure real part of refractive index

In general with X-rays:

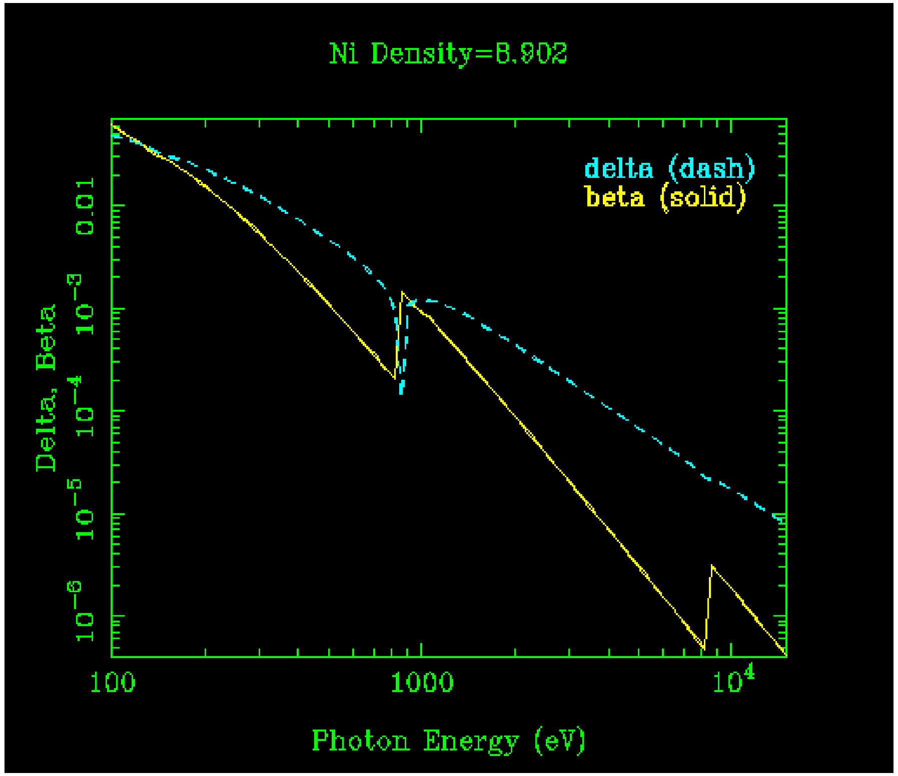
- **Natural sample contrast is often possible; staining not required**
- **Image structure of thick samples, sectioning not required**
- **More penetrating, less damage, less charging than with electrons**
- **In situ imaging – image samples in natural environment.**

Phase Contrast

Refractive index:

for X-rays it is less than 1 by about 1 part in a million

$$n = 1 - \delta - i\beta = 1 - \frac{r_e}{2\pi}\lambda^2 \sum_i n_i f_i(0)$$

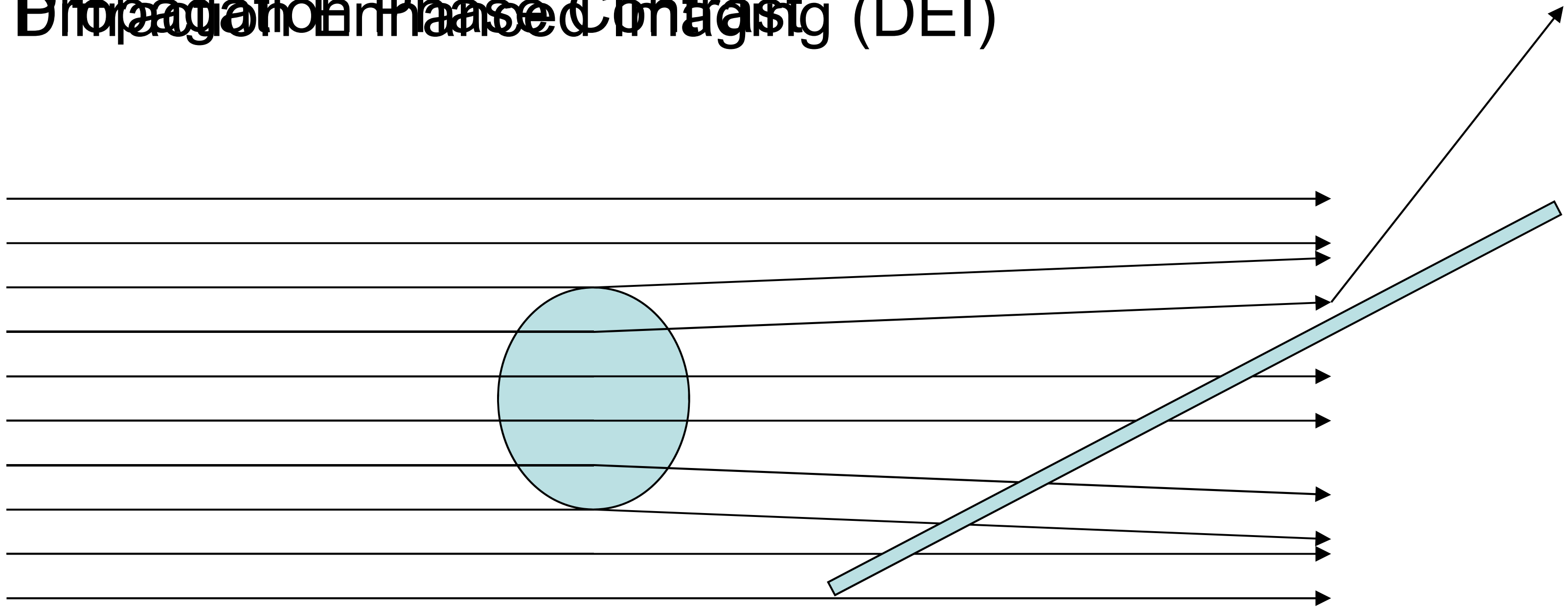


- Absorption contrast: sensitive to *Im(n)*
- Phase contrast: sensitive to *Re(n)*
- At high X-ray energies, phase contrast wins

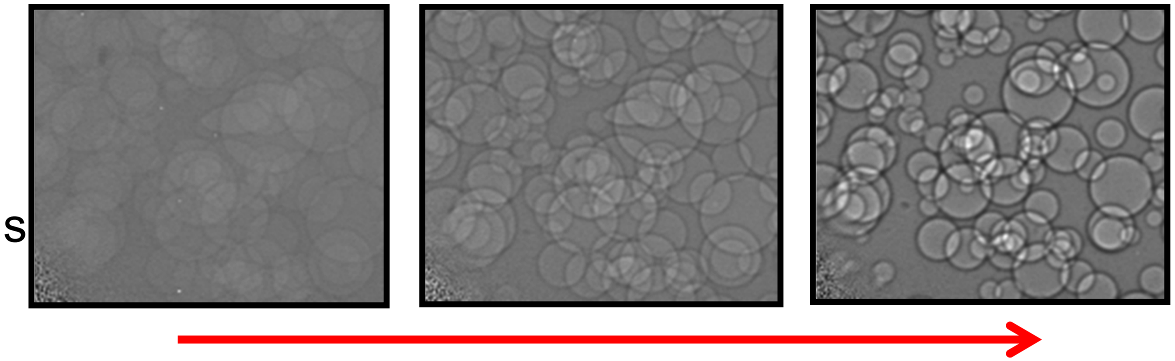
Phase Contrast

1. Propagation Phase Contrast

2. Diffraction Enhanced Imaging (DEI)



AS Medical Beamline
Wiggler Source
Phase contrast simulations
(Can recover phase shift)



Distance from sample

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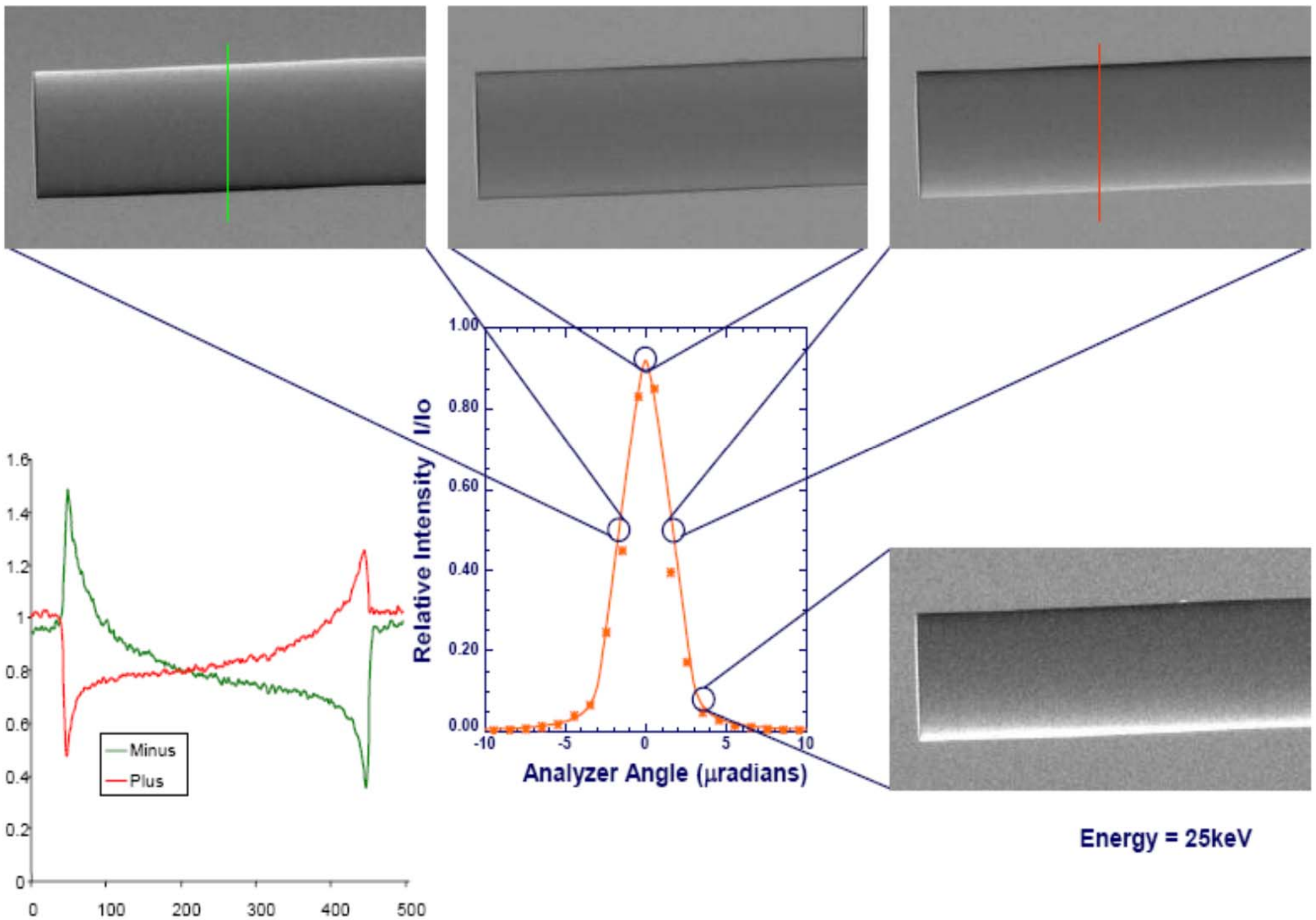
Diffraction Enhanced Imaging

- Edge/density gradient sensitive
- Move on rocking curve to change contrast



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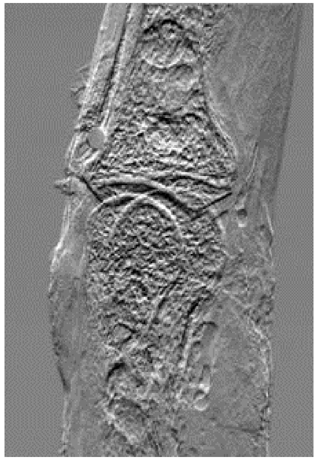
X-ray phase imaging: Biology and Materials

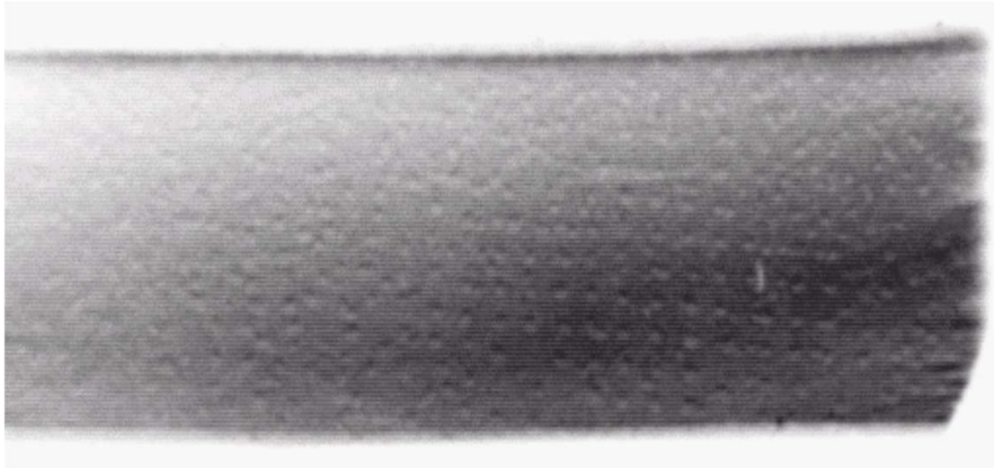
Conventional X-ray

Synchrotron



Synchrotron: propagation phase contrast

Rob Lewis, Monash University/
Energy = 20keV

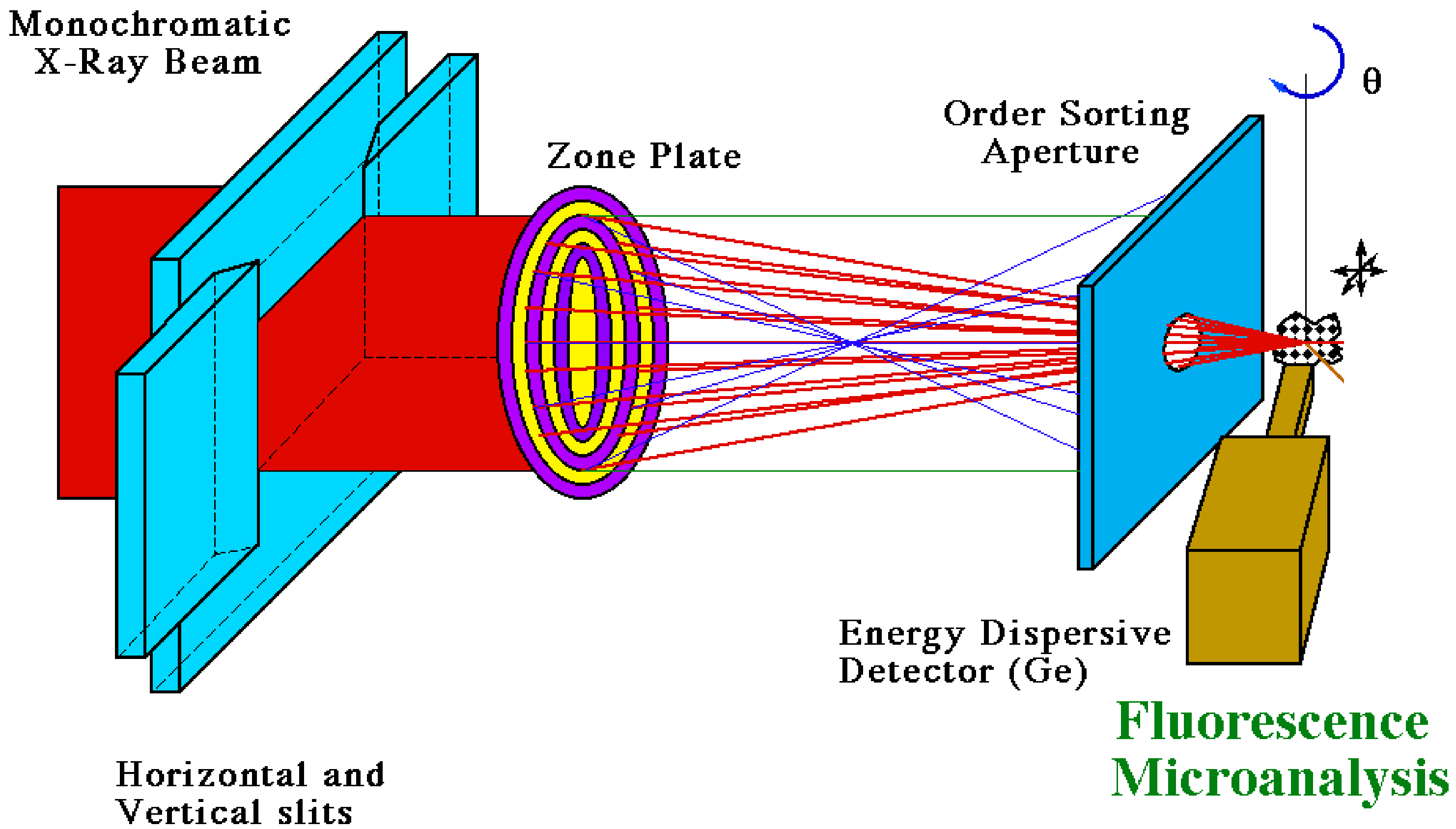


DEI "Dark field" phase image of bonded aluminium sheets @ 33 keV
Dots are bubbles in the epoxy bond.

Stevenson, Garrett, Hyodo et.al.

AOF Synchrotron Radiation

X-ray Fluorescence Microscopy

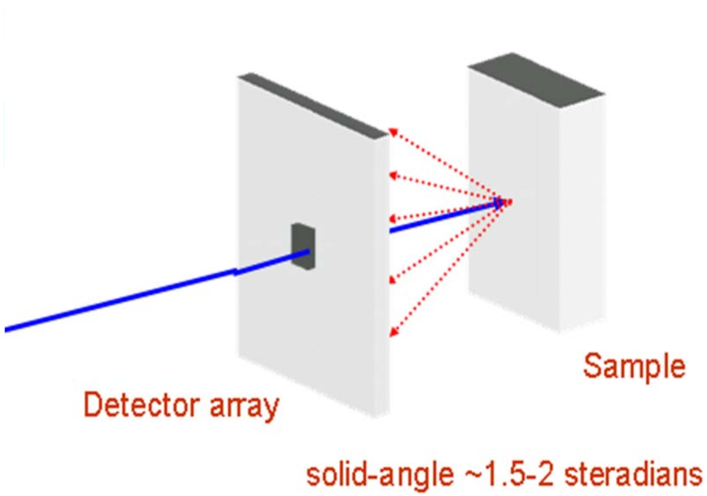


Conventional Fluorescence Microscope: APS 2ID-D

Advanced fluorescence detector at the AS

Annular geometry

- Maximises solid angle, sample @ 90°
- 384 Si pixel detector array (BNL, Siddons etal)
- No constraint on lateral sample size and scan range



+ Parallel data processing

- CSIRO: HYMOD2 pipelined, parallel processor (Ryan etal)
- Whole XRF spectrum acquired and analysed in real time

+ Fast Scanning Stage

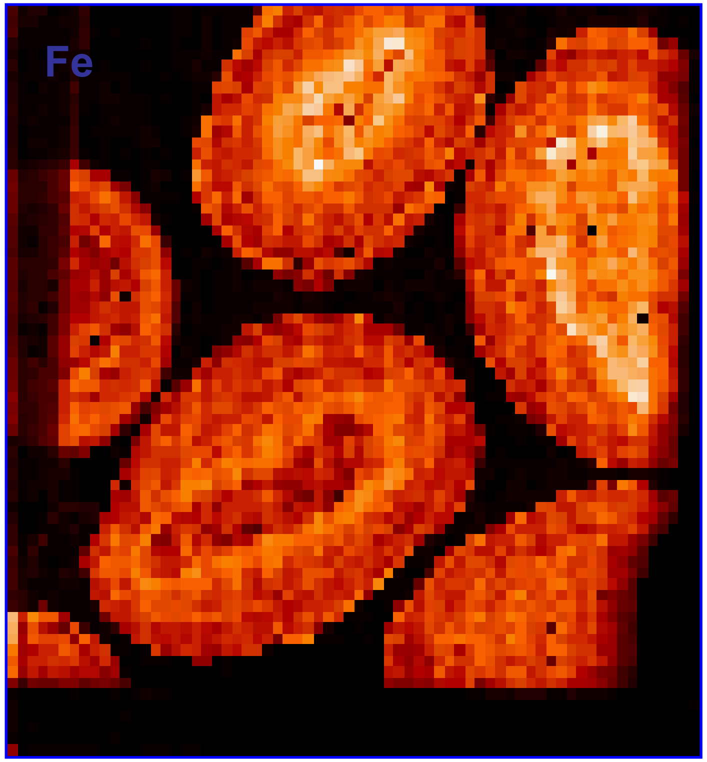
- Data acquired “on the fly”
- milli-second dwell times
  cf 1 second or greater normally

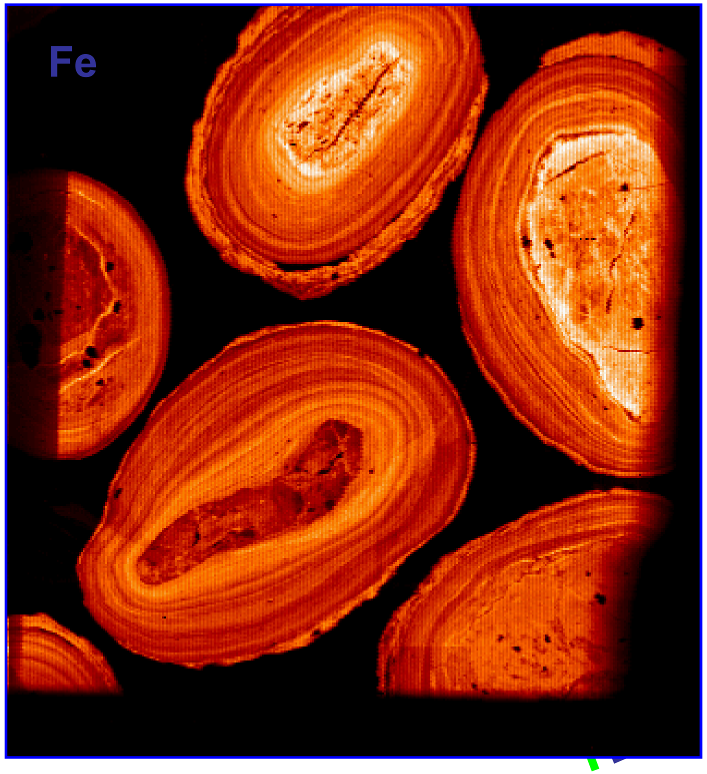
= New micro-XRF capability at the AS X-ray Fluorescence Microscope beamline

XFM image definition (number of pixels) limited by dwell time

Long dwell → Low Image Definition

- **~1 s / pixel** (for readout of 1-16 detector spectra)
- 1.3 hours → 67 x 67 pixels

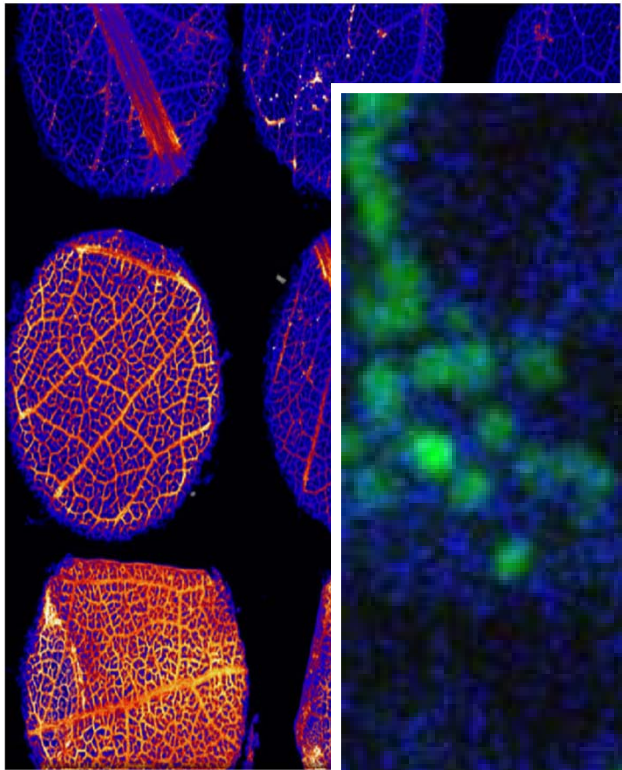


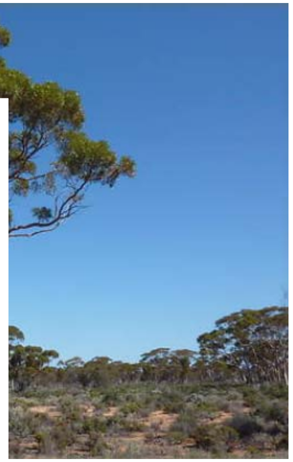


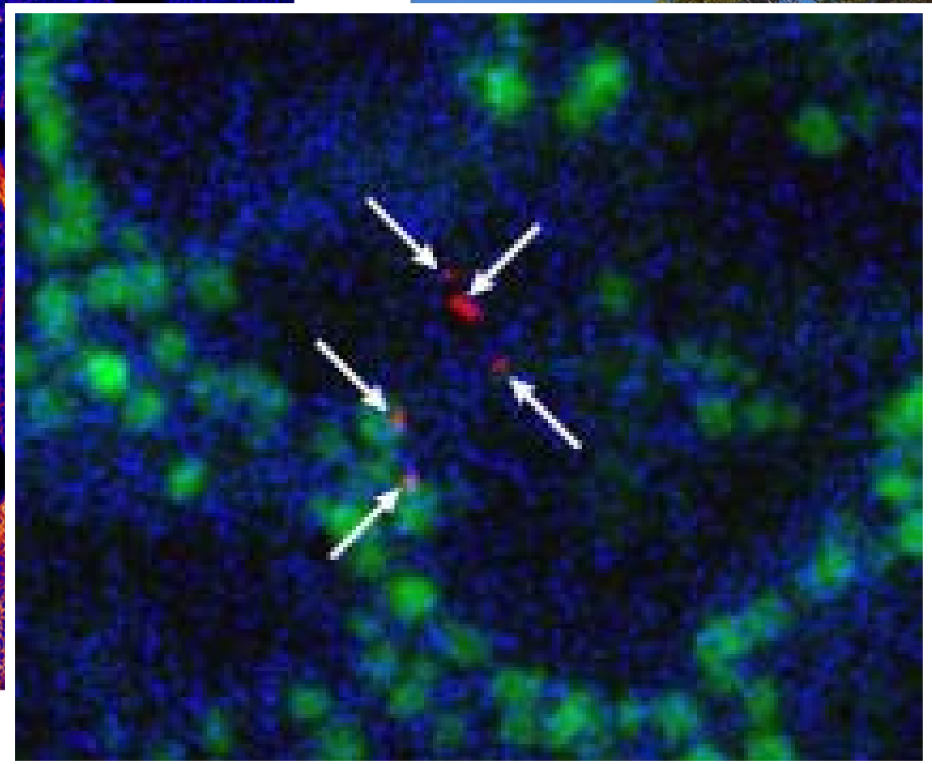
Short dwell → Good image definition

- 32 ms / pixel
- 1.3 hours → 375 x 375 pixels (30 fold increase)
- New Maia detector

Golden Gum Leaves





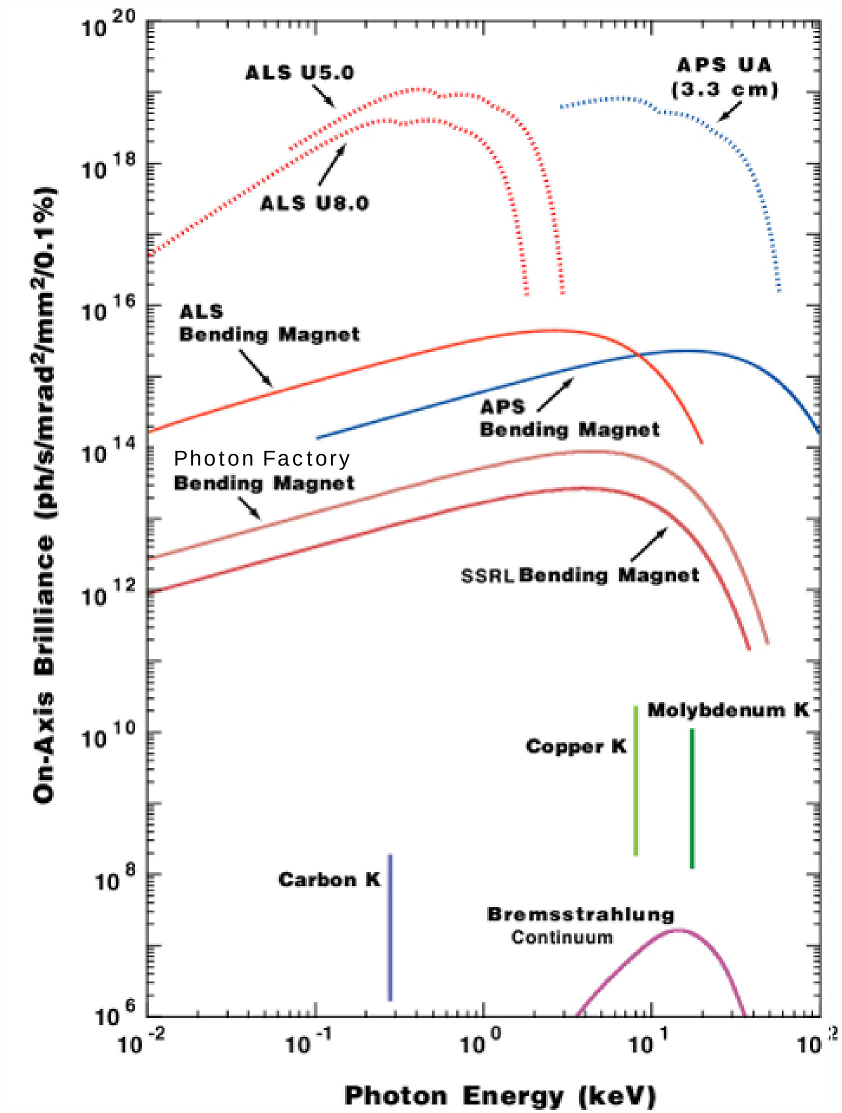


y gold 'nuggets'
. This has helped
how the gold moves
ntially leading to new
hat involve sampling
digging holes in the
ground

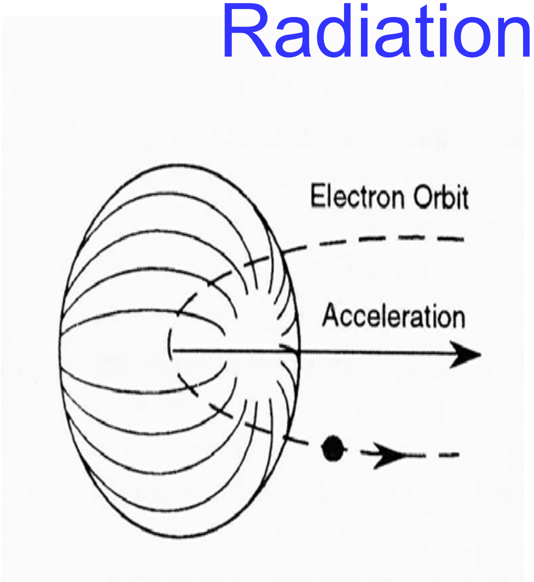
CSIRO Minerals Down Under Flagship (Mel Lintern)
The Australian Synchrotron

Characteristics of Synchrotron Radiation

- ✓ High brightness/flux
- ✓ Wide energy spectrum
- ✓ Plane polarised
- ✓ Pulsed



Generation of Synchrotron Radiation: Radiation from Accelerating Charge

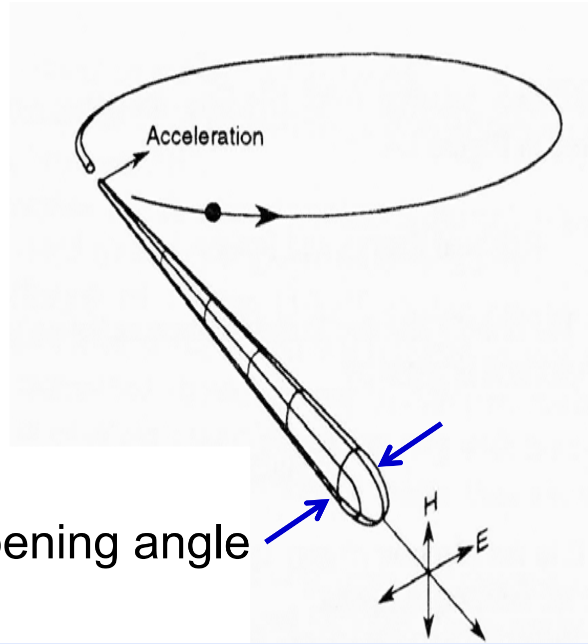


Low energy electrons OR electron frame:

Radiation in all directions

Example: Radio waves from a transmitter.

$$\frac{1}{\gamma} = \frac{m_0 c^2}{E} = \sqrt{1 - \left(\frac{v}{c}\right)^2}$$



$\pm\frac{1}{\gamma}$ Opening angle

High energy (relativistic) electrons – Laboratory frame:

Radiation pattern swept into a narrow cone in the forward direction = High brightness!

E = electron beam energy

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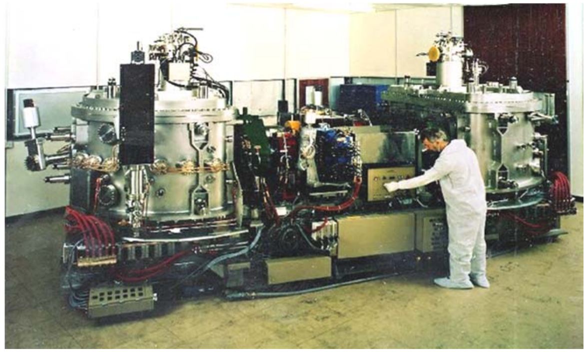


Singapore Light Source

700 MeV

$\gamma = 1400$

.7 mrad
.04º

Australian Synchrotron

3 GeV

$\gamma = 6000$

.2 mrad
.01º

Spring-8

8 GeV

$\gamma = 16000$

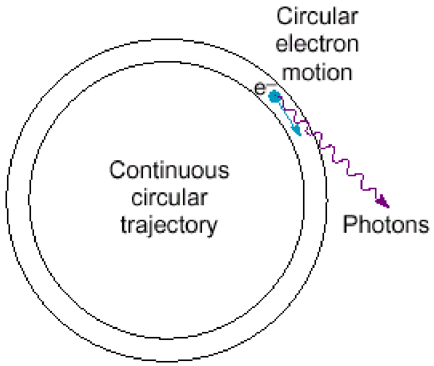
.06 mrad
.004º

AOF Synchrotron Radiation

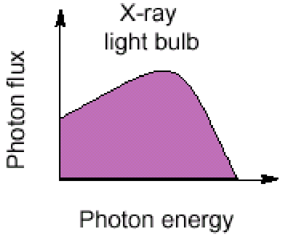
Third Generation Sources: Undulator Insertion Devices

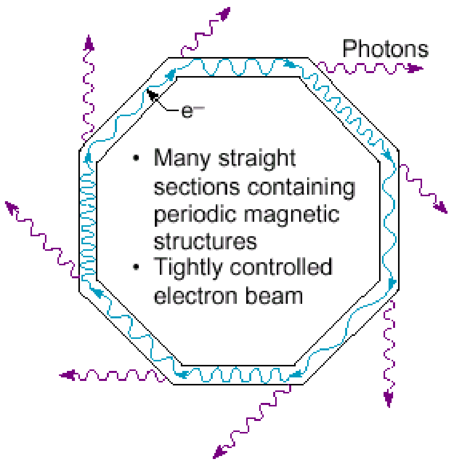
1st, 2nd Generation

3rd Generation: Insertion Devices

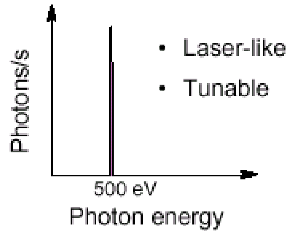


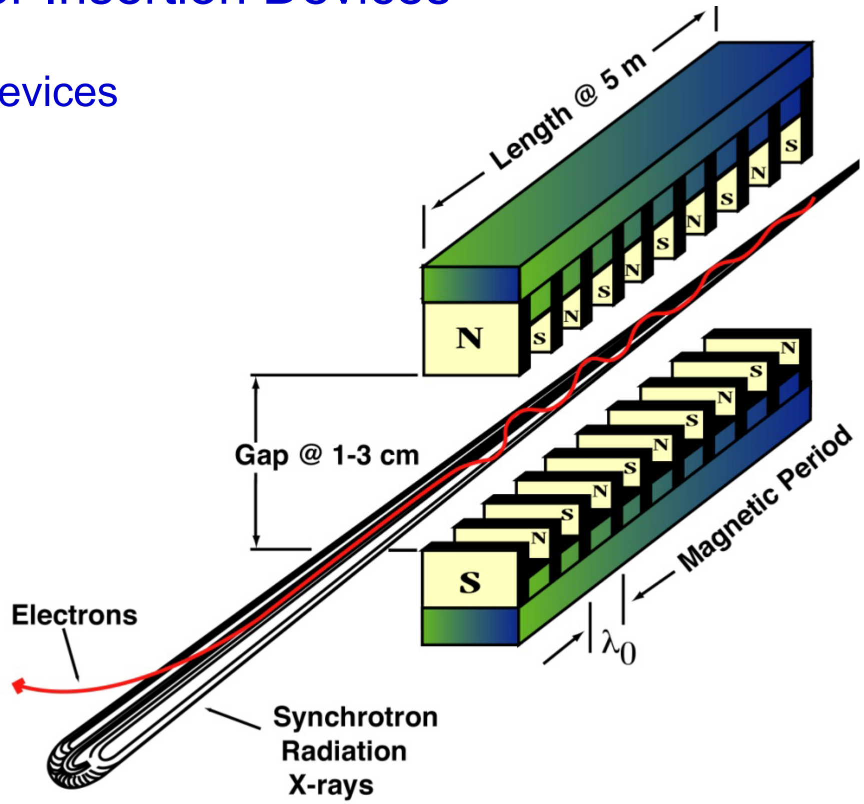
Bend Magnet Radiation

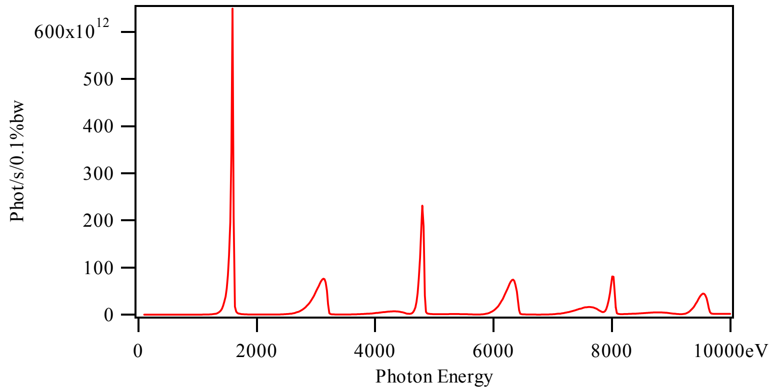




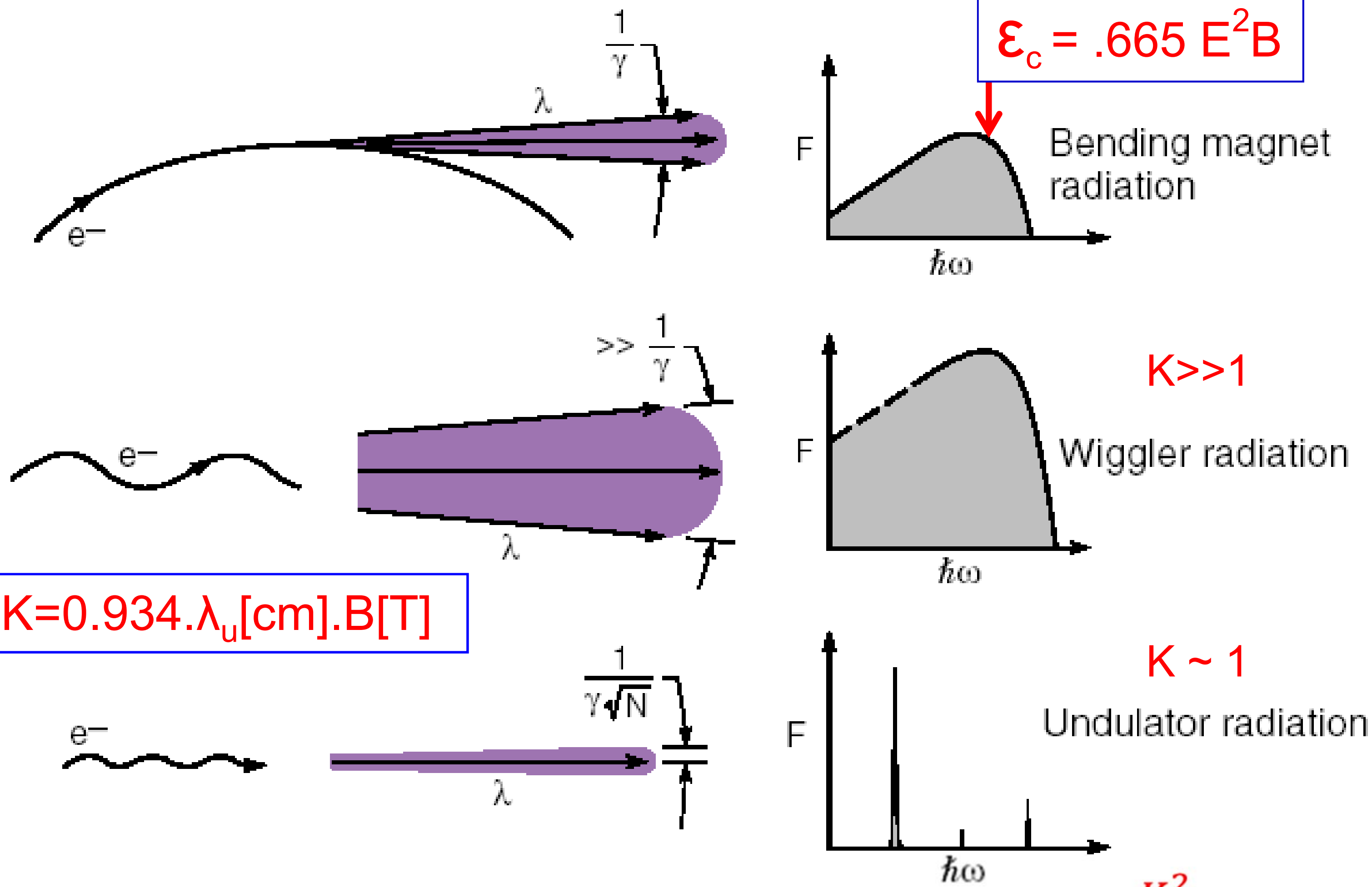
Undulator Radiation







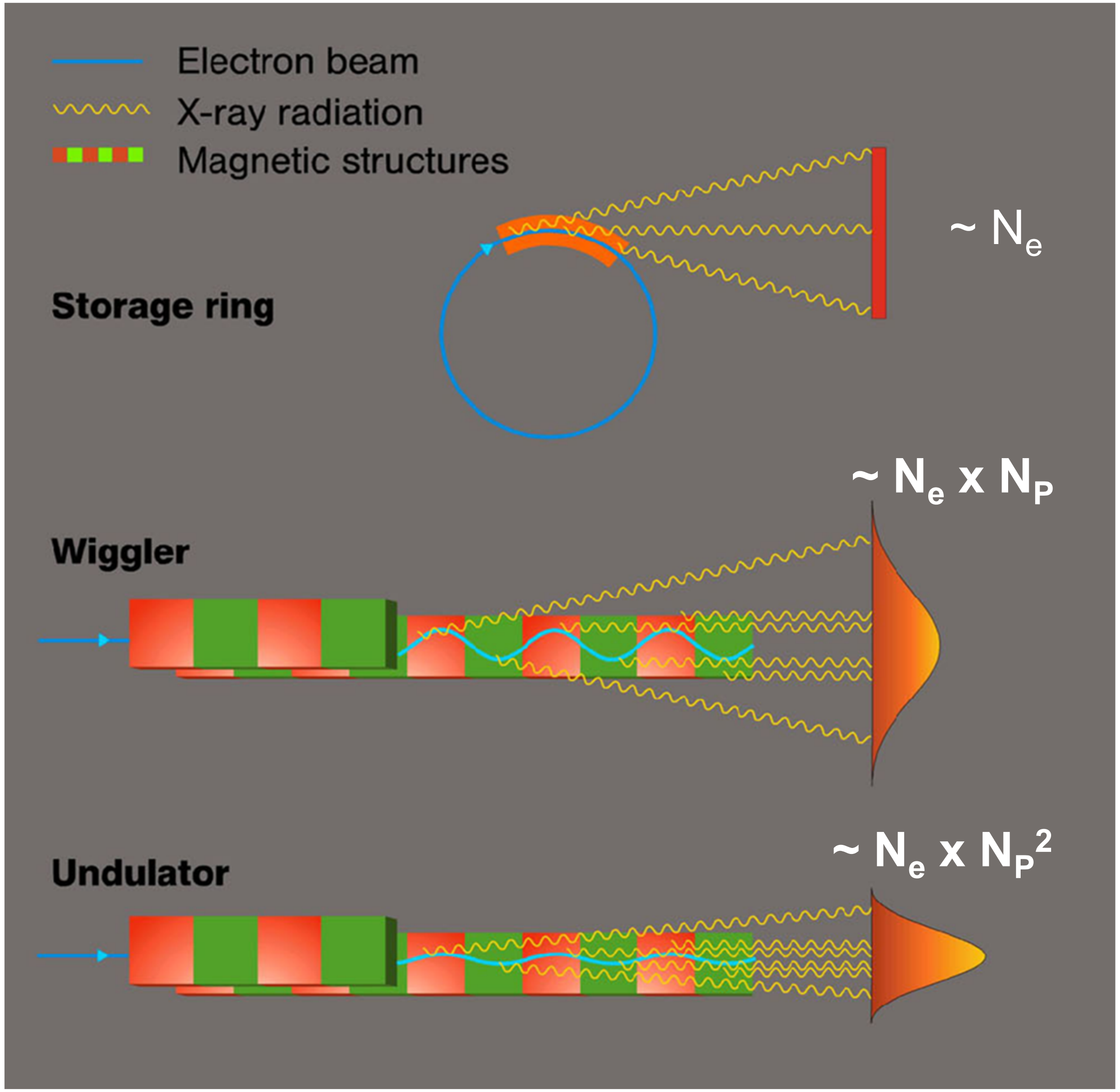
Three Forms of Synchrotron Radiation



$$\varepsilon_c = .665\ E^2 B$$

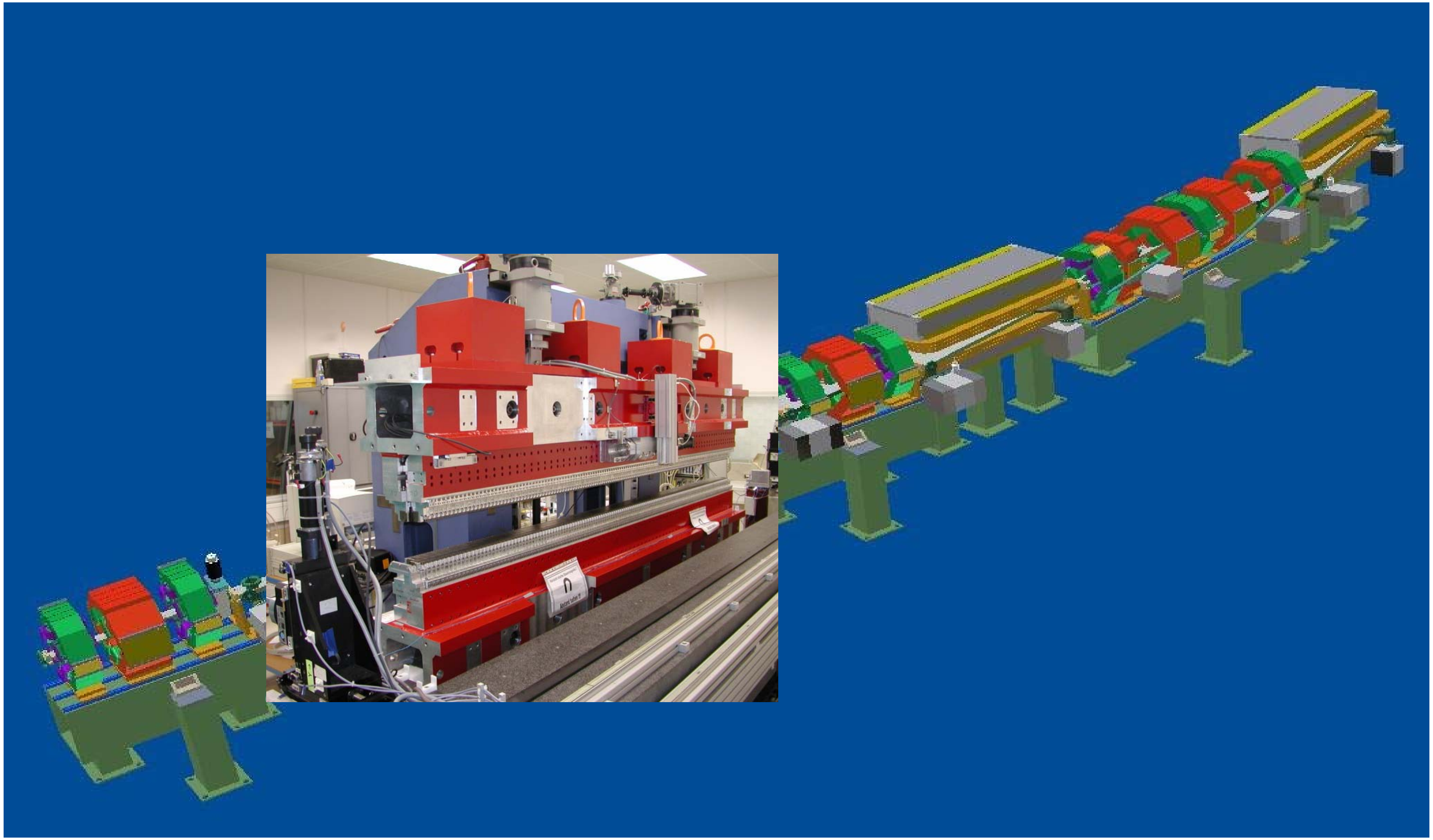
$$K = 0.934.\lambda_u[\mathrm{cm}].B[\mathrm{T}]$$

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



Electron beam
X-ray radiation
Magnetic structures
Storage ring
~ N_e
~ N_e x N_P
Wiggler
~ N_e x N_P^2
Undulator

Section of the Australian Synchrotron

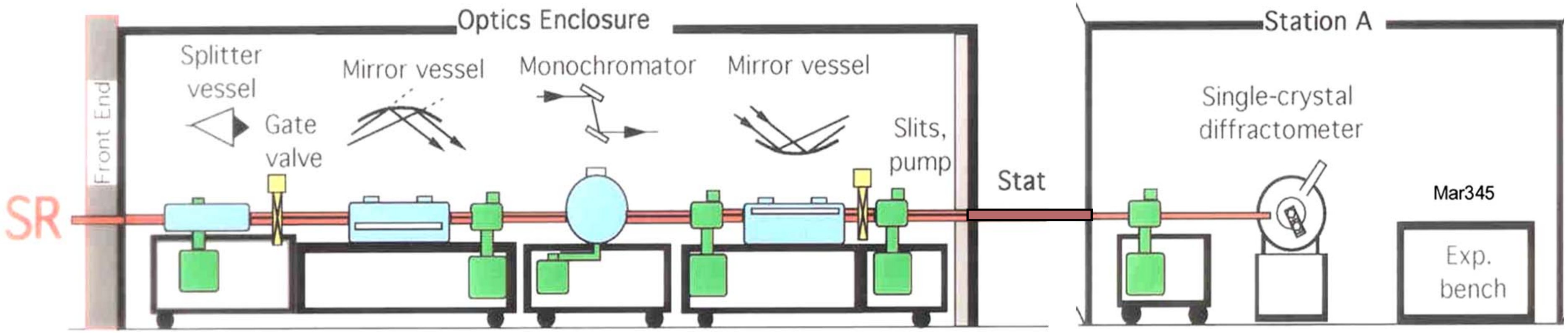


Beamline Design Goals

- Deliver the required X-ray beam to the experiment:
  - Energy and bandwidth
  - Spot size
  - Divergence/convergence
- Preserve source characteristics eg intensity, brightness, coherence
- Optimise signal / background
- Be very stable and reproducible, in position, intensity and energy
- Be safe to operate
- Be user friendly to operate
- Achieve all the above within a reasonable budget !

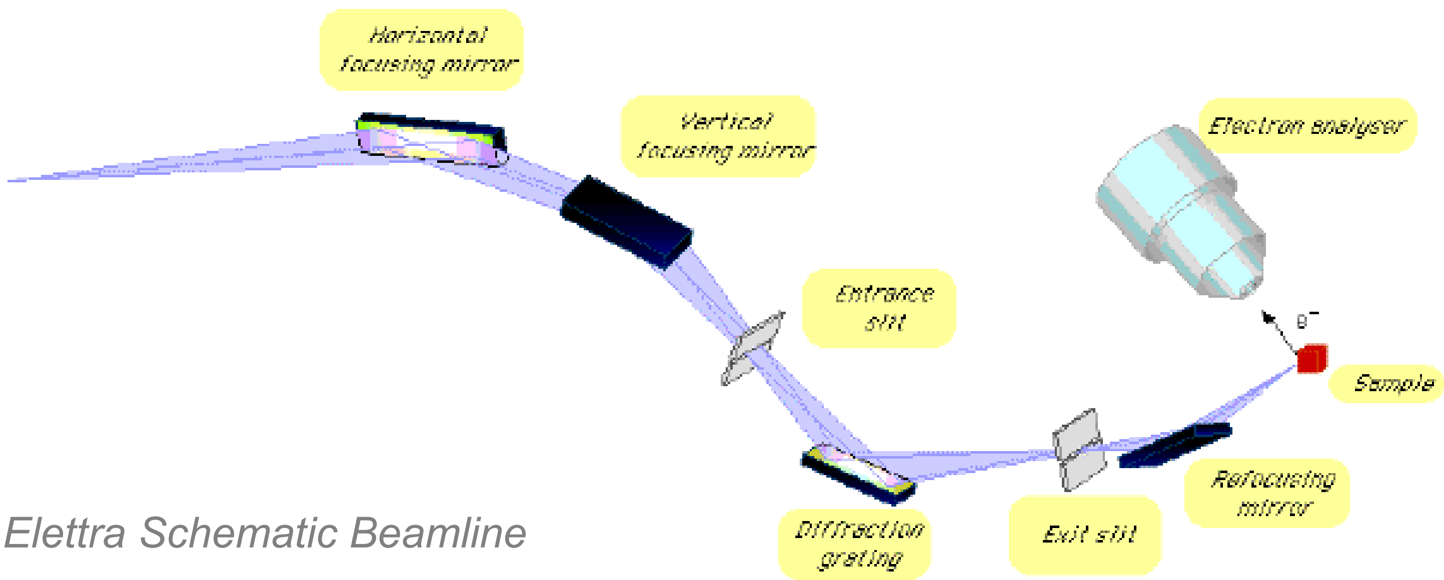
(Good Luck!)

Hard X-ray Beamline: Si crystal monochromator E > 4 keV



(Swiss-Norwegian beamline, ESRF)

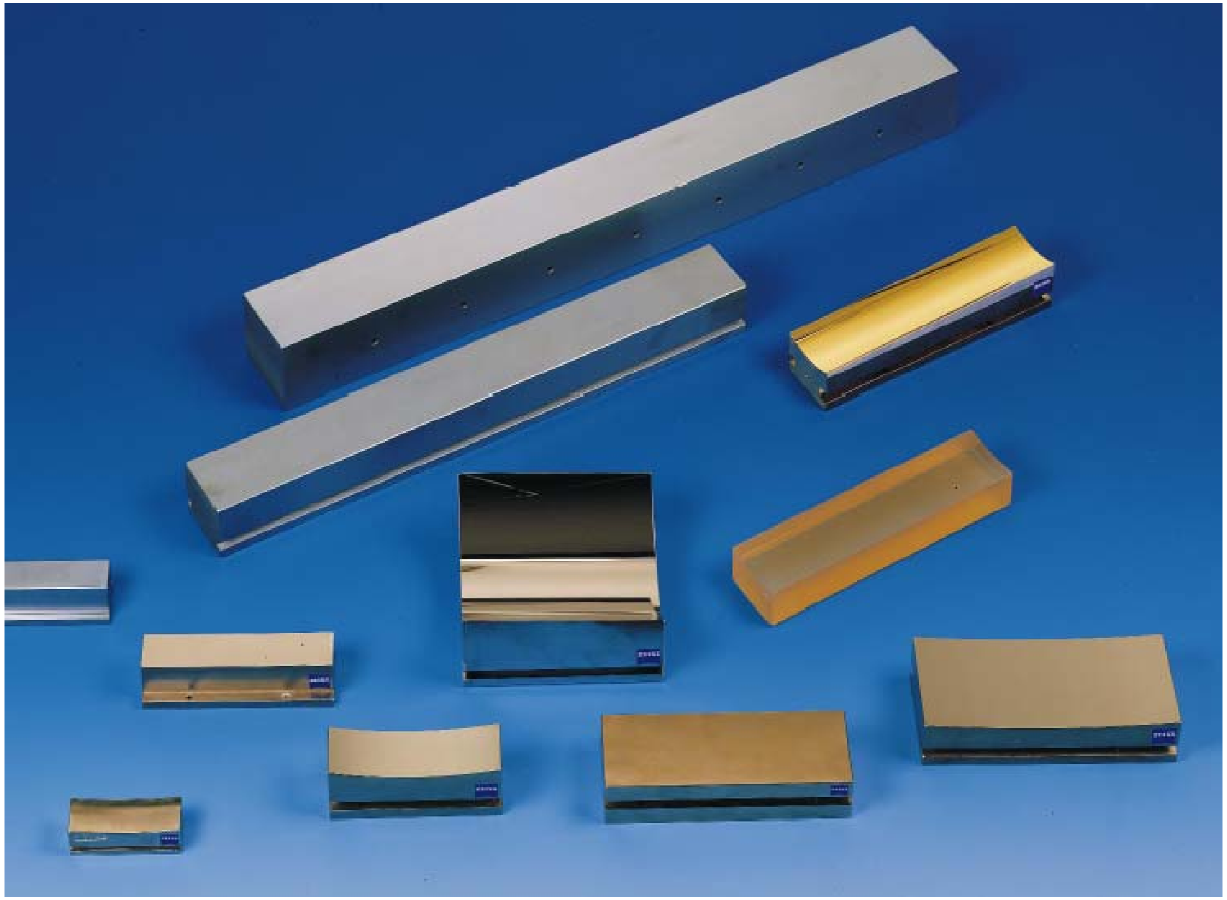
Soft X-ray Beamline: Grating monochromator E < 2 keV



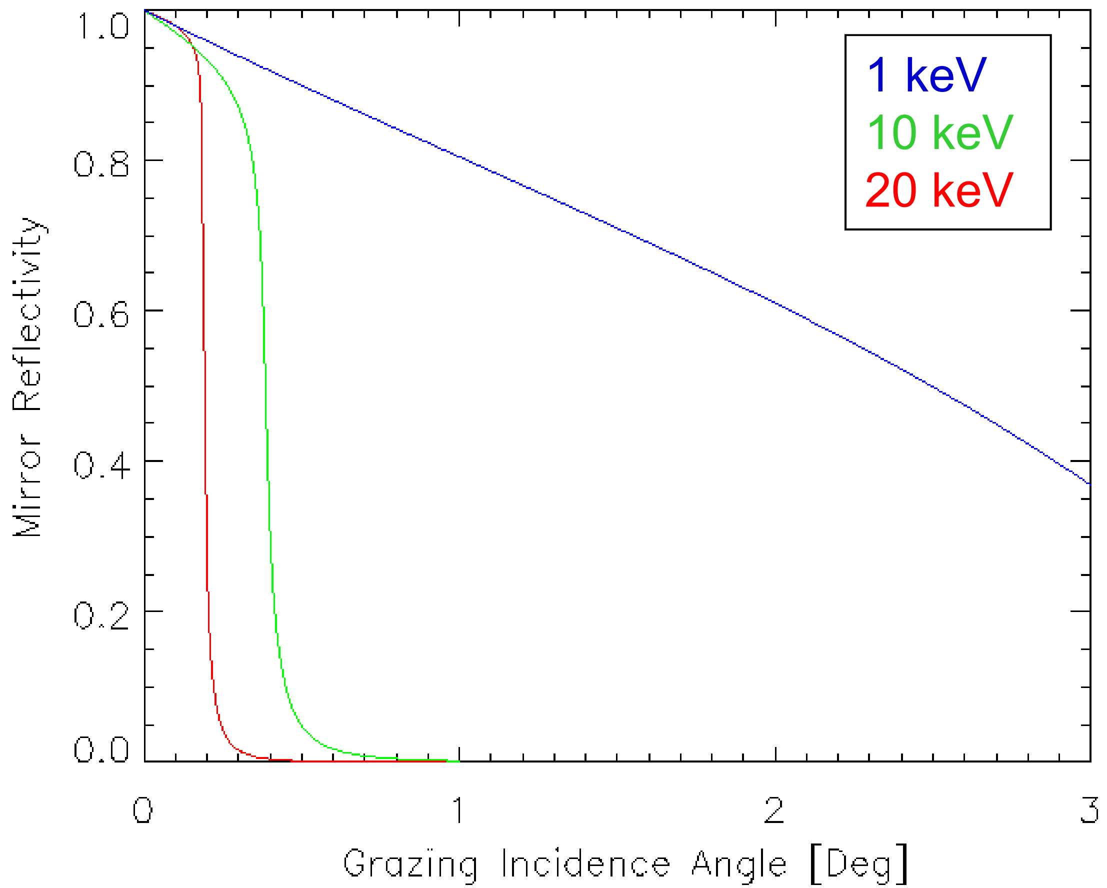
Elettra Schematic Beamline

Mirrors for Synchrotron Beamlines

- Deflection
- Focusing
- Harmonic Rejection
- Power Reduction



Critical Angle/Reflectivity with Energy: Rhodium Coated Mirror Example



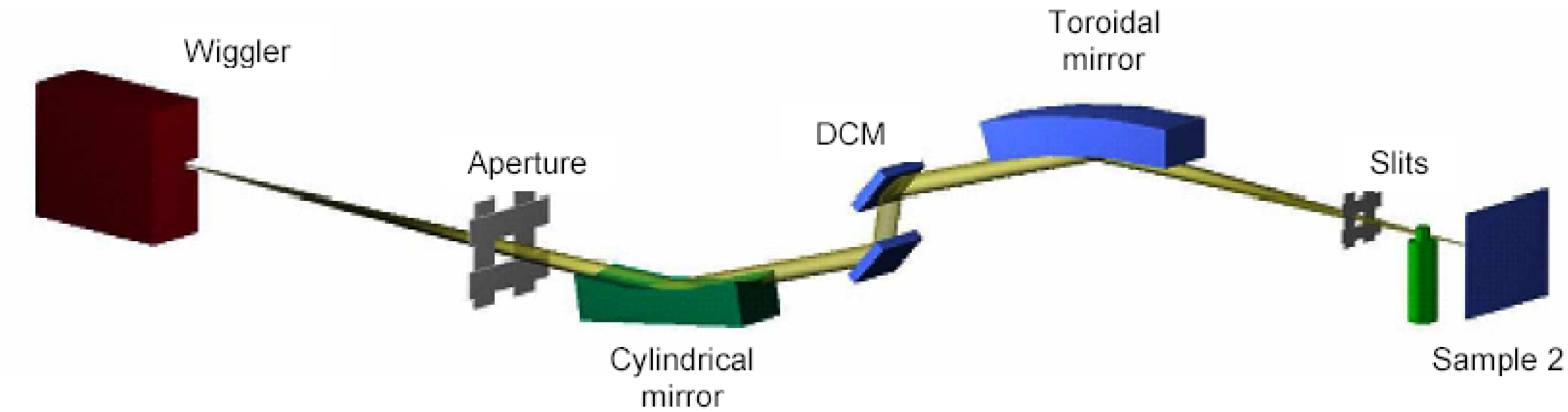
Harder X-rays need more grazing angles and longer mirrors:

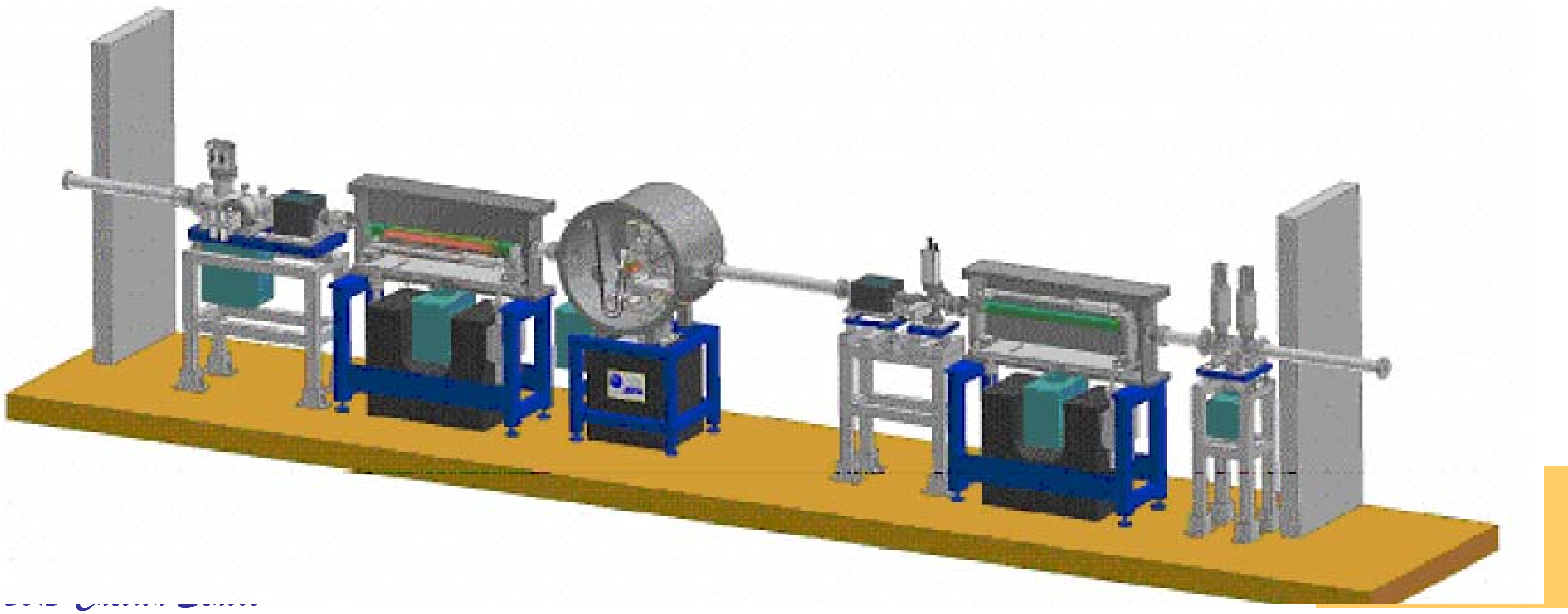
2 mm high beam needs:

≤ 10 cm mirror at 1 keV
≥ 80 cm mirror at 20 keV

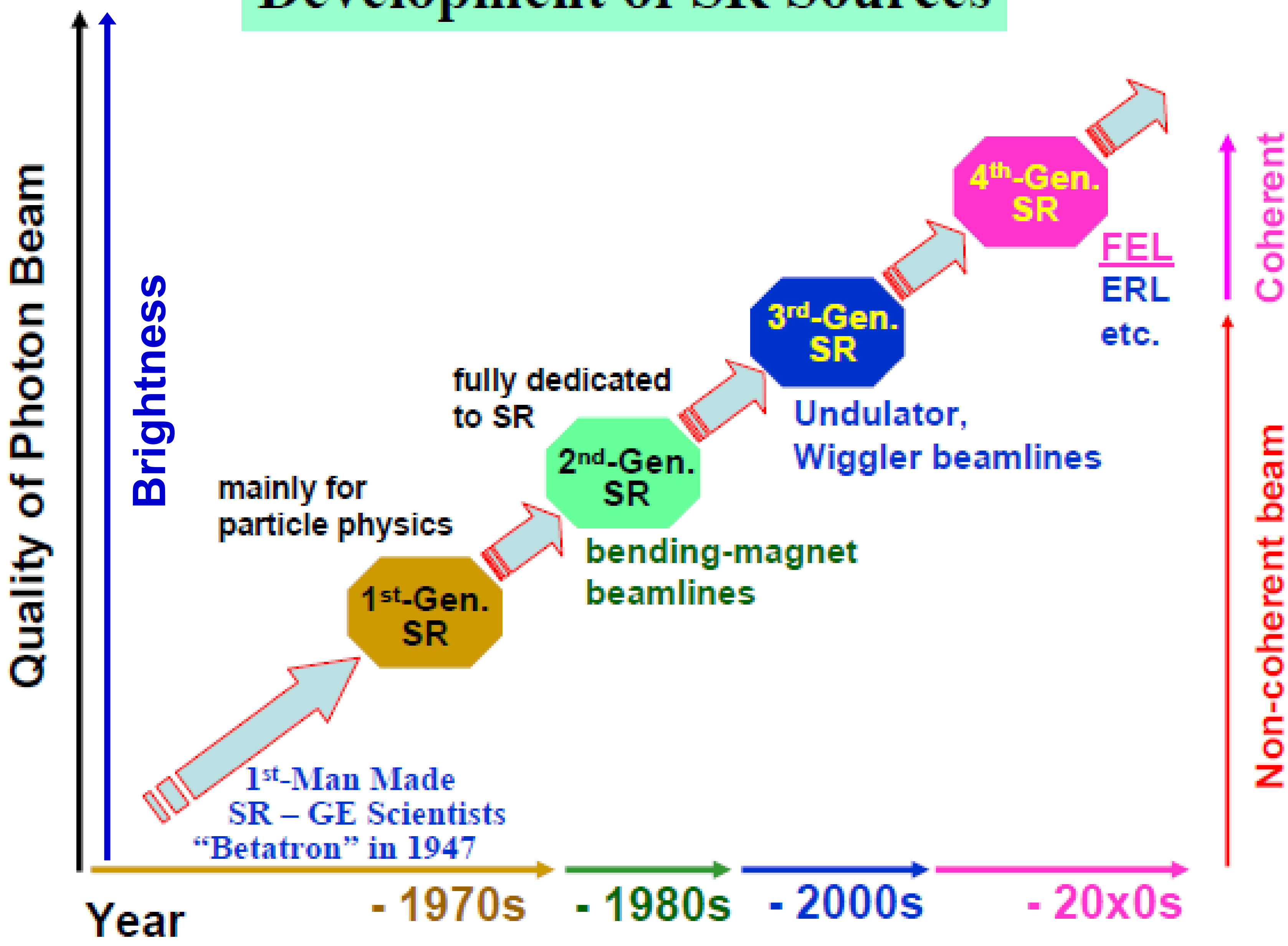
Mirrors are a low pass filter

An example beamline:
the AS Xray Absorption Spectroscopy Beamline





Development of SR Sources

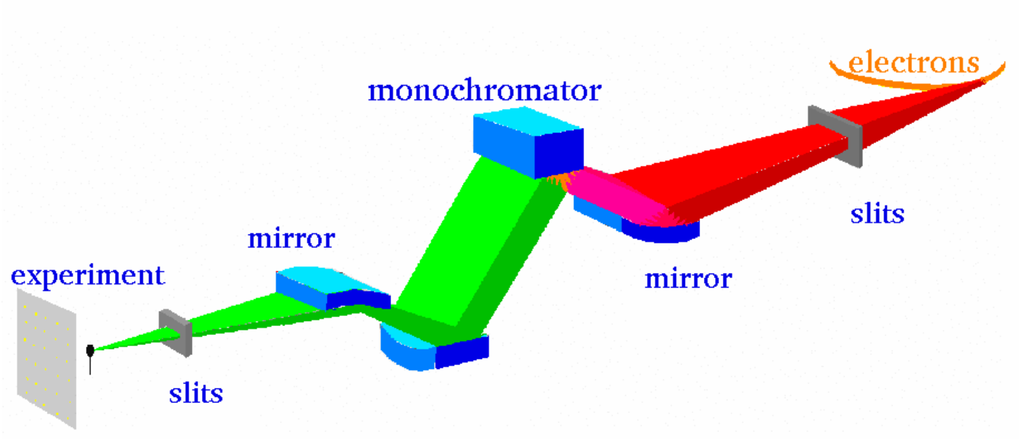


Courtesy M. Ree, PLS

SR Development is towards higher brightness – why?

Originally (2nd Generation sources) :-

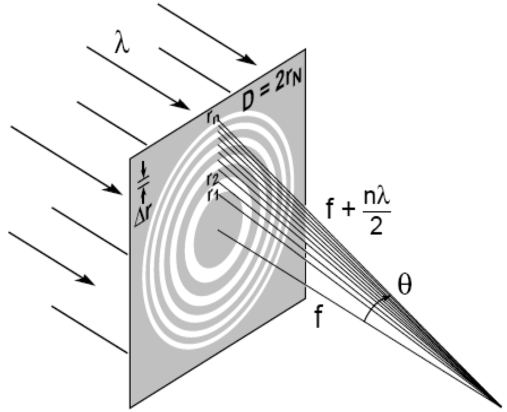
- High intensity through slits or on sample;
- High energy resolution:
  - Diffraction
  - Spectroscopy
- Focusing optics:
  - smaller samples
  - Fluorescence mapping

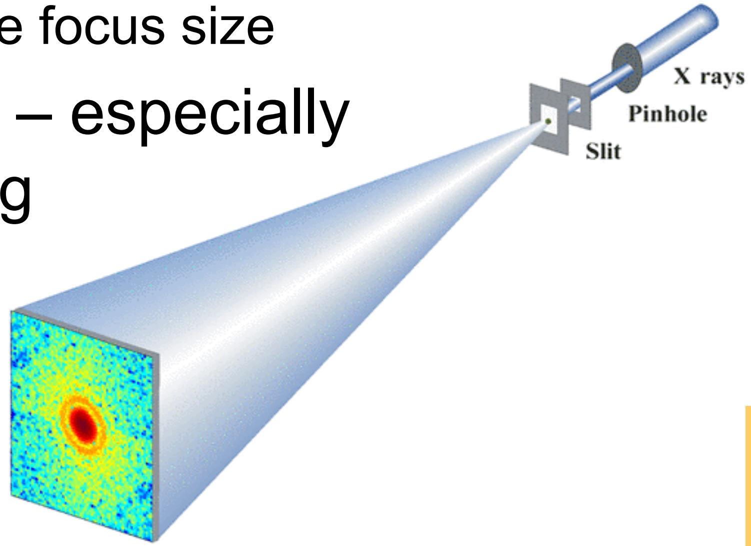


- Small vertical beam of 2nd and especially 3rd generation is good match to vertical dispersion & grazing optics.

SR Development is towards higher & higher brightness – part 2

- Higher spatial resolution:
  - Tiny samples (protein crystals…)
  - Nano-structure materials
  - Non-homogeneous samples…
- Focusing optics image the source
  - Smaller focus (smaller and smaller xtals) or
  - More working dist for same focus size
- New imaging techniques – especially coherence based imaging
- Many techniques brightness/coherence limited



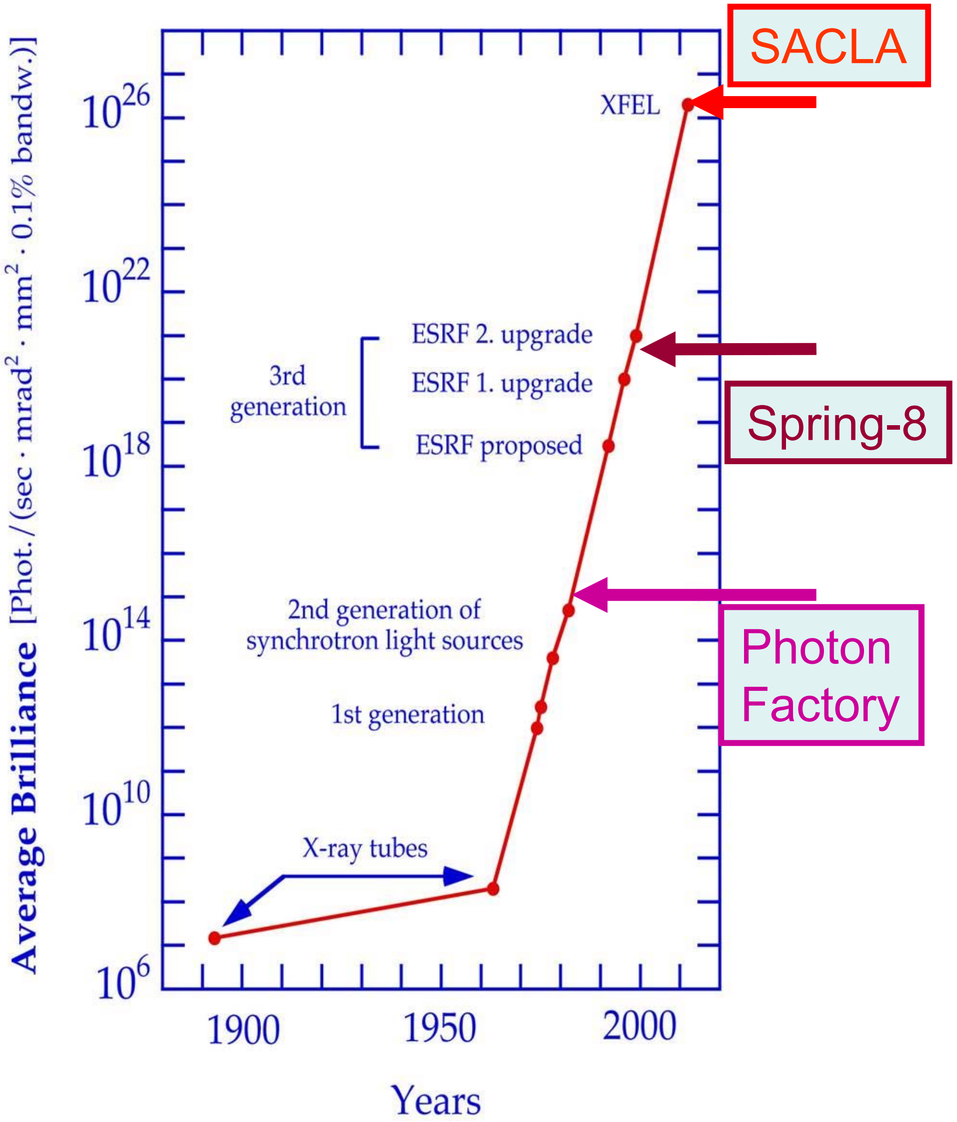


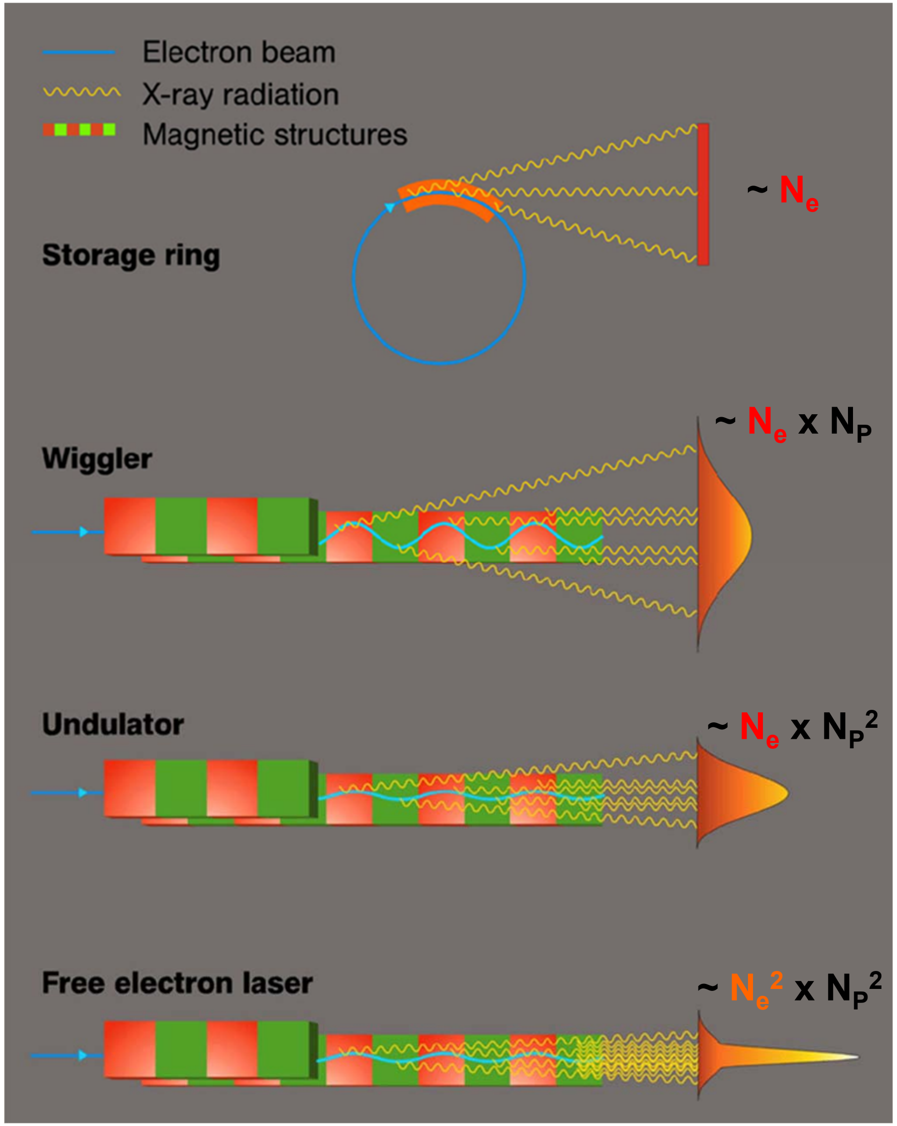
Synchrotron Radiation

New Sources:

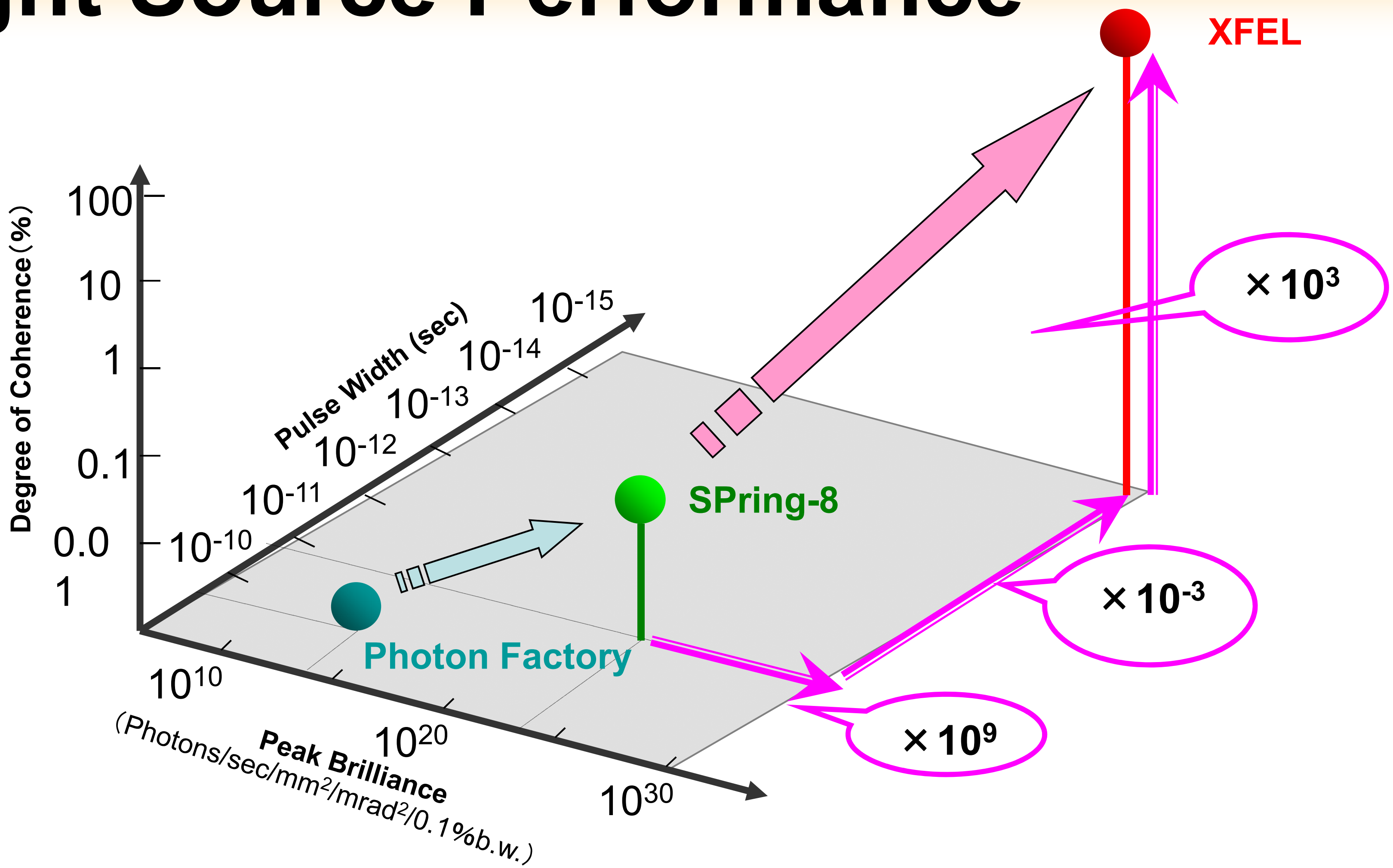
XFELs

Next Step - X-ray Lasers? Yes ➔ FELs





Light Source Performance

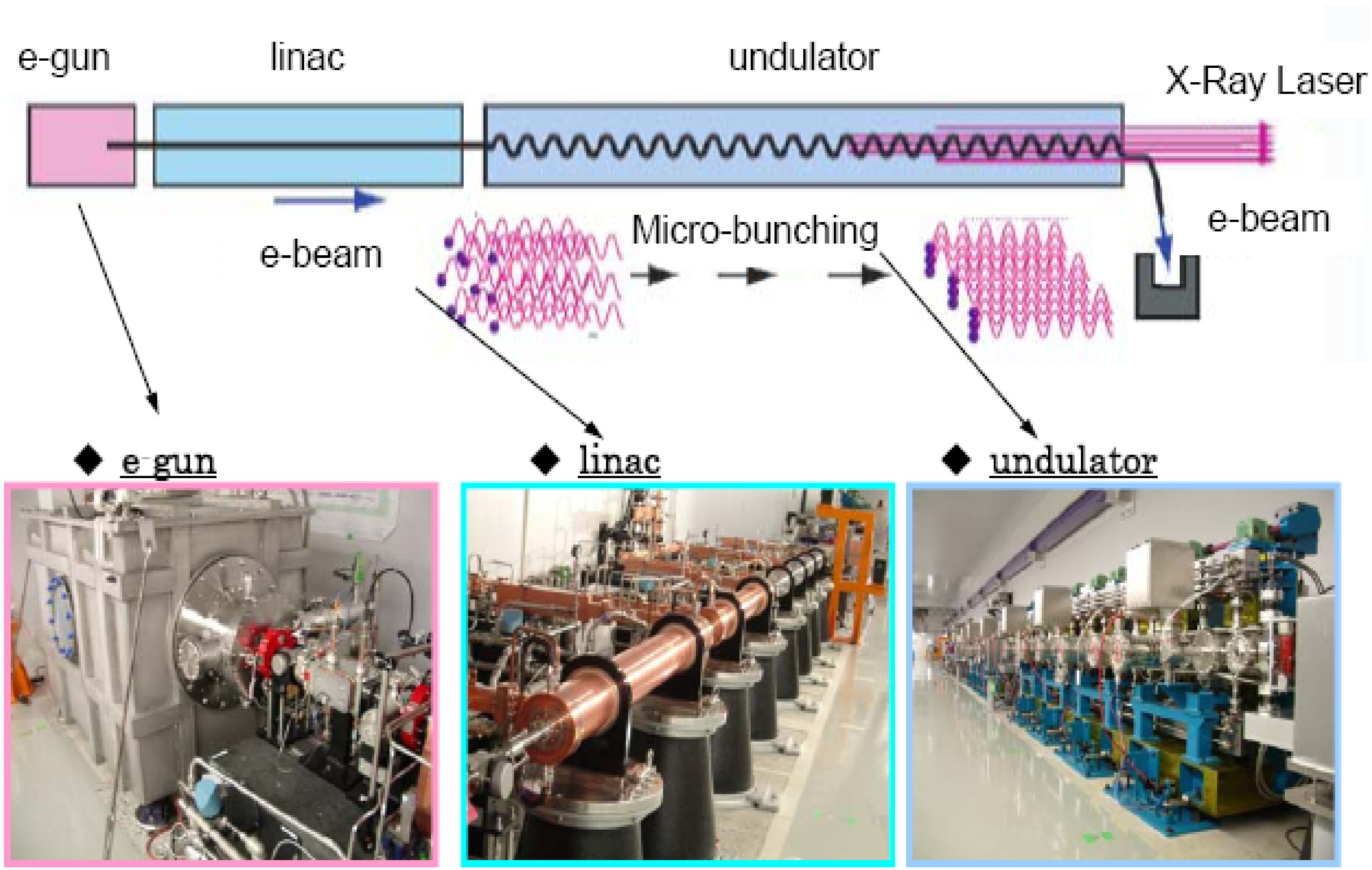


Remarkable Features of XFEL producing λ<0.1 nm X-Rays

◎ High Peak Brilliance
◎ Narrow Pulse Width
◎ High Degree of Coherence

RIKEN

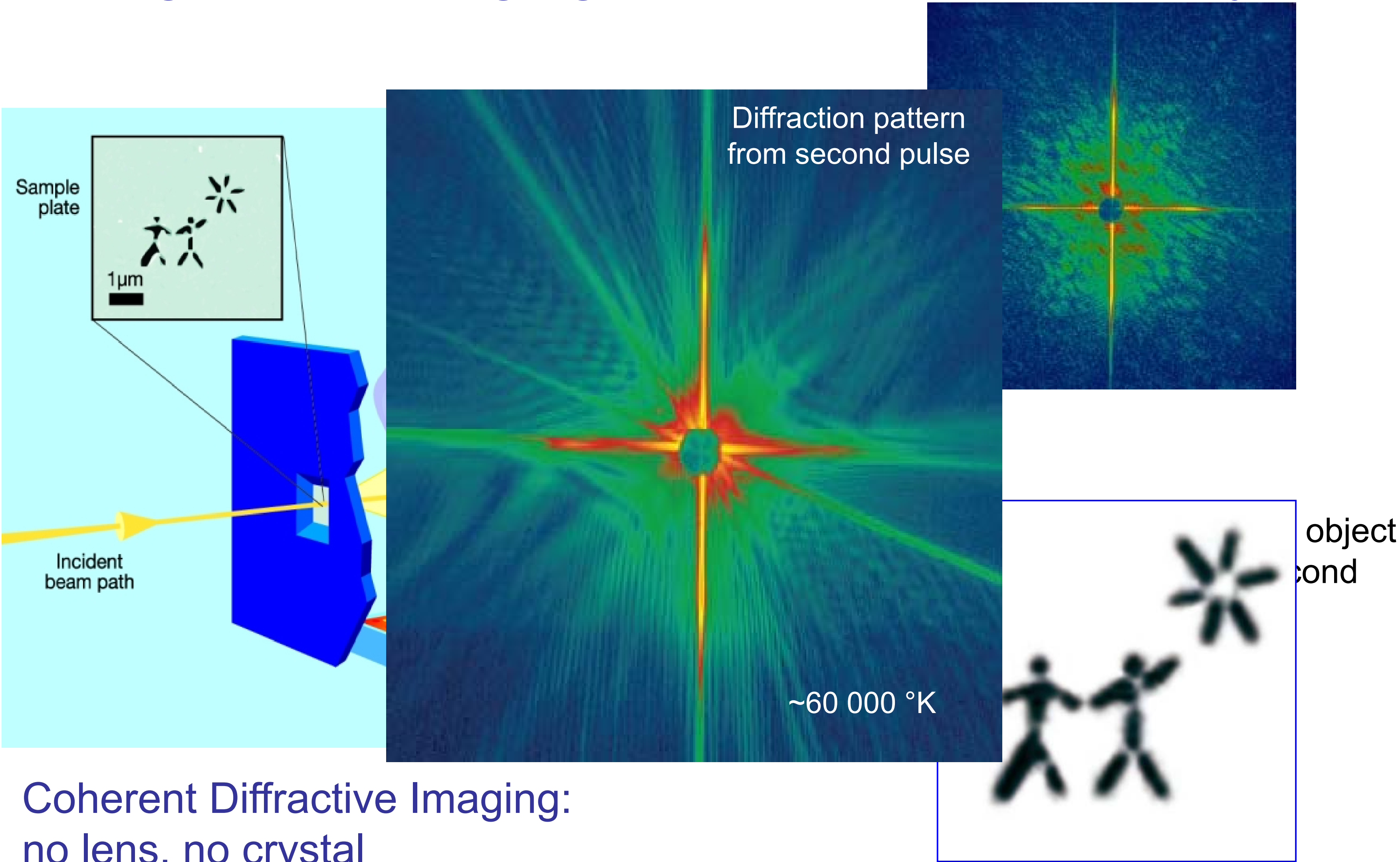
Linac-Based Free Electron Laser
Self-Amplified Spontaneous Emission (SASE)



SACLA 1st beamline: 90m Undulator

2012 Cheiron School Tour

“Diffract and Destroy”:
Single Shot Imaging at the FLASH Soft X-ray FEL



Coherent Diffractive Imaging:
no lens, no crystal

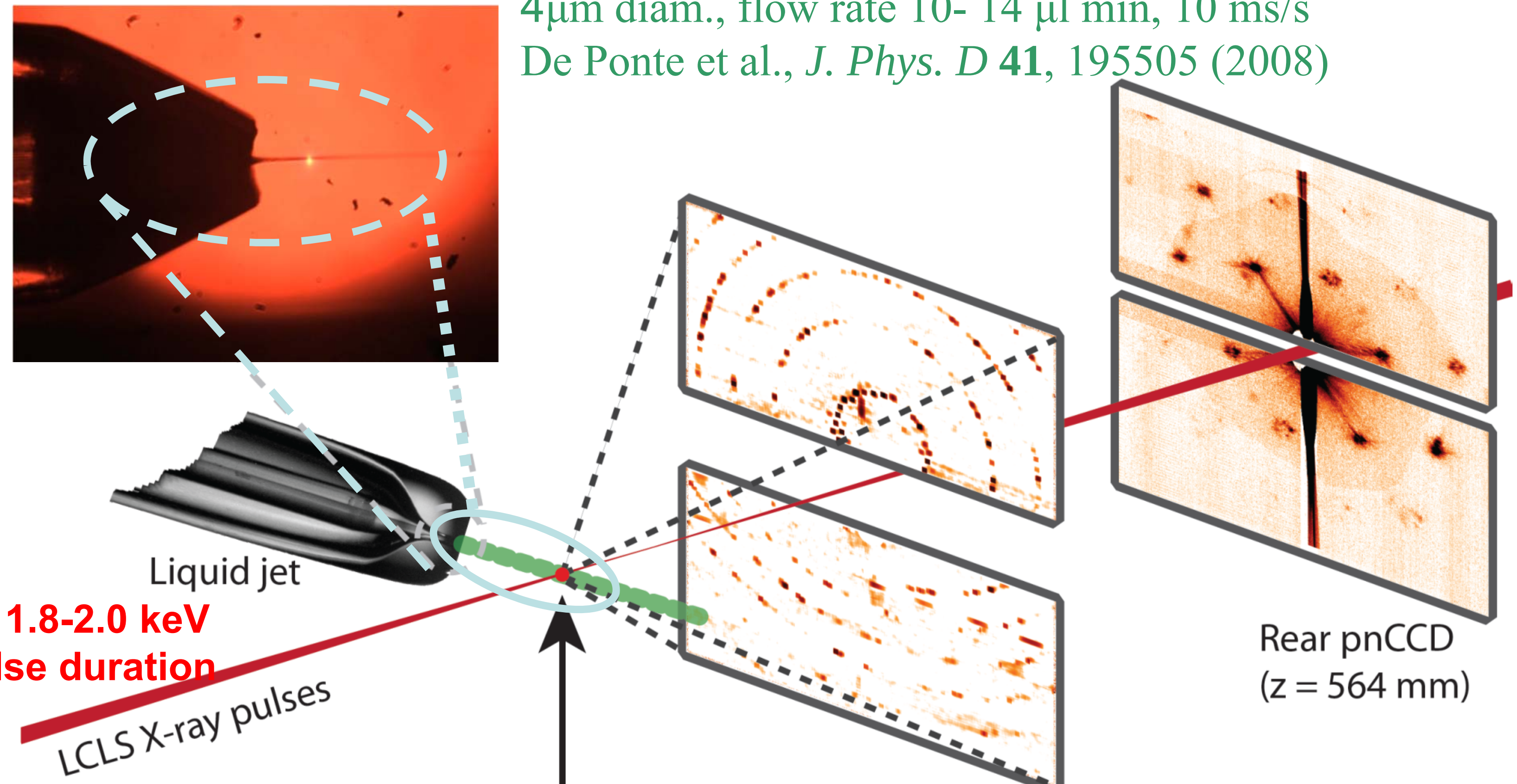
H. Chapman et al., *Nature Physics* 2, 839 (2006)

Reconstructed image: no signs of damage caused by the pulse.

First serial femtosecond crystallography experiments at LCLS/AMO/CAMP - 7 A resolution

Chapman et al
Nature 470: 73 (2011)

Gas focussed liquid jet:
4μm diam., flow rate 10- 14 μl min, 10 ms/s
De Ponte et al., *J. Phys. D* **41**, 195505 (2008)



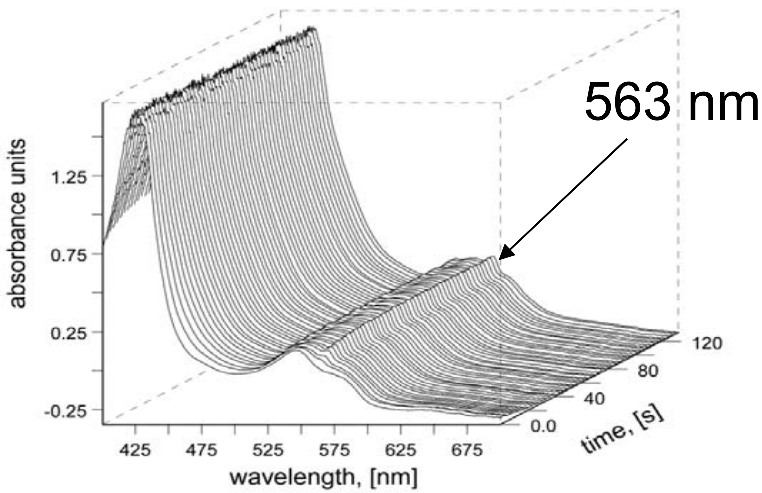
λ =6.2-6.9 Å, 1.8-2.0 keV
10-300 fs pulse duration
30 (60) Hz

10^{12} photons/pulse
900 J/cm^2
Dose/pulse: 300-700 MGy

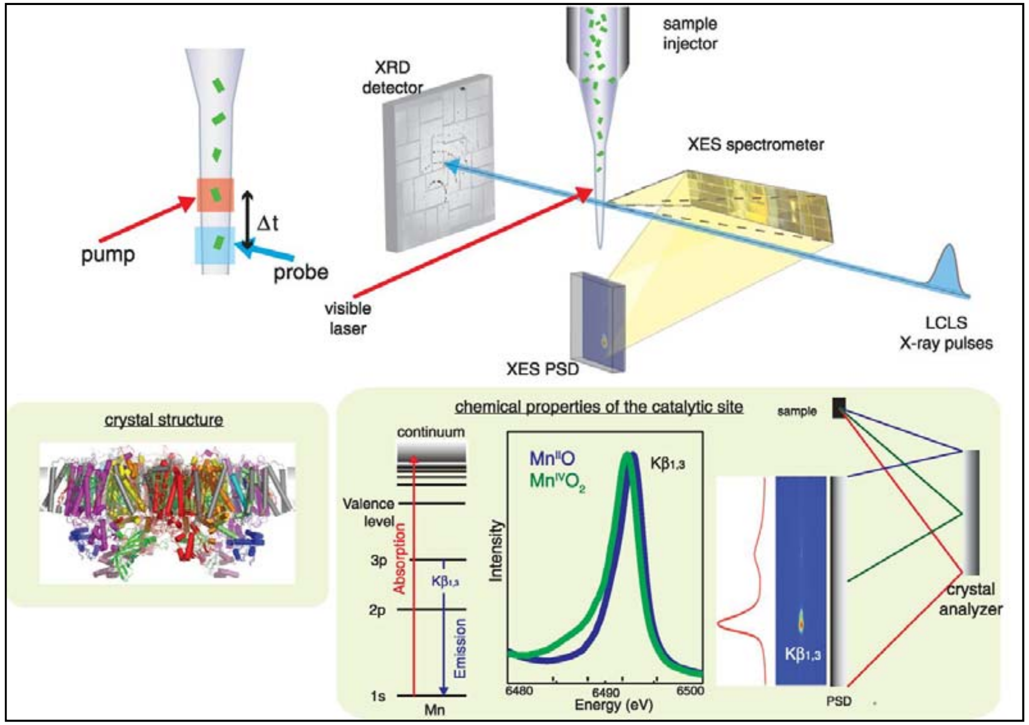
~ 7 μm diam.
~ 4 μm diam.

1800 (3600) patterns/min
5 TB in one night

Radiation damage-free data collection



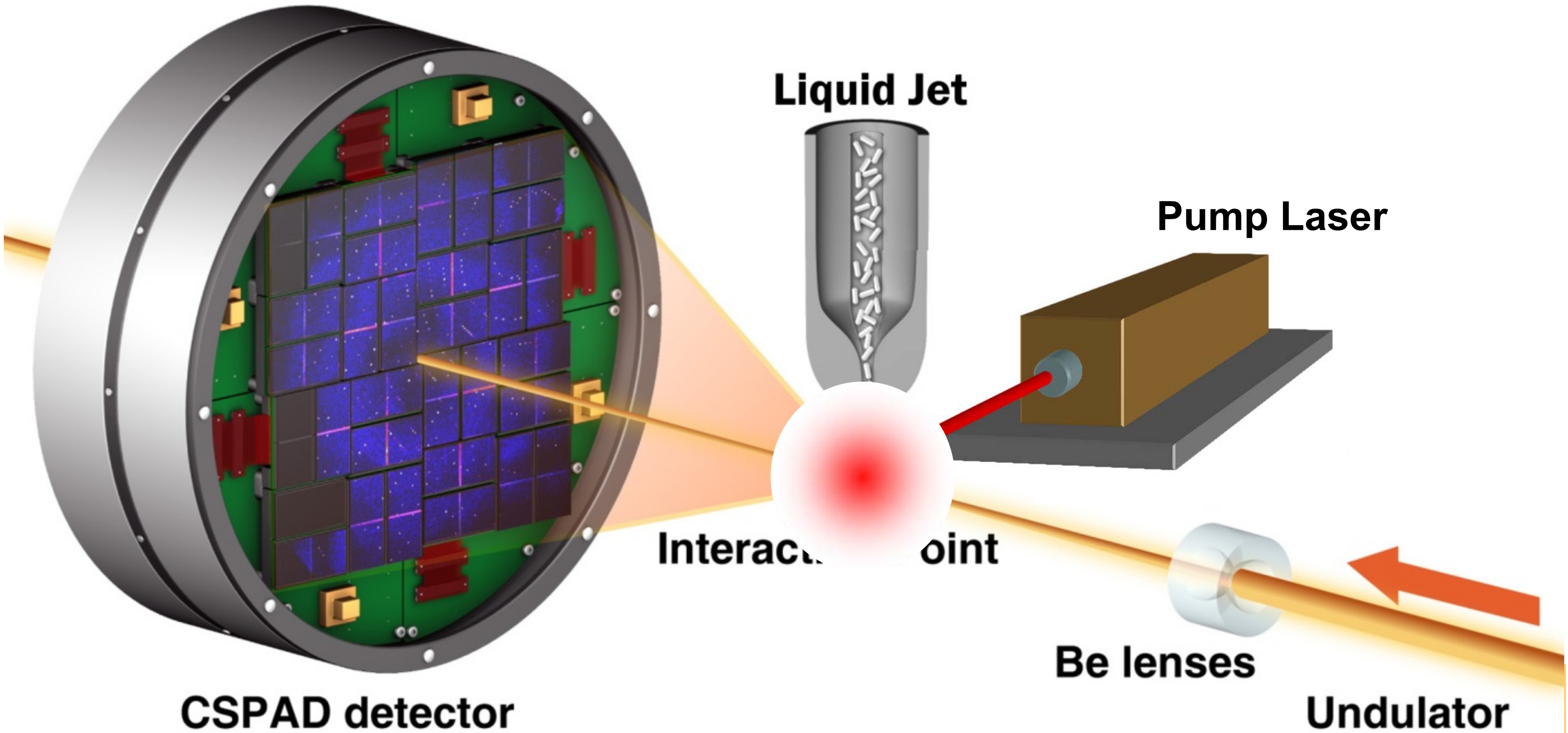
Beitlich *et al.*, JSR (2007)
→ on-line spectroscopy shows radiation damage in chloroperoxidase crystal at a synchrotron in seconds at a low dose rate (28 kGy/s)



Kern *et al.*, Science (2013)
→No radiation damage to metal cluster in Photosystem II during diffraction at LCLS

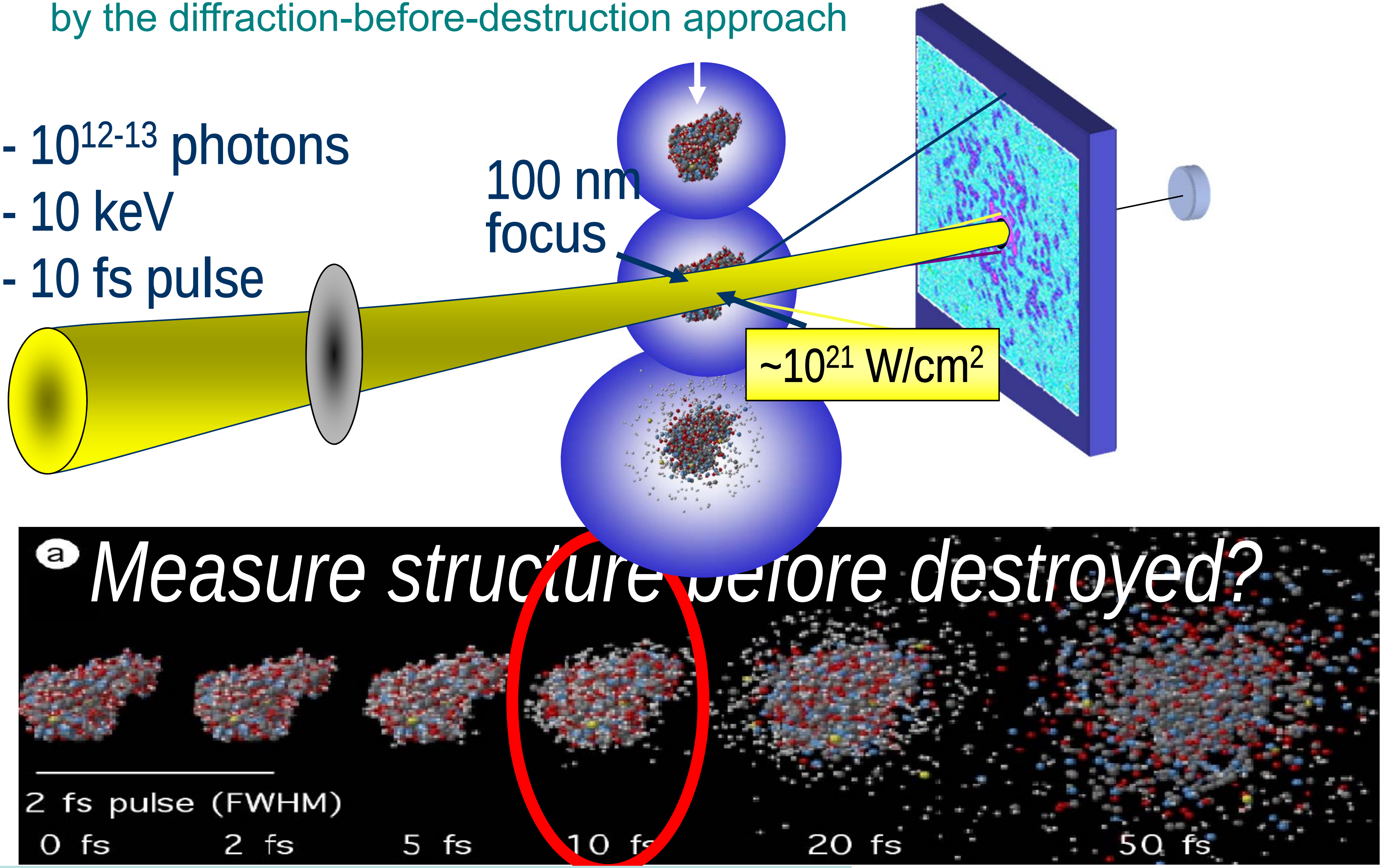
Time-resolved pump-probe experiments on photosensitive proteins

Best time-resolved MX (Laue, synchrotron) done by F. Schotte/Ph. Anfinrud has 100 ps time resolution. With FELs this can be reduced to ps/hundreds of fs.



Coherent diffractive imaging of single particles

by the diffraction-before-destruction approach



Calculations. in vacuum Neutze et al., Nature 2000

FELs: Many research areas

Femtosecond experiments

- pump-probe experiments on atoms and molecules (femto-chemistry)
- sum-frequency generation
- serial crystallography

Interaction of ultra-intense XUV pulses with matter

- multiphoton excitation of atoms, molecules, clusters…
- creation and characterizaton of dense plasmas
- imaging of nano-objects and biological samples

Investigation of extremely dilute samples

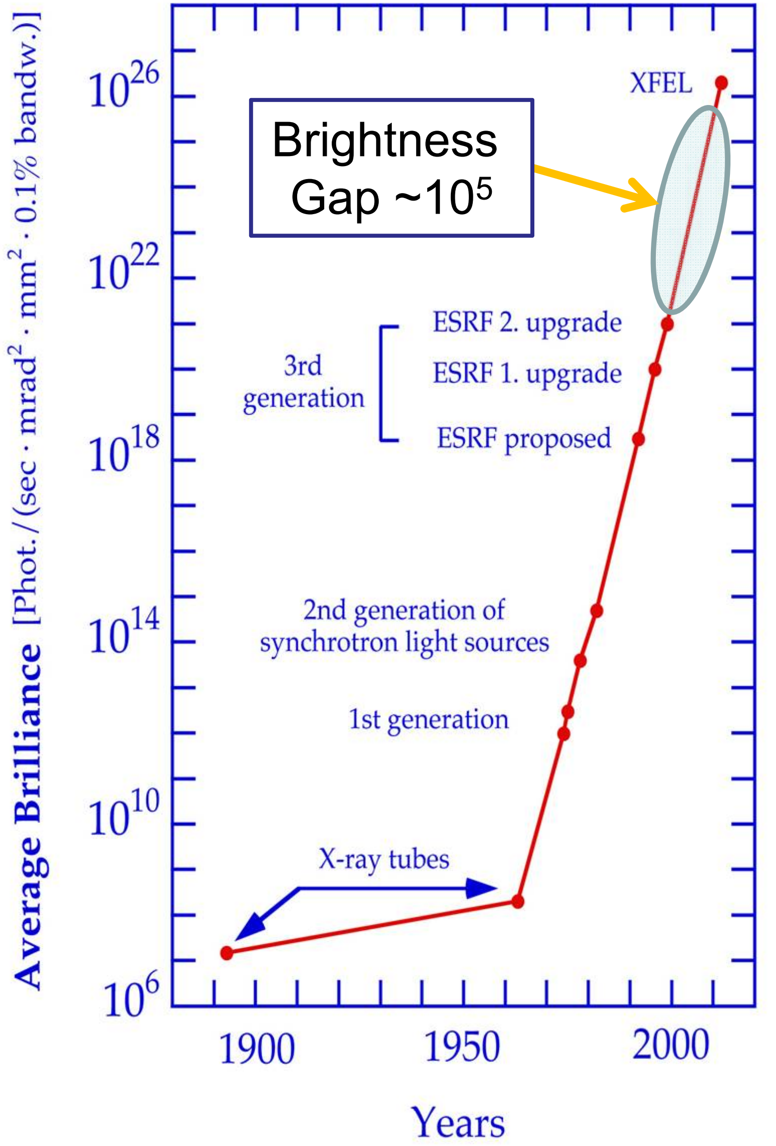
- photodissociation of molecular ions
- highly charged ions
- mass selected clusters

Investigation of surfaces and solids

- XUV laser desorption
- surface dynamics
- femto-magnetism
- study of highly correlated materials
- luminescence under FEL radiation
- meV-resolution photon and photoelectron spectroscopy of surfaces and solids with nm resolution

FELs are Great, BUT…

- Only a few of them and only a few (at the moment one) experiments at a time
  - Capacity very limited; difficult to access
  - Each experiment VERY expensive
- Technical challenges at every step
  - Source, optics, samples detectors, data etc
- SASE Process – every pulse different
- Can we make a brighter synchrotron light source to “fill the gap” ?
- Truly enable coherence-based techniques on storage rings



Brightness Limit is a Diffraction Limited Source

Emittance characterises the brightness of a source; it is the product of source size and divergence in a particular dimension.
For SR from a single electron, the emittance/brightness is diffraction limited:

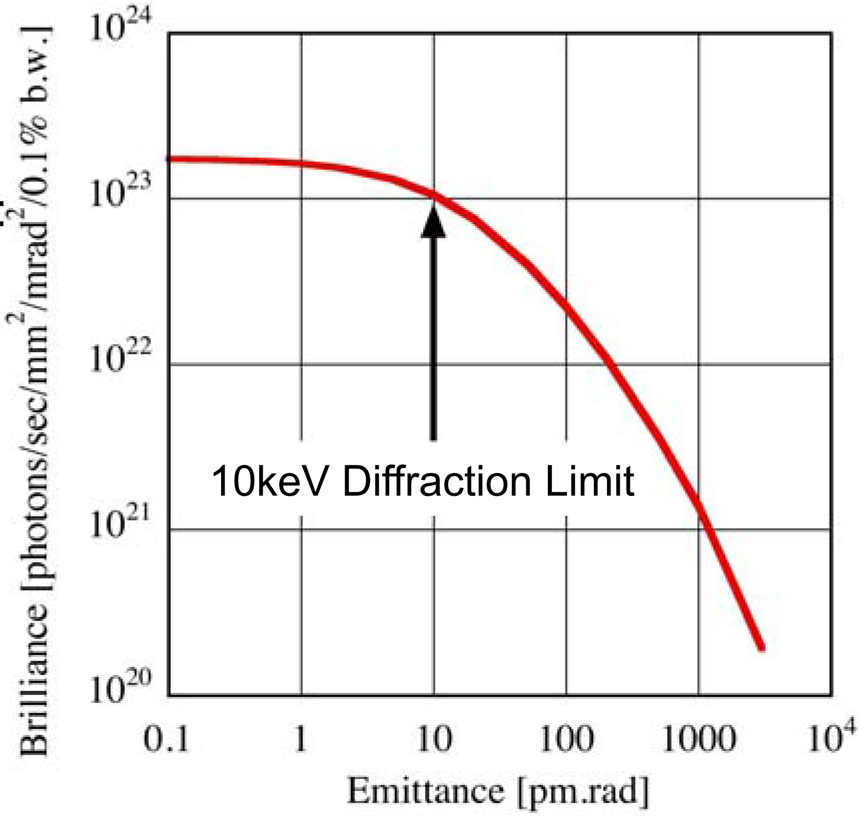
$$\epsilon_r = \sigma_r \sigma_{r'} = \lambda / 4\pi$$

So wavelength corresponding to the diffraction limit for a particular emittance:

$$\lambda_{\mathbf{DL(x,y)}} = 4\pi\epsilon_{\mathbf{x,y}}$$

Real emittance is combination of radiation emittance and real source size/divergence:

$$\Sigma_{\mathbf{x,y}} = \sqrt{\sigma^2_{\mathbf{x,y}} + \sigma^2_{\mathbf{r}}}$$
$$\Sigma_{\mathbf{x',y'}} = \sqrt{\sigma^2_{\mathbf{x',y'}} + \sigma^2_{\mathbf{r'}}}$$

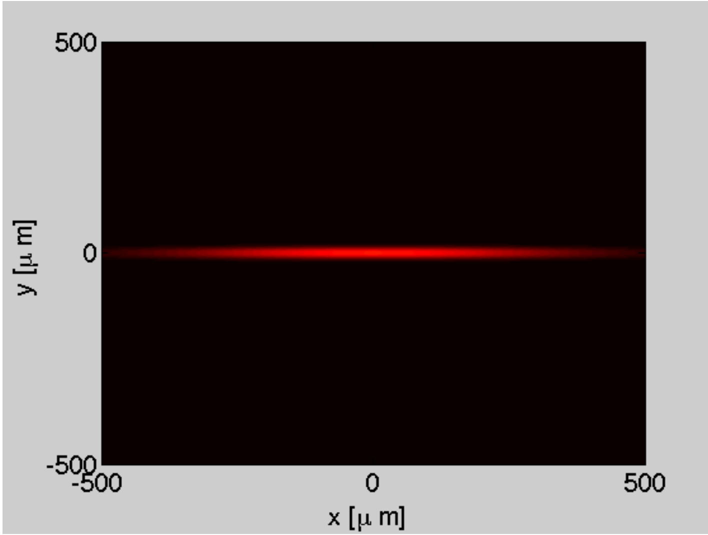


AOF Synchrotron Radiation

Brightest 3rd Generation Storage Ring Sources:

Source	energy GeV	ϵ_x nmrad	max. B_n 10^{20}	circ. m	λ_{Dlx} Å	lattice
ESRF	6	4	3.0	844	500	DBA
APS	7	3.1	1.4	1104	390	DBA
SPring-8	8	2.7	2.5	1436	340	DBA
DIAMOND	3	2.7	1.5	561	340	DBA

- Horizontal emittance 3-20 nm.rad
- Vertical emittance ~100 times less
- Very asymmetric beam in straight sections:
  - Horizontal ~ 1mm FWHM
  - Vertical ~ 10 μm
- Far from diffraction limit in Horizontal @ 10keV
- Close to diffraction limit in vertical



AOF Synchrotron Radiation

How to Design a Brighter Ring?

The horizontal emittance is a characteristic equilibrium quantity for each storage ring

$$\boxed{\epsilon_{\mathbf{x}} \propto \mathbf{E^2} \cdot \theta^{\mathbf{3}} \cdot \mathbf{\Gamma}}$$

electron energy: **E;** angle per bending magnet: *θ;* Lattice dependent quantity: $\mathbf{\Gamma}$

Emission of SR also reduces emittance – "natural emittance" of a storage ring is equilibrium between SR and energy spread.

Reduce energy (not too much or no X-rays)
Reduce angle of bending magnets
More synchrotron radiation

AOF Synchrotron Radiation

Diffraction Limited Storage Ring

If the "ultimate" target is a:

"Diffraction Limited Source" for 10keV Photons:

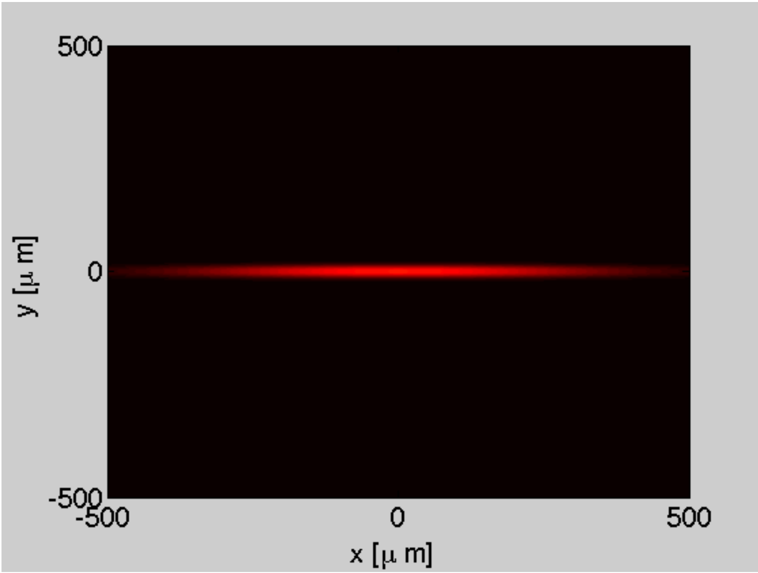
We Need $\varepsilon_x \sim \varepsilon_y \sim$ 10pmrad

Vertical emittance already there: challenge is:
Reduce horizontal or "natural" emittance ~100x

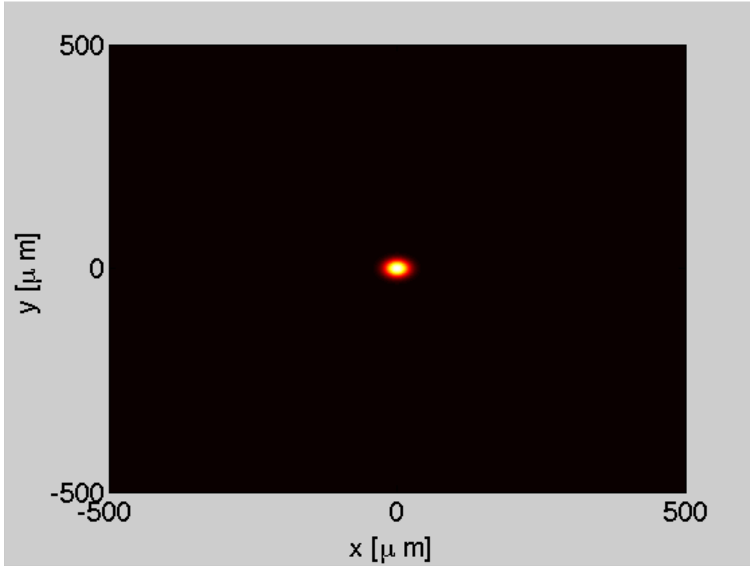
$$\boldsymbol{\varepsilon}_x \propto E^2.\theta^3.\,\Gamma$$

Synchrotron Radiation

Round beam = A “Nicer” Source



Current 3rd Generation Ring

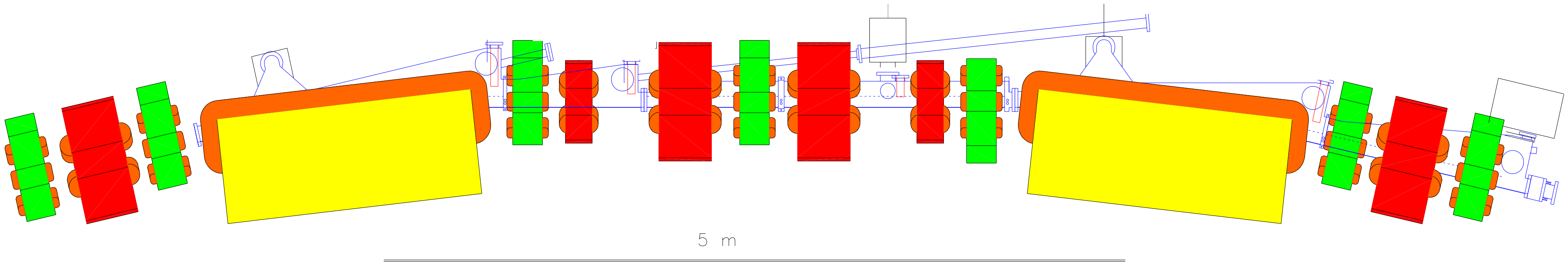


DLSR

What can be done to make $\epsilon_{\mathbf{x}} \propto \mathbf{E^2} \cdot \theta^{\mathbf{3}} \cdot \mathbf{\Gamma}$ small ?

Large ring with lots of cells, reduce electron beam energy

Most 3rd Generation are "double bend achromat" (DBA):

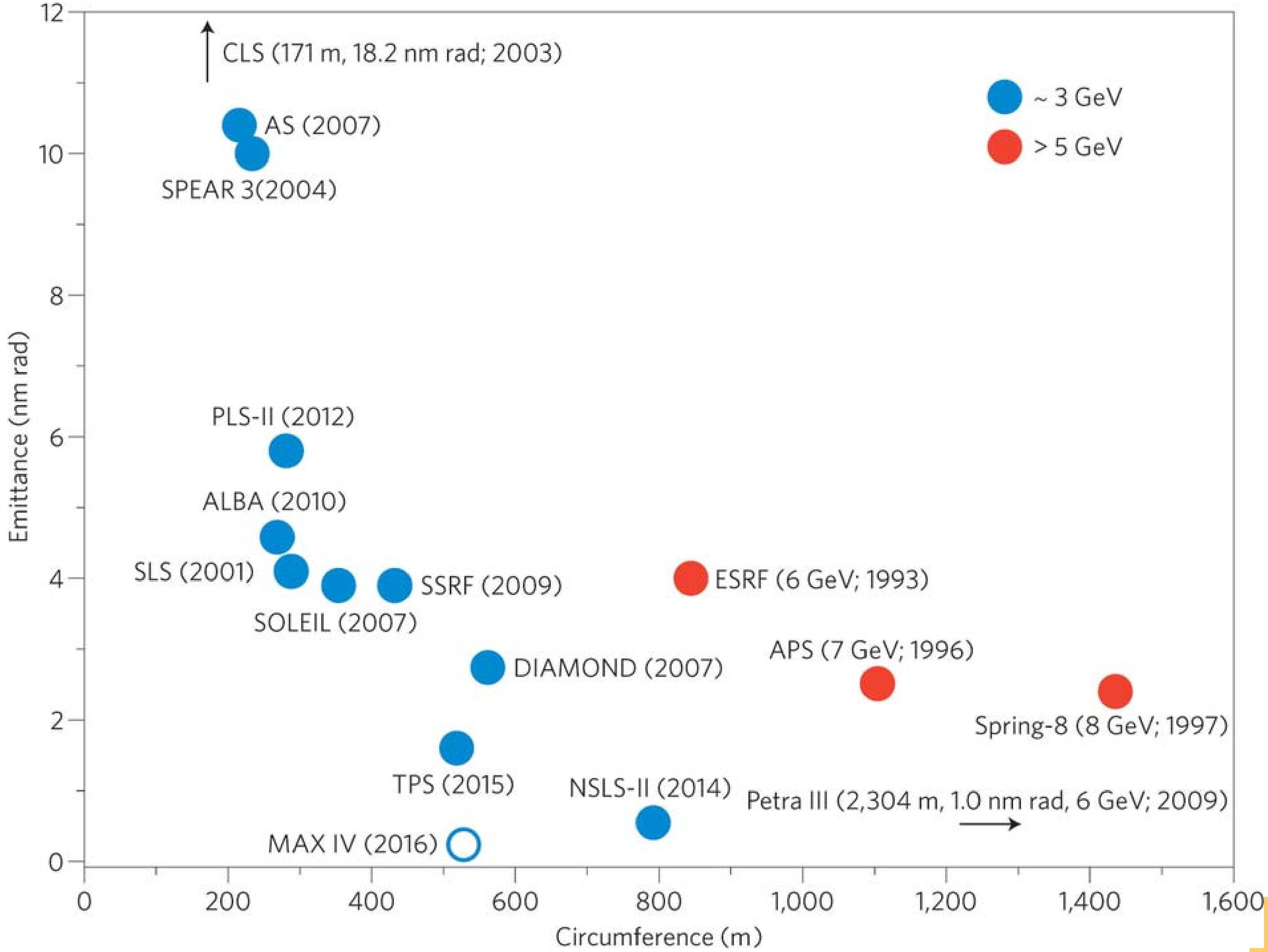


DBA Cell of the Australian Synchrotron

➔ many cells ➔ large storage rings
- ESRF: 32; APS: 40; Spring-8: 48

➔ High power "damping wigglers": much more SR produced
- NSLS II; PETRA III

Big is better?



Large rings, many bending magnets, reduce energy

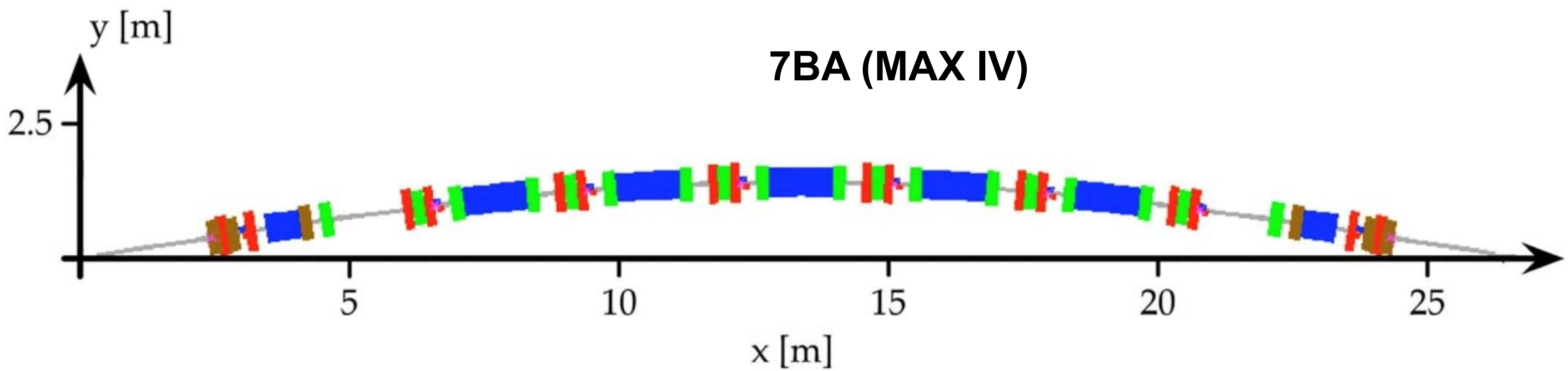
Wavelength corresponding to the diffraction limit: $\lambda_{\mathbf{DL(x,y)}} = 4\pi\epsilon_{\mathbf{x,y}}$

Source	energy GeV	ϵ_x nmrad	max. B_n 10^{20}	circ. m	λ_{Dlx} Å	lattice
ESRF	6	4	3.0	844	500	DBA
APS	7	3.1	1.4	1104	390	DBA
SPring-8	8	2.7	2.5	1436	340	DBA
DIAMOND	3	2.7	1.5	561	340	DBA
PETRA III	6	1	10	2408	126	DBA+DW
NSLS II	3	0.5	30	792	62.8	DBA+DW
PETRA III*	3	0.16	$\cdots$	2408	20	DBA+DW

What can be done to make $\epsilon_{\mathbf{x}} \propto \mathbf{E^2} \cdot \theta^{\mathbf{3}} \cdot \mathbf{\Gamma}$ small ?

Same size Ring, More Bending Magnets

“New” Idea: multi bend achromat (MBA)



- Reduce dispersion and control beam size in the bending magnets
- Achieved by refocusing beam ‘inside’ bending magnets:- need space
- ‘Split’ bending magnets -> Multi Bend Achromats

AOF Synchrotron Radiation

Towards Diffraction Limited Storage Rings – MBA Lattices

Wavelength corresponding to the diffraction limit: $\lambda_{\mathbf{DL(x,y)}} = 4\pi\epsilon_{\mathbf{x,y}}$

Source	energy GeV	ϵ_x nmrad	max. B_n 10^{20}	circ. m	λ_{Dlx} Å	lattice
ESRF	6	4	3.0	844	500	DBA
PETRA III*	3	0.16	···	2408	20	DBA+DW
MAX IV	3	≈ 0.25	40	528	31	7BA
SIRIUS	3	0.28	20	518	35	5BA
ESRF II	6	0.16	100	844	20	7BA
APS II	6	≈ 0.07	200	1104	8	(5-8)BA
Spring-8 II	6	0.10	100	1436	13	5BA

Study	E (GeV)	Circumf. (m)	ε_x (pm.rad)	λ_{Dlx}(Å)/E(keV)
PEP-X	4.5	2200	11	1.4/9
Tevatron	11	6280	1.3	0.16/76

New Storage Ring Projects

PETRA III @ DESY

Best emmittance today:
ε_h = 1 nm rad @ 6 GeV

MAX IV in Lund

Under construction
ε_h = 0.2-0.3 nm rad @ 3.7 GeV

NSLS II @ BNL

Under construction
ε_h = 0.55 nm rad @ 3 GeV

Upgrades

APS @ ANL

ε_h = 0.07 nm rad @ 6 GeV

ESRF in Grenoble

ε_h = 0.1-0.15 nm rad @ 6 GeV

Spring-8 in Hyogo, Japan

ε_h = 0.11 nm rad @ 6 GeV

Enjoy the Cheiron School!

Thanks to many people for slides
Particularly Edgar Weckert, DESY

2015 Cheiron School

IUCr KEK JASRI RIKEN AOF Synchrotron Radiation