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Storage Ring Light Sources

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Fundamentals of Accelerator Physics
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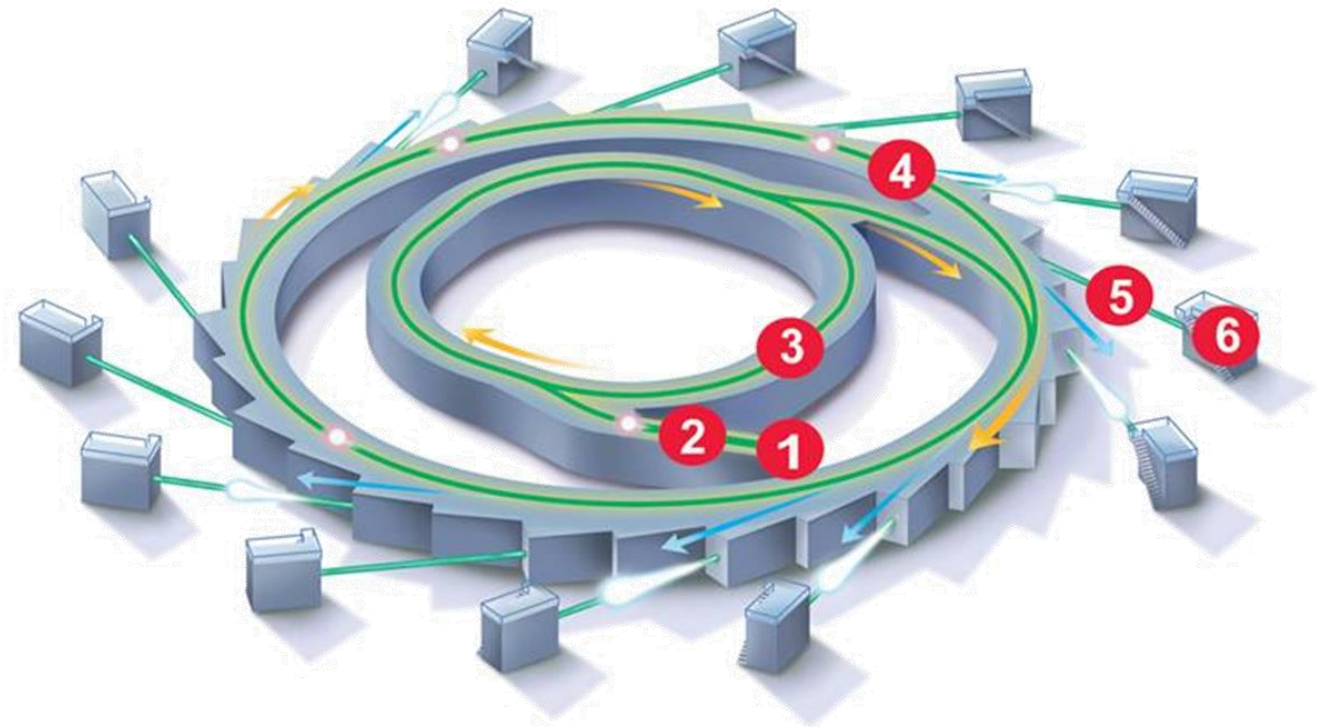
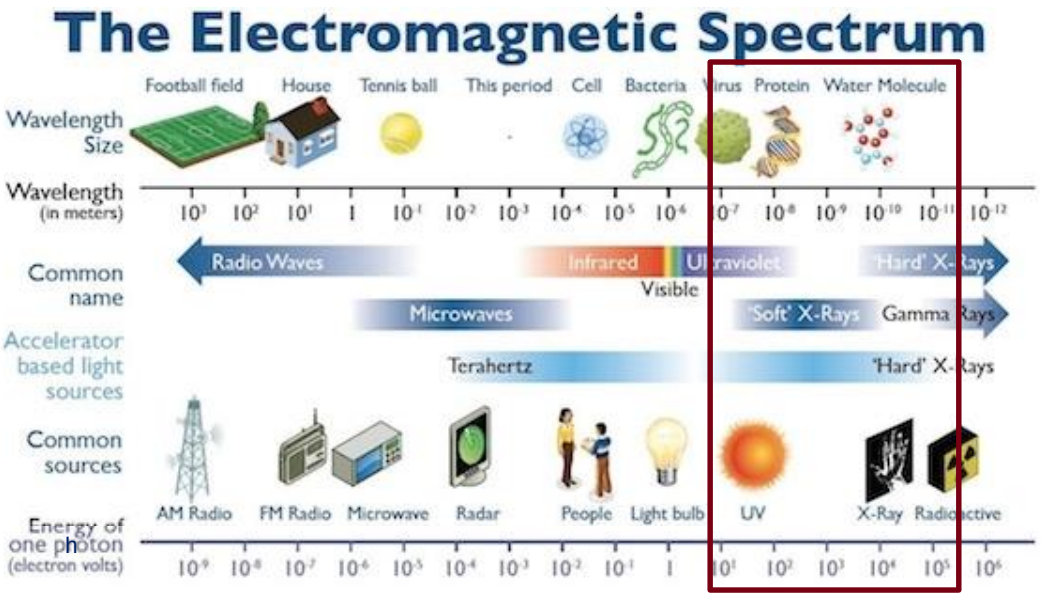
Third generation storage ring light sources

1. Electron gun
2. Linac
3. Booster synchrotron
4. Storage ring
   - bending magnets
   - insertion devices
5. Beamlines
6. Endstations



Why use synchrotron radiation?

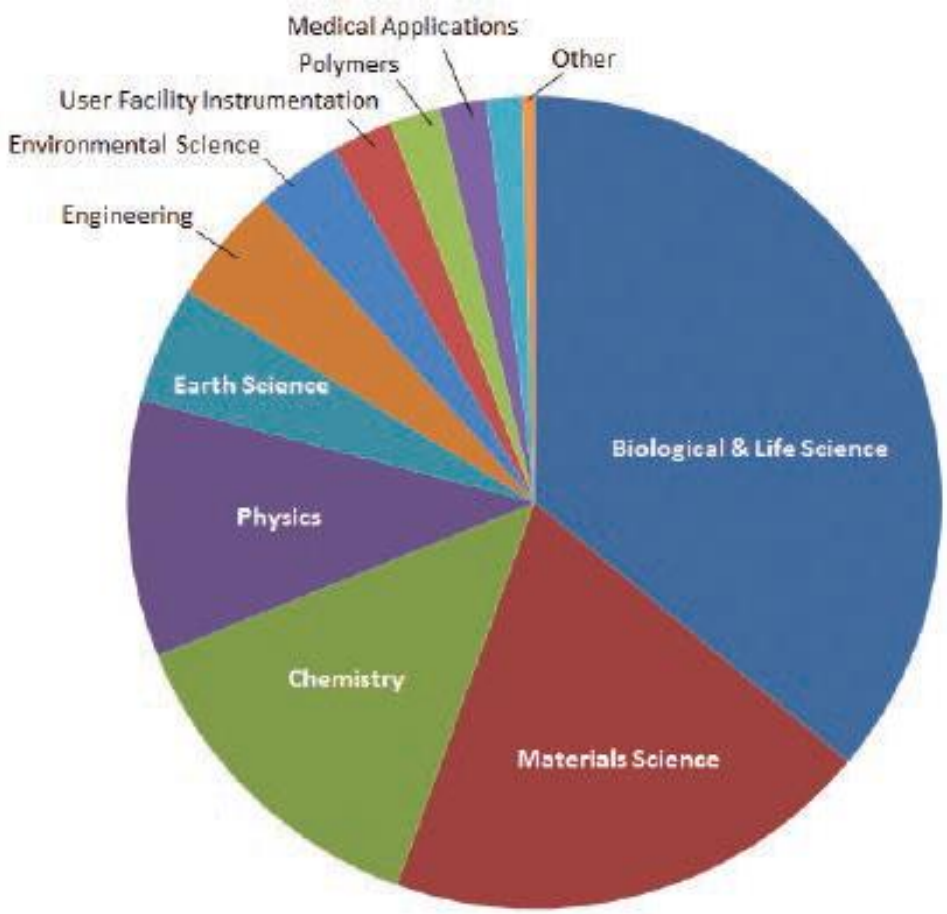
- Wavelength-tunable
  - 10 eV → 100 keV
- High intensity
- Spatial coherence
- Polarised
- Pulsed



Source: lightsources.org

Who uses synchrotron radiation as a light source?

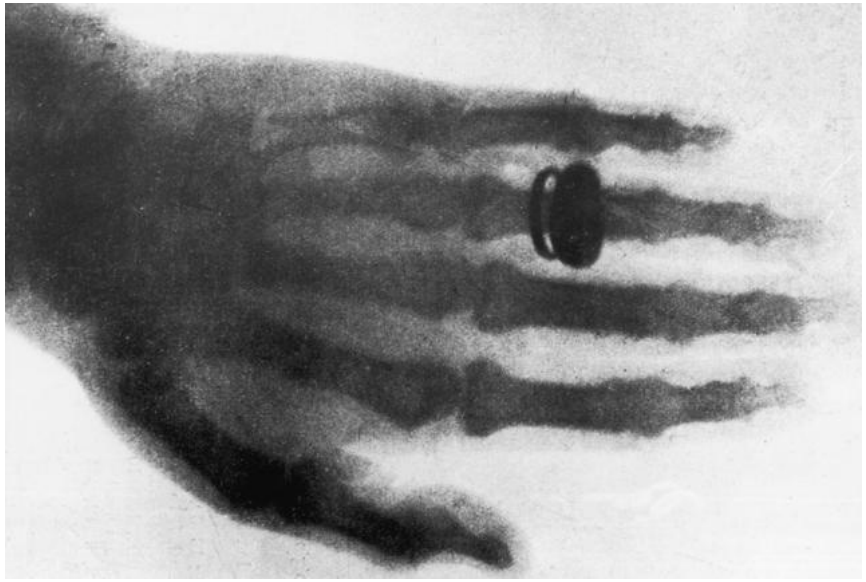
- Touches every aspect of science
- Benefits mostly outside physics
- Users predominantly working in universities, national laboratories



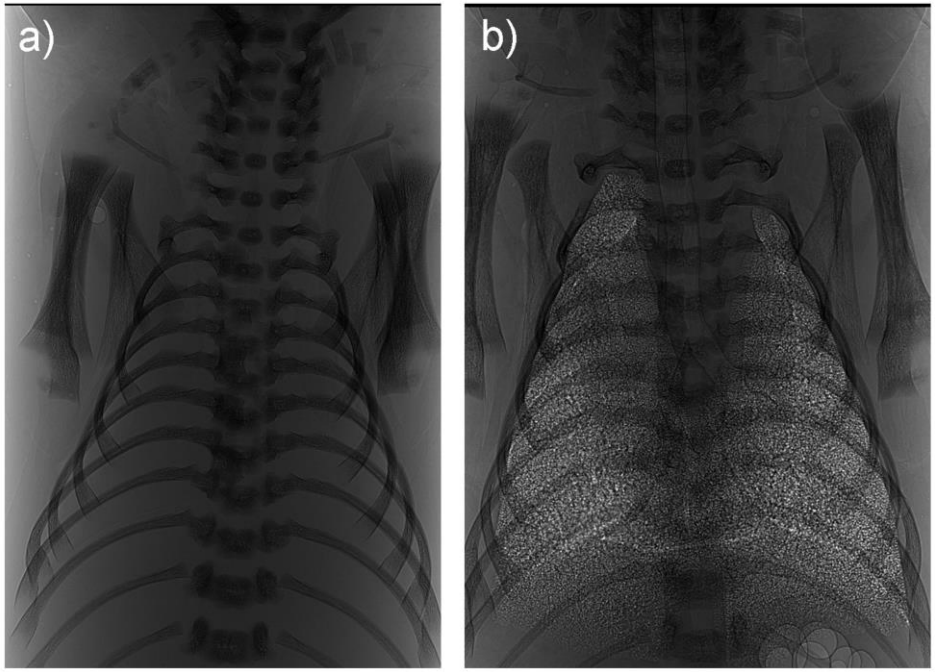
Source: Advanced Photon Source Annual Report 2014

Who uses SR? Imaging

Absorption contrast imaging

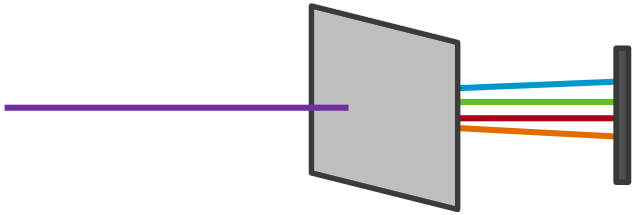


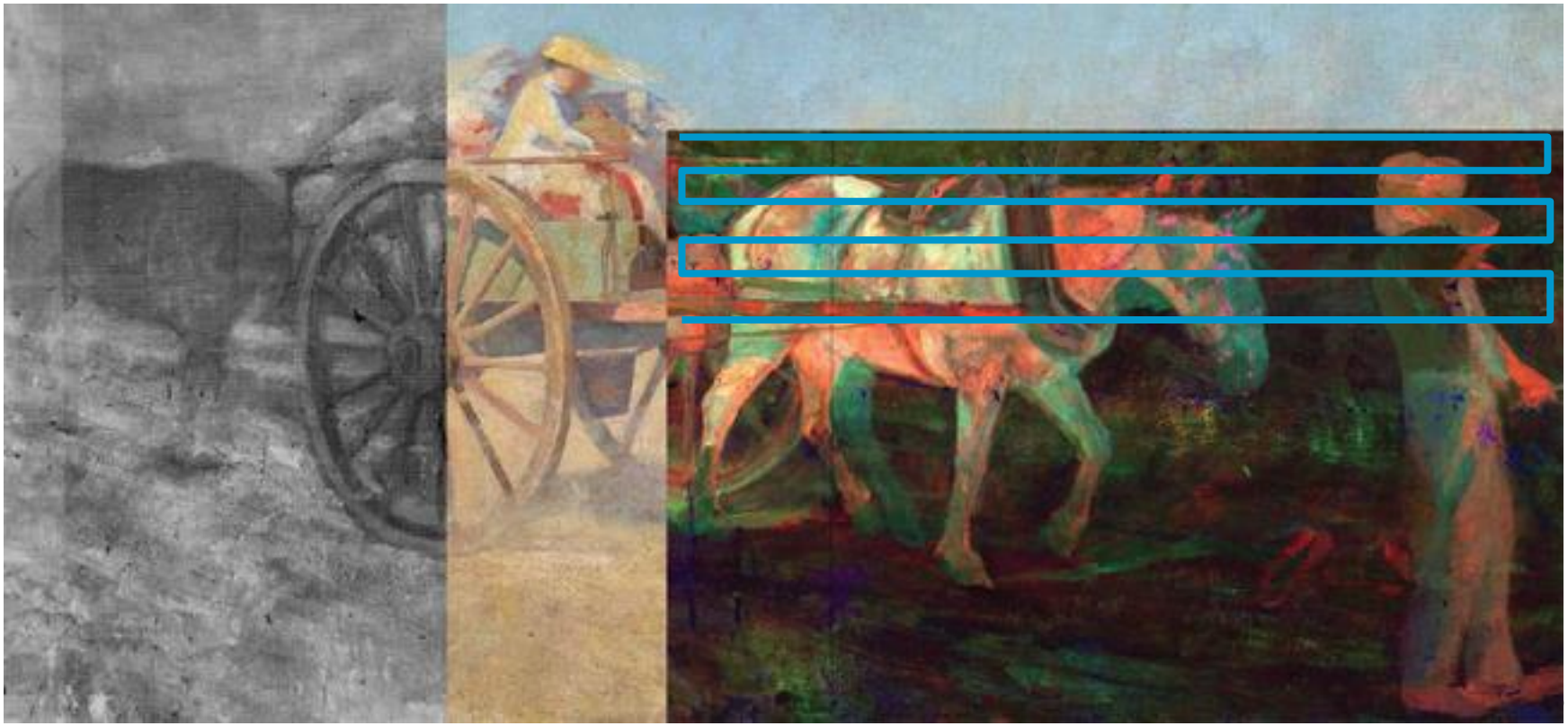
Phase contrast imaging



Who uses SR? Imaging

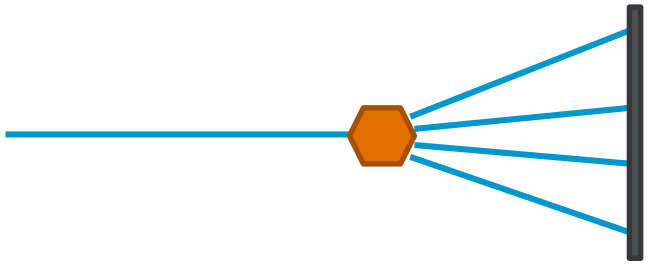
X-ray fluorescence mapping

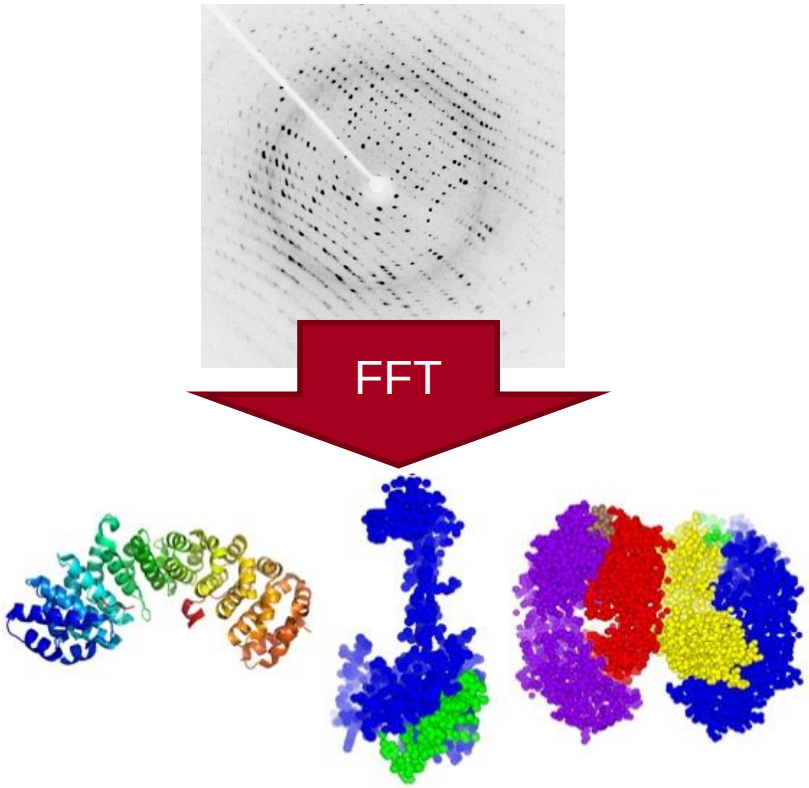




Who uses SR? Diffraction

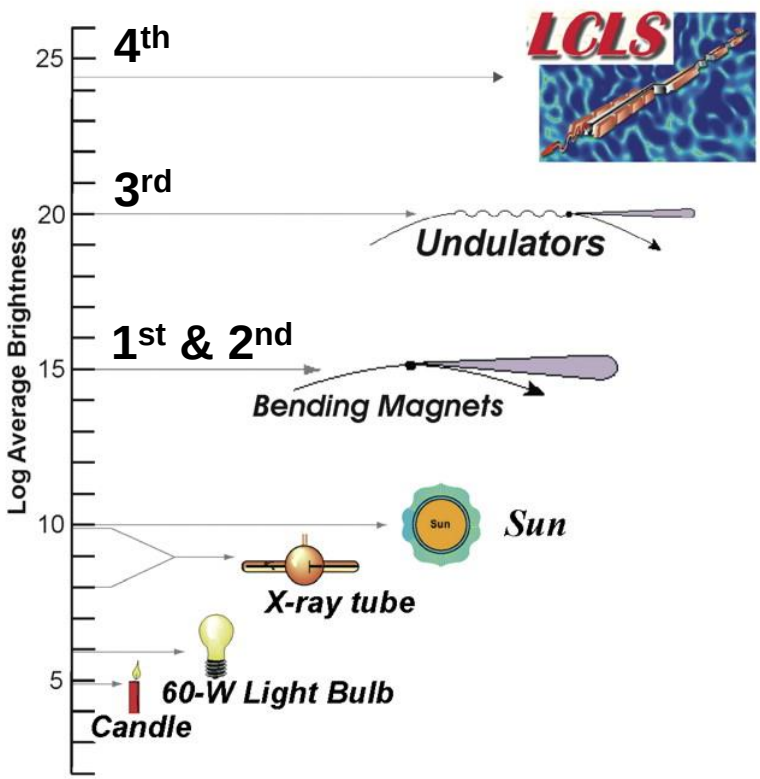
Protein crystallography

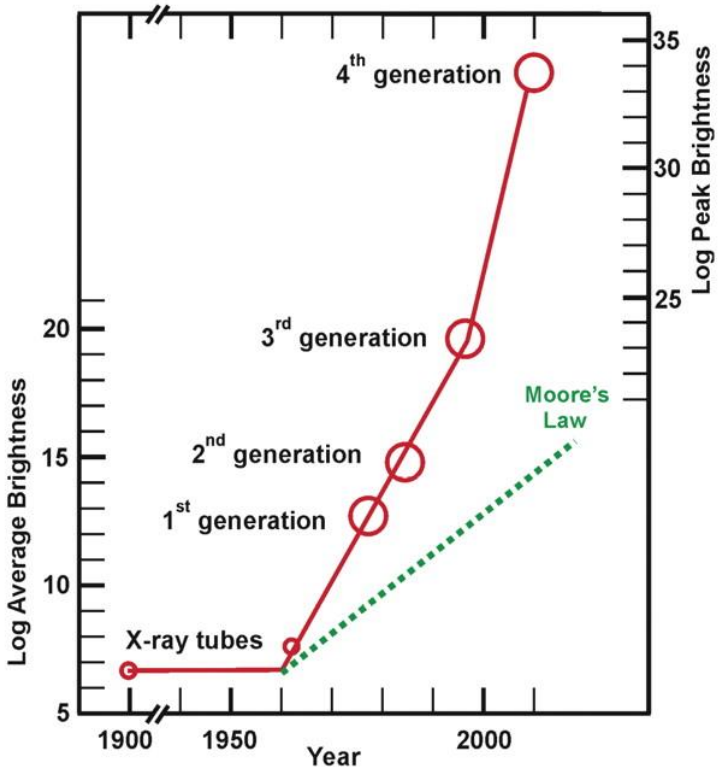




The arms race – light source brilliance

Brilliance/brightness $\mathcal{B} = \dfrac{F}{4\pi^2 \varepsilon_x \varepsilon_y}$





K. Wille, The Physics of Particle Accelerators: An Introduction, Oxford University Press, Oxford, UK (2000).
J. B. Parise and G. E. Brown, Jr., Elements, 2, 37-42 (2006).

Light sources of the world

Source: Advanced Photon Source Annual Report 2014

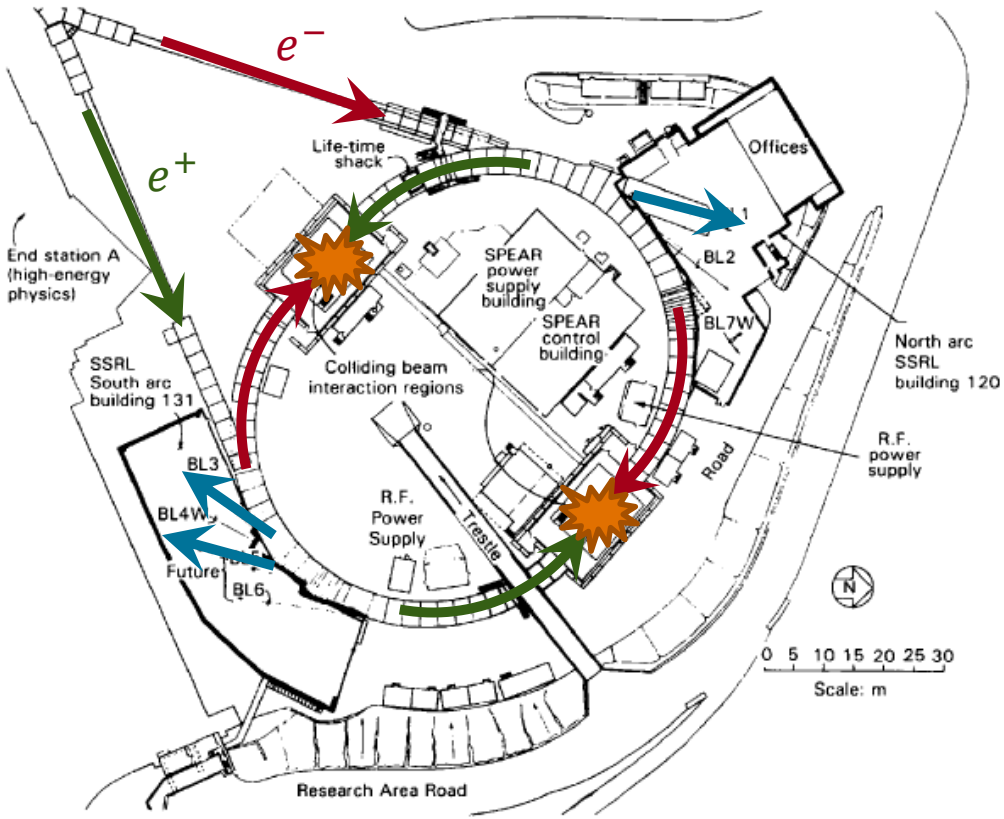
Outline – Overview of Light Sources

- Applications of synchrotron radiation
- Storage ring light sources
- First and second generation storage rings
  - FODO lattices
- Third generation storage rings
  - Achromat lattices
- Diffraction-Limited Storage Rings

Generations of storage ring light sources

First generation storage ring light sources

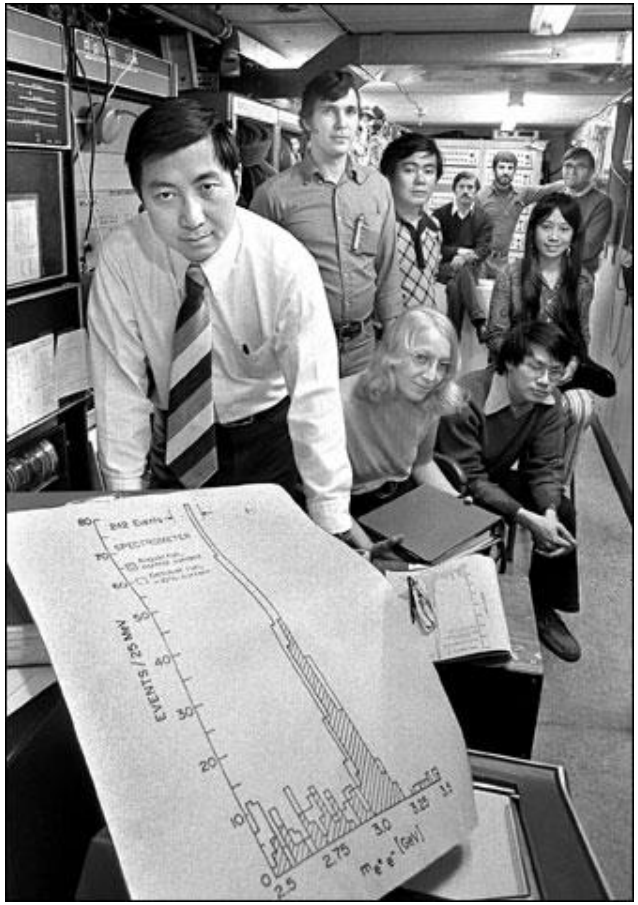
- Parasitic use of synchrotrons, storage ring colliders
- Bending magnet radiation (incoherent, broadband)



S. Doniach, et al., J. Synchrotron Radiat., 4, 380-395 (1997).

Particle physics discovery!

- Early 1960's – Anello di Accumulazione (AdA) collider
  - E = 1.5 GeV
  - Significant for accelerator physics, but no particle discovery
- Early 1970's – SPEAR-I
  - E = 4.5 GeV (maximum)
- 1974 – J/ψ $(c\bar{c})$ discovery kept machines at E = 1.55 GeV

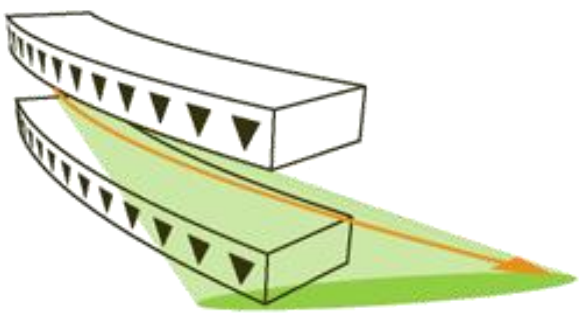


Source: Brookhaven National Laboratory

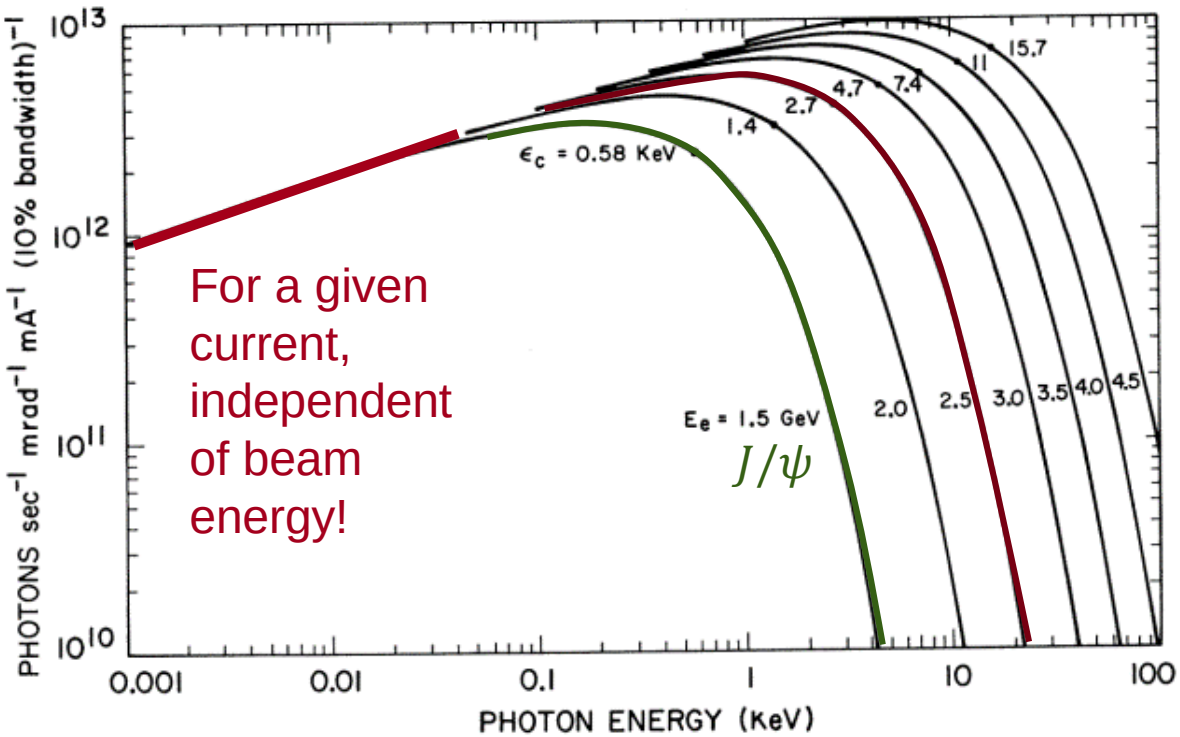
C. Bernardini, Phys. Perspect., 6, 156-183 (2004).
S. Williams, CERN Courier, 1 Jun, 2003 (2003).

Parasitic users of bending magnet radiation

- Critical photon energy $\epsilon_c \propto \frac{E^3}{\rho}$
- Colliders typically want maximum ρ (minimise SR power)
- Bending magnet light sources want minimum ρ (maximise SR)



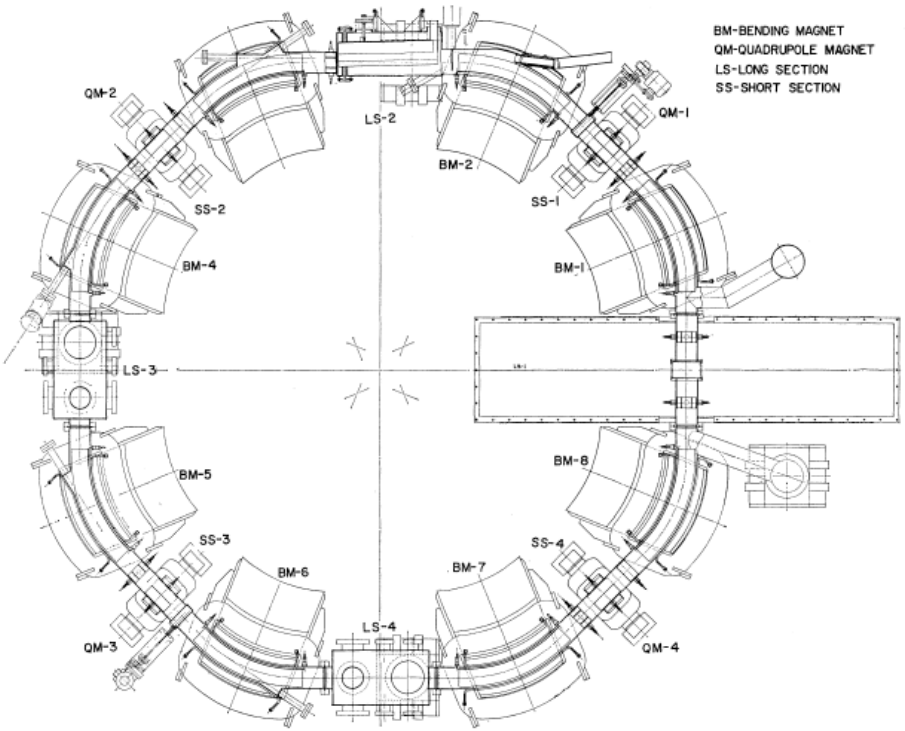
Source: Australian Synchrotron



H. Winick, 'Properties of Synchrotron Radiation', in Synchrotron Radiation Research, Springer, New York, (1980), p. 17

Second generation storage ring light sources

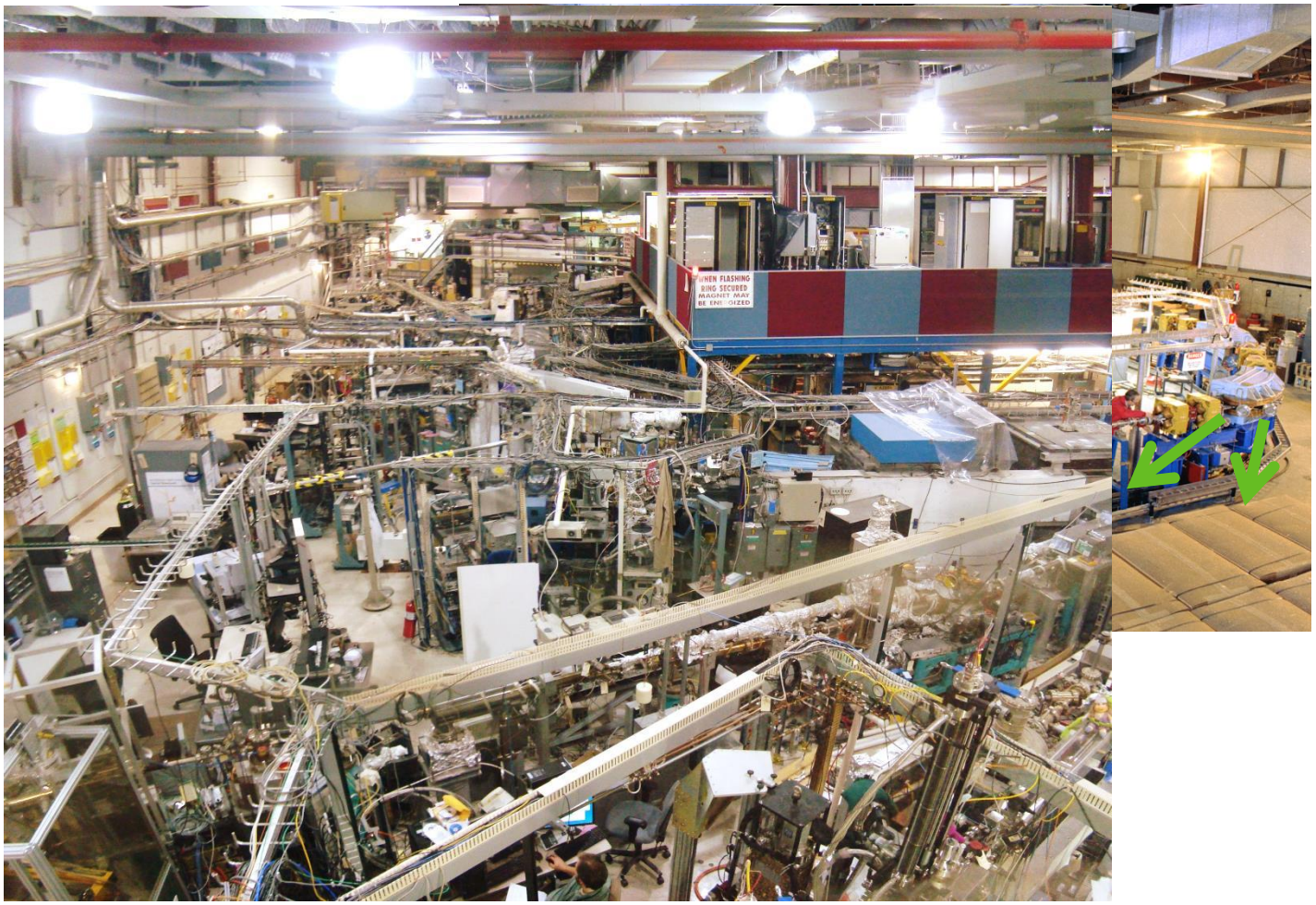
- Dedicated electron storage ring light sources
- Bending magnet radiation
- Predominantly separated-function FODO lattices
- Typically VUV, soft X-ray photon energies
- Some hard X-ray rings



E. Rowe and F. Mills, Part. Accel., 4, 211-227 (1973).

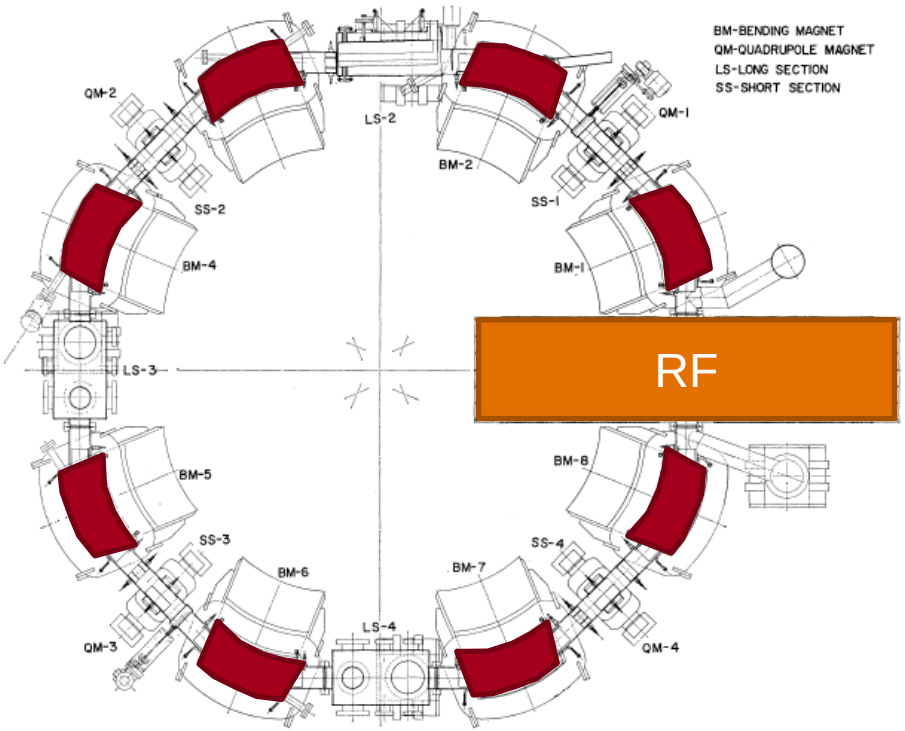
Second generation light source – beginning and end

National Synchrotron Light Source – I (Brookhaven)



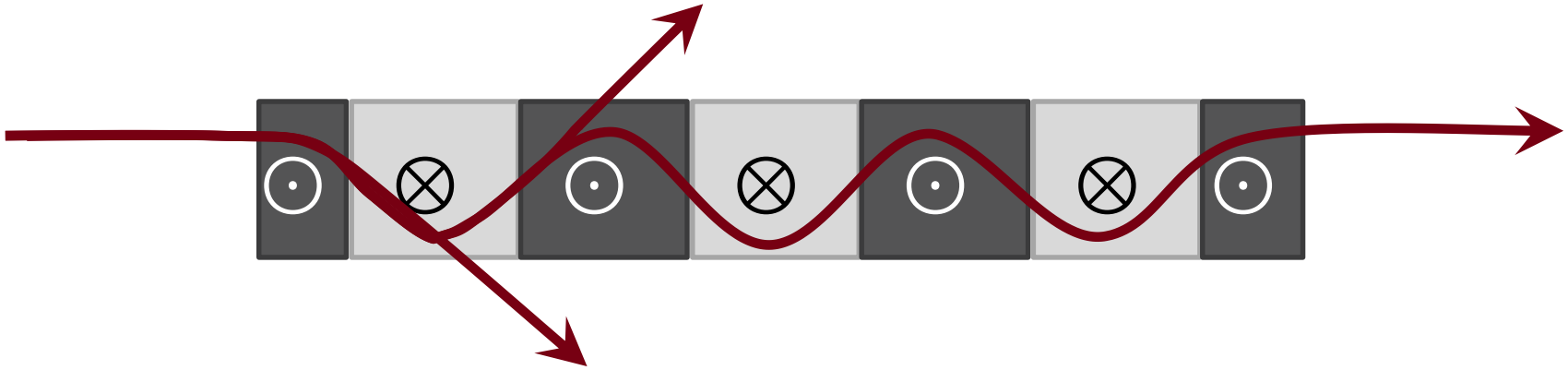
Wigglers

- Electron storage ring
- $B\rho = 3.3356E$
- For a given circumference of bending magnets, bending radius fixed (need to bend beam by 2π)
- For a given beam energy, no flexibility in magnetic field of bending magnets



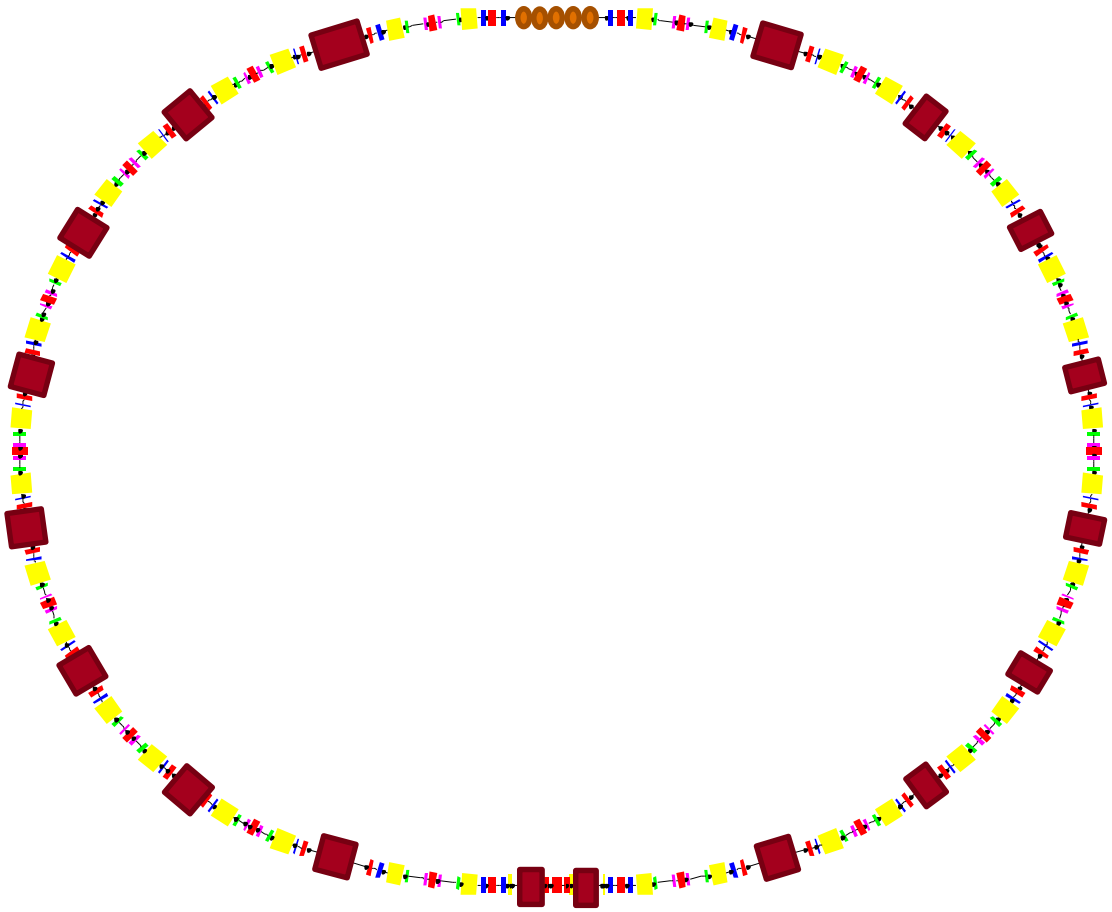
E. Rowe and F. Mills, Part. Accel., 4, 211-227 (1973).

Wigglers



Third generation storage ring light sources

- Dedicated storage rings designed specifically for wiggler and undulator light sources (insertion devices)



Lattices for light sources

- Optimisation? Brilliance/brightness

$$\boxed{\mathcal{B} = \frac{F}{4\pi^2 \varepsilon_x \varepsilon_y}}$$

- Vertical emittance ideally zero
  - Practically, $\varepsilon_y \approx 0.01\varepsilon_x$
  - Arising from uncorrected betatron coupling with horizontal plane
- Minimising equilibrium emittance ε_x is key

Lattices for light sources

- Equilibrium emittance scaling law

$$\boxed{\varepsilon_x = C_q \frac{\gamma^2}{\mathcal{J}_x} \frac{\oint \mathcal{H}/\rho^3 \mathrm{d}s}{\oint 1/\rho^2 \mathrm{d}s} \approx \mathcal{F} \frac{C_q \gamma^2}{\mathcal{J}_x} \theta^3}$$

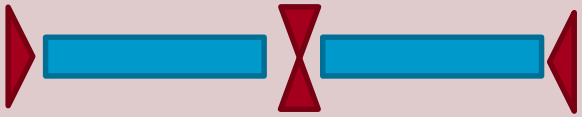
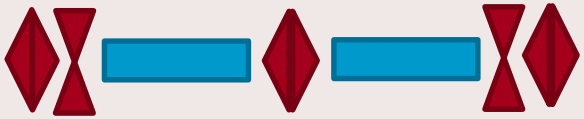
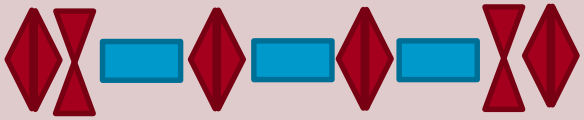
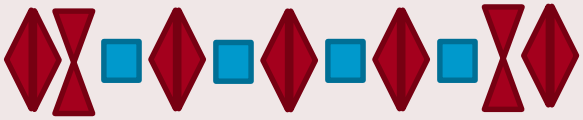
$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar c}{mc^2} = 3.84 \times 10^{-13}\ \mathrm{m}$$

- Scale factor $\mathcal{F}$ (not flux F)

M. Sommer, Optimization of the Emittance of Electrons (Positrons) Storage Rings, Laboratoire de l'Accélérateur Linéaire, LAL/RT/83-15 (1983).

Lattice scale factor $\mathcal{F}$

$$\varepsilon_x \approx \mathcal{F} \frac{C_q \gamma^2}{\mathcal{J}_x} \theta^3$$

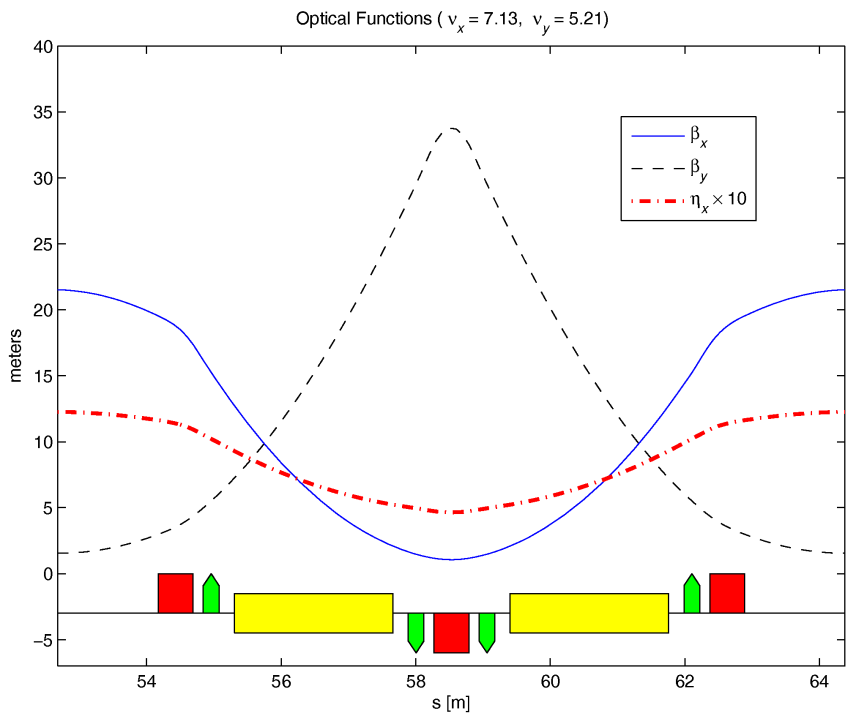
Name	Unit Cell	$\mathcal{F}$	Ref.
FODO		1.2 (minimum)	Wiedemann (1980) Wolski (2014)
TME		$\frac{1}{12\sqrt{15}} \approx 0.0215$	Wolski (2014)
TAL		$\frac{1}{\sqrt{15}} \approx 0.2582$	Ropert (1993)
DBA		$\frac{1}{4\sqrt{15}} \approx 0.0646$	Sommer (1981)
TBA		$\frac{7}{36\sqrt{15}} \approx 0.0502$	Ropert (1993)
MBA		$\frac{1}{12\sqrt{15}} \left(\frac{M+1}{M-1}\right)$	Wolski (2014)

What is the difference? Curly-H function

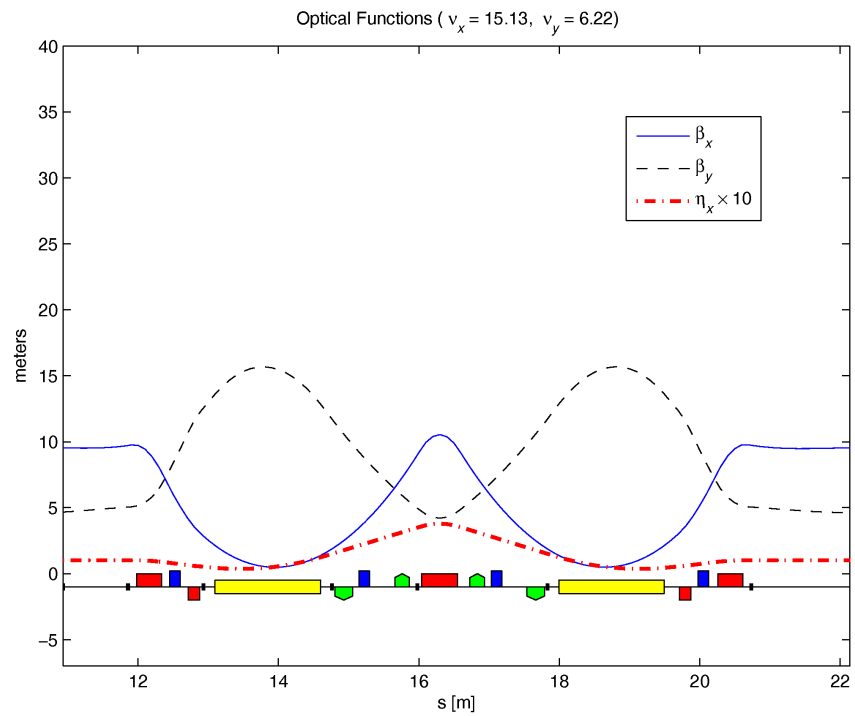
$$\mathcal{H} = \gamma_x D_x^2 + 2\alpha_x D_x D_x' + \beta_x D_x'^2$$

- Minimising horizontal dispersion function and its derivative in the bending magnets

SPEAR-2 (FODO)



SPEAR-3 (DBA)



Example: SPEAR-2 to SPEAR-3

$$\varepsilon_x \approx \mathcal{F}\frac{C_q\gamma^2}{\mathcal{J}_x}\theta^3$$

- Let's assume both rings
  - $\mathcal{J}_x = 1$
  - $E = 3.0\ \mathrm{GeV}\ (\gamma = 5871)$
- SPEAR-2, FODO lattice
  - FODO, $\mathcal{F} \approx 1.2$
  - 32 bending magnets ($\theta = 11.25° \equiv 0.196\ \mathrm{rad}$)
  - $\varepsilon_x \approx 120\ \mathrm{nm\ rad}$
- SPEAR-3, DBA lattice
  - DBA, $\mathcal{F} \approx 0.0646$
  - 36 bending magnets ($\theta = 10° \equiv 0.175\ \mathrm{rad}$)
  - $\varepsilon_x \approx 4.5\ \mathrm{nm\ rad}$

Real machines?

SPEAR-2
$\varepsilon_x = 160\ \mathrm{nm\ rad}$

SPEAR-3
$\varepsilon_x = 6\ \mathrm{nm\ rad}$

Real machines don't run at the theoretical limit!

R. Hettel, et al., Design of the SPEAR-3 Light Source, SLAC-PUB-9721 (2003)

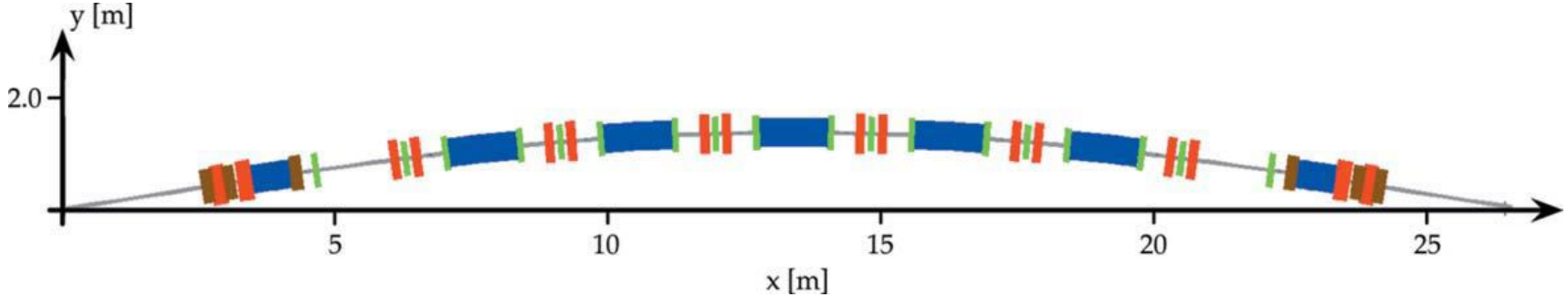
Diffraction-Limited Storage Rings

- How much can the average brightness be usefully increased?
  - ‘Continuous’ sources (e.g. storage rings)
- Use insertion devices (undulators, wigglers) as light sources (not bending magnets)
- Diffraction limited source emittance

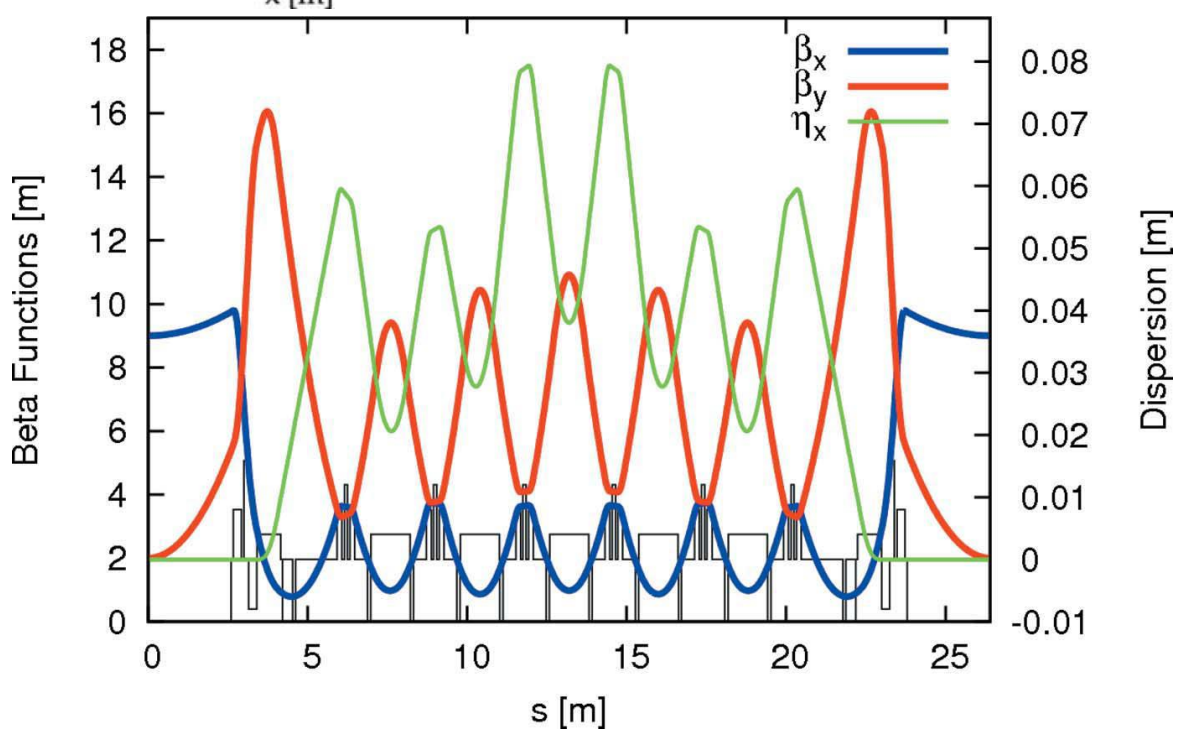
$$\varepsilon_x < \frac{\lambda}{4\pi}$$

- Soft X-rays, $\lambda \approx 1\ \mathrm{nm} \rightarrow \varepsilon_x < 80\ \mathrm{pm\ rad}$
- Strategy is to maximise number of bending magnets (separated by quadrupoles)

MAX-IV – a diffraction-limited storage ring

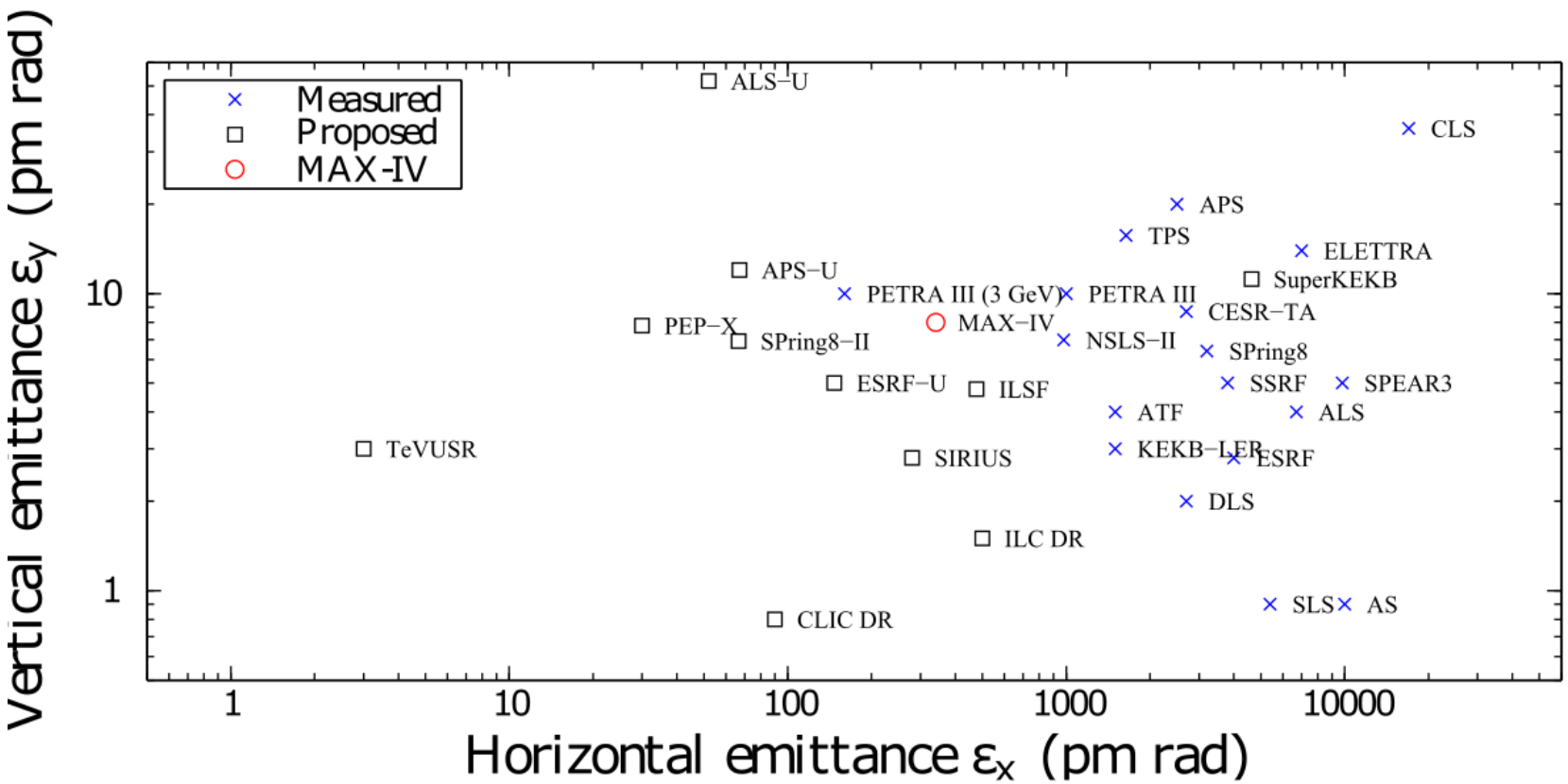


- MBA (seven-bend achromat)
- 20 unit cells
- $\varepsilon_x = 340\ \mathrm{pm\ rad}$
- Spatially coherent for $\lambda > 4\ \mathrm{nm}$

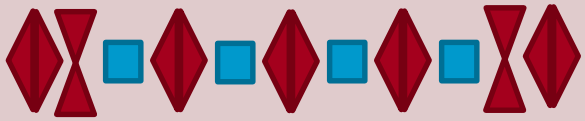


P. Tavares, et al., J. Synchrotron Radiat., 21, 862-877 (2014).

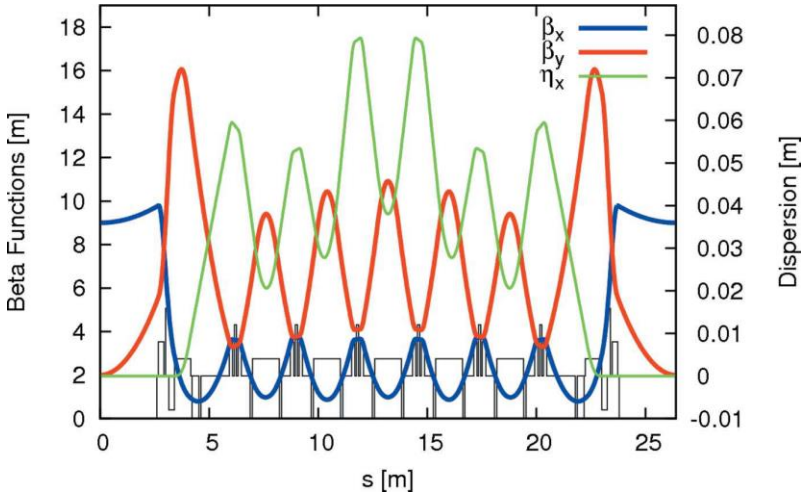
Electron rings – present and proposed



MAX-IV as an example

Name	Unit Cell	$\mathcal{F}$	Ref.
MBA		$\frac{1}{12\sqrt{15}}\left(\frac{M+1}{M-1}\right)$	Wolski (2014)

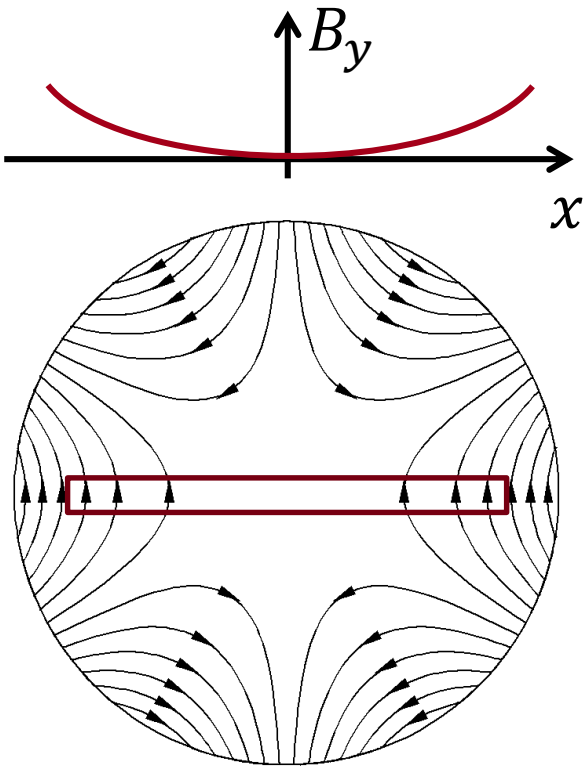
- Assume $\mathcal{J}_x = 1$
- Per cell, $5 \times 3°$ bends, $2 \times 1.5°$ bends
  - Assume 6-BA: $\mathcal{F} = 0.0286$
- 120 bending magnets, $\theta = 0.0524\ \mathrm{rad}$
- $E = 3.0\ \mathrm{GeV}\ (\gamma = 5871)$
- $\varepsilon_x \approx 57\ \mathrm{pm\ rad}$
- Real ring: $340\ \mathrm{pm\ rad}$



Emittance is just one lattice optimisation

Theoretical emittance limit and real machines

- Operating a lattice close to the theoretical limit requires strong quadrupole fields
  - Leads to large negative natural chromaticity
- Lattice has very small dispersion (deliberately)
  - Chromaticity compensation requires strong sextupole fields
  - Leads to strong third order resonances in tune space
  - Non-linear dynamics become the problem
- Dynamic aperture becomes very small
- Difficult to inject off-axis and store electron beams



Source: Wolski, CERN-2010-004.1 (2011).

3rd generation storage ring magnets, MAX-IV magnets

MAX-IV – a diffraction-limited storage ring

Summary

- Desirable properties of synchrotron radiation as a light source
- Historically, synchrotron radiation users parasitic
- Technologies such as insertion devices developed as a result
- Present day, dedicated synchrotron radiation laboratories
- Light source technology developing in two main directions
  - Average brightness (Diffraction-Limited Storage Rings)
  - Peak brightness (Free-Electron Lasers)

This work was supported in part by the Department of Energy contract DE-AC02-76SF00515.

Key references

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  - DOI: 10.1007/978-3-319-18317-6
- E. J. N. Wilson, An Introduction to Particle Accelerators, Oxford University Press, Oxford, UK (2001).
  - DOI: 10.1093/acprof:oso/9780198508298.001.0001
- A. Wolski, Beam Dynamics in High Energy Particle Accelerators, Imperial College Press, London, UK (2014).
  - DOI: 10.1142/p899

Virtual tour of SPEAR3

SPEAR3 storage ring

https://my.matterport.com/show/?m=P7yQkUGnNA2