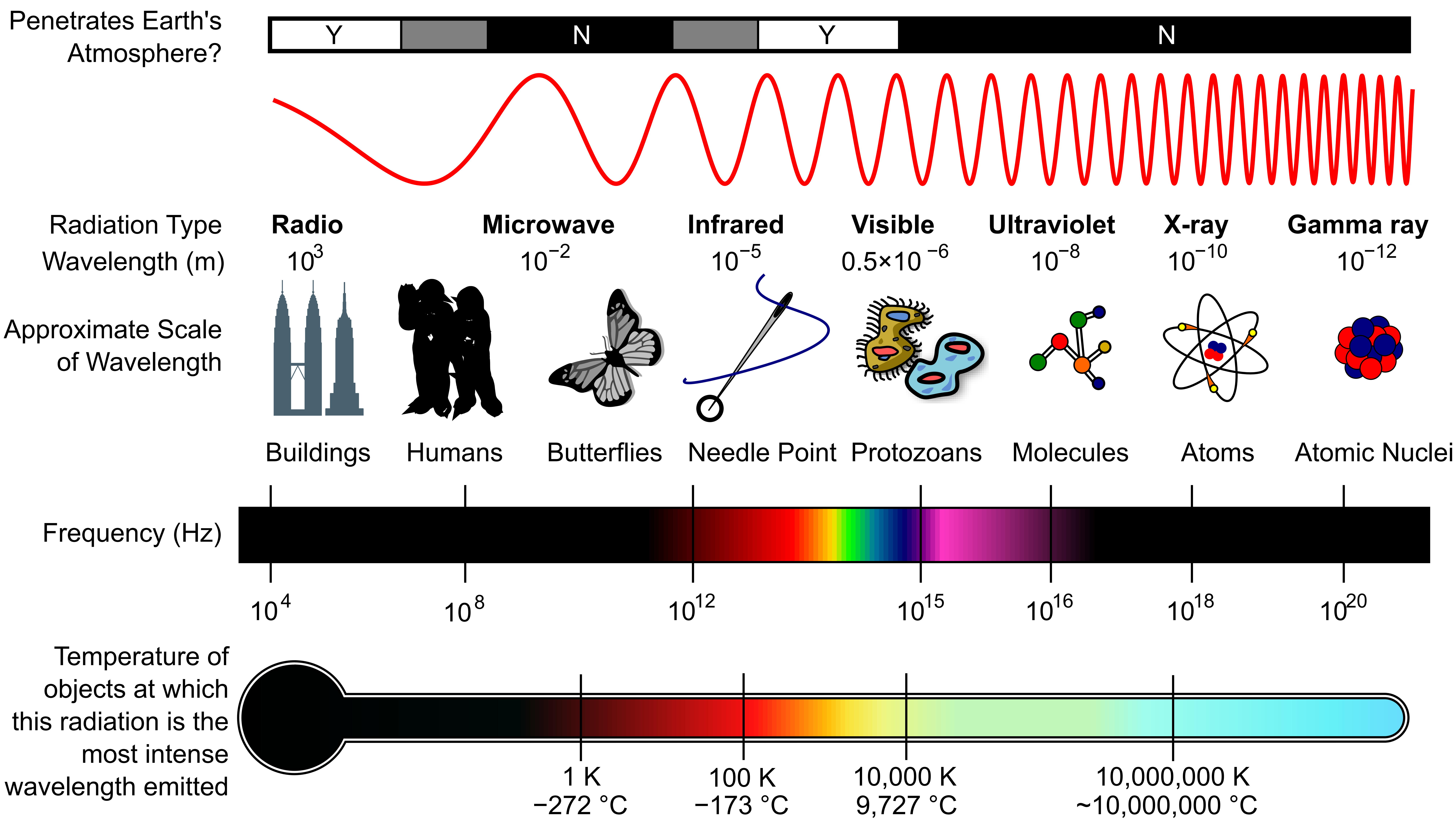
Rasmus Ischebeck

Synchrotron Radiation

Joint Universities Accelerator School


ABUS 500 kg

The Electromagnetic Spectrum



$$E_\gamma = h\nu = \hbar\omega$$

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Possibilities to Generate Electromagnetic Radiation

Nick Veasey

Time Plan

Monday	Tuesday	Wednesday	Thursday
Linear Imperfections	Synchrotron Radiation	Synchrotron Radiation	Synchrotron Radiation
Coffee Break	Coffee Break	Coffee Break	Coffee Break
Linear Imperfections	Machine Physics	Synchrotron Radiation	Synchrotron Radiation
Lunch	Lunch	Lunch	Lunch
Synchrotron Radiation	Linear Imperfections	Linear Imperfections	Linear Imperfections
Coffee Break	Coffee Break	Coffee Break	Coffee Break
Synchrotron Radiation	Linear Imperfections	Linear Imperfections	Linear Imperfections
	Free Electron Lasers		

Standing on the Shoulder of Giants

- Phil Willmott
- PSI / EPFL
- Online course on synchrotron radiation, available at
  https://actu.epfl.ch/news/mooc-synchrotrons-and-x-ray-free-electron-lasers/

- Andreas Streun
- PSI
- SLS 2.0 (private communication)

Standing on the Shoulder of Giants

- Bill Barletta
- Adjunct Professor of Physics at MIT, UCLA, and Old Dominion University
- US Particle Accelerator School course on synchrotron radiation: http://uspas.fnal.gov/materials/09UNM/Unit_11_Lecture_18_Synchrotron_radiation.pdf

- Riccardo Bartolini
- JUAS course on synchrotron radiation (2018): https://indico.cern.ch/event/683638/timetable/

Standing on the Shoulder of Giants

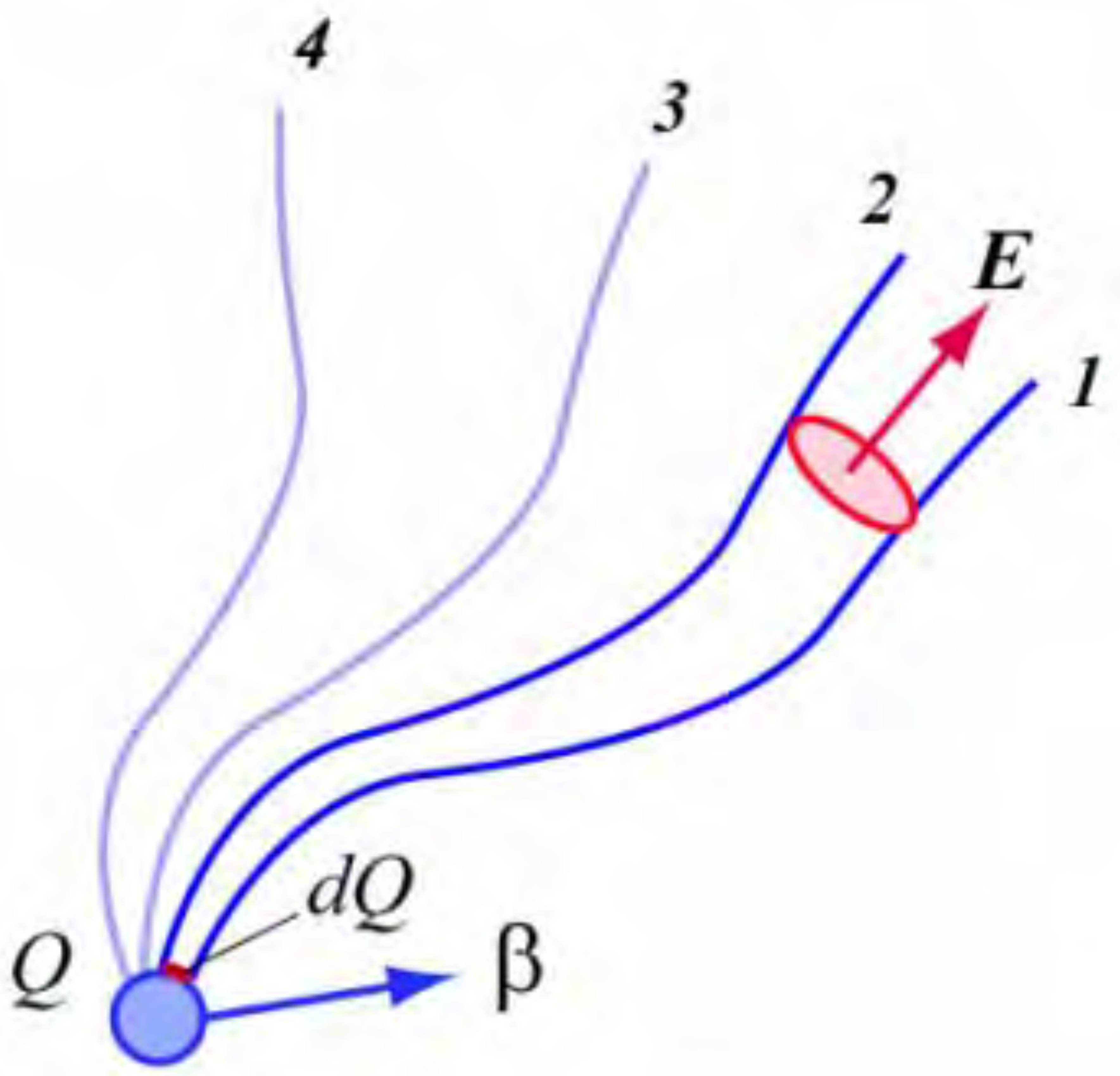
- Phil Bucksbaum
- Stanford
- Ultrafast X-Ray Summer School course on atomic and molecular physics: https://app.certain.com/accounts/register123/stanford/pulseinstitute/events/uxss2018/2018.UXSS.Bucksbaum.AMO.tutorial.pdf

- Federica Marone
- PSI
- X-ray tomography (private communication)

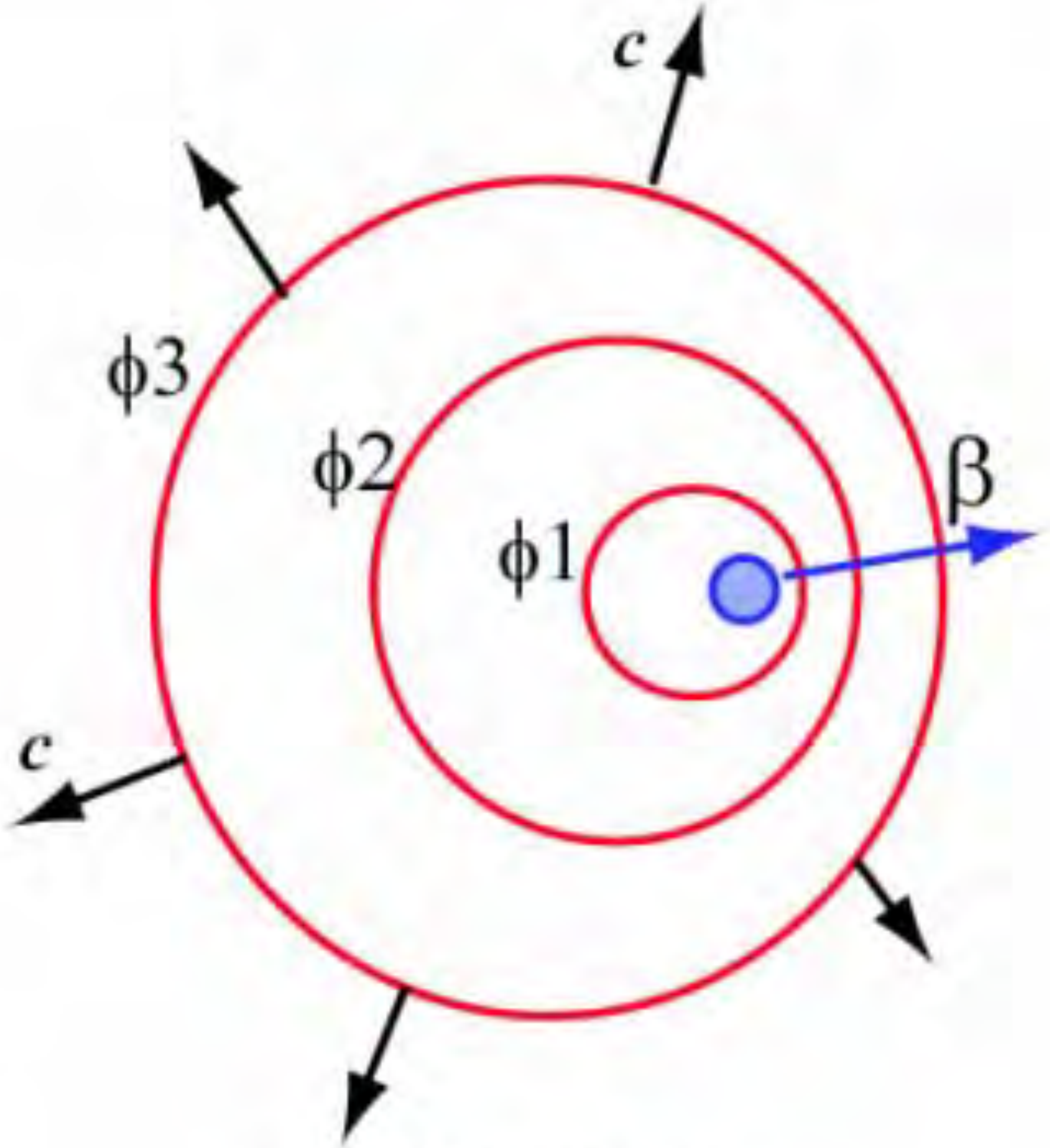
Quiz: Electromagnetic Radiation is Emitted by…

- Electrons flying in a circle
- Accelerated electrons
- Protons in LHC
- All of the above

Emission of Electromagnetic Radiation by an Accelerated Charge



(a) Electric Field Lines



(b) Wavefronts

Tsumoro Shintake

Radiation Emitted by Charge on a Circular Orbit

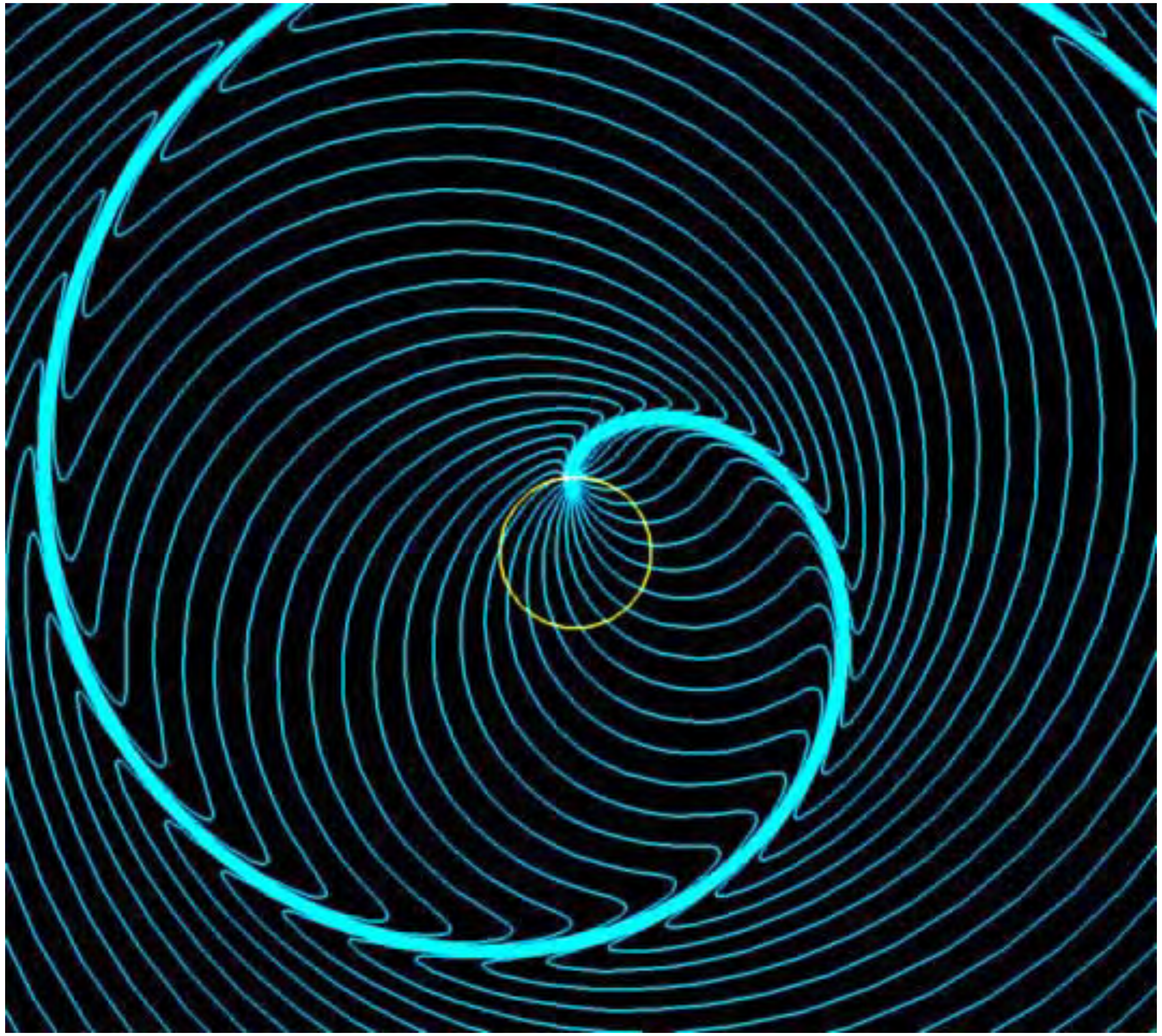
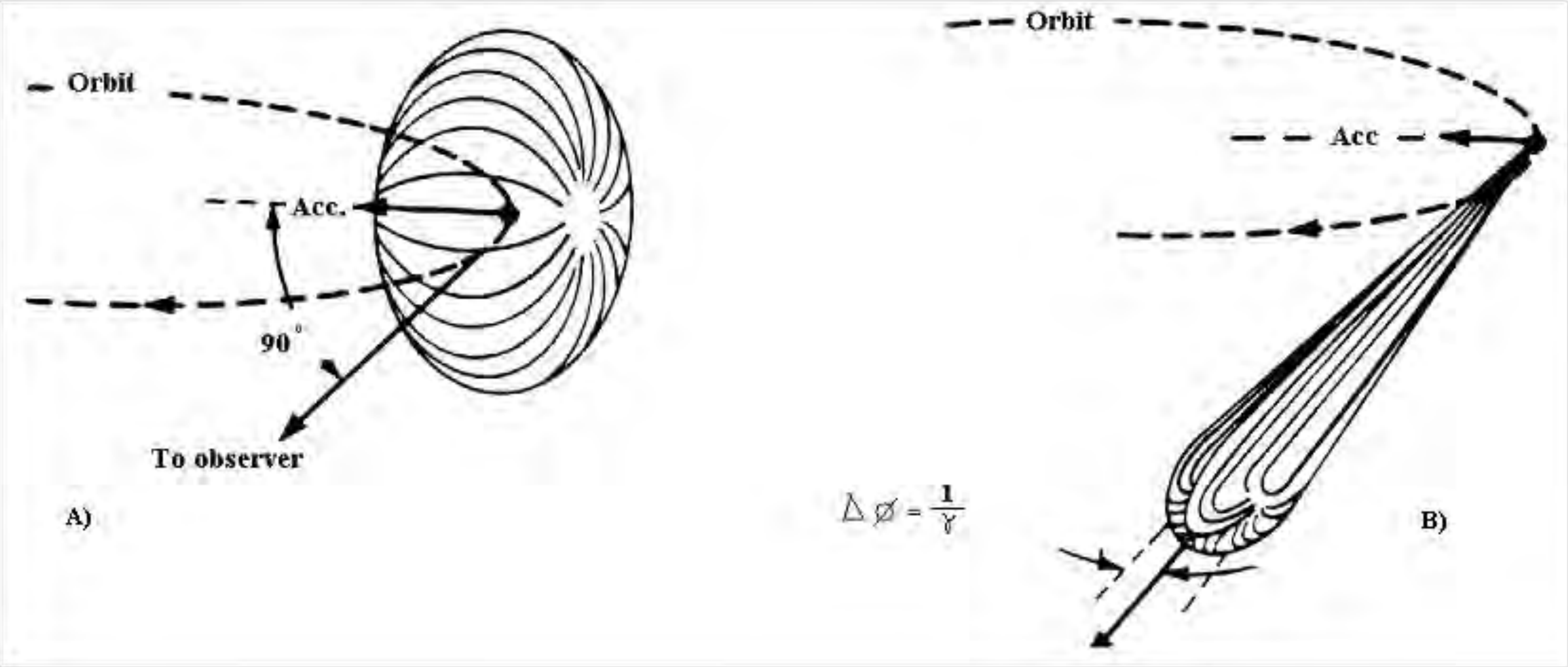


Fig. 4 Synchrotron radiation at v = 0.9c. Snapshot from the Radiation 2D.

Tsumoro Shintake

Emission by Relativistic Particles



D. H. Tomboulian and P. L. Hartman, Phys. Rev. 102 (1956)

Properties of Synchrotron Radiation

- High flux
- F = N/(s BW)
- High brilliance (spectral brightness)
- B = N/(s mm2 mrad2 BW)
- Polarization
- Pulsed time structure
- Stability
- Power can be computed from first principles

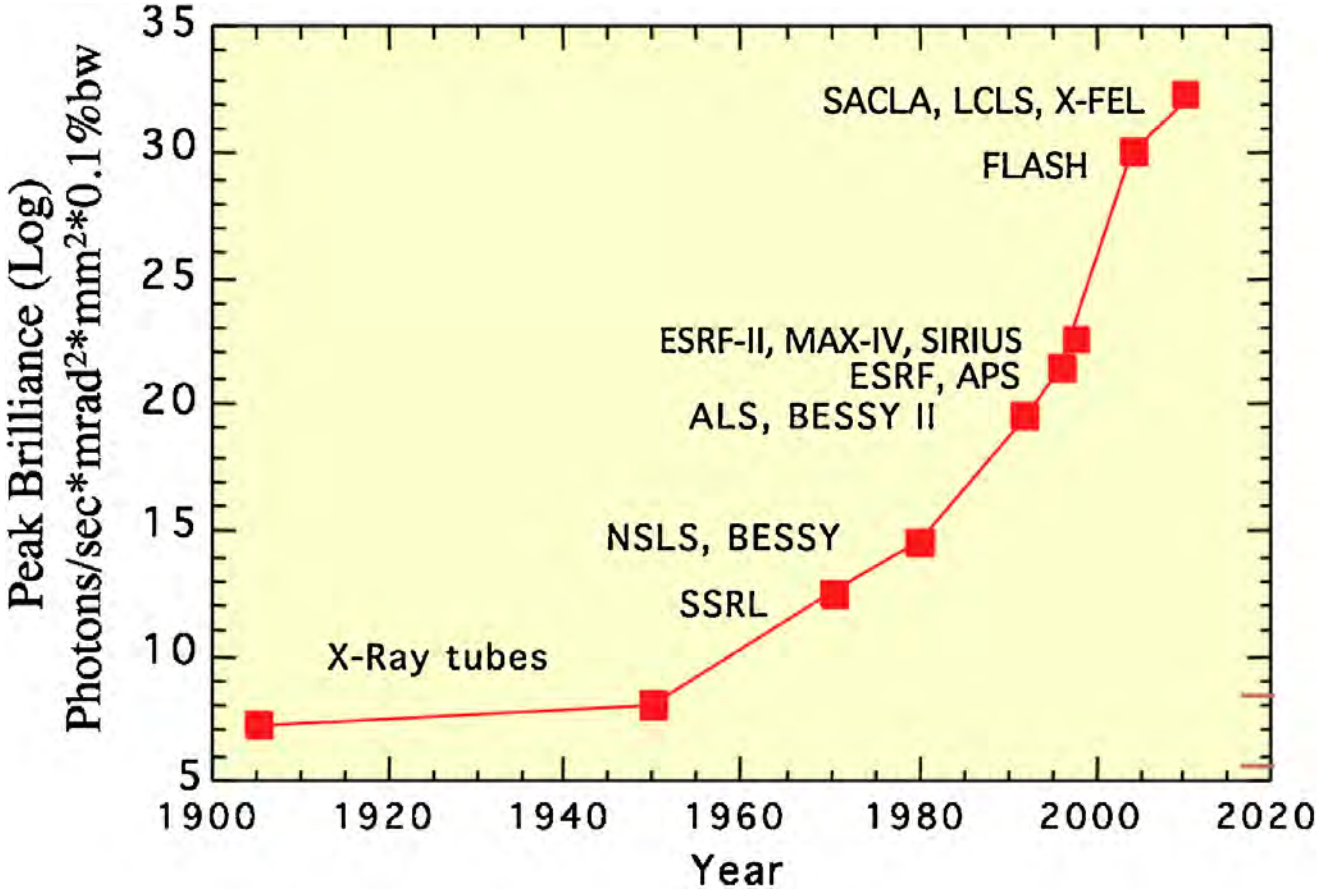
Brilliance

- Key figure of merit comparing different photon sources

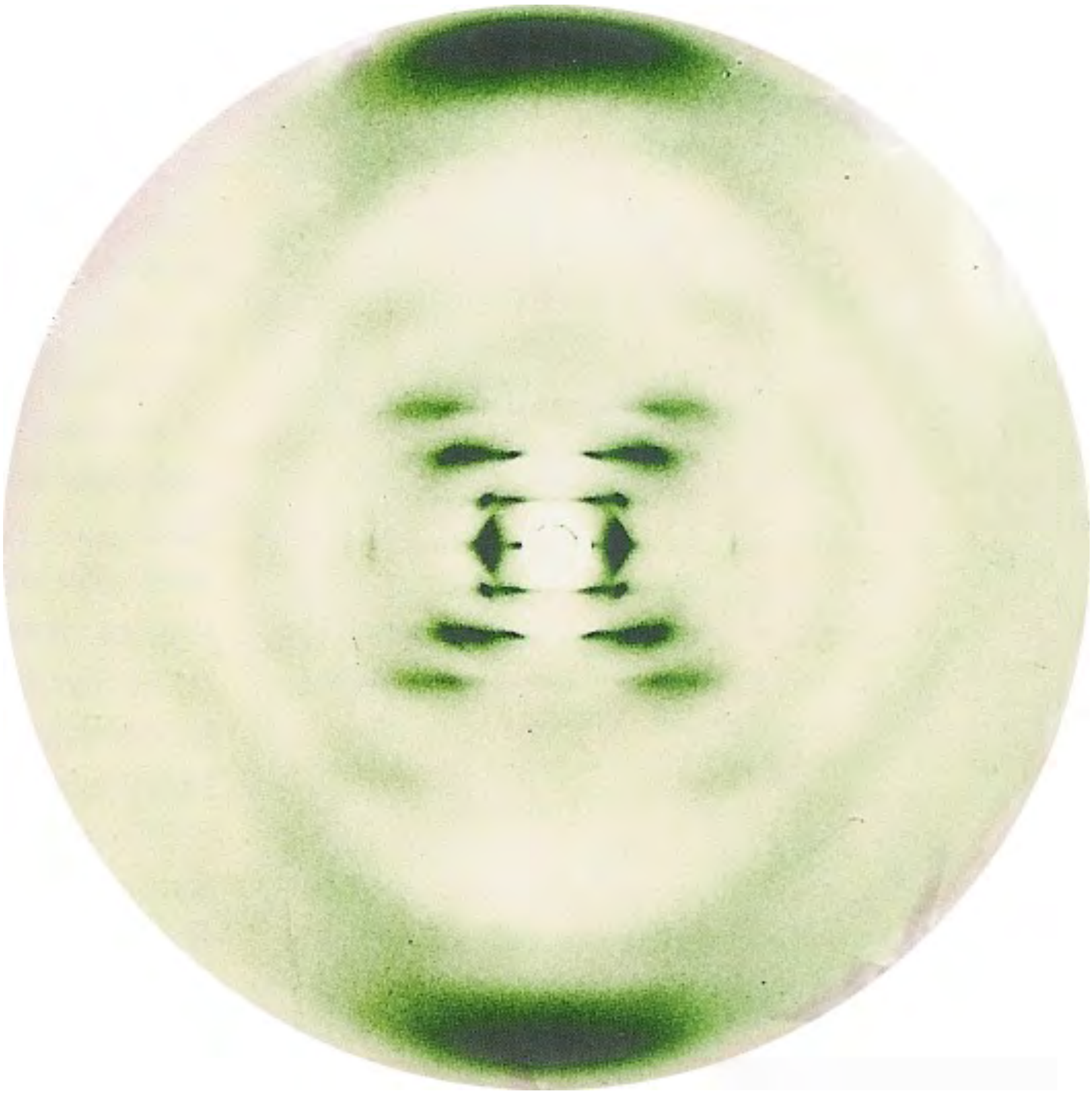
$$\mathcal{B} = \frac{\dot{N}_\gamma}{4\pi^2 \sigma_x \sigma_y \sigma_{x'} \sigma_{y'} (0.1\%\mathrm{BW})}$$

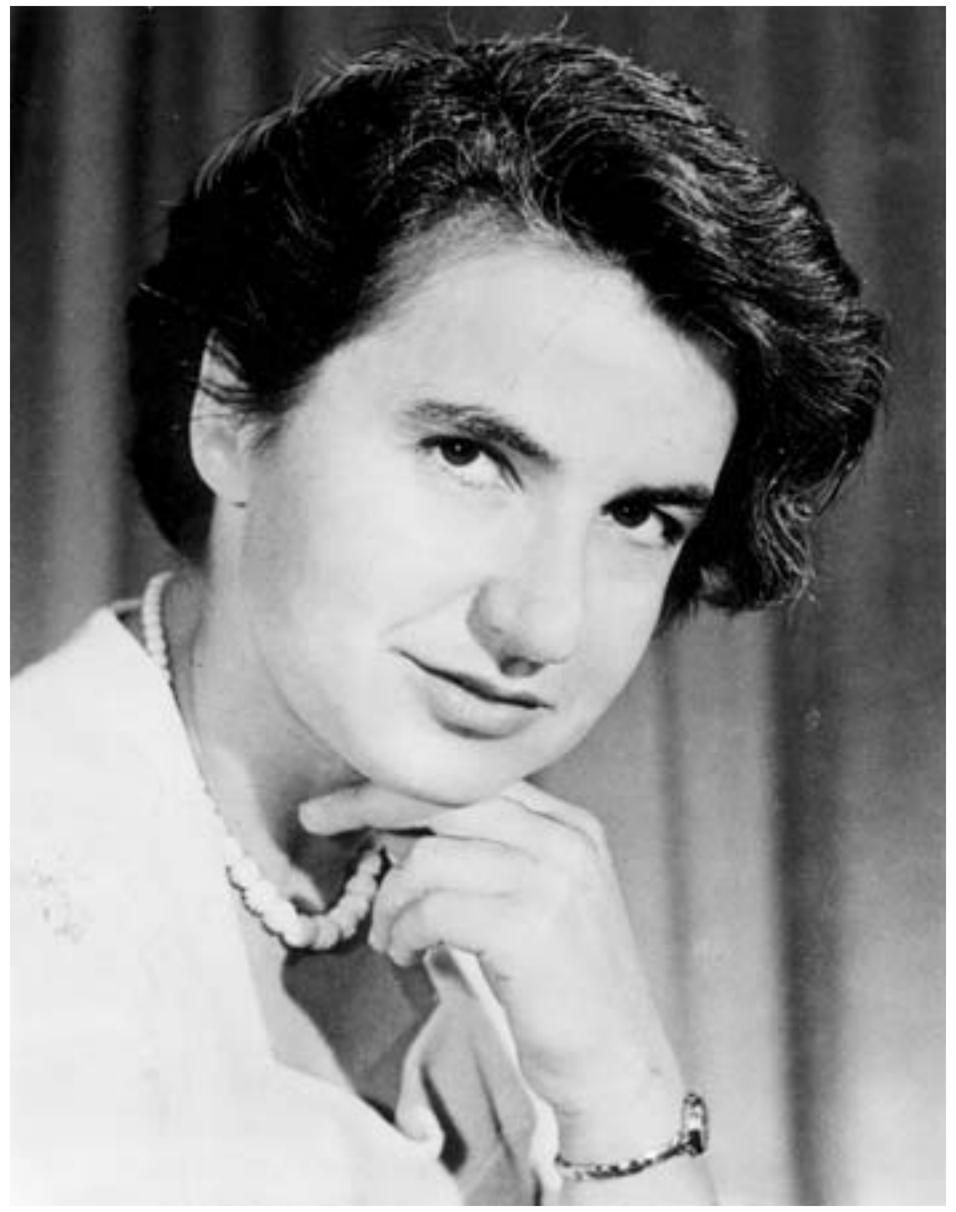
- Average brilliance for photon-hungry experiments
- For some experiments, the peak brilliance is very important
  - More in the lecture about the interaction of X-rays with matter
  - Free electron lasers have a peak brilliance that is 1’000’000’000 times larger than that of synchrotrons

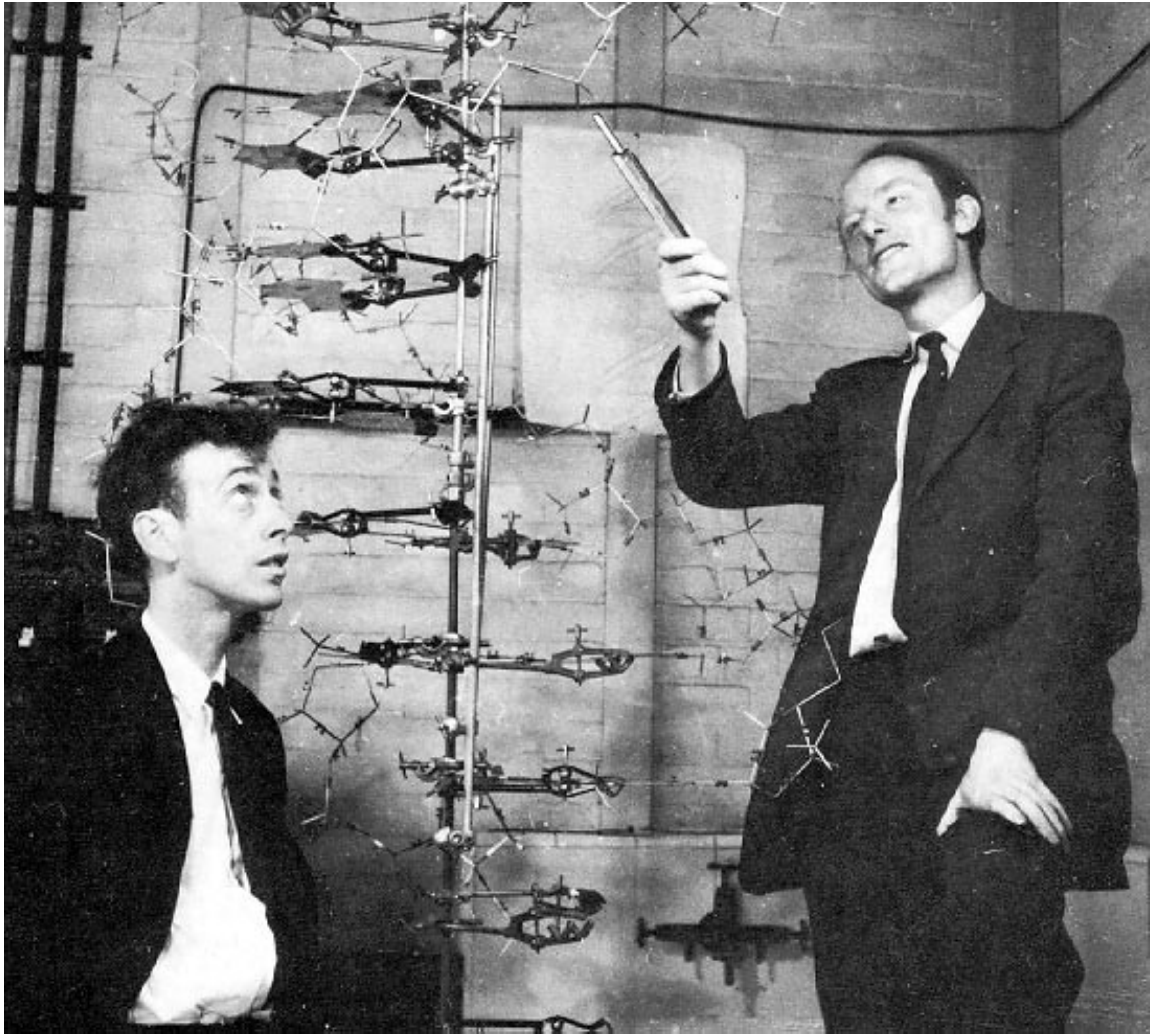
X-Ray Sources



W. Eberhardt / Journal of Electron Spectroscopy and Related Phenomena 200 (2015) 31–39







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Undulator Radiation

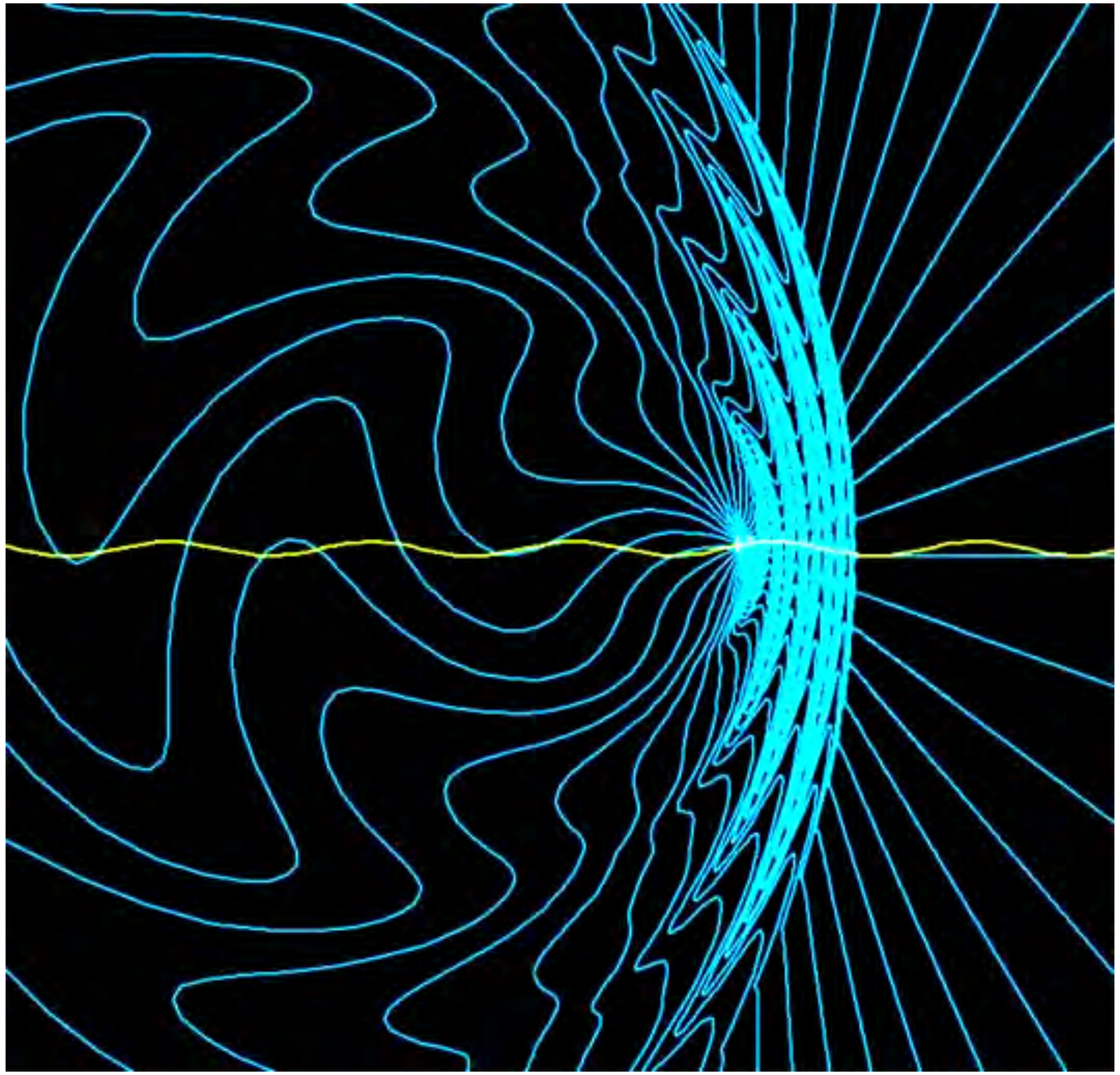
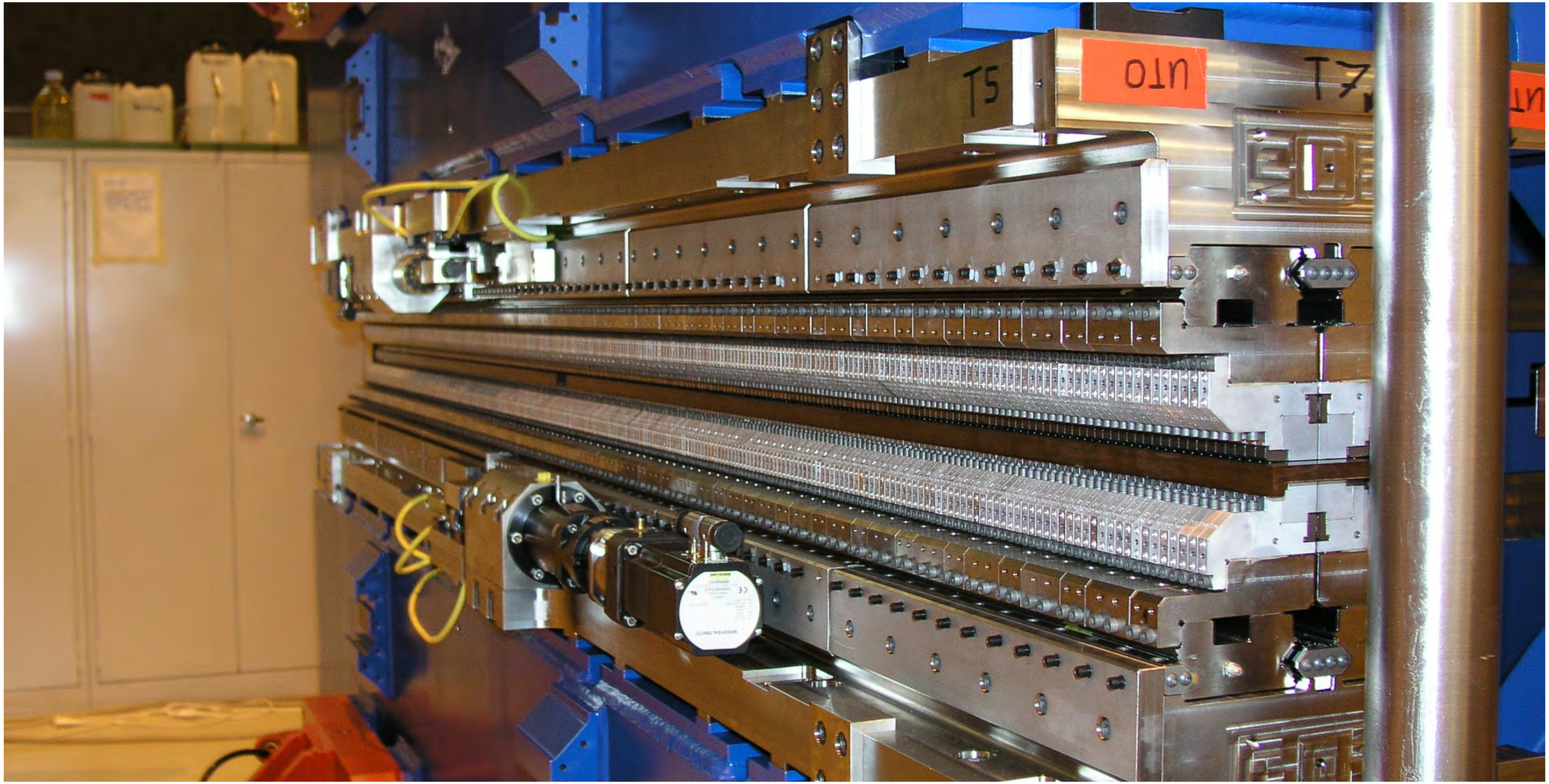


Fig. 5 Undulator radiation, v = 0.9c, K = 1. Snapshot from the Radiation 2D.

Tsumoro Shintake

Undulator Radiation



PSI Bilddatenbank

How Does the Brilliance of Radiation Emitted by an Undulator Grow with the Number of Magnet Poles?

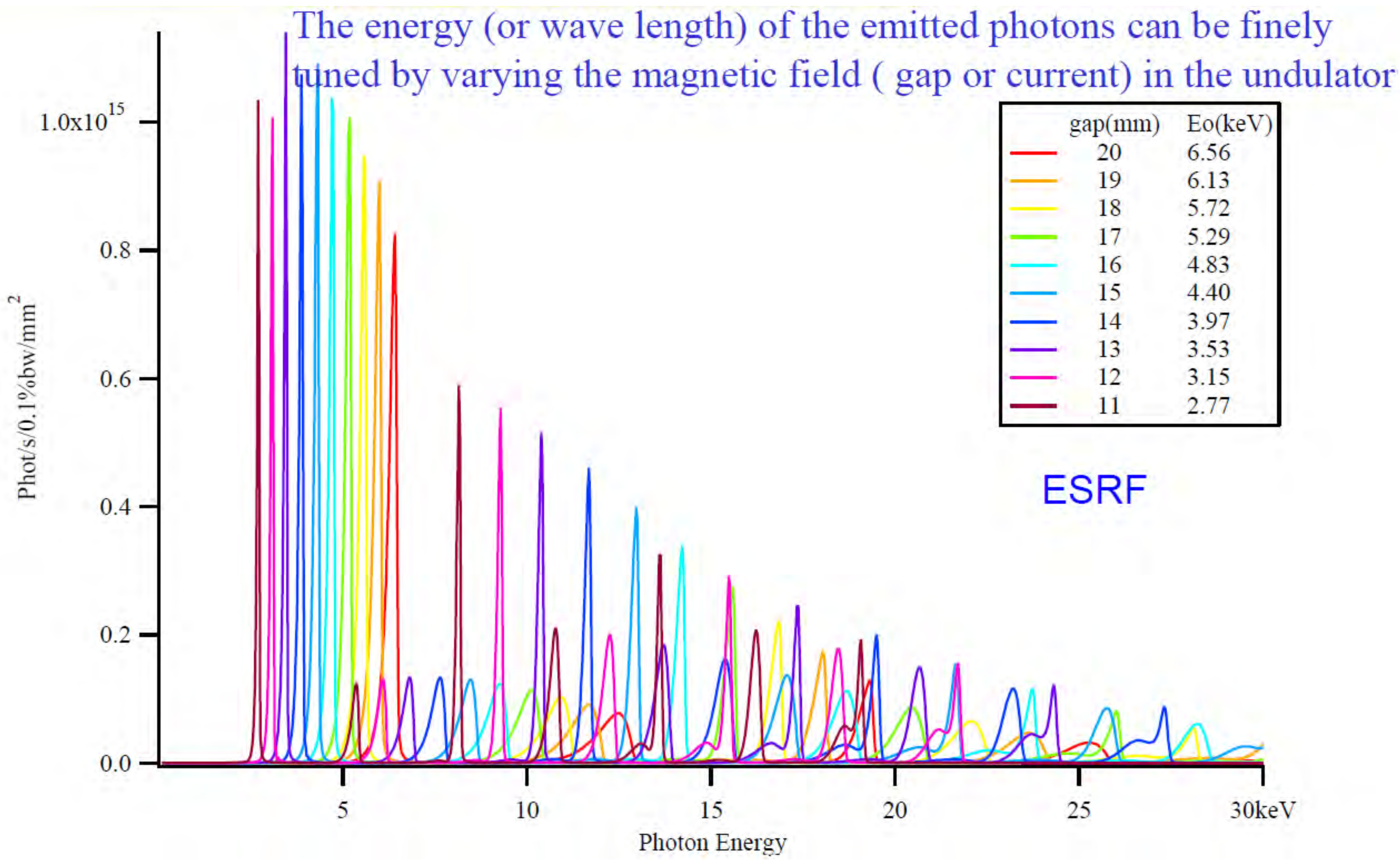
It is independent of the number of poles

It grows linearly

It grows quadratically

It grows exponentially

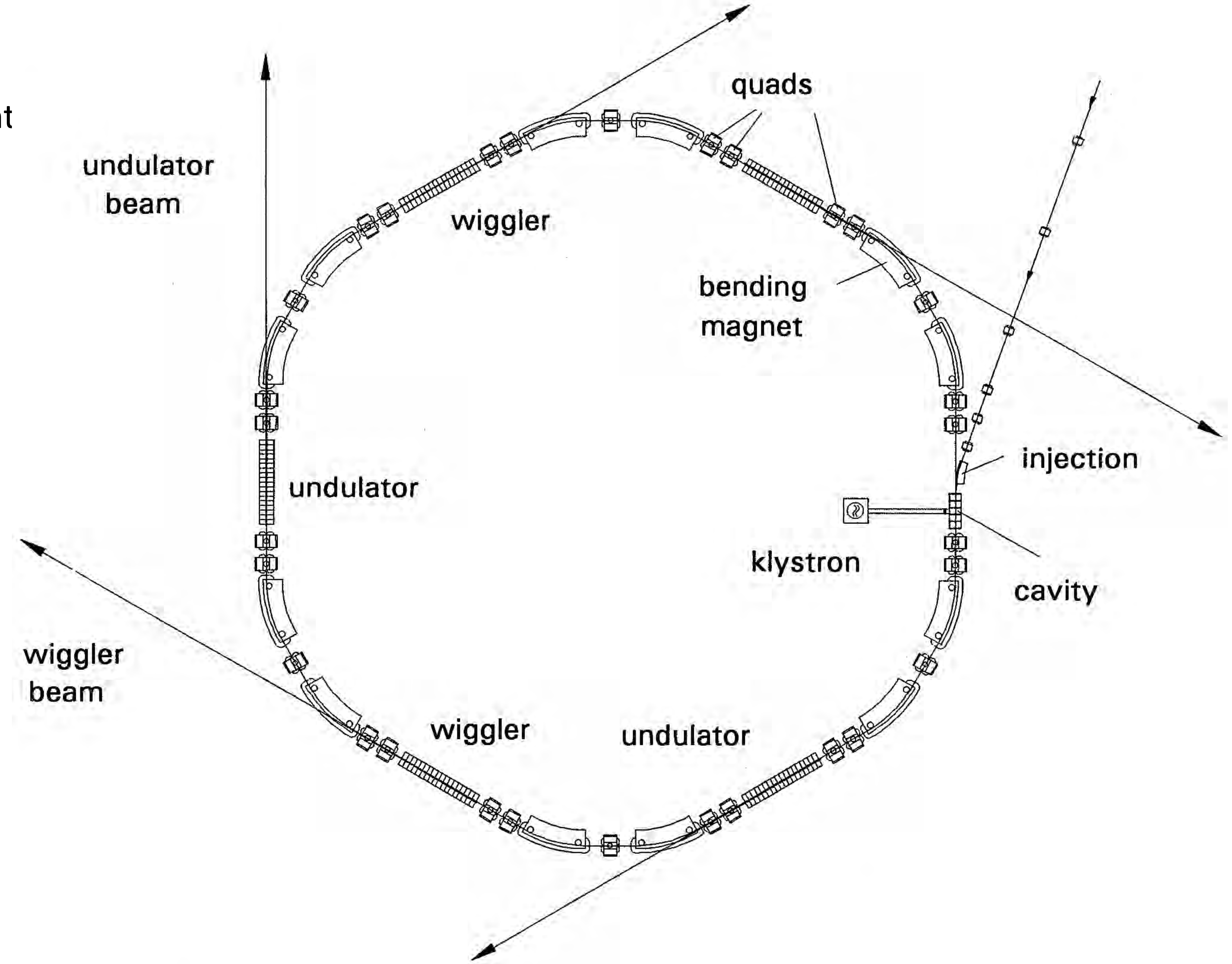
Tunability of undulator radiation



Courtesy J.M Filhol

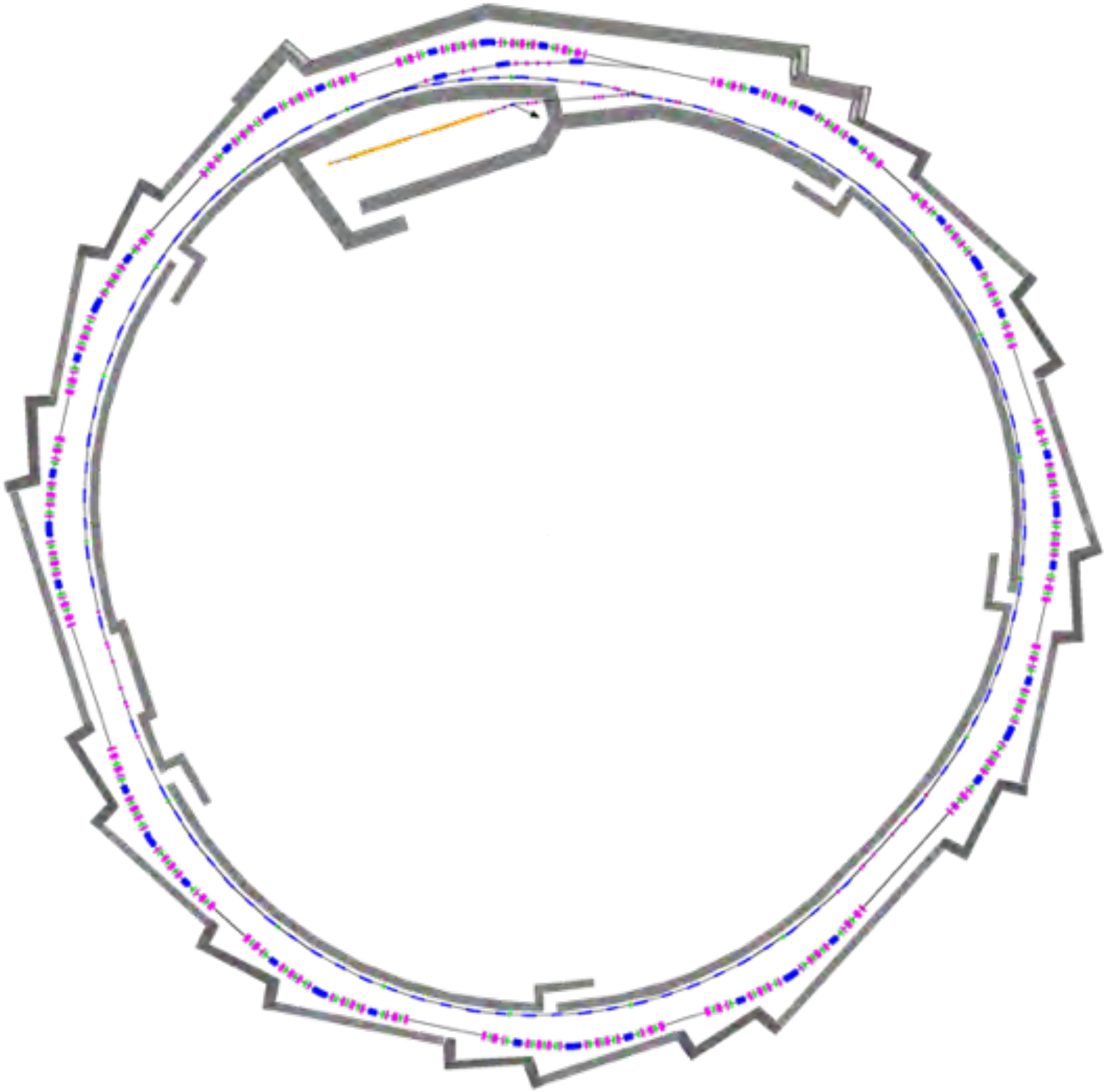
Layout of a Synchrotron Radiation Source

- Bends serve also as extraction point
- Straight sections for
  - injection
  - insertion devices

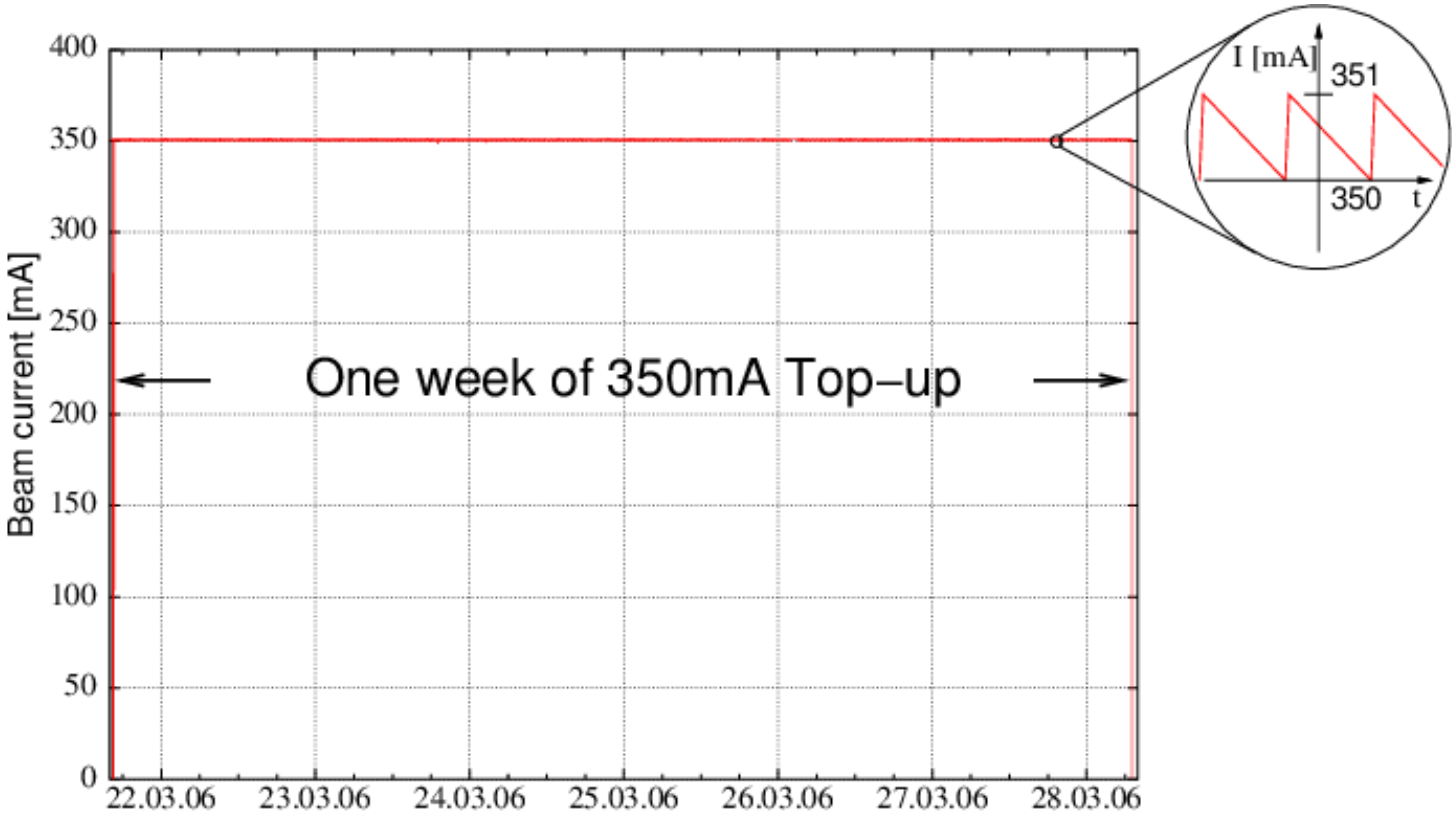


Layout of the Swiss Light Source

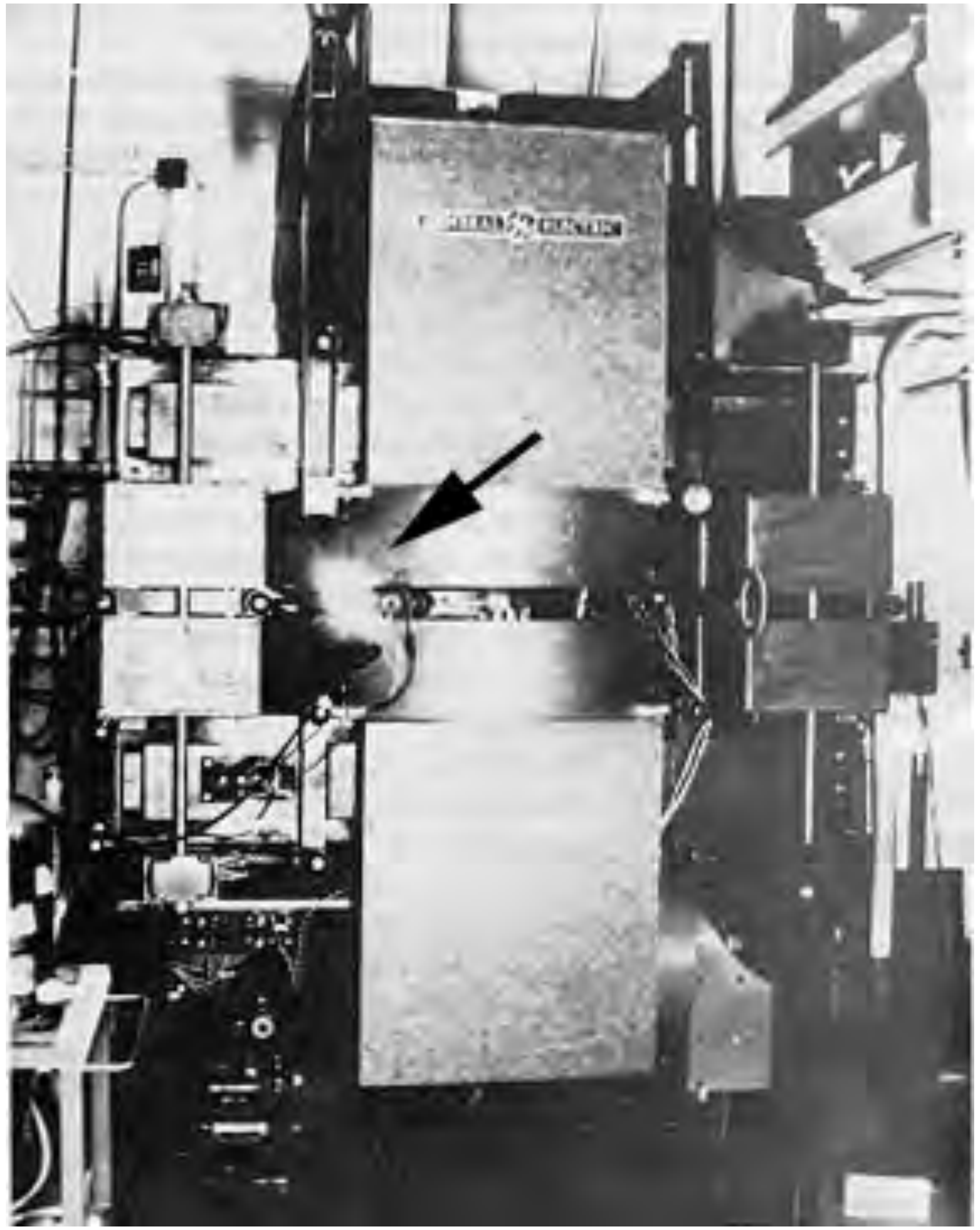
- 3rd generation light source
- Start of user operation in 2001
- Circumference: 288 m
- Particle energy: 2.4 GeV
- 12 triple bend achromats
- 12 straight sections
  - Dispersion-free
  - 1 for injection
  - 2 for acceleration
  - 1 for harmonic RF
  - 8 for undulators
- Injection at full energy
  - Top-up mode possible



Top-Up Operation

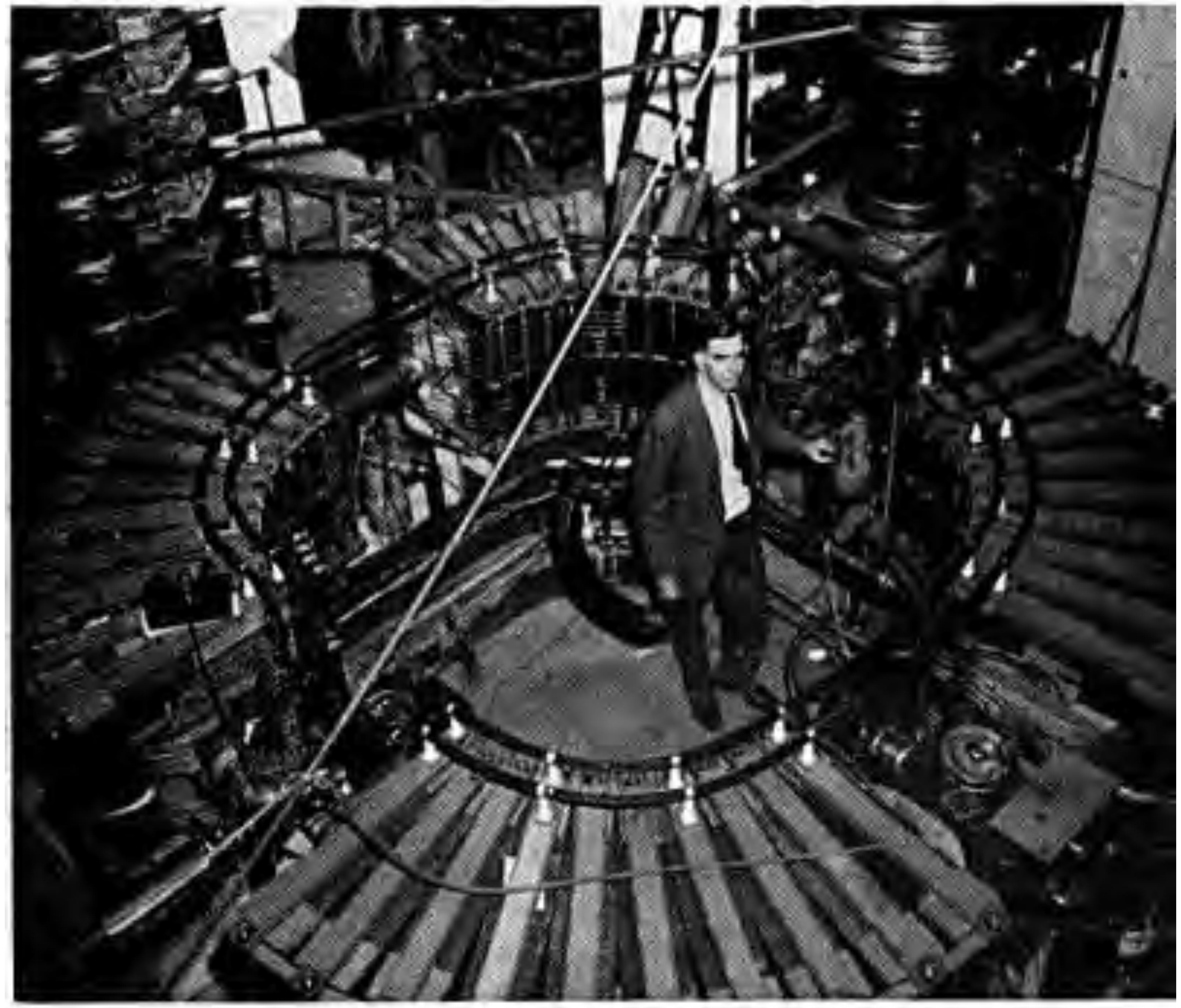


History of Synchrotron Radiation

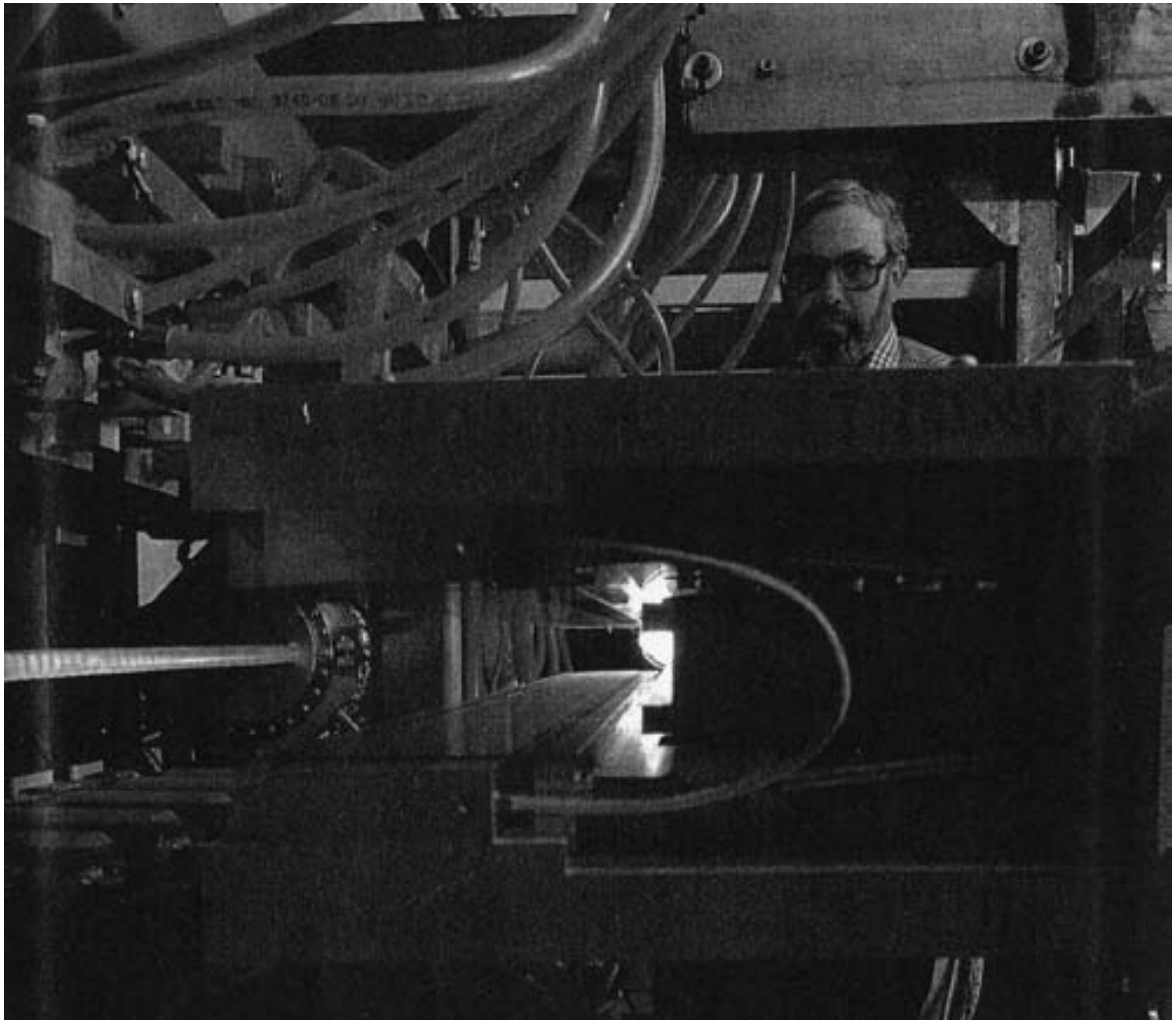


NSLS, Brookhaven

Evolution of Synchrotrons



Wigglers and Undulators



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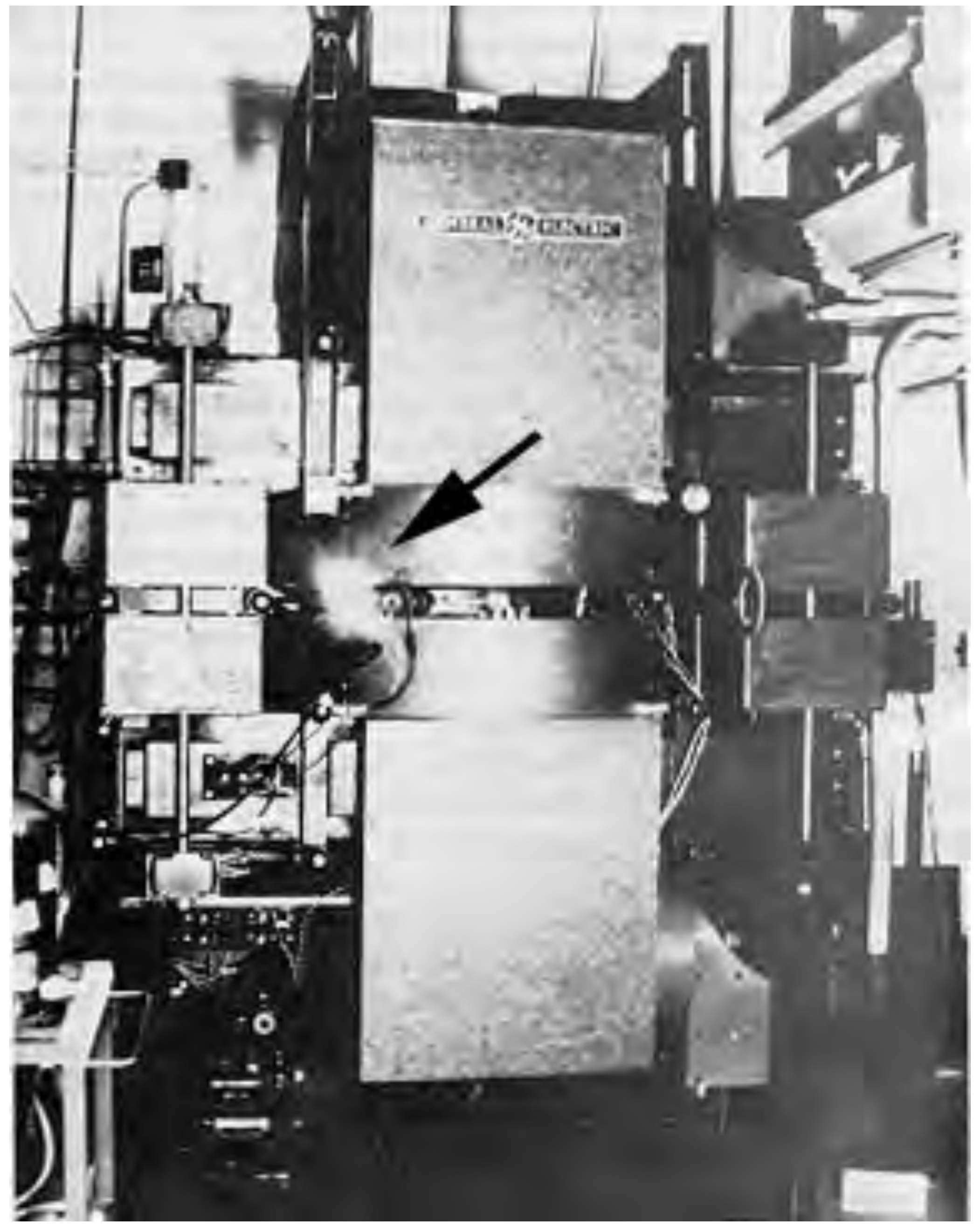
Evolution of synchrotron radiation sources (I)



- **First observation**:

  1947, General Electric, 70 MeV synchrotron

- **First user experiments**:

  1956, Cornell, 320 MeV synchrotron

- **1st generation light sources**: machine built for High Energy Physics or other purposes used parasitically for synchrotron radiation

- **2nd generation light sources**: purpose built synchrotron light sources, SRS at Daresbury was the first dedicated machine (1981 – 2008)

- **3rd generation light sources**: optimised for high brilliance with low emittance and Insertion Devices; ESRF, Diamond, …

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Evolution of synchrotron radiation sources (II)

• **4th generation light sources**: photoinjectors LINAC based Free Electron Laser sources;

FLASH (DESY) 2007

LCLS (SLAC) 2009

SACLA (Japan) 2011

Elettra (Italy) 2012

and in the near(?) future

• **4th generation light sources storage ring based**: diffraction limited storage rings

• …and even a **5th generation** with more compact and advanced accelerator technologies e.g. based on laser plasma wakefield accelerators

Synchrotrons around the World

Questions?

Nick Veasey