Introduction to synchrotron radiation.

Historical overview about X-ray production: from X-ray tubes to modern synchrotrons and X-ray free electron lasers. Brief introduction about synchrotron radiation (SR) light generation. Parts of the synchrotron. Properties of SR light that makes it unique (high brilliance, broad energy spectrum, polarization, pulsed time structure). SR sources and XFELs around the world (in Europe and closer to the Mediterranean basin).

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Why do we need X-rays to explore matter?

Understand materials behaviour

Detect pollutants

Image tissues

Cure diseases

Design improved materials

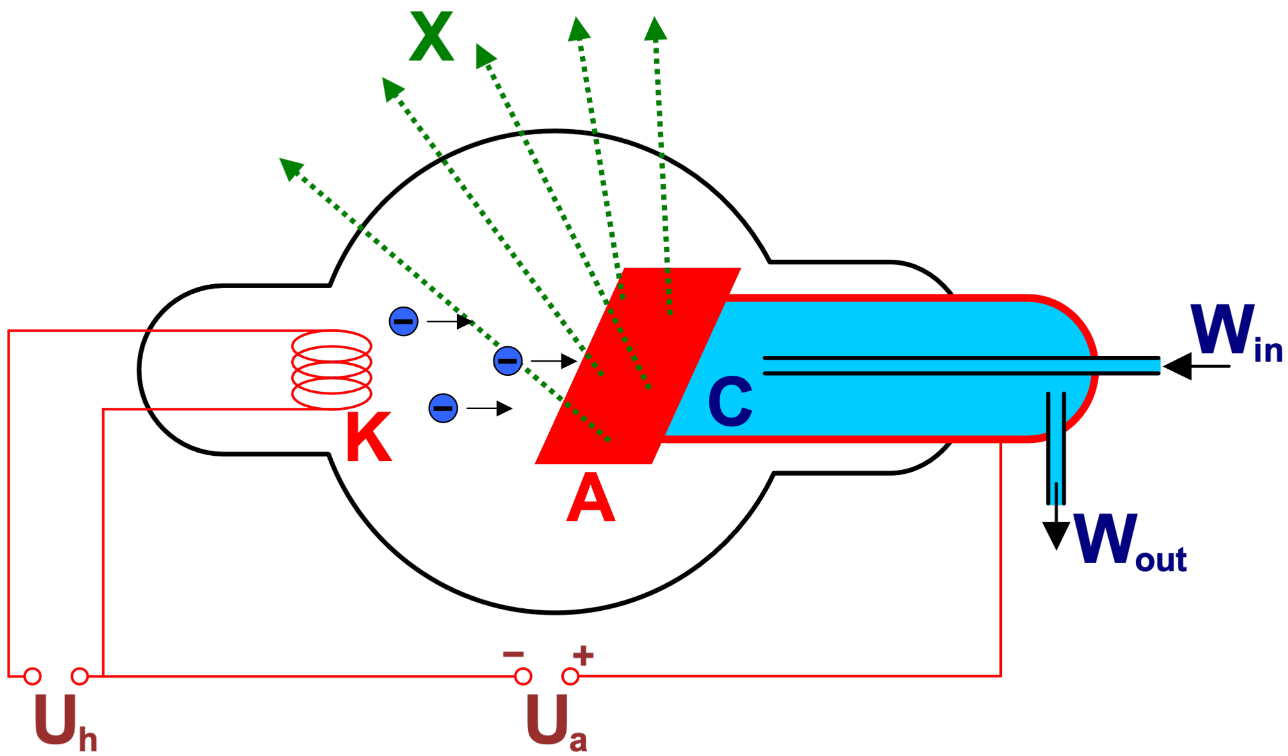
Protect cultural heritage

Continue to advance knowledge in all scientific disciplines

- First Physics Nobel price
  1901 Wilhelm RÖNTGEN

What are X –rays?

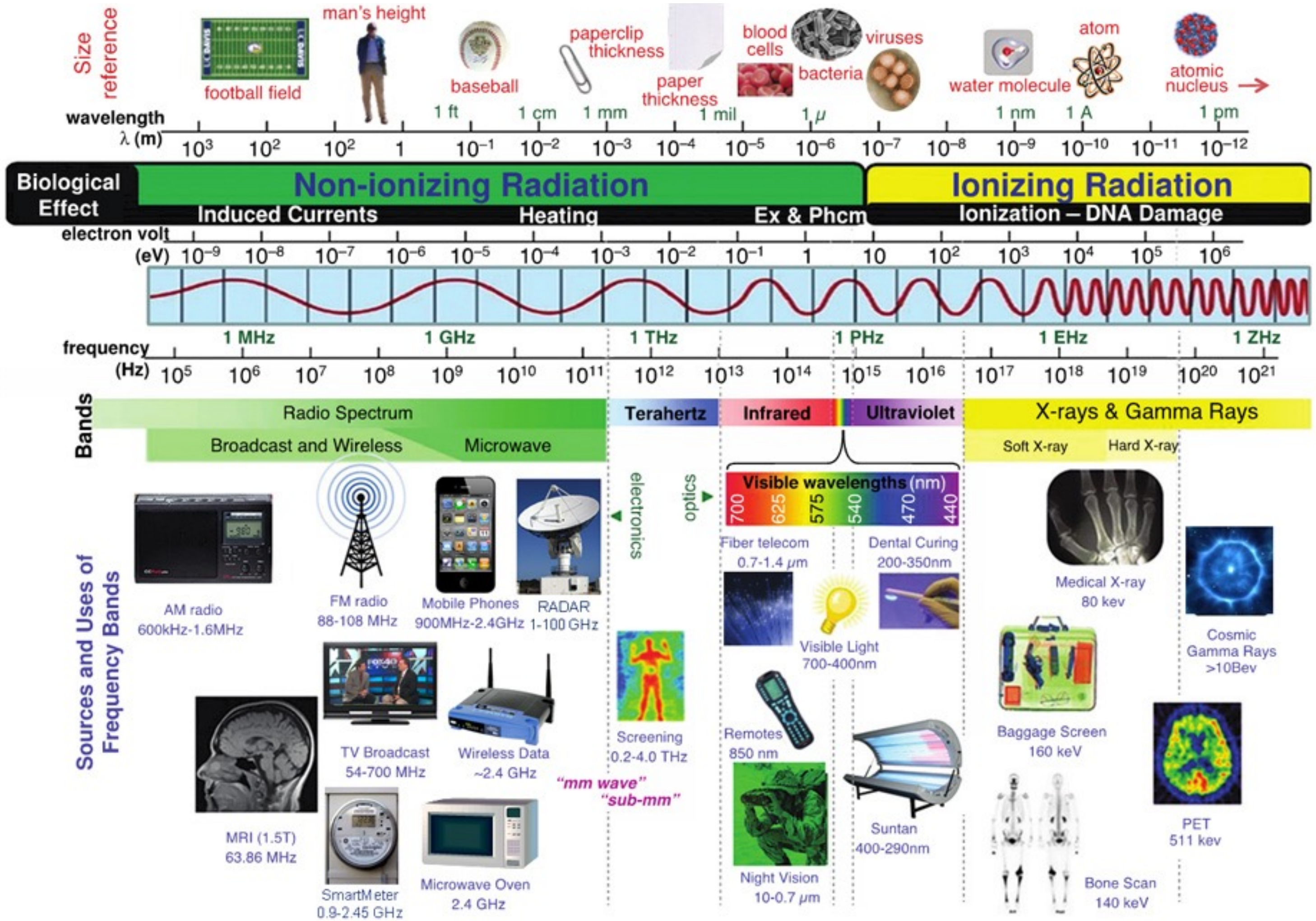
Schematic of W. RÖNTGEN experimental setup



Energetic negative charged particles colliding on an heavy atom containing anode produce x-rays. X-rays are travelling straight.

First ***Röntgenogram*** **:** the hand of Anna RÖNTGEN taken the 22nd december 1895

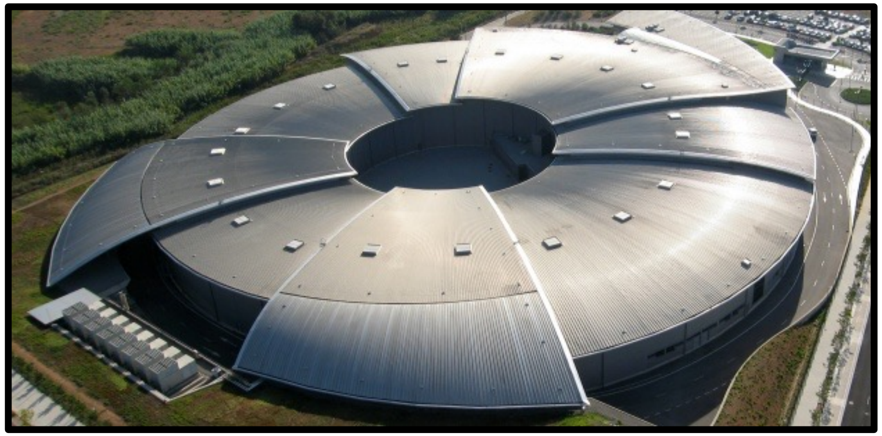
Electromagnetic radiation spectrum

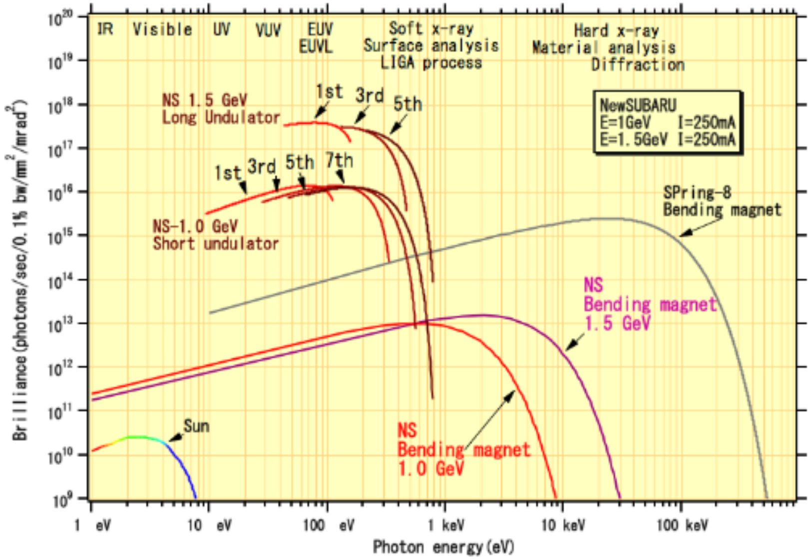


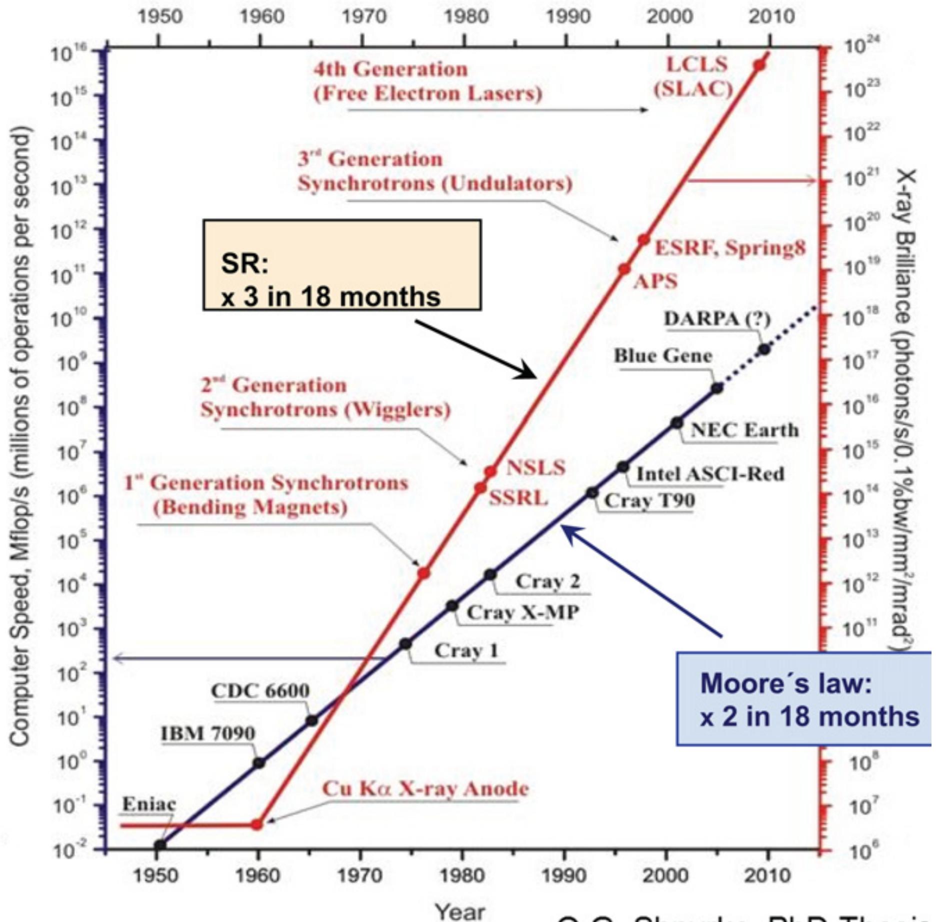
SYNCHROTRON RADIATION LIGHT

Why synchrotron light sources?

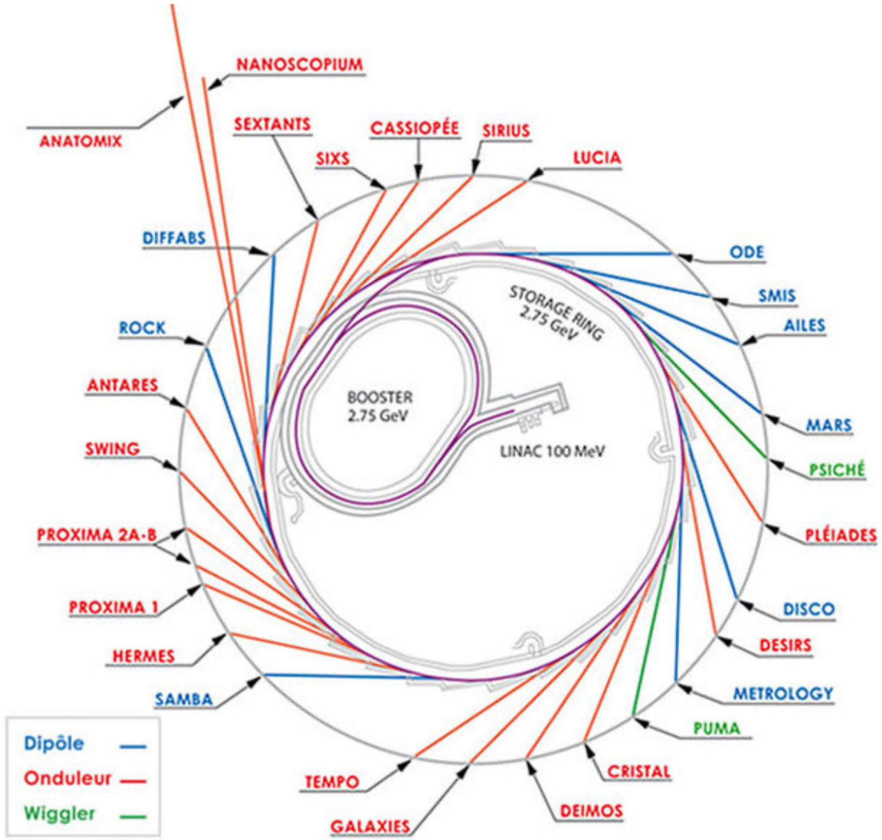
… much much… much more intense than laboratory sources







O.G. Shpyrko, PhD Thesis



Schematic overview of SOLEIL Synchrotron Radiation facility

Multidisciplinary infrastructure (Physics, Chemisty, Biology, environment, culture heritage…)

About 3000 scientist are participating to experiments at SOLEIL every year

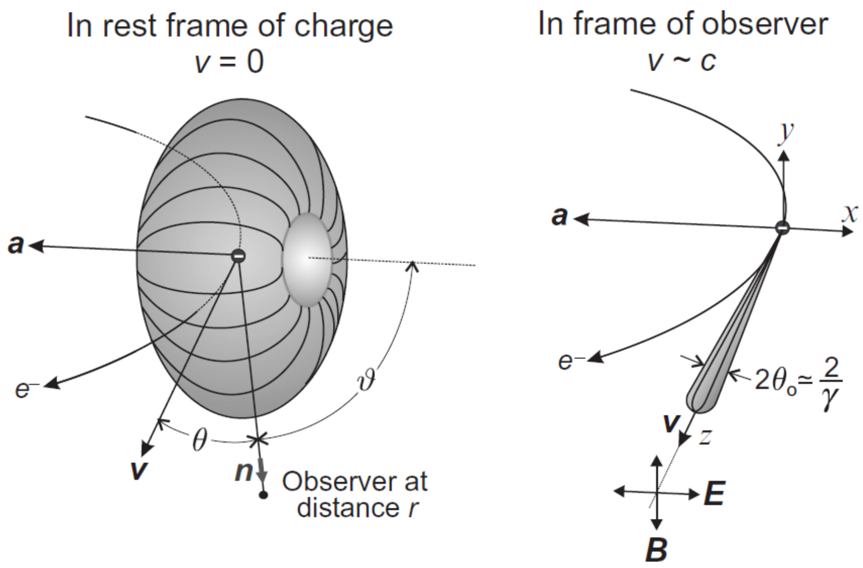
30 beamlines are working simultanously

How synchrotrons produce light?

… emission from accelerated charged particles

Emission of synchrotron radiation light is a **relativistic phenomenon** which occurs when an **accelerated charged particle** (e.g. electron), travelling at a **velocity close to the speed of light, curves its trajectory**.

The synchrotron radiation is **emitted tangentially to the electron orbit.**



$$\boxed{\frac{1}{\gamma} = \frac{m_o c^2}{E} = \sqrt{1 - (\frac{v}{c})^2}}$$

$\pm\frac{1}{\gamma}$: opening angle

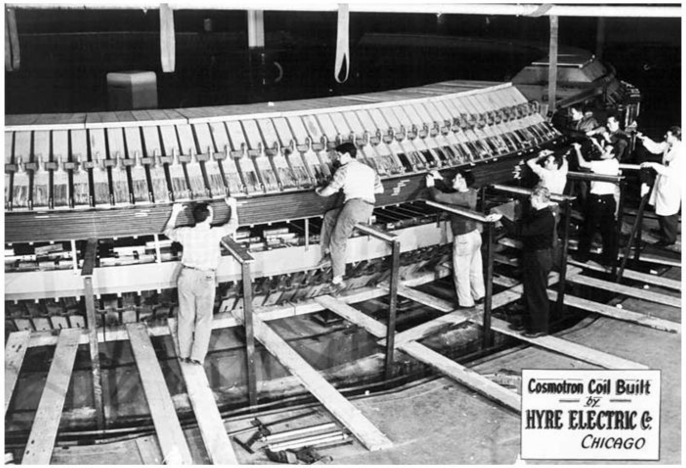
J. Stöhr and H.C. Siegmann, Magnetism: From Fundamentals to Nanoscale Dynamics (Springer , 2006)

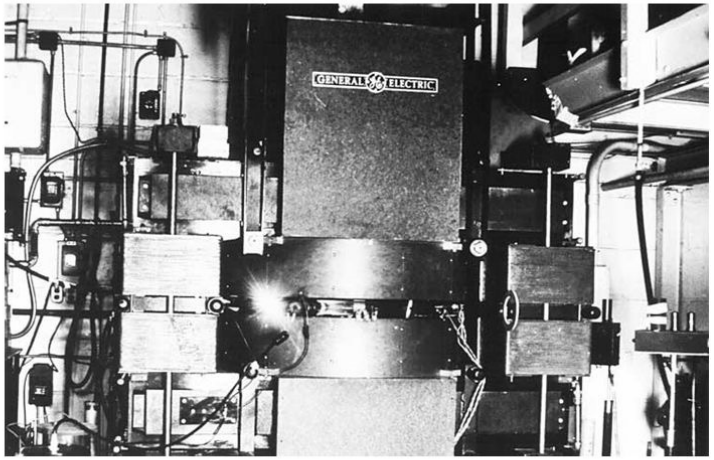
A bit of history…

- SR is as old as the stars…

Crab Nebula

1947: General Electric Research Laboratory in Schenectady (NY)





60's: start of the use of SL in accelerator

(First generation)

SR light properties

Then... why SR??

1. High spectral brightness
2. Broad Spectrum
3. Natural Narrow Angular Collimation
4. High Degree of Polarization
5. Pulsed Time Structure

SR Source Properties

1. High Brilliance/Brightness/spectral brightness:

Flux of photons per unit solid angle, or photons per second per area per unit solid angle and per 0.1% bandwidth.

It is necessary to account for the beam divergence. A perfectly collimated beam would have infinite brightness, regardless of the number of photons in it.

Spectral brightness: photons/(s·mm^2·mrad^2·(0.1% BW))

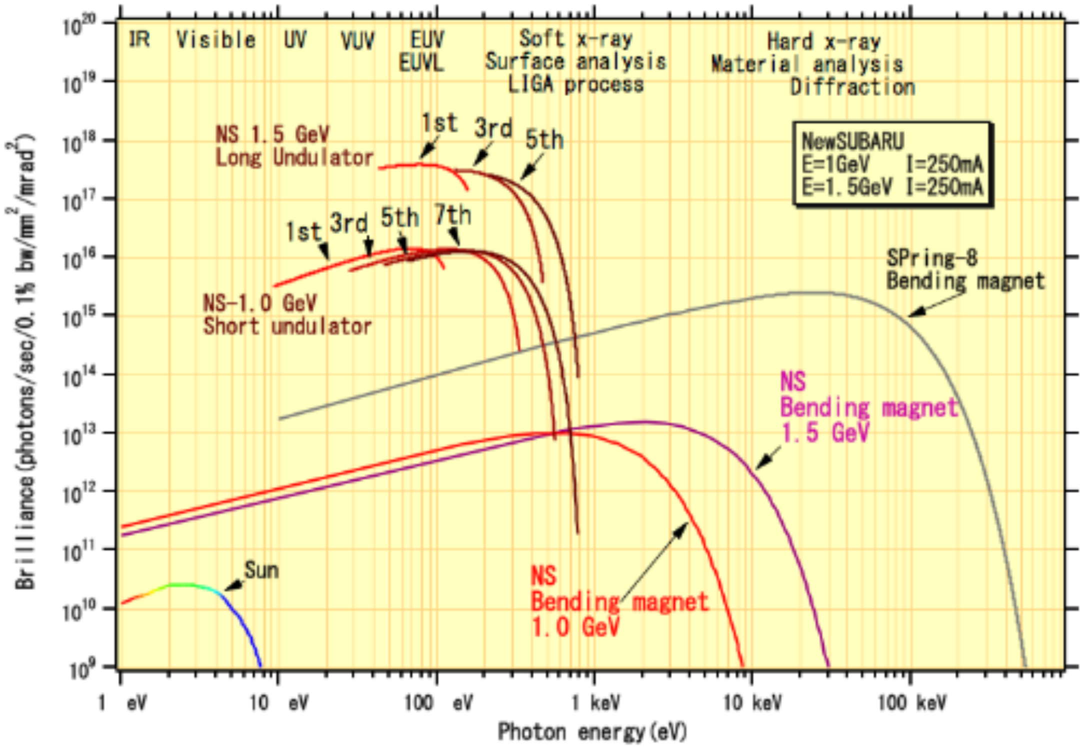
Low e-beam emittance is needed to achieve a high brilliance of SR light.

Gruner, S., Bilderback, D. And Tigner, M. White Paper. Synchrotron Radiation Sources for the Future.
http://www.lepp.cornell.edu/Publications/rsrc/LEPP/Publications/WebHome/ERLPub00_1.pdf

Mills et al., Report of the Working Group on Synchrotron Radiation Nomenclature – brightness, spectral brightness or brilliance?, J. Synchrotron Rad. (2005). 12, 385

SR Source Properties

2. Broad Spectrum: From far IR all the way to hard X-Rays

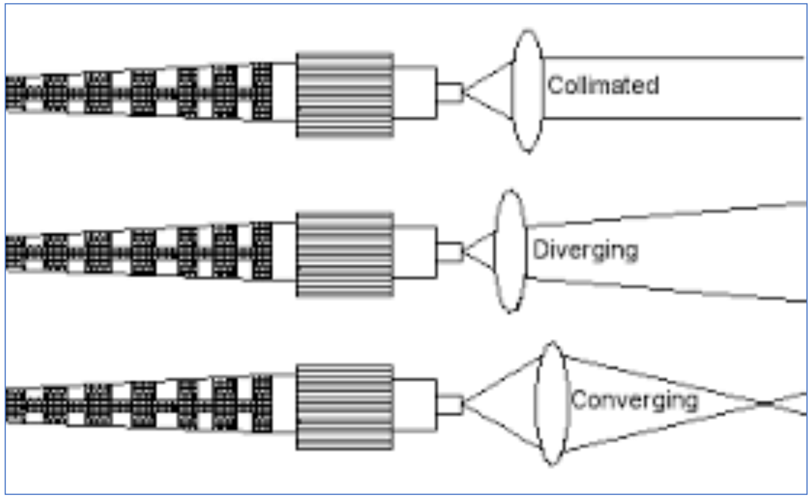


The wavelength can be tuned (monochromatized)

SR Source Properties

3. Natural Narrow Angular Collimation:

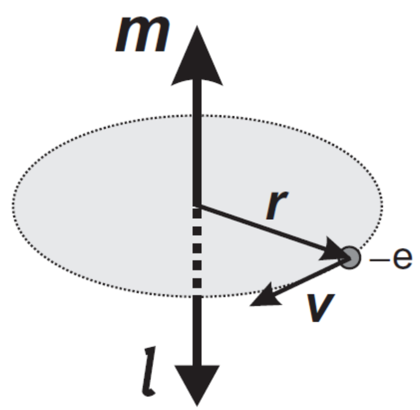
The divergence of the beam is very low that is, the beam is highly collimated (consisting of almost parallel rays)



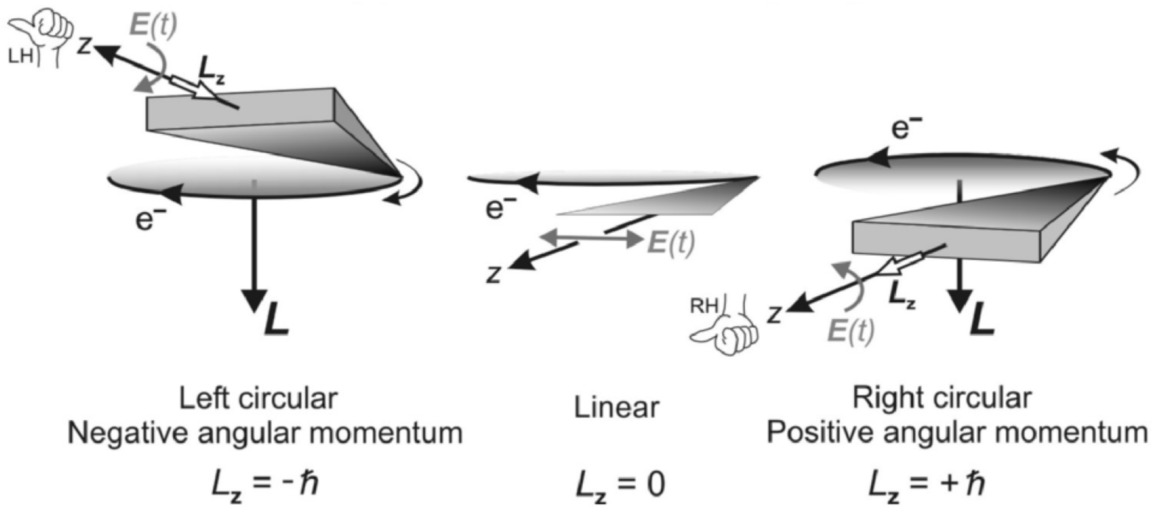
SR provides extremely high fluxes on very small areas

SR Source Properties

4. Polarization:



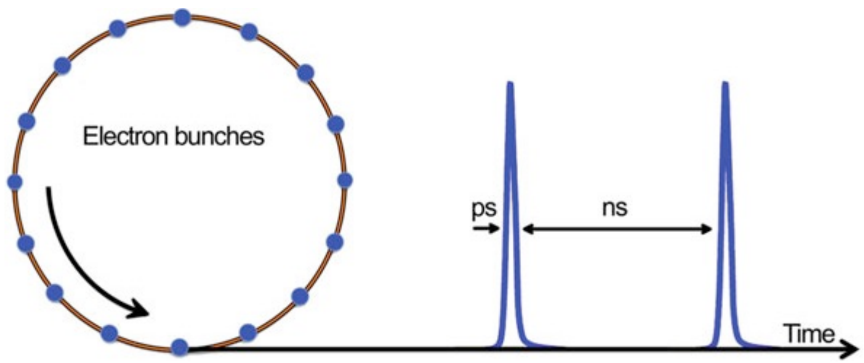
Electrons moving on a circular orbit have an angular momentum ***L***. When the accelerated electron radiates, it transfers both energy and angular momentum to the emitted photons.



SR Source Properties

5. Pulsed Time Structure:

The electrons are grouped in bunches and move in the circular orbit generating a pulsed light emission.



The frequency of these pulses is defined by the Radio Frequency (RF) cavity used and it is normally on the order of hundreds of MHz (ns).

The pulses have a time-width typically of few tens of ps (10^{-12} s!!).

What makes SR unique?

- The spectral brightness of the radiation emerging from storage ring is of the order of a billion times greater than from a typical laboratory X-ray source.

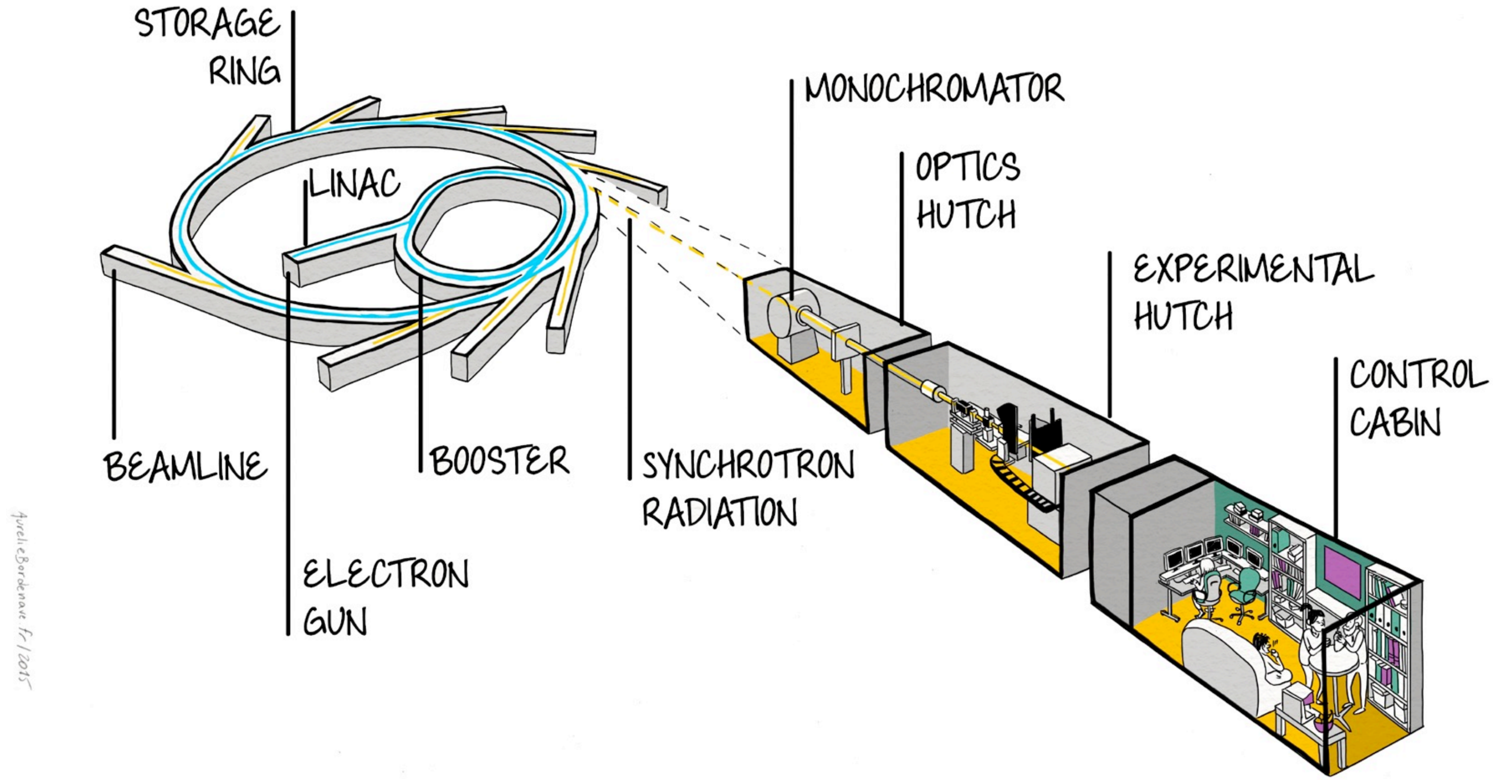
- The divergence of the beam is very low that is, the beam is highly collimated.

- The radiation extends from the IR to hard X-rays. Unlike most X-ray sources, it is tunable.

- The Synchrotron Radiation is naturally polarized.

- SR is pulsed with pulses typically 10-100 picoseconds in length separated by 10-100 nanoseconds (time structure).

Main Parts of a Synchrotron

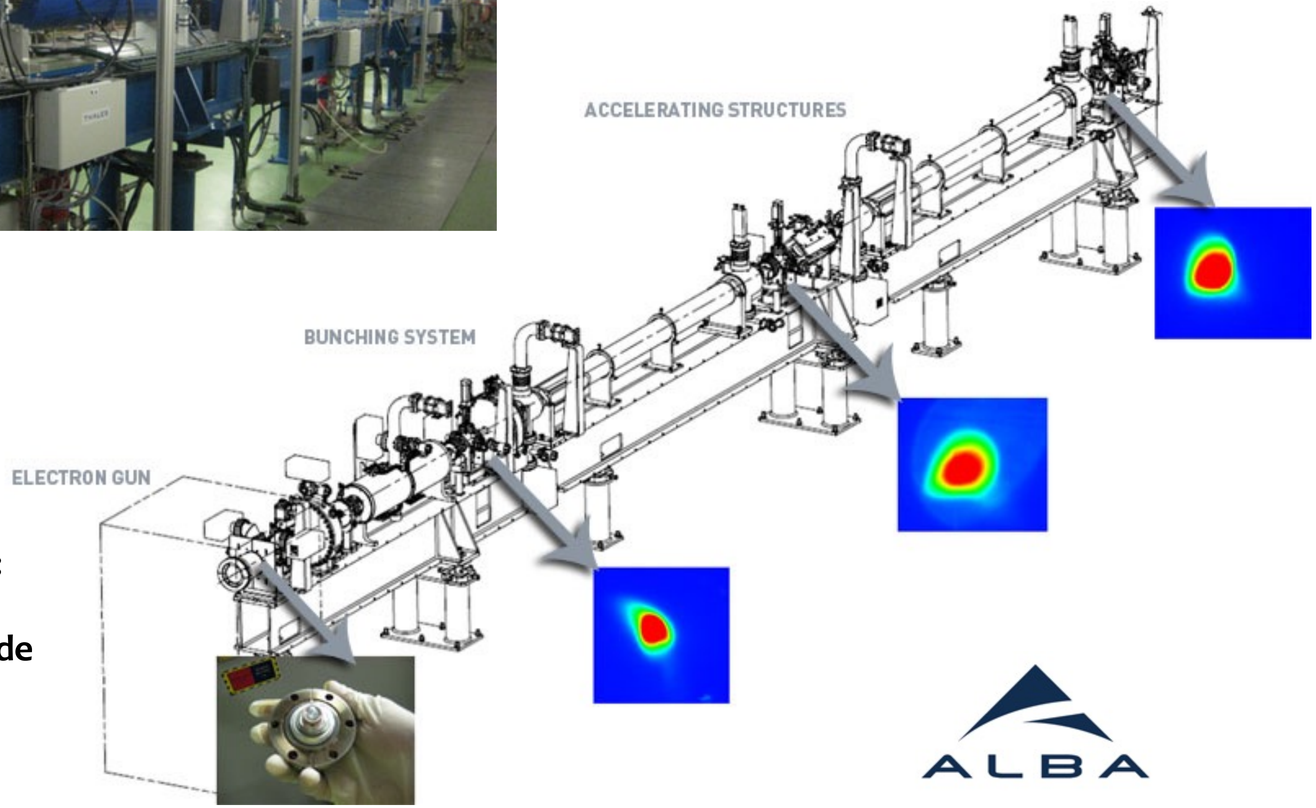


http://www.synchrotron-soleil.fr/Presse/Videos/Lumieres-de-SOLEIL
Synchrotron SOLEIL (illustration by AurelieBordenave.fr)

Acceleration of the electron bunches

LINAC (16 MeV → 110 MeV)

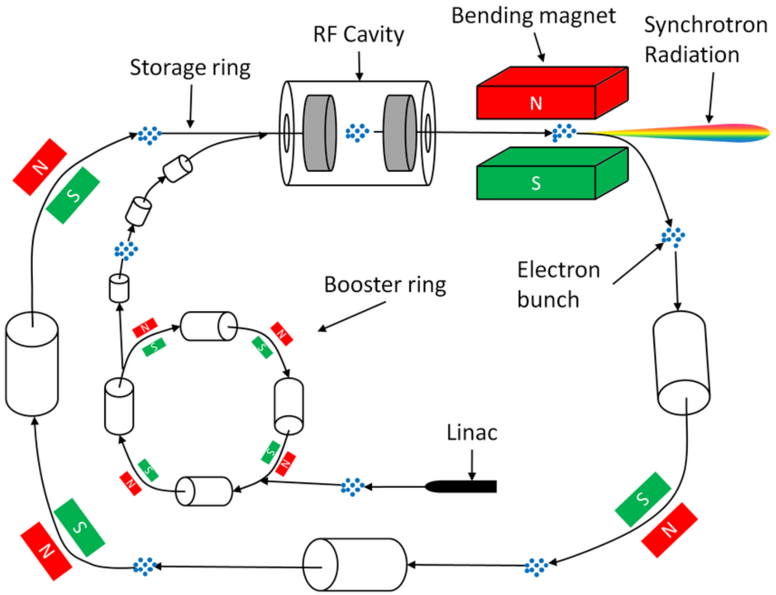
LINAC: LINear ACcelerator



Electron gun:
90kV DC
BaO@W cathode
(thermionic)

https://www.cells.es/en/accelerators/linac

The Electrons Travel along the Ring



BOOSTER RING (~100 MeV → GeV)

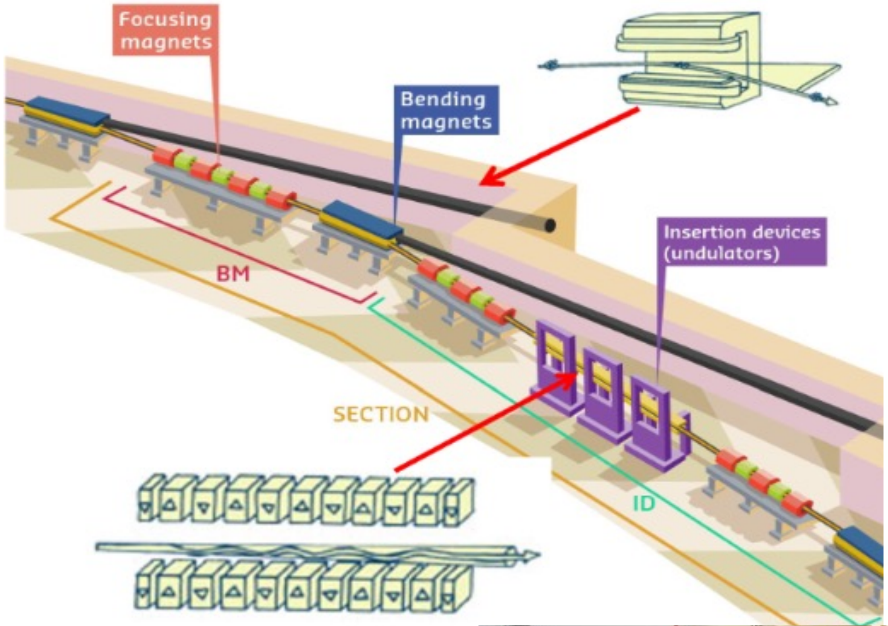
Tens of dipole magnets deflect the beam while the energy of the electron bunches is ramped up using RF cavities.

The magnetic lattices must provide an equilibrium emittance as low as 10 nm·rad. Such a small emittance, and electron beam size, provide high efficiency injection for the so-called top-up operation.

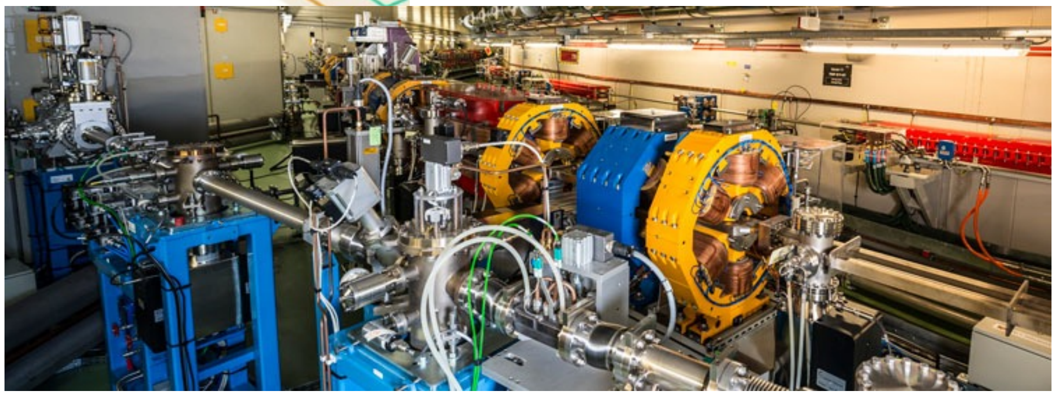
STORAGE RING (GeV)

Closed loop vacuum pipe in which the bunches circulate at nearly the speed of light. It is composed by several straight sections where the bunches are focused and deflected using magnetic fields. This deflection induces centripetal acceleration on the charged particles which produces synchrotron radiation light.

The Electrons Travel along the Ring



The storage ring is a very dense assembly of massive insertion devices and dipole magnets, complemented with focusing magnets, diagnostic devices, etc.



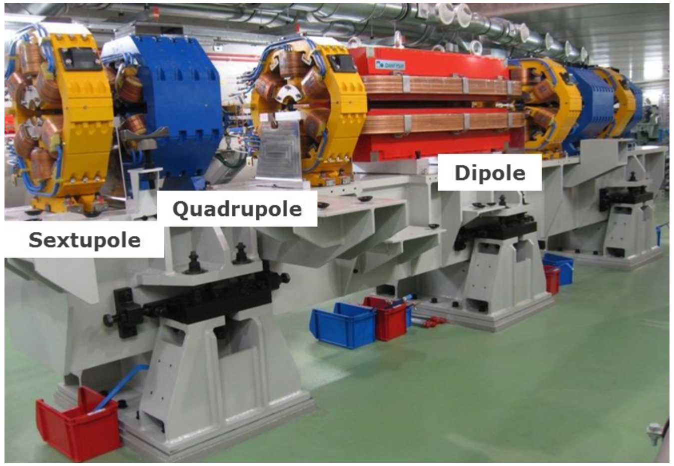
https://www.cells.es/en/accelerators/storage-ring

The Electrons Travel along the Ring

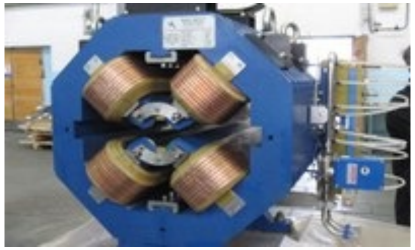
ALBA

Tunel: Thick concrete (and removable) slabs cover the booster and storage ring to prevent radiation to get out when the electron beam is in operation.

The Electrons Travel along the Ring



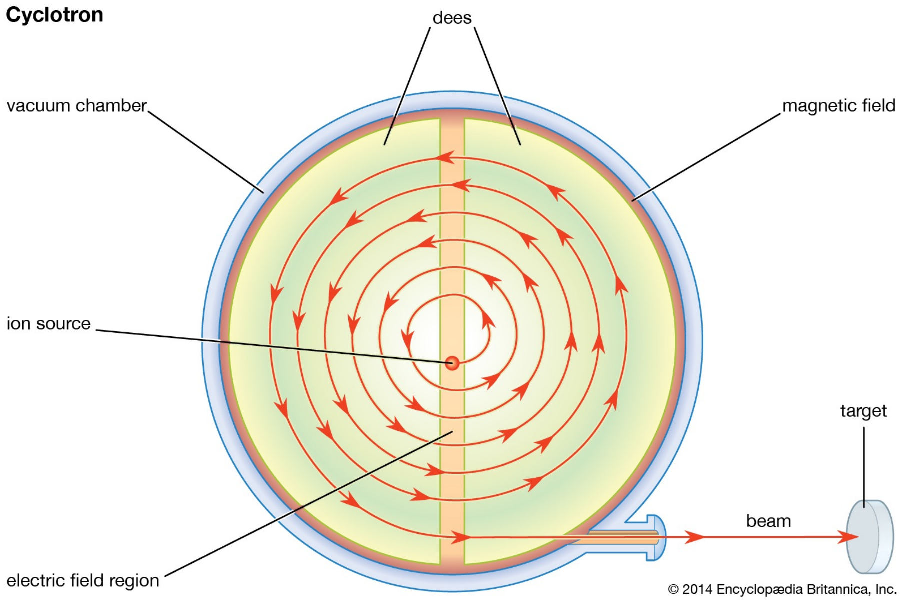
Electron beam energy	3 GeV
Storage Ring Circumference	269m



Quadrupole magnets: four magnetic poles (4 coils) in which the magnetic field increases linearly with the distance from the centre. Quadrupoles are <u>used to focus the electrons</u> and enable the transport of an electron beam over long distances.

Sextupole magnets: six magnetic poles are used to provide additional focusing <u>to correct chromatic aberrations</u>. The magnetic field increases quadratically with the distance from the centre.

Synchrotron (vs) Cyclotron



Contrary to the synchrotrons, in cyclotrons, the **beam is not "stored"** to generate light. The accelerated particles (MeV) are directed to a target where they collide.

Nowadays, cyclotrons are used for medical applications:

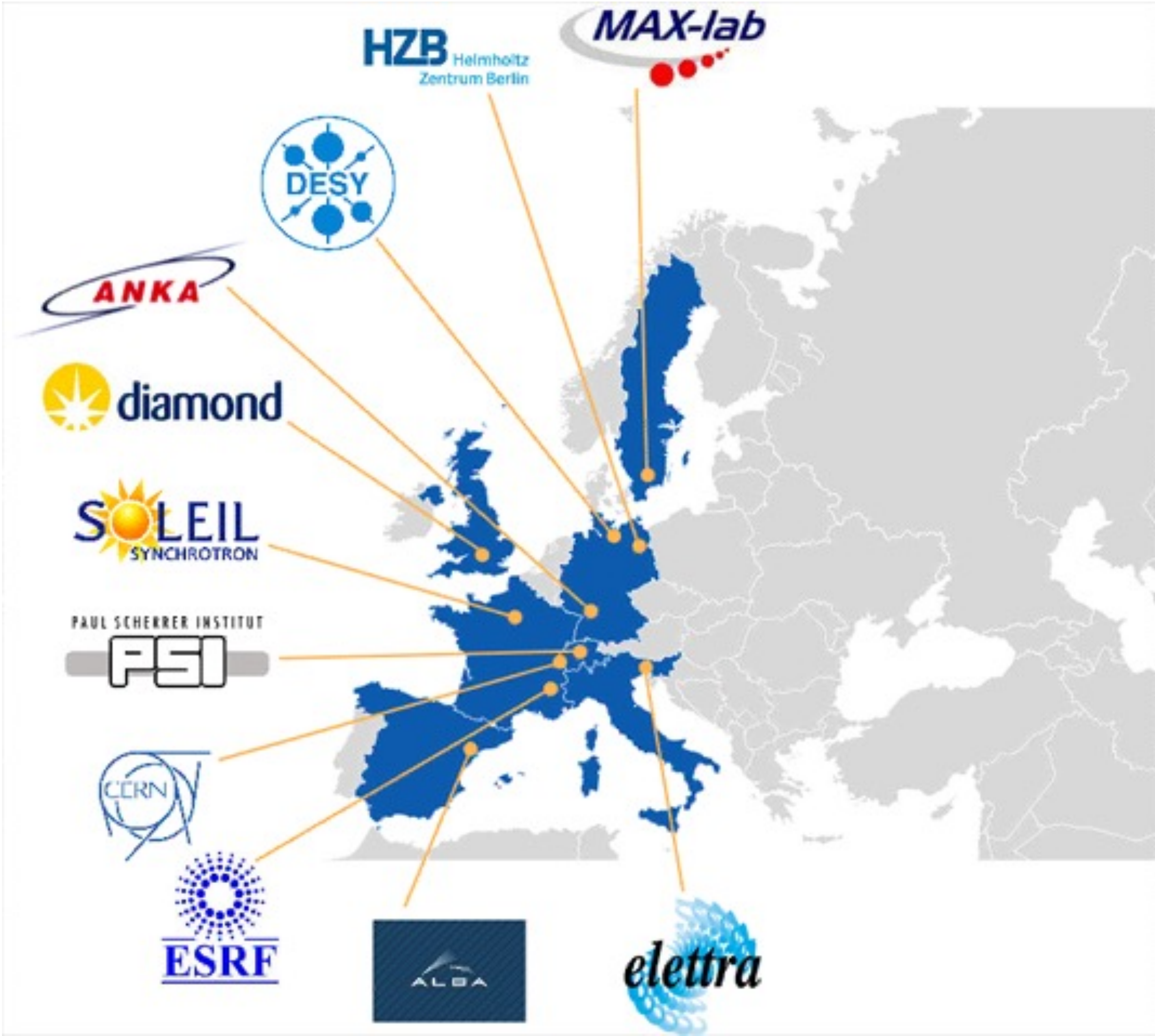
- Production of short-lived radioisotopes (e.g. Fluorine-18) for diagnostic imaging or radiotherapy.
- ion-beam therapy using proton beams

https://www.britannica.com/technology/cyclotron
https://www.ansto.gov.au/research/facilities/national-research-cyclotron
https://newscenter.lbl.gov/2010/10/18/ion-beam-therapy/

Synchrotron facilities worldwide

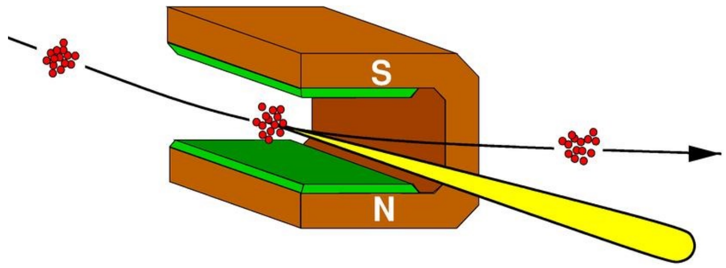
http://www.veqter.co.uk/

Synchrotron facilities in Europe

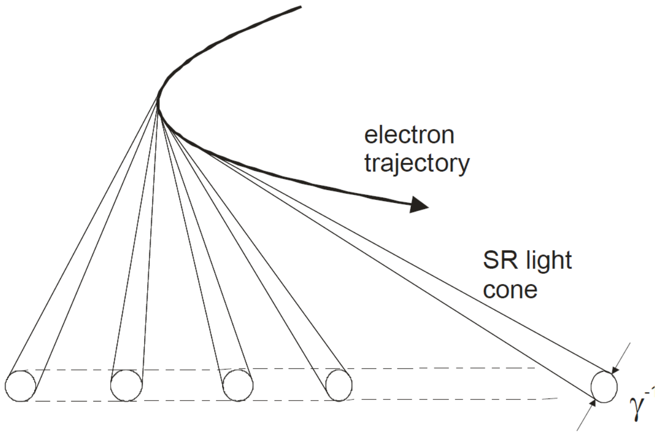


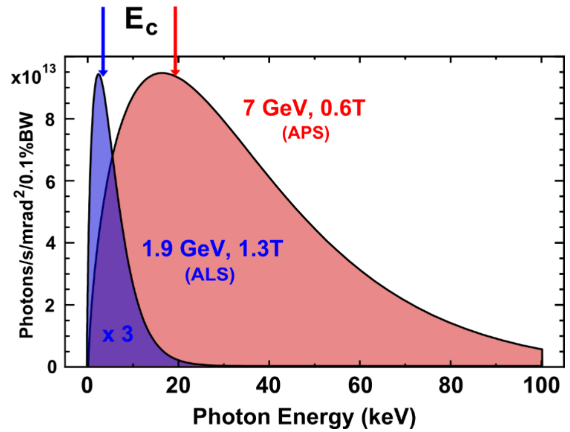
http://www.veqter.co.uk/

Generating Radiation



Bending Magnets





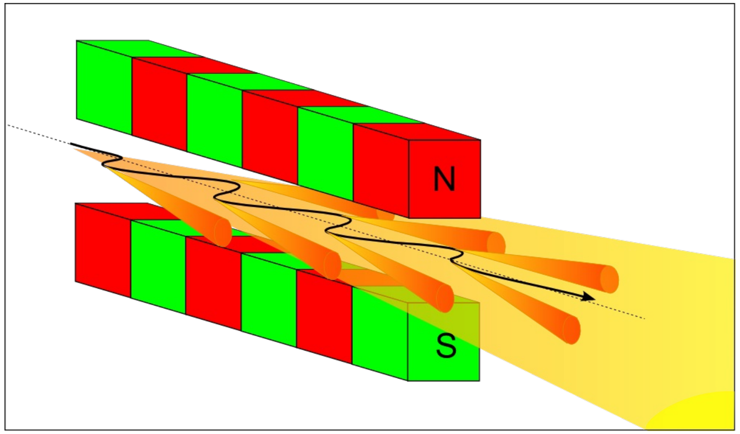
Synchrotron radiation emission pattern along a curved electron trajectory caused by the magnetic field generated with a dipole magnet. The figure illustrates SR light cones emitted at five singular points along the trajectory. The integral effect of all emission points along this curvature will result in a continuous horizontal “fan” of SR light.

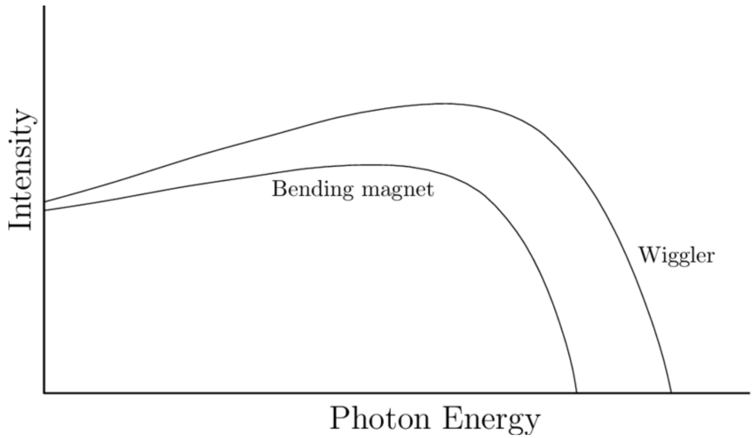
Generating Radiation

Insertion devices: Wiggler

The electron beam "wiggles" with a large deviation angle. As a result, bright and spectrally continuous light with short wavelengths is obtained.

Formed by lining up a series of bending magnets which enhances the intensity simply by the number of magnet poles: **superposition** of SR light.





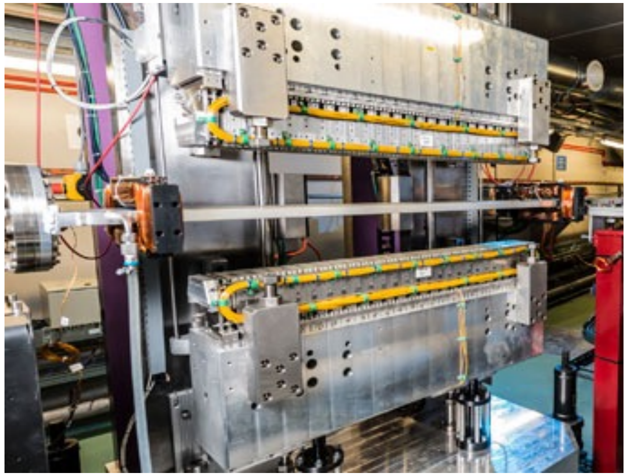
Generating Radiation

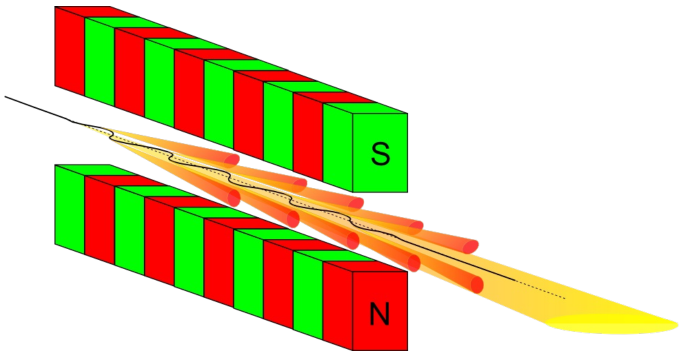
Insertion devices: Undulator:

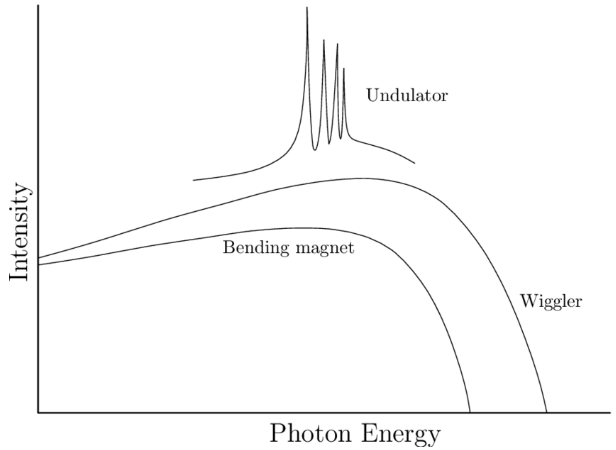
The electron beam wiggles with a small deviation angle. Ultra-bright quasi-monochromatic light is obtained by the **interference effect.**

The most powerful generators of synchrotron radiation at storage rings.

The light is spatially very concentrated into a narrow cone and producing harmonics.

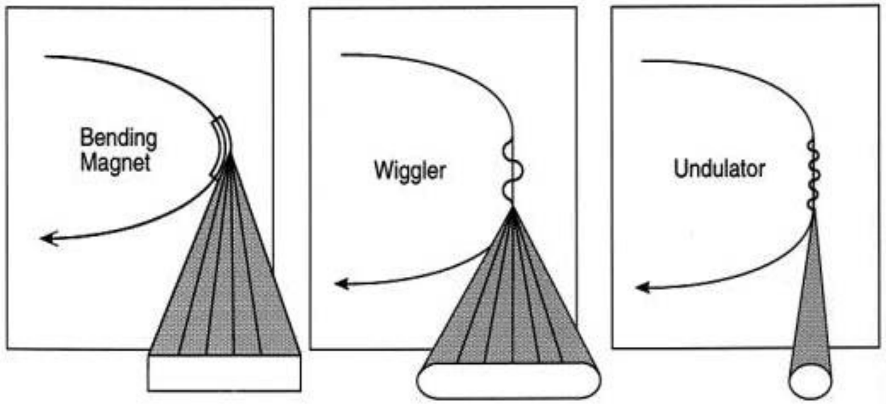


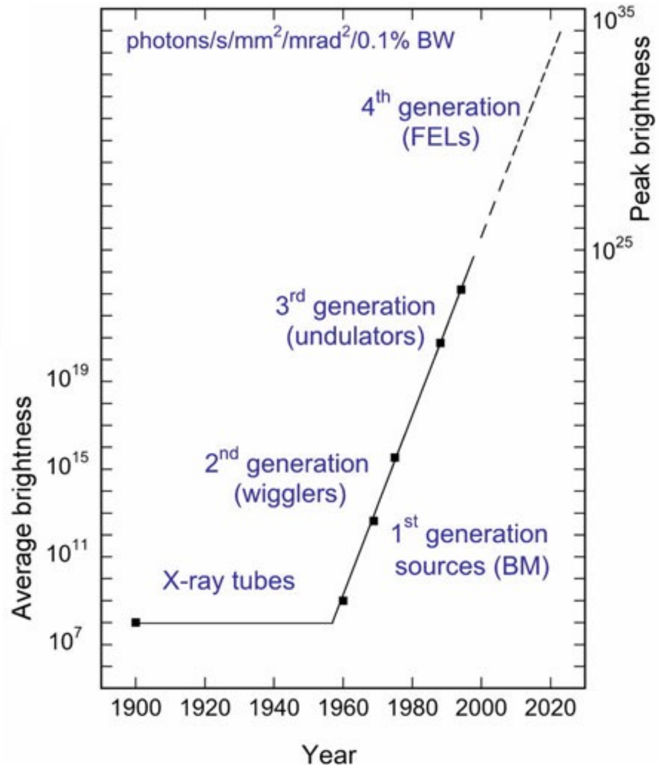




https://www.albasynchrotron.es/en/accelerators/insertion-devices

Generating Radiation



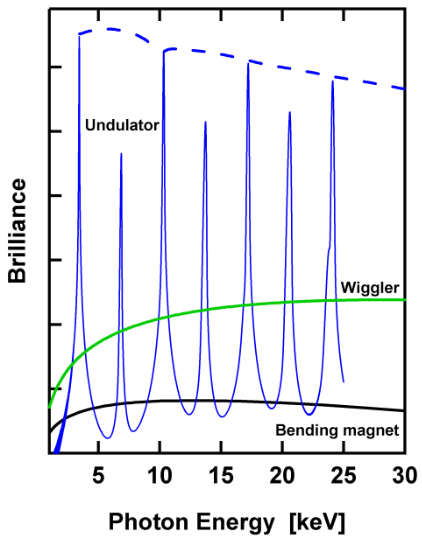


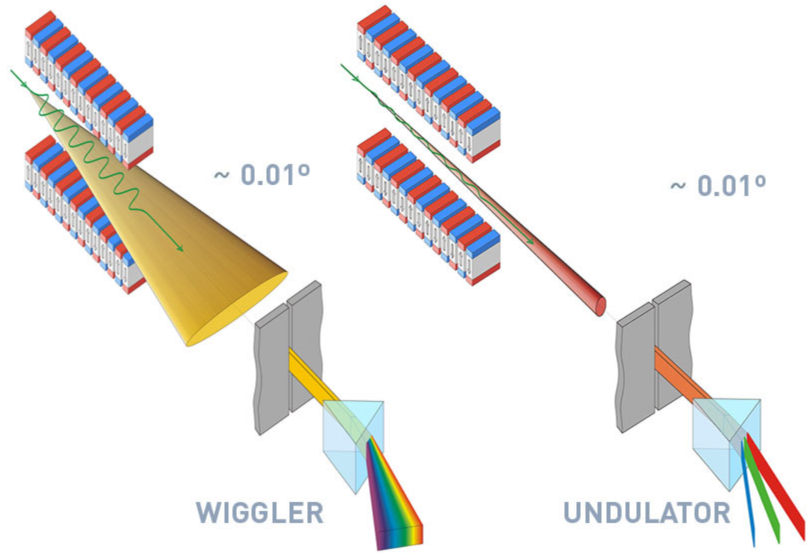
- The light, produced by the circulating electrons, is emitted tangentially to the curvature they follow.
- Bending magnets, the light is tangential to the arc described by electrons.
- Insertion devices, the light is emitted along the axis of oscillation.

http://unicorn.mcmaster.ca/research/synclight/synclight1.html

Generating Radiation

Bending magnet radiation	Wiggler radiation	Undulator radiation
• Broad spectrum	• Higher photon energies	• Brighter radiation
• Good photon flux	• More photon flux	• Smaller spot size
• No heat load	• Expensive magnet structure	• Partial coherence
• Less expensive	• Expensive cooled optics	• Expensive
• Easier access	• Less access	• Less access



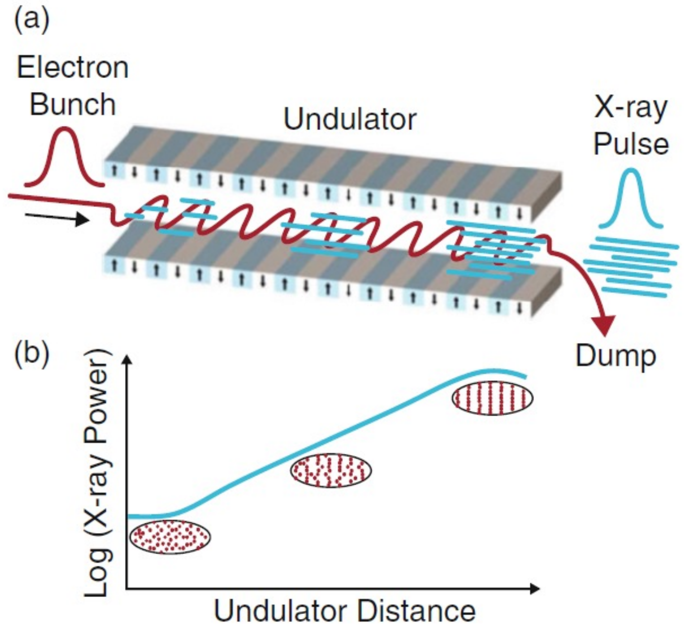


NEW TRENDS ON SR PRODUCTION

Fourth generation SR sources – X-ray Free-Electron Laser (XFEL)

Current X-ray sources are not bright enough to track changes with nanometer and nanosecond resolution. The **X-ray free electron laser (XFEL)** squeezes electrons into tighter bunches, leading to X-ray pulses that concentrate more photons into brighter beam.

Self-amplified spontaneous emission (SASE), an exponential growth in the radiated intensity via the interaction of the electron bunch with the previously emitted X-ray field as they co-propagate along the long undulator.



X-ray Free Electron Lasers A Revolution in Structural Biology
Springer Nature Switzerland AG (2018)
https://doi.org/10.1007/978-3-030-00551-1

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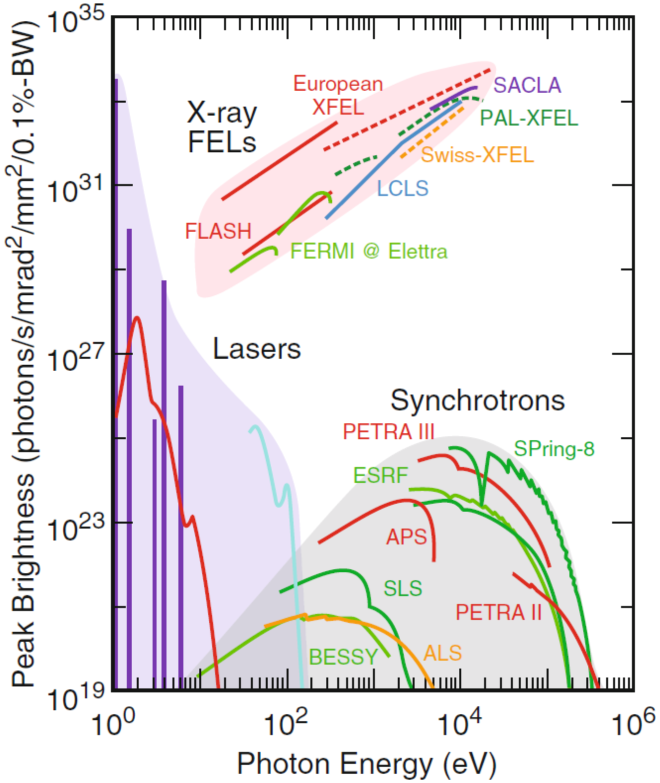
X-ray FEL pulse is roughly three orders of magnitude shorter than a typical shortest pulse from a synchrotron (but contains approximately the same number of photons that a synchrotron would produce in 1 s).



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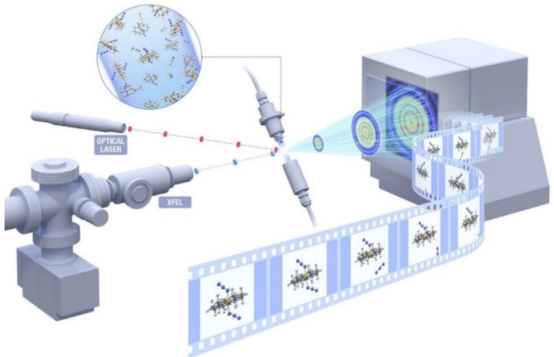
Fourth generation SR sources – X-ray Free-Electron Laser (XFEL)

European XFEL (Hamburg): 3.4 km-long facility will run (mostly underground)



up to 17.5 GeV !!

1.6×10^{25} (photons/s/mm^2/mrad^2/0.1% BW) !!!

100 fs pulses !!

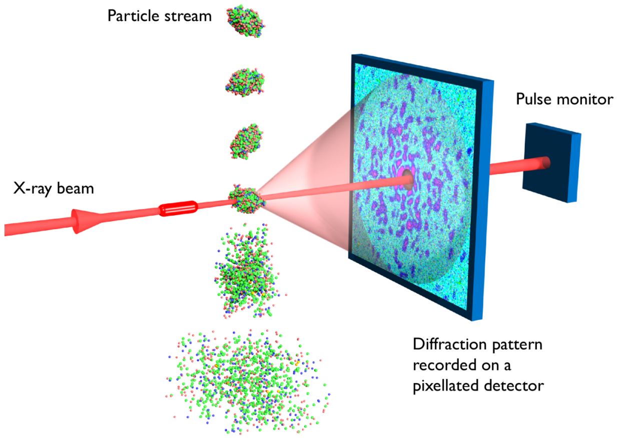
Useful for making **'molecular movies'** of chemical reactions

https://www.xfel.eu/
https://www-ssrl.slac.stanford.edu/stohr/xfels.pdf

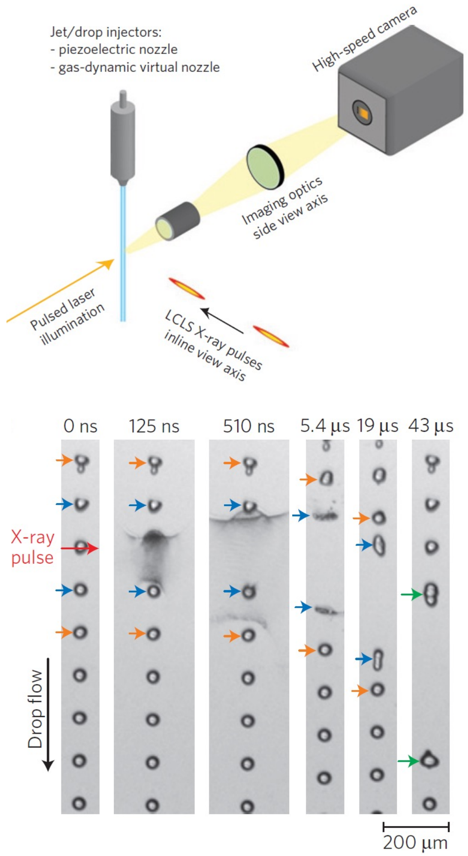
https://www-ssrl.slac.stanford.edu/stohr/xfels.pdf
Nature (2013) 500, 13–14

Fourth generation SR sources – X-ray Free-Electron Laser (XFEL)

Experimental set-up challenges… crystal heat loading and radiation damage of high repetition rate sources.

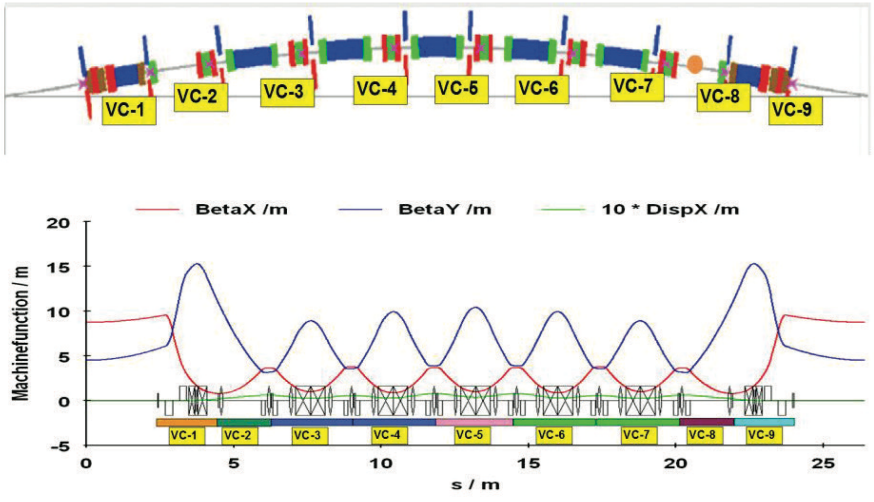


Science, 2007, 316, 1444-48



Nature Physics 12 (2016) 966

Diffraction Limited Storage Ring (DLSR)



Multi bend achromat lattice

→ increase of the brilliance by 2 orders of magnitude in the hard x-ray domain

→ coherence increased by 4-5 orders of magnitude

Already existing DLSR: MaxIV (Lund, Sweden), Sirius (Campinas, Brazil) and ESRF (Grenoble, France)

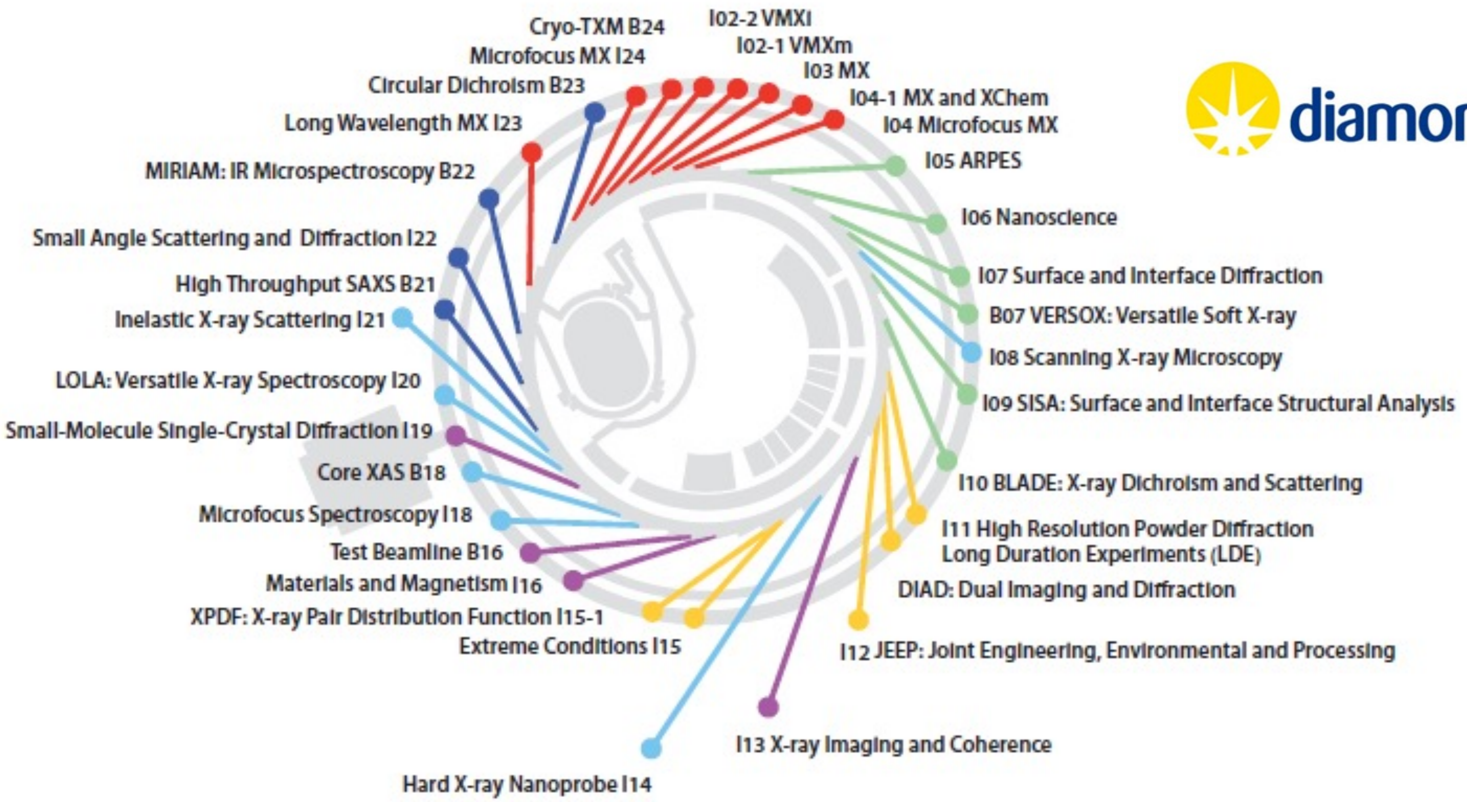
Advanced Photon Source (Argonne, US) upgrade under construction

Many Synchrotron Radiation facilities have upgrade projects

SR BEAMLINES

Beamlines at synchrotron radiation facilities

… different techniques for solving different problems



diamond

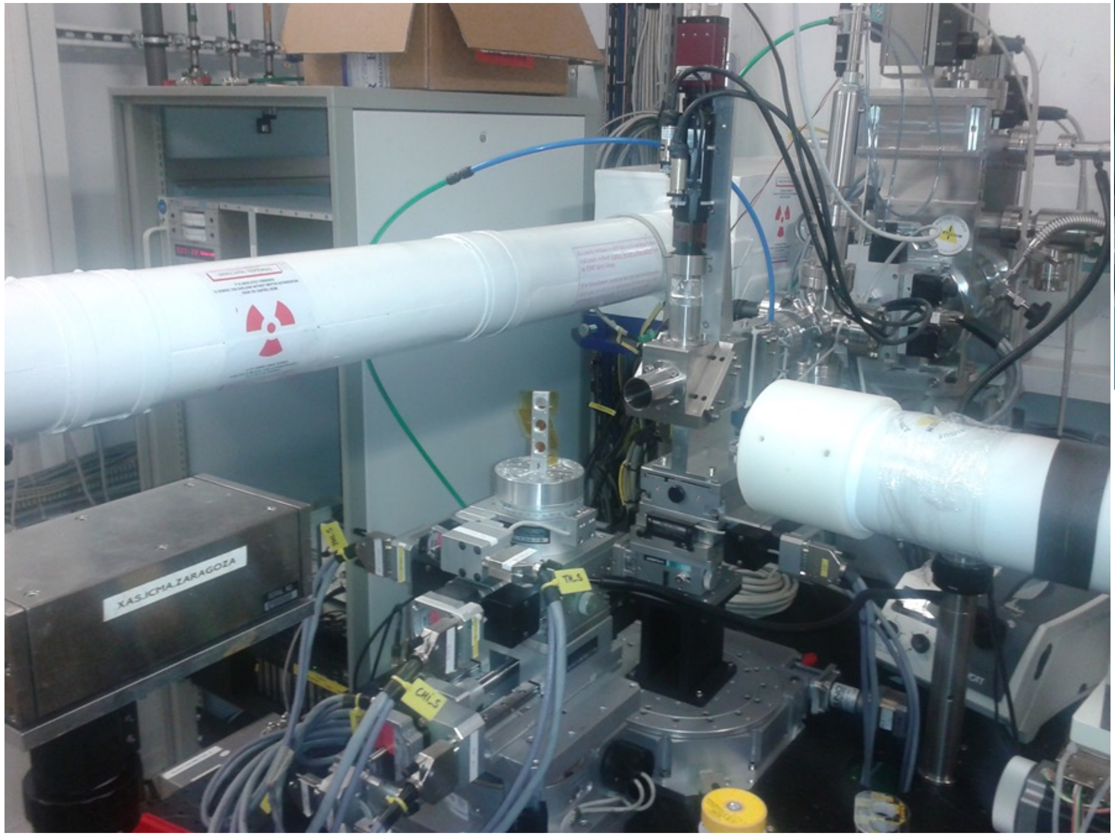
All the beamlines perform experiments simultaneously

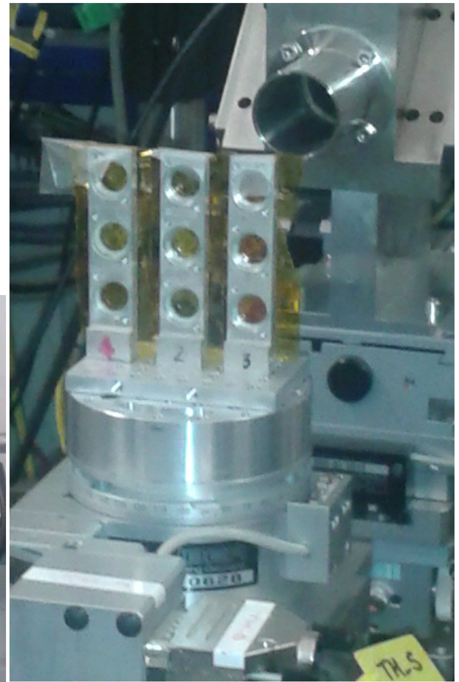
http://www.diamond.ac.uk/Beamlines.html

Into a Beamline

Experimental Hutch

End-Station Equipment: Manipulating Samples



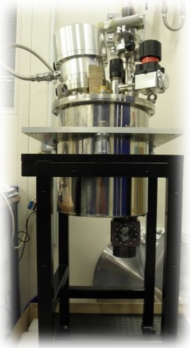
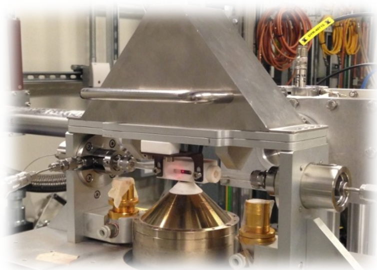
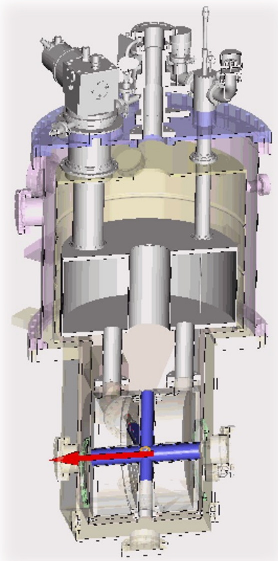
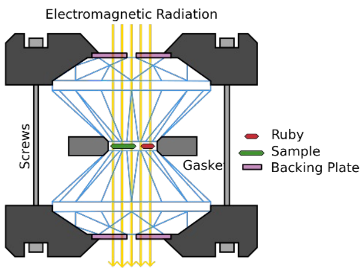


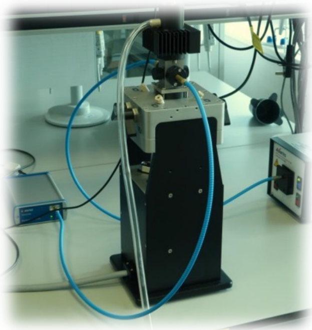
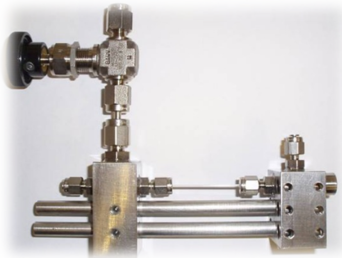
Into a Beamline

• Experimental Hutch – Sample environment

- Liquid N_2 and liquid He cryostats
- Liquid N_2 cryojet for capillary experiments
- IR furnace for X-ray fluorescence measurements
- Gas capillary cell for static measurements
- In-situ gas plug-flow reactor
- Gas portable system (gas mass flow controllers and switching valves)
- Liquid cells for RT and cryostat
- Stopped flow cell for liquid-liquid reactions
- Diamond anvil cells for applying high pressure
- High magnetic fields



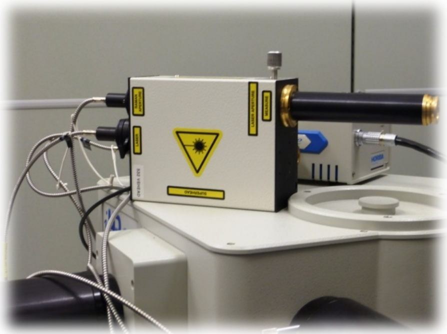





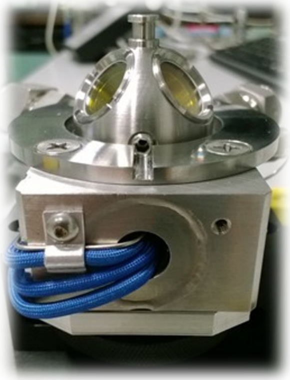



Into a Beamline

- Experimental Hutch – Complementary techniques

- UV-Vis spectrometer (300-1160 nm) with high temperature reflectance probe (up to 500 ^{o}C)
- Raman spectrometer
- Quadrupole mass spectrometer
- Diffuse reflectance infrared spectroscopy (DRIFTS)

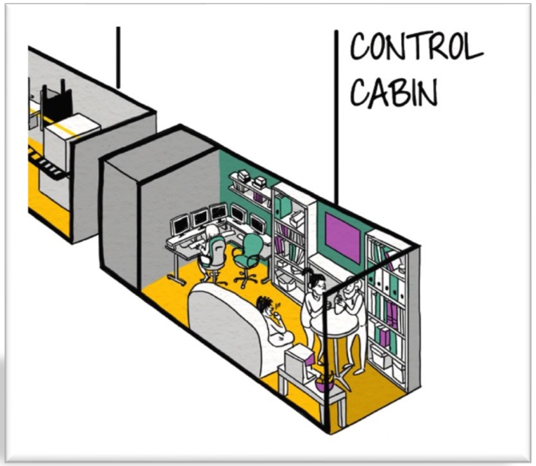




Into a Beamline: Radiation Shielding

- Control Room

Since modern synchrotron beamlines carry lethal doses of X-rays to the optical and experimental hutches, all optics and sample motions must be done under remote control inside locked, shielded stations.



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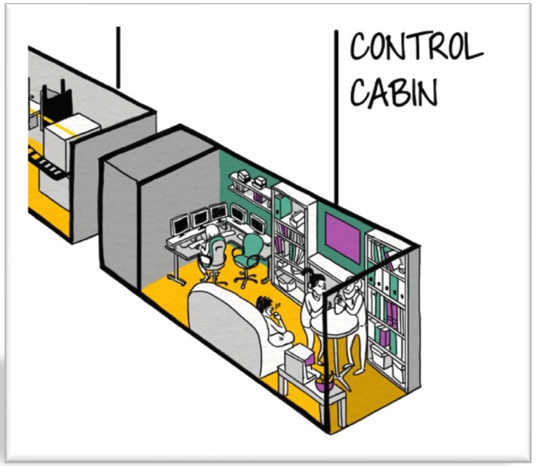
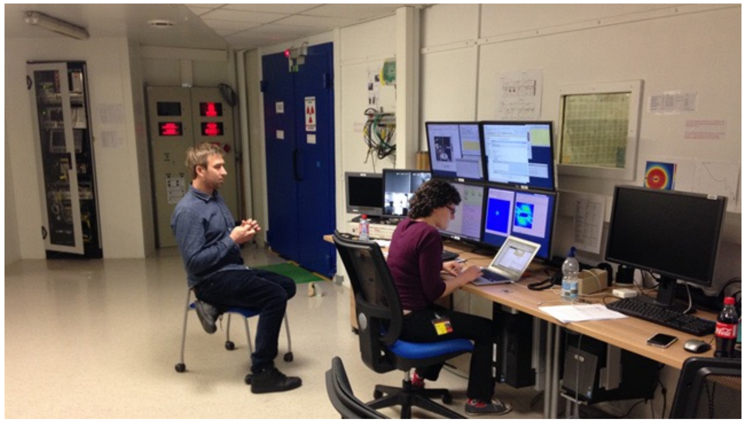
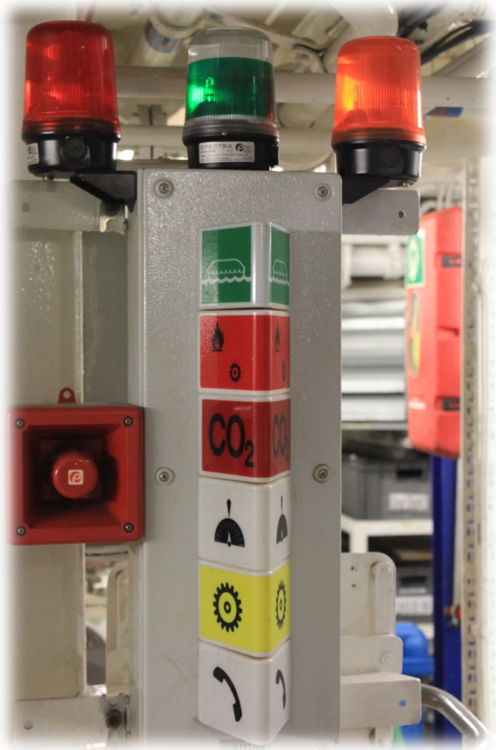




Into a Beamline: Safety – Control Systems

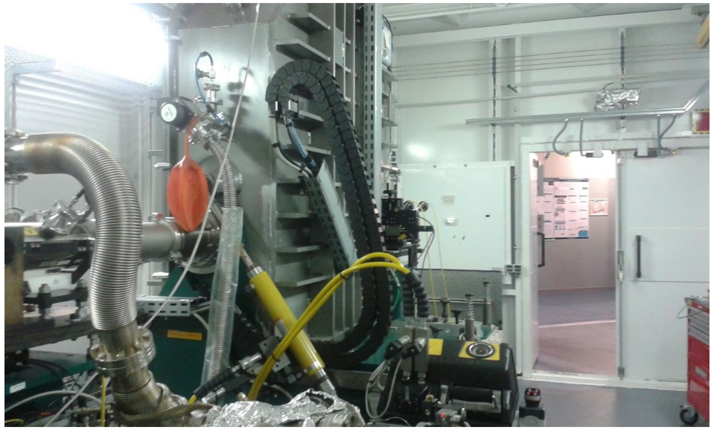
Radiation monitors and meters

Alarm monitors



Into a Beamline: Safety – Control Systems

Safety Interlock System (SIS)




KEEP
CALM
AND
BEAM
ON