BĒNINRĒVĒLĒ

African School of Fundamental Physics and Applications

Advanced Light Sources: A Worldwide State of the Art

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July 30, 2021

X-TechLab
Bright solutions for Africa

SÈMÈ CITY

Outline

- History
    - The late 19th pioneering work
    - The discovery of x-rays
    - Major breakthroughs of the 20th century
    - Modern sources: from the 1930's Berkeley/Livingstone cyclotron to the 1947 GE first synchrotron
    - First synchrotron spectroscopy study in 1956 at Cornell

- Today's >60 Advanced Light Sources (AdLS) worldwide
    - Modern AdLS worldwide: third generation synchrotrons
    - Third generation synchrotrons: the State of the Art
        - General layout and main components
        - LINAC
        - Booster
        - Storage ring, RF cavities, bending magnets
        - Insertion devices: wigglers and undulators

    - Free Electron lasers: a new generation of light sources

- The global role of AdLS in scientific infrastructure and collaboration

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Innovation
Made in Africa

A bit of
HISTORY

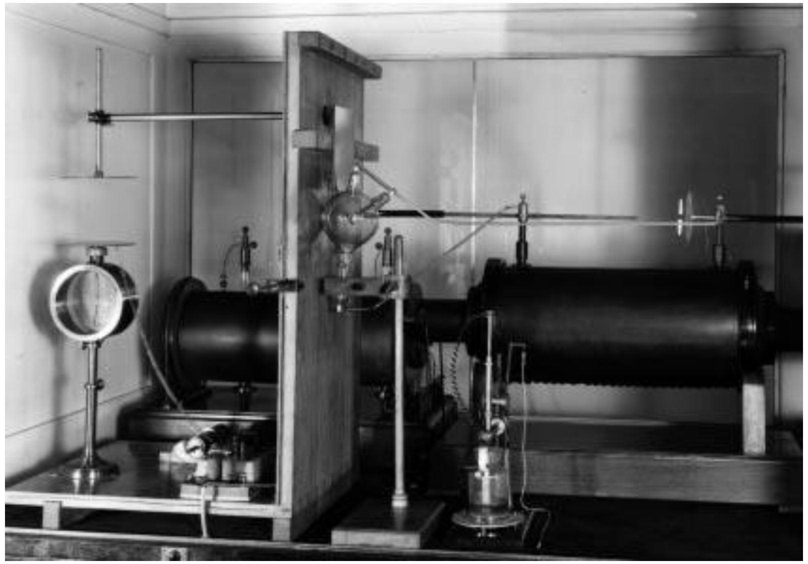
The late 19th century pioneering work

- Several European poles trying to gain insight into radiation mechanisms
  - UK: Thomson, Stokes, Barkla, Rutherford, Bragg
  - Germany: Hertz, Lenard, Roentgen, Planck, Sommerfeld, Laue
  - France: Poincaré, Becquerel, Villard, Curie
  - Netherlands: Haga, Werd

- 1890-1900: major advances
  - Electric discharges in gases
  - X rays
  - Radium
  - α,n β, γ radiation
  - Corpuscular nature of cathode rays

Crooke tubes used at the end of the 19th century to study electric discharges in gaseous media

1895: The discovery of X rays



Roentgen device for studying air ionization by X rays

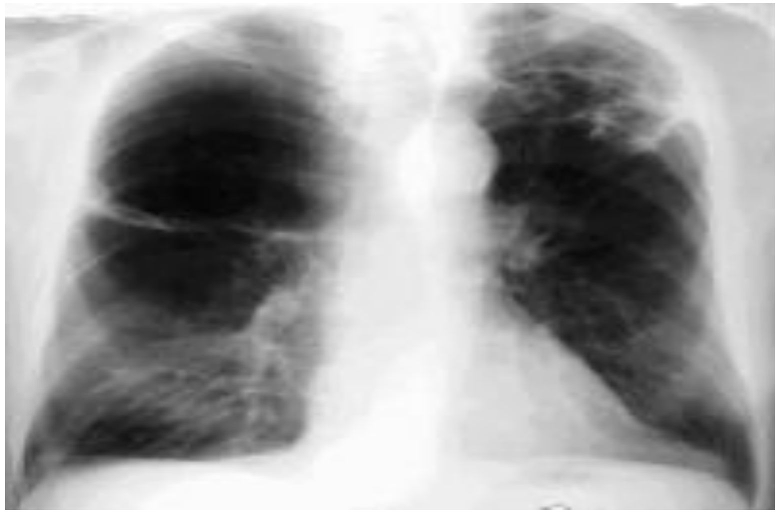
X ray imaging of hand phalanx

- Radiology
  - Object placed along X-ray beam trajectrory
  - Attenuation is a function of the density and structure of the object
- First Physics Nobel in 1901

Few charming illustrations

Bullet in brain…

Fractured thighbone…

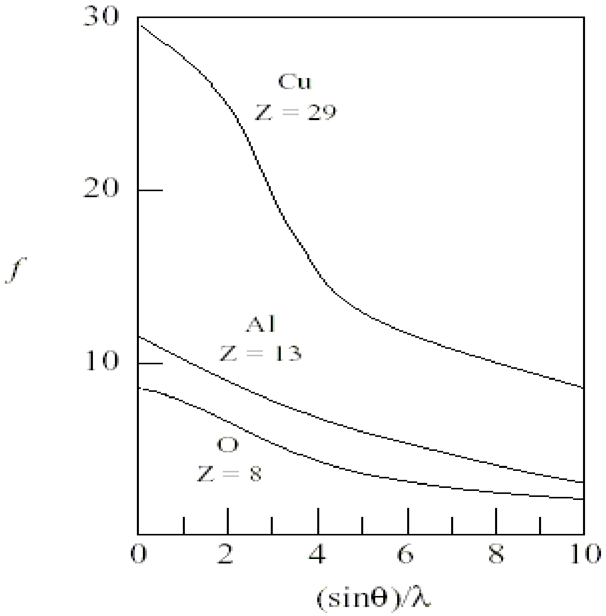


Tuberculous lung…

The end of a locust… (CEA Moronvillers)

20th century major breakthroughs: Crystallography

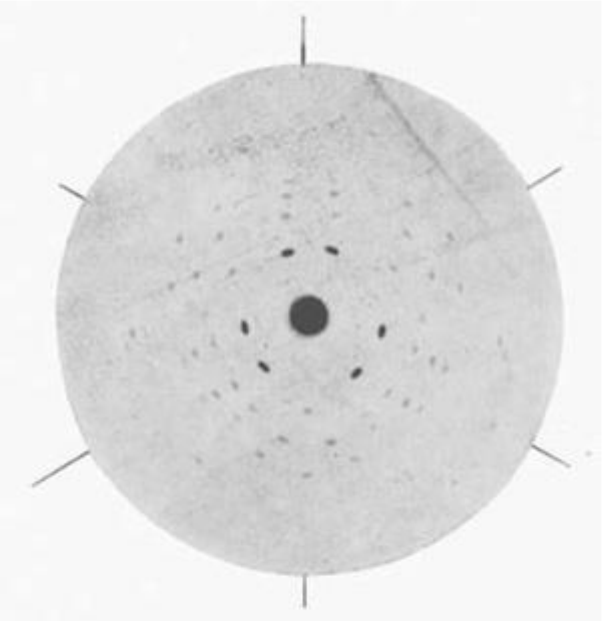
- X ray diffraction reveals structure at the atomic scale (λ~Å)
  - Spectral shape: order/disorder
  - Diffraction angle: d-spacing
  - Intensity: electron density
- Interaction mechanisms
  - X rays–electrons interaction
  - Diffraction intensity increases with atomic number and decreases when Bragg angle increases



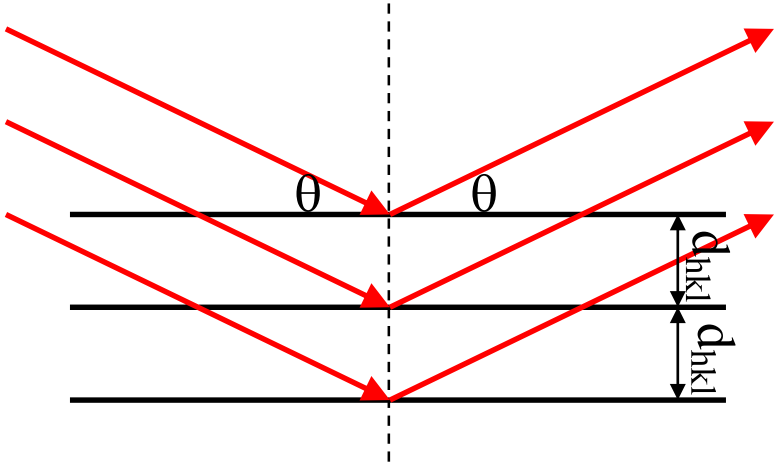
$$f^{o}(\sin\theta/\lambda) = \sum_{i=1}^{4} a_i \cdot e^{-b_i(\sin\theta/\lambda)^2} + c$$

Laue’s equation

$$\overrightarrow{k_d} - \overrightarrow{k_i} = \overrightarrow{K}$$

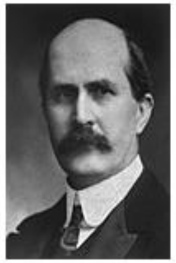


ZnS diffraction pattern



Bragg’s law

$$\lambda = 2d_{hkl}\sin\Theta_B$$

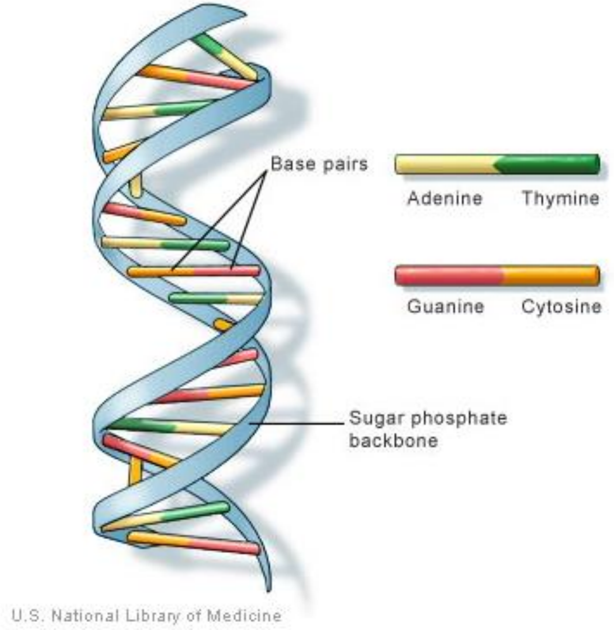


Sir William Henry Bragg

William Lawrence Bragg

20th century major breakthroughs: The DNA structure

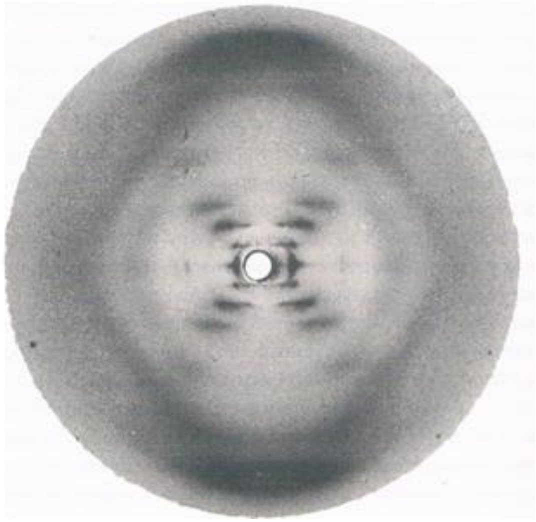
- Atomic arrangement determined
  - Crystal: dimensions and uniformity
  - Electron density and mean locations of atoms
  - Iteration over 180° for optimal resolution



U.S. National Library of Medicine

Double helicoidal DNA structure, Nobel Prize 1962 Watson, Crick et Wilkins

Deciphering of genetic code, protein synthsesis, cloning, sequencing of human genome,…
Tremendous impact on life science: biochemistry, genetics, medecine, agriculture,…



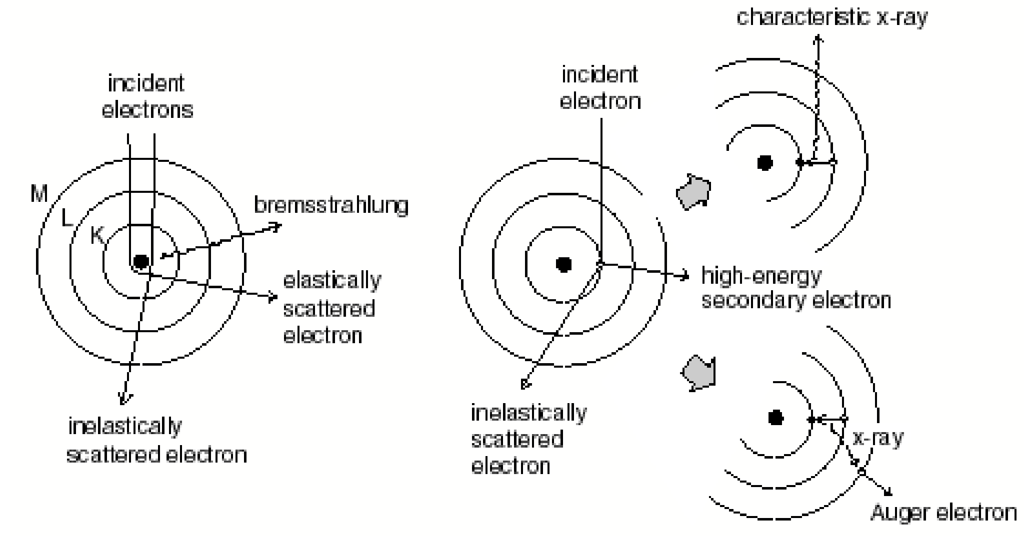
1952: Photo 51

Roselind Franklin

Maurice Wilkins Francis Crick James Watson

20th century major breakthroughs: Apart from X ray diffraction

- Characteristic X-rays (Nobel 1917)




Charles G. Barkla (1877-1944)


Henry G. J. Moseley (1887-1915)

- Systematic study of X-ray spectra
  - Mathematical relation between wavelength and atomic number
  - Number of lanthanides determined
  - Gap in periodic table evidenced

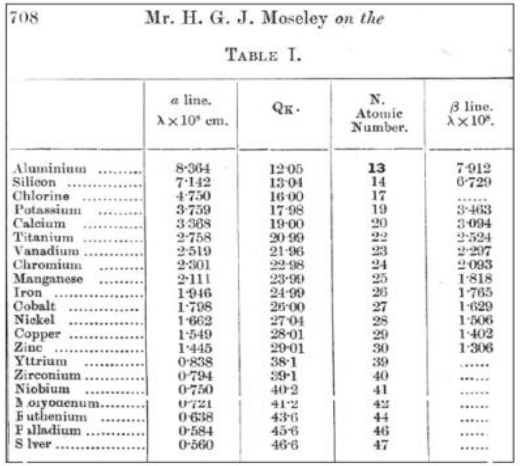

708 Mr. H. G. J. Moseley *on the*

TABLE I.

	a line. λ×10⁸ cm.	Q_K.	N. Atomic Number.	β line. λ×10⁸.
Aluminium	8·364	12·05	**13**	7·912
Silicon	7·142	13·04	14	6·729
Chlorine	4·750	16·00	17	......
Potassium	3·759	17·98	19	3·463
Calcium	3·368	19·00	20	3·094
Titanium	2·758	20·99	22	2·524
Vanadium	2·519	21·96	23	2·297
Chromium	2·301	22·98	24	2·093
Manganese	2·111	23·99	25	1·818
Iron	1·946	24·99	26	1·765
Cobalt	1·798	26·00	27	1·629
Nickel	1·662	27·04	28	1·506
Copper	1·549	28·01	29	1·402
Zinc	1·445	29·01	30	1·306
Yttrium	0·838	38·1	39	......
Zirconium	0·794	39·1	40	......
Niobium	0·750	40·2	41	......
Molybdenum	0·721	41·2	42	......
Ruthenium	0·638	43·6	44	......
Palladium	0·584	45·6	46	......
Silver	0·560	46·6	47	......

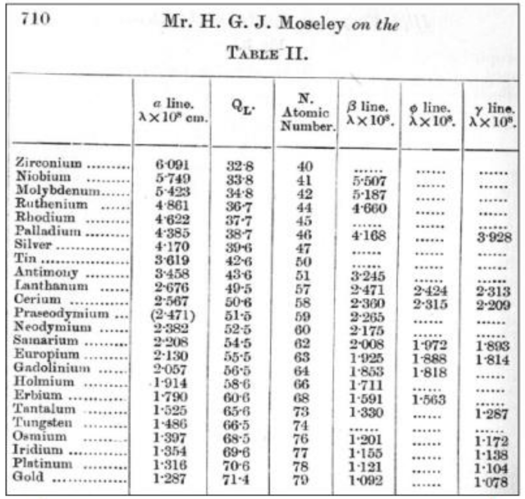

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TABLE II.

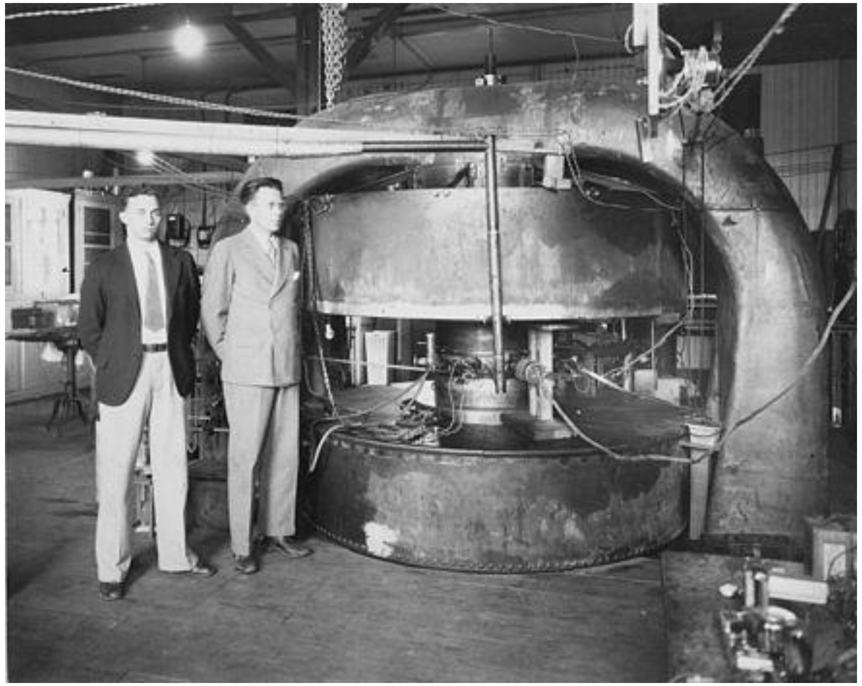
	a line. λ×10⁸ cm.	Q_L.	N. Atomic Number.	β line. λ×10⁸.	φ line. λ×10⁸.	γ line. λ×10⁸.
Zirconium	6·091	32·8	40	......	......	......
Niobium	5·749	33·8	41	5·507	......	......
Molybdenum	5·423	34·8	42	5·187	......	......
Ruthenium	4·861	36·7	44	4·660	......	......
Rhodium	4·622	37·7	45	......	......	......
Palladium	4·385	38·7	46	4·168	......	3·928
Silver	4·170	39·6	47	......	......	......
Tin	3·619	42·6	50	......	......	......
Antimony	3·458	43·6	51	3·245	......	......
Lanthanum	2·676	49·5	57	2·471	2·424	2·313
Cerium	2·567	50·6	58	2·360	2·315	2·209
Praseodymium	(2·471)	51·5	59	2·265	......	......
Neodymium	2·382	52·5	60	2·175	......	......
Samarium	2·208	54·5	62	2·008	1·972	1·893
Europium	2·130	55·5	63	1·925	1·888	1·814
Gadolinium	2·057	56·5	64	1·853	1·818	......
Holmium	1·914	58·6	66	1·711	......	......
Erbium	1·790	60·6	68	1·591	1·563	......
Tantalum	1·525	65·6	73	1·330	......	1·287
Tungsten	1·486	66·5	74	......	......	......
Osmium	1·397	68·5	76	1·201	......	1·172
Iridium	1·354	69·6	77	1·155	......	1·138
Platinum	1·316	70·6	78	1·121	......	1·104
Gold	1·287	71·4	79	1·092	......	1·078

$$Q_K = \sqrt{\frac{\nu}{\frac{3}{4}\nu_0}} \qquad Q_K \cong N - 1$$

$$Q_L = \sqrt{\frac{\nu}{\frac{5}{36}\nu_0}} \qquad Q_L \cong N - 7.4$$

The birth of modern X ray facilities: From cyclotrons to synchrotrons

- The E. Lawrence/ M. Livinsgtone Cyclotron (U. C. Berkeley, early 1930's)
  - Circular accelerator
  - Particles subject to constant magnetic field
  - Trajectories: successive half circles with increasing radii
  - Particles are accelerated to non-relativistic velocities and reach energies of few tens of MeV
  - Still used, mostly in nuclear medicine
- The synchrotron concept
  - Charged particles accelerated to relativistic velocities along circular path will produce « light » parallel to their trajectory (Einstein/Maxwell)
  - 1947: First observation of visible synchrotron light with the 70 MeV GE synchrotron,
  - 1956: Larger, higher energy machine, higher energy radiation towards X region, 320 MeV Cornell synchrotron, first spectroscopy study on Al, Be near K and L edges (Tomboulian and Harman)



Lawrence an d Livingstone with their 1930 cyclotron at Berkeley

X-TechLab
Bright solutions for Africa

OVER 60 ADVANCED LIGHT SOURCES WORLDWIDE

Modern AdLS worldwide Third generation synchrotrons

Very high-Energy, High Brilliance facilities (>5 GeV, >800m, >30 insertion devices, hard X-rays)

ESRF, Grenoble, 6 GeV, 844 m

APS, Argonne, 7 GeV, 1104 m

Spring-8, Harima, 8 GeV, 1436 m

Long wavelength sources, smaller, less expensive (<3 GeV, <600 m, UV-soft X-ray photons)

ALS, Berkeley 1,9 GeV, 196,8 m

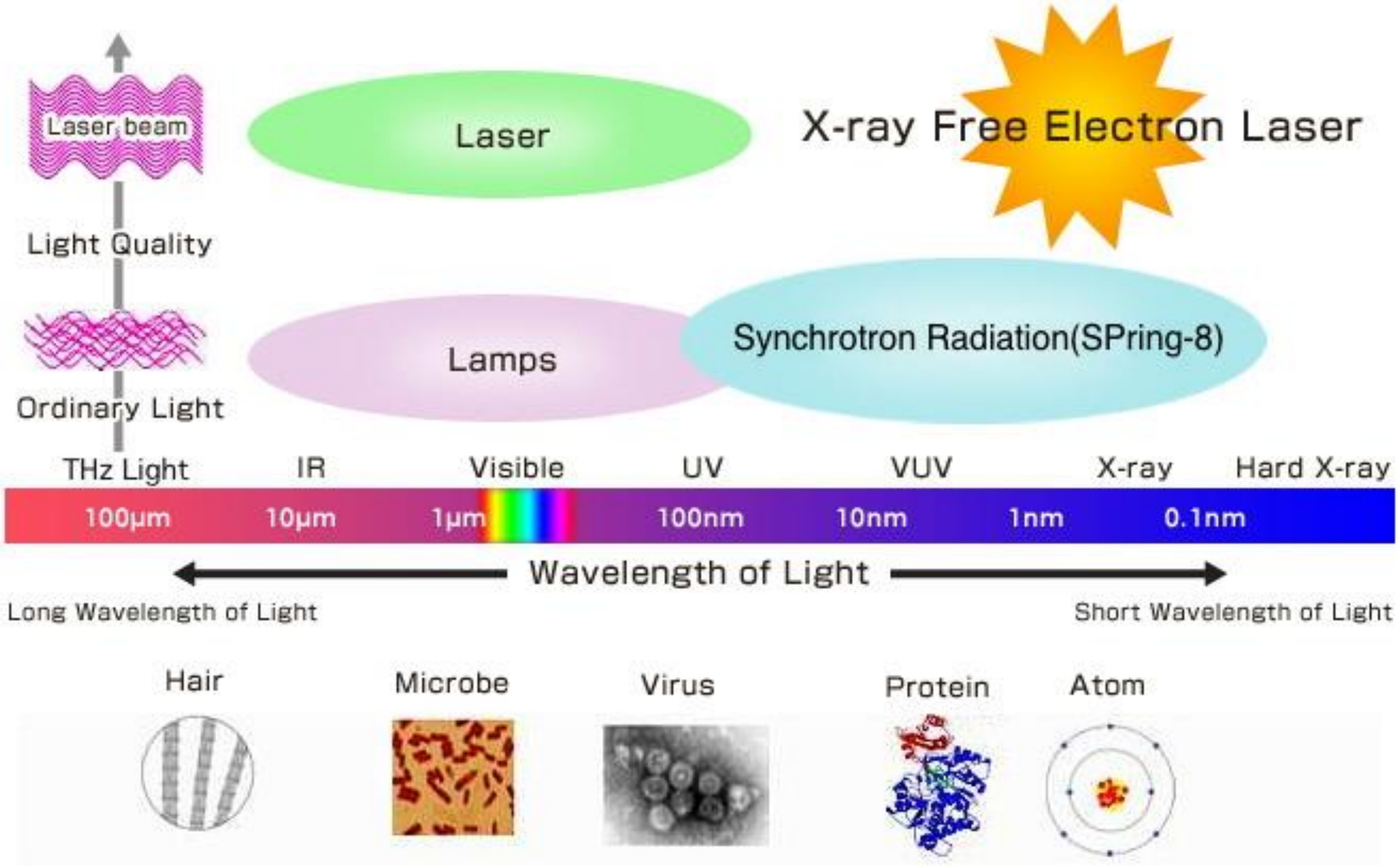
Elettra, Trieste 2,4 GeV, 260 m

NSRRC, Taiwan, 3 GeV, 518m

Modern synchrotrons storage rings energies

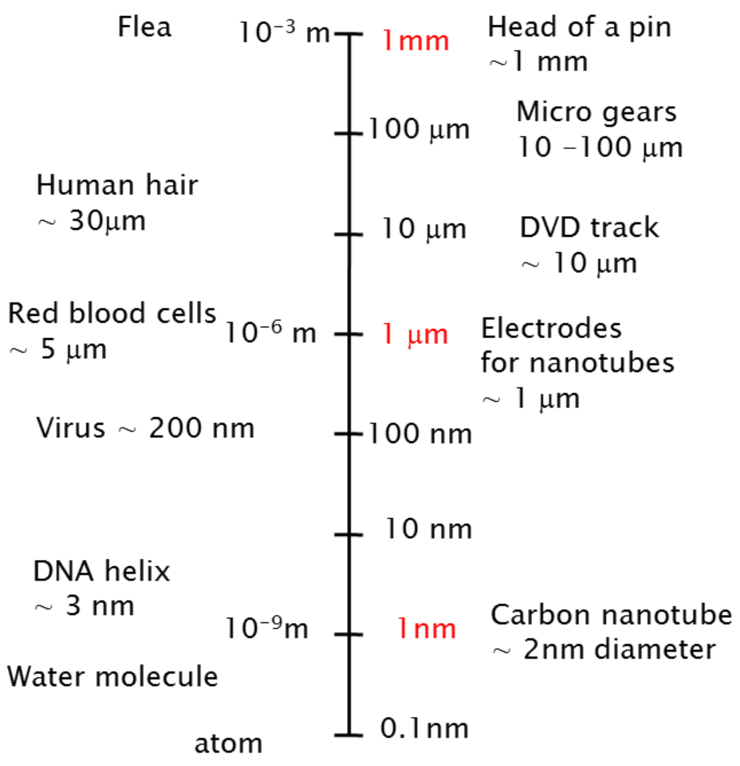
1992	**ESRF**, France (EU)	6 GeV
	ALS, US	1.5-1.9 GeV
1993	**TLS,** Taiwan	1.5 GeV
1994	**ELETTRA**, Italy	2.4 GeV
	PLS, Korea	2 GeV
	MAX II, Sweden	1.5 GeV
1996	**APS**, US	7 GeV
	LNLS, Brazil	1.35 GeV
1997	**Spring-8**, Japan	8 GeV
1998	**BESSY II**, Germany	1.9 GeV
2000	**ANKA**, Germany	2.5 GeV
	SLS, Switzerland	2.4 GeV
2004	**SPEAR3**, US	3 GeV
	CLS, Canada	2.9 GeV
2006:	**SOLEIL**, France	2.8 GeV
	DIAMOND, UK	3 GeV
	ASP, Australia	3 GeV
	MAX III, Sweden	700 MeV
	Indus-II, India	2.5 GeV
2008	**SSRF**, China	3.4 GeV
2009	**PETRA-III**, D	6 GeV
2011	**ALBA**, E	3 GeV

Synchrotron EM spectrum



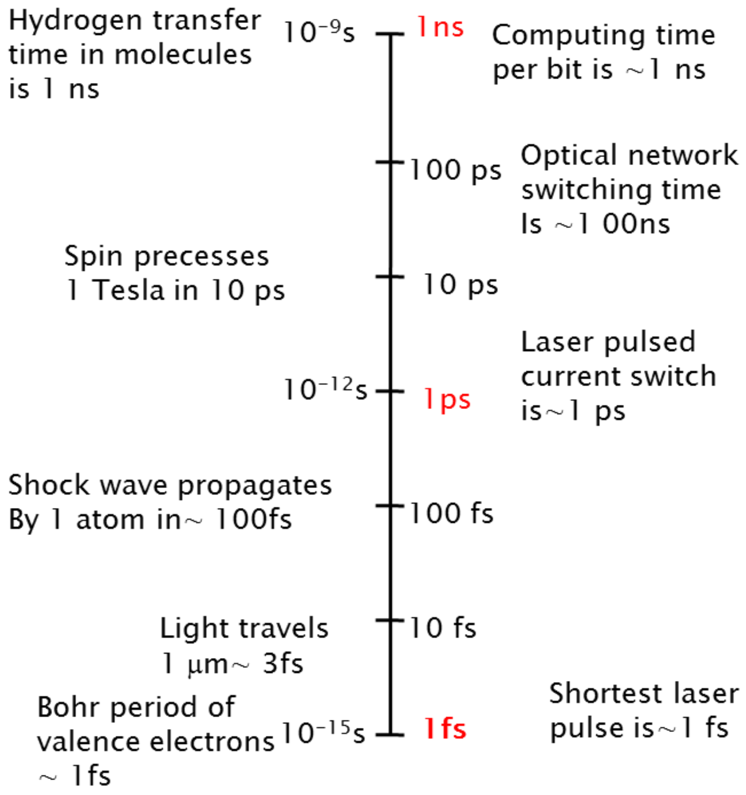
A broad range of applications

Ultra Small



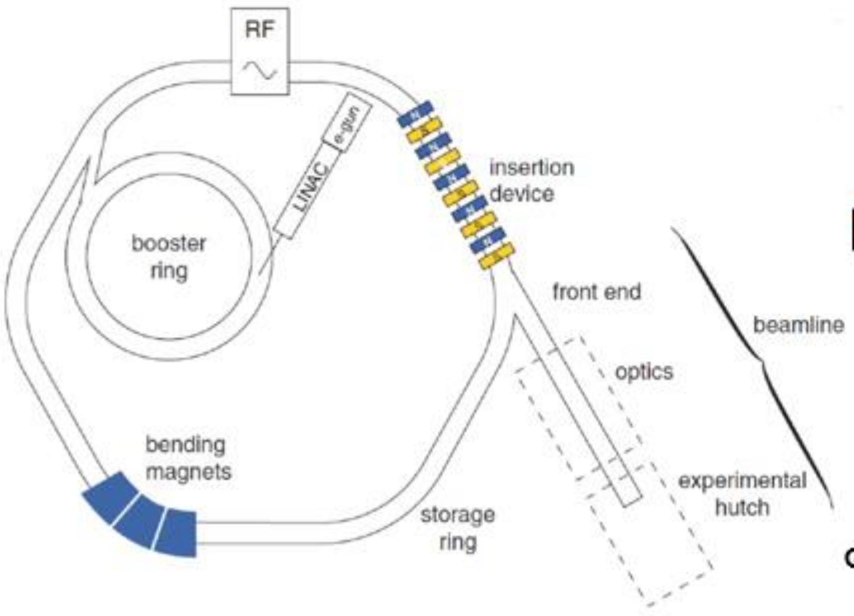
Natural			Man Made
Flea	10^{-3} m	1mm	Head of a pin ~1 mm
		100 μm	Micro gears 10 –100 μm
Human hair ~ 30μm		10 μm	DVD track ~ 10 μm
Red blood cells ~ 5 μm	10^{-6} m	1 μm	Electrodes for nanotubes ~ 1 μm
Virus ~ 200 nm		100 nm	
		10 nm	
DNA helix ~ 3 nm	10^{-9}m	1nm	Carbon nanotube ~ 2nm diameter
Water molecule			
atom		0.1nm	

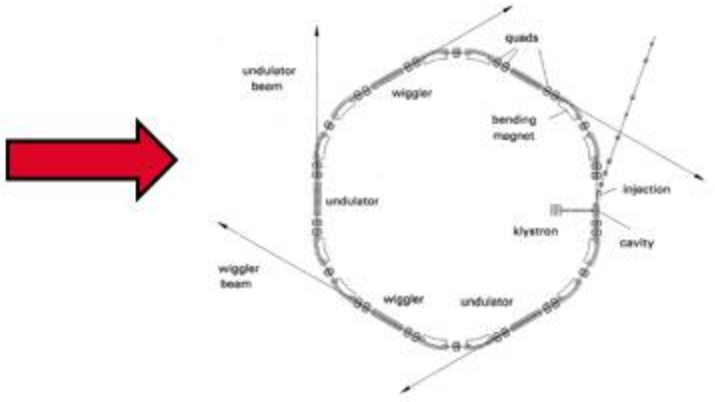
Ultra Fast



Natural			Man Made
Hydrogen transfer time in molecules is 1 ns	10^{-9}s	1ns	Computing time per bit is ~1 ns
		100 ps	Optical network switching time Is ~1 00ns
Spin precesses 1 Tesla in 10 ps		10 ps	
	10^{-12}s	1ps	Laser pulsed current switch is~1 ps
Shock wave propagates By 1 atom in~ 100fs		100 fs	
Light travels 1 μm~ 3fs		10 fs	
Bohr period of valence electrons ~ 1fs	10^{-15}s	1fs	Shortest laser pulse is~1 fs

Third generation synchrotrons: A state of the art

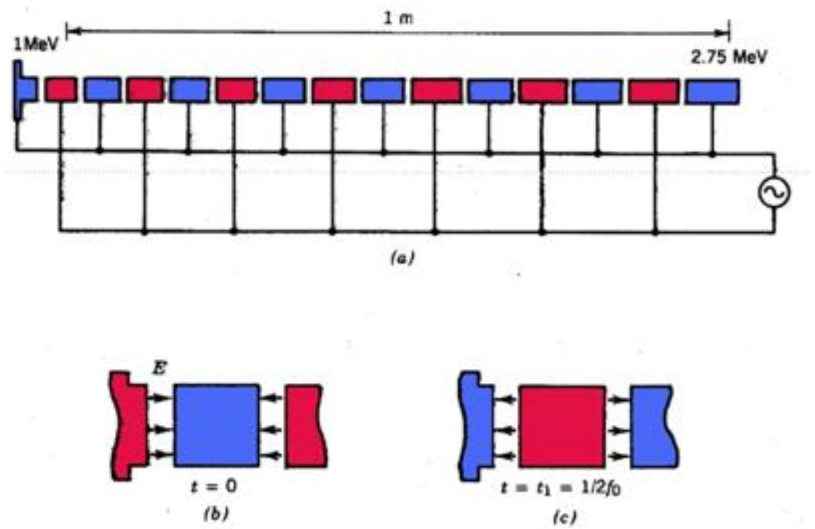




General layout of a third-generation synchrotron

- Main components
  - Heated electron gun
  - Linear Accelerator (LINAC)
  - Booster
  - Storage ring
    - ➢Filling modes: uniform, single bunch, hybrid
    - ➢Klystrons
    - ➢Bending magnets
    - ➢Insertion devices: wigglers and undulators
  - Beamline optics
  - Experimental hutch

LINAC



Wideroe-type LINAC for heavy ions. (a) Scale drawing accelerator with following parameters: ion species Cs-137, f=10 MHz, V_0=100 kV; (b) Electric fields in accelerator gaps 1 and 2 at ion injection, (b) Emectric fields at time t= 1/2f, where f is the frequency

A view of the APS LINAC

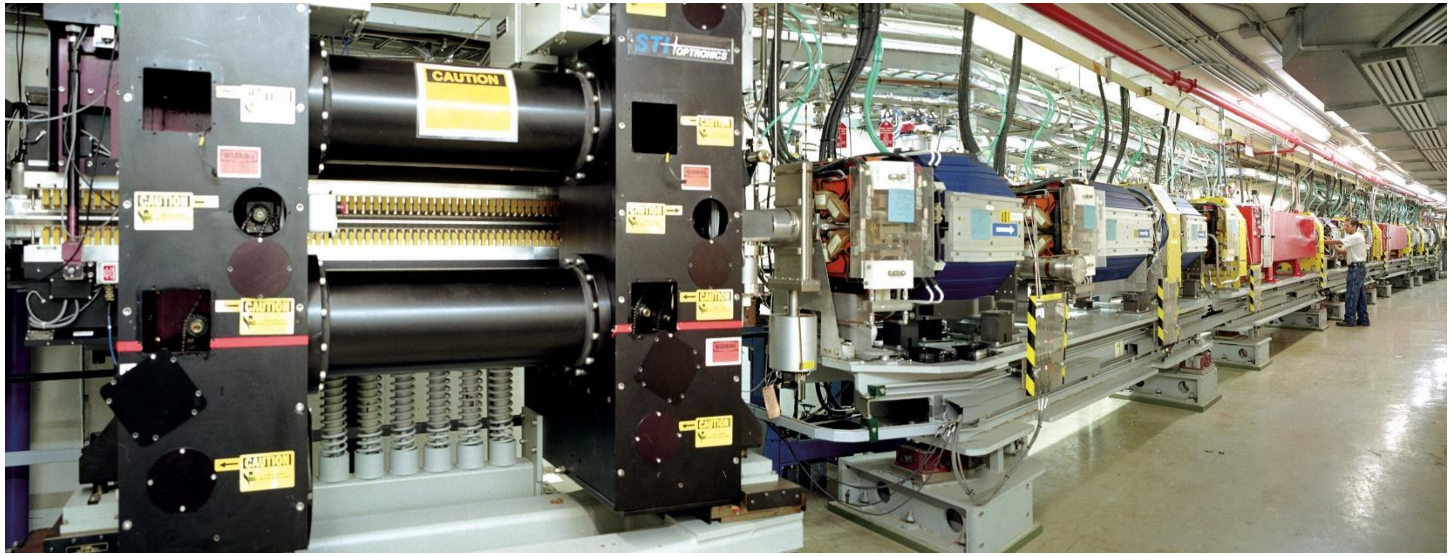
- LINAC: Electrons accelerated to 450 MeV and reach 99,999% of speed of light!
  - High voltage accelerating electric field >200 kV
  - High Power Amplifier (Klystrons) generate highly stable short-pulsed RF (power~30 MW)
  - Electrons energy tripled over 1m (Figure of merit is acceleration gradient)
  - Selective phasing drives electron to 450 MeV
  - Electrons virtually moves at speed of light

BOOSTER

A view of the APS BOOSTER

- **Booster (~300 m)**
  - Race-track shaped ring electromagnets
  - Electrons accelerated from 450 MeV to 6-8 GeV in 0.5 s
  - Accelerated force supplied by 4 RF cavities
  - Orbital path of electrons maintained using bending and focusing magnets which increase electron field strength in synchronization with the RF field

STORAGE RING



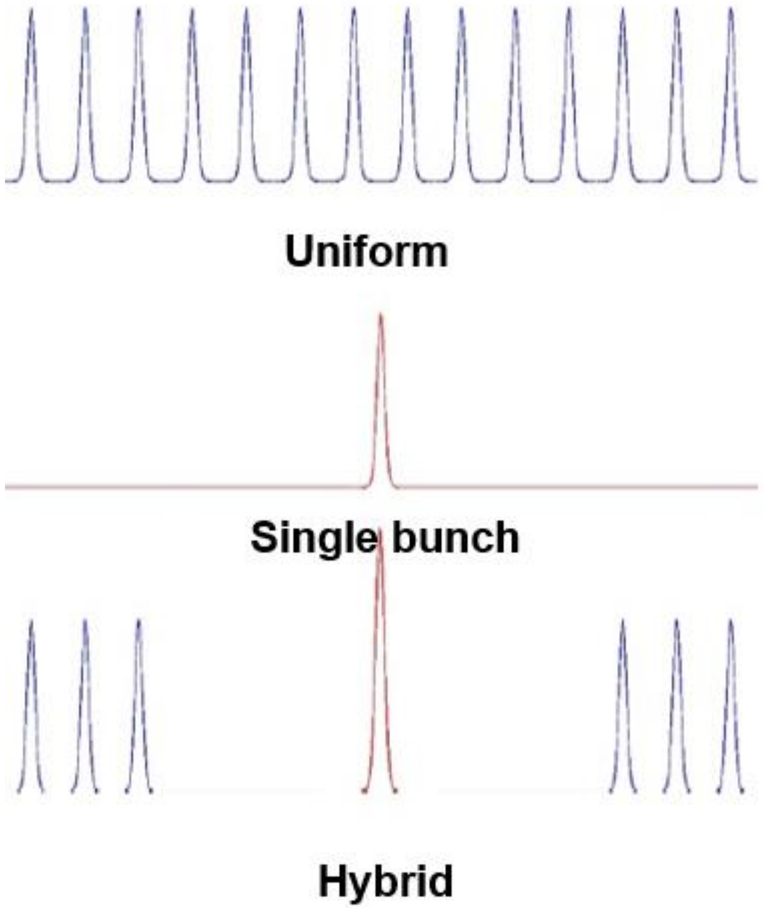
A view of the APS STORAGE RING

- STORAGE RING
  - 6-8 GeV electrons injected in 800-1400 m circumference ring
  - Storage ring equipped with >1000 electromagnets
  - Ring located in radiation-proof concrete inside experimental hall
  - Powerful electromagnetic field focuses electrons into narrow beam bent on circular path along a vacuum aluminum pipe running through the center of the electromagnets
  - ~40 straight sections (5 equipped with RF cavities and insertion devices, the remaining for beamlines)

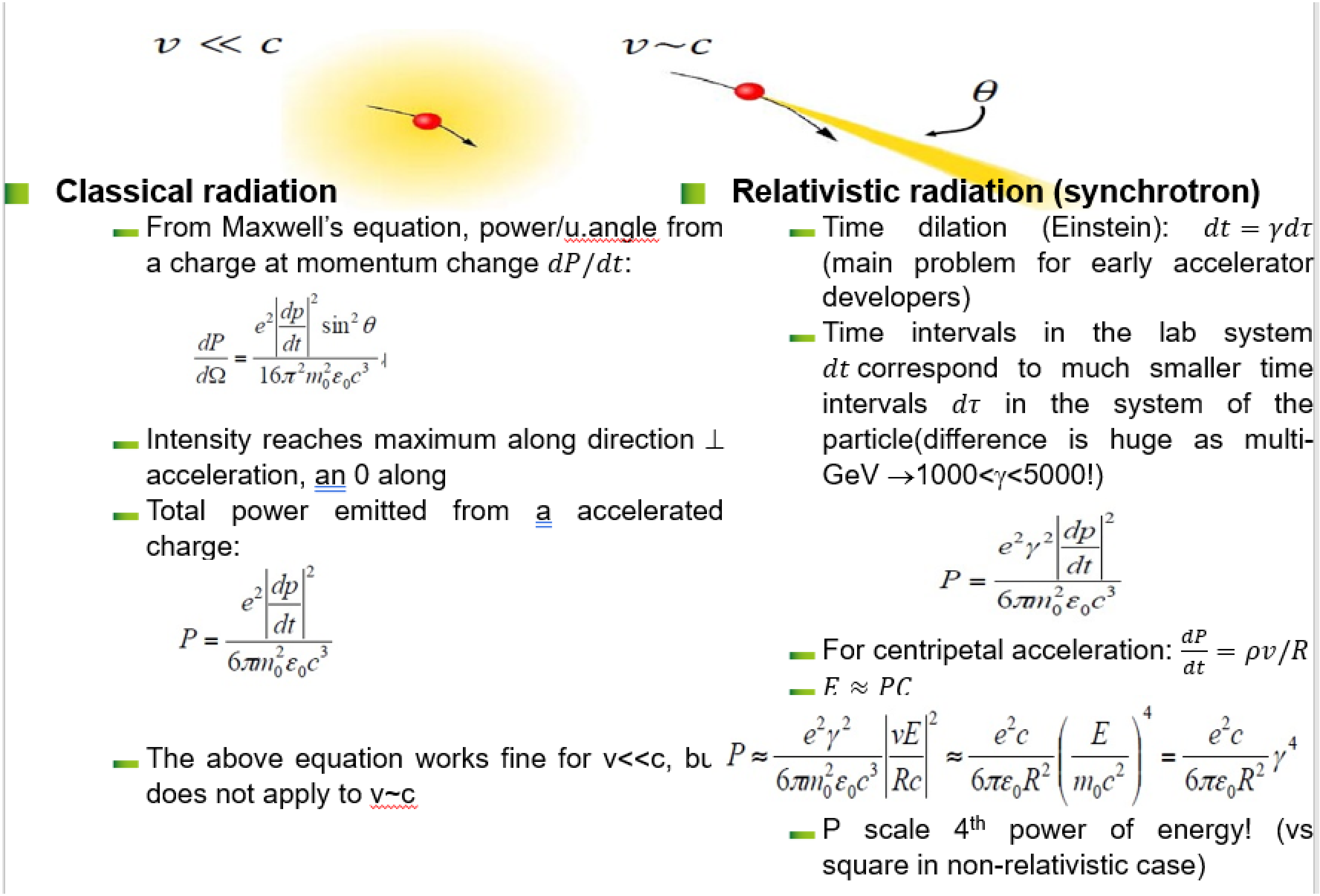
STORAGE RING: Filling modes

- Uniform filling
  - ~1000 electron bunches distributed over entire ring circumference
  - Beam current ~ 200 mA
  - Lifetime~ 60 hrs
  - Convenient for most experiments except time-resolved
  - Refill time: 3 mn

- Single bunch
  - One single bunch of electrons circling around ring
  - Beam current is lower (1-20 mA), but
  - Very convenient for time-resolved experiments
- Hybrid modes
  - 7/8 +1 filling mode: a train of 868 bunches (7/8 of the Storage Ring circumference) filled with 200 mA (0.23 mA / bunch); both edges of the train are filled with 1 mA single bunch; the remaining 1/8 gap is filled in its center with a cleaned 2 mA-single bunch
  - 24*8 +1 filling mode:One clean 4mA single bunch diametrically opposed to a ~ 196 mA multi-bunch beam composed of 24 groups of bunches spread over 3/4 of the storage ring circumference



STORAGE RING: Accelerated charged particles radiate



- **Classical radiation**
  - From Maxwell's equation, power/u.angle from a charge at momentum change dP/dt:

$$\frac{dP}{d\Omega} = \frac{e^2 \left|\frac{dp}{dt}\right|^2 \sin^2\theta}{16\pi^2 m_0^2 \varepsilon_0 c^3}$$

  - Intensity reaches maximum along direction ⊥ acceleration, an 0 along
  - Total power emitted from a accelerated charge:

$$P = \frac{e^2 \left|\frac{dp}{dt}\right|^2}{6\pi m_0^2 \varepsilon_0 c^3}$$

  - The above equation works fine for v<<c, bu does not apply to v~c

- **Relativistic radiation (synchrotron)**
  - Time dilation (Einstein): $dt = \gamma d\tau$ (main problem for early accelerator developers)
  - Time intervals in the lab system dt correspond to much smaller time intervals $d\tau$ in the system of the particle(difference is huge as multi-GeV →1000<γ<5000!)

$$P = \frac{e^2 \gamma^2 \left|\frac{dp}{dt}\right|^2}{6\pi m_0^2 \varepsilon_0 c^3}$$

  - For centripetal acceleration: $\frac{dP}{dt} = \rho v / R$
  - $E \approx PC$

$$P \approx \frac{e^2 \gamma^2}{6\pi m_0^2 \varepsilon_0 c^3} \left|\frac{vE}{Rc}\right|^2 \approx \frac{e^2 c}{6\pi \varepsilon_0 R^2} \left(\frac{E}{m_0 c^2}\right)^4 = \frac{e^2 c}{6\pi \varepsilon_0 R^2} \gamma^4$$

  - P scale 4th power of energy! (vs square in non-relativistic case)

STORAGE RING: Klystron Power loss and need to re-pump

- **Energy loss per revolution in circular orbit**

$$\Delta E = P\frac{2\pi R}{v} \approx \frac{e^2\gamma^4}{3\varepsilon_0 R}$$

  - Where we use $v \approx c$
  - In convenient units:

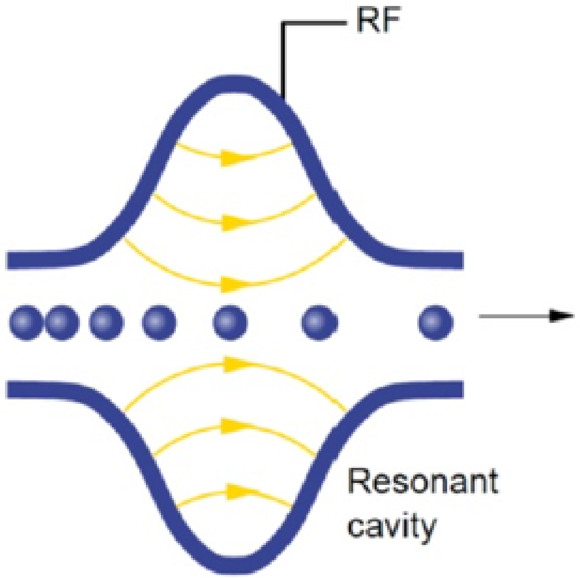
$$\Delta E(MeV) = 8.85\cdot 10^{-2}\,\frac{E^4(GeV)}{R(m)}$$

Power loss~1MW at 400mA storage current, for each loop, energy drop is about 1% of total energy

- **Radiated power from a storage ring** (with beam current I**,** of radius R and total straight sections of length L)

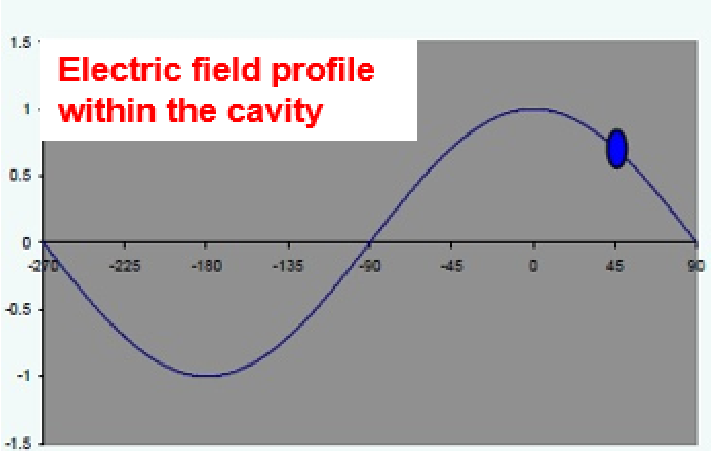
$$P(kW) = 8.85\cdot 10^{-2}\,\frac{E^4(GeV)}{R+\frac{L}{2\pi}(m)}\,I(mA)$$

- **Need to compensate power loss by pumping energy back into electrons using klystron (RF cavities)**
  - Electric field across resonant cavity
  - Electrons are accelerated if they enter cavity at the right time in RF cycle:

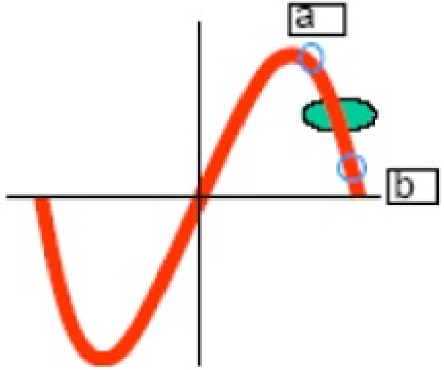


Basic principles of RF acceleration

- **The RF source supplies power to create a strong oscillating electric field across the cavity**
- **This electric field supplies energy to the particles through acceleration**
- **This compensates for the synchrotron radiation losses**

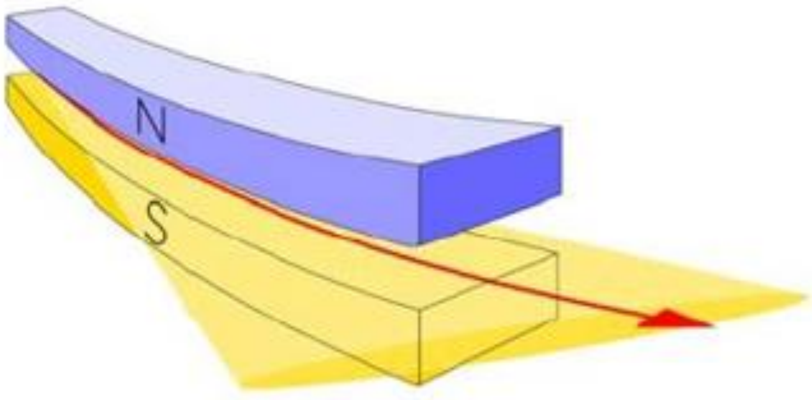


Electric field profile within the cavity



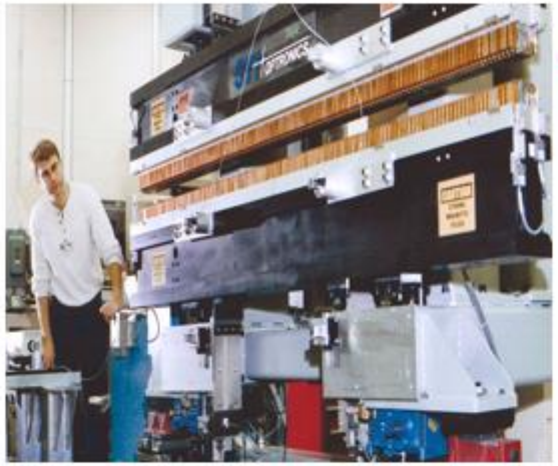
- **Centre of the bunch crossing the cavity is called "the synchronous particle"**
- **Particles see voltage :** $\boldsymbol{V_0 \sin 2\pi\omega_{rf} = V_0 \sin\varphi(t)}$
  - For synchronous particle, φ_S =0, no acceleration
  - Particle arriving early see $\varphi < 0$,
  - Particle arriving late see $\varphi > 0$,
- **Energy of those in advance is decreased and vice versa: « bunching »**
- To accelerate, make $0 < \varphi_S < \pi$, $\Delta E = qV_0 \sin\varphi_S$
- For longitudinal phase stability, make $-\frac{\pi}{2} < \varphi_S < +\pi/2$

STORAGE RING: Bending magnets

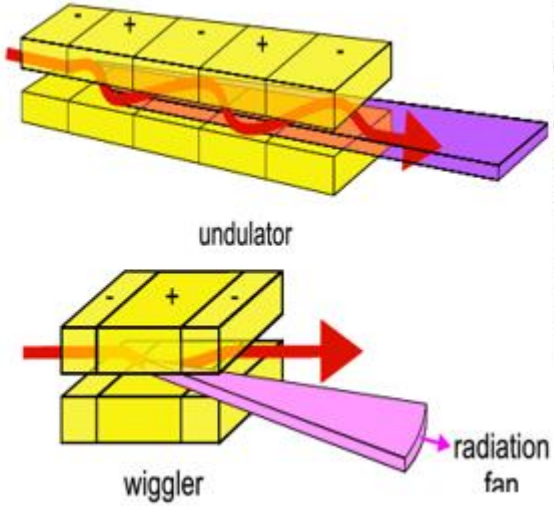


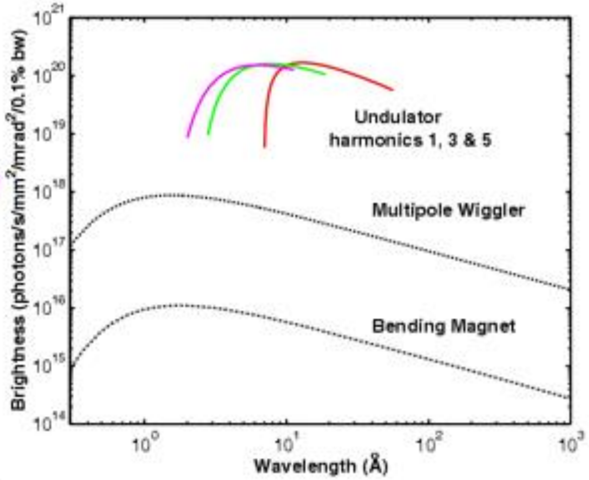
- **Main function: keeps electrons in a closed path**
  - Superconducting magnets: B~ 5 Tesla
  - Flux scales with B^2
  - Produce broadband radiation
  - Radiation fan:
    - Vertical divergence= $1/\gamma$
    - Horizontal divergence= angular change in path of electrons~10°

Third generation synchrotrons: INSERTION DEVICES

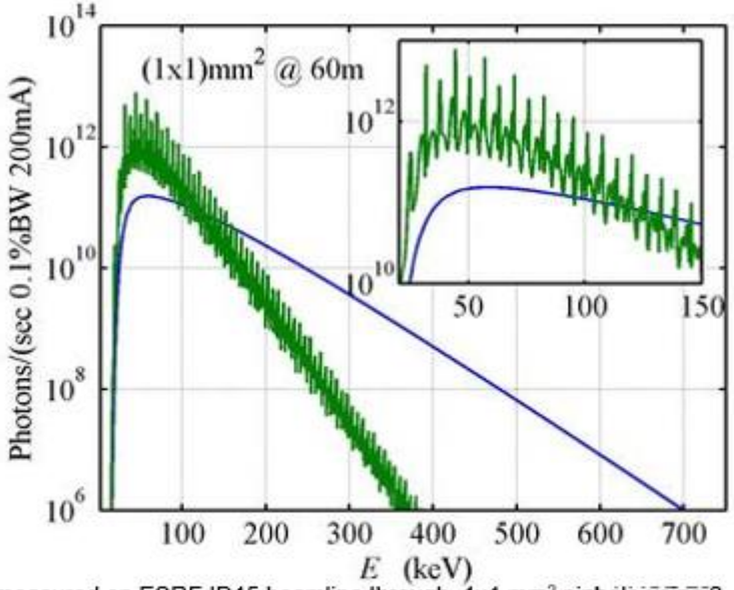


A view of the APS INSERTION DEVICE





- **INSERTION DEVICES: wigglers and undulators**
  - Produce periodically alternating field at the beam axis
  - Significantly improve flux and brilliance
  - Wigglers radiate intense flux over a large angular spread (>1/γ)
  - Undulators produce narrow bandwidth radiation at well defined energies (or wavelengths)



Flux measured on ESRF ID15 beamline through 1x1 mm^2 pinhole using 2 different insertion devices: AMPW in blue, U22 in green

Flux and Brilliance: (key indication of beamline facility)

FLUX

- Number of photons in narrow energy bandwidth, passing through a defined area

$$Flux = \frac{photons}{second.0.1\%\ bandwidth}$$

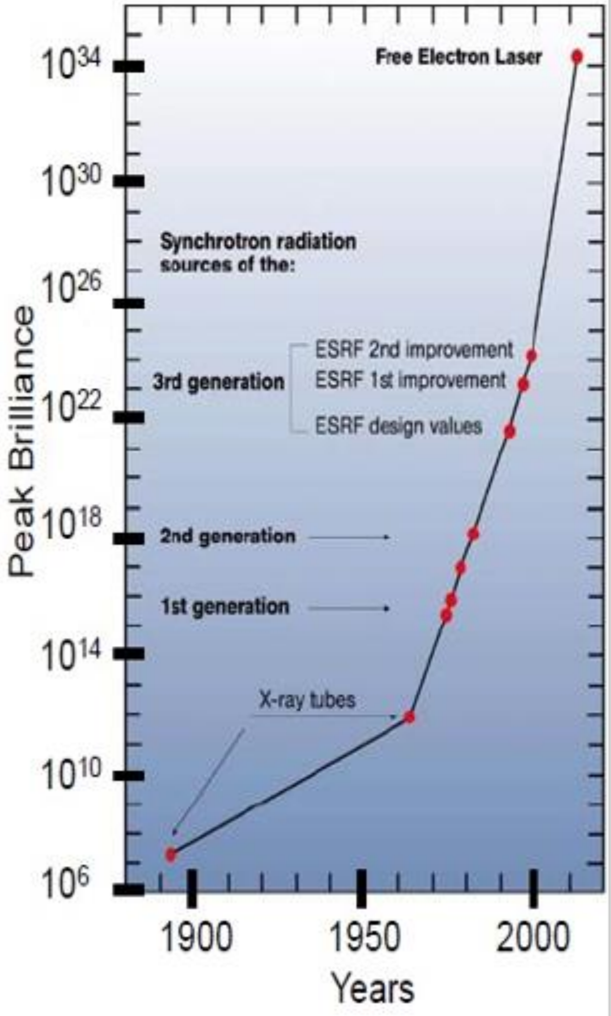
- Key parameter for experiment in which the entire, unfocused beam is required (e.g tomography)

BRILLIANCE

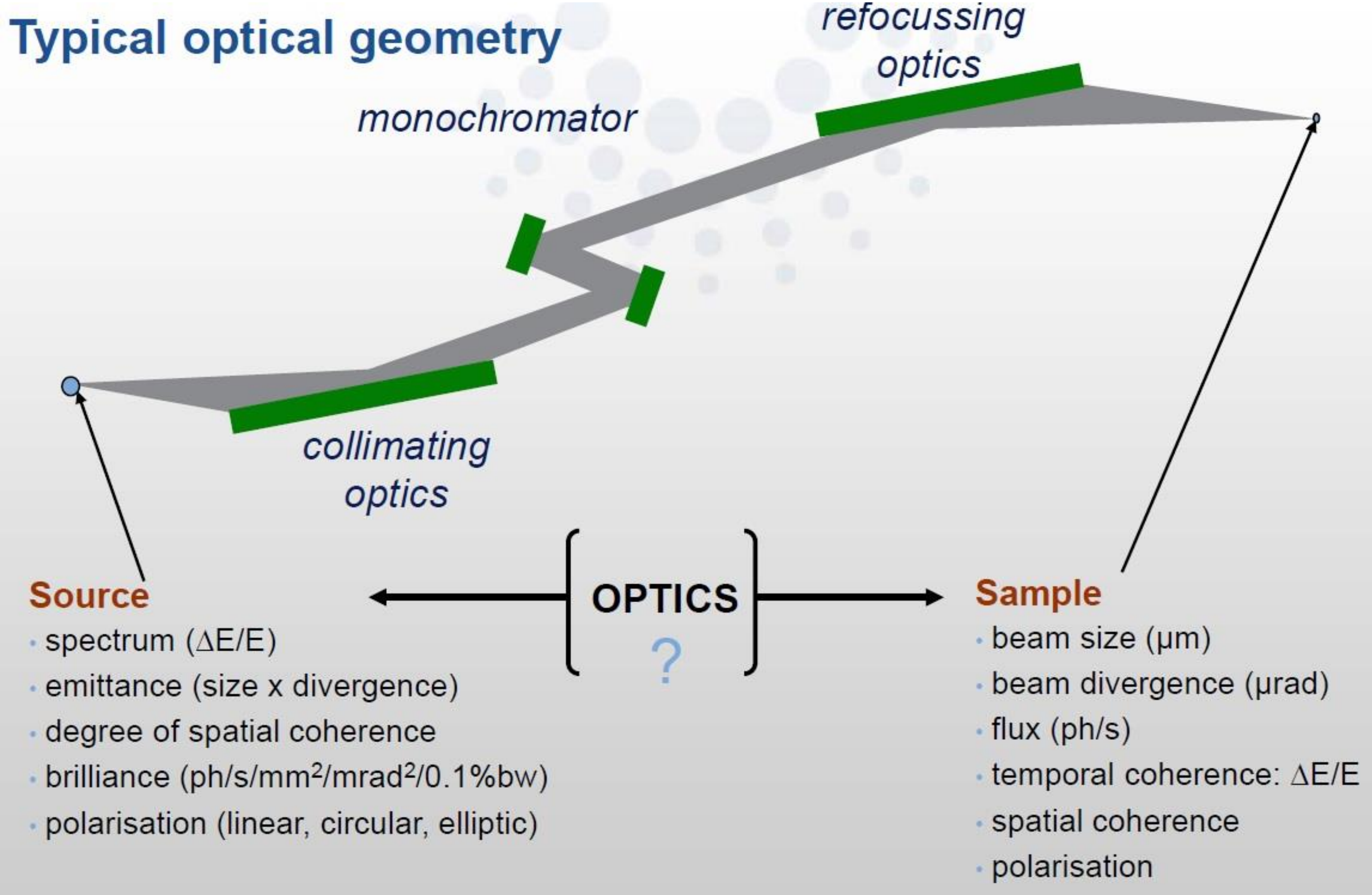
- Brilliance: a measure of the intensity and directionality of an x-ray beam. It determines the smallest spot onto which an x-ray beam can be focused.

$$Brilliance = \frac{photons}{second.unit\ area\ source\ size.mrad^2.0.1\%\ bandwidth}$$

- It is a measure of how flux is distributed, depends of X-ray optics, key parameter for experiments in which tight and parallel focusing is needed (protein crystallography, X-ray fluorescence,…)
- Higher brilliance → More flux on small samples!



X-ray Optics



Source
- spectrum (ΔE/E)
- emittance (size x divergence)
- degree of spatial coherence
- brilliance (ph/s/mm^2/mrad^2/0.1%bw)
- polarisation (linear, circular, elliptic)

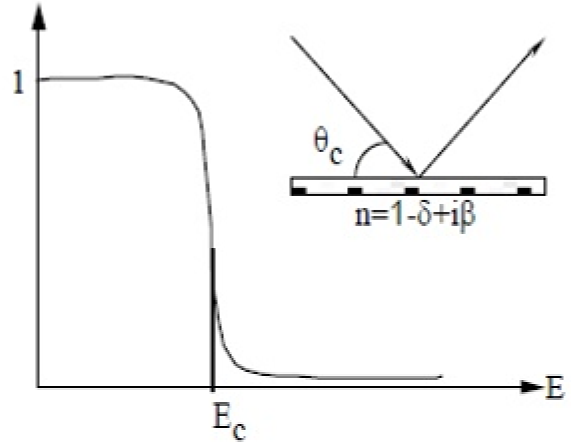
Sample
- beam size (μm)
- beam divergence (μrad)
- flux (ph/s)
- temporal coherence: ΔE/E
- spatial coherence
- polarisation

- **Main task: transform X-ray beam in order to obtain best match to experimental requirements**

X-ray optics: Mirrors

Main functions

- Deflecting:
- Collimation: matching the monochromator angular acceptance with the beam divergence
- Focusing: various shape (spherical, cylindrical and toroidal)
- Power filter: decreases incident power on sensitive optical components

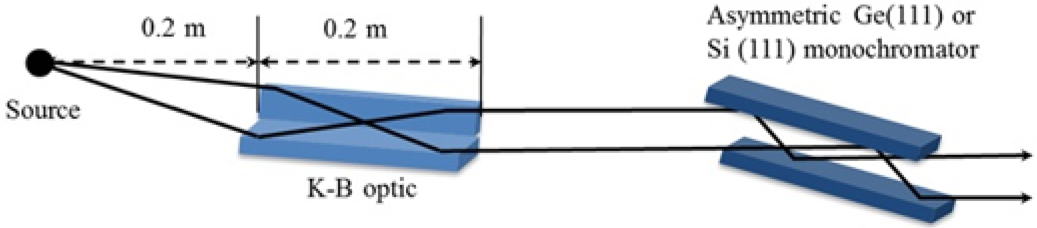


Requirements

- Ultra-smooth surface: roughness < 5 rms
- Ultra-precise shaping
- Very accurate and stable mechanical mounting
- Efficient cooling
- Reflectivity must tend to100% (for small enough angles)
- Small angles mean mirrors need to be long

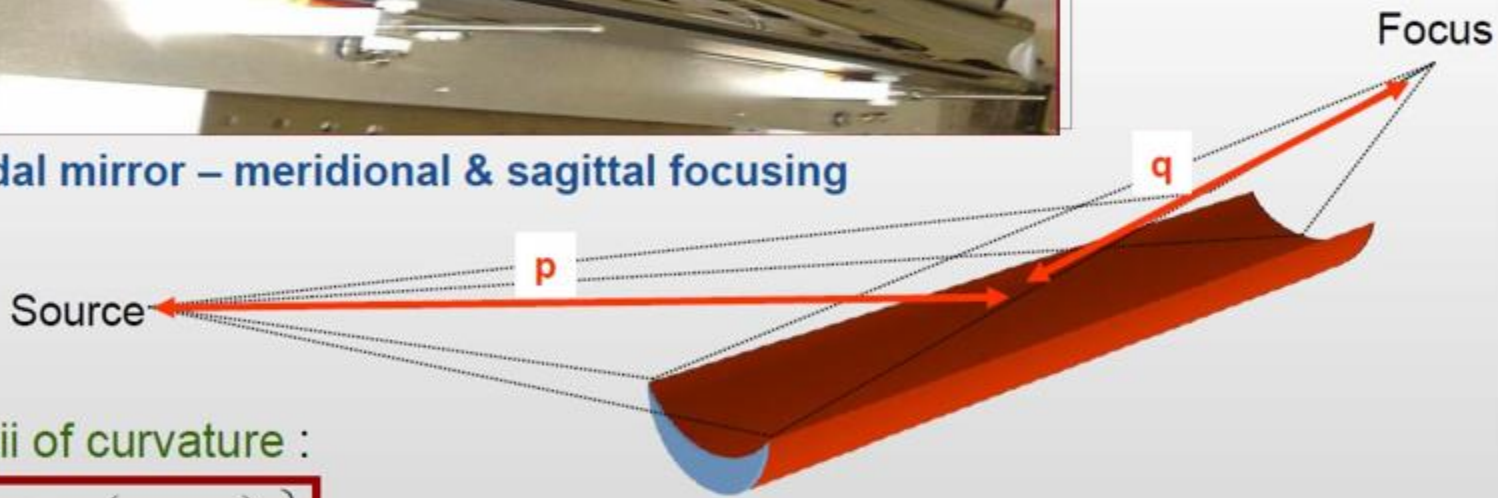
Materials: Si, SiC, Rh-coated Si

Example of collimating setup



Example: toroidal focusing mirror

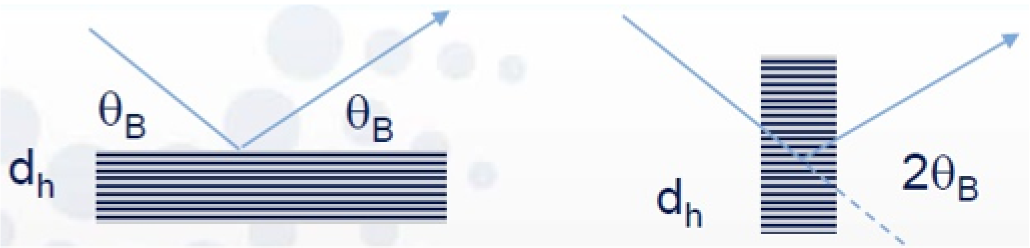
e.g. toroidal mirror – meridional & sagittal focusing

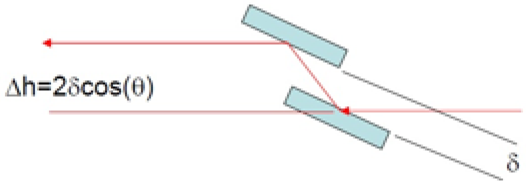


Radii of curvature :

$$\boxed{\begin{aligned} R_m &= \frac{2}{\sin\theta_i}\left(\frac{pq}{p+q}\right) \\ R_s &= 2\sin\theta_i\left(\frac{pq}{p+q}\right) \end{aligned}} \longrightarrow \boxed{R_s \approx R_m\theta^2} \xrightarrow{\theta\,=\,10\text{mrad}} \boxed{\begin{aligned} R_s &\sim mm \\ R_m &\sim km \end{aligned}}$$

X-ray Optics: Monochromators





Reflection: Bragg

$$E=\frac{hc}{\lambda}=\frac{hc}{2d_{hkl}\sin\theta_B}$$

Transmission: Laue

$$\frac{\Delta E}{E}=\frac{\Delta\lambda}{\lambda}=\sqrt{\omega_s^{\,2}+\psi_0^{\,2}}\cot\theta_B$$

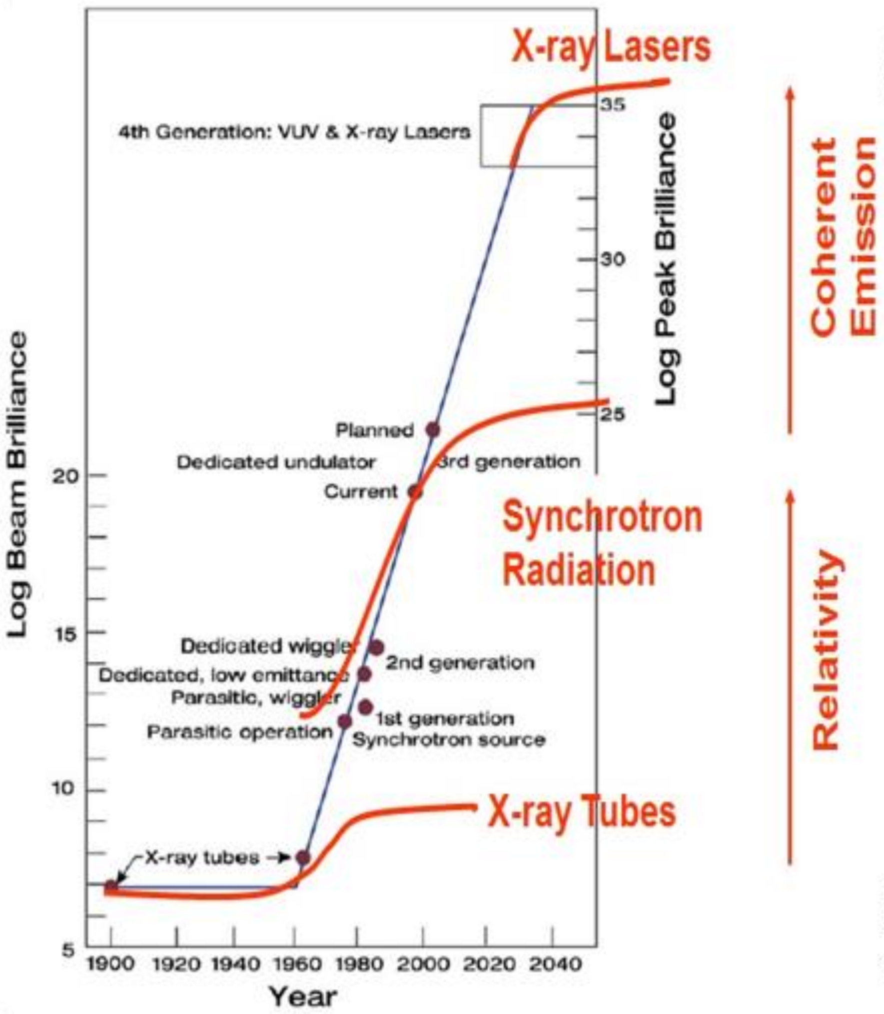
ω_s: Angular Darwin width
ψ_0 divergence of incident beam

- **Main functions**
  - Reduces incident beam to a narrow energy (wavelength) bandwidth
  - Double monochromator minimizes beam motion with angle change
  - Energy bandwidth depends on:
    - ➢ crystal types
    - ➢ Reflecting planes
    - ➢ Divergence of incident beam
  - Collimation: matching the monochromator angular acceptance with the beam divergence

- **Requirements**
  - Perfect crystals: Si, Ge, Diamond, but need to be tailored **very precisely:**
    - ➢ Orientation, cutting, polishing,,,,
    - ➢ Strain free, accurate and stable mounting
  - Efficient cooling

- **Materials: Si, Ge, Diamond**

Free Electron Lasers (FEL): a new generation of light sources

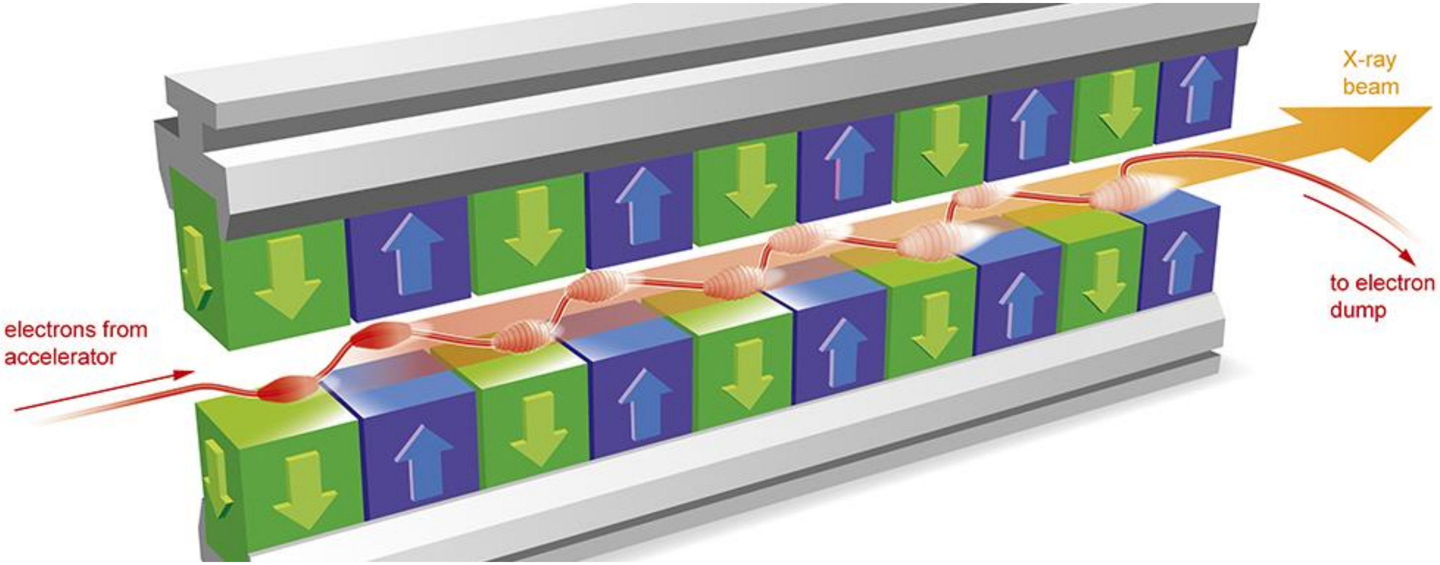


LCLS, Stanford, 280 eV-11.2 keV, 40-300 fs

RIKEN, Harima,

European XFEL, Hamburg, 5-25 keV 1-100 fs

Free Electron Lasers (FEL): a new generation of light sources



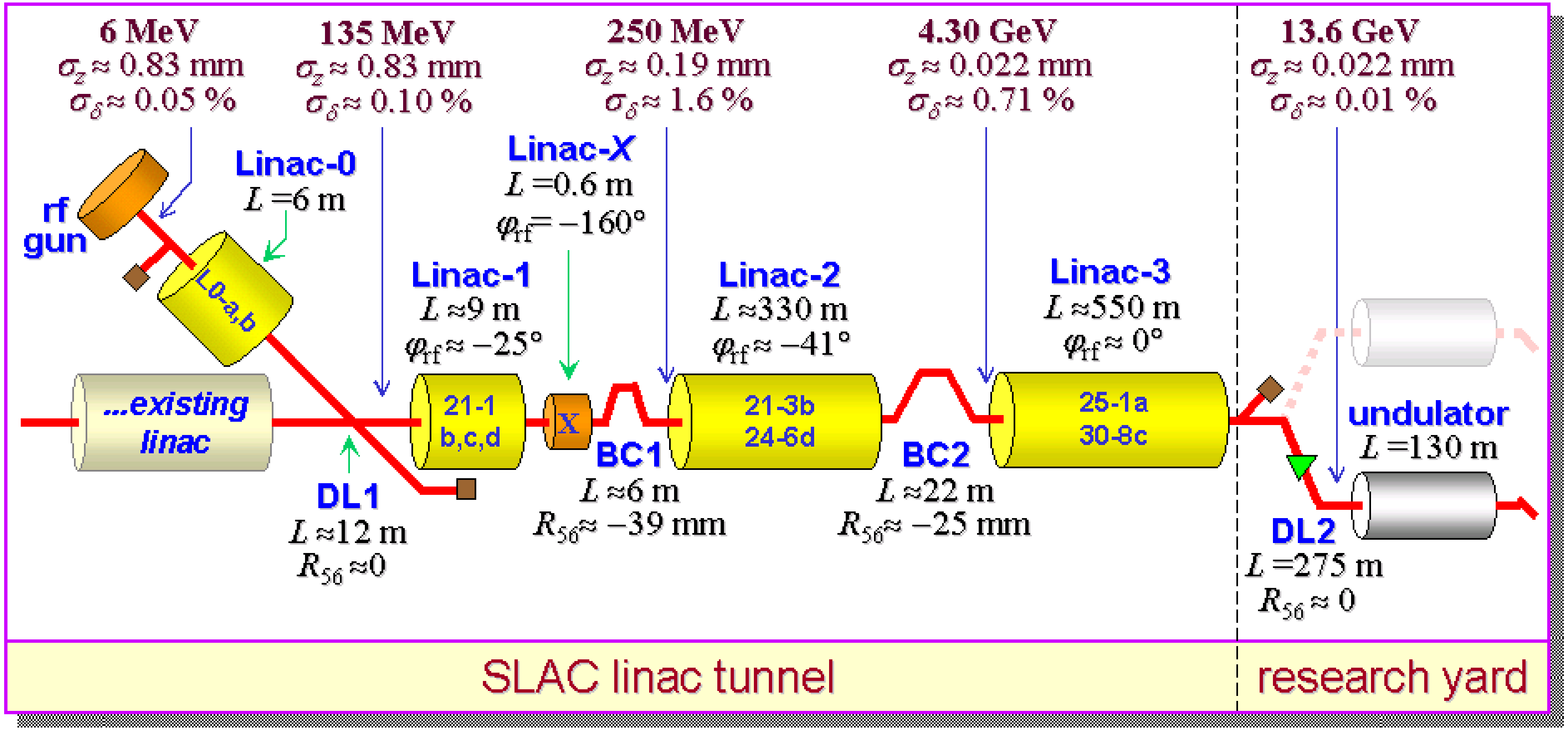
Principle:

- Short intense bunches of electrons injected in the LINAC
- Electrons are accelerated (up to 15 GeV) and passed through compressors (packed)
- Bunches oscillate through undulator magnet and emit x-rays
- X-rays are emitted **coherently** and at the **same** λ (unlike synchrotron)
- Tremendous brightness achieved using SASE (Self Amplified Spontaneous Emission)

Characteristics

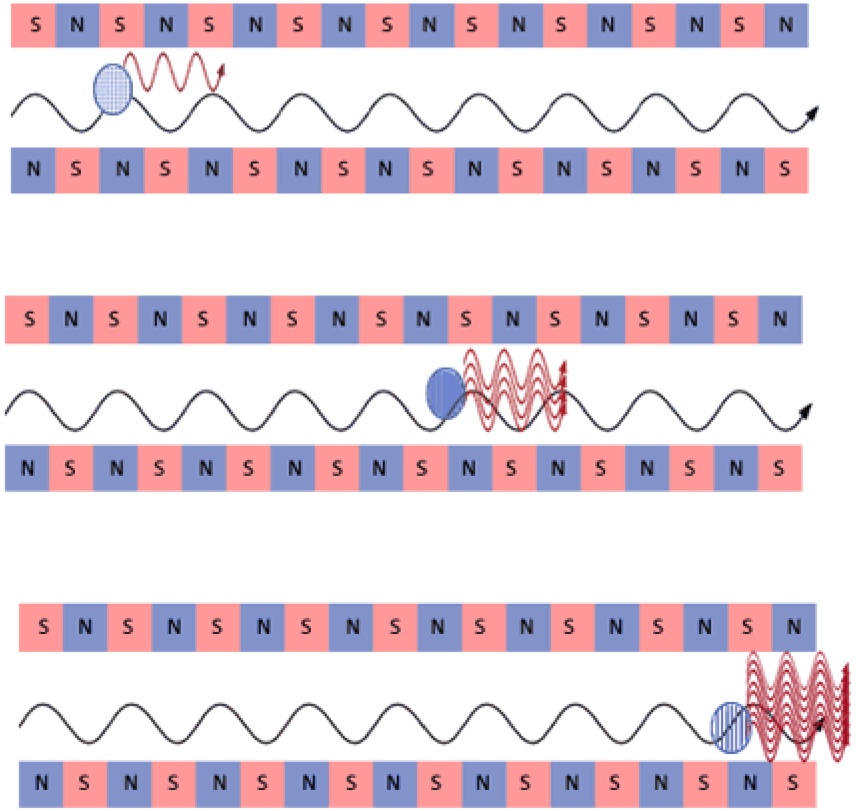
- Photons between 1.5 and 15 Å (8 keV and 800 eV)
- 10^{12} photons in a needle-thin beam
- Pulse duration: 1 -230 fs

FEL general scheme



FEL main specificity: The Self-Amplified Spontaneous Emission emission

Principle



- Electrons are forced to sinusoidal motion through a series of magnets with alternating poles
- Electrons produce synchrotron radiation
- Electron motion modified by electromagnetic fields of its own radiation
- Electrons bunch split into micro bunches due both the undulator and emitted synchrotron light
- Micro-bunches separated by a half wavelength of emitted radiation
- Micro-bunches radiate as if they were single particles with huge charge
- One single bunch generates an coherent X-ray pulse of 10^{12} photons

The global role of AdLS in scientific infrastructure and collaboration

- Advanced light sources are the most transformative scientific instruments similar to the invention of conventional lasers and computers.
- Advanced light sources are revolutionizing fundamental and applied sciences, including agriculture, biology, biomedicine, chemistry, climate and environmental eco-systems science, energy, engineering, geology, heritage studies, materials science, nanotechnology, paleontology, pharmaceutical discoveries, physics, with an accompanying impact on sustainable industry.
- The community of researchers around the world are striving collaboratively to construct ever more intense sources of electromagnetic radiation, specifically derived from synchrotron light sources and X-ray free-electron lasers (XFELs), to address the most challenging questions in living and condensed matter sciences.
- An African Light Source is expected to contribute significantly to the African Science Renaissance, the return of the African Science Diaspora, the enhancement of University Education, the training of a new generation of young researchers, the growth of competitive African industries, and the advancement of research that addresses issues, challenges and concerns relevant to Africa.
- For African countries to take control of their destinies and become major players in the international community, it is inevitable that a light source must begin construction somewhere on the African continent in the near future, which will promote peace and collaborations amongst African nations and the wider global community.

BÉNIN**RÉVÉLÉ**

LE NOUVEAU DÉPART