Design and operation of accelerator chain and storage rings

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Outline

Motivations to Synchrotron Light Sources

Beam Energy

Magnetic Lattice

Diffraction-Limited Storage Rings

Accelerator Chain

Conclusions

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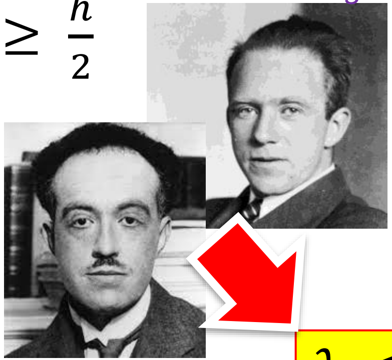
Why do we need X-rays?

photon energy ~ spatial resolution

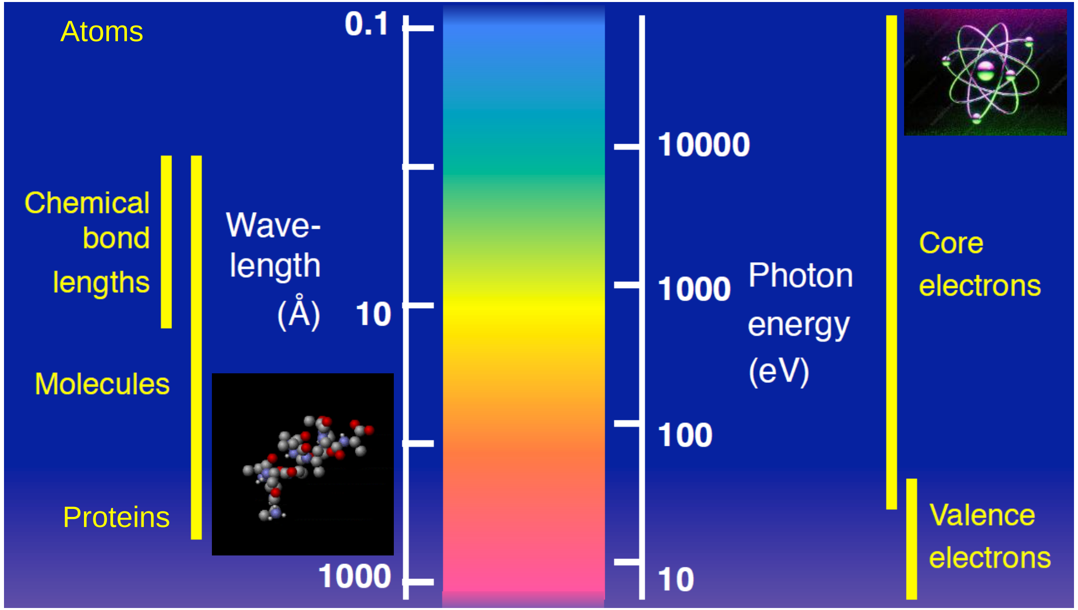
$$\begin{cases} \Delta z \cdot \Delta p \geq \frac{h}{2} \\ p = \frac{h}{\lambda} \end{cases}$$

W. Heisenberg



L. De Broglie

$$\lambda \leq \Delta z$$
$$\Delta\lambda/\lambda \ll 1$$



EUV and X-rays are ideal probes of chemical bonds, where most of science is rooted. They can be used to ***visualize*** proteins structure, molecular dynamics, atomic levels and orbitals…

How do we *generate* and *use* X-rays?

$$P_{SR} \propto \frac{\gamma^4}{R^2} \propto \frac{E^2 B_y^2}{m_0^4}$$

- High energy electrons
- Strong magnetic field

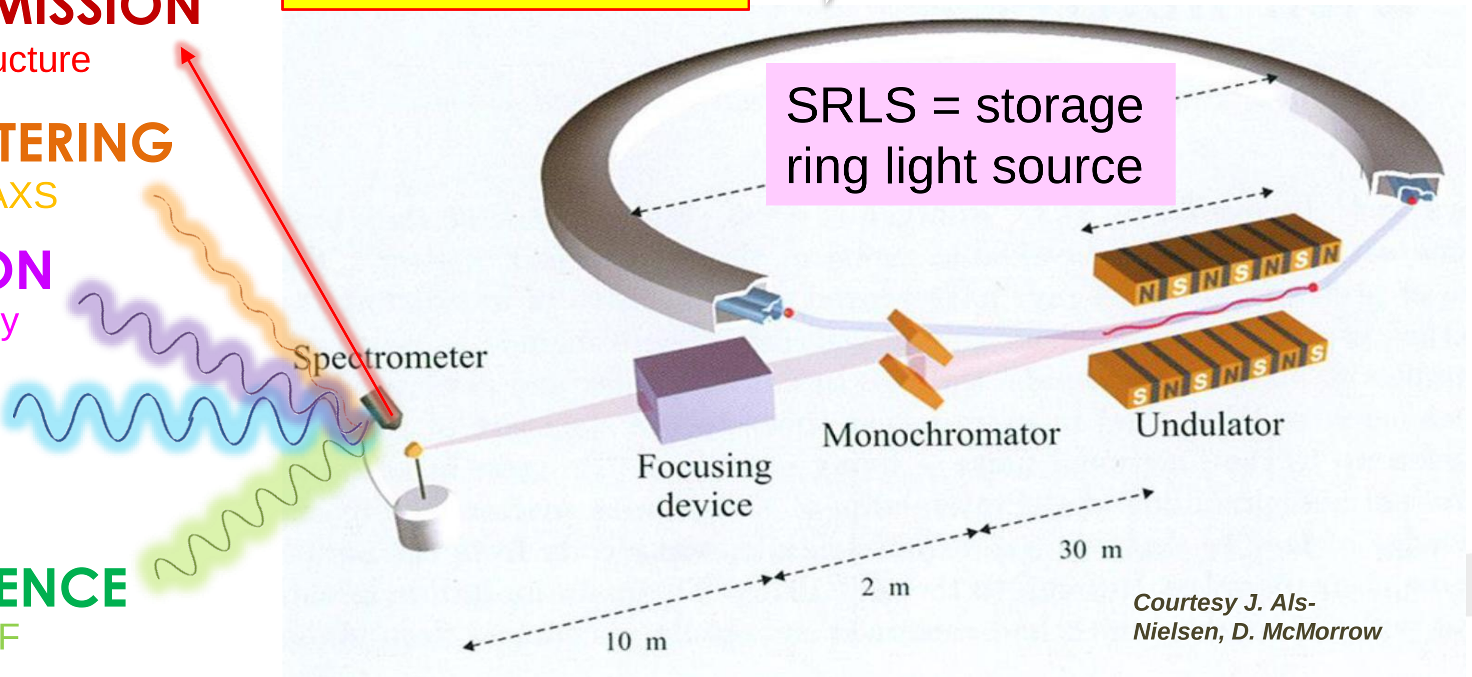
e- PHOTO-EMISSION
electronic structure

SCATTERING
SAXS

DIFFRACTION
Cristallography

ABSORPTION
Spectroscopy,
EXAFS, XANES

FLUORESCENCE
EXAFS, XRF



Courtesy J. Als-Nielsen, D. McMorrow

Why *accelerator*-based light sources?

Almost all experimental techniques gain from a large *6-D photon density*, or *brilliance* (also, *spectral brightness*)

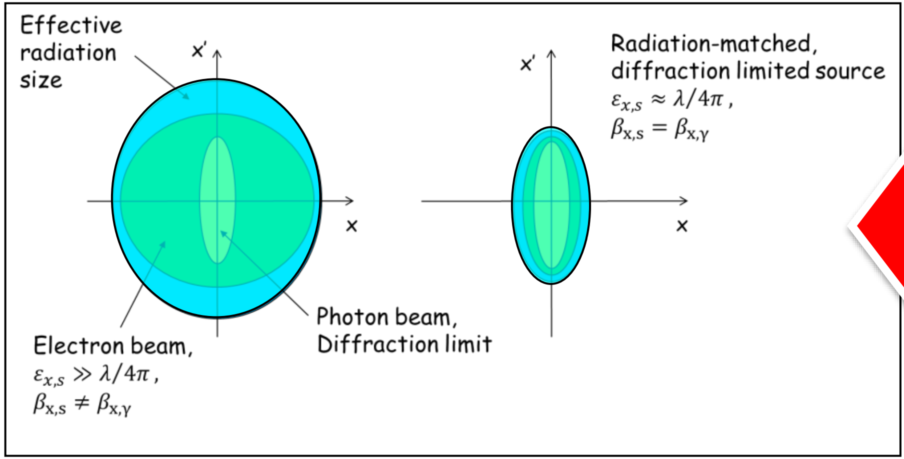
$$B_\gamma = \frac{dN_\gamma/dt}{\Delta\omega/\omega} \times \frac{1}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

$$\sigma_u \sigma_{u'} = \varepsilon_{x,y} \le \frac{\lambda}{4\pi}$$

Diffraction Limit

$$B_\gamma = \frac{dN_\gamma/dt}{\Delta\omega/\omega} \frac{1}{(\lambda^2/2)(\kappa+1)}$$

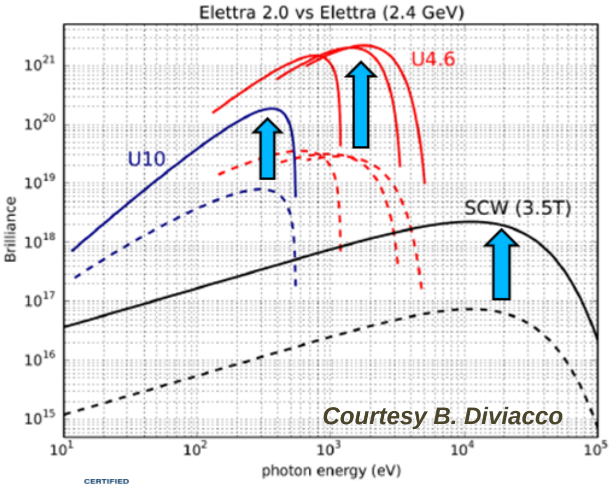
Coupling, $\kappa = \frac{\varepsilon_y}{\varepsilon_x} \le 1$

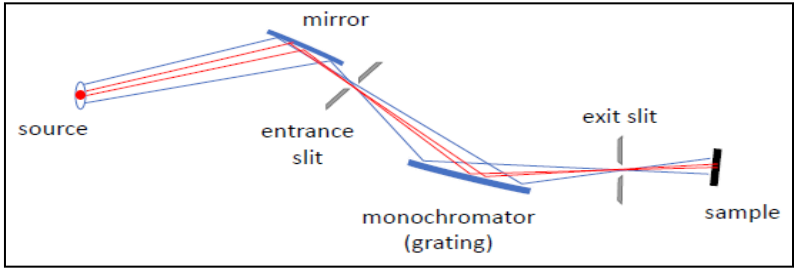


This drives the race to 4th generation synchrotron light sources, for **ultra-low emittance**, **matched** beams.

The importance of being *brilliant*

- $\frac{dN_\gamma/dt}{\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}}$ is a **conserved quantity** in a *perfect* optical system. However, a ***real beamline*** includes slits, mirrors, gratings, etc. for manipulation of the light pulse. They show geometrical and surface **imperfections**, which are stronger for larger spatial and angular **footprint of the light on the optical elements**.





Courtesy A. Bianco

Machine design at the state-of-the-art is a good investment because **the higher the brilliance at the *source* is, the higher the brilliance at the *sample is!***

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Development of SRLS

- **First observation**:

  1947, General Electric, 70 MeV synchrotron

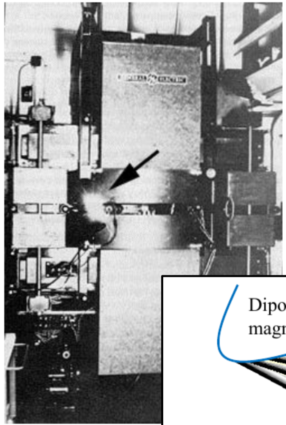
- **First user experiments**:

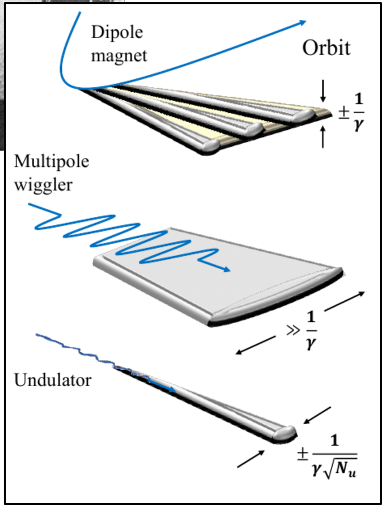
  1956, Cornell, 320 MeV synchrotron

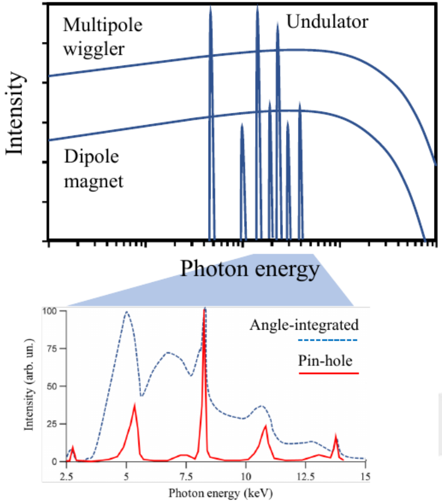
- **1st generation light sources**: machine built for High Energy Physics or other purposes used parasitically for synchrotron radiation

- **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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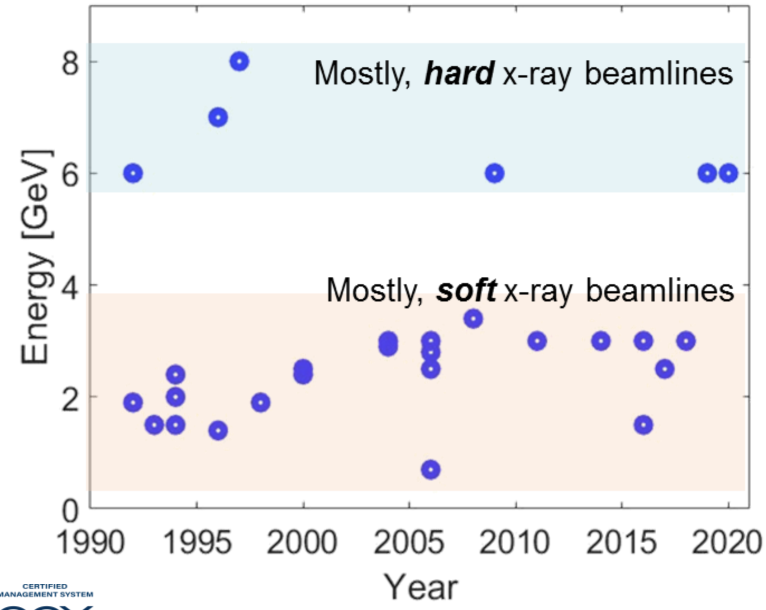
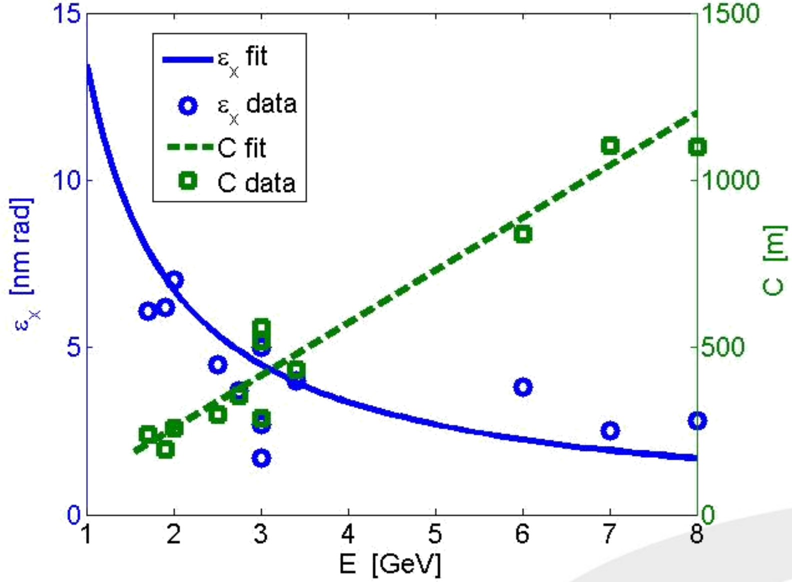
Accelerator size

- The e-beam energy determines the **photon energy range:** $\boldsymbol{\omega_c \approx \frac{c\gamma^3}{R}}$



- The beam energy roughly sets the **SRLS size:**

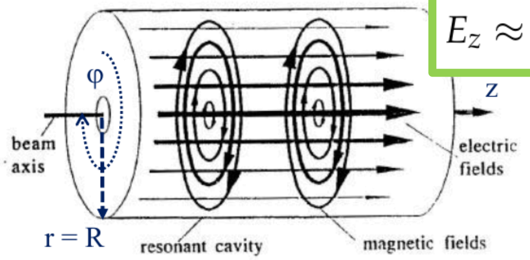
$$\frac{mv_z^2}{R} = F_{L,x} = ev_zB_y \quad \Rightarrow \quad \boldsymbol{p_z = eB_yR}$$



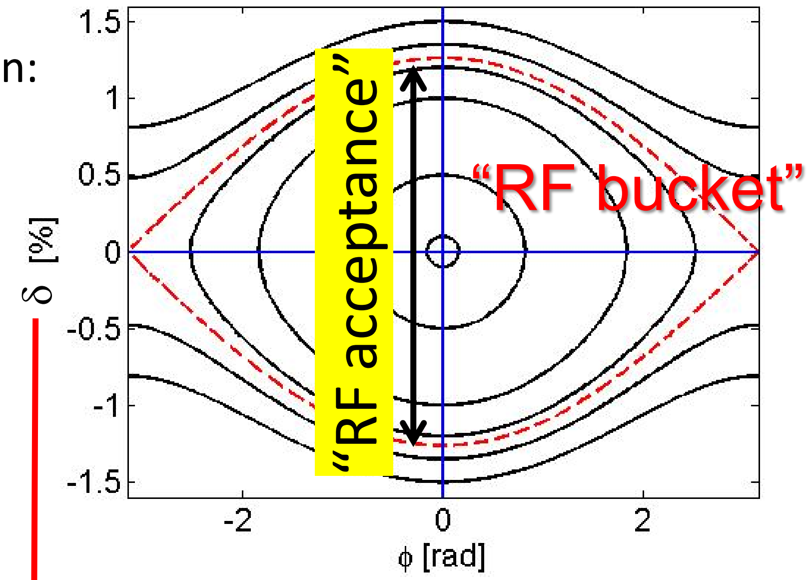
Synchrotron oscillations

- **RF cavities** replenish the energy lost every turn
  $\Rightarrow$ beam energy is constant *on average* in a turn:

PILL-BOX (standing-wave):



$$E_z \approx E_{z,0}\cos(\omega t + \phi_0)$$



Synchrotron oscillations:

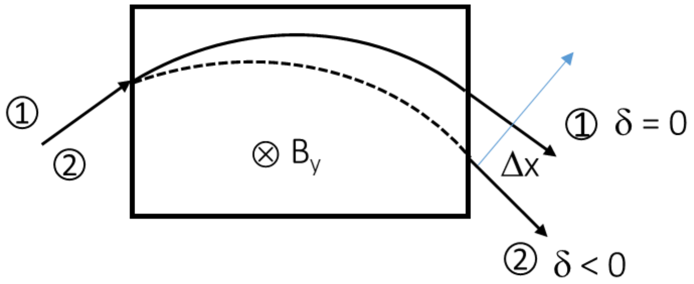
$$\Omega_s(t) := \frac{2\pi}{T_s} = \sqrt{-\frac{qV_0\eta\omega_{RF}\sin\psi_s}{Cp_s}}$$

typically, $\sigma_\delta \approx 0.1\%$

typically, $\sigma_t \approx 5-30\ ps$ *(zero-current limit)*

Dispersion function

High energy electrons on a circular path:



$$E \longrightarrow E - E_{sr} + \ldots$$
$$\delta := \Delta E / E$$
$$p_z = e B_y R$$

Dispersion function:

$$\boxed{D_x(s) := \frac{x(s)}{\delta}}$$

Revolution frequency difference per unit of energy deviation (“slip factor”):

$$\eta := \frac{d\omega/\omega_s}{dp_z/p_{z,s}} = \boxed{\frac{1}{\gamma^2} - \alpha_c} \xrightarrow[\text{GeV energies}]{} -\alpha_c = \frac{dL/L_s}{dp_z/p_{z,s}} = \boxed{-\frac{1}{C}\int ds \frac{D_x(s)}{R(s)}}$$

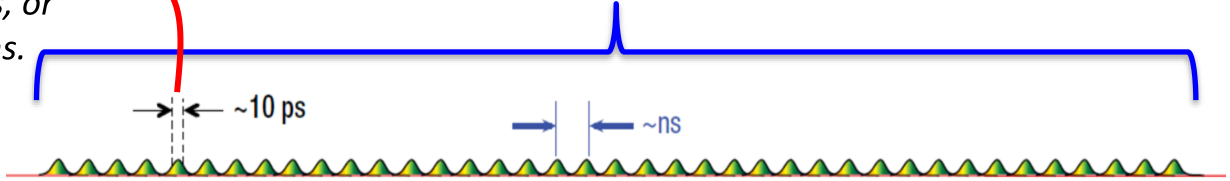
Depending on the magnetic lattice’s properties, off-energy particles arrive either earlier or later at the RF cavity, w.r.t. the on-energy (“synchronous”) particle.

Filling pattern

- RF field imposes a synchronization with the particles' arrival time: $\omega = h\omega_{riv}, \quad h \in \dot{\mathbb{N}}(\gg 1)$
  - The **harmonic number *h*** is the max. number of "spaces" to be filled (**RF buckets**)

***Shorter photon pulses** can be produced in dedicated schemes of few bunches, or with advanced e-beam manipulations.*

$T_{riv} \sim 1 - \text{few } \mu s$



Adapted from NGLS CDR

- **1.5 - 8 GeV, 200 – 500 mA, 100 – 1000 bunches per turn**
- **10 – 50 photon beamlines operating simultaneously**
- **> 5000 hours per year (24h, 7/7), ~1000 hours reserved for machine physics**
- **> 1000 users / year**

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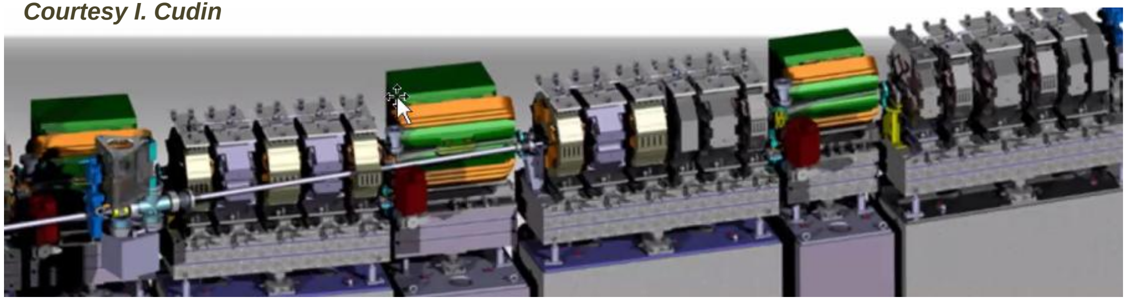
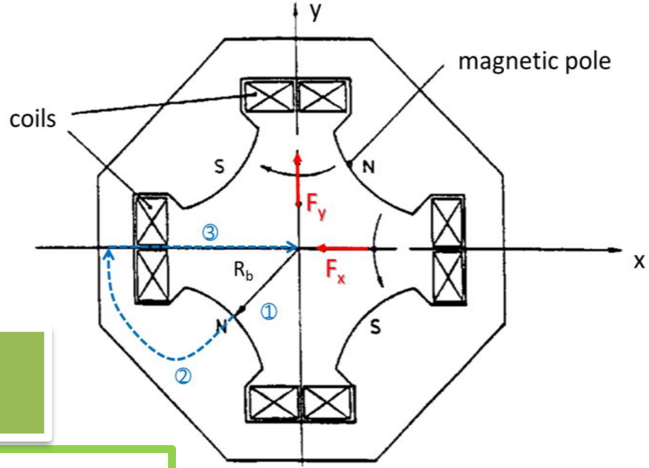
Strong focusing

Courtesy I. Cudin



Vacuum chamber (Al, Cu, Steel) at ultra-low pressure (< 10^{-9} mbar), to avoid gas-scattering



Particle beam must be kept in!

→ ***external magnetic focusing***

300 MV/m !

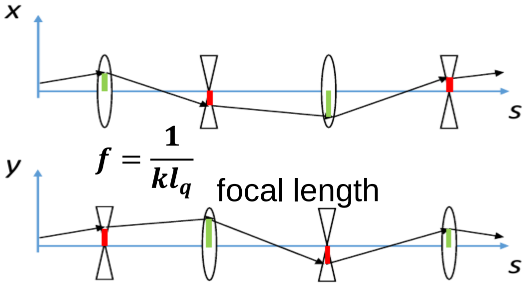
$$\frac{|\vec{F}_e|}{|\vec{F}_m|} = \frac{q|\vec{E}|}{q|\vec{v}\wedge\vec{B}|} = \frac{E}{vB} \equiv 1 \Rightarrow \frac{|\vec{E}|}{|\vec{B}|} = \beta c$$

1 Tesla…

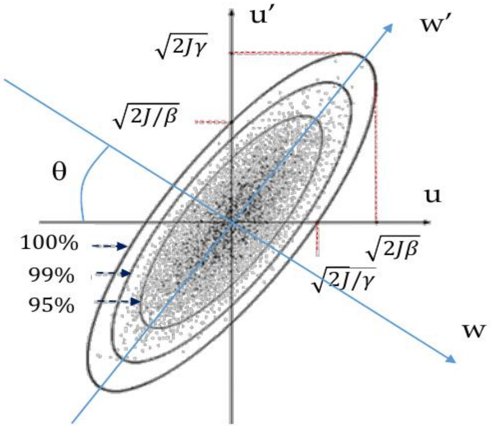
Normalized quad strength:

$$k[m^{-2}] = 0.2998\frac{g[T/m]}{p_z[GeV/c]}$$

Betatron motion



$$f = \frac{1}{kl_q}$$ focal length



Alternated focusing and defocusing quads can provide effective focusing, i.e. ***stability***, simultaneously in ***both planes***.

Hill's eqs. *(pseudo-oscillators) assume* *linear motion* *&* *no frictional forces*:

$$\begin{cases} u(s) = \sqrt{2J_u\beta_u}\cos\Delta\mu_u \\ u'(s) = -\sqrt{\dfrac{2J_u}{\beta_u}}\left(\alpha_u\cos\Delta\mu_u + \sin\Delta\mu_u\right) \end{cases}$$

Emittance:

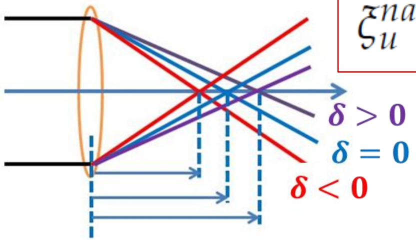
$$\epsilon_u = \frac{Area}{\pi} = \sigma_u\sigma_{u'}$$

Betatron tune = # oscillations per turn

$$Q_u = \frac{\Delta\mu_u}{2\pi} = \oint\frac{ds}{\beta_u(s)} \equiv \frac{2\pi R_s}{\bar{\beta}_u}$$

Nonlinearities

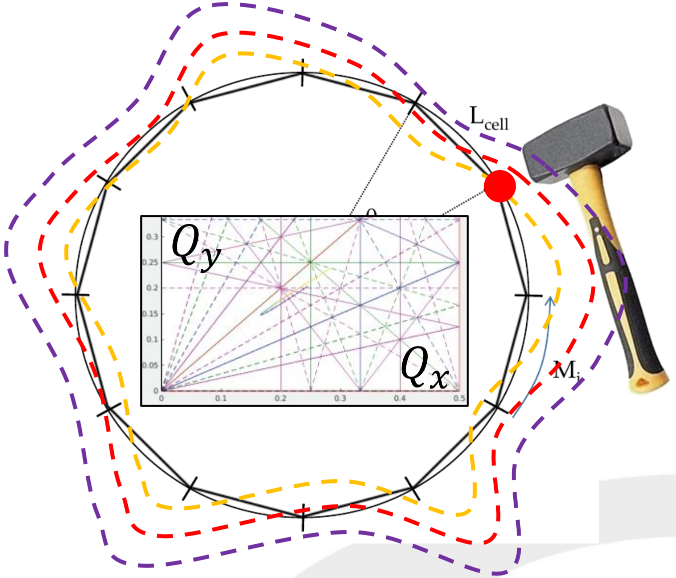
1. Particles at (slightly) different energies are focused differently – ***linear chromaticity:***



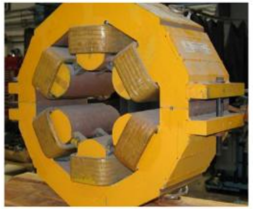
$$\xi_u^{nat} := \frac{\Delta Q_u}{\delta} = -\frac{1}{4\pi}\oint ds\,\beta_u(s)k(s)$$

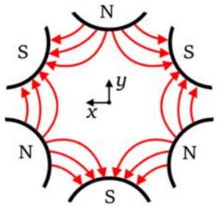
effect enhanced by many strong quads

2. Magnets' misalignment and field errors "resonate" with *rational* tunes – ***resonances*** can lead to beam loss!



3. ***Sextupole*** magnets correct the chromaticity, but at the cost of higher order aberrations!



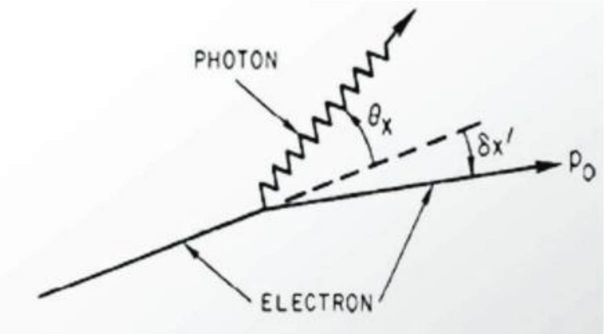


$$m_{sext} \propto \frac{1}{\eta_x} \propto \frac{1}{\theta_b} = \frac{N_b}{2\pi}$$

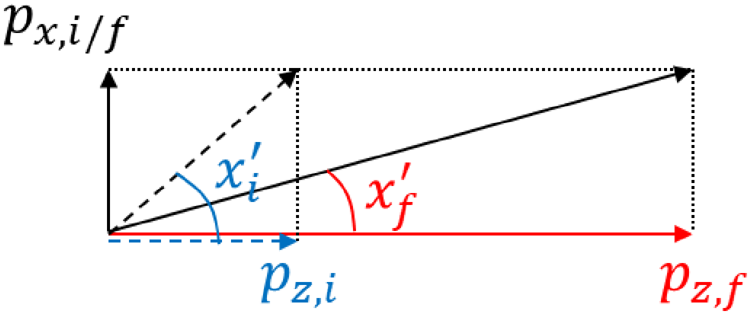
effect enhanced by many dipoles

Radiation damping, quantum excitation

- Radiation quanta emitted with small but non-zero angle. ***Total momentum*** of electrons is reduced.



- RF cavities restore the ***longitudinal momentum only***. Transverse divergence of electrons is reduced.



- Average variation of oscillation amplitude^2 in a turn:

$$\left\langle \frac{d}{dt}\langle dA_x^2\rangle_\phi \right\rangle_R = \left\langle \frac{d}{dt}\langle dA_{x,\beta}^2\rangle_\phi \right\rangle_R + \left\langle \frac{H_x}{E_0^2}\frac{dN_{ph}}{dt}\langle u^2\rangle_n \right\rangle_R = -2\frac{\langle A_{x,\beta}^2\rangle_R}{\tau_x} + \frac{55}{24\sqrt{3}}\frac{\langle H_x P_0 u_c\rangle_R}{E_0^2} \equiv 0$$

Characteristic **damping time**: $\boxed{\tau \approx T_0 \frac{E_0}{U_0}}$

Radiated **power** & **dispersive** motion

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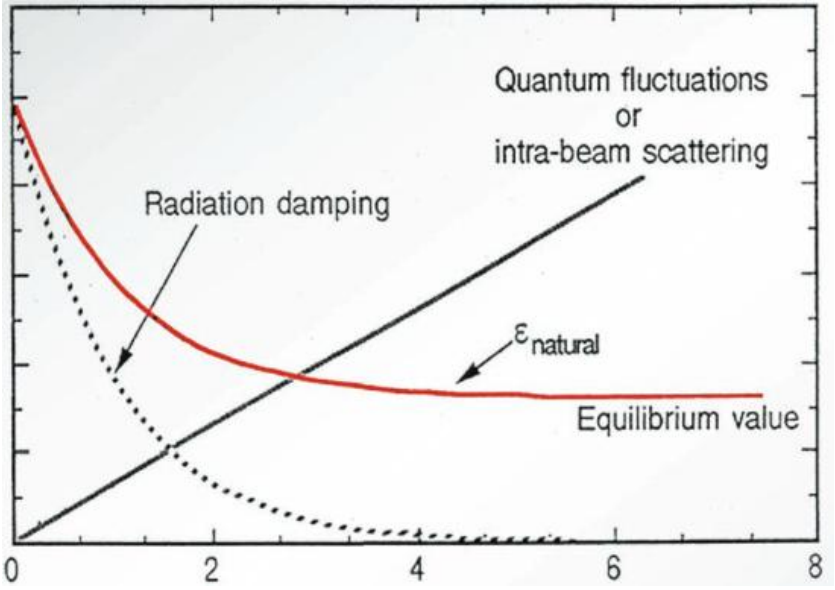
Horizontal emittance



damping times

$$\varepsilon_{natural} = \varepsilon_1 e^{-2t/\tau_d} + \varepsilon_{eq}\left(1 - e^{-2t/\tau_d}\right)$$

$$\boxed{\epsilon_{x,eq} =} \; C_e \frac{\gamma^2}{J_x}\frac{\langle H_x \rangle_R}{R} \; \boxed{= F \frac{C_e}{J_x}\frac{\gamma^2}{N_b^3}}$$

This is driving world-wide upgrades to multi-bend lattices (4th generation). Radiation is far more collimated and more intense – higher "brilliance"!

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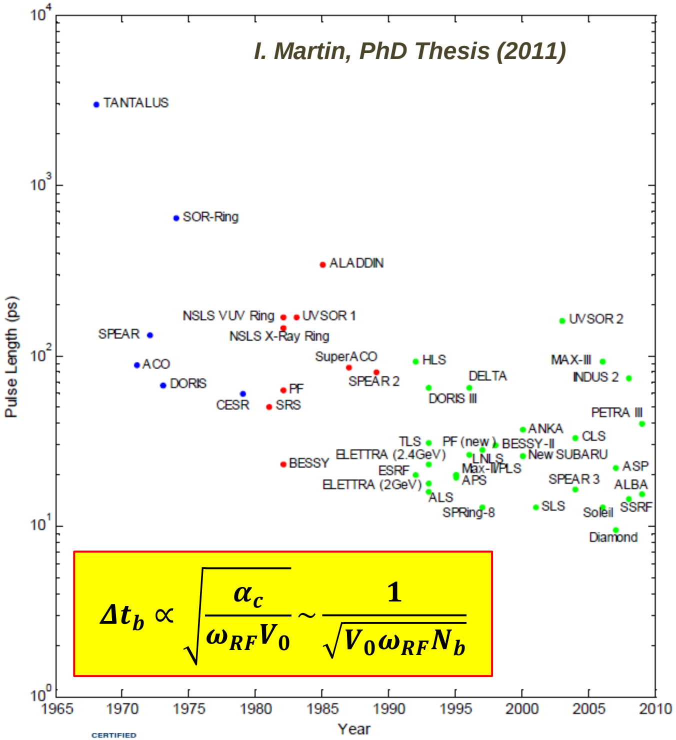
Bunch length

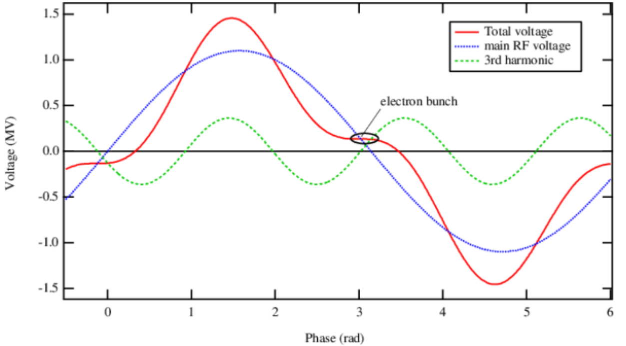
- **Intrabeam scattering** (multiple small angle events) enlarges the emittances through diffusion, in proportion to the 3D charge density.
  - Mitigated through higher ***harmonic RF cavity***, used to flatten the beam longitudinal phase space and make 3–10 × longer bunches.
    - Still, ***(sub-)ps X-ray pulses*** are being considered. Flux and transparency to standard operation remain a challenge.

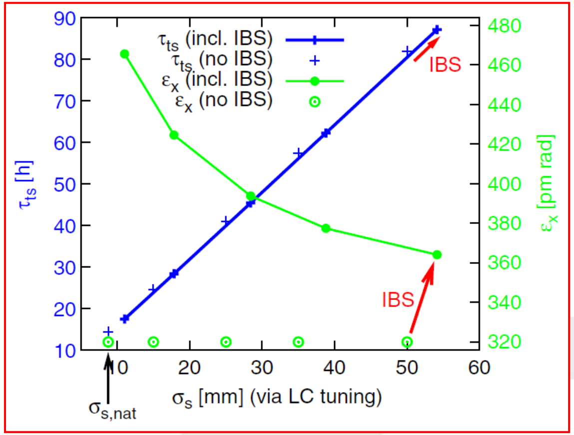
I. Martin, PhD Thesis (2011)



$$\Delta t_b \propto \sqrt{\frac{\alpha_c}{\omega_{RF} V_0}} \sim \frac{1}{\sqrt{V_0 \omega_{RF} N_b}}$$

S.C. Leemann, PRST-AB 17, 050705 (2014)





Liouville's theorem

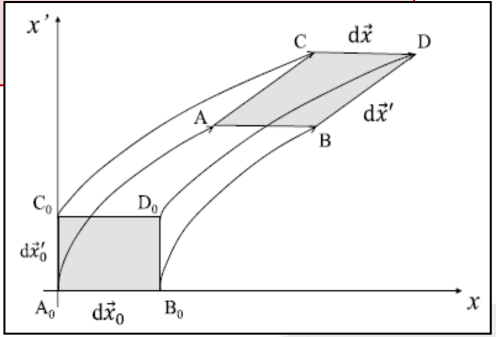
The dynamics of a non-dissipative system obeys ***Hamilton's equations:*** $\dot{q} = \frac{\partial H}{\partial p}$ $\dot{p} = -\frac{\partial H}{\partial q}$

The ***phase space area*** (hyper-volume) in proximity of an orbit is a ***constant of motion***.

A storage ring is ***not*** a Hamiltonian system because of radiation emission and acceleration.

However, it behaves ***as if it were*** a Hamiltonian system.

⇒ The "phase space" beam emittance is a constant of motion



A storage ring is ***not*** a ***linear*** system because of high order magnetic field components.

However, it behaves as a ***linearized system***.

⇒ The "statistical" beam emittance is a constant of motion

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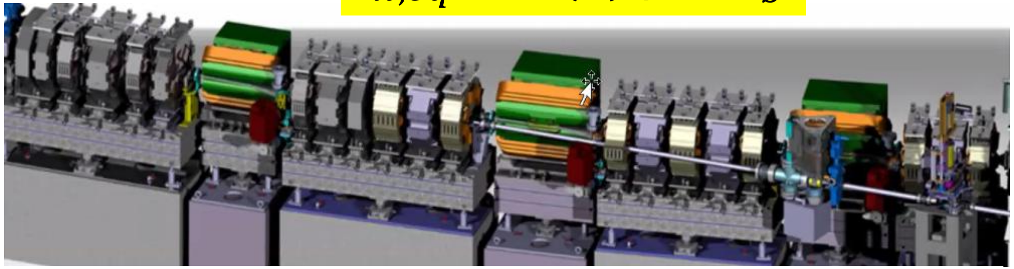
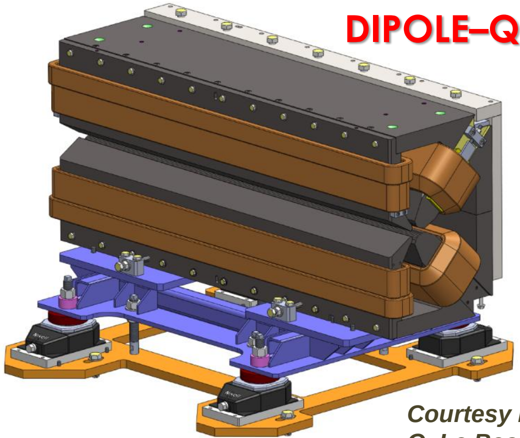
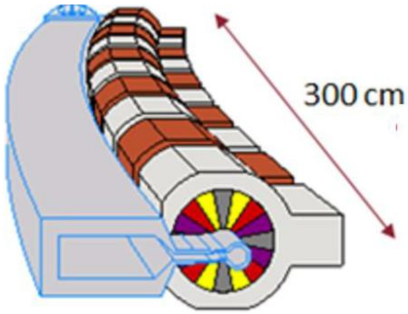
Multi-bend lattices

$$\varepsilon_{x,eq} \propto F(k)\gamma^2/N_b^3$$







Courtesy I. Cudin, G. Le Bec, T. Shaftan

- From relatively sparse to **tight, dense, strong focusing lattices**

  - Complex dipoles with transverse and/or longitudinal gradients
  - Combined multipole magnets
  - Fringe-field interference

  - 3-D "AI"-driven optimization of magnets design

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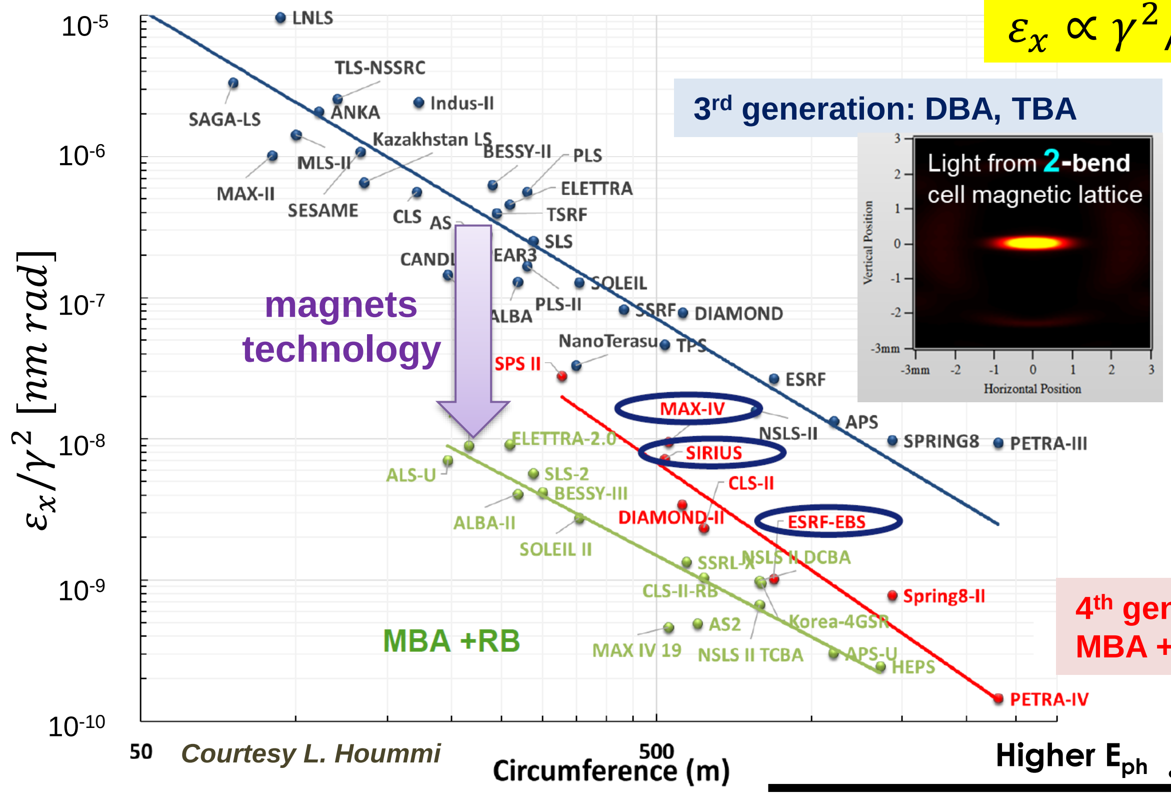
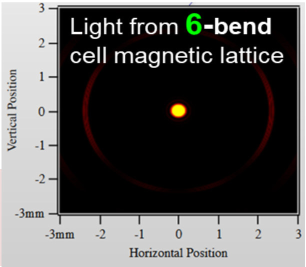
Emittance landscape

$$\varepsilon_x \propto \gamma^2 / N_b^3$$



Courtesy L. Hoummi

4th generation: MBA + RB



Higher E_{ph}

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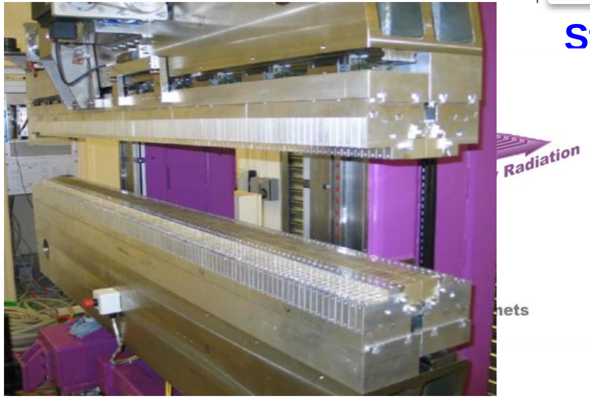
Smaller beams drive undulator technology

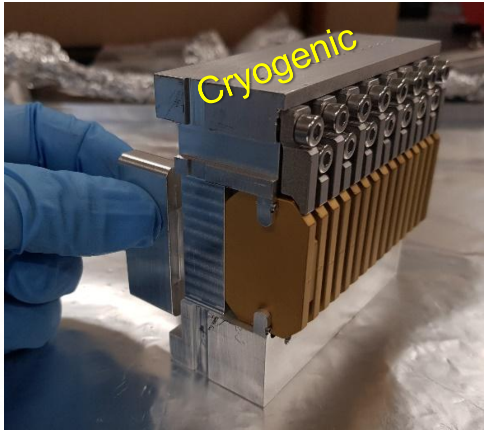


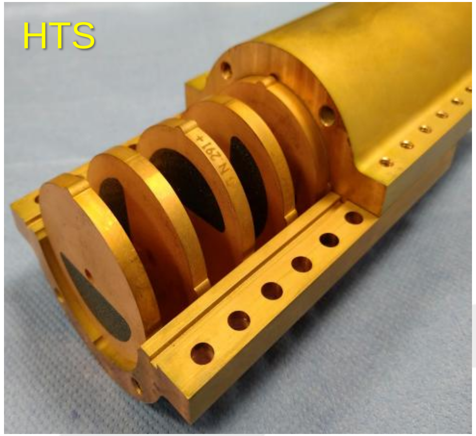
Stronger field by shorter poles → *technological challenge*

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

Shorter poles permit lower beam energies → *energy & cost saving*

Courtesy B. Diviacco, H. Tarawneh, M. Valleau, S. Casalbuoni, M. Calvi





4^{th} generation SRLS are running already!

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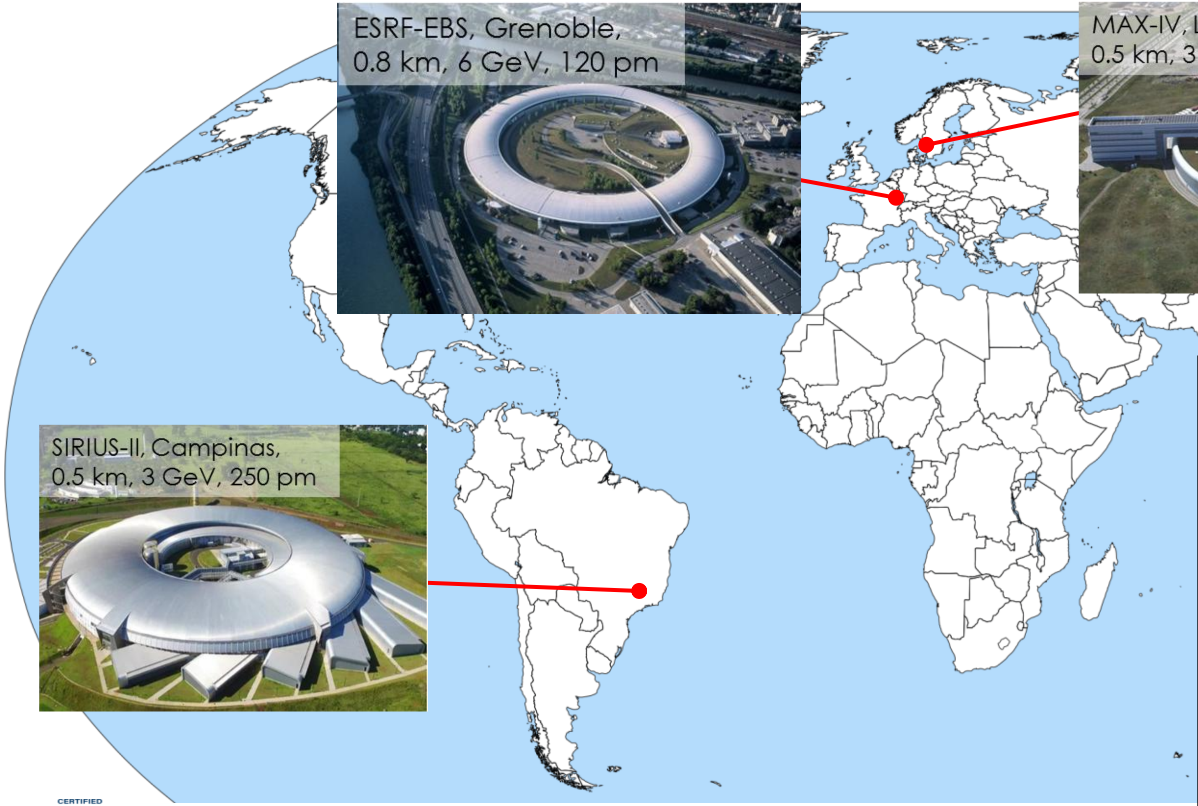
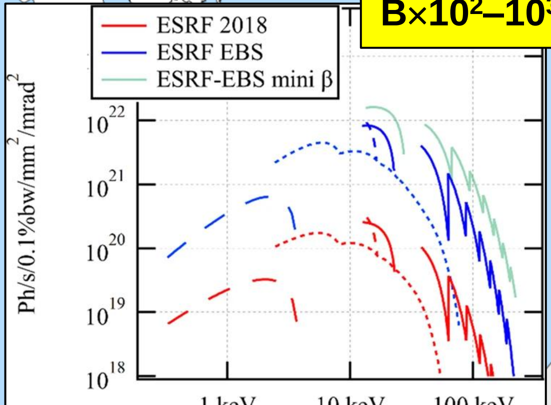


B×10^2–10^3



Commun. Phys **6**, 82 (2023).

…and more are coming

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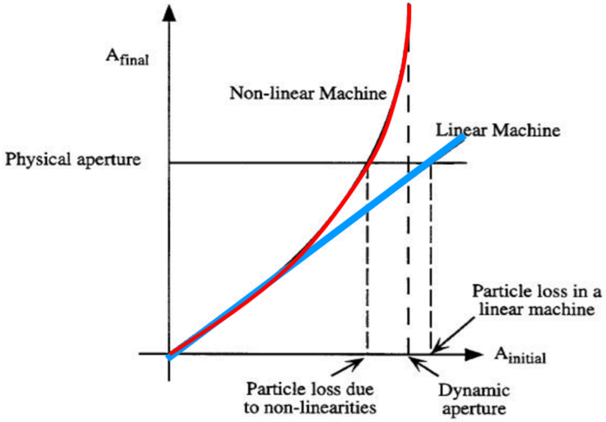
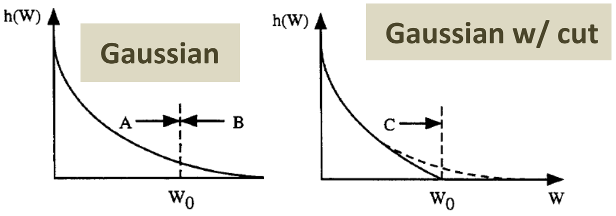
e-Beam lifetime

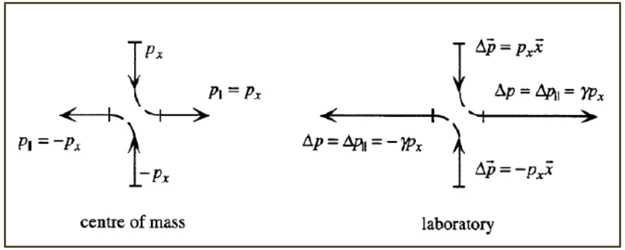
Dynamic aperture:



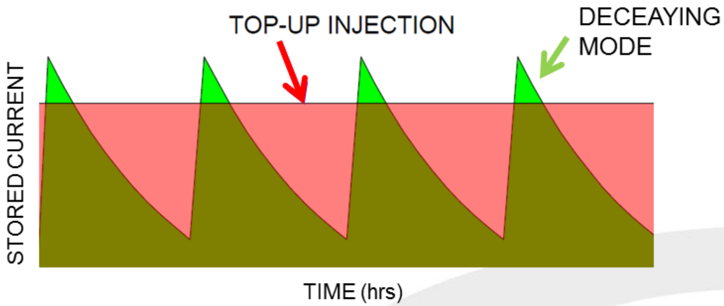
Quantum lifetime:



Touschek lifetime:



- Due to physical or dynamic boundaries, the beam current decreases exponentially with time.
  - **Top-up** = frequent (mins.) refill to keep the current constant, hence the beam more stable (avoid thermal drifts of components)



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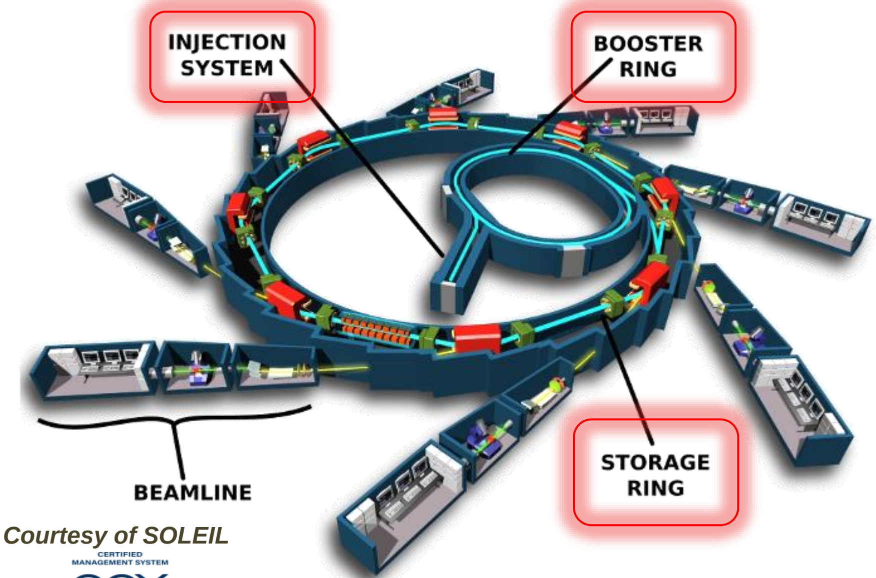
Injection chain



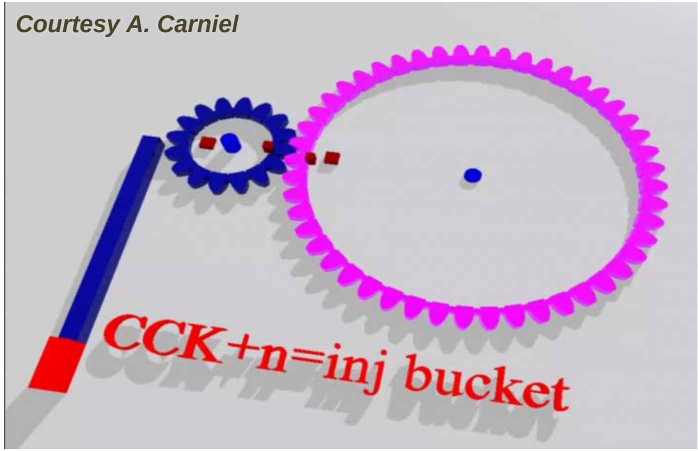
Courtesy of SOLEIL

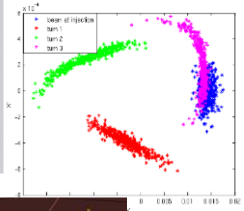
1. **Thermoionic gun** + RF buncher + linac ("pre-injector"):
   - high charge, single bunch or
   - low charge, train of bunches
   - ~ 100 MeV

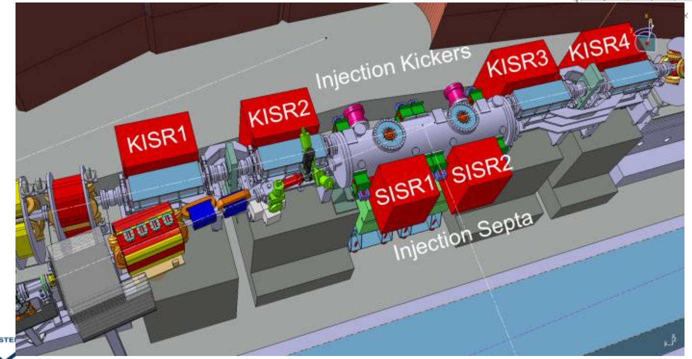
2. **Booster ring:**
   - energy ramp to GeV scale (magnets, RF)
   - ~ Hz rep. rate
   - emittance control for injection efficiency

3. **Booster-to-Storage ring** transfer line:
   - dc and pulsed electro-magnets for injection
   - optics matching
   - collimation and diagnostics

Injection schemes (ring-based)







- Structured **synchronization** system is essential to satisfy ***diverse fill pattern*** in the storage ring
  - single or few bunches, trains, alternated bunches, etc.

- Large variety of injection schemes, exploring **6-D separation** of stored and injected beam, and eventually ***coalescence*** in a damping time or so.
  - Transverse separation
  - Energy/phase separation
  - Swap-out (on-axis beam out–beam in)

- Stored beam should **not be disturbed** by injection.
  - Tiny beams in ***DLSRs*** make this a challenge.
  - Sub-μm accuracy in orbit control

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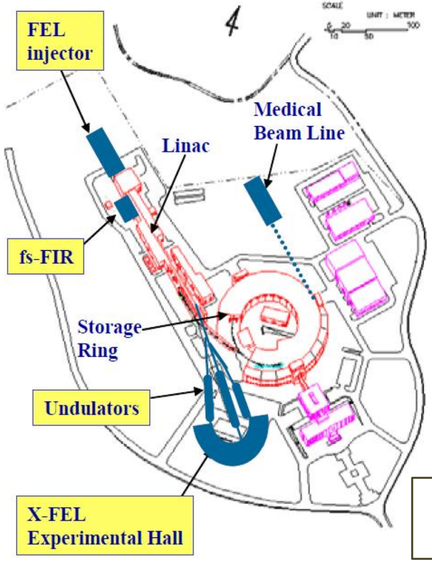
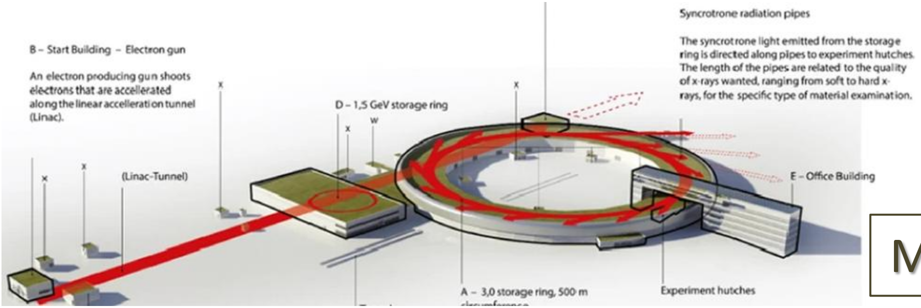
Injection schemes (linac-based)

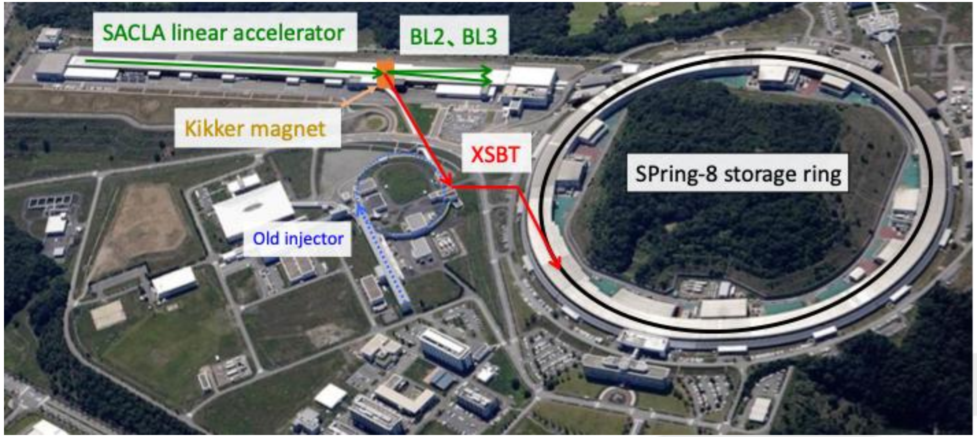


PAL



MAX IV

SACLA



- High energy e-linacs provide short, low emittance beams, well suited to high injection efficiency.
    - Often shared with FELs.

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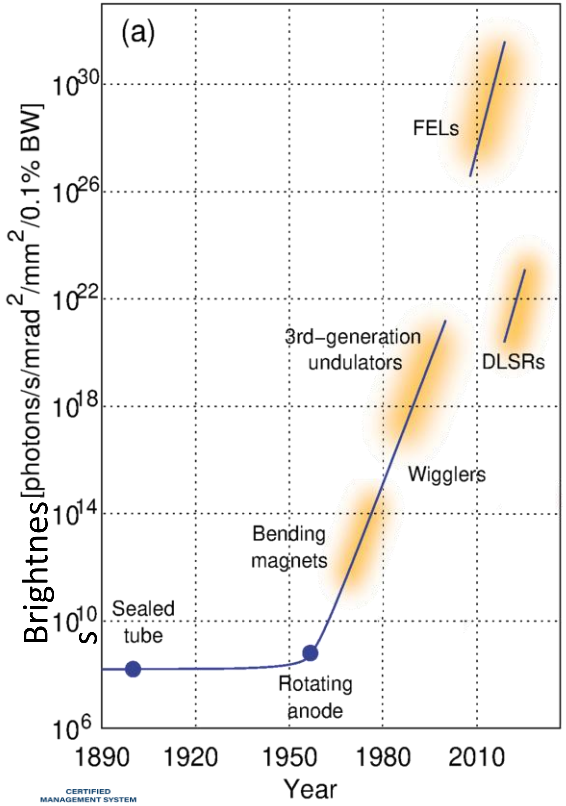
Outline

- Motivations to Synchrotron Light Sources
- Beam Energy
- Magnetic Lattice
- Diffraction-Limited Storage Rings
- Accelerator Chain
- **Conclusions**

Light sources



1. Accelerator-based light sources are the most brilliant sources on Earth, largely coherent.
2. Other strong points are polarization, repetition rate and diversified radiation sources at SRLS.
3. Light sources drive technology: RF, magnets, ultra-vacuum mechanics, lasers.
4. Light sources are multi-purpose science drivers. No one ideal source: pick the one most suited to your experiment!

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Strong points of SRLS

- Synchrotrons provide light up to **tens of beamlines simultaneously**, each beamline receiving light from a dedicated insertion device.
- **Large flexibility** in tuning or selecting radiation wavelength and intensity. Spectrum from IR to hard x-rays.
- High **average radiation power** at the expense of low peak power (incoherent emission) and long pulses (several 10s ps).
- Extremely **stable**.
- Now approaching **transverse coherence** in X-rays.

Promises of DLSR

- Reduction in the source emittance, thus increase in **brilliance,** will lead to:
  - significant ***gain in the emitted or transmitted signals*** from the samples;
  - ***reduced acquisition time*** for all types of spectroscopies and x-ray scattering techniques;
  - implementation of ***photon-hungry techniques*** such as: high pressure experiments with anvil cells and dilute samples, and spin-resolved ARPES;
  - improvement of the ***lateral resolution*** with focusing optics down to a few-nm scale (e.g. nano-PES, nano-ARPES)
- Higher degree of transverse **coherence** will open unique opportunities for:
  - ***Coherent Diffraction Imaging*** (CDI) with chemical specificity
  - ***Ptychography***
  - ***X-ray photon correlation spectroscopy*** (XPCS)

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What does the future look like?

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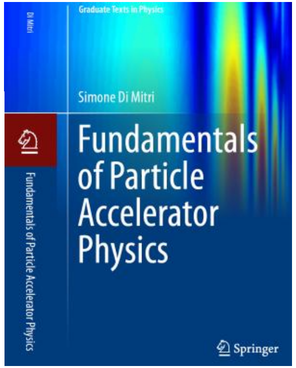

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Thank you for your attention

Questions are very welcome

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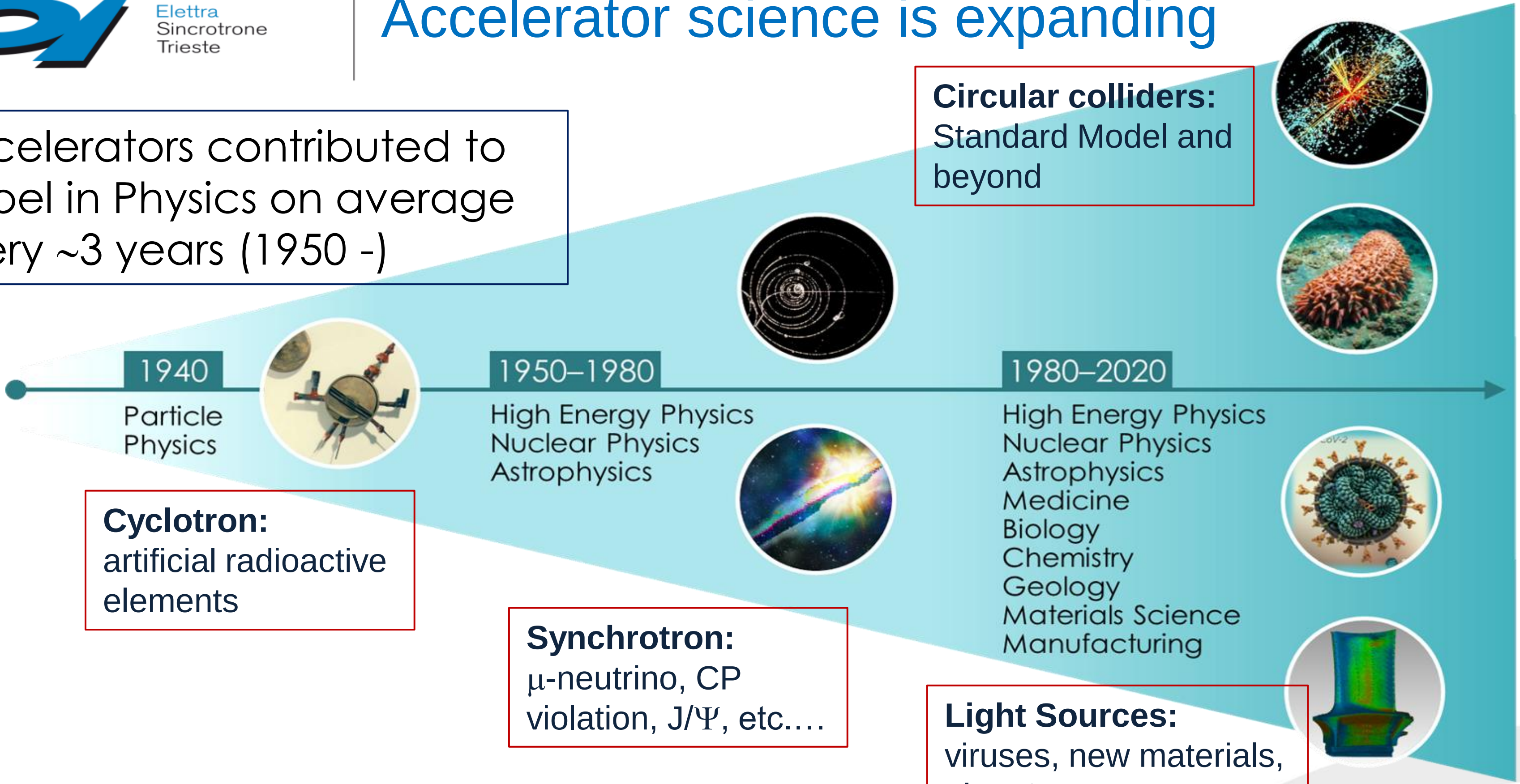
Accelerator science is expanding

Accelerators contributed to Nobel in Physics on average every ~3 years (1950 -)



Circular colliders: Standard Model and beyond

Cyclotron: artificial radioactive elements

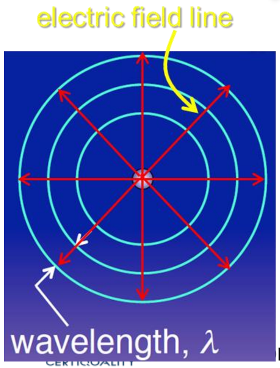
Synchrotron: μ-neutrino, CP violation, J/Ψ, etc.…

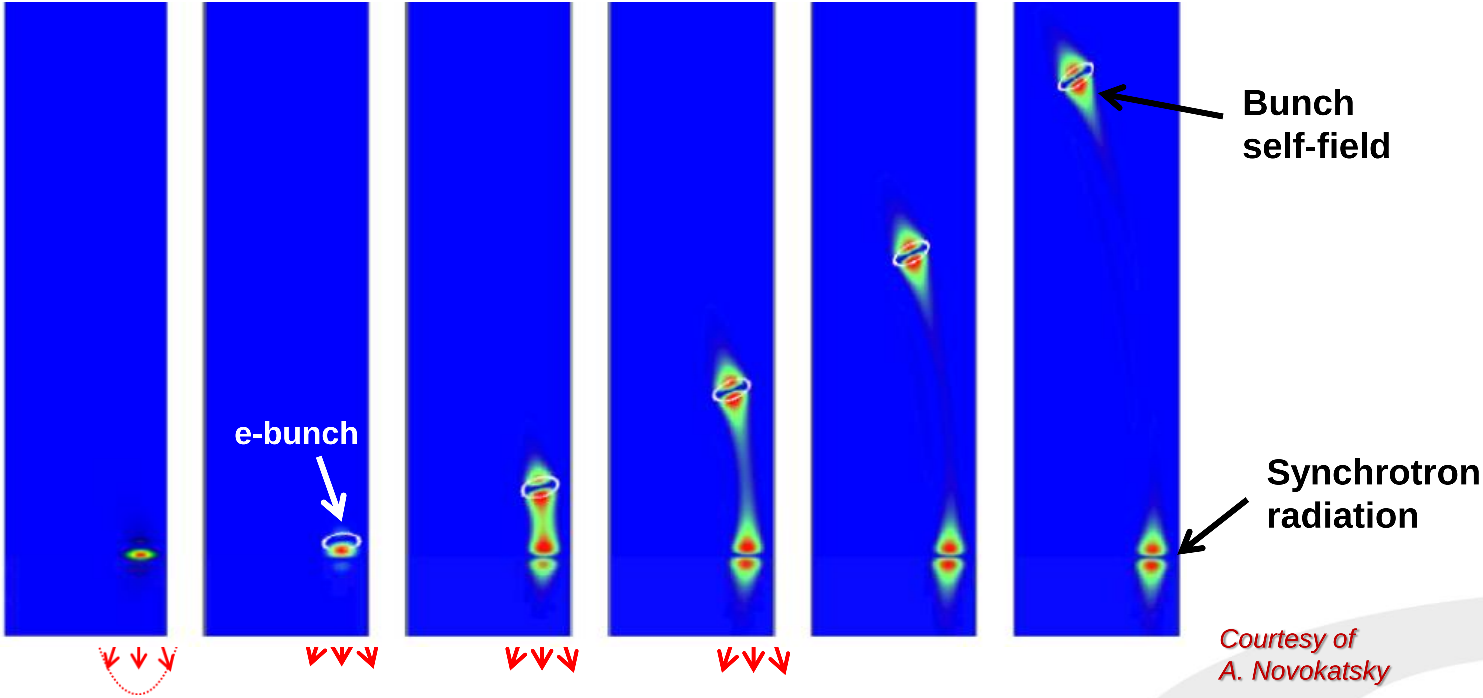
Light Sources: viruses, new materials, planetary processes,…

Synchrotron radiation

Synchrotron radiation is e.m. energy de-coupled from a charge by centripetal acceleration. For example, an ultra-relativistic electron in a magnetic dipole field.

$$\vec{E}_r \sim \frac{q}{r^3}\hat{r}$$





Courtesy of A. Novokatsky

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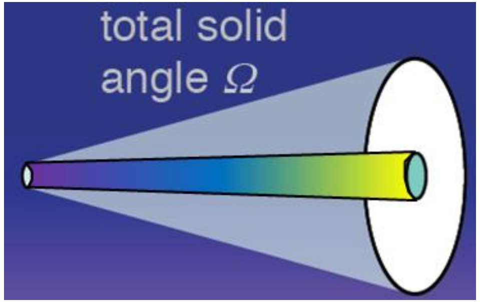
Degeneracy parameter

Coherence of radiation ~ in-phase photons ~ more effective light-matter interaction

- The fraction of spectral flux **transversally** coherent is the one emitted by a source at, or below, the diffraction limit:



$$\Sigma_x \Sigma_y \Sigma_{x'} \Sigma_{y'} \approx \left(\frac{\lambda}{4\pi}\right)^2$$

$$\boxed{\left(\frac{dN_\gamma/dt}{\Delta\omega/\omega}\right)_{\perp,coh} = \boldsymbol{B} \times \left(\frac{\lambda}{2}\right)^2}$$

- The number of photons **transversally *and* longitudinally** coherent is:

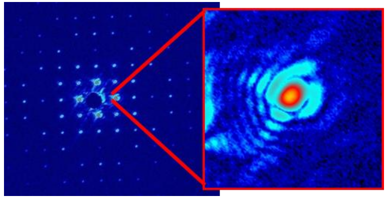
$$\boxed{n_{coh} = \left(\frac{dN_\gamma/dt}{\Delta\omega/\omega}\right)_{\perp,coh} \cdot \Delta t_{coh} \cdot \frac{\Delta\omega}{\omega} = B\left(\frac{\lambda}{2}\right)^2 \frac{\lambda^2}{2c\Delta\lambda}\frac{\Delta\lambda}{\lambda} = \frac{B\lambda^3}{8c}}$$

Number of photons in the "coherent volume" λ^3

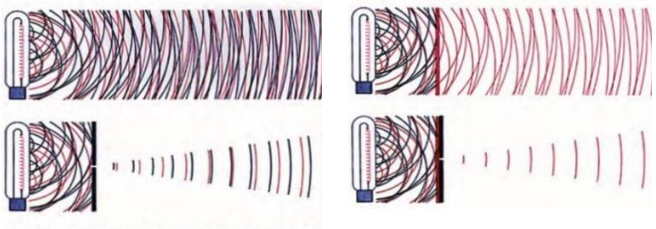
It is more difficult to get full coherence at shorter wavelengths

Transverse coherence

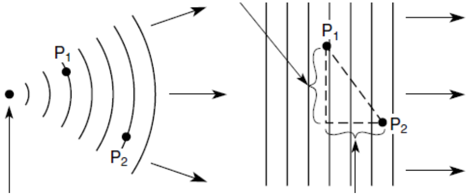
Interference fringes



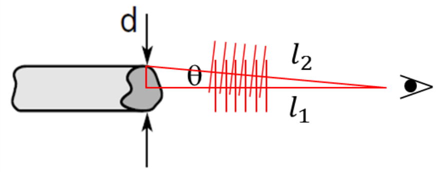
Collimated, monochromatic light



Phase-correlated field

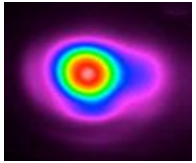


Classical model: path length over which two waves become **out of phase**



Uncertainty Principle: the smallest **phase space area** occupied by the light pulse

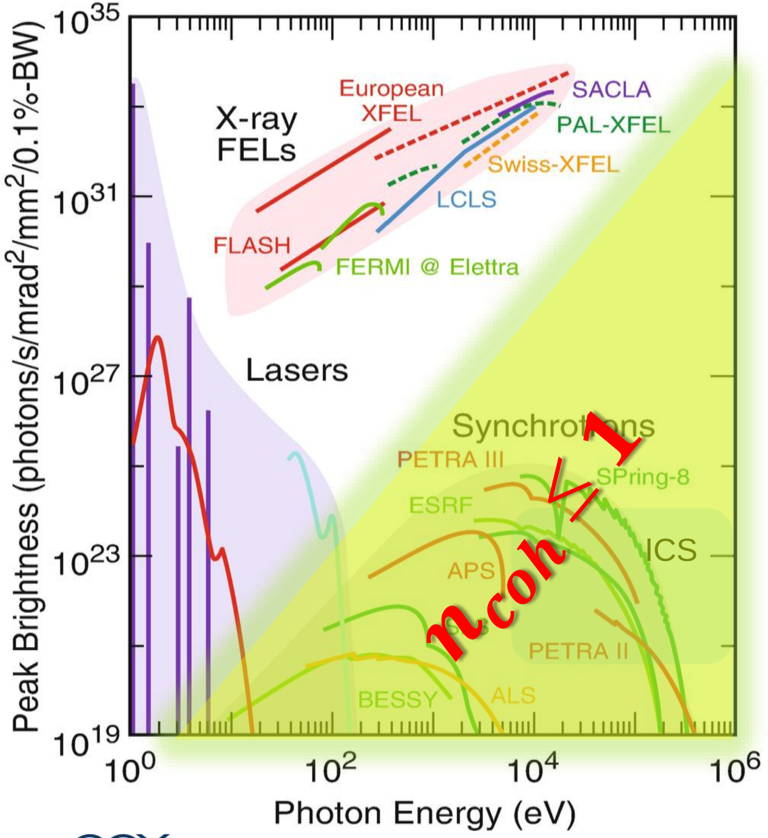
$$\Delta x \Delta p_x \geq \frac{\hbar}{2} \quad and\ \theta = \frac{\Delta p_x}{p_z} \cong \frac{\Delta p_x}{(h/\lambda)} \quad \Rightarrow \frac{d}{2}\theta_c = \frac{\lambda}{4\pi}$$



TEM00

Minimum transverse phase space area (**"emittance"**) of a transversally coherent light pulse

Why *accelerator-based* light sources?



- Almost all experimental techniques gain from a large ***6-D photon density***, or ***brilliance:*** (brightness)

$$B_{max} \cong \frac{dN_\gamma/dt}{\Delta\omega/\omega}\frac{1}{(\lambda^2/2)}$$ for **Diffraction Limit** $$\sigma_u\sigma_{u'} = \varepsilon_u \leq \frac{\lambda}{4\pi}$$

Race to **ultra-low emittance SRLS**

- The number of ***fully coherent*** photons is smaller at shorter wavelengths:

$$n_{coh} = \left(\frac{dN_\gamma/dt}{\Delta\omega/\omega}\right)_{\perp,coh} \cdot \Delta t_{coh} \cdot \frac{\Delta\omega}{\omega} = \frac{B\lambda^3}{8c}$$

Race to fully coherent **X-ray FELs**

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Practical use of Brilliance

peak flux
- larger S/N-ratio due to larger emitted or transmitted signal
- implementation of photon-hungry techniques, such as high preassure exps. (anvil cellls, diluted samples) and spin-resolved ARPES
- multi-ionization processes
- single-shot diffraction imaging
- nonlinear harmonic generation from solids

average flux
- reduced acquisition time for all spectroscopies and x-ray scattering exps.

transverse coherence
- nm-scale lateral resolution with focusing optics for, e.g., nano-ARPES
- coherent diffraction imaging with chemical specificity, holography, nanocrystallography, ptychography
- x-ray photon correlation spectroscopy

longitudinal coherence
- pump-probe exps
- fast dynamical processes such as core level photo-electron spectroscopy
- 4-wave mixing (transient grating, etc.)