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Design and operation of accelerator chain and storage rings

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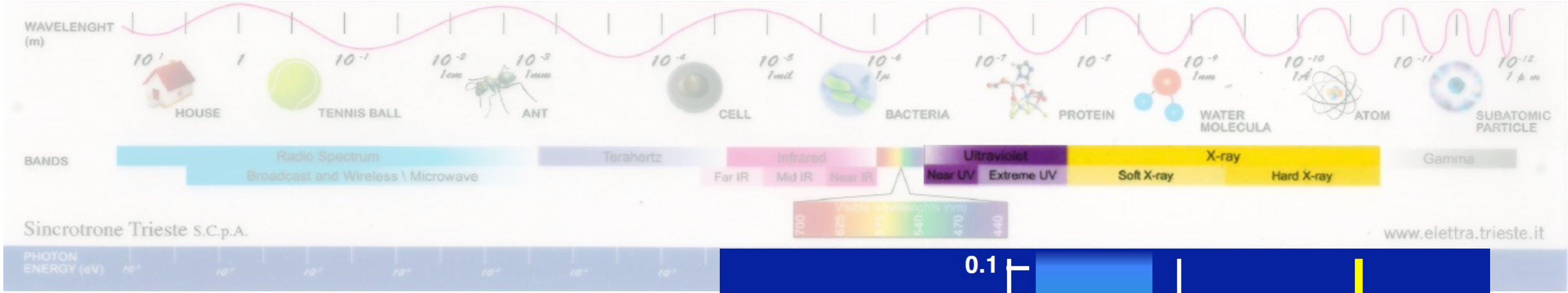
Outline

1. How does a synchrotron light source look like ?
2. What are the main physical processes ?
3. How does it work ?

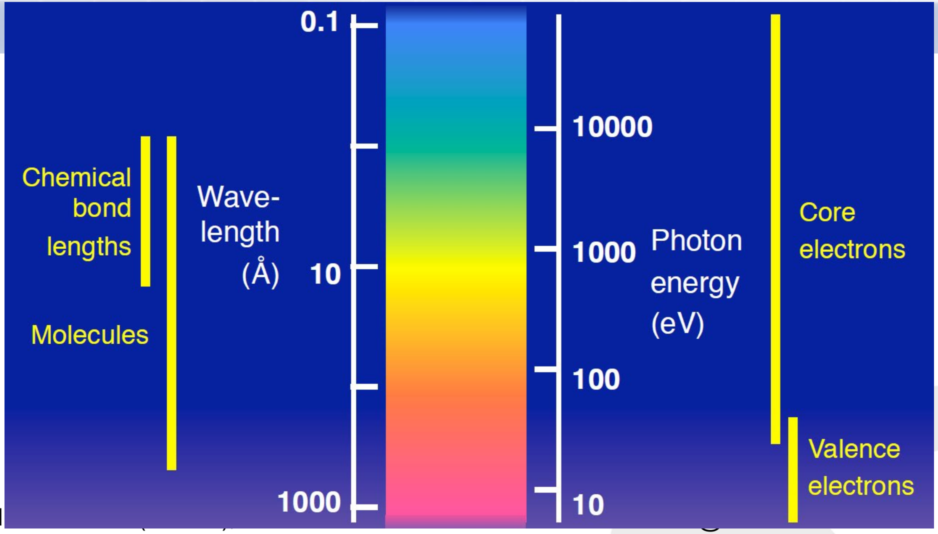
- ❑ Synchrotron radiation – recap
- ❑ Single particle linear motion
  - Longitudinal – phase stability, synchrotron oscillations
  - Transverse – dispersion, betatron tunes, emittance
- ❑ Perturbations to linear dynamics
  - Equilibrium distribution
  - Chromaticity, resonances, dynamic aperture
  - Beam lifetime
- ❑ Operation
  - Beam injection and storage.
  - Brilliance, diffraction limit.

Why do we need x-ray sources?

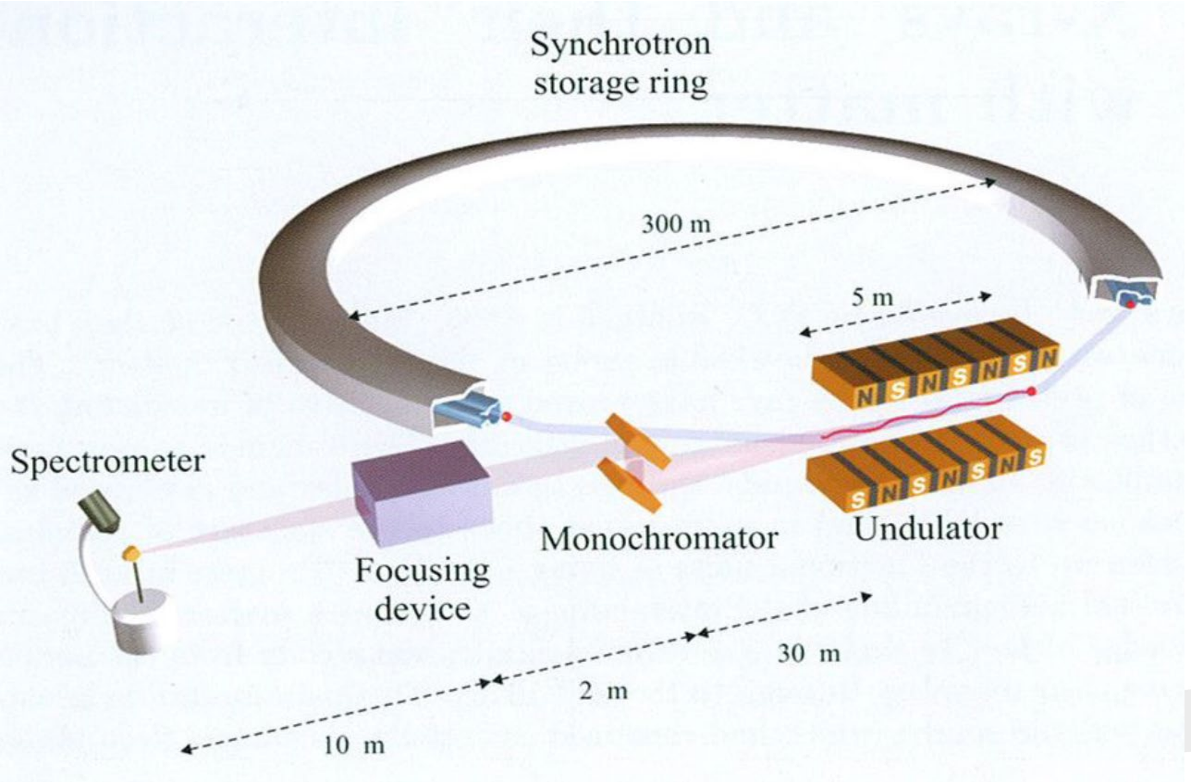


X-rays are ideal probes of chemical bonds, where most of science is rooted.

They can be used to visualize proteins structure, molecular dynamics, atomic levels and orbitals…



Serving as a Microscope



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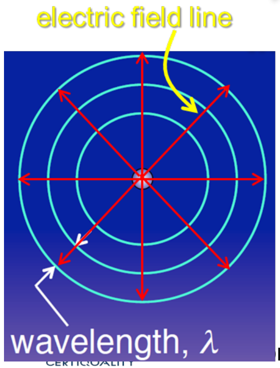
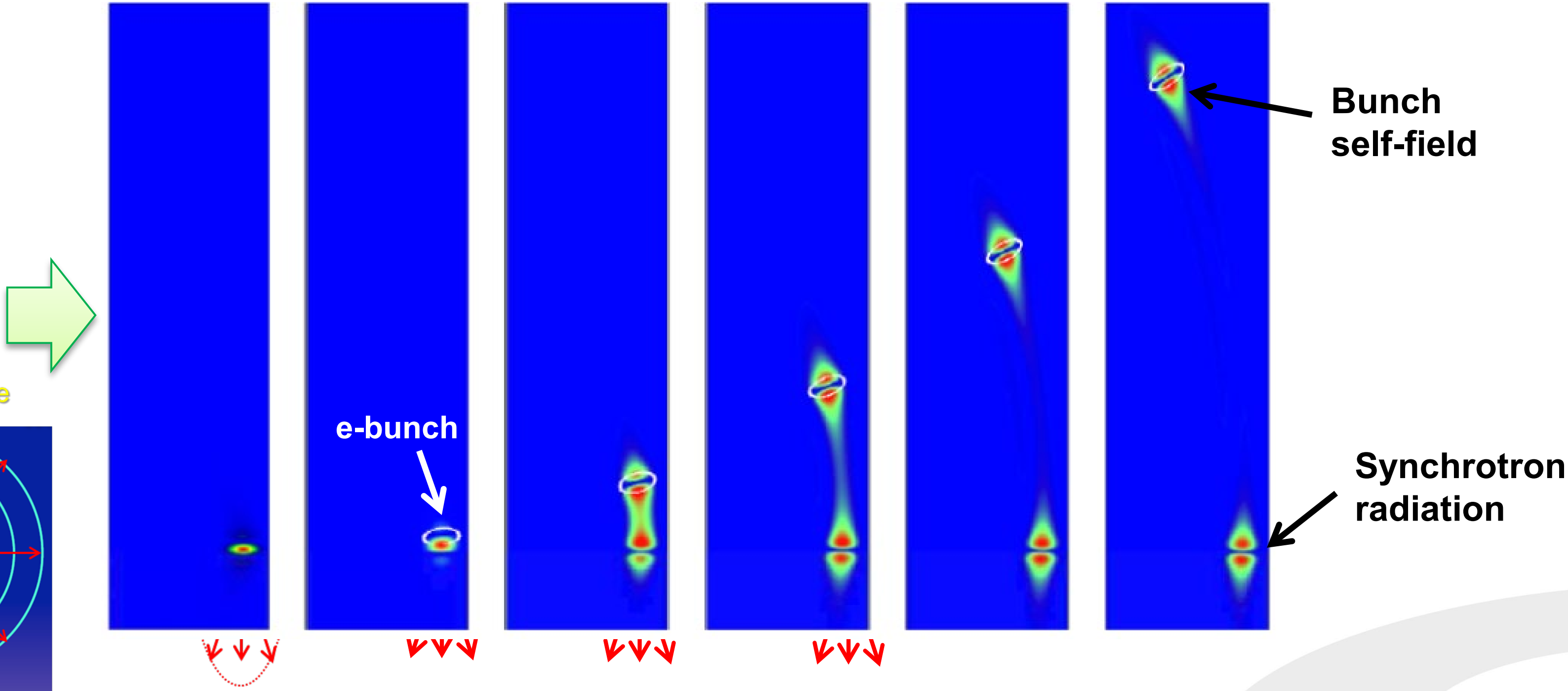
Synchrotron radiation

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.

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





Power

v << c: $P'_{SR} \propto |\boldsymbol{S}'| \propto |E'_{\boldsymbol{x}}|^2 \propto \left(\frac{F'_x}{m_e}\right)^2 \propto a'^2_x$

Lorentz-transform to Lab frame:

$$\begin{cases} t' \to t/\gamma \\ x' \to x \end{cases} \Rightarrow a'^2_x \to \gamma^4\, a^2_x$$

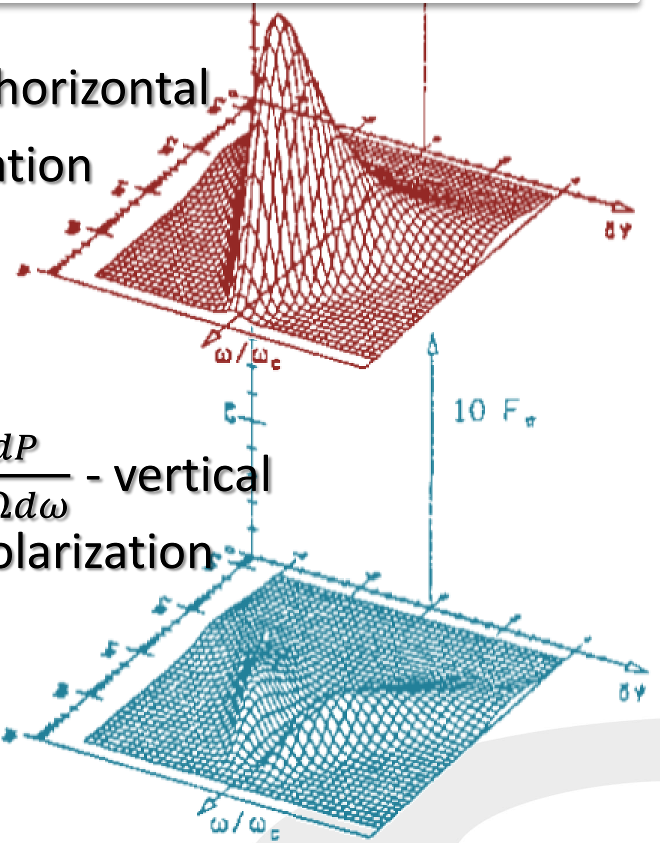
$$P_{SR} \propto \gamma^4 = \frac{E^4}{m_0^4}$$

Strong increase with particle ***total* energy**

***"Light"* particles** (e.g., leptons) radiate *more than "heavy"* ones (e.g., hadrons).

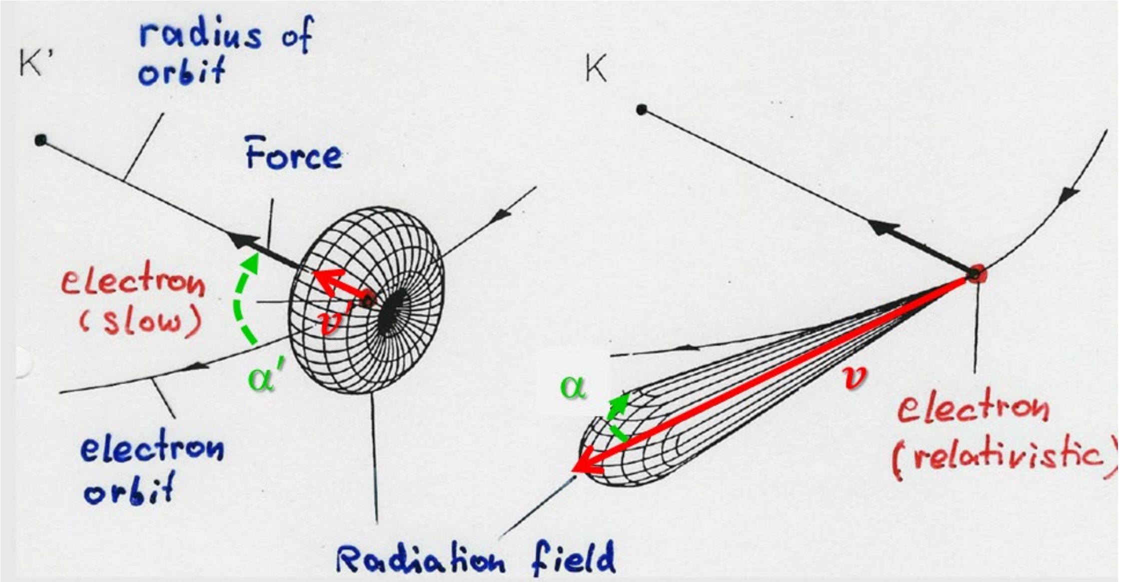
$\frac{dP}{d\Omega d\omega}$ - horizontal polarization

$\frac{dP}{d\Omega d\omega}$ - vertical polarization



Angular distribution

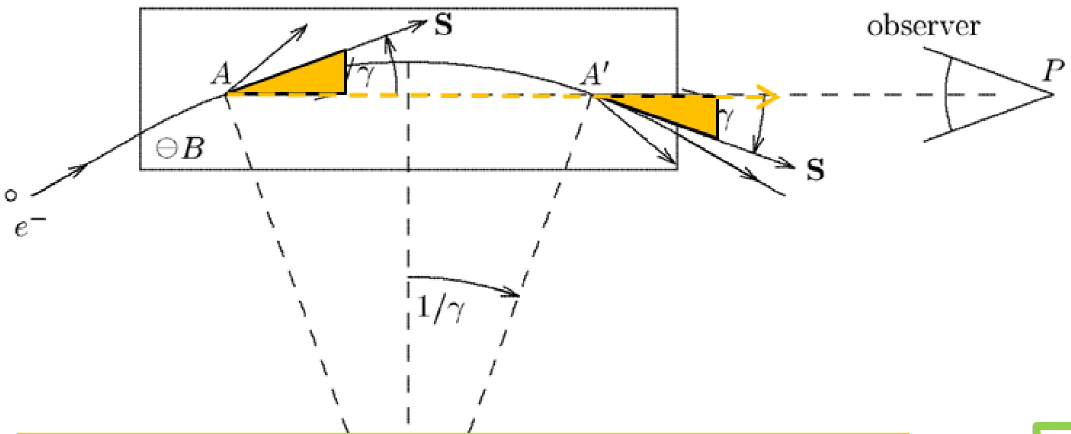
Electron rest frame: electric dipole emission, max. intensity at $\alpha' = \pi/2$.



Lab reference frame: forward collimated emission, $\alpha \approx 1/\gamma$.

$$\tan\alpha = \frac{\sin\alpha'}{\gamma(\beta + \cos\alpha')}\bigg|_{\alpha'=\frac{\pi}{2}} = \frac{1}{\beta\gamma} \cong \frac{1}{\gamma} << 1$$

Spectrum



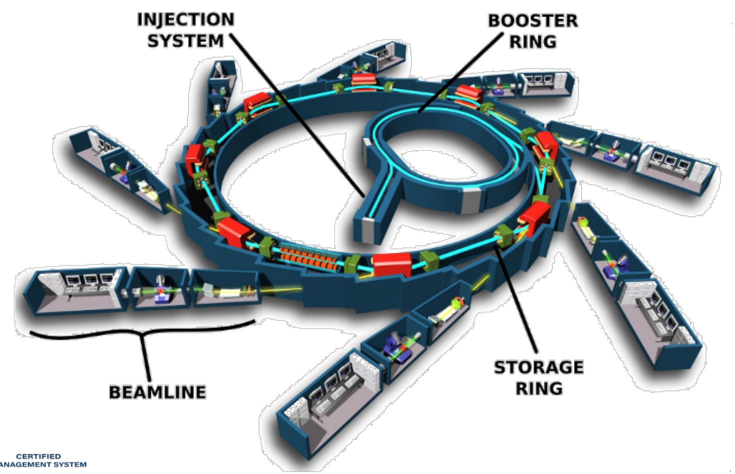
$$\Delta t_{SR} = t_A - t_{A'} = \frac{2R}{c}\left(\frac{1}{\beta\gamma} - \sin\frac{1}{\gamma}\right) \cong \frac{R}{c\gamma^3}$$

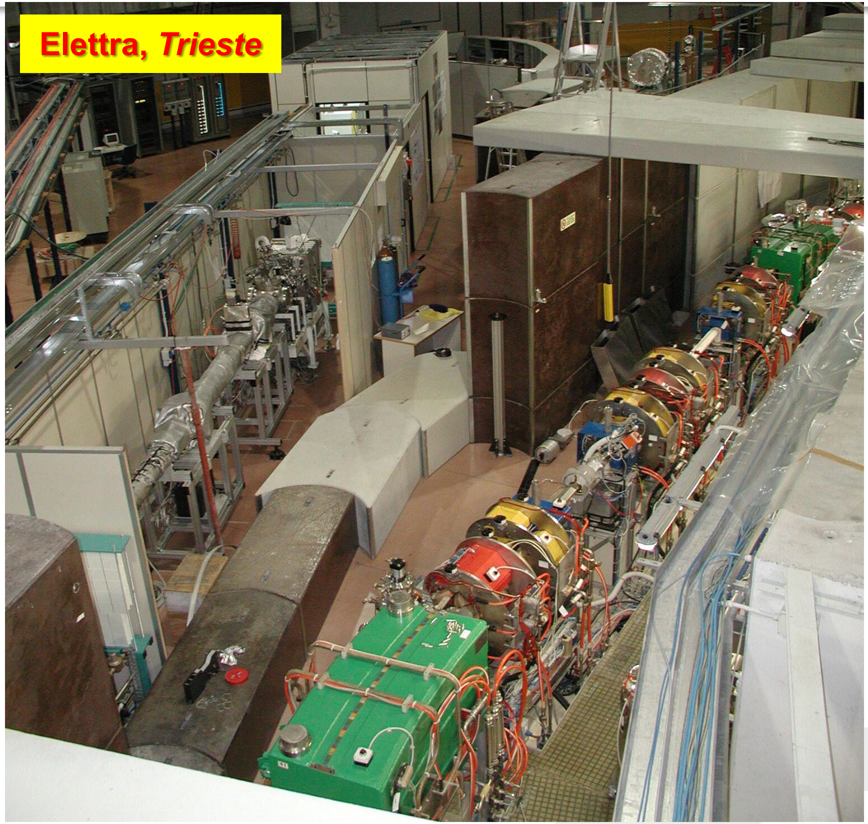
Dipole emission is a ***short*** flash light of duration Δt_{sr}.

The spectral bandwidth, of the order of $\Delta\omega \approx 1/\Delta t_{sr}$, is ***broad*** $\Delta\omega/\omega_c \approx 1$.

$$\Rightarrow \omega_c \approx \Delta\omega \approx \frac{1}{\Delta t_{sr}} \approx \frac{c\gamma^3}{R}$$

Bird eye view





Evolution of SRLS

- **First observation**:

  1947, General Electric, 70 MeV synchrotron

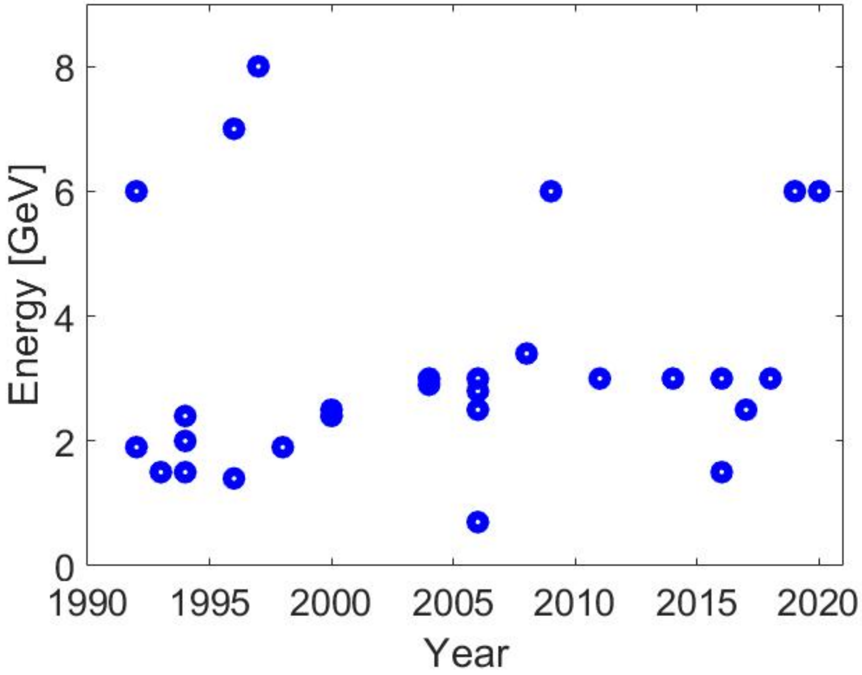
- **First user experiments**:

  1956, Cornell, 320 MeV synchrotron

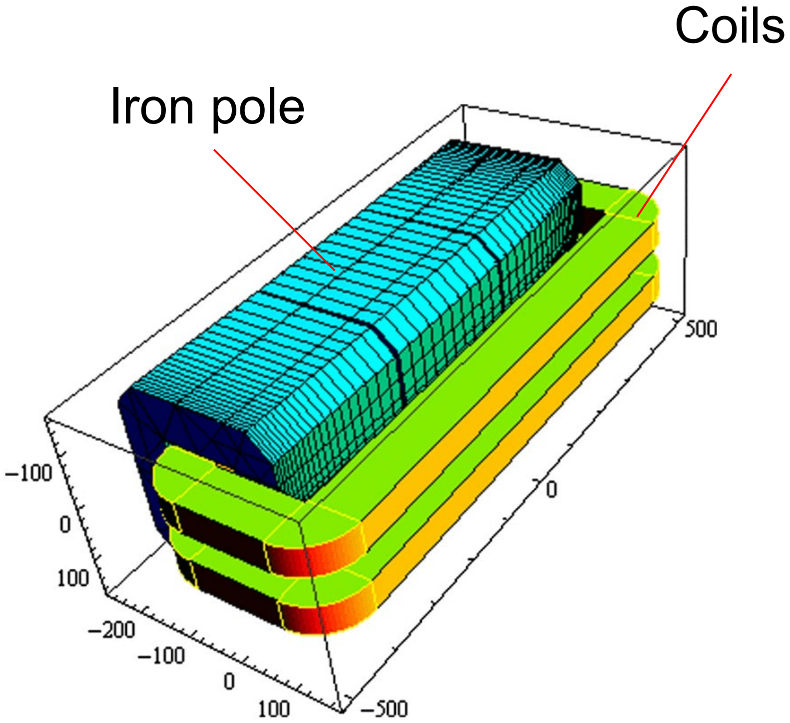
- **1st generation light sources**: machine built for High Energy Physics or other purposes used parasitically for synchrotron radiation

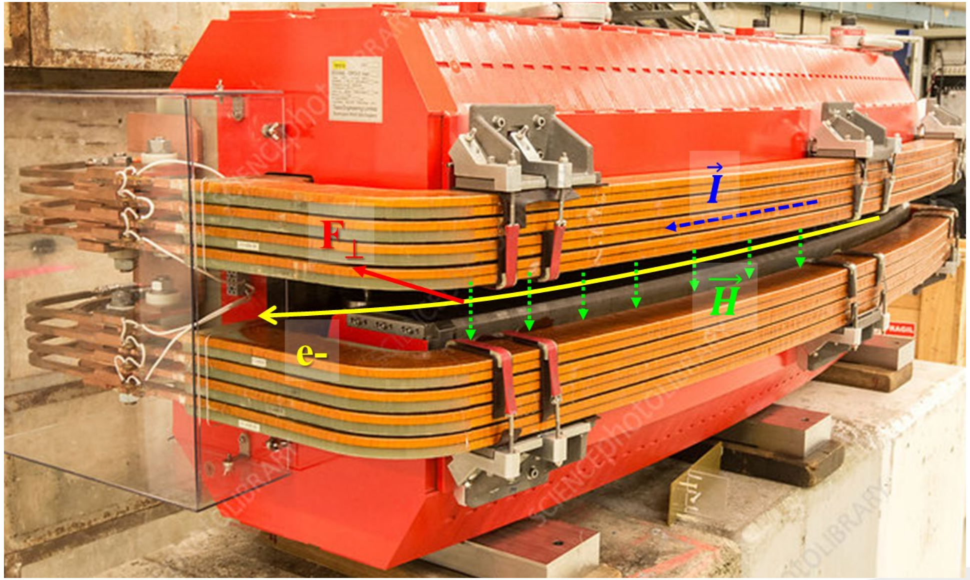
- **2nd generation light sources**: purpose built synchrotron light sources, SRS at Daresbury was the first dedicated machine (1981 – 2008)

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



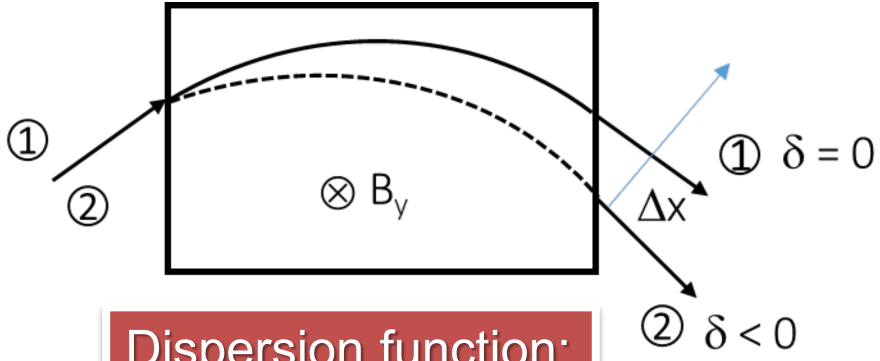
Dipole magnet





Energy-dispersion function

High energy electrons on a circular path → ***powerful collimated x-rays***



$$\frac{mv_z^2}{R} = F_{L,x} = ev_z B_y;$$

$$p_z = eB_y R$$

$$E \longrightarrow E - E_{sr} + \ldots$$

Dispersion function:

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

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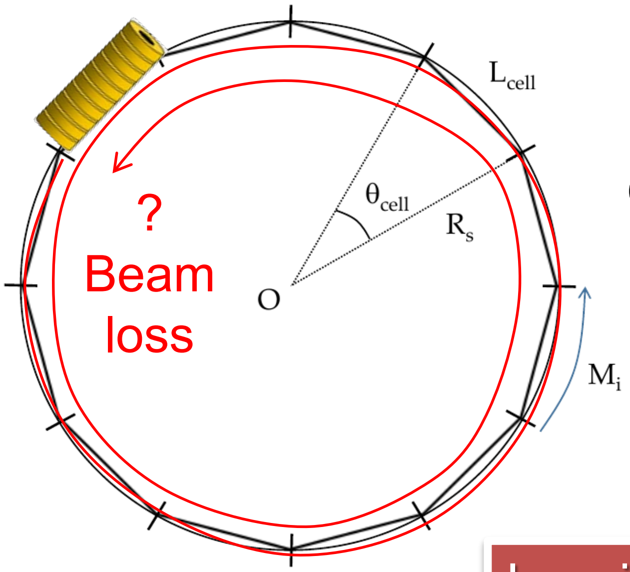
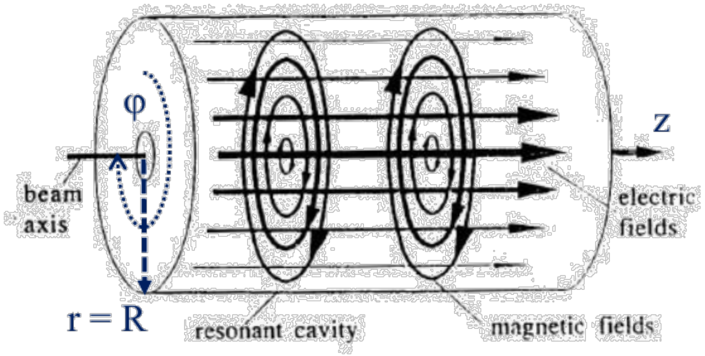
Accelerating (RF) cavity



RF cavities replenish the beam by the energy lost every turn ⇒ beam energy per turn is constant *(on average)*.



Longitudinal electric field:

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

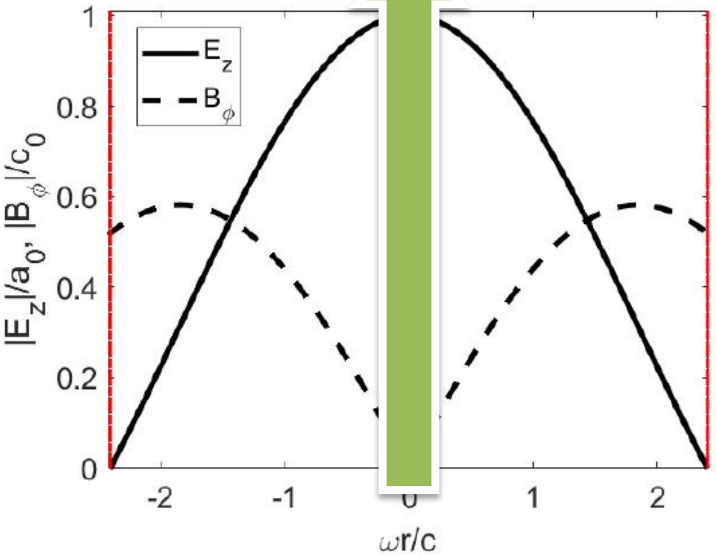
E.M. field in a Pill-box

$$\begin{cases} \left(\vec{\nabla} \wedge \vec{E}\right)_\phi = -\dfrac{\partial B_\phi}{\partial t} \\ \left(\vec{\nabla} \wedge \vec{B}\right)_z = -\dfrac{1}{c^2}\dfrac{\partial E_z}{\partial t} \end{cases} \Rightarrow \begin{cases} \cancel{\dfrac{\partial E_r}{\partial z}} - \dfrac{\partial E_z}{\partial r} = -\dfrac{\partial B_\phi}{\partial t} & \cdot\, \partial_r \\ \dfrac{1}{r}\left[\dfrac{\partial (rB_\phi)}{\partial r} - \cancel{\dfrac{\partial B_r}{\partial \phi}}\right] = -\dfrac{1}{c^2}\dfrac{\partial E_z}{\partial t} & \cdot\, \partial_t \end{cases}$$

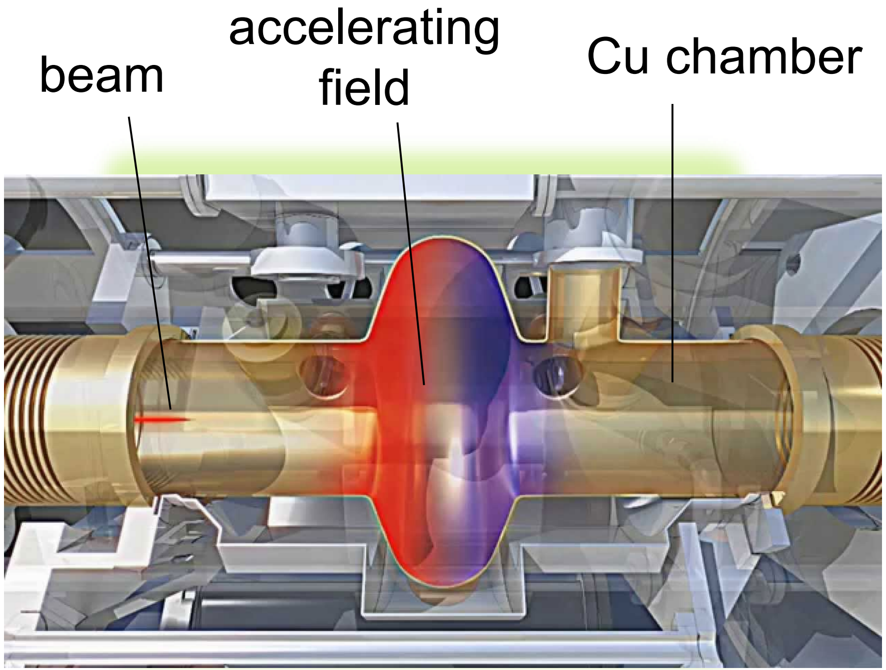
$$\begin{cases} \dfrac{\partial^2 E_z}{\partial r^2} = \dfrac{\partial^2 B_\phi}{\partial r \partial t} \\ \dfrac{1}{r}\dfrac{\partial B_\phi}{\partial t} + \dfrac{\partial^2 B_\phi}{\partial r \partial t} = \dfrac{1}{c^2}\dfrac{\partial^2 E_z}{\partial t^2} \end{cases} \Rightarrow \quad \frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} = \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2}$$

$$A(r) = a_0 J_0\left(\frac{\omega r}{c}\right)$$

$$J_0(r \approx 0) \approx 1 \quad \Rightarrow \quad E_z \approx E_{z,0}\cos(\omega t + \phi_0)$$



Synchronization



Synchronization of particle arrival time and RF field:

$$\omega = h\omega_{riv},\ \ h \in \dot{\mathbb{N}}(\gg 1)$$

- *How many consecutive bunches can be stored in a ring ("train")?*

Slip factor

Orbit difference:

$$dR = \frac{C_2 - C_1}{\theta_b} = \frac{1}{\theta_b}\left(\oint ds_2 - \oint ds_1\right) = \frac{1}{\theta_b}\oint d\theta\,[(R_1 + x) - R_1] = \frac{1}{\theta_b}\oint x d\theta = \langle x \rangle_\theta$$

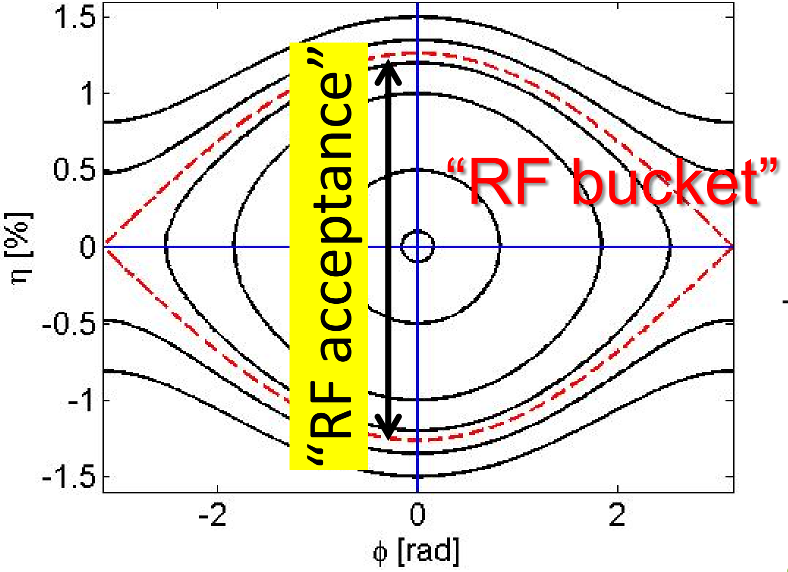
Orbit difference per unit of energy deviation (“momentum compaction”):

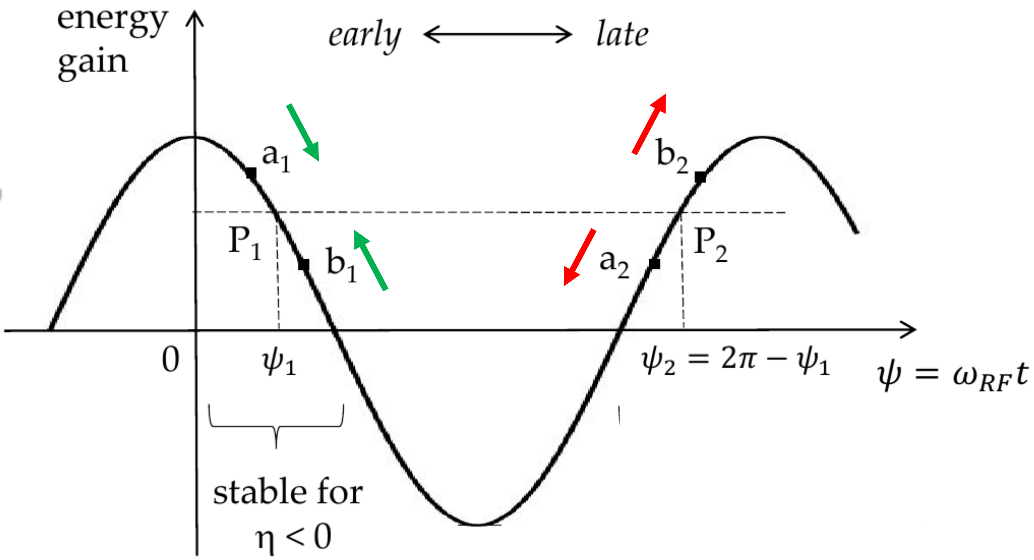
$$\alpha_c = \frac{dR/R}{\delta} = \frac{1}{R}\frac{\langle x \rangle_\theta}{\delta} = \frac{\langle D_x \rangle_\theta}{R} = \frac{1}{R\theta_b}\int d\theta D_x = \frac{1}{C}\int ds \frac{D_x(s)}{R(s)}$$

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

$$\eta := \frac{d\omega/\omega_s}{dp_z/p_{z,s}} = \frac{1}{\gamma^2} - \alpha_c \xrightarrow{\text{GeV energies}} -\alpha_c$$

Phase stability

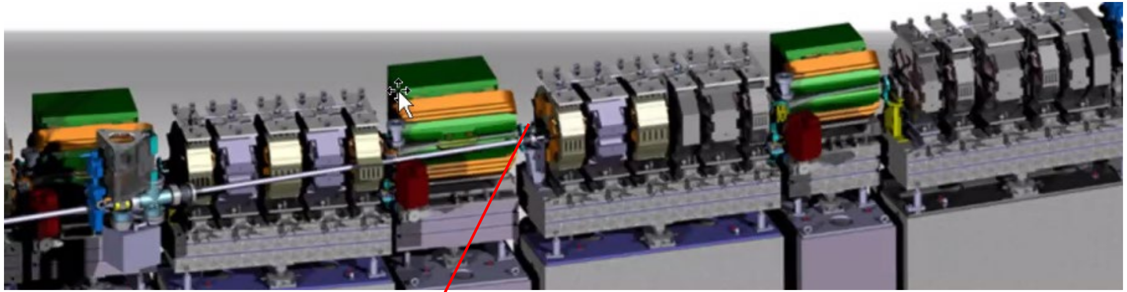




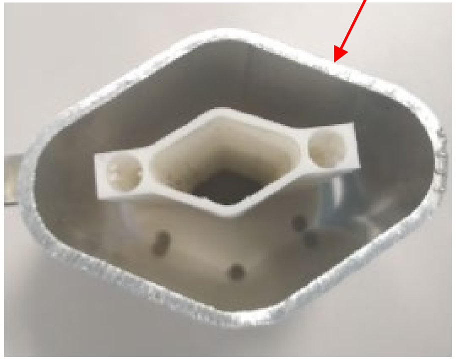
Synchrotron oscillations:

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

Bending and Focusing



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



Particle beam must be kept in!

---> ***external focusing***

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

300 MV/m !

1 Tesla …

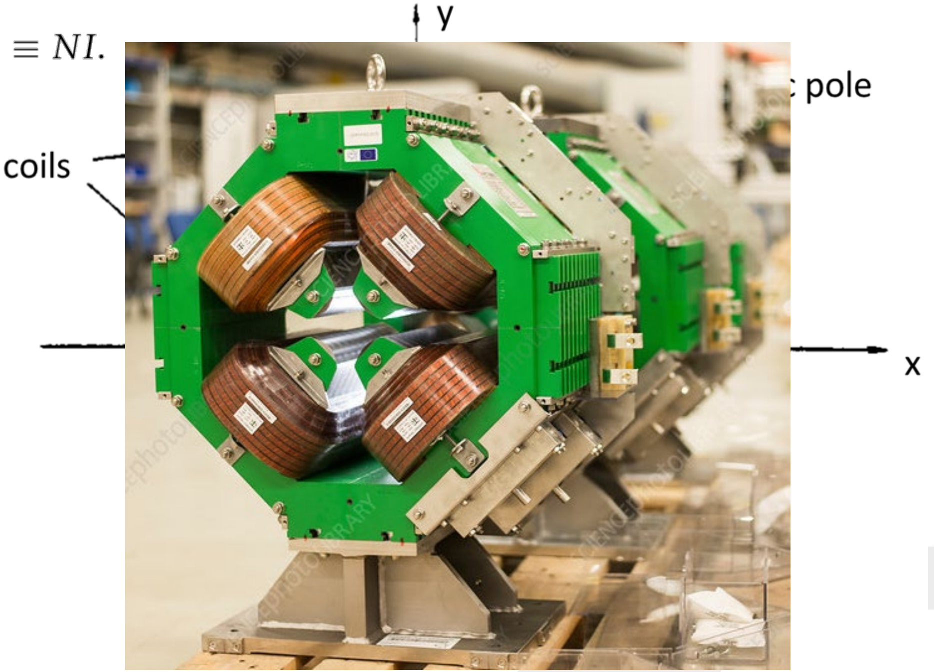
Quadrupole magnet

$(\mu_r \gg \mu_0)$:

$$\oint \vec{H}d\vec{s} = \int_1 \vec{H}d\vec{s} + \int_2 \vec{H}d\vec{s} \int_3 \vec{H}d\vec{s} = \int_0^{R_b} H(r)dr + \int_1^2 \vec{H}d\vec{s} + \int_2^3 H_y dx =$$

$$= \int_0^{R_b} \frac{1}{\mu_0}\frac{\partial B_r}{\partial r} r dr + \int_1^2 \frac{1}{\mu_r} B_x dx + 0 \approx \int_0^{R_b} \frac{g}{\mu_0} r dr = \frac{g R_b^2}{2\mu_0} \equiv NI.$$

$$\Rightarrow g = \frac{2\mu_0 NI}{R_b^2}$$



Normalized quadrupole strength:

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

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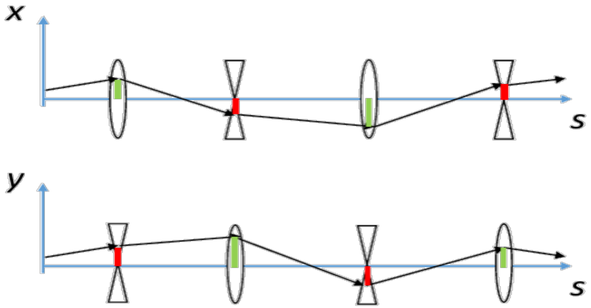
Transverse motion (linear approx.)



Betatron oscillations

$$x(s) = x_\beta(s) + x_\epsilon(s) = $$
$$= x_\beta(s) + D_x(s)\delta$$

Alternated gradient strengths (*Hill's eq. assumes* ***linear motion*** *&* ***no frictional forces***):

$$\ddot{y}(s) - k(s)(1-\delta)y(s) = 0$$

$$\ddot{x}(s) + \left[k(s)(1-\delta) \qquad\qquad \right] x(s) = 0$$

"Strong" focusing

Relative energy deviation

"Weak" focusing

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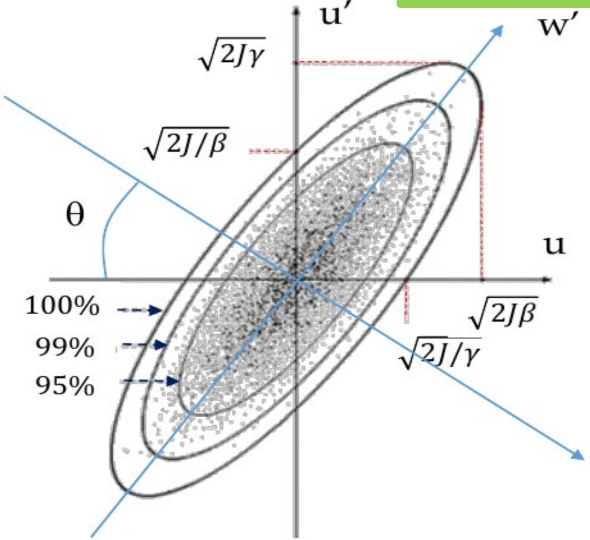
Phase space

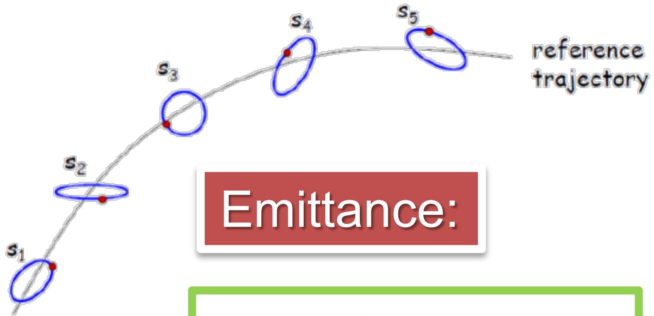
$$\begin{cases} u(s) = \sqrt{2J_u\beta_u}\cos\Delta\mu_u \\ u'(s) = -\sqrt{\frac{2J_u}{\beta_u}}\left(\alpha_u\cos\Delta\mu_u + \sin\Delta\mu_u\right) \end{cases}$$

Quasi-harmonic oscillator in (x,x') and (y,y') ----> the oscillation amplitude depends on s: $\beta_u(s),\alpha_u(s)$

Betatron tune:

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





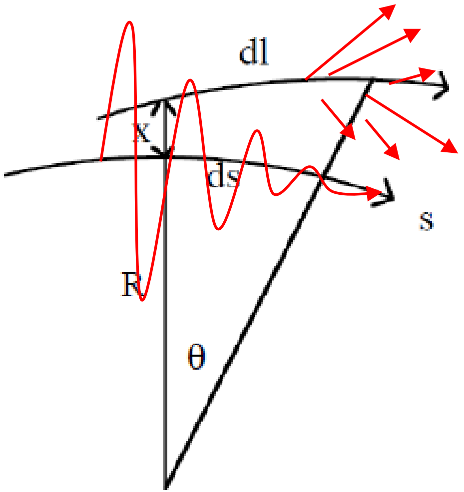
Emittance:

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

Equilibrium distribution

Oscillations:

$$\begin{cases} \epsilon(t) = A_\epsilon(t)\cos(\Omega_s \frac{\Delta z}{c} + \phi_0) \equiv A_\epsilon(t)\cos\phi \\ \tau(t) = -\left(\frac{\alpha_c}{E_0\Omega_s}\right) A_\epsilon(t)\sin\phi \end{cases} \Rightarrow \begin{cases} A_\epsilon^2 = \epsilon^2 + \tau^2\left(\frac{E_0\Omega_s}{\alpha_c}\right)^2 \\ \langle\epsilon^2(t)\rangle_\phi = \frac{A_\epsilon^2(t)}{2} \end{cases}$$



Emission of synchrotron radiation:

$$\langle\delta A_\epsilon^2\rangle_\phi = \langle\delta\epsilon^2\rangle + \langle\delta\tau^2\rangle\left(\frac{E_0\Omega_s}{\alpha_c}\right)^2 = 2\langle\epsilon\delta\epsilon\rangle + \frac{1}{2}\langle(2\delta\epsilon)\delta\epsilon\rangle = -2\langle\epsilon u\rangle + \langle u^2\rangle \cong$$

$$\cong -2\langle\epsilon\frac{du}{d\epsilon}\epsilon\rangle + \langle u^2\rangle = -A_\epsilon^2\frac{du}{d\epsilon} + \langle u^2\rangle$$

"damping" "excitation"

Equilibrium:

$$\langle\frac{d}{dt}\langle\delta A_\epsilon^2\rangle_\phi\rangle_R \cong \frac{d\langle A_\epsilon^2\rangle_R}{dt} = -\langle A_\epsilon^2\rangle_R\langle\frac{d}{dt}\frac{du}{d\epsilon}\rangle_R + \langle\frac{d}{dt}\langle u^2\rangle_\phi\rangle_R \equiv 0$$

Characteristic **damping time** to reach **equilibrium** Gaussian distribution:

$$\tau \approx T_0\frac{E_0}{U_0}$$

Beam size and emittance

Remind: $u(s) = \sqrt{2J_u\beta_u}\cos\Delta\mu_u$

$$\sigma_x = \sqrt{\varepsilon_x\beta_x}$$

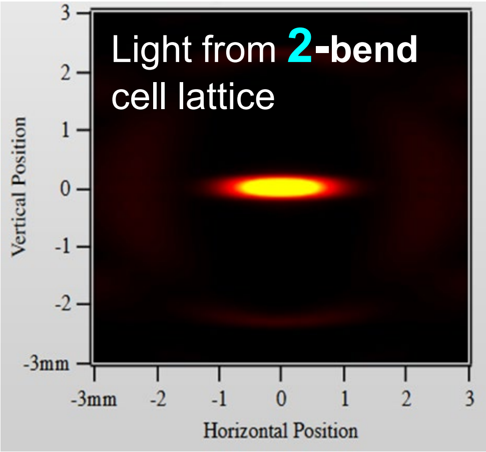
β_x: *depends on quads strength only; varies through the lattice*

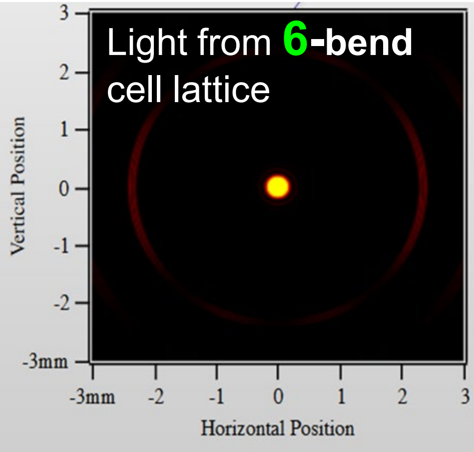
ε_x: *constant through the lattice ("equilibrium")*

$$\epsilon_{x,eq} = C_e\frac{\gamma^2}{J_x}\frac{\langle H_x\rangle_R}{R}$$

$$\frac{\langle H_x\rangle_R}{R} \approx \frac{1}{R}\left(\frac{1}{\beta_x}\langle D_x^2\rangle + \beta_x\langle D_x'^2\rangle\right) \propto \frac{\theta_b}{l_b}\left[\frac{l_b^2\theta_b^2}{4\beta_x} + \beta_x\theta_b^2\right] \propto \theta_b^3\left(\frac{l_b}{\beta_x} + \frac{\beta_x}{l_b}\right) \propto \left(\frac{2\pi}{N_b}\right)^3$$

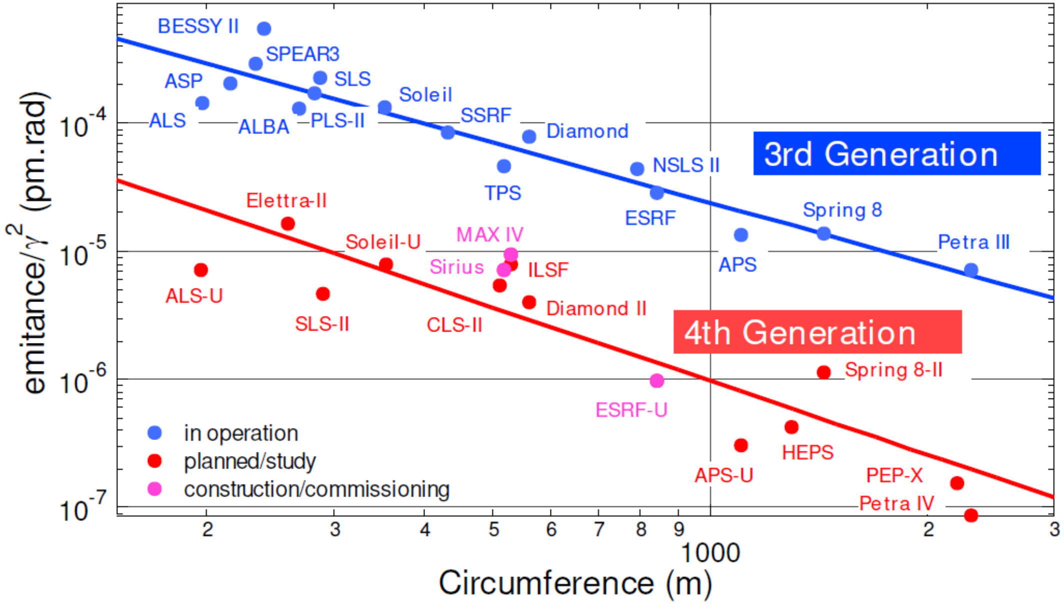
$$\Rightarrow \epsilon_{x,eq} = F\frac{C_e}{J_x}\frac{\gamma^2}{N_b^3}$$

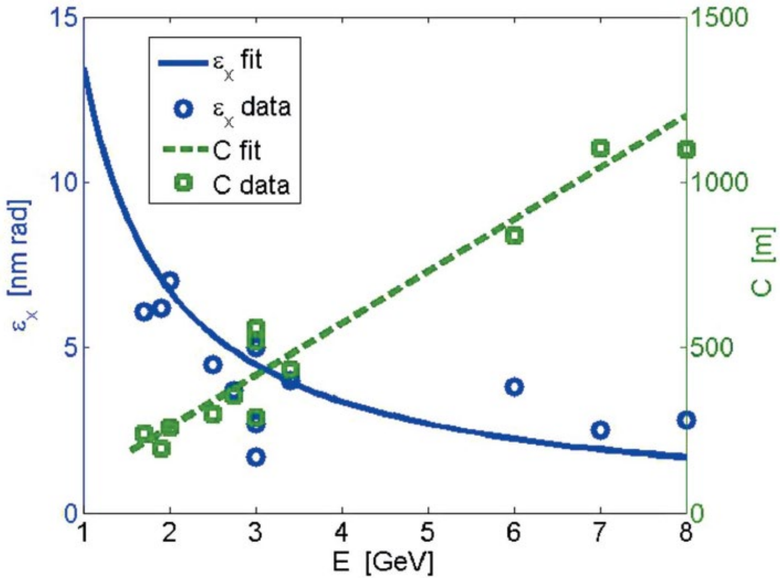




This is driving world-wide upgrades to multi-bend lattices. Radiation is far more collimated and more intense – higher "brilliance"!

Scaling laws





- *Can you explain the emittance trend in the two plots?*

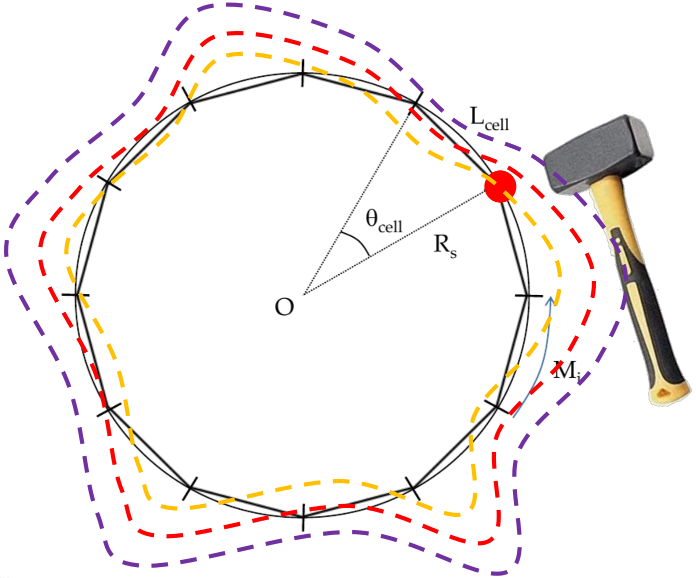
$$\epsilon_{x,eq} = C_e \frac{\gamma^2}{J_x} \frac{\langle H_x \rangle_R}{R}$$

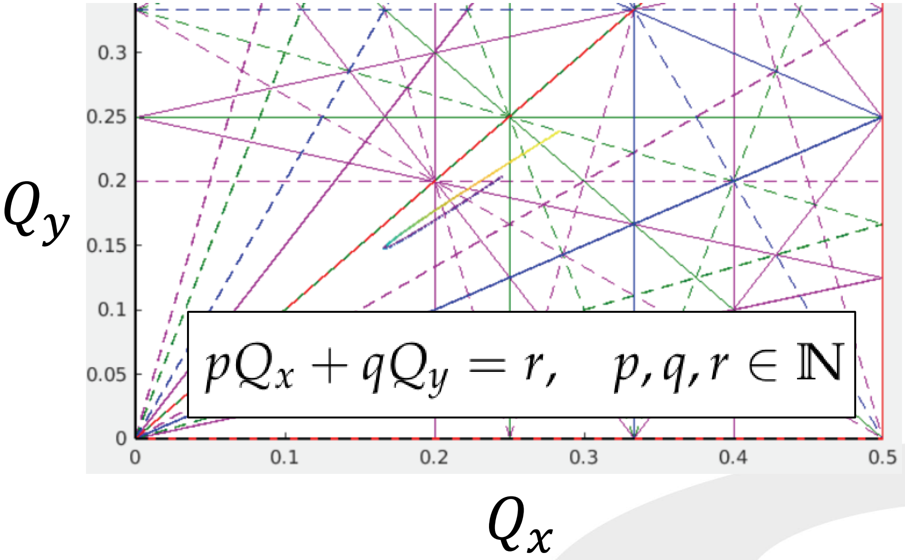
Resonances

Remind:

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

The error sum coherently if the particles goes back to it with same amplitude and phase (position and angle) every r-turns

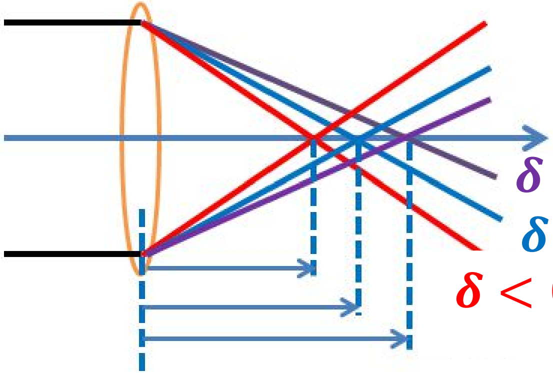




$$pQ_x + qQ_y = r, \quad p,q,r \in \mathbb{N}$$

Chromaticity

Particles at (slightly) different energies are focused differently:



- *Would more quads help to "zeroing" chromaticity?*

1. *Phase advance*

$$\tan(\Delta\mu_u) \approx -\beta_u \frac{u'}{u}$$

2. *Small phase variation by error kick:*

$$\mathrm{d}(\tan(\Delta\mu_u)) \approx d(\Delta\mu_u) \approx -\beta_u \frac{du'}{u}$$

3. *Quad error kick:* $\Delta u' \approx \boldsymbol{k\delta} \cdot ds \cdot u$

4. *Local tune change:*

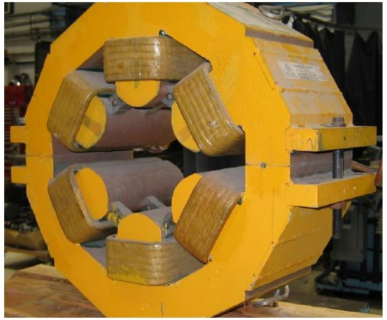
$$\mathrm{d}Q_u = \frac{d(\Delta\mu_u)}{2\pi} \approx -\frac{1}{2\pi}\beta_u\, k\delta ds$$

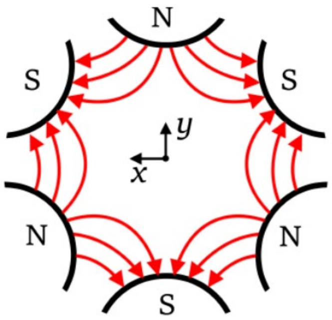
5. *Global tune change (chromaticity):*

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

Sextupole magnet

$$\begin{cases} \xi_x^{cor} = \frac{\Delta Q_x}{\delta} = -\frac{1}{4\pi}\oint \beta_x(s)\left[k(s) + m(s)\eta_x(s)\right] ds \\ \xi_y^{cor} = \frac{\Delta Q_y}{\delta} = -\frac{1}{4\pi}\oint \beta_y(s)\left[-k(s) + m(s)\eta_x(s)\right] ds \end{cases}$$





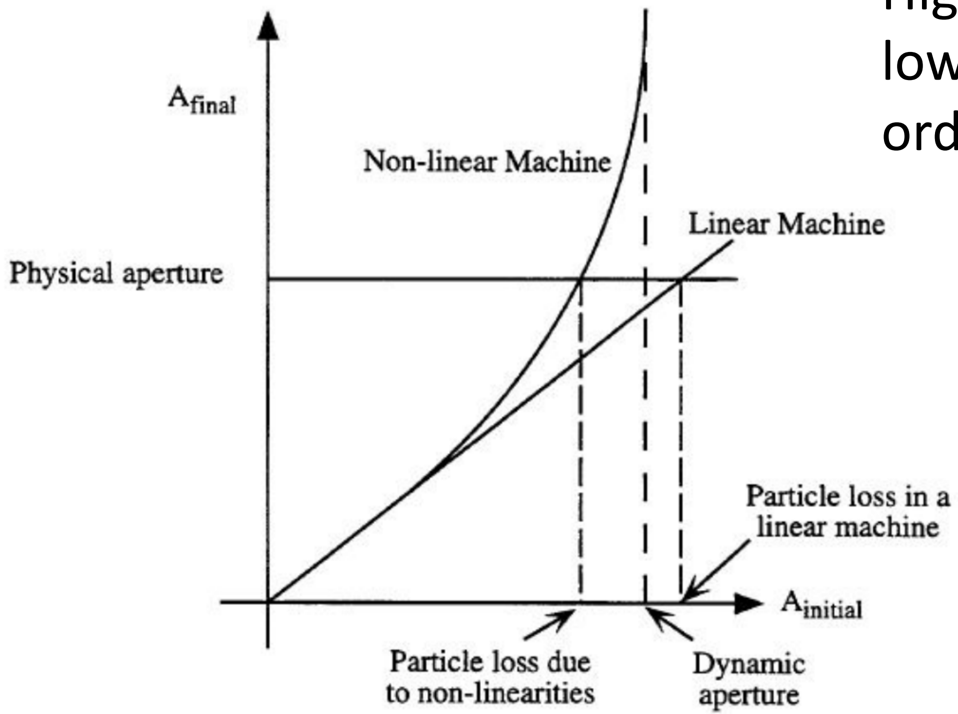
N.B.: $m_{sext} \propto \frac{1}{\eta_x} \propto \frac{1}{\theta_b} = \frac{N_b}{2\pi}$

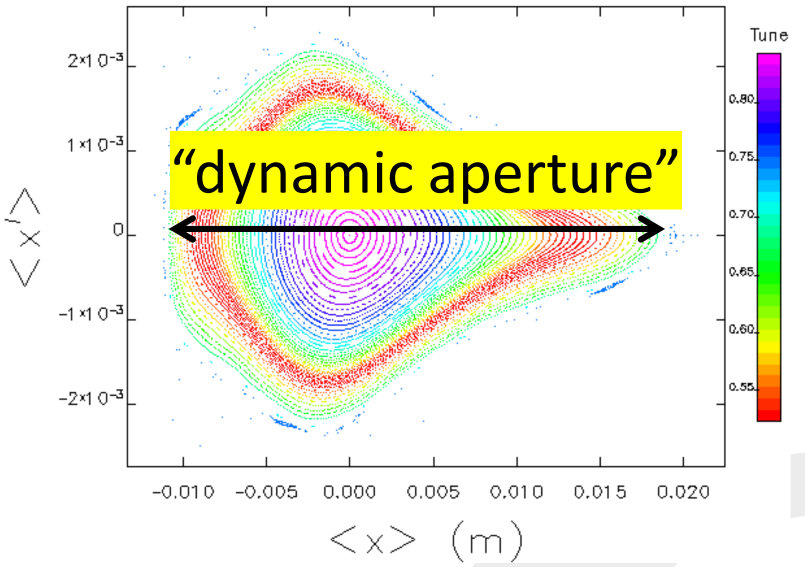
Sextupoles acts as a quadrupole of normalized gradient proportional to the dispersion function.

- *How many sextupole "families" would we need to correct the chromaticity in both x- and y- plane?*

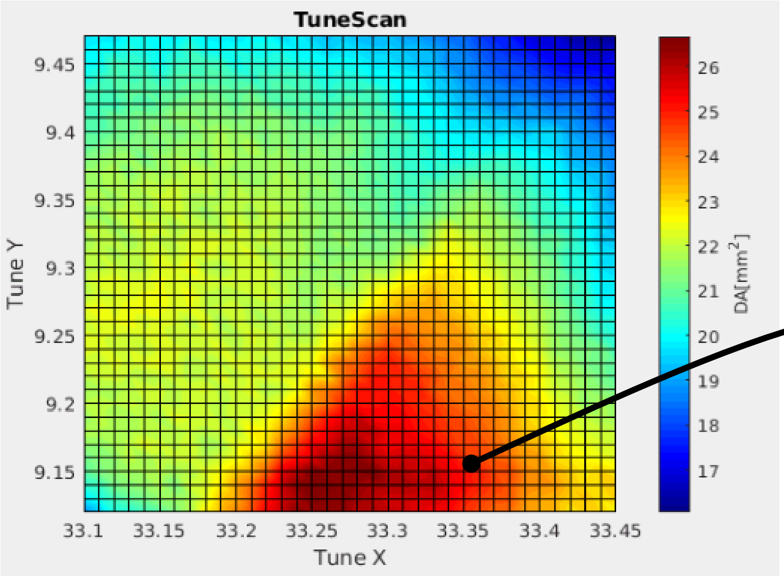
Dynamic aperture

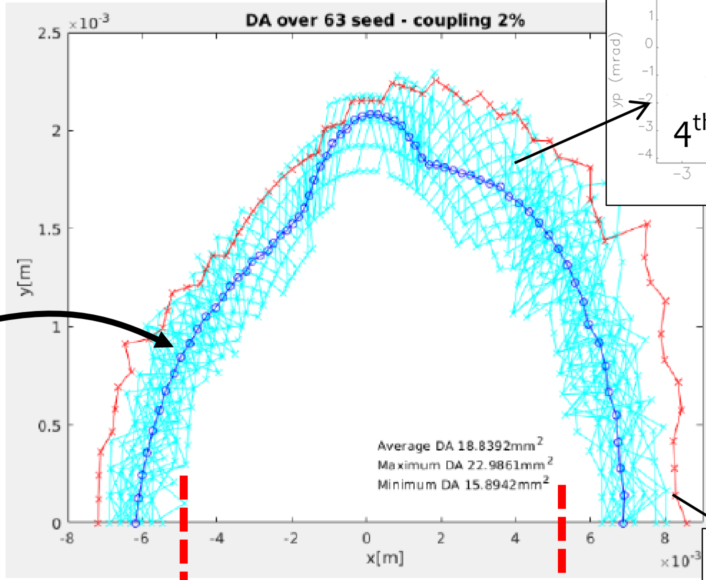
Higher order multi-pole magnets correct lower order errors, but they add higher order perturbations (nonlinear motion).

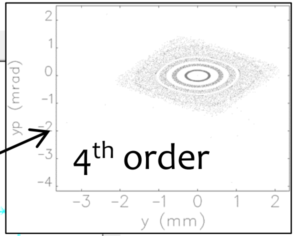


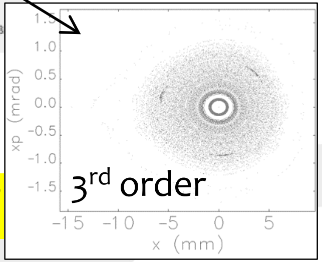


Nonlinear dynamics









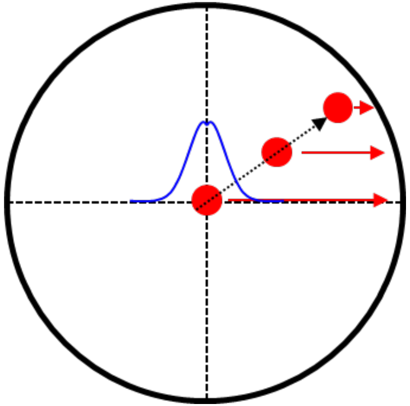
Errors of alignment, field uniformity, calibrations,…

DA @ 3% off-energy

"momentum acceptance"

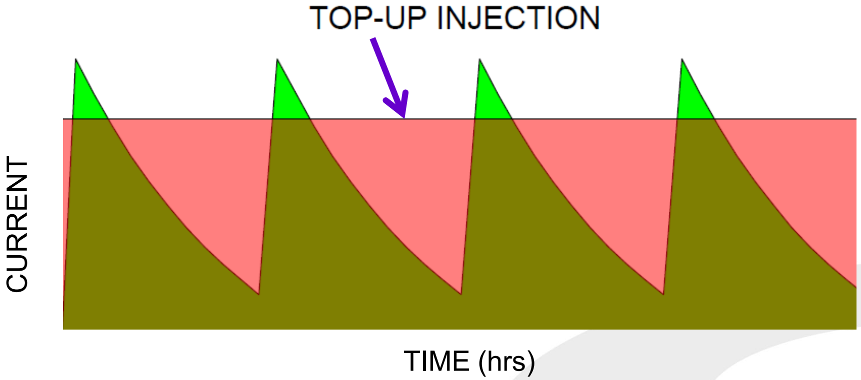
Lifetime

$$\left(\frac{dN}{dt}\right)_{W_c} = \left(\frac{dN}{dW}\frac{dW}{dt}\right)_{W_c}, where \begin{cases} dN(W) = N\rho dW \\ W(t) = \hat{W}e^{-\frac{2t}{\tau}} \end{cases} \Rightarrow \begin{cases} \frac{dN}{dW} = \frac{N}{\langle W\rangle}e^{-\frac{W}{\langle W\rangle}} \\ \frac{dW}{dt} = -\frac{2}{\tau} \end{cases}$$



$$\left(\frac{dN}{dt}\right)_{W_c} = -\frac{2N}{\tau}\frac{W_c}{\langle W\rangle}e^{-\frac{W_c}{\langle W\rangle}} \Rightarrow \begin{cases} N(t) = N_0 e^{-\frac{t}{\tau_q}} \\ \tau_q = \frac{\tau}{2}\frac{\langle W\rangle}{W_c}e^{\frac{W_c}{\langle W\rangle}} = \frac{\tau}{2}\frac{e^{\xi}}{\xi} \end{cases}$$

Due to physical (apertures) or dynamic boundaries (transverse and longitudinal acceptance), the beam current decreases exponentially.



Particle Scattering

Touschek scattering:

single, large angle event

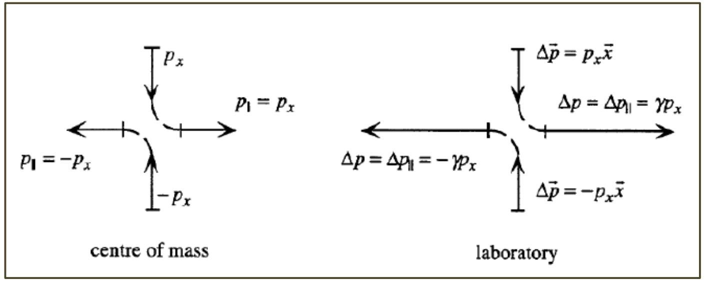
If two particles collide in the c.m. frame transferring their (transverse) momentum $\vec{p}_i' = (p_x', 0)$ into (longitudinal) momentum $\vec{p}_f' = (0, p_z') = (0, p_x')$,

$$\Delta p_z = p_{z,f} - p_{z,i} = \gamma(p'_{z,f} + \tfrac{\beta}{c}E'_f) - \gamma(p'_{z,i} + \tfrac{\beta}{c}E'_i) = \gamma\Delta p'_z + \gamma\tfrac{\beta}{c}\Delta E' =$$

$$= \gamma(p'_{z,f} - p'_{z,i}) = \gamma p'_x = \gamma p_x = \gamma p_z \sigma_{u'}$$

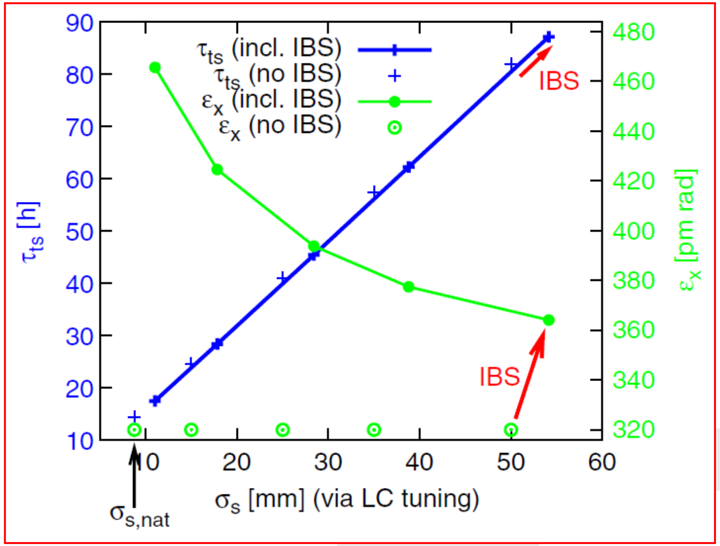
$$\Rightarrow \frac{\Delta p_z}{p_z} \approx \gamma\sqrt{\frac{\epsilon_u}{\beta_u}}, \quad u = x, y$$

must be << long. acceptance



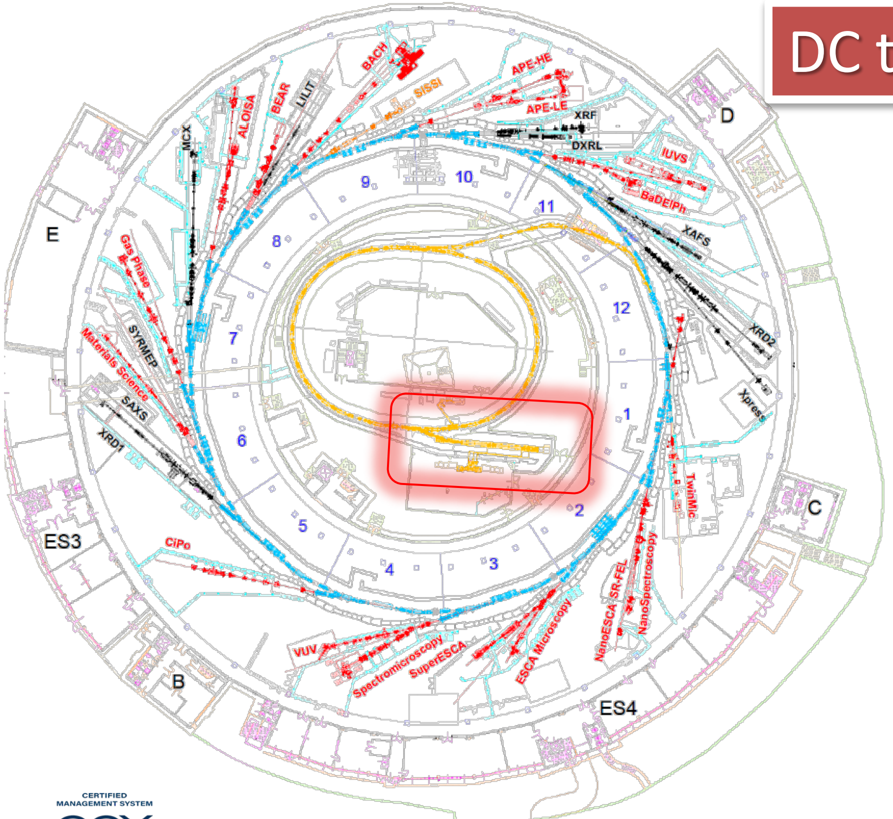
Intrabeam scattering:

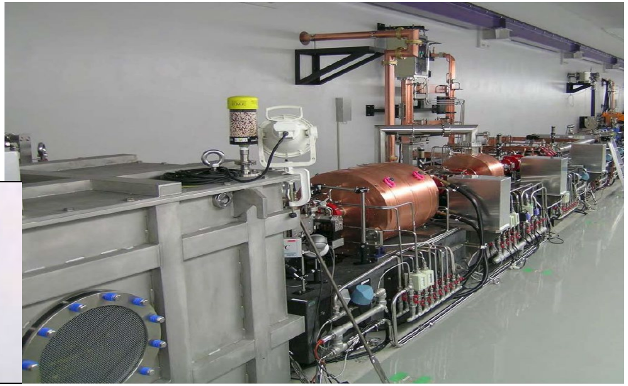
multiple small angle events (diffusion)

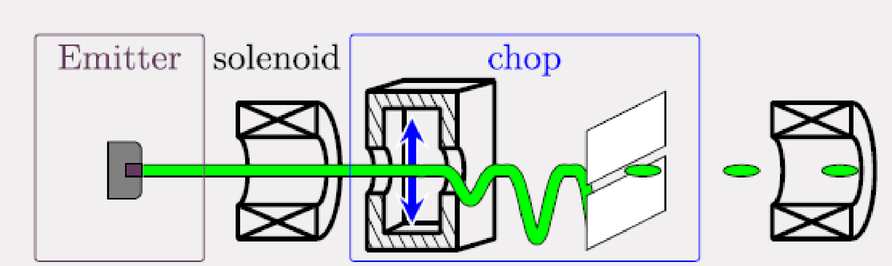


Injection chain - LINAC

DC thermo-ionic Gun + “buncher” + RF







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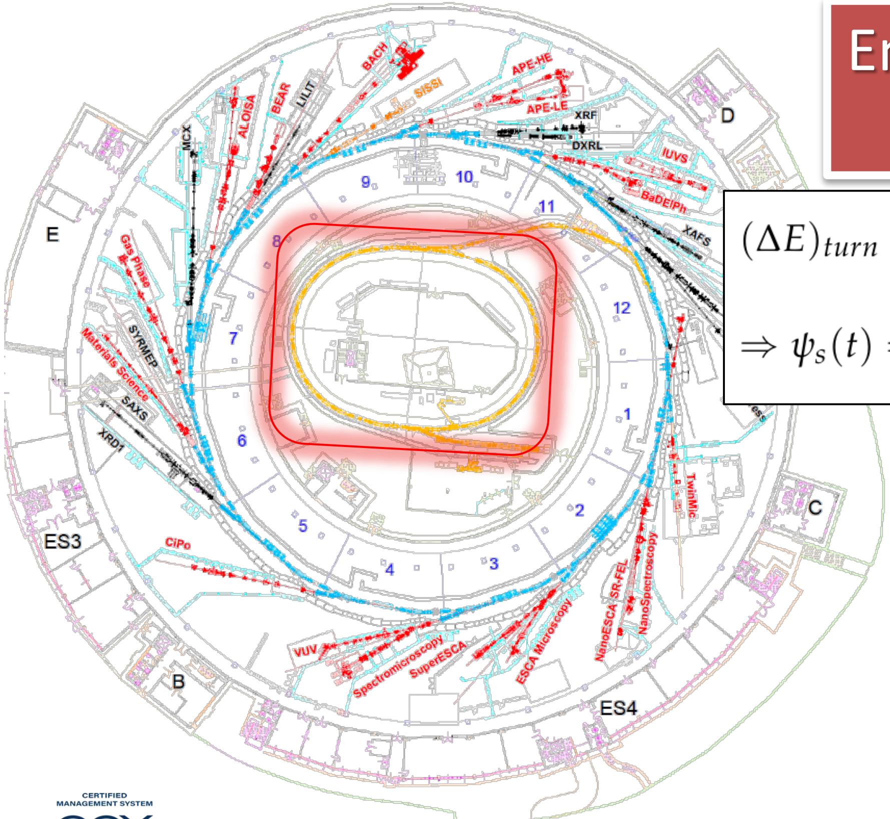
Injection chain - BOOSTER

Energy ramp ---> magnetic field ramp, frequency shift

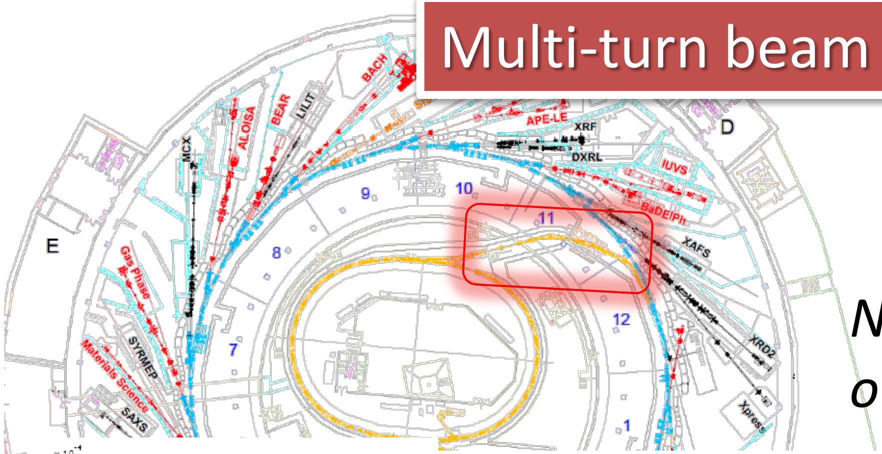
$$(\Delta E)_{turn} = (\Delta p_z)_{turn}\beta c = e\dot{B}_y r T_0 \beta c = 2\pi R_s r q \dot{B}_y \equiv q V_0 cos(\psi_s - \psi_0)$$

$$\Rightarrow \psi_s(t) = \psi_0 + \arccos\left(2\pi R_s r \frac{\dot{B}_y}{V_0}\right)$$



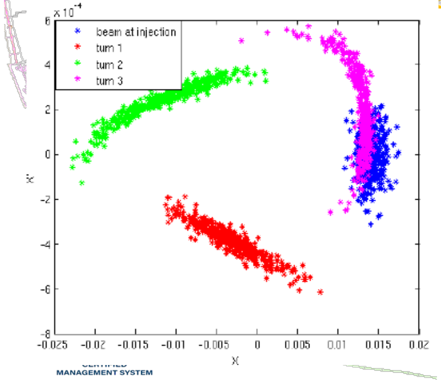
Injection chain - BUMP

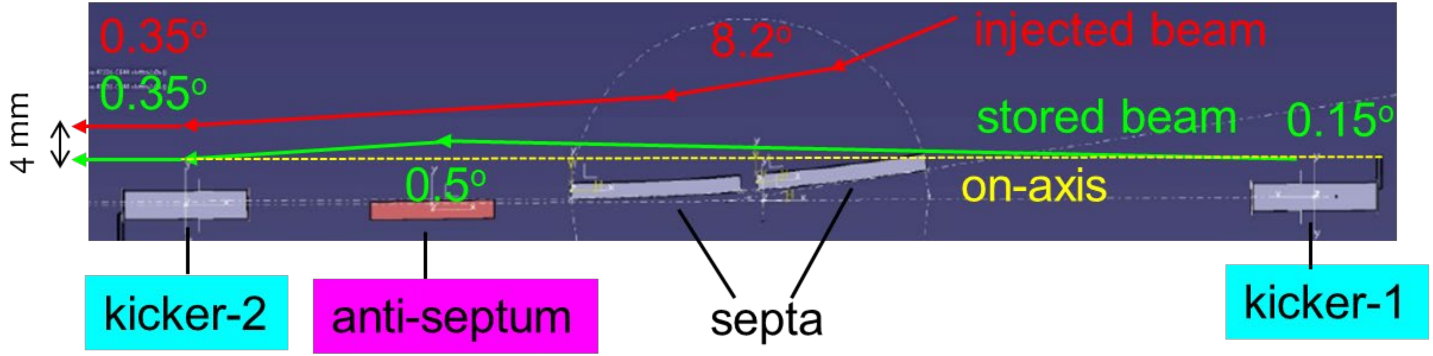
Multi-turn beam accumulation (e.g., off-axis injection)



- Injection efficiency.
- Transparency to stored beam (users)

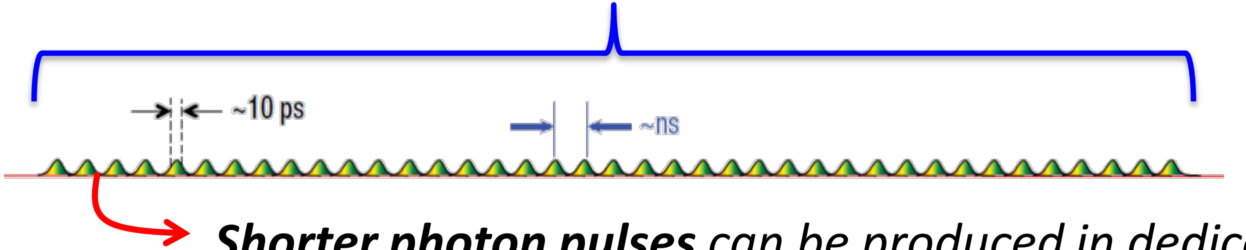
New schemes: single-kicker, on-axis (swap-out), longitudinal injection, linac,…





Filling pattern

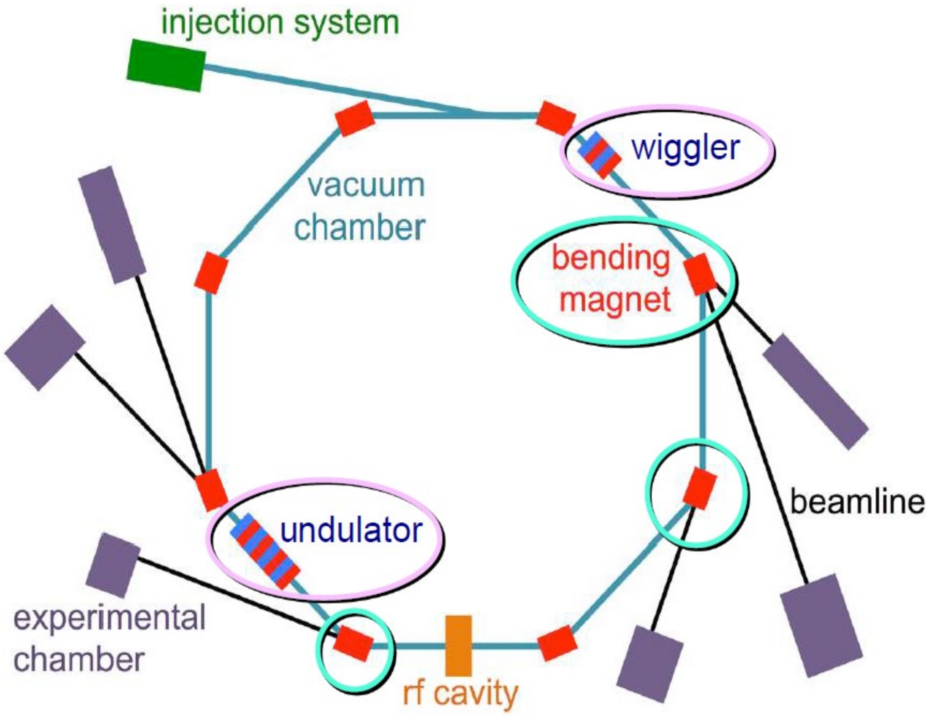
$T_{riv} \sim 1$ – few μs



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

- **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**

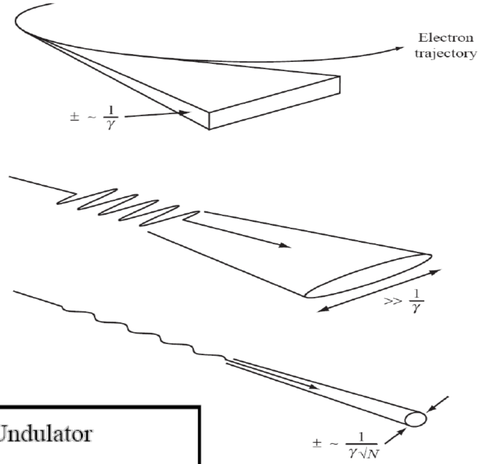
Insertion devices

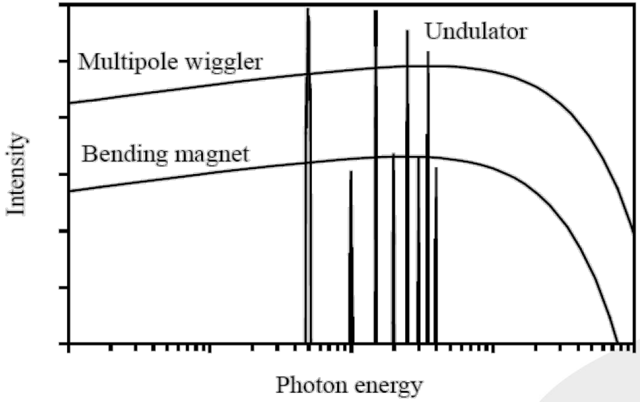


Dipole magnet

Wiggler (K>>1)

Undulator (K≈1)





Brilliance

Brilliance = 6-D photon density:

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

Effective radiation size (at the source)

$$\Sigma_u = \sqrt{\sigma_{u,s}^2 + \sigma_{u,R}^2} \cong \sqrt{(\beta\varepsilon)_{u,s} + (\beta\varepsilon)_{u,R}}$$

$$\Sigma_{u'} = \sqrt{\sigma_{u',s}^2 + \sigma_{u',R}^2} \cong \sqrt{(\varepsilon/\beta)_{u,s} + (\varepsilon/\beta)_{u,R}}$$

- It is maximized by **source-radiation matching:** $\beta_{u,s} = \beta_{u,R}$

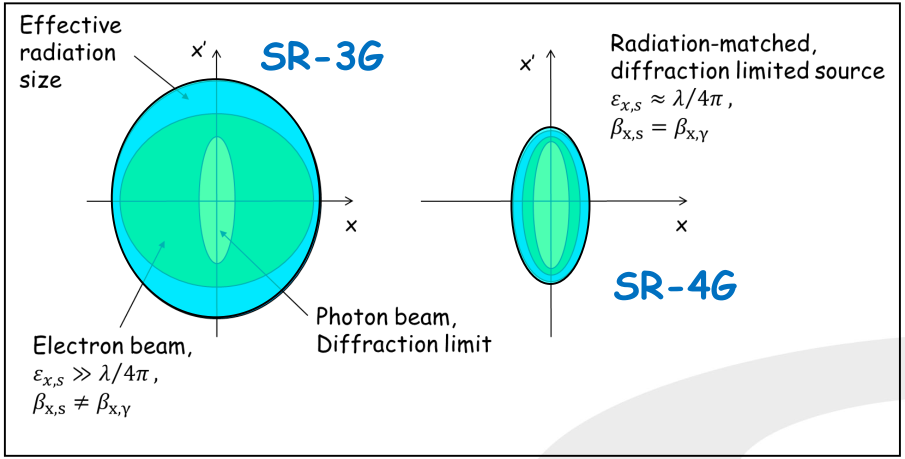
$$B_\gamma = \frac{dN_\gamma/dt}{4\pi^2 \Delta\omega/\omega} \frac{1}{(\varepsilon_{x,s} + \varepsilon_R)(\varepsilon_{y,s} + \varepsilon_R)}$$

- and by a **diffraction limited source:**

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

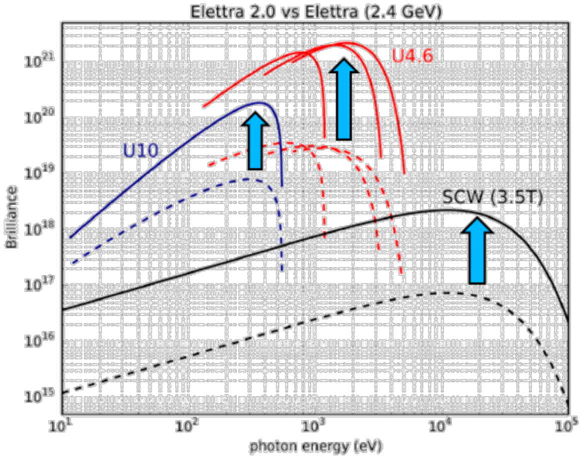
$$\varepsilon_{x,s} = \varepsilon_R = \frac{\lambda}{4\pi}$$

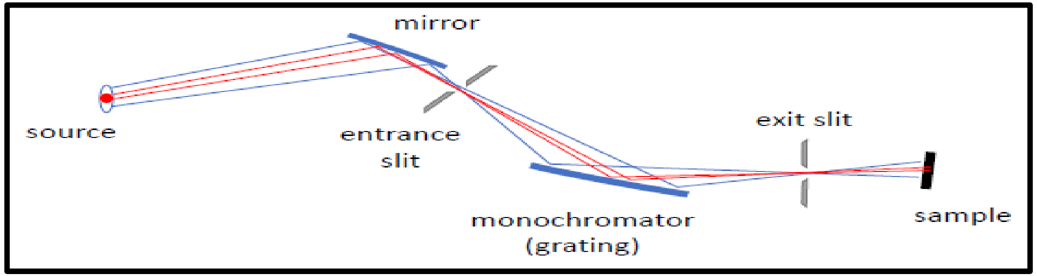
$$\kappa = \frac{\varepsilon_{y,s}}{\varepsilon_{x,s}}$$ **Coupling coefficient**



Practical use of brilliance

- $\frac{dN_\gamma/dt}{\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}}$ is a **conserved quantity** in a *perfect* optical system. However, a ***real beamline*** includes slits, mirrors, gratings, etc. for manipulation of the pulse. They show geometrical and surface **imperfections** ---> **optical aberrations, wavefront distortion, absorption, scattering.**





- ***Flux is maximized.***
- ***Smaller and higher quality mirrors.***
- ***Higher degree of transverse coherence.***

Strong points of SRLS

- Synchrotrons provide light up to **tens of beamlines simultaneously**, each beamline receiving light from its own insertion device (undulators allow independent tuning).
- **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 10’s ps).
- Extremely **stable**.

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Why diffraction limit in x-rays

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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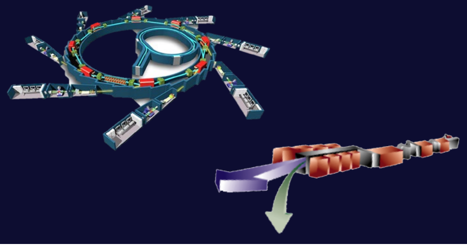
EU initiative

A new consortium of excellence in Europe devising a transformative level of coordination and integration

13 European Synchrotron Radiation and 6 FEL Facilities are joining forces to master the challenges of the next decades.



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