PHY 554

Fundamentals of Accelerator Physics

Lecture 15: Beam Dynamics in an Electron Storage Ring
Part 2

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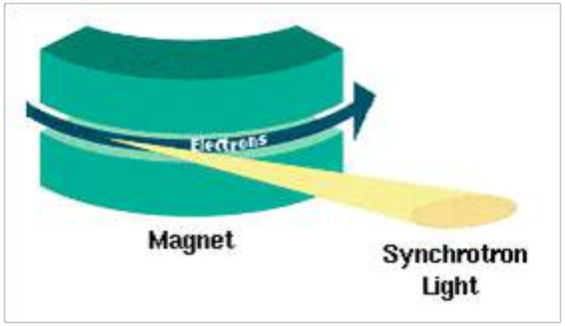
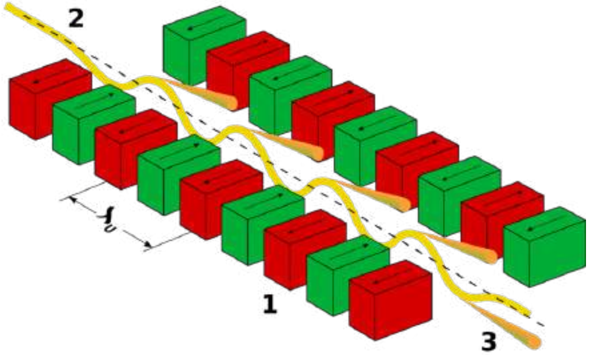
Why electron/positron storage rings are different?

SYNCHROTRON RADIATION

- Energy emitted to infinity or other boundary condition.
  - Form: Electromagnetic waves
  - Source: acceleration of charged particles
  - Direction: Along the tangent of the beam trajectory





Effects of Synchrotron Radiation

- In last class we learned that SR could cause damping of betatron and synchrotron oscillations.
- Does it mean that beam sizes will collapse to zero and we will have zero beam sizes and infinitely dense beam?
- The answer is no – there are effects which prevent this collapse
- Today we will study the main effect which does exactly this – quantum fluctuations of synchrotron radiation

Radiation Damping

$$\mathbf{E}_o = \gamma_o mc^2; \gamma >> 1, \beta \cong 1; \; r_c = e^2 / mc^2$$

$$\frac{\Delta E_{SR}}{\mathbf{E}_o} = -\frac{2e^2}{3\mathbf{E}_o \beta_o^2} \gamma_o^4 I_2 \cong -\frac{2r_c}{3} \gamma_o^3 \cdot I_2$$

$$\bar{D} = \frac{I_4}{I_2}; \; I_4 = \oint ds \cdot DK_o \left(2K_x - K_o^{\,2}\right)$$

$$I_2 = \oint_C \frac{ds}{\rho^2} \equiv \oint_C K_o^{\,2}(s)\, ds$$

$$\xi_y(C) \cong \frac{r_c}{3} \gamma_o^3 \cdot I_2$$

$$y = a_y \sqrt{\beta_y} \cos\psi_y e^{-\xi_y(s)}$$

$$\xi_x(C) = \frac{r_c}{3} \gamma_o^3 \cdot I_2 \left(1 - \bar{D}\right)$$

$$x = a_x \sqrt{\beta_x} \cos\psi_x e^{-\xi_x(s)}$$

$$\xi_s = \frac{r_c}{3} \gamma_o^3 \cdot I_2 \left(2 + \bar{D}\right)$$

$$\delta = a_\delta \cos\left(n\Omega_s + \varphi\right) \cdot e^{-n\xi_s}$$

$$\xi_{SR} = -\frac{\Delta E_{SR}}{2\mathbf{E}_o}; \quad \xi_{x,y,s} = \zeta_{x,y,s} \cdot \xi_{SR};$$

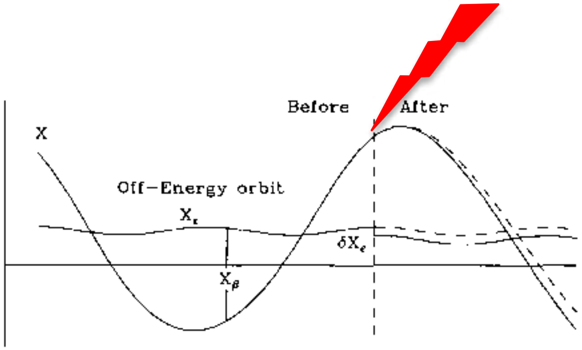
$$\zeta_x = 1 - \bar{D} \qquad \zeta_y = 1 \qquad \zeta_s = 2 + \bar{D}$$

$$\zeta_x + \zeta_y + \zeta_s = 4$$

Quantum Fluctuations of Synchrotron Radiation

- Synchrotron radiation is not a continuous emission
- Instead, photons are radiated at random moments and energy loss has quantum nature
- The emission obeys Poisson distribution
- It serves as a source of the noise that excites (heat) motion of particles in the electron beam.
- Since energy jumps are random there is not correlations, and we need to find how to handle this source of "random noise"

Sudden change in energy δE_{ph} not only excite energy oscillations but also induce horizontal oscillations about "new E- δE_{ph} orbit"



How to handle random jumps?

- 1 D case (Brownian motion) – no definitive *x*

$$\dot{x} = \sum \delta x_i \cdot \delta\left(t - t_i\right); \left\langle \delta x_i \right\rangle = 0 \Rightarrow x\left(t\right) = \sum_{t>t_i} \delta x_i = ?$$

- It is not true for x^2

$$\delta x^2 = \left(x + \delta x_i\right)^2 - x^2 = 2x\delta x_i + \delta x_i^{\ 2} \rightarrow \left\langle \delta x^2 \right\rangle = 2\underbrace{\left\langle x\delta x_i \right\rangle}_{0} + \left\langle \delta x_i^{\ 2} \right\rangle > 0$$

$$\left\langle x^2\left(t + \Delta t\right)\right\rangle = \left\langle x^2\left(t\right)\right\rangle + \left\langle \sum_{t<t_i<t+\Delta t} \delta x_i^{\ 2} \right\rangle = \left\langle x^2\left(t\right)\right\rangle + \dot{N}\left\langle \delta x_i^{\ 2}\right\rangle \Delta t$$

- Rate of jumps and diffusion coefficient:

$$\dot{N}\left(t\right) = \lim_{\Delta t -> 0} \frac{\left\langle \sum_{t<t_i<t+\Delta t} \delta x_i^{\ 2} \right\rangle}{\Delta t \cdot \left\langle \delta x_i^{\ 2} \right\rangle}; \frac{d\left\langle x^2 \right\rangle}{dt} = \mathbf{D};\ \mathbf{D} = \dot{N}\left(t\right)\left\langle \delta x_i^{\ 2} \right\rangle = \left\langle \dot{N}\delta x_i^{\ 2} \right\rangle$$

- Statistically average $<x^2>$ is well defined!

How to handle random noise?

- What about an oscillator?

$$x = a \cdot \sin\varphi;\ p = a\omega \cdot \cos\varphi;\ x \to x + \delta x_i;\ p \to p + \delta p_i$$

$$a^2 = x^2 + \frac{p^2}{\omega^2};\ \langle \delta a^2 \rangle = 2\langle x\delta x_i \rangle\downarrow_0 + \frac{2}{\omega^2}\langle p\delta p_i \rangle\downarrow_0 + \langle \delta x_i^2 \rangle + \frac{\langle \delta p_i^2 \rangle}{\omega^2} > 0$$

- Diffusion coefficient for amplitude squared

$$N'_x(s) = \lim_{\Delta s \to 0} \frac{\left\langle \sum_{s<s_i<s+\Delta s} \delta x_i^2 \right\rangle}{\Delta s \langle \delta x_i^2 \rangle};\ N'_p(s) = \lim_{\Delta s \to 0} \frac{\left\langle \sum_{s<s_j<s+\Delta s} \delta p_j^2 \right\rangle}{\Delta s \langle \delta p_j^2 \rangle};$$

$$\frac{d\langle a^2 \rangle}{ds} = \mathbf{D}(s);\ \mathbf{D}(s) = \langle N'_x \delta x_i^2 \rangle + \frac{\langle N'_p \delta p_j^2 \rangle}{\omega^2}$$

- Statistically average a^2 is well defined!

Noise +damping

- 1 D case

$$\dot{x} = -\xi x + \sum \delta x_i \cdot \delta\left(t - t_i\right); \left\langle \delta x_i \right\rangle = 0;\ t_1 = t + \Delta t;\ \ d\tilde{x} = \sum_{t<t_i<t+\Delta t} \delta x_i$$

$$\Delta x^2 = \left(x + \delta\tilde{x} - \xi x \cdot \Delta t\right)^2 - x^2 = 2x\left(\delta\tilde{x} - \xi x \cdot \Delta t\right) + \left(\delta\tilde{x} - \xi x \cdot \Delta t\right)^2$$

$$\left\langle \Delta x^2 \right\rangle = -2\xi\left\langle x^2 \right\rangle \Delta t + \mathbf{D}\Delta t \rightarrow \frac{d\left\langle x^2 \right\rangle}{dt} = \mathbf{D} - 2\xi\left\langle x^2 \right\rangle$$

- Statistically average x^2 is well defined

$$\frac{d\left\langle x^2 \right\rangle}{dt} = \mathbf{D} - 2\xi\left\langle x^2 \right\rangle = 0 \Rightarrow \left\langle x^2 \right\rangle = \frac{\mathbf{D}}{2\xi} = \frac{\left\langle \dot{N}\delta x_i^{\,2} \right\rangle}{2\xi}$$

Noise +damping

- Damping of the oscillator?

$$a = a_o e^{-\xi(s)} \Rightarrow \frac{da^2}{ds} = -2\xi'(s) a^2$$

- Combine with diffusion and assume slow evolution

$$\frac{d\langle a^2\rangle}{ds} = \mathbf{D}(s) - 2\xi'(s)\langle a^2\rangle \Rightarrow \frac{d\langle a^2\rangle}{ds} = \langle \mathbf{D}(s)\rangle - 2\langle \xi'(s)\rangle\langle a^2\rangle$$

- Defines average action

$$\langle a^2\rangle = \frac{\langle \mathbf{D}(s)\rangle}{2\langle \xi'(s)\rangle}; \ \mathbf{D}(s) = \langle N'_x \delta x_i^{\ 2}\rangle + \frac{\langle N'_x \delta p_j^{\ 2}\rangle}{\omega^2}$$

Quantum Fluctuations of Synchrotron Radiation

- If ε is the emitted photon energy, the average amplitude of energy deviation is

$$\frac{d\langle\delta^2\rangle}{dt} = \frac{\langle\dot{N}_i\varepsilon_i^{\,2}\rangle}{\mathbf{E}_o^2}; \langle\dot{N}_i\varepsilon_i^{\,2}\rangle = \sum_i \dot{N}_i\varepsilon_i^{\,2} \cong \int \varepsilon^2 f(\varepsilon)\,d\varepsilon$$

$$\left(\frac{\delta}{a_\delta}\right)^2 + \left(\frac{\Delta\phi}{a_\phi}\right)^2 = 1 \qquad \frac{a_\delta}{a_\phi} = \sqrt{\frac{eV_{rf}\left|\cos\phi_s\right|}{2\pi h|\eta|\beta^2\mathbf{E}_o}} = \frac{Q_s}{h|\eta|}$$

$$\frac{d\langle a_\delta^{\,2}\rangle}{dt} = \frac{1}{\mathbf{E}_o^2}\int \varepsilon^2 f(\varepsilon)\,d\varepsilon - 2\frac{\xi_s}{T_o}\langle a_\delta^{\,2}\rangle; \; T_o = \frac{C}{\mathrm{v}_o} \cong \frac{C}{c}$$

- And we need to evaluate the integral on RHS

How to calculate <u^2>

- We need to use spectral properties of synchrotron radiation

$$P_{SR} = \sum_i \bar{\dot{n}}_i \varepsilon_i = \int_0^\infty \dot{n}(\varepsilon) d\varepsilon \equiv \int_0^\infty U(u) du; \quad u = \frac{\varepsilon}{\varepsilon_c} = \frac{\hbar\omega}{\hbar\omega_c} \equiv \frac{\omega}{\omega_c}; \; \omega_c = \frac{3}{2}\frac{c}{|\rho|}\gamma^2$$

$$U(u) = \frac{3\sqrt{3}}{4\pi}\frac{e^2 c}{\rho^2}\gamma^4 \cdot u \int_u^\infty K_{5/3}(u') du'$$

similarly, we can calculate diffusion

$$\sum_i \bar{\dot{n}}_i \varepsilon_i^2 = \int_0^\infty \varepsilon \cdot \dot{n}(\varepsilon) d\varepsilon \equiv \hbar\omega_c \int_0^\infty u U(u) du; \quad \varepsilon = u \cdot \hbar\omega_c$$

$$\sum_i \bar{\dot{n}}_i \varepsilon_i^2 = \frac{3\sqrt{3}}{4\pi}\frac{e^2 c}{\rho^2}\gamma^4 \cdot \hbar\omega_c \int_0^\infty \left(u^2 \int_u^\infty K_{5/3}(u') du' \right) du = \frac{55}{24\sqrt{3}}\frac{\gamma^7}{|\rho|^3}\hbar c^2 e^2$$

$$\mathbf{D}_\delta = \frac{\langle \delta E^2 \rangle}{E_o^2} = \frac{55}{24\sqrt{3}}\gamma^5 \frac{c}{|\rho|^3}\frac{\hbar}{mc}\frac{e^2}{mc^2} \equiv \frac{55}{24\sqrt{3}}\gamma^5 \frac{c}{|\rho|^3} \lambda_c r_c$$

$$\lambda_c = \frac{\hbar}{mc}; \quad r_c = \frac{e^2}{mc^2}$$

Equilibrium energy spread

- The damping and excitation will reach a steady sate.

$$\left\langle a_\delta{}^2 \right\rangle = \frac{\left\langle \mathbf{D}_\delta \right\rangle}{2\xi_s} \cdot \frac{C_o}{c} = \frac{1}{2\xi_s c} \oint \mathbf{D}_\delta ds, \;\; \xi_s = \frac{r_c}{3} \gamma_o^3 \cdot I_2 \left(2 + \bar{D}\right)$$

$$\oint \mathbf{D}_\delta ds / c = \frac{55}{24\sqrt{3}} \gamma_o{}^5 \lambda\!\!\!^{-}{}_c r_c I_3; \;\; I_3 = \oint \frac{ds}{\left|\rho(s)\right|^3} \equiv \oint \left| K_o^3(s) \right| ds;$$

$$\left\langle a_\delta{}^2 \right\rangle = \frac{55}{16\sqrt{3}} \lambda\!\!\!^{-}{}_c \gamma_o^2 \cdot \frac{I_3}{I_2\left(2 + \bar{D}\right)}$$

Since phases of oscillations are random, $\left\langle \cos^2\left(\Omega_s n + \varphi\right) \right\rangle = \frac{1}{2}$

and the relative rms energy spread is twice loser than $<a_\delta{}^2>$

$$\delta = a_\delta \cos\left(\Omega_s n + \varphi\right); \;\; \sigma_\delta^2 \equiv \left\langle \delta^2 \right\rangle = \left\langle a_\delta{}^2 \right\rangle \left\langle \cos^2\left(\Omega_s n + \varphi\right) \right\rangle = \frac{\left\langle a_\delta{}^2 \right\rangle}{2}$$

$$\sigma_\delta^2 = \frac{55}{32\sqrt{3}} \lambda\!\!\!^{-}{}_c \gamma_o^2 \cdot \frac{I_3}{I_2\left(2 + \bar{D}\right)}$$

Equilibrium energy spread II

- The equilibrium of the relative energy spread:

$$\sigma_\delta^2 \equiv \left(\frac{\sigma_E}{\mathbf{E}_o}\right) = \frac{55}{32\sqrt{3}} \lambda\!\!\!^{-}_c \gamma_o^2 \cdot \frac{I_3}{I_2\left(2+\bar{D}\right)} = \frac{C_q \cdot \gamma_o^2}{\left(2+\bar{D}\right)} \cdot \frac{\left\langle |\rho|^{-3} \right\rangle}{\left\langle \rho^{-2} \right\rangle};$$

Radiation Integral I_3

Radiation Integral I_2

$$C_q = \frac{55}{32\sqrt{3}} \lambda\!\!\!^{-}_c = 3.83 \cdot 10^{-13} m$$

- It does not depend on the RF voltage, but the bunch length does:

$$\frac{\sigma_\delta}{\sigma_\phi} = \frac{a_\delta}{a_\phi} = \sqrt{\frac{eV_{rf}\left|\cos\phi_s\right|}{2\pi h|\eta|\beta^2 \mathbf{E}_o}} = \frac{Q_s}{h|\eta|} \rightarrow \sigma_\phi = \frac{h|\eta|}{Q_s}\sigma_\delta$$

Excitation of horizontal betatron oscillations

- Radiation of the photon changes electron's energy, but does not change its location

$$\Delta E = -\varepsilon_{ph};\ \Delta x = 0;\ \Delta x' = -x' \cdot \frac{\varepsilon_{ph}}{E_o};$$

- At the same time, the closed orbit for new electron changes, which results in excitation of betatron oscillations

$$\Delta x = \Delta x_\beta + D\frac{\Delta E}{E_o} = 0;\ \Delta x' = \Delta x'_\beta + D'\frac{\Delta E}{E_o} = -x' \cdot \frac{\varepsilon_{ph}}{E_o};$$

$$\Delta x_\beta = -D\frac{u_{ph}}{E_o}; \Delta x'_\beta = -D'\frac{\varepsilon_{ph}}{E_o} - x' \cdot \frac{\varepsilon_{ph}}{E_o}$$

- The second term on the right-hand side with $\Delta x'$ is a part of radiation damping, and is already considered

Excitation of horizontal betatron oscillations

- Let's calculate the induced amplitude of betatron oscillations

$$x = a_x\sqrt{\beta_x}\cdot\cos\psi; x' = -\frac{a_x}{\sqrt{\beta_x}}\cdot(\sin\psi + \alpha_x\cos\psi)$$

$$\Delta\left(a_x\sqrt{\beta_x}\cdot\cos\psi\right) = -D\frac{\varepsilon_{ph}}{E_o};\ \Delta\left(\frac{a_x}{\sqrt{\beta_x}}(\alpha_x\cos\psi + \sin\psi)\right) = D'\frac{\varepsilon_{ph}}{E_o}$$

$$\Delta a_x\cdot\cos\psi - \cdot\sin\psi\cdot a_x\Delta\psi = -\frac{D}{\sqrt{\beta_x}}\frac{\varepsilon_{ph}}{E_o}$$

$$\Delta a_x(\alpha_x\cos\psi + \sin\psi) + (\cos\psi - \alpha_x\sin\psi)\cdot a_x\Delta\psi = \sqrt{\beta_x}D'\frac{\varepsilon_{ph}}{E_o}$$

$$\begin{bmatrix}\cos\psi & -\sin\psi\\ \alpha_x\cos\psi+\sin\psi & \cos\psi-\alpha_x\sin\psi\end{bmatrix}\cdot\begin{bmatrix}\Delta a_x\\ a_x\Delta\psi\end{bmatrix} = \frac{\varepsilon_{ph}}{E_o}\begin{bmatrix}-\frac{D}{\sqrt{\beta_x}}\\ \sqrt{\beta_x}D'\end{bmatrix}$$

$$\begin{bmatrix}\Delta a_x\\ a_x\Delta\psi\end{bmatrix} = \frac{\varepsilon_{ph}}{E_o}\begin{bmatrix}\cos\psi-\alpha_x\sin\psi & \sin\psi\\ -\alpha_x\cos\psi-\sin\psi & \cos\psi\end{bmatrix}\begin{bmatrix}-\frac{D}{\sqrt{\beta_x}}\\ \sqrt{\beta_x}D'\end{bmatrix}$$

- giving us

$$\Delta a_x = -\frac{\varepsilon_{ph}}{E_o}\left(\frac{D}{\sqrt{\beta_x}}(\cos\psi - \alpha_x\sin\psi) - \sqrt{\beta_x}D'\sin\psi\right); \langle\cos\psi\sin\psi\rangle = 0; \langle\cos\psi^2\rangle = \langle\sin\psi^2\rangle = \frac{1}{2}$$

$$\langle\Delta a_x{}^2\rangle = \frac{1}{2E_o{}^2}\left\langle\varepsilon_{ph}{}^2\left(\frac{D^2}{\beta_x}(1+\alpha_x{}^2) + 2D'D\alpha_x + \beta_x D'^2\right)\right\rangle = \frac{\langle\varepsilon_{ph}{}^2 H\rangle}{2E_o{}^2};$$

$$H(s) = \frac{D^2(1+\alpha_x{}^2) + 2D'D\beta_x\alpha_x + (\beta_x D')^2}{\beta_x} = \gamma_x\cdot D^2 + 2\alpha_x\cdot D'D + \beta_x D'^2$$

Horizontal betatron oscillations

- Equation for the amplitude square is

$$\frac{d\left\langle a_x^{\ 2}\right\rangle}{dt} = \mathbf{D}_x - 2\xi_x'\left\langle a_x^{\ 2}\right\rangle; \ \mathbf{D}_x = \frac{H\left\langle \varepsilon_{ph}^{\ 2}\right\rangle}{2E_o^{\ 2}} = \frac{55c}{24\sqrt{3}}\gamma^5 \bar{\lambda}_c r_c \frac{H(s)}{\left|\rho\right|^3};$$

$$\frac{d\left\langle a_x^{\ 2}\right\rangle}{dn} = \oint \mathbf{D}_x \, ds - 2\xi_x(C)\left\langle a_x^{\ 2}\right\rangle; \ \xi_x(C) = \frac{r_c}{3}\gamma_o^3 \cdot I_2\left(1-\bar{D}\right); \ \oint \mathbf{D}_x \, ds = \frac{55c}{24\sqrt{3}}\gamma^5 \bar{\lambda}_c r_c I_5$$

$$I_5 = \oint \frac{H(s)}{\left|\rho(s)\right|^3} ds \equiv \oint ds \left|K_o(s)\right|^3 \left(\gamma_x(s)\cdot D(s)^2 + 2\alpha_x(s)\cdot D'(s)D(s) + \beta_x(s)D'(s)^2\right)$$

- Or in simplified form

$$\frac{d\left\langle a_x^{\ 2}\right\rangle}{dn} = \frac{55c}{24\sqrt{3}}\gamma^5 \bar{\lambda}_c r_c \cdot I_5 - \frac{2r_c}{3}\gamma_o^3 \cdot I_2\left(1-\bar{D}\right)$$

Transverse equilibrium

- Horizontal emittance

$$\frac{d\langle a_x^{\ 2}\rangle}{dn} = \frac{55c}{24\sqrt{3}}\gamma_o^5 \lambdabar_c r_c \cdot I_5 - \frac{2r_c}{3}\gamma_o^3 \cdot I_2\left(1-\bar{D}\right) = 0;$$

$$\varepsilon_x = \left\langle \frac{a_x^{\ 2}}{2} \right\rangle = \frac{55c}{32\sqrt{3}}\gamma_o^2 \lambdabar_c \cdot \frac{I_5}{I_2\left(1-\bar{D}\right)} = C_q \cdot \gamma_o^2 \cdot \frac{I_5}{I_2\left(1-\bar{D}\right)};$$

$$C_q \frac{55}{32\sqrt{3}} \lambdabar_c = 3.83 \cdot 10^{-13} m$$

- and beam size

$$\sigma_x^2 = \left\langle \left(x_\beta + D\delta\right)^2 \right\rangle = \left\langle x_\beta^{\ 2} \right\rangle + 2D\left\langle x_\beta \delta \right\rangle \underset{0}{\downarrow} + D^2\left\langle \delta^2 \right\rangle$$

$$\left\langle x_\beta^{\ 2} \right\rangle = \beta_x \left\langle a_x^{\ 2} \right\rangle \left\langle \cos^2 \psi \right\rangle = \beta_x \varepsilon_x \Rightarrow \sigma_x^2 = \beta_x \varepsilon_x + D^2 \sigma_\delta^2$$

Vertical emittance

- In storage ring with ideal plane orbit, there is no direct coupling between energy jumps and vertical oscillations. The same treatment as for horizontal direction will result in zero vertical emittance
- There is minuscular diffusion in vertical direction as result of finite angular spread of the radiated photons:

$$\delta y' \propto \frac{1}{\gamma_o}\frac{\varepsilon_{ph}}{E_o} \Rightarrow \mathbf{D}_y \propto \frac{\mathbf{D}_x}{\gamma_o{}^2}$$

- Estimated vertical equilibrium would not depend on the beam energy and would be e unrealistically small

$$\varepsilon_y \propto C_q \frac{\langle \beta_z \rangle}{\rho}$$

- IN reality, vertical emittance is defined by coupling with horizontal motion. It is result of imperfections in the beam’s orbit and skew-quadrupole errors

Transverse Coupling (definition)

- Coupling of emittances κ is defined as

$$\varepsilon_{nat} = C_q \cdot \gamma_o^2 \cdot \frac{I_5}{I_2\left(1-\bar{D}\right)}$$

$$\varepsilon_x = \frac{1}{1+\kappa}\varepsilon_{nat} \qquad \varepsilon_y = \frac{\kappa}{1+\kappa}\varepsilon_{nat}$$

Summary: Radiation Integral

Index	Integrals	Properties
1	$I_1 = \oint D/\rho ds$	$\alpha_c = I_1 \times C$
2	$I_2 = \oint 1/\rho^2 ds$	$U_{SR} = \frac{C_\gamma E^4}{2\pi} I_2$
3	$I_3 = \oint 1/\lvert\rho\rvert^3 ds$	$\left(\frac{\sigma_E}{E}\right)^2 = C_q \gamma^2 \frac{I_3}{2I_2 + I_4}$
4	$I_4 = \oint (D/\rho)\left(1/\rho^2 + 2K(s)\right) ds$	$\bar{D} = I_4/I_2$
5	$I_5 = \oint H(s)/\lvert\rho\rvert^3 ds$	$\epsilon_x = C_q \gamma^2 \frac{I_5}{I_2 - I_4}$

Typical “good’ numbers

- Revolution time: ~ micro-second (300 m)
- Longitudinal oscillation: sub-millisecond
- Damping time: few thousand turns
  - Several millisecond
- Relative energy spread $\sim 10^{-3}$
- Rms transverse emittance ~ nm-rad
- Rms vertical emittance ~ few pm-rad

Additional sources of emittance growth

- Emittance and energy spread can also grow from other effects, for example:
  - Scattering on residual gas
  - Collisions of particles inside the beam (called intra-beam scattering or IBS)
  - Beam instabilities (will be discussed later in this course)
  - High frequency noise in RF and magnetic fields

Beam life-time

- Quantum lifetime
  - Although the equilibrium emittance is small, there is chance that, for one single electron, continuous random emission drive the electron out of aperture
  - Longitudinal or Transverse.
- Touschek lifetime
  - Coulomb scattering in the bunch may transfer transverse momentum to longitudinal plane and cause beam loss.