Electron dynamics with Synchrotron Radiation

Lenny Rivkin

Paul Scherrer Institute (PSI) and Swiss Federal Institute of Technology Lausanne (EPFL)



Electron Beam Dynamics, L. Rivkin, October 4, 2021, Chavannes de Bogis



Radiation is emitted into a narrow cone



Synchrotron radiation power

Power emitted is proportional to:

$$P_{\gamma} = \frac{cC_{\gamma}}{2\pi} \cdot \frac{E^4}{\rho^2}$$

$$C_{\gamma} = \frac{4\pi}{3} \frac{r_e}{(m_e c^2)^3} = 8.858 \cdot 10^{-5} \left[\frac{\mathrm{m}}{\mathrm{GeV}^3}\right]$$



$$P_{\gamma} = \frac{2}{3}\alpha\hbar c^2 \cdot \frac{\gamma^4}{\rho^2}$$



$$\hbar c = 197 \text{ Mev} \cdot \text{fm}$$



PAUL SCHERRER INSTITUT



$$U_0 = C_{\gamma} \cdot \frac{E^4}{\rho}$$



Electron Beam Dynamics, L. Rivkin, October 4, 2021, Chavannes de Bogis

Radiation effects in electron storage rings

Average radiated power restored by RF

- Electron loses energy each turn to synchrotron radiation
- RF cavities accelerate electrons back to the nominal energy

Radiation damping

 Average rate of energy loss produces DAMPING of electron oscillations in all three degrees of freedom (if properly arranged!)

Quantum fluctuations

 Statistical fluctuations in energy loss (from quantized emission of radiation) produce RANDOM EXCITATION of these oscillations

Equilibrium distributions

 The balance between the damping and the excitation of the electron oscillations determines the equilibrium distribution of particles in the beam

 $U_0 \cong 10^{-3} \text{ of } E_0$ gy $V_{RF} > U_0$

Radiation damping

Transverse oscillations



Electron Beam Dynamics, L. Rivkin, October 4, 2021, Chavannes de Bogis



Average energy loss and gain per turn

 Every turn electron radiates small amount of energy

$$E_1 = E_0 - \frac{U_0}{E_0} = E_0 \left(1 - \frac{U_0}{E_0} \right)$$

 only the amplitude of the momentum changes

- Only the longitudinal component of the momentum is increased in the RF cavity
- Energy of betatron oscillation



$$A_1^2 = A_0^2 \left(1 - \frac{U_0}{E_0} \right)$$
 or $A_1 \cong A_0 \left(1 - \frac{U_0}{2E_0} \right)$





Damping of vertical oscillations

But this is just the exponential decay law!

$$\frac{\Delta A}{A} = -\frac{U_0}{2E} \qquad \qquad A = A_0 \cdot e^{-t/\tau}$$

 The oscillations are exponentially damped with the damping time (milliseconds!)

$$\tau = \frac{2ET_0}{U_0}$$

the time it would take particle to 'lose all of its energy'

In terms of radiation power

$$\tau = \frac{2E}{P_{\gamma}}$$

nce
$$P_{\gamma} \propto E^4$$



Adiabatic damping in linear accelerators

In a linear accelerator:

$$x' = \frac{p_{\perp}}{p}$$
 decreases $\propto \frac{1}{E}$



In a **storage ring** beam passes many times through same RF cavity



Clean loss of energy every turn (no change in x')

- Every turn is re-accelerated by RF (x' is reduced)
- Particle energy on average remains constant

Emittance damping in linacs:



Radiation damping

Longitudinal oscillations



Electron Beam Dynamics, L. Rivkin, October 4, 2021, Chavannes de Bogis



Longitudinal motion: compensating radiation loss U_0



- RF cavity provides accelerating field $f_{RF} = h \cdot f_0$ with frequency
 - h harmonic number
- The energy gain:

$$U_{RF} = eV_{RF}(\tau)$$

- Synchronous particle:
 - has design energy
 - gains from the RF on the average as as it loses per turn $\rm U_{\rm 0}$



Longitudinal motion: phase stability



- Particle ahead of synchronous one
 - gets too much energy from the RF
 - goes on a longer orbit (not enough B)
 >> takes longer to go around
 - comes back to the RF cavity closer to synchronous part.
- Particle behind the synchronous one
 - gets too little energy from the RF
 - goes on a shorter orbit (too much B)
 - catches-up with the synchronous particle

Longitudinal motion: energy-time oscillations

energy deviation from the design energy, or the energy of the synchronous particle



longitudinal coordinate measured from the position of the synchronous electron

Orbit Length

Length element depends on x

$$dl = \left(1 + \frac{x}{\rho}\right) ds$$



Horizontal displacement has two parts:

$x = x_{\beta} + x_{\varepsilon}$

- To first order x_{β} does not change L
- x_{ϵ} has the same sign around the ring

Length of the off-energy orb
$$L_{\varepsilon} = \oint dl = \oint \left(1 + \frac{x_{\varepsilon}}{\rho}\right) ds = L_0 + \Delta L$$

$$\Delta L = \delta \cdot \oint \frac{D(s)}{\rho(s)} ds \quad \text{where} \quad \delta = \frac{\Delta p}{p} = \frac{\Delta E}{E} \qquad \qquad \frac{\Delta L}{L} = \alpha \cdot \delta$$

PAUL SCHERRER INSTITUT

Electron Beam Dynamics, L. Rivkin, October 4, 2021, Chavannes de Bogis

Something funny happens on the way around the ring...

Revolution time changes with energy



Particle goes faster (not much!)

while the orbit length increases (more!)

$$T_0 = \frac{L_0}{c\beta}$$

$$\frac{d\beta}{\beta} = \frac{1}{\gamma^2} \cdot \frac{dp}{p} \quad \text{(relativity)}$$

$$\frac{\Delta L}{L} = \mathbf{\alpha} \cdot \frac{dp}{p}$$

• The "slip factor" $\eta \cong \alpha$ since $\alpha >> \frac{1}{\gamma^2}$

$$\frac{\Delta T}{T} = \left(\boldsymbol{\alpha} - \frac{1}{\gamma^2} \right) \cdot \frac{dp}{p} = \boldsymbol{\eta} \cdot \frac{dp}{p}$$

isochronous ring:

$$\eta = 0 \text{ or } \gamma = \gamma_{tr}$$

Not only accelerators work above transition



Dante Aligieri Divine Comedy



here the synchronous phase

$$\psi_s = \arcsin\left(\frac{U_0}{e\hat{V}}\right)$$

Momentum compaction factor



Like the tunes Q_x , Q_y - α depends on the whole optics

• A quick estimate for separated function guide field:

$$\alpha = \frac{1}{L_0 \rho_0} \oint_{\text{mag}} D(s) ds = \frac{1}{L_0 \rho_0} \langle D \rangle \cdot L_{mag} \begin{bmatrix} \rho = \rho_0 & \text{in dipoles} \\ \rho = \infty & \text{elsewhere} \end{bmatrix}$$

• But
$$L_{mag} = 2\pi\rho_0$$

$$\boldsymbol{\alpha} = \frac{\langle D \rangle}{R}$$

Since dispersion is approximately

$$D \approx \frac{R}{Q^2} \Rightarrow \alpha \approx \frac{1}{Q^2}$$
 typically < 1% and the orbit change for ~ 1% energy deviation

$$\frac{\Delta L}{L} = \frac{1}{Q^2} \cdot \delta \approx 10^{-4}$$

Energy balance

Energy gain from the RF system: $U_{RF} = eV_{RF}(\tau) = U_0 + eV_{RF} \cdot \tau$

- synchronous particle ($\tau = 0$) will get exactly the energy loss per turn
- we consider only linear oscillations

$$\dot{V}_{RF} = \frac{dV_{RF}}{d\tau}\Big|_{\tau=0}$$

Each turn electron gets energy from RF and loses energy to radiation within one revolution time T₀

$$\Delta \varepsilon = (U_0 + eV_{RF} \cdot \tau) - (U_0 + U' \cdot \varepsilon)$$

$$\frac{d\varepsilon}{dt} = \frac{1}{T_0} (e V_{RF} \cdot \tau - U' \cdot \varepsilon)$$

An electron with an energy deviation will arrive after one turn at a different time with respect to the synchronous particle

$$\frac{d\tau}{dt} = -\alpha \; \frac{\varepsilon}{E_0}$$

Synchrotron oscillations: damped harmonic oscillator



the solution is then:

 $\varepsilon(t) = \hat{\varepsilon}_0 e^{-\alpha_{\varepsilon} t} \cos\left(\Omega t + \theta_{\varepsilon}\right)$

similarly, we can get for the time delay:

 $\tau(t) = \hat{\tau}_0 e^{-\alpha_{\varepsilon} t} \cos\left(\Omega t + \theta_{\tau}\right)$

Synchrotron (time - energy) oscillations

The ratio of amplitudes at any instant

$$\hat{\tau} = \frac{\alpha}{\Omega E_0} \hat{\varepsilon}$$

Oscillations are 90 degrees out of phase



The motion can be viewed in the phase space of conjugate variables





Longitudinal Phase Space Longitudinal motion: $P_{\gamma} \propto E^2 B^2$ damping of synchrotron oscillationsDuring one period of synchrotron oscillation:• when the particle is in the upper half-plane, it loses more
energy per turn, its energy gradually reduces



 when the particle is in the lower half-plane, it loses less energy per turn, but receives U₀ on the average, so its energy deviation gradually reduces

The synchrotron motion is damped

the phase space trajectory is spiraling towards the origin

Robinson theorem: Damping partition numbers

- Transverse betatron oscillations are damped with
- Synchrotron oscillations are damped twice as fast

$$\tau_x = \tau_z = \frac{2ET_0}{U_0}$$

$$\tau_{\varepsilon} = \frac{ET_0}{U_0}$$

 The total amount of damping (Robinson theorem) depends only on energy and loss per turn

$$\frac{1}{\tau_{x}} + \frac{1}{\tau_{y}} + \frac{1}{\tau_{\varepsilon}} = \frac{2U_{0}}{ET_{0}} = \frac{U_{0}}{2ET_{0}} (J_{x} + J_{y} + J_{\varepsilon})$$

the sum of the partition numbers

$$J_x + J_z + J_\varepsilon = 4$$

Radiation loss



Displaced off the design orbit particle sees fields that are different from design values

energy deviation &

> different energy:

$$P_\gamma \propto E^2$$

different magnetic field B particle moves on a different orbit, defined by the off-energy or dispersion function D_x

both contribute to linear term in $P_{\gamma}(\mathcal{E})$

betatron oscillations: zero on average

Radiation loss



To first order in ε

$$\mathbf{U}_{\mathrm{rad}} = \mathbf{U}_{0} + \mathbf{U}' \cdot \boldsymbol{\varepsilon}$$

electron energy changes slowly, at any instant it is moving on an orbit defined by $\mathbf{D}_{\mathbf{x}}$

after some algebra one can write



$$U' = \frac{U_0}{E_0} \left(2 + \mathbf{\mathcal{D}}\right)$$

$$\mathcal{D} \neq 0$$
 only when $\frac{k}{\rho} \neq 0$

Damping partition numbers



Typically we build rings with no vertical dispersion

$$J_z = 1 \qquad \qquad J_x + J_\varepsilon = 3$$

 Horizontal and energy partition numbers can be modified via ①:

$$J_x = 1 - \mathcal{D}$$

$$J_\varepsilon = 2 + \mathcal{D}$$

- Use of combined function magnets
- Shift the equilibrium orbit in quads with RF frequency

Equilibrium beam sizes



Electron Beam Dynamics, L. Rivkin, October 4, 2021, Chavannes de Bogis



Radiation effects in electron storage rings

Average radiated power restored by RF

- Electron loses energy each turn to synchrotron radiation
- RF cavities accelerate electrons back to the nominal energy

Radiation damping

 Average rate of energy loss produces **DAMPING** of electron oscillations in all three degrees of freedom (if properly arranged!)

Quantum fluctuations

 Statistical fluctuations in energy loss (from quantized emission of radiation) produce RANDOM EXCITATION of these oscillations

Equilibrium distributions

 The balance between the damping and the excitation of the electron oscillations determines the equilibrium distribution of particles in the beam

$$U_0 \cong 10^{-3} \text{ of } E_0$$

 $|V_{RF} > U_0$

Quantum nature of synchrotron radiation

Damping only

- If damping was the whole story, the beam emittance (size) would shrink to microscopic dimensions!*
- Lots of problems! (e.g. coherent radiation)

* How small? On the order of electron wavelength

$$E = \gamma mc^2 = h\nu = \frac{hc}{\lambda_e} \implies \lambda_e = \frac{1}{\gamma} \frac{h}{mc} = \frac{\lambda_C}{\gamma}$$

 $\varepsilon \ge \frac{\lambda_C}{4\pi \gamma} (\times N^{\frac{1}{3}} - \text{fermions})$

 $\lambda_{C} = 2.4 \cdot 10^{-12} m$ – Compton wavelength Diffraction limited electron emittance

Quantum nature of synchrotron radiation

Quantum fluctuations

 Because the radiation is emitted in quanta, radiation itself takes care of the problem!

 It is sufficient to use quasi-classical picture:
 » Emission time is very short
 » Emission times are statistically independent (each emission - only a small change in electron energy)

Purely stochastic (Poisson) process

Visible quantum effects

I have always been somewhat amazed that a purely quantum effect can have gross macroscopic effects in large machines;

and, even more,

that Planck's constant has just the right magnitude needed to <u>make practical</u> the construction of large electron storage rings. A significantly larger or smaller value of

would have posed serious -- perhaps insurmountable -problems for the realization of large rings.

Mathew Sands

Quantum excitation of energy oscillations

Photons are emitted with typical energy at the rate (photons/second) $u_{ph} \approx \hbar \omega_{typ} = \hbar c \, \frac{\gamma^3}{\rho}$ $\mathcal{N} = \frac{P_{\gamma}}{u_{ph}}$

Fluctuations in this rate excite oscillations

During a small interval Δt electron emits photons $N = \mathcal{N} \cdot \Delta t$

 $\frac{\text{losing energy of}}{N \cdot u_{ph}}$

Actually, because of fluctuations, the number is $N \pm \sqrt{N}$

resulting in spread in energy loss

 $\pm \sqrt{N} \cdot u_{ph}$

For large time intervals RF compensates the energy loss, providing damping towards the design energy E_{θ}

Steady state: typical deviations from E_{θ} \approx typical fluctuations in energy during a damping time τ_{ε} Equilibrium energy spread: rough estimate

We then expect the rms energy spread to be

$$\sigma_{\varepsilon} \approx \sqrt{N \cdot \tau_{\varepsilon}} \cdot u_{ph}$$

and since $\tau_{\varepsilon} \approx \frac{E_0}{P_{\gamma}}$ and $P_{\gamma} = N \cdot u_{ph}$

 $\sigma_{\epsilon} \approx \sqrt{E_0 \cdot u_{ph}}$ geometric mean of the electron and photon energies!

Relative energy spread can be written then as:

$$\frac{\sigma_{\varepsilon}}{E_0} \approx \gamma \sqrt{\frac{\lambda e}{\rho}}$$

$$\hat{\lambda}_e = \frac{\hbar}{m_e c} \simeq 4 \cdot 10^{-13} m$$

it is roughly constant for all rings



 $\frac{\sigma_{\varepsilon}}{E_0} \sim const \sim 10^{-3}$

Equilibrium energy spread More detailed calculations give

for the case of an 'isomagnetic' lattice

 $\rho(s) = \frac{\rho_0}{\infty}$ in dipoles elsewhere

$$\left(\frac{\sigma_{\varepsilon}}{E}\right)^2 = \frac{C_q E^2}{J_{\varepsilon} \rho_0}$$

with
$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar c}{(m_e c^2)^3} = 1.468 \cdot 10^{-6} \left[\frac{\mathrm{m}}{\mathrm{GeV}^2}\right]$$

It is difficult to obtain energy spread < 0.1%

• limit on undulator brightness!

Equilibrium bunch length

Bunch length is related to the energy spread

 Energy deviation and time of arrival (or position along the bunch) are conjugate variables (synchrotron oscillations)



 $\hat{\tau} = \frac{\alpha}{\Omega} \left(\frac{\varepsilon}{E} \right)$

recall that



Two ways to obtain short bunches:

RF voltage (power!)

$$\sigma_{\tau} \propto V_{\sqrt{V_{RF}}}$$

• Momentum compaction factor in the limit of $\alpha = 0$ isochronous ring: particle position along the bunch is frozen

$$\sigma_{ au} \propto lpha$$

0 3

Excitation of betatron oscillations





$$\Delta \varepsilon = \gamma \Delta x_{\beta}^{2} + 2\alpha \Delta x_{\beta} \Delta x_{\beta}' + \beta \Delta x_{\beta}'^{2} = \left[\gamma D^{2} + 2\alpha D D' + \beta D'^{2} \right] \cdot \left(\frac{\varepsilon_{\gamma}}{E} \right)^{2}$$

Excitation of betatron oscillations

Electron emitting a photon

- at a place with non-zero dispersion
- starts a betatron oscillation around a new reference orbit

$$x_{\beta} \approx D \cdot \frac{\varepsilon_{\gamma}}{E}$$



Horizontal oscillations: equilibrium

Emission of photons is a random process

Again we have random walk, now in **x**. How far particle will wander away is limited by the radiation damping The balance is achieved on the time scale of the damping time $\tau_x = 2 \tau_e$

$$\sigma_{x\beta} \approx \sqrt{\mathcal{N} \cdot \tau_x} \cdot D \cdot \frac{\varepsilon_{\gamma}}{E} = \sqrt{2} \cdot D \cdot \frac{\sigma_{\varepsilon}}{E}$$

Typical horizontal beam size ~ 1 mm

Quantum effect visible to the naked eye!

Vertical size - determined by coupling

Beam emittance

Betatron oscillations

 Particles in the beam execute betatron oscillations with different amplitudes. $\sigma_{x'}$

Transverse beam distribution

- Gaussian (electrons)
- "Typical" particle: 1σ ellipse (in a place where $\alpha = \beta' = 0$)

Emittance
$$\equiv \frac{\sigma_x^2}{\beta}$$

Units of
$$\varepsilon \quad [m \cdot rad]$$

 $\varepsilon = \sigma_x \cdot \sigma_{x'}$
 $\sigma_x = \sqrt{\varepsilon \beta}$
 $\sigma_{x'} = \sqrt{\varepsilon \beta}$
 $\beta = \frac{\sigma_x}{\sigma_{x'}}$

m. rad

Area = $\pi \cdot \varepsilon$

► X

 σ_{x}

Equilibrium horizontal emittance Detailed calculations for isomagnetic lattice

$$\varepsilon_{x0} \equiv \frac{\sigma_{x\beta}^2}{\beta} = \frac{C_q E^2}{J_x} \cdot \frac{\langle \mathcal{H} \rangle_{mag}}{\rho}$$

where

$$\mathcal{H} = \gamma D^2 + 2\alpha D D' + \beta D'^2$$
$$= \frac{1}{\beta} [D^2 + (\beta D' + \alpha D)^2]$$



2-D Gaussian distribution



• Probability to be inside $n-\sigma$ ellipse

$$P_n = 1 - e^{-n^2/2}$$

FODO cell lattice





Ionization cooling



similar to radiation damping, but there is multiple scattering in the absorber that blows up the emittance

to minimize the blow up due to multiple scattering in the absorber we can **focus** the beam

Minimum emittance lattices



Quantum limit on emittance

- Electron in a storage ring's dipole fields is accelerated, interacts with vacuum fluctuations: «accelerated thermometers show increased temperature»
- synchrotron radiation opening angle is ~ $1/\gamma$ -> a lower limit on equilibrium vertical emittance
- independent of energy

$$\epsilon_y = \frac{13}{55} C_q \frac{\oint \beta_y(s) |G^3(s)| ds}{\oint G^2(s) ds}$$

G(s) = curvature, C_q = 0.384 pm

in case of SLS: 0.2 pm

isomagnetic lattice

$$\mathcal{E}_{y} = 0.09 \, \text{pm} \cdot \frac{\left\langle \beta_{y} \right\rangle_{\text{Mag}}}{\rho}$$



SLS beam cross section compared to a human hair:



Summary of radiation integrals

Momentum compaction factor



Energy loss per turn

$$U_0 = \frac{1}{2\pi} C_{\gamma} E^4 \cdot I_2$$



$$C_{\gamma} = \frac{4\pi}{3} \frac{r_e}{(m_e c^2)^3} = 8.858 \cdot 10^{-5} \left[\frac{\text{m}}{\text{GeV}^3}\right]$$

Summary of radiation integrals (2)

Damping parameter

$$\mathcal{D} = \frac{I_4}{I_2}$$

Damping times, partition numbers

$$J_{\varepsilon} = 2 + \mathcal{D}, \quad J_{x} = 1 - \mathcal{D}, \quad J_{y} = 1$$



Equilibrium energy spread



Equilibrium emittance

$$\varepsilon_{x0} = \frac{\sigma_{x\beta}^2}{\beta} = \frac{C_q E^2}{J_x} \cdot \frac{I_5}{I_2}$$

$$I_{1} = \oint \frac{D}{\rho} ds$$

$$I_{2} = \oint \frac{ds}{\rho^{2}}$$

$$I_{3} = \oint \frac{ds}{|\rho^{3}|}$$

$$I_{4} = \oint \frac{D}{\rho} \left(2k + \frac{1}{\rho^{2}}\right) ds$$

$$I_{5} = \oint \frac{\mathcal{H}}{|\rho^{3}|} ds$$

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar c}{(m_e c^2)^3} = 1.468 \cdot 10^{-6} \left[\frac{\mathrm{m}}{\mathrm{GeV}^2}\right]$$

$$\mathcal{H} = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Damping wigglers

Increase the radiation loss per turn U₀ with WIGGLERS

reduce damping time

$$\tau = \frac{E}{P_{\gamma} + P_{wig}}$$

emittance control

wigglers at high dispersion: blow-up emittance e.g. storage ring colliders for high energy physics

wigglers at zero dispersion: decrease emittance

e.g. damping rings for linear colliders e.g. synchrotron light sources (PETRAIII, 1 nm.rad)

