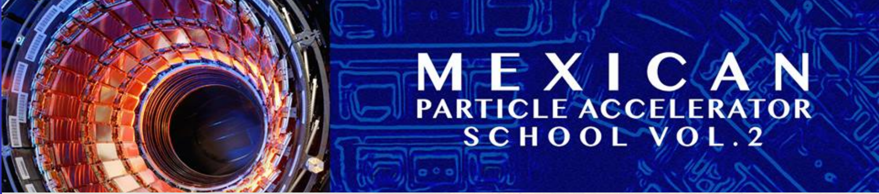

Beam Dynamics: Lectures I - V

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División de Ciencias e Ingenierías

Guanajuato, GTO, Mexico | *November, 2015*

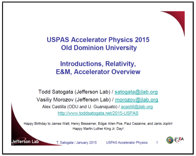
Syllabus

- Six lectures:
  - Two on Friday 13th.
  - Two on Saturday 14th.
  - Two on Tuesday 17th.
- We will focus on circular machines.
- Homework:
  - Assigned each lecture.
  - Collected at the start of the following day.
  - Work in groups.
  - Assigned time at the end of the day for doing homework.
- Final exam: similar to homework. Notes allowed?
- MePAS grade: 60% homework, 40% final exam.
- Our emails:
  a.castilla@cern.ch
  lmedinam@cern.ch

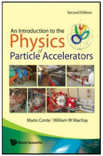
Begging for caffeine and eating churros at the Ferney market...

Bibliography

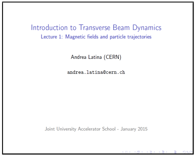
This course is mostly based on the USPAS courses by **Todd Satogata** (JLAB), available at `http://toddsatogata.net/`, which in turn follows

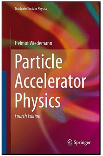


M. Conte, W. W. MacKay, *An Introduction to the Physics of Particle Accelerators*. Second Edition. World Scientific. Singapore, 2008.

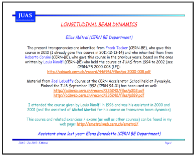


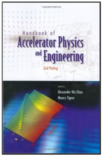
Some extracts has been taken from the JUAS 2015 courses on Transverse Dynamics **Andrea Latina** (CERN) and on Longitudinal Dynamics by **Elias Metral** (CERN). Both of them are available at `https://indico.cern.ch/event/356897/`





Of course, **Wiedemann**'s book and the **Chao and Tigner**'s Handbook are the canonical bibliography on Beam Dynamics...





Also... **Free lectures**[1] on accelerators and more (on demand)! Visit `https://www.cockcroft.ac.uk/lectures`

[1] Please send an email to `graeme.burt@cockroft.ac.uk` and tell Graeme you are using them (this is only for internal statistics).

Contents

Contents

Relativity review

Particle accelerators: applied electromagnetism and **special relativity**.

It will come in handy writing down some of the useful formulas,

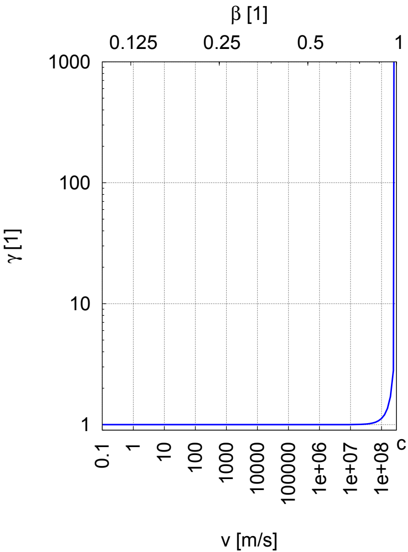
Lorentz factors

$$\beta_r \equiv \frac{v}{c}, \qquad \gamma_r \equiv \frac{1}{\sqrt{1-\beta_r^2}} \tag{1.1}$$

where v is the speed of the object and c is the speed of light,

$$\begin{aligned} c &= 299,792,458\ \frac{\mathrm{m}}{\mathrm{s}} \\ &\approx 3 \times 10^8\ \frac{\mathrm{m}}{\mathrm{s}} \end{aligned} \tag{1.2}$$

Note that β_r and γ_r are dimensionless.



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Example: *Lorentz factors*

For a car traveling at 150 km/h,

$$v = 150 \ \frac{\text{km}}{\text{h}} \cdot \frac{1000 \text{ m}}{\text{km}} \cdot \frac{3600 \text{ s}}{\text{h}} = 41.7 \ \frac{\text{m}}{\text{s}}$$

$$\beta_r = \frac{41.7 \text{ m/s}}{3 \times 10^8 \text{ m/s}} = 0.00000014$$

$$\gamma = \frac{1}{\sqrt{1-(1.4 \times 10^{-7})^2}} \approx 1$$

The Helios-2 probe (the fastest man- made object), travels at 70.2 km/s, This corresponds to the Lorentz factors

$$\beta_r = 0.00023, \quad \gamma_r = 1.00000003$$

Compare both results to

$$\beta_r = 0.99999999, \quad \gamma_r = 7453.56$$

corresponding to a proton in the LHC.

Relativity review (cont.)

Rest energy

$$E_0 = mc^2 \tag{1.3}$$

Total energy

$$E = \gamma_r mc^2 \tag{1.4}$$

Kinetic energy

$$E_K = T = E - E_0 = (\gamma_r - 1)mc^2 \tag{1.5}$$

Momentum

$$p = \gamma_r m(\beta_r c) = \beta_r \frac{E}{c} \tag{1.6}$$

for an object with mass m.

The unit of energy in the International System is the joule (J). A more suitable unit in particle Physics is the

Electron-volt (eV)

$$\begin{aligned} 1 \text{ eV} &= (1.602 \times 10^{-19}\ \text{C})(1\ \text{V}) \\ &= 1.602 \times 10^{-19}\ \text{J} \end{aligned} \tag{1.7}$$

It corresponds to the amount of **energy gained/lost** by a particle with a charge e (the **elementary charge**), when it is moved across an electric potential difference of **one volt**.

Relativity review (cont.)

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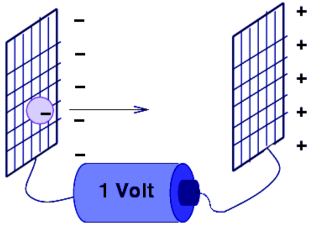


Energy units

Prefix	Sym.	Value
tera-	T	10^{12}
giga-	G	10^{9}
mega-	M	10^{6}
kilo-	k	10^{3}
mili-	m	10^{-3}
micro-	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

Table 1: SI prefixes.

	Unit
Energy	eV
Mass	eV/c^2
Momentum	eV/c

Table 2: Units of energy, mass and momentum in terms of eV. **Note: it is often set $c = 1$.**

Example: *Energies in eV*

The mass of an electron is 1.673×10^{-27} kg. According to (7), its rest energy is

$$\begin{aligned} E_0 &= (1.673 \times 10^{-27}\ \mathrm{kg})(3 \times 10^8\ \mathrm{m/s})^2 \\ &= 8.19 \times 10^{-14}\ \mathrm{J} \cdot \frac{1\ \mathrm{eV}}{1.602 \times 10^{-19}\ \mathrm{J}} \\ &\approx 511,000\ \mathrm{eV} \end{aligned}$$

Since $E_0 = mc^2$, the mass can also be written in terms of eV (instead of kg). So, for an electron,

$$m = \frac{E_0}{c^2} = \mathbf{0.511\ MeV/c^2}$$

If it is traveling at 10% of the speed of light, then

$$v = 0.1c, \qquad \beta_r = 0.1, \qquad \gamma_r = 1.005$$

Thus, the total energy of the electron is

$$E = 1.005 \cdot 0.511\ \frac{\mathrm{MeV}}{\mathrm{c}^2} \cdot c^2 = 0.513\ \mathrm{MeV}$$

Electromagnetism review

The

Newton's second law

$$\vec{F} = m\vec{a} = \frac{d\vec{p}}{dt} \qquad (1.8)$$

describes the **motion** of a particle of mass m due to an **external force** $\vec{F}$.

The

Lorentz force

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \qquad (1.9)$$

defines the **force** experienced by a charge q under and **electric and magnetic fields**.

Example: *Electric vs. magnetic forces*

Typical values for the strength of electric and magnetic fields are

$$|\vec{E}| \approx 1\ \frac{\mathrm{MV}}{\mathrm{m}}, \qquad |\vec{B}| \approx 1\ T = 1\ \frac{\mathrm{Vs}}{\mathrm{m}^2}$$

Suppose we have a particle with the elementary charge and velocity equal to $v = \beta_r c$. Then, the ratio between the magnetic and electric forces is

$$\begin{aligned}\frac{F_m}{F_e} &= \frac{q|\vec{v}||\vec{B}|}{q|\vec{E}|} = \frac{e(\beta_r c)(1\ \frac{\mathrm{Vs}}{\mathrm{m}^2})}{e(1\ \frac{\mathrm{MV}}{\mathrm{m}})} \\ &= \frac{\beta_r\left(3 \times 10^8\ \frac{\mathrm{m}}{\mathrm{s}}\right)\frac{\mathrm{Vs}}{\mathrm{m}^2}}{1 \times 10^6\ \frac{\mathrm{V}}{\mathrm{m}}} = 300\beta_r\end{aligned}$$

What can we conclude from this?

For charged particles with speeds close to c, $\beta_r \approx 1$. Then, if we want to exert a force to change its motion, we better use magnetic forces (they're 300× stronger!).

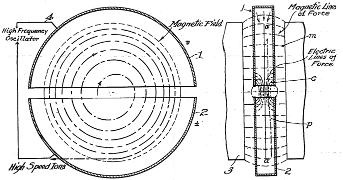
The cyclotron I

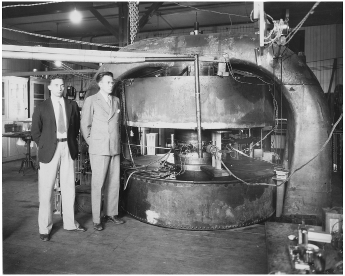
Equating (1.8) and (1.9) in the absence of electric field ($\vec{E} = 0$),

$$
\begin{aligned}
q\vec{v} \times \vec{B} &= \frac{d\vec{p}}{dt} = \frac{d(\gamma_r m \vec{v})}{dt} \\
&= m\left(\gamma_r \frac{d\vec{v}}{dt} + \frac{d\gamma_r}{dt}\vec{v}\right) \\
&= \gamma_r m \frac{d\vec{v}}{dt}
\end{aligned}
$$

since $\beta_r = |\vec{\beta}_r|$ is constant, which implies $d\gamma_r/dt = 0$. Now, with the aid of the **angular velocity** $\vec{\omega}$, defined by $\vec{v} \equiv \vec{\omega} \times \vec{\rho}$,

$$
\begin{aligned}
q\vec{v} \times \vec{B} &= \gamma_r m \frac{d(\vec{\omega} \times \vec{\rho})}{dt} \\
&= \gamma_r m \left(\vec{\omega} \times \frac{d\vec{\rho}}{dt} + \frac{d\vec{\omega}}{dt} \times \vec{\rho}\right)
\end{aligned}
$$





The cyclotron II

or

$$q\vec{v} \times \vec{B} = \gamma_r m\vec{\omega} \times \frac{d\vec{\rho}}{dt}$$

since ω is constant for a central force of constant magnitude. Now, the **cyclotron (or bending) radius** ρ is just the radius of the particle's orbit, then,

$$q\vec{v} \times \vec{B} = \gamma_r m\vec{\omega} \times \vec{v}$$

In the particular case when $\vec{B}$ and $\vec{v}$ are perpendicular,

$$qvB = \gamma_r m\omega v = \frac{\gamma_r m v^2}{\rho} \qquad (1.10)$$

with $\omega = v/\rho$. Arranging this equation,

$$qB = \frac{\gamma_r m v}{\rho} = \frac{p}{\rho} \qquad (1.11)$$

we get the

Rigidity

$$(B\rho) = \frac{p}{q} \qquad (1.12)$$

and its units are Tm.

The **rigidity** give us an idea on *how hard/easy* is a particle to deflect, Note how relates machines properties *(left)* with beam properties *(right)*.

When working with particles with the **elementary charge**, we can rewrite the

Rigidity (in practical units)

$$p\ [\mathrm{GeV/c}] \approx 0.3\ B\ [\mathrm{T}]\ \rho\ [\mathrm{m}] \qquad (1.13)$$

The cyclotron III

Example: *Rigidity*

Let us consider an electron ring with radius $R = 200$ m. If only 50% of the circumference $C = 2\pi R$ is occupied by bending magnets, this length has to correspond to a circumference given by $2\pi\rho$. In other words,

$$0.5C = 0.5 \cdot 2\pi R = 2\pi\rho$$

or

$$\rho = 0.5R = 100 \text{ m}$$

If the momentum of the electrons is 12 GeV/c, the rigidity is

$$B\rho \approx \frac{p[\text{GeV/c}]}{0.3} = 40 \text{ Tm}$$

and therefore $B = 0.4$ T.

Rearranging (1.10) in a different way, we obtain the

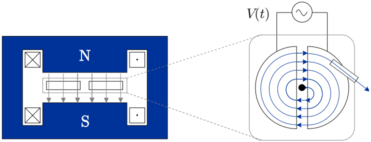
Cyclotron (angular) frequency

$$\omega = \frac{qB}{\gamma_r m}, \qquad f = \frac{\omega}{2\pi} \tag{1.14}$$

which gives us the **number of turns** a particle can perform in the cyclotron, **per unit of time**.

In order to accelerate the particles, an RF voltage has to be provided, and its frequency has to match the revolution frequency,

$$f_{rf} = f = \frac{\omega}{2\pi} \tag{1.15}$$



Contents

Parametrization and approximations

The **ideal particle** defines a trajectory, the **design orbit**.

To describe the motion of a given particle, we use a **local coordinate system** $(\hat{x}, \hat{y}, \hat{s})$ that moves (rotates) with the ideal particle, the so-called Frenet-Serret frame.

From the figure,

$$R = \rho + x \tag{2.1}$$

where

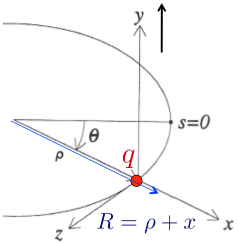
$$\theta = \frac{s}{R} = \frac{(\beta_r c)t}{R} \tag{2.2}$$

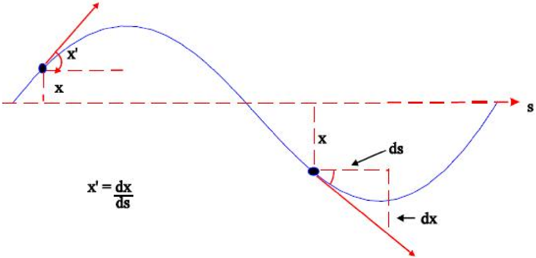
The slope

$$x' \equiv \frac{dx}{ds} = \frac{1}{R}\frac{dx}{d\theta} \tag{2.3}$$

is the local trajectory angle. Also note

$$x' = \frac{v_x}{v_z} = \frac{p_x}{p_s} \approx \frac{p_y}{p} \tag{2.4}$$





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Approximations

1. No local currents (near-vacuum).
2. Paraxial approximation:
$$x', y' \ll 1, \text{ or } p_x, p_y \ll p_s \qquad (2.5)$$
3. Perturbative coordinates:
$$x, y \ll \rho \qquad (2.6)$$
4. Transverse linear $\vec{B}$ field:
$$\begin{aligned}\vec{B} &= B_x\hat{x} + B_y\hat{y} \\ &= B_0\hat{y} + (x\hat{y} + y\hat{x})\frac{\partial B_y}{\partial x} \qquad (2.7)\end{aligned}$$
where $B_0 \neq 0$.
5. Negligible $\vec{E}$ field: $\gamma_r \approx$ constant.

Equations of motion I

We begin with the Lorentz force equation of motion,

$$\vec{F} = q\vec{v} \times \vec{B} = \frac{d(\gamma_r m\vec{v})}{dt} \qquad (2.8)$$

Given the **position** vector,

$$\vec{r} = R\hat{x} + y\hat{y} \qquad (2.9)$$

we need to calculate the corresponding **velocity** and **acceleration** as follows,

$$\vec{v} = \dot{\vec{r}} = \dot{R}\hat{x} + R\dot{\hat{x}} + \dot{y}\hat{y} = \dot{R}\hat{x} + R\dot{\theta}\hat{s} + \dot{y}\hat{y} \qquad (2.10)$$

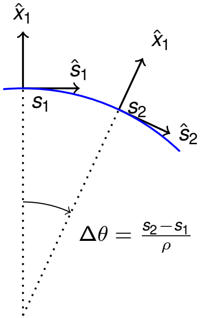
$$\vec{a} = \dot{\vec{v}} = \ddot{R}\hat{x} + (2\dot{R}\dot{\theta} + R\ddot{\theta})\hat{s} + R\dot{\theta}\dot{\hat{s}} + \ddot{y}\hat{y} \qquad (2.11)$$

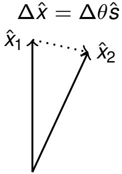
If we calculate $\dot{\hat{s}}$,

$$\dot{\hat{s}} = -\dot{\theta}\hat{x} = -\frac{v}{R}\hat{x} \qquad (2.12)$$

and insert it in (2.11), we obtain

$$\begin{aligned}\vec{a} &= (\ddot{R} - R\dot{\theta}^2)\hat{x} + (2\dot{R}\dot{\theta} + R\ddot{\theta})\hat{s} + \ddot{y}\hat{y} \\ &= \left(\ddot{x} - \frac{v^2}{R}\right)\hat{x} + \frac{2\dot{x}v}{R}\hat{s} + \ddot{y}\hat{y} \qquad (2.13)\end{aligned}$$





Equations of motion II

We study **each component** separately. For the vertical motion,

$$F_y = q\beta_r c B_x = \gamma_r m \ddot{y} \qquad (2.14)$$

Solving for $\ddot{y}$,

$$\ddot{y} - \frac{q\beta_r c B_x}{\gamma_r m} = 0 \qquad (2.15)$$

We can change the derivative w.r.t. (*with respect to*) **time**, to a derivative w.r.t. the **angle** θ:

$$t = \frac{R}{\beta_r c}\theta \quad \Rightarrow \quad \frac{d}{dt} = \frac{\beta_r c}{R}\frac{d}{d\theta} \qquad (2.16)$$

By doing so,

$$\left(\frac{\beta_r c}{R}\right)^2 \frac{d^2 y}{d\theta^2} - \frac{q\beta_r c B_x}{\gamma_r m} = 0 \qquad (2.17)$$

After dropping the common term $\beta_r c$, and multiplying the equation by R^2,

$$\frac{d^2 y}{d\theta^2} - \frac{qB_x}{\gamma_r m \beta_r c} R^2 = 0 \qquad (2.18)$$

Following a similar procedure in the horizontal plane, we get

$$\begin{aligned} F_x &= -q\beta_r c B_y \\ &= \gamma_r m \left(\ddot{x} - \frac{v^2}{R}\right) \end{aligned} \qquad (2.19)$$

or

$$\frac{d^2 x}{d\theta^2} + \left(\frac{qB_y}{p} R - 1\right) R = 0 \qquad (2.20)$$

We know from the **rigidity** that

$$p = qB_0\rho \qquad (2.21)$$

and we can also replace R by (2.1) with the **paraxial aproximation**,

$$R = \rho\left(1 + \frac{x}{\rho}\right) \qquad (2.22)$$

Equations of motion III

to get

$$\frac{d^2x}{d\theta^2} + \left[\frac{B_y}{B_0}\left(1 + \frac{x}{\rho}\right) - 1\right] R = 0 \tag{2.23}$$

Since the approximation on the **linearization** of the magnetic field is $\vec{B} = B_x\hat{x} + B_y\hat{y}$, where

$$B_x = \left(\frac{\partial B_y}{\partial x}\right) y, \qquad B_y = B_0 + \left(\frac{\partial B_y}{\partial x}\right) x \tag{2.24}$$

then, in the case of the horizontal equation of motion, we obtain

$$\frac{d^2x}{d\theta^2} + \left[\left(1 + \frac{1}{B_0}\frac{\partial B_y}{\partial x}x\right)\left(1 + \frac{x}{\rho}\right) - 1\right] \rho \left(1 + \frac{x}{\rho}\right) = 0$$

After performing the multiplications, we will ignore terms of second order on x and higher. On the vertical equation, we apply of course the same series of approximations. The resulting equations gives us what is known as the

Betatron motion

$$\frac{d^2x}{d\theta^2} + (1-n)x = 0 \tag{2.25}$$

$$\frac{d^2y}{d\theta^2} + ny = 0 \tag{2.26}$$

Stability condition

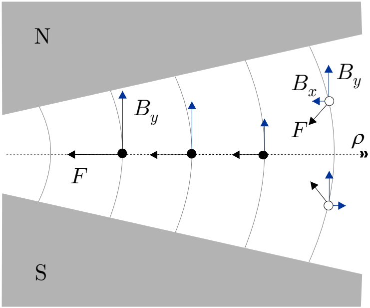
where n is the

Field index

$$n \equiv -\frac{\rho}{B_0}\left(\frac{\partial B_y}{\partial x}\right) \tag{2.27}$$

Note that in order to have a **stable motion** in both planes, the following conditions must be satisfied:

$$0 < n < 1 \tag{2.28}$$



Equations (2.25) and (2.26) describe the **weak focusing**. Note that they are **simple harmonic oscillators**, therefore their solutions are well known. In particular, for the horizontal plane,

$$x(\theta) = A\cos(\theta\sqrt{1-n}) \quad + B\sin(\theta\sqrt{1-n}) \tag{2.29}$$

with derivative

$$\frac{dx}{d\theta} = \sqrt{1-n}[-A\sin(\theta\sqrt{1-n}) + B\cos(\theta\sqrt{1-n})] \tag{2.30}$$

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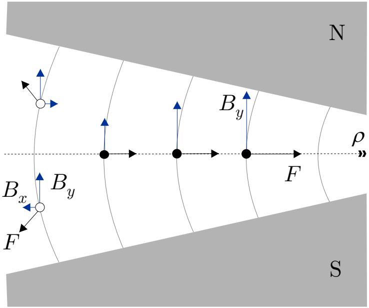

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Betatron motion

Applying the **initial conditions**

$$x_0 = x(\theta = 0) = A, \qquad x_0' = \frac{1}{\rho}\left(\frac{dx}{d\theta}\right)_{\theta=0} = \frac{\sqrt{1-n}}{\rho}B \tag{2.31}$$

the constants are given in terms of them,

$$A = x_0, \qquad B = \frac{\rho}{\sqrt{1-n}}x_0' \tag{2.32}$$

Substituting the last equations in the equation of motion,

$$x(\theta) = \cos(\theta\sqrt{1-n})x_0 + \frac{\rho}{\sqrt{1-n}}\sin(\theta\sqrt{1-n})x_0' \tag{2.33}$$

$$x'(\theta) = \frac{1}{\rho}\frac{dx}{d\theta}\frac{1}{\rho} = -\frac{\sqrt{1-n}}{\rho}\sin(\theta\sqrt{1-n})x_0 + \cos(\theta\sqrt{1-n})x_0' \tag{2.34}$$

we can write the solution in **matrix form** (for the vertical plane follow the same steps),

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos\phi_x & \frac{\rho}{\sqrt{1-n}}\sin\phi_x \\ -\frac{\sqrt{1-n}}{\rho}\sin\phi_x & \cos\phi_x \end{pmatrix}\begin{pmatrix} x_0 \\ x_0' \end{pmatrix} = M_H\begin{pmatrix} x_0 \\ x_0' \end{pmatrix} \tag{2.35}$$

$$\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} \cos\phi_y & \frac{\rho}{\sqrt{n}}\sin\phi_y \\ -\frac{\sqrt{n}}{\rho}\sin\phi_y & \cos\phi_y \end{pmatrix}\begin{pmatrix} y_0 \\ y_0' \end{pmatrix} = M_V\begin{pmatrix} y_0 \\ y_0' \end{pmatrix} \tag{2.36}$$

Betatron tune

where the **phase advances** are given by

$$\phi_x(s) \equiv \theta\sqrt{1-n} = \frac{s}{\rho}\sqrt{1-n} \quad (2.37)$$

$$\phi_y(s) \equiv \theta\sqrt{n} = \frac{s}{\rho}\sqrt{n} \quad (2.38)$$

Particles move in transverse **betatron oscillations** around the design trajectory.

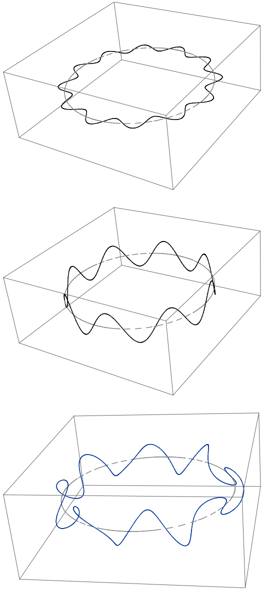
The **number of oscillations** performed by a particle in a particular plane (horizontal or vertical), is accounted by the

Betatron tune

$$Q_{x,y} = \frac{\phi_{x,y}(2\pi)}{2\pi} \quad (2.39)$$

Note that the weak focusing condition can be written as

$$Q_x^2 + Q_y^2 = 1 \quad (2.40)$$



Contents

Field expansion

The **transverse magnetic field** is

$$\vec{B} = B_x\hat{x} + B_y\hat{y} \tag{3.1}$$

Making a **Taylor expansion** of the field components we get

$$B_x = B_{0x} + \frac{\partial B_x}{\partial y}y + \frac{1}{2!}\frac{\partial^2 B_x}{\partial y^2}y^2 + \dots \tag{3.2}$$

$$B_y = B_{0y} + \frac{\partial B_y}{\partial x}x + \frac{1}{2!}\frac{\partial^2 B_y}{\partial x^2}x^2 + \dots \tag{3.3}$$

The first terms in both expansions correspond to **dipole** terms, the second terms to **quadrupoles**, then **sextupoles**, and so on.

Due to the **Maxwell's equation** for $\nabla \times \vec{H}$, in the absence of electric fields and currents,

$$\frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y} \tag{3.4}$$

Most of the time we are not interested in vertical bending dipoles, then $B_{0x} = 0$, and we label $B_{0y} = B_0$.

We can write the **linear** field as

$$\begin{aligned}\vec{B} &= \left(\frac{\partial B_y}{\partial x}y\right)\hat{x} + \left(B_0 + \frac{\partial B_y}{\partial x}x\right)\hat{y} \\ &= B_0\hat{y} + (x\hat{y} + y\hat{x})\left(\frac{\partial B_y}{\partial x}\right)\end{aligned} \tag{3.5}$$

Another way to make the expansion, via **multipoles** (in complex notation):

$$B_x + iB_y = B_0\sum_{n=0}^{\infty}(a_n + ib_n)\left(\frac{x+iy}{a}\right)^n \tag{3.6}$$

where $n = 0$ corresponds to dipoles, $n = 1$ to quadrupoles, etc. The coefficients b_n and a_n are called **normal** and **skew**, respectively.

Unfortunately, this is not the only convention!

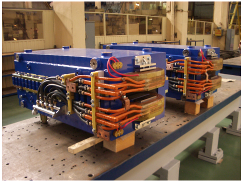
Linear optical elements

We can have two types of optical elements (magnets) with a linear magnetic field:

Dipoles

- Long magnets that **bend** the design trajectory.
- They may or may not include focusing (combined function).
- Special case: **drifts** (no field).

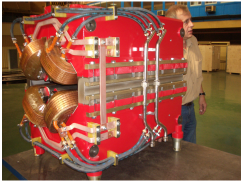
$$\vec{B} = B_0\hat{y} + (x\hat{y} + y\hat{x})\left(\frac{\partial B_y}{\partial x}\right) \tag{3.7}$$



Quadrupoles

- Design trajectory is **straight**.
- **Focus** particles moving out of the design orbit.
- Special case: **thin lens approximation**.

$$\vec{B} = (x\hat{y} + y\hat{x})\left(\frac{\partial B_y}{\partial x}\right) \tag{3.8}$$



The solution of the equation of motion of a particle that passes along each of them can be described with their corresponding **transport matrix**. We have already found the one for the dipole.

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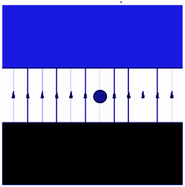

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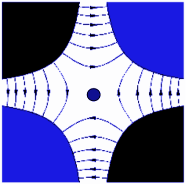

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Transport matrices

Therefore, we can build the accelerator optics out of *Lego* transport matrices.

Let $\vec{w}_0$ be the set of initial **transverse coordinates**. They are transformed to $\vec{w}$ after crossing a system represented by the matrix M according to

$$\vec{w} = M\vec{w}_0 \tag{3.9}$$

A **lattice** is usually made of substructures or **cells**, an array of magnets repeating along the machine. To describe the motion of a particle along the accelerator, we can simply **multiply** the piecewise solutions given by the transport matrices.

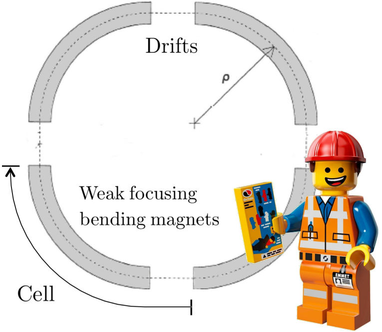
Take for example the machine on the right. Each cell is made of a drift and a dipole (bending),

$$M_{cell} = M_B M_D$$

The order in which we have to perform the matrices is from right to left, since it is the order in which the particle encounters the elements. For the machine composed of 4 cells,

$$M = (M_{cell})^4 = (M_B M_D)^4$$

gives the solution after one turn.



Dipoles

We know the general transport matrix for a **dipole without focusing**,

$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix} = \begin{pmatrix} \cos\phi_x & \frac{\rho}{\sqrt{1-n}}\sin\phi_x & 0 & 0 \\ -\frac{\sqrt{1-n}}{\rho}\sin\phi_x & \cos\phi_x & 0 & 0 \\ 0 & 0 & \cos\phi_y & \frac{\rho}{\sqrt{n}}\sin\phi_y \\ 0 & 0 & -\frac{\sqrt{n}}{\rho}\sin\phi_y & \cos\phi_y \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \end{pmatrix} \tag{3.10}$$

Remember that the phase advances are given by

$$\phi_x(s) = \frac{s}{\rho}\sqrt{1-n}, \qquad \phi_y(s) = \frac{s}{\rho}\sqrt{n}$$

Then, taking the field index to zero ($n \to 0$), we have the transport of a

Dipole (no focusing)

$$\begin{pmatrix} x(\theta) \\ x'(\theta) \\ y(\theta) \\ y'(\theta) \end{pmatrix} = \begin{pmatrix} \cos\theta & \rho\sin\theta & 0 & 0 \\ -\frac{1}{\rho}\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & \rho\theta \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \end{pmatrix} \tag{3.11}$$

with bending angle θ and **no focusing**.

Note: In a circular machine composed of N dipoles of length L_B, the **integrated dipole field over one turn** is

$$\oint B\,ds \approx NBL_B = 2\pi\frac{p}{q} \tag{3.12}$$

Careful with units!

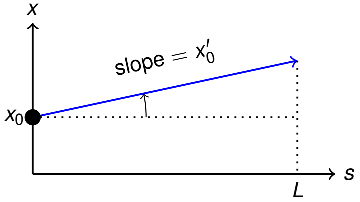
Drifts

The sub-matrix for the vertical plane represents a field-free **drift** where no bending is performed. This is valid in general for x or y when there is no field:

Drift

$$\begin{pmatrix} x(s) \\ x'(s) \\ y(s) \\ y'(s) \end{pmatrix} = \begin{pmatrix} 1 & s & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & s \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \end{pmatrix} \tag{3.13}$$

where s is the length of the drift.



Interlude:

Note that we have switched to **4** $\times$ **4** matrices. In fact, a more complete study requires 6 coordinates and thus, 6×6 matrices): x, x', y, y', s, δ (as we will see later).

Nevertheless, when horizontal and vertical motions are **uncoupled** (that is, they are independent of each other), we can split our 4×4 matrices,

$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix} = \begin{pmatrix} \multicolumn{2}{c}{M_x} & 0 & 0 \\ & & 0 & 0 \\ 0 & 0 & \multicolumn{2}{c}{M_y} \\ 0 & 0 & & \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \end{pmatrix} \tag{3.14}$$

in pure horizontal/vertical motion, with our usual 2×2 matrices:

$$\vec{X} = M_x \vec{X}_0, \quad \vec{Y} = M_y \vec{Y}_0 \tag{3.15}$$

Quadrupoles: Quadrupole gradient

For the quadrupoles, the components of the magnetic field (3.8) are commonly written as

$$B_x = Gy, \qquad B_y = Gx \tag{3.16}$$

where G, measured in T/m, is the

Quadrupole gradient

$$G = \frac{B_{pole}}{a} = \frac{2\mu_0 NI}{a^2} \approx \frac{\partial B_y}{\partial x} \tag{3.17}$$

B_{pole} is the field at the pole tips, a is the inner radius of the quadrupole, μ_0 is the vacuum magnetic permeability,

$$\mu_0 = 4\pi \times 10^{-7}\ \frac{\text{Tm}}{\text{A}} \tag{3.18}$$

and N is the number of turns of current I around the poles.

We simply follow a similar procedure (and approximations) to the derivation of the equations of betatron motion.

The corresponding horizontal and vertical forces

$$F_x = -q\beta_r cGx \tag{3.19}$$

and

$$F_y = q\beta_r cGy \tag{3.20}$$

lead to the equations

$$x'' + \frac{G}{B_0\rho}x = 0 \tag{3.21}$$

and

$$y'' - \frac{G}{B_0\rho}y = 0 \tag{3.22}$$

Quadrupoles: Quadrupole strength

where we have replaced the derivatives w.r.t. θ to derivatives w.r.t. s,

$$\frac{d}{d\theta} = \frac{1}{R}\frac{d}{ds} \tag{3.23}$$

By using the

Quadrupole strength[2]

$$K \equiv \frac{1}{(B_0\rho)}\left(\frac{\partial B_y}{\partial x}\right) = \frac{G}{(B_0\rho)} \equiv k^2 \tag{3.24}$$

with units of m^{-2}, the equations of motion are

$$x'' + Kx = 0, \qquad y'' - Ky = 0 \tag{3.25}$$

where $''$ denotes derivation w.r.t. s.

The horizontal equation of motion in (3.25) is again a harmonic oscillator and its solution is given in terms of **sine and cosine**. In the vertical plane, the solution is given by **hyperbolic sine and cosine**.

We can then express the general transport matrix of a

[2] Two remarks: 1) Careful with K vs. k! 2) Some authors define K with a negative sign!

Quadrupoles: Focusing and defocusing

Quadrupole (horizontal **focusing** / vertical defocusing)

$$\begin{pmatrix} x(s) \\ x'(s) \\ y(s) \\ y'(s) \end{pmatrix} = \begin{pmatrix} \cos(ks) & \frac{1}{k}\sin(ks) & 0 & 0 \\ -k\sin(ks) & \cos(ks) & 0 & 0 \\ 0 & 0 & \cosh(ks) & \frac{1}{k}\sinh(ks) \\ 0 & 0 & k\sinh(ks) & \cosh(ks) \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \end{pmatrix} \tag{3.26}$$

This represent a **horizontal focusing** / **vertical defocusing quadrupole**.

To compensate this, quadrupoles are commonly placed in pairs, being the second quadrupole **horizontal defocusing** / **vertical focusing**.

Quadrupole (horizontal **defocusing** / vertical focusing)

$$\begin{pmatrix} x(s) \\ x'(s) \\ y(s) \\ y'(s) \end{pmatrix} = \begin{pmatrix} \cosh(ks) & \frac{1}{k}\sinh(ks) & 0 & 0 \\ k\sinh(ks) & \cosh(ks) & 0 & 0 \\ 0 & 0 & \cos(ks) & \frac{1}{k}\sin(ks) \\ 0 & 0 & -k\sin(ks) & \cos(ks) \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \end{pmatrix} \tag{3.27}$$

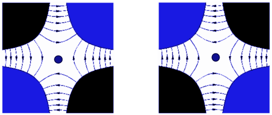
Another important remark: $k = \sqrt{K}$, and K is always taken positive, so for defocusing quads corresponding to negative K, the sign is explicitly written: $-K$.

Quadrupoles: Thin Lenses

Note that this correspond to change K (defined positive) to $-K$ since

$$\begin{aligned} \sinh u &= -i\sin(iu) \\ \cosh u &= \cos(iu) \end{aligned} \tag{3.28}$$

Physically, this represents a 90° rotation of the quadrupole, so the north and south poles end up interchanged.



In the **thin lens approximation**, we make $s = L \to 0$ while keeping KL constant. In addition, the **focal length** of the quadrupole is given by

$$f \equiv \frac{1}{KL} = \frac{1}{k^2 L} \tag{3.29}$$

The corresponding matrices are then

Thin quadrupole (horizontal focusing / vertical defocusing)

$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -\frac{1}{f} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \end{pmatrix} \tag{3.30}$$

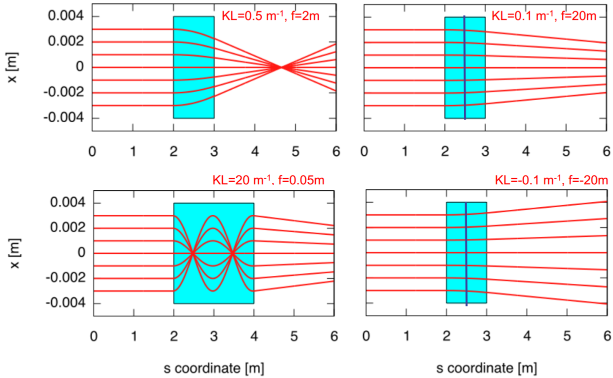
and

Thin quadrupole (horizontal defocusing / vertical focusing)

$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ \frac{1}{f} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \end{pmatrix} \tag{3.31}$$

when we change $f \to -f$.

Quadrupoles: Focal Length

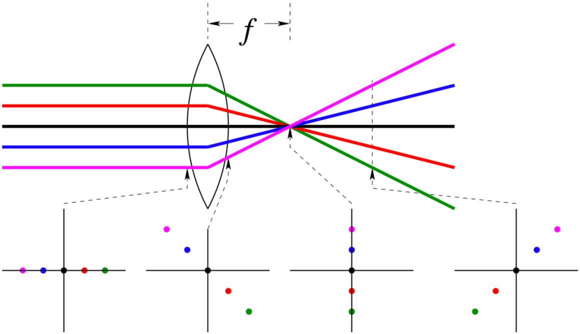


In general, a quadrupole can be treated as a thin quadrupole when

$$|f| \gg L \tag{3.32}$$

and then we can use the simpler transport matrices (3.30)-(3.31) instead of (3.26)-(3.27) where the trigonometric functions make the oscillatory motion evident (as in the thick quadrupole in the bottom left corner).

Quadrupoles: Focal Length



In general, a quadrupole can be treated as a thin quadrupole when

$$|f| \gg L \qquad (3.32)$$

and then we can use the simpler transport matrices (3.30)-(3.31) instead of (3.26)-(3.27) where the trigonometric functions make the oscillatory motion evident (as in the thick quadrupole in the bottom left corner).

Quadrupoles: Doublet I

Example: *Doublet*

A **doublet** is a system formed by a pair of quadrupoles, separated by a drift. Consider only the horizontal plane. If the first quadrupole is focusing and the second is defocusing, the transfer matrix of the system is

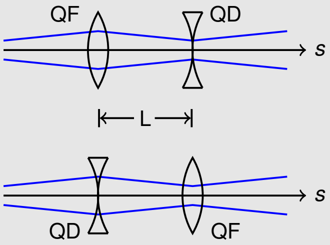
$$M_{\text{doublet}} = \begin{pmatrix} 1 & 0 \\ \frac{1}{f_D} & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_F} & 1 \end{pmatrix} = \begin{pmatrix} 1 - \frac{L}{f_F} & L \\ \frac{1}{f_D} - \frac{1}{f_F} - \frac{L}{f_F f_D} & 1 + \frac{L}{f_D} \end{pmatrix} \tag{3.33}$$

The element m_{12} gives us the inverse of the focal length of this system,

$$\frac{1}{f_{\text{doublet}}} \equiv \frac{1}{f_D} - \frac{1}{f_F} - \frac{L}{f_F f_D} \tag{3.34}$$

In the particular case that $f_D = f_F = f$,

$$\frac{1}{f_{\text{doublet}}} = -\frac{L}{f^2} \tag{3.35}$$



An **alternating gradient** system as this one provides **net focusing**, a fundamental feature for accelerator **strong focusing**.

Quadrupoles: Doublet II

Example: *Doublet (cont.)*

Consider an incoming paraxial ray $(x_0, 0)$. Then, after passing the doublet,

$$\begin{pmatrix} x \\ x' \end{pmatrix} = M_{\text{doublet}} \begin{pmatrix} x_0 \\ 0 \end{pmatrix} = \begin{pmatrix} \left(1 - \frac{L}{f}\right) x_0 \\ -\frac{L}{f^2} x_0 \end{pmatrix} = \begin{pmatrix} 1 - \frac{L}{f} \\ -\frac{L}{f^2} \end{pmatrix} x_0 \qquad (3.36)$$

In order this to be focusing, x and x' must have **opposite signs**. Since both L and f are positive, we can analyse two cases:

If	$x_0 > 0,$	$x_0 < 0,$
then the slope	$x' = -\frac{L}{f^2} x_0 < 0,$	$x' = -\frac{L}{f^2} x_0 > 0,$
which demands	$x = \left(1 - \frac{L}{f}\right) x_0 > 0.$	$x = \left(1 - \frac{L}{f}\right) x_0 < 0\ .$
Now, since (again)	$x_0 > 0,$	$x_0 < 0,$
then	$1 - \frac{L}{f} > 0$	$1 - \frac{L}{f} > 0$
or	$f > L.$	$f > L.$

That is, an equal-strength doublet is **net focusing** under condition that the focal length of each lens is greater than the distance between them.

In the reversed case (defocusing quad first, followed by the focusing one), the same condition is reached after following a same procedure. Then, alternating quadrupoles continuously produces a system that is **overall net focusing and stable**.

Dispersion I

So far we have assumed that the design trajectory particle and our particle have the **same momentum**.

What happen when this is not the case? Let us suppose that

$$p = p_0 + \Delta p = p_0(1+\delta) \qquad (3.37)$$

where

Momentum deviation

$$\delta \equiv \frac{\Delta p}{p_0} \ll 1 \qquad (3.38)$$

Then, the equation of motion for the dipole in the **horizontal** plane is

$$\frac{d^2x}{d\theta^2} + \left(\frac{qB_y}{p_0(1+\delta)}R - 1\right)R = 0 \qquad (3.39)$$

Compare this equation with (2.20). Using the approximation

$$\frac{1}{1+\epsilon} \approx 1 - \epsilon \qquad (3.40)$$

we get

$$\frac{d^2x}{d\theta^2} + \left(\frac{qB_y}{p_0}(1-\delta)R - 1\right)R = 0 \qquad (3.41)$$

Rearranging,

$$\frac{d^2x}{d\theta^2} + \left(\frac{qB_y}{p_0}R - 1\right)R = \frac{qB_y}{p_0}R^2\delta \qquad (3.42)$$

we obtain

$$\frac{d^2x}{d\theta^2} + (1-n)x = \rho\delta \qquad (3.43)$$

where n is the **field index** defined in (2.27) and δ is **constant**.

The momentum effect is called **dispersion**.

Dispersion II

We can see that the only change is the addition of an **inhomogeneous** term to the ordinary differential equation. Therefore, the solution of is given by the sum of the **homogeneous solution** x_h (already derived, a harmonic oscillator) and the **particular solution** x_p,

$$x(\theta) = x_h(\theta) + x_p(\theta) \tag{3.44}$$

Based on the form of the differential equation, we propose $x_p = C$, with C a constant, as particular solution. Substituting into the equation,

$$\frac{d^2C}{d\theta^2} + (1-n)C = 0 + (1-n)C = \rho\delta \tag{3.45}$$

where we can solve for C,

$$x_p = C = \frac{\rho\delta}{1-n} \tag{3.46}$$

The complete solution is then

$$x(\theta) = A\cos(\theta\sqrt{1-n}) + B\sin(\theta\sqrt{1-n}) + \frac{\rho}{1-n}\delta \tag{3.47}$$

We now get its derivative,

$$\frac{dx}{d\theta} = \sqrt{1-n}[-A\sin(\theta\sqrt{1-n}) + B\cos(\theta\sqrt{1-n})] \tag{3.48}$$

Dispersion III

in order to get A and B in terms of the initial conditions (x_0, x_0'). By doing so, we obtain the constants

$$A = x_0 - \frac{\rho}{1-n}\delta, \qquad B = \frac{\rho}{\sqrt{1-n}}x_0' \tag{3.49}$$

The solution can be written with a 3×3-matrix:

$$\begin{pmatrix} x \\ x' \\ \delta \end{pmatrix} = \begin{pmatrix} \cos\phi_x & \frac{\rho}{\sqrt{1-n}}\sin\phi_x & \frac{\rho}{1-n}(1-\cos\phi_x) \\ -\frac{\sqrt{1-n}}{\rho}\sin\phi_x & \cos\phi_x & \frac{1}{1-n}\sin\phi_x \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ \delta_0 \end{pmatrix} \tag{3.50}$$

where $\phi_x = \theta\sqrt{1-n}$. Note that δ has become a **"coordinate"**. If we take $n \to 0$, we obtain the transport matrix for a

Dipole (no focusing, with dispersion)

$$\begin{pmatrix} x \\ x' \\ \delta \end{pmatrix} = \begin{pmatrix} \cos\theta & \rho\sin\theta & \rho(1-\cos\theta) \\ -\frac{1}{\rho}\sin\theta & \cos\theta & \sin\theta \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ \delta_0 \end{pmatrix} \tag{3.51}$$

The momentum deviation **does not** gives rise to vertical dispersion in the presence of horizontal dipoles, as can be verified by carrying similar calculations out for the **vertical** plane.

Dispersion IV

Example: 180° *spectrometer magnet*

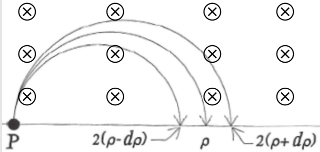
A mass **spectrometer** separates particles according to their energy.

Suppose a 180° bending magnet (π rad); its corresponding transport matrix is then

$$M = \begin{pmatrix} \cos\pi & \rho\sin\pi & \rho(1-\cos\pi) \\ -\frac{1}{\rho}\sin\pi & \cos\pi & \sin\pi \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 0 & \rho[1-(-1)] \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

In this magnet, a particle with initial coordinates $(0, 0, \pm\delta)$, will experience deflection and, at the exit of the dipole its final coordinates will be

$$\begin{pmatrix} x \\ x' \\ \delta \end{pmatrix} = M \begin{pmatrix} x_0 \\ x'_0 \\ \delta_0 \end{pmatrix} = \begin{pmatrix} -1 & 0 & 2\rho \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ \pm\delta \end{pmatrix} = \begin{pmatrix} \pm2\rho\delta \\ 0 \\ \pm\delta \end{pmatrix}$$



Dispersion IV

Example: 180° *spectrometer magnet*

A mass **spectrometer** separates particles according to their energy.

Suppose a 180° bending magnet (π rad); its corresponding transport matrix is then

$$M = \begin{pmatrix} \cos\pi & \rho\sin\pi & \rho(1-\cos\pi) \\ -\frac{1}{\rho}\sin\pi & \cos\pi & \sin\pi \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} -1 & 0 & \rho[1-(-1)] \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

In this magnet, a particle with initial coordinates $(0, 0, \pm\delta)$, will experience deflection and, at the exit of the dipole its final coordinates will be

$$\begin{pmatrix} x \\ x' \\ \delta \end{pmatrix} = M \begin{pmatrix} x_0 \\ x_0' \\ \delta_0 \end{pmatrix} = \begin{pmatrix} -1 & 0 & 2\rho \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ \pm\delta \end{pmatrix} = \begin{pmatrix} \pm 2\rho\delta \\ 0 \\ \pm\delta \end{pmatrix}$$

Consider a 0.1 T magnet, used in a 20 MeV/c beam. Then, particles at the reference position, but with 1% deviation of momentum, will be displaced a distance

$$x = 2\rho\delta = 2\cdot\frac{p[\mathrm{GeV/c}]}{0.3B[\mathrm{T}]}\cdot\delta = 2\cdot\frac{0.02\ \mathrm{GeV/c}}{0.3(0.1\ \mathrm{T})}\cdot 0.01 = 2(0.67\ \mathrm{m})(0.01) \approx 1.33\ \mathrm{cm}$$

from the ideal orbit at the exit of the spectrometer.

Summary: Prerequisites, Lectures I to II I

Lorentz factors:

$$\beta_r \equiv \frac{v}{c}, \qquad \gamma_r \equiv \frac{1}{\sqrt{1-\beta_r^2}}$$

Rest energy:

$$E_0 = mc^2$$

Total energy:

$$E = \gamma_r mc^2$$

Kinetic energy:

$$E_K = T = E - E_0 = (\gamma_r - 1)mc^2$$

Momentum:

$$p = \gamma_r m(\beta_r c) = \beta_r \frac{E}{c}$$

Electron-volt (eV):

$$1\ \text{eV} = 1.602 \times 10^{-19}\ \text{J}$$

Rigidity (in Tm):

$$(B\rho) = p/q$$

Rigidity (in practical units, valid only for a particle with $q = e$):

$$p\ [\text{GeV/c}] \approx 0.3\ B\ [\text{T}]\ \rho\ [\text{m}]$$

Cyclotron (angular) frequency:

$$\omega = \frac{qB}{\gamma_r m}, \qquad f = \frac{\omega}{2\pi}$$

Betatron tunes:

$$Q_{x,y} = \frac{\phi_{x,y}(2\pi)}{2\pi}$$

Integrated dipole field over a circumference:

$$NBL_B = 2\pi \frac{p}{q}$$

Remember that $T = \frac{Vs}{m^2}$.

Summary: Prerequisites, Lectures I to II II

Dipole (no focusing):

$$M_B = \begin{pmatrix} \cos\theta & \rho\sin\theta & 0 & 0 \\ -\frac{1}{\rho}\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & \rho\theta \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Drift:

$$M_D = \begin{pmatrix} 1 & s & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & s \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Quadrupole gradient:

$$G = \frac{B_{pole}}{a} = \frac{2\mu_0 NI}{a^2} \approx \frac{\partial B_y}{\partial x}$$

Quadrupole strength:

$$K \equiv \frac{1}{(B_0\rho)}\left(\frac{\partial B_y}{\partial x}\right) = \frac{G}{(B_0\rho)} \equiv k^2$$

Focusing quadrupole:

$$M_{QF} = \begin{pmatrix} \cos(ks) & \frac{1}{k}\sin(ks) \\ -k\sin(ks) & \cos(ks) \end{pmatrix}$$

Defocusing quadrupole:

$$M_{QD} = \begin{pmatrix} \cosh(ks) & \frac{1}{k}\sinh(ks) \\ k\sinh(ks) & \cosh(ks) \end{pmatrix}$$

Thin focusing quadrupole:

$$M_{QF} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$$

Thin defocusing quadrupole:

$$M_{QD} = \begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix}$$

Quadrupole focal length:

$$f = \frac{1}{KL} = \frac{1}{k^2 L}$$

Summary: Prerequisites, Lectures I to II III

Thin lens approximation:

$$|f| \gg L$$

Momentum deviation:

$$\delta = \frac{\Delta p}{p_0} \ll 1$$

Dipole (no focusing, with dispersion):

$$M_B = \begin{pmatrix} \cos\theta & \rho\sin\theta & \rho(1-\cos\theta) \\ -\frac{1}{\rho}\sin\theta & \cos\theta & \sin\theta \\ 0 & 0 & 1 \end{pmatrix}$$

Contents

The functions $K_{x,y}(s)$

In general, when we obtain the equations of motion in the transverse planes we get, after **normalizing** to $B_0\rho$,

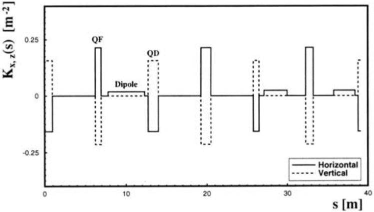
$$x'' + \left[K_{0x}x + K_{1x}x + K_{2x}\left(\frac{x^2 - y^2}{2}\right)\dots\right] = 0 \quad (4.1)$$

$$y'' + \left[K_{0y}y - K_{1y}y - K_{2y}xy\dots\right] = 0 \quad (4.2)$$

where

$$K_{0x} = \frac{1}{\rho^2}, \quad K_{1x} = \frac{1}{(B_0\rho)}\frac{\partial B_y}{\partial x}, \dots \quad (4.3)$$

$$K_{0y} = 0, \quad K_{1y} = \frac{1}{(B_0\rho)}\frac{\partial B_y}{\partial x}, \dots \quad (4.4)$$



Like previously pointed out, K_0 corresponds to **dipoles**, K_1 to **quadrupoles**, K_2 to **sextupoles**, etc.

- The effect of dipoles is the deflection of the beam in the horizontal plane, while in the vertical plane they have no effect at all.
- The notation of this functions with the letter K is motivated by the definition of strength in quadrupoles.

Hill's equation I

If $K_{x,y}$ are periodic functions in s with **periodicity** $K_{x,y}(s+C) = K_{x,y}(s)$, the equations in (3.25) are known as

Hill's equations

$$x'' + K_x(s)x = 0, \qquad y'' - K_y(s)y = 0 \tag{4.5}$$

Such periodicity of $K_{x,y}$ can be **one revolution** around the accelerator, or one repeated **cell** of the layout.

Let us focus on the horizontal plane, and make $K_x = K$. In order to solve (4.5), consider the following ansatz:

$$x(s) = Aw(s)\cos[\phi(s) + \phi_0] \tag{4.6}$$

that is, a **quasi-periodic harmonic oscillator**, where the **amplitude** $w(s)$ is periodic in C but the **phase** $\phi(s)$ is not.

Consider the horizontal plane. The first derivative of x gives

$$x' = Aw'\cos[\phi + \phi_0] - Aw\phi'\sin[\phi + \phi_0] \tag{4.7}$$

and the second derivative

Courant-Snyder parameters I

$$x'' = A(w'' - w\phi'^2)\cos[\phi + \phi_0] - A(2w'\phi' + w\phi'')\sin[\phi + \phi_0] \tag{4.8}$$

Substituting into the Hill's equation $x'' + K(s)x = 0$, we obtain

$$-A(2w'\phi' + w\phi'')\sin[\phi + \phi_0] + A(w'' - w\phi'^2 + Kw)\cos[\phi + \phi_0] = 0 \tag{4.9}$$

For $w(s)$ and $\phi(s)$ to be independent of ϕ_0, coefficients of sine and cosine terms must **vanish identically**. For the first one,

$$2ww'\phi' + w^2\phi'' = (w^2\phi')' = 0, \qquad \text{then} \qquad \phi' = \frac{\kappa}{w^2(s)} \tag{4.10}$$

where κ is a constant. From the cosine term,

$$w'' - \frac{\kappa^2}{w^3} + Kw = 0, \qquad \text{then} \qquad w^3(2w'' + Kw) = \kappa^2 \tag{4.11}$$

We introduce a new set of functions, the so-called

Courant-Snyder parameters (or Twiss functions)

$$\beta(s) \equiv \frac{w^2(s)}{\kappa}, \qquad \alpha(s) \equiv -\frac{1}{2}\beta'(s), \qquad \gamma(s) \equiv \frac{1 + \alpha^2(s)}{\beta(s)} \tag{4.12}$$

Solving the Hill's equation I

Note that wherever β reaches a **maximum/minimum**, $\boldsymbol{\alpha = 0}$ (and $x' = 0$).

Using the β function, we can write

$$\phi' = \frac{1}{\beta(s)} \qquad (4.13)$$

and easily solve for the

Phase advance

$$\phi(s) = \int_s \frac{d\tau}{\beta(\tau)} \qquad (4.14)$$

With the aid of the Twiss functions we can also rewrite (4.11) as

$$K\beta = \gamma + \alpha' \qquad (4.15)$$

The **Twiss functions** $\alpha(s)$, $\beta(s)$, and $\gamma(s)$, are **periodic** in C, but the **phase advance** $\phi(s)$ is **not**.

We can now write the solution (4.6) as

$$x(s) = A\sqrt{\beta(s)}\cos\phi(s) + B\sqrt{\beta(s)}\sin\phi(s) \qquad (4.16)$$

Note that $\pm\sqrt{\beta(s)}$ provides an **envelope** for particle oscillations. If we derive this equation,

$$\begin{aligned} x'(s) \quad &= \quad \frac{1}{\sqrt{\beta(s)}}\{[B - \alpha(s)A]\cos\phi(s) \\ &\qquad -[A + \alpha(s)B]\sin\phi(s)\} \end{aligned} \qquad (4.17)$$

we can get the constants A and B in terms of the initial conditions (x_0, x_0'),

$$\begin{aligned} A &= \frac{x_0}{\sqrt{\beta(s)}} \\ B &= \frac{1}{\sqrt{\beta(s)}}[\beta(s)x_0' + \alpha(s)x_0] \end{aligned} \qquad (4.18)$$

Periodic system I

In matrix form, as usual, we get the transport matrix of a

Periodic system

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{s_0+C} = \begin{pmatrix} \cos\phi_C + \alpha\sin\phi_C & \beta\sin\phi_C \\ -\gamma\sin\phi_C & \cos\phi_C - \alpha\sin\phi_C \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}_{s_0} \qquad (4.19)$$

where the **(betatron) phase advance**

$$\phi_C = \phi(C) = \int_{s_0}^{s_0+C} \frac{ds}{\beta(s)} \qquad (4.20)$$

is independent of s.

Note that the transport matrix of the periodic system is **unimodular**, that is,

$$\det M = 1 \qquad (4.21)$$

In fact, it can be written as

$$M = I\cos\phi_C + J\sin\phi_C \qquad (4.22)$$

where

$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad (4.23)$$

$$J = \begin{pmatrix} \alpha(s) & \beta(s) \\ -\gamma(s) & -\alpha(s) \end{pmatrix} \qquad (4.24)$$

Since $J^2 = -I$, the matrix can also be expressed as

$$M = e^{J(s)\phi_C} \qquad (4.25)$$

Stability condition I

The coordinates of a particle can be transformed after ***n* turns in a periodic system by applying *n* times** the corresponding transport matrix,

$$\begin{pmatrix} x \\ x' \end{pmatrix} = M^n \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \tag{4.26}$$

We are interested in this system to be **stable** as $n \to \infty$.

Let V_1 and V_2 the eigenvectors of the 2×2 matrix M, with corresponding eigenvalues λ_1, λ_2. Then,

$$M^n \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} = A\lambda_1^n V_1 + B\lambda_2^n V_2 \tag{4.27}$$

Since M is **unimodular**,

$$\lambda_{1,2} = e^{\pm i\phi} \tag{4.28}$$

where ϕ is, in general, a complex number. Nevertheless, in order $\lambda_{1,2}^n$ to remain bounded, ϕ must be **real**.

Then, it is possible to transform M into diagonal form with the eigenvalues on the diagonal. This does not change the **trace** of the matrix,

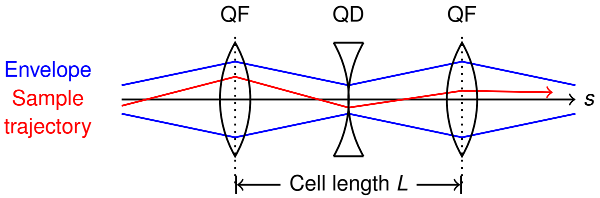
$$\mathrm{tr}\, M = e^{i\phi} + e^{-i\phi} = 2\cos\phi \tag{4.29}$$

Since $|\cos\phi| \leq 1$ for all real ϕ, we end up with the

Stability condition

$$\phi \in \Re \quad \Rightarrow \quad -1 \leq \frac{1}{2}\,\mathrm{tr}\, M \leq 1 \tag{4.30}$$

The FODO cell I



One of the most used cells in accelerator lattices is the **FODO cell**.

It is composed of a doublet of opposite-strength quadrupoles (hence the F and D in the name), separated by drifts (represented by the Os) where dipoles can be placed.

The transport matrix of the FODO cell is then

$$M = M_D M_{QD} M_D M_{QF} \tag{4.31}$$

Since this cell repeats, it can also be studied as

$$M = M_{QF/2} M_D M_{QD} M_D M_{QF/2} \tag{4.32}$$

or any other permutation.

We already know the matrices for the elements involved. In the case of the quadrupole split in half,

$$f \to 2f \tag{4.33}$$

Then, we perform the multiplication:

The FODO cell II

$$M = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f} & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{L}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{L}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f} & 1 \end{pmatrix} = \begin{pmatrix} 1 - \frac{L^2}{8f^2} & \frac{L^2}{4f} + L \\ \frac{L^2}{16f^3} - \frac{L}{4f^2} & 1 - \frac{L^2}{8f^2} \end{pmatrix} \tag{4.34}$$

where we used the thin lens approximation for the quadrupoles.

The trace of M is

$$\mathrm{tr}\, M = 2 - \frac{L^2}{4f^2} = 2\cos\phi_C \tag{4.35}$$

where the term in the right comes from (4.29). Remember that ϕ_C is the phase advance at the exit of the **periodic system**, in this case, the FODO cell.

Then,

$$1 - \frac{L^2}{8f^2} = \cos\phi_C \tag{4.36}$$

Since

$$\sin\frac{u}{2} = \sqrt{\frac{1+\cos u}{2}} \tag{4.37}$$

we get

$$1 - \frac{L^2}{8f^2} = 1 - 2\sin^2\frac{\phi_C}{2} \tag{4.38}$$

or, solving for the trigonometric function, we get the

Phase advance in a FODO cell

$$\sin\frac{\phi_C}{2} = \pm\frac{L}{4f} \tag{4.39}$$

The FODO cell III

Note that in order ϕ_C to be real,

$$f > \frac{L}{4} \tag{4.40}$$

The **maximum** value of the **beta** function in a FODO cell occurs in the center of the focusing quadrupole (that's why we chose them at the entrance/exit).

Comparing the m_{12} term of the transport matrix, with the corresponding term in (4.19), we get

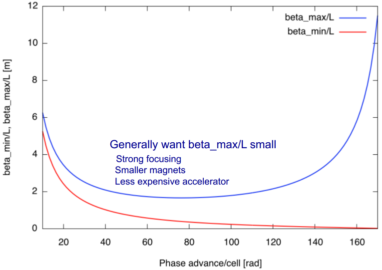
$$m_{12} = \beta^+ \sin\phi_C = L\left(\frac{L}{4f} + 1\right) \tag{4.41}$$

where β^+ denotes the maximum value of β for this system. When we substitute (4.39) and solve for β^+, we obtain the

Max/min beta in a FODO cell

$$\beta^{\pm} = \frac{L}{\sin\phi_C}\left(1 \pm \sin\frac{\phi_C}{2}\right) \tag{4.42}$$

To get the **minimum beta** β^-, follow the same procedure applied to a "DOFO" cell.



General solution I

In **general**, for two given locations s_0 and s in a machine, we have the matrix for a

General non-periodic system

$$M = \begin{pmatrix} \sqrt{\frac{\beta(s)}{\beta(s_0)}}\left[\cos\Delta\phi + \alpha(s_0)\sin\Delta\phi\right] & \sqrt{\beta(s_0)\beta(s)}\sin\Delta\phi \\ -\frac{[\alpha(s)-\alpha(s_0)]\cos\Delta\phi + [1+\alpha(s_0)\alpha(s)]\sin\Delta\phi}{\sqrt{\beta(s_0)\beta(s)}} & \sqrt{\frac{\beta(s_0)}{\beta(s)}}\left[\cos\Delta\phi - \alpha(s)\sin\Delta\phi\right] \end{pmatrix} \tag{4.43}$$

Note that **det** $\boldsymbol{M} = \mathbf{1}$.

It is worthy to note that after **one turn**, (4.43) reduces to the **periodic** matrix,

$$M(s_0, s_0 + C) = \begin{pmatrix} \cos\mu + \alpha_0\sin\mu & \beta_0\sin\mu \\ -\gamma_0\sin\mu & \cos\mu - \alpha_0\sin\mu \end{pmatrix} = I\cos\mu + J\sin\mu \tag{4.44}$$

where μ is the phase advance after one turn.

To derive the general matrix, we start with the solution to the equation of motion

$$x(s) = Aw(s)\cos\phi(s) + Bw(s)\sin\phi(s) \tag{4.45}$$

General solution II

and its derivative

$$x'(s) = A\left[w'(s)\cos\phi(s) - \frac{\sin\phi(s)}{w(s)}\right] + B\left[w'(s)\sin\phi(s) + \frac{\cos\phi(s)}{w(s)}\right] \qquad (4.46)$$

We **solve** then for the **constants** A and B in terms of the **initial conditions** at $s = s_0$, that is (x_0, x_0') and (w_0, ϕ_0). We obtain

$$\begin{aligned} A &= \left(w_0'\sin\phi_0 + \frac{\cos\phi_0}{w_0}\right)x_0 - (w_0\sin\phi_0)x_0' \\ B &= -\left(w_0'\cos\phi_0 - \frac{\sin\phi_0}{w_0}\right)x_0 + (w_0\cos\phi_0)x_0' \end{aligned} \qquad (4.47)$$

When we substitute A and B in x and x', and using the trigonometric formulas

$$\begin{aligned} \sin(u \pm v) &= \sin u\cos v \pm \cos u\sin v \\ \cos(u \pm v) &= \cos u\cos v \mp \sin u\sin v \end{aligned} \qquad (4.48)$$

we can proceed to write the **result** in **matrix form** as follows

$$\begin{pmatrix} x(s) \\ x'(s) \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}\begin{pmatrix} x_0 \\ x_0' \end{pmatrix} \qquad (4.49)$$

General solution III

where $\Delta\phi \equiv \phi(s) - \phi_0$, and

$$m_{11}(s) = \frac{w(s)}{w_0}\cos\Delta\phi - w(s)w_0'\sin\Delta\phi \qquad (4.50)$$

$$m_{12}(s) = w(s)w_0\sin\Delta\phi \qquad (4.51)$$

$$m_{21}(s) = \frac{1 + w(s)w_0w'(s)w_0'}{w(s)w_0}\sin\Delta\phi - \left[\frac{w_0'}{w(s)} - \frac{w'(s)}{w_0}\right]\cos\Delta\phi \qquad (4.52)$$

$$m_{22}(s) = \frac{w_0}{w(s)}\cos\Delta\phi + w_0w'(s)\sin\Delta\phi \qquad (4.53)$$

To get the final result, use the Courant-Synder parameter $\alpha(s)$ when appropriate, and remember that $w(s) = \sqrt{\beta(s)}$.

Even though M looks complicated, note that it can be expressed as

$$M = \begin{pmatrix} C & S \\ C' & S' \end{pmatrix} \qquad (4.54)$$

where C and S are **cosine-** and **sine-like** terms, and the second row is the **derivative** of the first one.

Propagation of the Courant-Snyder parameters I

If we know the **Twiss parameters** at s_0, and we have the transport matrix $M(s_0, s)$, we can compute[3] at the given s the

Propagation of Courant-Snyder parameters (Twiss functions)

$$\begin{pmatrix} \beta(s) \\ \alpha(s) \\ \gamma(s) \end{pmatrix} = \begin{pmatrix} m_{11}^2 & -2m_{11}m_{12} & m_{12}^2 \\ -m_{11}m_{21} & m_{11}m_{22} + m_{12}m_{21} & -m_{12}m_{22} \\ m_{21}^2 & -2m_{21}m_{22} & m_{22}^2 \end{pmatrix} \begin{pmatrix} \beta(s_0) \\ \alpha(s_0) \\ \gamma(s_0) \end{pmatrix} \tag{4.55}$$

where m_{ij} are the elements of the matrix M.

[3] This result comes from Liouville's theorem, which can be stated as the preservation of the phase space area.

Contents

Dispersion I

We now study the horizontal **Hill's equation** taking into account **dispersion**,

$$x'' + K(s)x = \frac{\delta}{\rho(s)} \tag{5.1}$$

where

$$\delta = \frac{\Delta p}{p_0} \tag{5.2}$$

is constant, and

$$K(s) = \frac{1}{\rho^2} + \frac{q}{p_0}\frac{\partial B_y}{\partial x} \tag{5.3}$$

We know that the generalized **solution** of the **homogeneous equation** ($\delta = 0$) is, in the horizontal plane, given by

$$\vec{X}(s) = M(s)\vec{X}_0 \tag{5.4}$$

with

$$M = \begin{pmatrix} C & S \\ C' & S' \end{pmatrix}, \quad \vec{X} = \begin{pmatrix} x \\ x' \end{pmatrix} \tag{5.5}$$

or

$$x(s) = C(s)x_0 + S(s)x_0' \tag{5.6}$$

Then, the generalized solution of the **inhomogeneous equation** ($\delta \neq 0$) can be written as

$$x(s) = C(s)x_0 + S(s)x_0' + D(s)\delta_0 \tag{5.7}$$

where

$$\begin{aligned} D(s) &= S(s)\int_0^s \frac{C(\tau)}{\rho(\tau)}d\tau \\ &\quad - C(s)\int_0^s \frac{S(\tau)}{\rho(\tau)}d\tau \end{aligned} \tag{5.8}$$

(This comes from the theory of differential equations! See for example H. Wiedemann, "Particle Accelerator Physics", 4th edition, pages 120 - 122.)

Dispersion II

As always, we can express the solution in matrix form in terms of the initial conditions (x_0, x_0') at $s = 0$.

To do so, we need the slope,

$$x'(s) = C'(s)x_0 + S'(s)x_0' + D'(s)\delta_0 \tag{5.9}$$

Comparing term by term in the l.h.s. and r.h.s. of the each of the following equations,

$$\begin{aligned} x_0 &= C(0)x_0 + S(0)x_0' + D(0)\delta_0 \\ x_0' &= C'(0)x_0 + S'(0)x_0' + D'(0)\delta_0 \end{aligned} \tag{5.10}$$

we see that

$$\begin{aligned} C(0) &= S'(0) = 1 \\ C'(0) = S(0) &= 0 \\ D(0) &= D'(0) = 0 \end{aligned} \tag{5.11}$$

Since the energy spread is assumed to be **constant**, the trajectory equations can be put in matrix form for $\delta \neq 0$,

$$\begin{pmatrix} x \\ x' \\ \delta \end{pmatrix} = \begin{pmatrix} C(s) & S(s) & D(s) \\ C'(s) & S'(s) & D'(s) \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ \delta_0 \end{pmatrix} \tag{5.12}$$

Note that one of the eigenvectors of this matrix is $\lambda_3 = +1$. The other two are determined only by the 2×2 sub-matrix in the top-left corner.

The eigenvector corresponding to the $\lambda_3 = +1$ can be written as

$$\begin{pmatrix} \eta(s)\delta \\ \eta'(s)\delta \\ \delta \end{pmatrix} = \begin{pmatrix} \eta(s) \\ \eta'(s) \\ 1 \end{pmatrix} \delta \tag{5.13}$$

where $\eta(s)$ is called the **dispersion function**.

Dispersion III

The matrix equation for this eigenvector is

$$\begin{pmatrix} \eta \\ \eta' \\ 1 \end{pmatrix} = \begin{pmatrix} C & S & D \\ C' & S' & D' \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \eta_0 \\ \eta_0' \\ 1 \end{pmatrix} \tag{5.14}$$

We can solve this for η and η' by writting

$$\begin{aligned} \begin{pmatrix} \eta \\ \eta' \end{pmatrix} &= \begin{pmatrix} C & S \\ C' & S' \end{pmatrix} \begin{pmatrix} \eta \\ \eta' \end{pmatrix} + \begin{pmatrix} D \\ D' \end{pmatrix} \\ &= M \begin{pmatrix} \eta \\ \eta' \end{pmatrix} + \begin{pmatrix} D \\ D' \end{pmatrix} \end{aligned} \tag{5.15}$$

where M is the 2×2 matrix with the $C(s)$ and $S(s)$ elements (and their derivatives). Then

$$(I - M) \begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} D \\ D' \end{pmatrix} \tag{5.16}$$

or

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = (I - M)^{-1} \begin{pmatrix} D \\ D' \end{pmatrix} \tag{5.17}$$

After computing the inverse of the matrix $(I - M)$, we can finally get

$$\eta(s) = \frac{(1 - S')D + SD'}{2(1 - \cos\mu)} \tag{5.18}$$

$$\eta'(s) = \frac{(1 - C)D' + C'D}{2(1 - \cos\mu)} \tag{5.19}$$

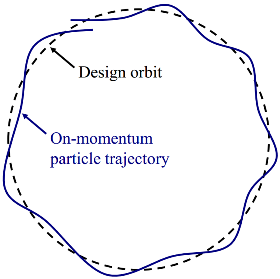
where we have used the fact that

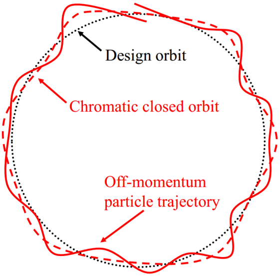
$$\operatorname{tr} M = C + S' = 2\cos\mu \tag{5.20}$$

To sum up, the solution of Hill's equation with dispersion can be written as

$$x(s) = x_\beta(s) + x_p(s) \tag{5.21}$$

Dispersion IV





That is, it can be written as the sum of the **betatron oscillation** $x_\beta(s)$, and

$$x_p(s) = \eta(s)\delta \qquad (5.22)$$

which is due to **dispersion**.

It is important to note that

$$\eta(s) = \frac{dx}{d\delta} \qquad (5.23)$$

is different from the matrix element

$$D(x) = \frac{\partial x}{\partial \delta} \qquad (5.24)$$

Also, the dispersion function is **periodic** with period C (for example the circumference of the machine):

$$\eta(s_0)\delta_0 = \eta(s_0 + C)\delta = \eta\delta \qquad (5.25)$$

Dispersion in linear elements I

We can extend the 2×2 transport matrices in order to take into account dispersion.

To do so, we make use of

$$D(s) = S(s) \int_0^s \frac{C}{\rho} d\tau - C(s) \int_0^s \frac{S}{\rho} d\tau$$

The case of **drifts** and **quadrupoles** is easy since $\rho \to \infty$:

Drift (with dispersion)

$$M_D = \begin{pmatrix} 1 & L & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{5.26}$$

Thin quad. (with dispersion)

$$M_{\substack{QF \\ QD}} = \begin{pmatrix} 1 & 0 & 0 \\ \mp\frac{1}{f} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{5.27}$$

For **dipoles**,

$$C(s) = \cos\theta = \cos\frac{s}{\rho} \tag{5.28}$$

$$S(s) = \rho\sin\theta = \rho\sin\frac{s}{\rho} \tag{5.29}$$

Then, performing the integral,

$$D(s) = \rho\left(1 - \cos\frac{s}{\rho}\right) \tag{5.30}$$

and $D'(s)$ is simply its derivative,

$$D'(s) = \sin\frac{s}{\rho} \tag{5.31}$$

If we put this in matrix form, we get the result in (3.51) previously obtained:

Dipole (with dispersion)

Equation (3.51)

Dispersion in a FODO cell I

We now come back to the FODO cell. Replacing the drifts with two equal dipoles of length $\rho\theta_C/2$, we get a total cell length of $L = \rho\theta_C$ if we use the thin lens approximation.

Starting the FODO at the middle of the focusing quadrupole,

$$M = M_{QF/2} M_D M_{QD} M_D M_{QF/2} \tag{5.32}$$

where

$$M_{QF/2} = \begin{pmatrix} 1 & 0 & 0 \\ -\frac{1}{2f} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{5.33}$$

$$M_{QD} = \begin{pmatrix} 1 & 0 & 0 \\ \frac{1}{f} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{5.34}$$

$$M_B = \begin{pmatrix} 1 & \frac{L}{2} & \frac{L\theta_C}{8} \\ 0 & 1 & \frac{\theta_C}{2} \\ 0 & 0 & 1 \end{pmatrix}. \tag{5.35}$$

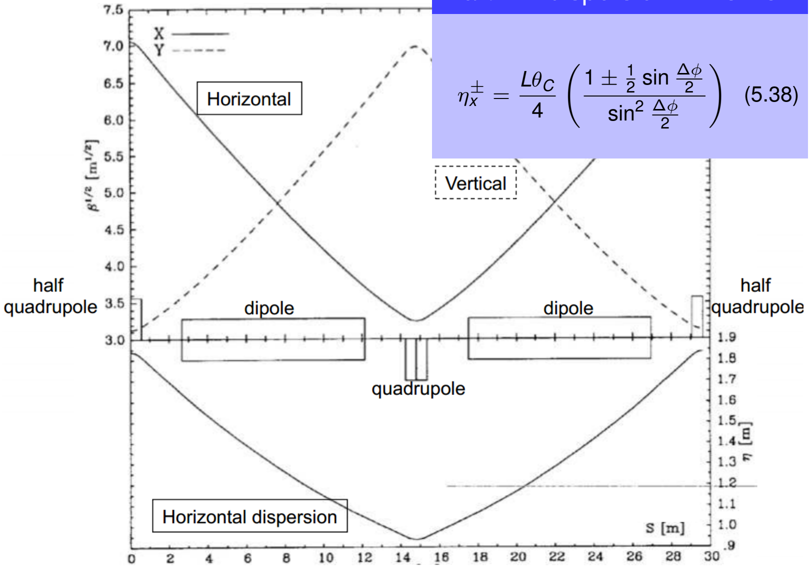
The result is

$$M = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \tag{5.36}$$

where

$$\begin{aligned}
m_{11} &= 1 - \frac{L^2}{8f^2} = m_{22} \\
m_{12} &= L\left(1 + \frac{L}{4f}\right) \\
m_{13} &= \frac{L}{2}\left(1 + \frac{L}{8f}\right)\theta_C \\
m_{21} &= -\frac{L}{4f^2}\left(1 - \frac{L}{4f}\right) \\
m_{23} &= \left(1 - \frac{L}{8f} - \frac{L^2}{32f^2}\right)\theta_C \\
m_{31} &= 0 = m_{32} \\
m_{33} &= 1
\end{aligned} \tag{5.37}$$

Dispersion in a FODO cell II



Max/min dispersion in FODO

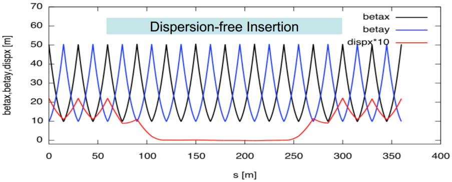
$$\eta_x^{\pm} = \frac{L\theta_C}{4}\left(\frac{1 \pm \frac{1}{2}\sin\frac{\Delta\phi}{2}}{\sin^2\frac{\Delta\phi}{2}}\right) \quad (5.38)$$

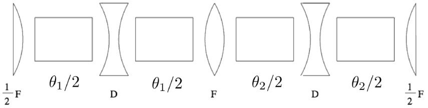
Insertions I

An accelerator is usually made of a series of repeating **cells**, giving the machine a **regular (periodic) optics**.

However, sometimes it is needed a sections in the lattice with a particular optics for a specific purpose: they are called **insertions**.

A **dispersion suppressor** takes the value of the dispersion function to **zero**.





This insertion consists of two FODO cells, fulfilling the following conditions:

$$\theta_1 = \left(1 - \frac{1}{4\sin^2\frac{\mu}{2}}\right)\theta, \qquad \theta_2 = \left(\frac{1}{4\sin^2\frac{\mu}{2}}\right)\theta, \qquad \theta = \theta_1 + \theta_2 \tag{5.39}$$

where μ is the phase advance per cell. In particular, for $\mu = \pi/3 = 60°$, we see that $4\sin^2\frac{\mu}{2} = 1$, and

$$\theta_1 = 0, \qquad \theta_2 = \theta \tag{5.40}$$

This is called a **missing magnet dispersion suppressor**.

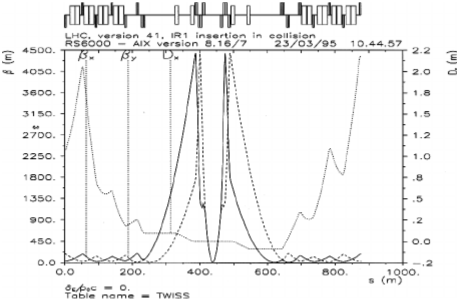
Insertions II

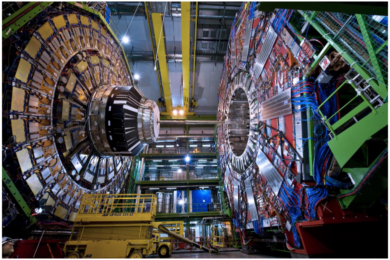
Another type of insertion is the **low-beta insertion**; it **reduces** the beta functions in the middle of the insertion in order to make the beam as narrow as possible.

It is useful, for example, in **colliders**, where a smaller beam size translates into higher luminosity.
In a low-beta insertion, the beta function can be written as

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*} \qquad (5.41)$$

where β^* is the beta function evaluated at the **interaction point**, located in the middle of the insertion ($s = 0$).





Courant-Snyder invariant I

In the equation of motion,

$$x(s) = A\sqrt{\beta(s)}\cos[\phi(s) + \phi_0] \quad (5.42)$$

we assumed that A was a constant. Note that it can be express in terms of the initial coordinates as

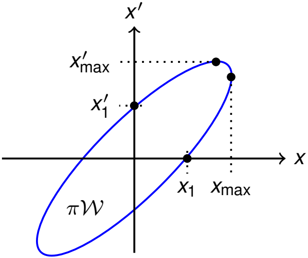
$$\mathcal{W} \equiv A^2 = \gamma_0 x_0^2 + 2\alpha_0 x_0 x_0' + \beta_0 {x_0'}^2 \quad (5.43)$$

In fact, this is an **invariant of motion**, known as the

Courant-Snyder invariant

$$\mathcal{W} = \gamma x^2 + 2\alpha x x' + \beta {x'}^2 \quad (5.44)$$

where x, x', α, β, and γ are functions of s. Being an invariant means that $\mathcal{W}$ has the same value for any s.



In the **phase space** (x, x'), $\mathcal{W}$ looks like an **elliptical area** and the transport matrices look like scaled rotations of it.

Some important points on the ellipse:

$$x_1 = \sqrt{\mathcal{W}/\gamma(s)} \quad (5.45)$$

$$x_{max} = \sqrt{\mathcal{W}\beta(s)} \quad (5.46)$$

$$x'_1 = \sqrt{\mathcal{W}/\beta(s)} \quad (5.47)$$

$$x'_{max} = \sqrt{\mathcal{W}\gamma(s)} \quad (5.48)$$

Emittance I

The

(Geometric) Emittance

$$\epsilon_{x,y} = \pi \mathcal{W}_{x,y} \tag{5.49}$$

is the (**constant**) **area** of the ellipse inscribed by any given particle in phase space, as it travels along the accelerator.

We define the

Beam size

$$\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta_{x,y}(s)} \tag{5.50}$$

and, as we can see, depends on s.

The beam size is often taken to correspond to the rms sigma of a 2-dimensional Gaussian distribution of particles,

$$\sigma^{rms}_{x,y} = \sqrt{\epsilon_{x,y}\beta_{x,y}(s)} \tag{5.51}$$

This emittance contains then 39% of the beam particles.

During **acceleration**, however, the emittance **is not** an **invariant**: even though x doesn't change as we accelerate, x' does since

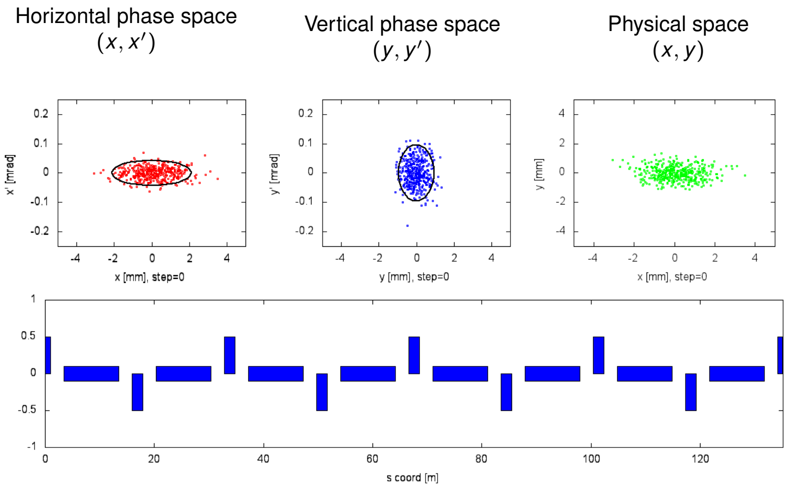
$$x' \equiv \frac{dx}{ds} = \frac{p_x}{p_0} \tag{5.52}$$

and p_0 is changing. Since p_0 scales with the relativistic β_r and γ_r, the invariant in this case is the

Normalized emittance

$$\epsilon^{N}_{x,y} = \beta_r\gamma_r\epsilon_{x,y} \tag{5.53}$$

Emittance II



Evolution of horizontal and vertical beta functions, $\beta_x(s)$, $\beta_y(s)$, and phase space ellipses along a lattice made of 4 FODO cells.

Tunes

Remember the definition of the

Tunes

$$Q_{x,y} = \frac{\Delta\phi_{x,y}}{\Delta\theta} = \frac{1}{2\pi}\oint \frac{ds}{\beta_{x,y}(s)} \tag{5.54}$$

They represents the **number of oscillations** in **one revolution** around the ring (in a given plane).

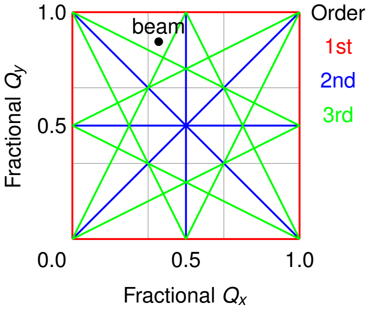
The tunes are a direct indication of the *amount of focusing* in the accelerator, and they are a critical parameter of its performance.

Resonances can occur when

$$nQ_x + mQ_y = k \tag{5.55}$$

with n, m, k integers, causing

Tune plot



an unstable motion. The **order** of a resonance is given by $|n| + |m|$.

The pair (Q_x, Q_y) is known as the **working point** of the accelerator, and has to be chosen away from resonance lines.

Chromaticity I

Just like the *amount* of **bending** depends on momentum, causing **dispersion**, the *amount* of **focusing** (and thus the tunes) depends on **momentum** too.

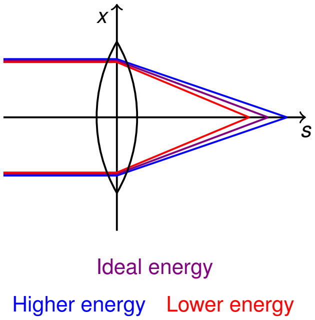
The variation of the tunes with δ is characterized by the **chromaticity**. There are two common definitions:

Chromaticity I

$$\Delta Q_{x,y} \equiv \xi_{x,y} \frac{\Delta p}{p} \tag{5.56}$$

Chromaticity II

$$\frac{\Delta Q_{x,y}}{Q_{x,y}} \equiv \xi_{x,y} \frac{\Delta p}{p} \tag{5.57}$$



Consider (in the horizontal plane) the following: a perturbation on momentum is equivalent to the addition of a small extra focusing to the one-turn matrix, that depends on the unperturbed focusing K,

Chromaticity II

$$M(\delta) = \begin{pmatrix} 1 & 0 \\ K\delta ds & 1 \end{pmatrix} \begin{pmatrix} \cos(2\pi Q_0) + \alpha\sin(2\pi Q_0) & \beta\sin(2\pi Q_0) \\ -\gamma\sin(2\pi Q_0) & \cos(2\pi Q_0) - \alpha\sin(2\pi Q_0) \end{pmatrix} \tag{5.58}$$

After performing the multiplication, the components of the resulting matrix are

$$m_{11} = \cos(2\pi Q_0) + \alpha\sin(2\pi Q_0) \tag{5.59}$$

$$m_{12} = \beta\sin(2\pi Q_0) \tag{5.60}$$

$$m_{21} = -\gamma\sin(2\pi Q_0) + K\delta[\cos(2\pi Q_0) + \alpha\sin(2\pi Q_0)] \tag{5.61}$$

$$m_{22} = \cos(2\pi Q_0) - \alpha\sin(2\pi Q_0) + \beta K\delta\sin(2\pi Q_0)ds \tag{5.62}$$

Now, we know that the **trace** is related to the new **tune**,

$$\cos(2\pi Q) = \frac{1}{2}\,\mathrm{tr}\,M = \frac{1}{2}\left[2\cos(2\pi Q_0) + \beta k_0\delta\sin(2\pi Q_0)ds\right] \tag{5.63}$$

IN the other hand, if we suppose that the change in the tune, $dQ = Q - Q_0$ is small,

$$\begin{aligned} \cos(2\pi Q) &= \cos[2\pi(Q_0 + dQ)] \\ &= \cos(2\pi Q_0)\cos(2\pi dQ) - \sin(2\pi Q_0)\sin(2\pi dQ) \\ &\approx \cos(2\pi Q_0) - 2\pi\sin(2\pi Q_0)dQ \end{aligned} \tag{5.64}$$

Chromaticity III

Equating the last two equations, we can solve for dQ

$$dQ = -\frac{K(s)\delta}{4\pi}\beta(s)ds \qquad (5.65)$$

and thus integrate around the ring to get the total **tune shift**,

$$\Delta Q = -\frac{\delta}{4\pi}\oint K(s)\beta(s)ds \qquad (5.66)$$

Finally, using the first definition of chromaticity (the most common), we get, in general for x and y, the

Natural chromaticity

$$\xi^N_{x,y} = -\frac{1}{4\pi}\oint K_{x,y}(s)\beta_{x,y}(s)ds \qquad (5.67)$$

The term *natural* refers to the fact that it arises from the quadrupoles, which are **linear** elements. Higher order multipoles such as sextupoles also contribute to the **total chromaticity**.

Of course, if we would've used the second definition,

$$\xi^N_{x,y} = -\frac{1}{4\pi Q_{x,y}}\oint K_{x,y}\beta_{x,y}ds \qquad (5.68)$$

and they are normalized to the tunes.

From the field expansion, we can see write for a **sextupole** in the horizontal plane:

$$B_y = b_2x^2 \qquad (5.69)$$

where

$$b_2 = \frac{1}{(B\rho)}\frac{\partial^2 B_y}{\partial x^2} \qquad (5.70)$$

Chromaticity IV

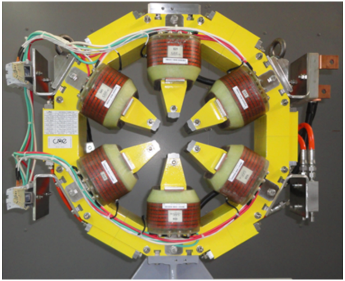
Substituting the orbit given by $x(s) = x_\beta(s) + \eta_x(s)\delta$,

$$B_y \approx b_2 x_\beta^2 + 2b_2 x_\beta \eta_x \delta \qquad (5.71)$$

having neglected the term in δ^2.

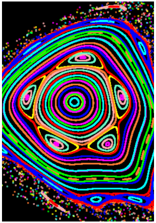
Note that the first term is **nonlinear**, while the second is linear (**quadrupole-like**).

Then, sextupoles also contribute to chromaticity (in a similar way to quadrupoles), and we have a



Total chromaticity

$$\xi_{x,y} = -\frac{1}{4\pi} \oint (K_{x,y}(s) \mp 2b_2(s)\eta_x(s))\beta_{x,y}(s)ds \qquad (5.72)$$



By an appropriate choice of b_2 (the **sextupole stength**) it is possible, in principle, to *correct* the chromaticity: if we make the integrand to vanish, ξ is **zero**.

Ring made of FODOs

For a machine composed of n_{cell} identical FODO, it follows that

Tune of ring made of FODOs

$$Q_{x,y} = n_{cell} \frac{\mu_{x,y}}{2\pi} \tag{5.73}$$

where $\mu_{x,y}$ is the phase advance of each cell.

It can also be shown that

Chromaticity of a FODO cell

$$\xi^N_{x,y} = -\frac{1}{\pi} \tan \frac{\mu_{x,y}}{2} \tag{5.74}$$

and therefore,

Chromaticity of ring of FODOs

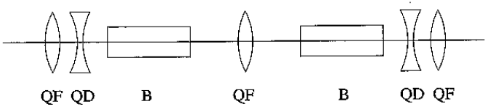
$$\xi^N_{x,y} = -\frac{1}{\pi} n_{cell} \tan \frac{\mu_{x,y}}{2} \tag{5.75}$$

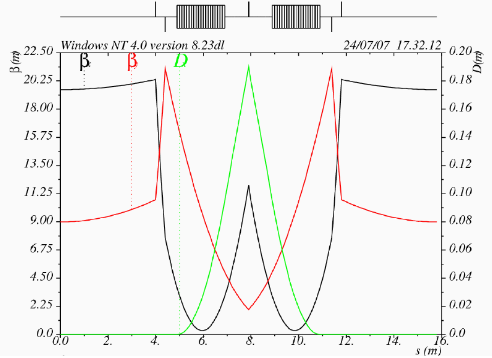
Achromatic insertions: DBA I

There exist insertions (arcs) that do not introduce dispersion.

The simplest of this structures is called **double bend achromat (DBA)**, and it is particularly useful in **light sources**.

In principle, dispersion can be suppressed by one focusing quadrupole and one bending magnet, and then matching the dispersion to zero outside the insertion with quadrupoles. This way dispersion is concentrated in the middle.





Mathematically:

$$M_{DBA} = (M_B M_D M_{QF/2})(M_{QF/2} M_D M_B) = M_{-DBA/2} M_{DBA/2} \tag{5.76}$$

Achromatic insertions: DBA II

Then, we impose

$$\begin{pmatrix} \eta_c \\ 0 \\ 1 \end{pmatrix} = M_{DBA/2} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad (5.77)$$

where f is the focal length of the focusing quadrupole, θ and L are the bend angle and length of the dipole, and L_1 is the distance between the dipole and center of the quad.

Solving we get the following condition:

$$f = \frac{1}{2}\left(L_1 + \frac{L}{2}\right) \qquad (5.78)$$

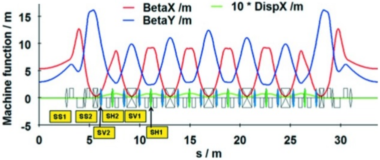
and the resulting dispersion is:

$$\eta_c = \left(L_1 + \frac{L}{2}\right)\theta \qquad (5.79)$$

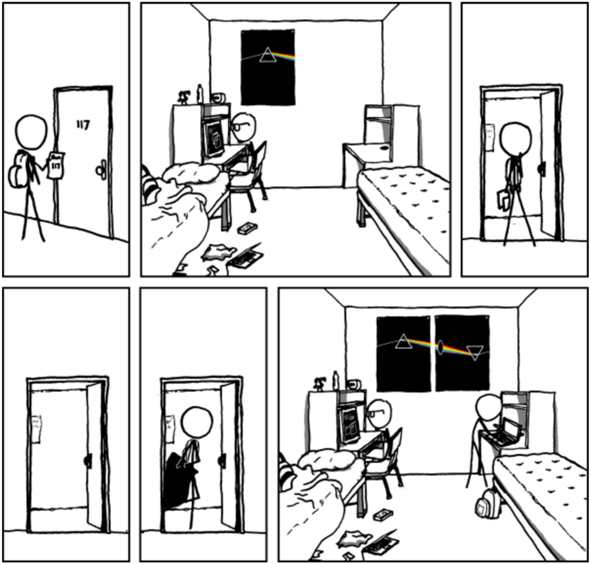
Each type of cell give rise an specific **natural emittance**.

Triple-, quadruple- and multiple- (or n-) bend achromats (TBA, QDA, MBA or nBA, respectively), are improvements to the DBA since their natural emittances are **lower** and lower...

Such bending achromats are widely used in **synchrotron light sources** (like the one under design in Mexico!)



Achromatic insertions: DBA III



http://www.xkcd.org/964/

Summary: Prerequisites, Lectures I to IV I

Lorentz factors:

$$\beta_r \equiv \frac{v}{c}, \qquad \gamma_r \equiv \frac{1}{\sqrt{1-\beta_r^2}}$$

Rest energy:

$$E_0 = mc^2$$

Total energy:

$$E = \gamma_r mc^2$$

Kinetic energy:

$$E_K = T = E - E_0 = (\gamma_r - 1)mc^2$$

Momentum:

$$p = \gamma_r m(\beta_r c) = \beta_r \frac{E}{c}$$

Electron-volt (eV):

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

Rigidity (in Tm):

$$(B\rho) = p/q$$

Rigidity (in practical units, valid only for a particle with $q = e$):

$$p\ [\mathrm{GeV/c}] \approx 0.3\ B\ [\mathrm{T}]\ \rho\ [\mathrm{m}]$$

Cyclotron (angular) frequency:

$$\omega = \frac{qB}{\gamma_r m}, \qquad f = \frac{\omega}{2\pi}$$

Betatron tunes:

$$Q_{x,y} = \frac{\phi_{x,y}(2\pi)}{2\pi}$$

Integrated dipole field over a circumference:

$$NBL_B = 2\pi \frac{p}{q}$$

Remember that $T = \frac{Vs}{m^2}$.

Summary: Prerequisites, Lectures I to IV II

Dipole (no focusing):

$$M_B = \begin{pmatrix} \cos\theta & \rho\sin\theta & 0 & 0 \\ -\frac{1}{\rho}\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & \rho\theta \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Drift:

$$M_D = \begin{pmatrix} 1 & s & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & s \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Quadrupole gradient:

$$G = \frac{B_{pole}}{a} = \frac{2\mu_0 NI}{a^2} \approx \frac{\partial B_y}{\partial x}$$

Quadrupole strength:

$$K \equiv \frac{1}{(B_0\rho)}\left(\frac{\partial B_y}{\partial x}\right) = \frac{G}{(B_0\rho)} \equiv k^2$$

Focusing quadrupole:

$$M_{QF} = \begin{pmatrix} \cos(ks) & \frac{1}{k}\sin(ks) \\ -k\sin(ks) & \cos(ks) \end{pmatrix}$$

Defocusing quadrupole:

$$M_{QD} = \begin{pmatrix} \cosh(ks) & \frac{1}{k}\sinh(ks) \\ k\sinh(ks) & \cosh(ks) \end{pmatrix}$$

Thin focusing quadrupole:

$$M_{QF} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$$

Thin defocusing quadrupole:

$$M_{QD} = \begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix}$$

Quadrupole focal length:

$$f = \frac{1}{KL} = \frac{1}{k^2 L}$$

Summary: Prerequisites, Lectures I to IV III

Thin lens approximation:

$$|f| \gg L$$

Hill's equation:

$$x'' + K(s)x = 0$$

K is periodic:

$$K(s+C) = K(s)$$

Courant-Snyder parameters (or Twiss functions):

$$\beta(s) \equiv w^2(s)$$

$$\alpha(s) \equiv -\frac{1}{2}\beta'(s)$$

$$\gamma(s) \equiv \frac{1+\alpha^2(s)}{\beta(s)}$$

Phase advance:

$$\phi(s) = \int_s \frac{d\tau}{\beta(\tau)}$$

Solution to Hill's equation:

$$x(s) = A\sqrt{\beta(s)}\cos[\phi(s) - \phi_0]$$

Periodic system (from $s_0 \to s_0 + C$):

$$M = \begin{pmatrix} \cos\phi_C + \alpha\sin\phi_C & \beta\sin\phi_C \\ -\gamma\sin\phi_C & \cos\phi_C - \alpha\sin\phi_C \end{pmatrix}$$

where

$$\phi_C = \int_{s_0}^{s_0+C} \frac{ds}{\beta(s)}, \qquad \text{and} \qquad \det M = 1$$

Stability condition:

$$\operatorname{tr} M = \cos\phi \quad \Rightarrow \quad -1 \le \frac{1}{2}\operatorname{tr} M \le 1 \quad \text{for } \phi \in \Re$$

Summary: Prerequisites, Lectures I to IV IV

Transverse Dynamics

Phase advance in a FODO cell:

$$\sin\frac{\phi_C}{2} = \pm\frac{L}{4f}$$

Max./min. beta in a FODO cell:

$$\beta^{\pm} = \frac{L}{\sin\phi_C}\left(1 \pm \sin\frac{\phi_C}{2}\right) \qquad (5.80)$$

General non-periodic system:

$$M = \begin{pmatrix} \sqrt{\frac{\beta(s)}{\beta(s_0)}}\left[\cos\Delta\phi + \alpha(s_0)\sin\Delta\phi\right] & \sqrt{\beta(s_0)\beta(s)}\sin\Delta\phi \\ -\frac{[\alpha(s)-\alpha(s_0)]\cos\Delta\phi + [1+\alpha(s_0)\alpha(s)]\sin\Delta\phi}{\sqrt{\beta(s_0)\beta(s)}} & \sqrt{\frac{\beta(s_0)}{\beta(s)}}\left[\cos\Delta\phi - \alpha(s)\sin\Delta\phi\right] \end{pmatrix}$$

Propagation of Courant-Snyder parameters (Twiss functions):

$$\begin{pmatrix} \beta(s) \\ \alpha(s) \\ \gamma(s) \end{pmatrix} = \begin{pmatrix} m_{11}^2 & -2m_{11}m_{12} & m_{12}^2 \\ -m_{11}m_{21} & m_{11}m_{22} + m_{12}m_{21} & -m_{12}m_{22} \\ m_{21}^2 & -2m_{21}m_{22} & m_{22}^2 \end{pmatrix} \begin{pmatrix} \beta(s_0) \\ \alpha(s_0) \\ \gamma(s_0) \end{pmatrix}$$

Hill's equation with dispersion:

$$x'' + K(s)x = \frac{\delta}{\rho(s)}, \qquad \text{with} \qquad K(s) = \frac{1}{\rho^2} + \frac{q}{p_0}\frac{\partial B_y}{\partial x} \qquad (5.81)$$

Summary: Prerequisites, Lectures I to IV V

Momentum deviation:

$$\delta = \frac{\Delta p}{p_0} \ll 1$$

Solution to Hill's equation with dispersion:

$$x(s) = x_\beta(s) + x_p(s)$$

where $x_\beta(s)$ is the solution to the homogeneous equation, and

$$x_p(s) = \eta(s)\delta$$

Extension of transport matrices to include dispersion:

$$\begin{pmatrix} C & S \\ C' & S' \end{pmatrix} \to \begin{pmatrix} C & S & D \\ C' & S' & D' \\ 0 & 0 & 1 \end{pmatrix}$$

where

$$\begin{aligned} D(s) &= S(s)\int_0^s \frac{C(\tau)}{\rho(\tau)}d\tau \\ &\quad -C(s)\int_0^s \frac{S(\tau)}{\rho(\tau)}d\tau \end{aligned}$$

Dispersion function:

$$\eta(s) = \frac{(1-S')D + SD'}{2(1-\cos\mu)} = \eta(s+C)$$

Drift (with dispersion):

$$M_D = \begin{pmatrix} 1 & L & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thin quad. (with dispersion):

$$M_{\substack{QF \\ QD}} = \begin{pmatrix} 1 & 0 & 0 \\ \mp\frac{1}{f} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Summary: Prerequisites, Lectures I to IV VI

Dipole (no focusing, with dispersion):

$$M_B = \begin{pmatrix} \cos\theta & \rho\sin\theta & \rho(1-\cos\theta) \\ -\frac{1}{\rho}\sin\theta & \cos\theta & \sin\theta \\ 0 & 0 & 1 \end{pmatrix}$$

Max./min. dispersion in a FODO cell:

$$\eta_x^{\pm} = \frac{L\theta_C}{4}\left(\frac{1 \pm \frac{1}{2}\sin\frac{\Delta\phi}{2}}{\sin^2\frac{\Delta\phi}{2}}\right)$$

Courant-Snyder invariant:

$$\mathcal{W} = \gamma x^2 + 2\alpha x x' + \beta {x'}^2$$

(Geometric) Emittance:

$$\epsilon_{x,y} = \pi \mathcal{W}_{x,y}$$

Beam size:

$$\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta_{x,y}(s)}$$

Normalized emittance:

$$\epsilon^N_{x,y} = \beta_r\gamma_r\epsilon_{x,y}$$

Tunes:

$$Q_{x,y} = \frac{\Delta\phi_{x,y}}{\Delta\theta} = \frac{1}{2\pi}\oint\frac{ds}{\beta_{x,y}(s)}$$

Chromaticity:

$$\Delta Q_{x,y} \equiv \xi_{x,y}\frac{\Delta p}{p}$$

Natural chromaticity:

$$\xi^N_{x,y} = -\frac{1}{4\pi}\oint K_{x,y}(s)\beta_{x,y}(s)ds$$

Total chromaticity:

$$\xi_{x,y} = -\frac{1}{4\pi}\oint\left[K_{x,y} \mp 2b_2\eta_x\right]\beta_{x,y}ds$$

Summary: Prerequisites, Lectures I to IV VII

Tune of ring made of n_{cell} FODOs:

$$Q_{x,y} = n_{cell}\frac{\mu_{x,y}}{2\pi}$$

Chromaticity of a FODO cell:

$$\xi^N_{x,y} = -\frac{1}{\pi}\tan\frac{\mu_{x,y}}{2}$$

Chromaticity of ring of FODOs:

$$\xi^N_{x,y} = -\frac{1}{\pi}n_{cell}\tan\frac{\mu_{x,y}}{2}$$

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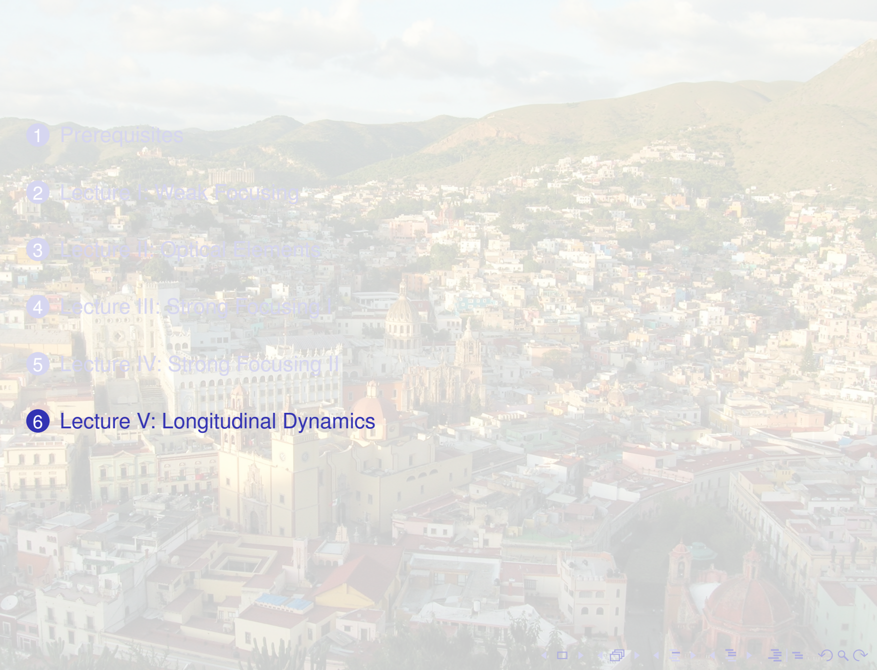
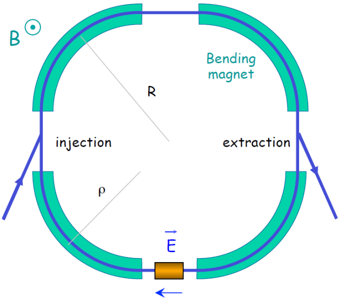


Transition energy I



Recall the **revolution frequency**, inverse to the **revolution period**,

$$f = \frac{1}{\tau} = \frac{\beta_r c}{C}, \qquad \omega = 2\pi f \qquad (6.1)$$

where C is the circumference, given by $C = 2\pi R$, with R the average radius of the synchrotron (different from ρ).

Deriving the following differential,

$$\frac{d\omega}{\omega} = \frac{d\beta_r}{\beta_r} - \frac{dC}{C} \qquad (6.2)$$

In order to rewrite the previous equation, remember that

$$p_0 = \gamma_r m(\beta_r c) = \frac{mc\beta_r}{\sqrt{1-\beta_r^2}} \qquad (6.3)$$

$$\Rightarrow \quad \frac{dp}{p_0} = \gamma_r^2 \frac{d\beta}{\beta} \qquad (6.4)$$

In the other hand, we define the

Momentum compaction factor

$$\alpha_p \equiv \frac{dC/C}{dp/p_0} \qquad (6.5)$$

which measures the dependence in an accelerator of the **length of the ideal orbit** with **momentum**.

Transition energy II

Example: *Velocity spread*

A typical value of δ is 10^{-3}. For a particle traveling near the speed of light, and with an energy corresponding to $\gamma_r = 10^4$, its momentum deviation corresponds to a velocity spread of

$$d\beta = \frac{\beta}{\gamma_r^2}\delta = \frac{c}{(10^4)^2} \cdot 10^{-3} \approx 3 \text{ mm/s}$$

Then, we can rewrite,

$$\frac{d\omega}{\omega} = \left(\frac{1}{\gamma_r^2} - \alpha_p\right)\frac{dp}{p_0} \tag{6.6}$$

The quantity in parenthesis defines the

Phase slip factor

$$\eta = \frac{1}{\gamma_r^2} - \alpha_p \tag{6.7}$$

Note that something special occurs when the **phase slip factor** (or simply slip factor) is **zero**. In this case we have the

Transition energy

$$\eta = 0 \quad \Rightarrow \quad \gamma_{tr} \equiv \frac{1}{\sqrt{\alpha_p}} \tag{6.8}$$

So, we can rewrite the phase slip factor as

$$\eta = \frac{1}{\gamma_r^2} - \frac{1}{\gamma_{tr}^2} \tag{6.9}$$

To summarize, when a particle in an accelerator has the **transition energy**, that is $U_{tr} = \gamma_{tr} mc^2$ (specific for that machine), then the phase slip factor is null, and the **particle revolution frequency does not depend on its momentum**, according to (6.6).

Transition energy III

For a ring made of FODOs, the momentum compaction factor is

$$\alpha_p \approx 1/Q_x^2 \tag{6.10}$$

Thus, the transition energy of the same ring is given by

$$\gamma_{tr} \approx Q_x \tag{6.11}$$

Two regimes exist then:

Below transition ($\gamma_r < \gamma_{tr}$)

- In this case, $\eta > 0$.
- Higher momentum (energy) results in higher revolution frequency.
- This is the case of strong focusing machines with low energy (for example at injection) and linear accelerators (since $\alpha_p = 0$*).

* The average radius is infinite.

Above transition ($\gamma_r > \gamma_{tr}$)

- In this case, $\eta < 0$.
- Higher momentum (energy) results in lower revolution frequency: this is called the **negative mass effect**.
- This is the case of strong focusing machines with high energy, and, in general, for **electron machines** (and thus, for synchrotron light sources), since typically $\gamma_r \gg \gamma_{tr}$.

Energy loss and RF acceleration I

Remember the **Lorentz force**,

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \tag{6.12}$$

So far, we have used the **magnetic field** to **deflect** the particles, and keep the bunches focused. This correspond to the **transverse dynamics**.

We are now interested in the **electric field** that, as we can see, acts along the **direction of motion**.

In the **longitudinal** plane, we have two effects:

- When particles are bend, they **lose energy** to **synchrotron radiation**.
- Particle bunches **spread** in the longitudinal plane (just as in the transverse plane, which is corrected by means of the strong **focusing**).

Note: From now on we will use U to denote energy instead of E to avoid confusion with the electric field.

For particles in machine with equal dipoles,

Energy loss per turn

$$U_\gamma = C_\gamma \frac{U^4}{\rho} \tag{6.13}$$

where

$$C_\gamma \equiv \frac{4\pi}{3} \frac{r_{e,p}}{(m_{e,p}c^2)^3} \tag{6.14}$$

$$= \begin{cases} 8.85 \times 10^{-5} \\ 7.79 \times 10^{-18} \end{cases} \tag{6.15}$$

in units of $\mathrm{m}/(\mathrm{GeV})^3$, and $r_{e,p}$ is the **classical electron/proton radius**,

Energy loss and RF acceleration II

$$r_{e,p} = \frac{q^2}{4\pi\epsilon_0 m_{e,p} c^2} \quad (6.16)$$

$$= \begin{cases} 2.82 \times 10^{-15} \text{ m} \\ 1.53 \times 10^{-18} \text{ m} \end{cases} \quad (6.17)$$

Note the big **difference** between **protons** and **electrons** in a circular machine!

Example: *Energy loss comparison*

For the LHC (proton machine) and a generic light source (electron machine), their beam energies and bending radius are 7 TeV with $\rho = 2.8$ km, and 2.5 GeV with $\rho = 6.9$ m, respectively.

Using (88) for each machine, the ratio of energy losses per turn is then

$$\frac{(U_\gamma)_{l.s.}}{(U_\gamma)_{LHC}} \approx \frac{0.5 \text{ MeV}}{6.7 \text{ keV}} = 75 \quad (6.18)$$

To overcome the two problems above, we use **RF fields**. With them,

- When can **restore** the **lost energy** to keep the beam at p_0 constant. Moreover, we can **accelerate** it as a whole.
- Keep the bunches focused (**phase stability**).

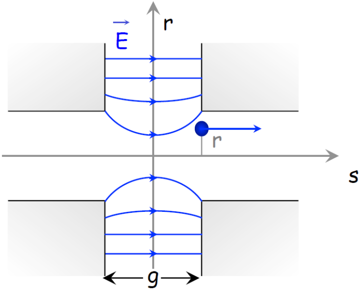
Such fields are provided by **RF cavities**. The potential difference between their two electrodes is used to accelerate particles. They run at a frequency ω_{rf} proportional to the **revolution frequency** of particles ω.

The **proportionality** is given by the

Harmonic number

$$\omega_{rf} = h\omega \quad (6.19)$$

Energy gain per turn

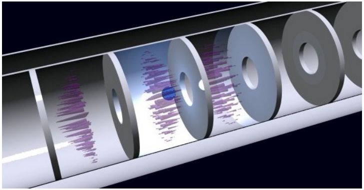


The electric field in a **short cavity** is

$$\vec{E}(s,t) = E(s,t)\hat{s}$$
$$= \hat{s} V_0 \sin(\omega_{rf} t + \phi_s) \quad (6.20)$$

where V_0 is the voltage amplitude and ϕ_s is the **synchronous phase** of the **synchronous particle** (the one that sees always the same phase (at each turn) in the RF cavity.

Careful! For **linear accelerators**, the convention is to use **cosine** instead of sine!



Gain in energy due to RF cavity

$$\Delta U = q V_0 \sin(\omega_{rf} \Delta t + \phi_s) \quad (6.21)$$

where Δt is the time difference w.r.t. the synchronous particle. Of course, for the synchronous particle,

$$\Delta U = q V_0 \sin \phi_s \quad (6.22)$$

Change in magnetic field

As the energy of the synchronous particle increases each turn, the magnetic field must increase in order to keep the particles in a **closed orbit** according to

Magnetic field increase

$$\dot{B} = \frac{\Delta U}{2\pi\rho R q} = \frac{V_0 \sin\phi_s}{2\pi\rho R} \quad (6.23)$$

Example: *Energy gain in the PS*

The ring of the Proton Synchrotron (PS), has $R = 100$ m, and $\dot{B} = 2.4$ T/s, and it is composed of 100 dipoles of 4.398 m. The harmonic number is 20.

We can compute the bending radius as follows: 100 dipoles of 4.398 m make a total length of 439.8 m. This length corresponds to circumference equal to $2\pi\rho$, thus $\rho = 70$ m.

The energy gain per turn is

$$\Delta U = 2\pi\rho R q \dot{B} = 2\pi(70\text{ m})(100\text{ m})e(2.4\text{ T/s}) = 106\text{ keV}$$

since $\text{T} = \text{Vs/m}^2$.

The minimum rf voltage required is obtained when $\sin\phi_s$ is maximum, that is, equal to 1. In that case,

$$V_0 = \frac{\Delta U}{q\sin\phi_s} = \frac{106\text{ keV}}{e\cdot 1} = 106\text{ kV}$$

Synchronous particle

Suppose that we **do not** want to accelerate the beam as a whole (for example, if the particles do not lose energy to radiation), and that we are below transition. Then,

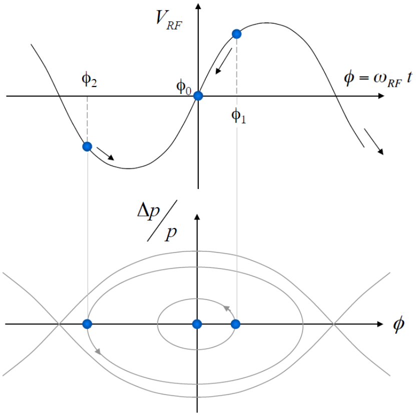
- The **magnetic field** in the dipoles remains **constant**.
- For the synchronous particle, $\phi_s = 0$, and therefore $E = 0$.

A particle at ϕ_1:

- Arrives **after** the synchronous particle.
- Sees a positive voltage and is **accelerated**.
- Next turn it will be closer to the synchronous particle.

A particle at ϕ_2:

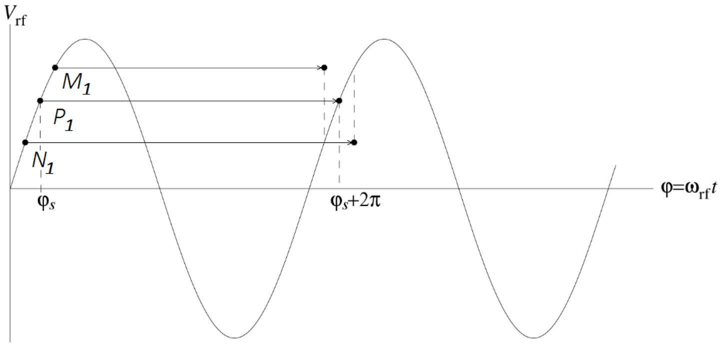
- Arrives **before** the synchronous particle.
- Sees a negative voltage and is **decelerated**.
- Next turn it will be closer to the synchronous particle.



In the longitudinal phase space (bottom), we can see such oscillations.

Phase Stability I

By design, particles at then synchronous phase ϕ_s gain just enough energy to balance radiation losses.

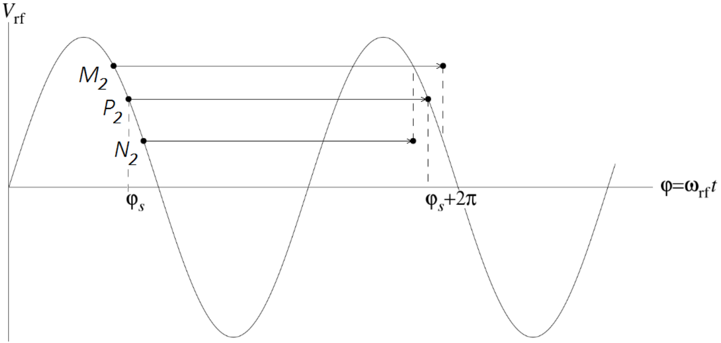


Below transition: linacs

- P_1 are the design particles: they *ride* the wave exactly in phase.
- Increased energy means increased frequency:
  - M_1 and N_1 move towards P_1 $\rightarrow$ Local stability (**Phase stability**).

Phase Stability II

By design, particles at then synchronous phase ϕ_s gain just enough energy to balance radiation losses.



Above transition: electron machine

- P_2 are the design particles: they *ride* the wave exactly in phase.
- Increased energy means decreased frequency:
  - M_2 and N_2 move towards P_2 $\rightarrow$ Local stability (**Phase stability**).

Synchrotron oscillations

We define the deviation from the synchrotron phase as

$$\varphi \equiv \phi - \phi_s \tag{6.24}$$

Since the electric force is sinusoidal, we expect the motion to be something like a pendulum.

Indeed, the **equation of motion** describing the **synchrotron oscillations** is

$$\ddot{\varphi} + \frac{h\omega_s^2 \eta q V_0}{2\pi\beta_r^2 U_s}\left[\sin(\phi_s + \varphi) - \sin\phi_s\right] = 0 \tag{6.25}$$

If this phase oscillations are **small**, the equation is **linearized** using

$$\sin(\phi_s + \varphi) \approx \varphi \cos\phi_s + \sin\phi_s \tag{6.26}$$

So we end up with a **simple harmonic oscillator**,

Small synchrotron oscillations

$$\ddot{\varphi} + \Omega_s^2 \varphi = 0 \tag{6.27}$$

where we define the

Synchrotron frequency

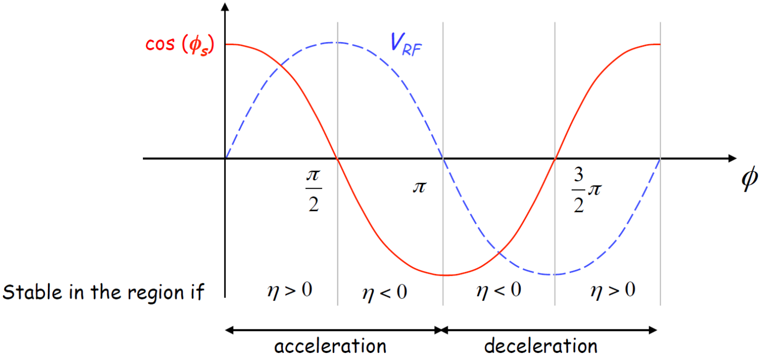
$$\Omega_s \equiv \omega_s \sqrt{\frac{h\eta\cos\phi_s}{2\pi\beta_r^2\gamma_r}\frac{qV_0}{mc^2}} \tag{6.28}$$

and the

Synchrotron tune

$$Q_s \equiv \frac{\Omega_s}{\omega_s} = \sqrt{\frac{h\eta\cos\phi_s}{2\pi\beta_r^2\gamma_r}\frac{qV_0}{mc^2}} \tag{6.29}$$

Phase stability (again)



We will not discuss large oscillations...

Phase stability is obtained when the angular frequency of the oscillator, Ω_s^2 is real positive. This implies that

Phase stability

$$\eta \cos \phi_s > 0 \qquad (6.30)$$

Longitudinal dynamics: final remarks

For acceleration:

- Below transition:

$$0 < \phi_s < \frac{\pi}{2}$$

$$\phi_s < \phi < \pi - \phi_s$$

- **At transition:**

$$\boldsymbol{\phi_s \rightarrow \phi_s = \pi - \phi_s}$$

- Above transition:

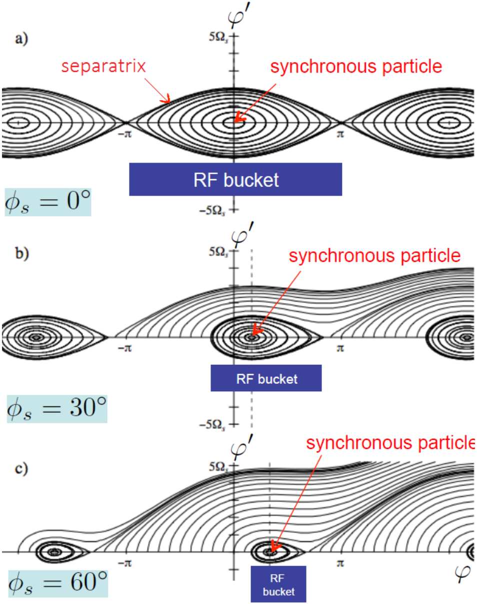
$$\frac{\pi}{2} < \phi_s < \pi$$

$$\pi - \phi_s < \phi < \phi_s$$

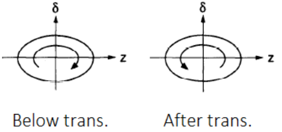
Longitudinal phase space: ϕ, s, or t, vs. ϕ', δ, or ΔE...

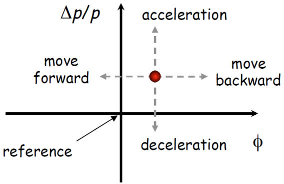
Bucket and **separatrix**.

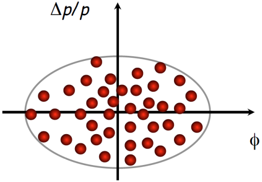
Longitudinal emittance, usually in [eV s].

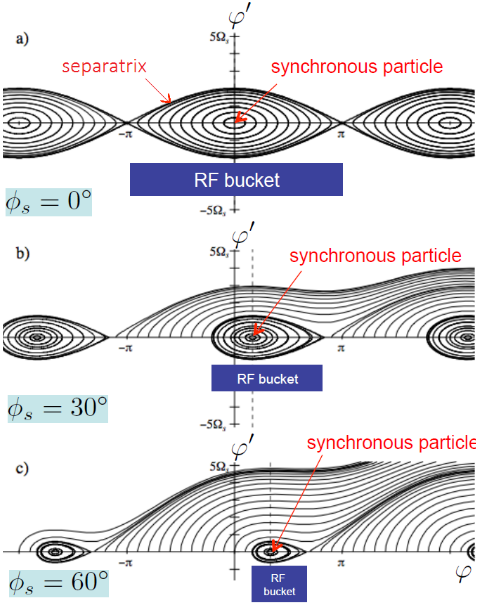


Longitudinal dynamics: final remarks









Summary: Lecture V I

Longitudinal Dynamics

Momentum compaction factor:

$$\alpha_p \equiv \frac{dC/C}{dp/p_0}$$

Phase slip factor:

$$\eta = \frac{1}{\gamma_r^2} - \alpha_p$$

Transition energy:

$$\eta = 0 \quad \Rightarrow \quad \gamma_{tr} \equiv \frac{1}{\sqrt{\alpha_p}}$$

Momentum compaction factor and transition energy of a ring made of FODOs:

$$\alpha_p \approx \frac{1}{Q_x^2}, \qquad \gamma_{tr} \approx Q_x$$

Below transition:	Above transition:
$\gamma_r < \gamma_{tr}$	$\gamma_r > \gamma_{tr}$
$\eta > 0$	$\eta < 0$
$0 < \phi_s < \frac{\pi}{2}$	$\frac{\pi}{2} < \phi_s < \pi$
$\phi_s < \phi < \pi - \phi_s$	$\pi - \phi_s < \phi < \phi_s$

At transition:

$$\phi_s \rightarrow \phi_s = \pi - \phi_s$$

Energy loss per turn:

$$U_\gamma = C_\gamma \frac{U^4}{\rho}$$

where

$$C_\gamma = \begin{cases} 8.85 \times 10^{-5} & \text{for electrons} \\ 7.79 \times 10^{-18} & \text{for protons} \end{cases}$$

in units of m/(GeV)^3.

Summary: Lecture V II

Longitudinal Dynamics

Harmonic number:

$$\omega_{rf} = h\omega$$

Gain in energy due to RF cavity:

$$\Delta U = qV_0 \sin(\omega_{rf}\Delta t + \phi_s)$$

Magnetic field increase:

$$\dot{B} = \frac{\Delta U}{2\pi\rho R q} = \frac{V_0 \sin\phi_s}{2\pi\rho R}$$

Small synchrotron oscillations:

$$\ddot{\varphi} + \Omega_s^2 \varphi = 0 \qquad (6.31)$$

Synchrotron frequency:

$$\Omega_s \equiv \omega_s \sqrt{\frac{h\eta\cos\phi_s}{2\pi\beta_r^2\gamma_r}\frac{qV_0}{mc^2}} \qquad (6.32)$$

Synchrotron tune:

$$Q_s \equiv \frac{\Omega_s}{\omega_s} = \sqrt{\frac{h\eta\cos\phi_s}{2\pi\beta_r^2\gamma_r}\frac{qV_0}{mc^2}} \qquad (6.33)$$

Phase stability:

$$\eta\cos\phi_s > 0$$

What's next?

- **Linear imperfections** and **non-linear dynamics**.
- Particle **tracking** and **dynamic aperture**.
- **Measurement** methods.
- Instabilities: **space charge**, **beam-beam**.
- **Colliders** and luminosity.
- Bunch **manipulations**.
- Polarization and spin dynamics.
- **Synchrotron radiation**.
- **Light sources** and FELs.

  ⋮