Tools for Lattice Design

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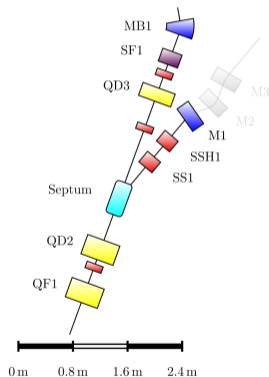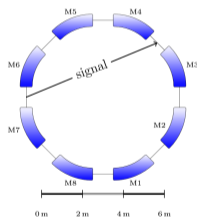
1 November 2019

Outline

- What do we mean by lattice?
- An arrangement of magnets to transport a beam of charged particles.

Drawing Lattices

- LaTeX package `tikz-palattice`.
- Nice way to visualise a lattice concept (if you are into LaTeX).

Lorentz Force

The force on a particle with charge q by electric field **E** and magnetic field **B** is the sum of the forces from these fields

$$F = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}).$$

For highly relativistic particles $v \sim c$ so the electric and magnetic fields have the same magnitude for $\mathbf{E} = c\mathbf{B}$. However, for $B = 1$ T which can easily be achieved technically, this equates to $E = 8 \times 10^8$ Vm^{-1}, which is beyond present engineering capabilities. Therefore we will concentrate on steering and focusing of charged particles in magnetic fields and analogous with light is called **beam optics**.

Transverse motion

Since magnetic fields produce forces perpendicular to the motion of a charged particle they cause transverse motion, i.e. in the horizontal and vertical planes. We can define our coordinate system as
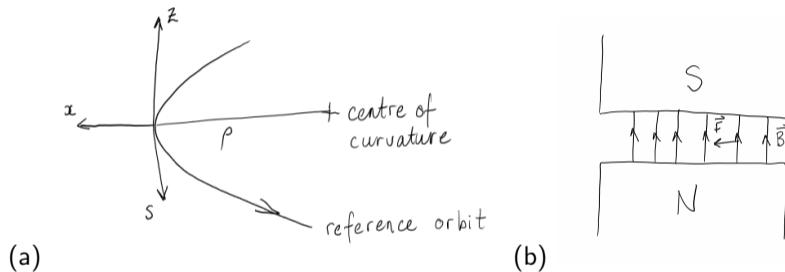

Figure 1: (a) Coordinate system for charged particle in motion in a magnetic field. (b) End view of a dipole magnet.

The coordinates are s which is tangent to the motion and follows along with the particle, x which is positive outwards along the radius of curvature and z which is positive vertically upwards.

Divergence

A beam consists of a bundle of trajectories which move about the reference orbit and have a certain divergence from the orbit s in each plane given by

$$x' = \frac{dx}{ds} \text{ and } z' = \frac{dz}{ds}.$$

In each plane a particle will have the coordinates (x, x', z, z') to describe their transverse motion. We use magnetic fields to chance the position x and direction x' as they move in an accelerator. We shall look at bending that force a particle in a horizontal (x) circular orbit, like in a storage ring, and at focusing magnets that contain the divergence x' and z' of the beam so the trajectories don't escape the machine.

Magnetic rigidity
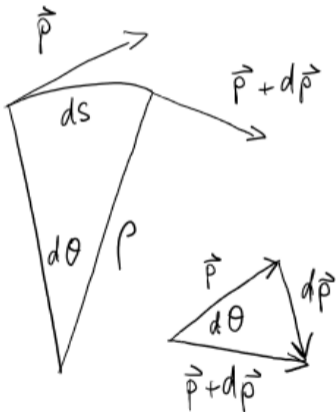
For relativistic momentum **p** a magnetic field **B** cases a change in momentum $d\mathbf{p}$ given by

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} = e\mathbf{v} \times \mathbf{B}$$

$$\frac{d|\mathbf{p}|}{dt} = |\mathbf{p}|\frac{d\theta}{dt} = \frac{|\mathbf{p}|}{\rho}\frac{ds}{dt}.$$

We can also rewrite magnitude of the Lorentz force as

$$e|\mathbf{v} \times \mathbf{B}| = e|\mathbf{B}|\frac{ds}{dt}$$

Magnetic rigidity

Combining the two equations we get what is know as the *magnetic rigidity*

$$B\rho = \frac{p}{e}.$$

If we work in units where the momentum is expressed as *pc* which are units of energy rather than units of momentum, then we get the formula
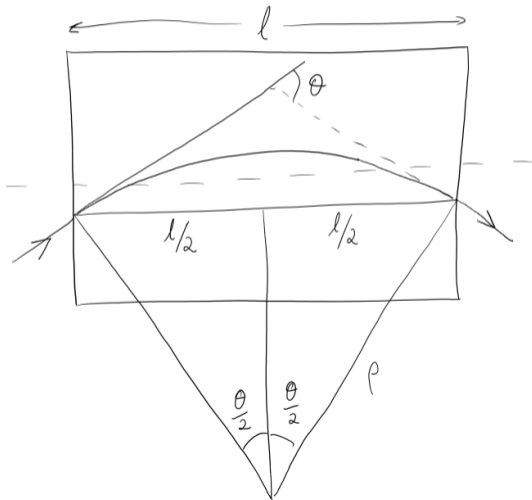
$$B\rho \ [\text{Tm}] = 3.34 \ [\text{GeV/c}]$$

For the CLS we get $B\rho \sim 9.7$ Tm.

Bending magnet

Now if we want to bend a beam by a certain angle θ we have the following:

From the geometry we get for small angles

$$\sin\frac{\theta}{2} = \frac{(\ell/2)}{\rho} = \frac{\ell B}{2(B\rho)}$$

$$\theta \approx \frac{\ell B}{B\rho}.$$

CLS bend magnet

For example, the CLS with the 2.9 GeV beam energy and the magnetic rigidity of 9.7 Tm, we have dipole magnets that are 1.873 m long with a field of 1.354 T, so we get a bend angle from one diople of

$$\theta_{bend} = \frac{\ell B}{2(B\rho)} = \frac{1.87 \cdot 1.35}{9.7} = 0.26 \text{ rad.}$$

Now we want the beam to go a full circle of 2π, so we need a number of these dipole in the CLS

$$N_{bend} = \frac{2\pi}{\theta_{bend}} = 24.$$

The bend magnets are arranged in pairs across 12 symmetrical cells to form a 24 sided polygon referred to as a ring for short hand.

Focusing

In visible light optics we are familiar with a focusing lens to magnify or concentrate light.

In geometric optics, light rays passing through a thin lens are deflected through an angle towards a focal point. Rays coming into the lens further from the horizontal axis are bent with a larger angle.
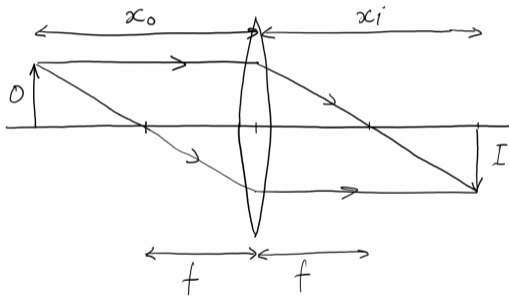
How do we construct such a lens to focus charged particles?
We need to construct a magnetic field that increases with distance from the reference orbit.

Quadrupole magnet

Instead of using two parallel poles to produce a uniform field, we use four poles with hyperbolic curve shapes on the poles to produce a field gradient. The field is cancelled at the centre of the quadrupole and increases linearly along the positive x-direction.
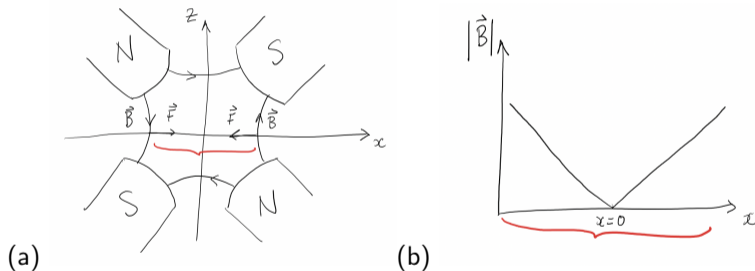

Figure 2: (a) End view of a quadrupole magnet. (b) Field of a quadrupole in the horizontal plane.

About the central point $x = 0$ the magnitude of the field increases in both directions, the opposite direction of the **B** field ensures the force is always pointing to the centre of the quadrupole.

Quadrupole strength

The strenght of the quadrupole can also be given in terms of the magnetic rigidity

$$k = \frac{1}{B\rho}\frac{dB_z}{dx}.$$

Then the angle of deflection of a particle at point x in a magnet of length l is

$$\Delta x' = \theta = \frac{\ell(dB_z/dx)x}{B\rho} = \ell k x.$$

Comparing to a focussing optical lens where the deflection is given by

$$\Delta x' = -\frac{x}{f},$$

we can define the focal length of a horizontally focusing quadrupole as

$$f = -\frac{1}{k\ell}$$

Mechanical analogy

If we place a series of these dipole and quadrupole magnets together we get bending and focusing forces analogous to a marble running down a gutter.
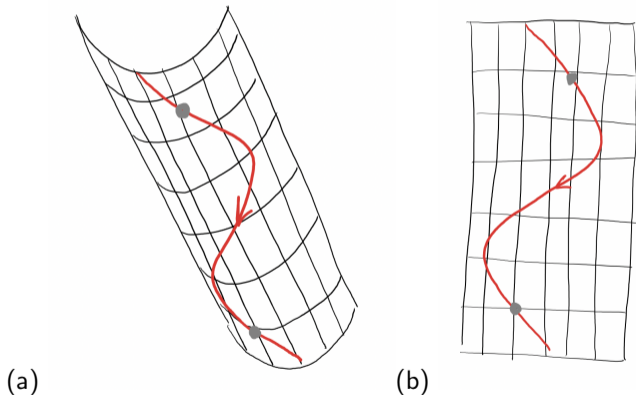

Figure 3: A marble running through a gutter (a) angle, (b) top view, as an analogy to a particle in a circular accelerator.

When we observe the position and angle of a particle at one point each time it circulates, it carves out an ellipse in $x - x'$ phase space.
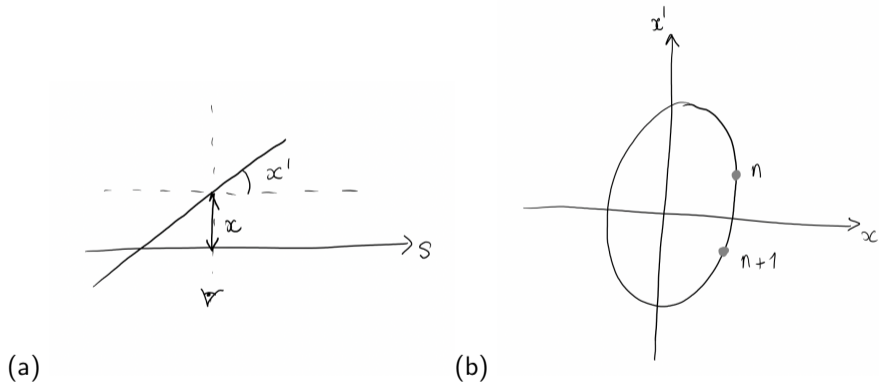

(a)   (b)

Figure 4: (a) Horizontal position and angle at a point in s. (b) Lucus of points traces out by a particle circulating in a storage ring.
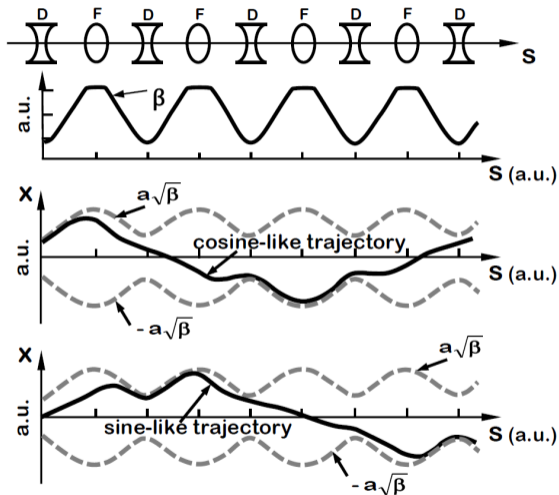
particle dynamics equation of motion

$$\frac{d\mathbf{p}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}), \frac{d\mathcal{E}}{dt} = \mathbf{F} \cdot \mathbf{v},$$

where we use the relativistic momentum and energy

$$\mathbf{p} = \gamma m \mathbf{v}, \mathcal{E} = \gamma m c^2.$$

Hills equation for linear motion in magnetic fields:

$$\frac{d^2 y}{ds^2} + K y(s) y = 0$$

A. Seryi, *Unifying Physics of Accelerators, Lasers and Plasma*, 2015.

Matrix formalism

- Goal: transport particle coordinates (x_1, x_1') to another point in the accelerator lattice (x_2, x_2').
- Require matrices that describe the that describe the function of field free *drifts*, dipoles, quadrupoles, etc. as determined from the equations of motion.
- Mainly focus on circular machines or transport lines with alernating gradients and strong focusing.
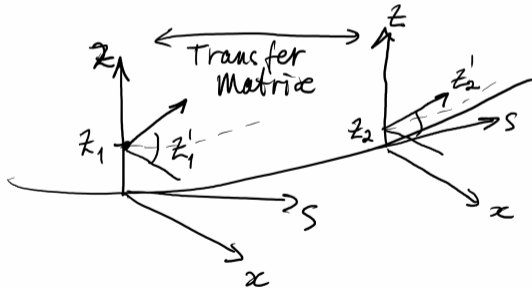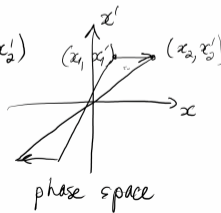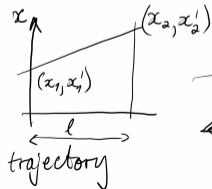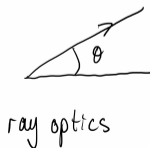
Example matrix – drift

Consider a particle with an initial position and angle (x_1, x_1') passing through a field-free drift space of lenth ℓ

$$\left(\begin{array}{c} x_2 \\ x_2' \end{array} \right) = \left(\begin{array}{cc} 1 & \ell \\ 0 & 1 \end{array} \right) \left(\begin{array}{c} x_1 \\ x_1' \end{array} \right).$$

We see the angle does not change but there is an additional position offset dependent on the initial angle.

$$x_2 = x_1 + \ell x_1'$$
$$x_2' = x_1'$$

ray optics   trajectory   phase space

Example matrix – quad

Consider a particle with an initial position and angle (x_1, x_1') passing through a thin quadrupole of strength k

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}.$$

We see the position does not change but there is an additional angle offset dependent on the initial position $x_2 = x_1$ and $x_2' = -\frac{x_1}{f} + x_1'$.
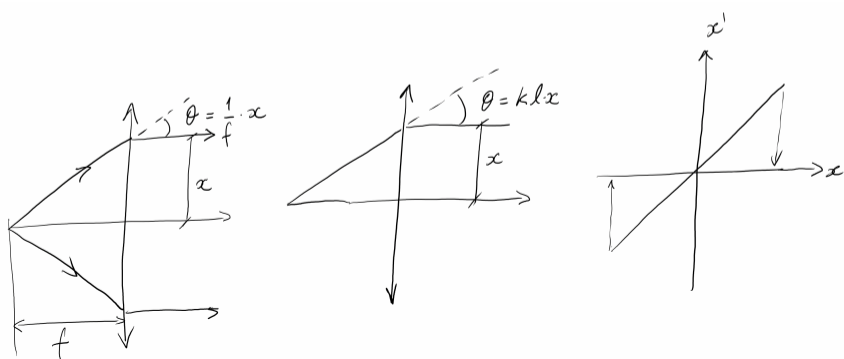
Recap of Hill's equation

Hill's equation (linear periodic coefficients), where y is used to denote either the x or z transverse coordinate.

$$\frac{d^2y}{ds^2} + k(s)y = 0,$$

where a restoring force at the quadrupoles is give by

$$k = -\frac{1}{B\rho}\frac{dB_z}{dx}.$$

A solution in the horizontal plane

$$x = \sqrt{\beta(x)\epsilon}\cos(\phi(s) + \phi_0).$$

Condition

$$\phi = \int \frac{ds}{\beta(s)}.$$

Property of a particular machine

$$\sqrt{\beta(s)}$$

Property of a particle beam ϵ. Physical meanings:

- Beam envelope $\sqrt{\beta(s)\epsilon}$.
- Maximum particle excursions $y = \sqrt{\beta(s)\epsilon}$ and $y' = \sqrt{\beta(s)/\epsilon}$.

Check Hill's equation

Differentiate $y = \sqrt{\beta(s)\epsilon}\cos(\phi(s) + \phi_0)$ and substitute $w = \sqrt{\beta}$ and $\phi = \phi(s) + \phi_0$ we get

$$y' = \sqrt{\epsilon}\left[w'(s)\cos\phi - \frac{d\phi}{ds}w(s)\sin\phi\right].$$

For a solution to this equation we need $\frac{d\phi}{ds} = \frac{1}{\beta(s)} = \frac{1}{w^2(s)}$. Substitute and differentiate again we get

$$y' = \sqrt{\epsilon}\left[w'(s)\cos\phi - \frac{1}{w(s)}\sin\phi\right]$$

$$y'' = \sqrt{\epsilon}\left[w''(s)\cos\phi 0 - \frac{w'(s)}{w^2(s)}\sin\phi + \frac{w'(s)}{w^2(s)}\sin\phi - \frac{1}{w^3}\cos\phi\right].$$

Now substitute into $y'' + ky = 0$

$$w'' - \frac{1}{w^3} + kw = 0.$$

This has no general analytical solution but if we put it back in terms of β we have the constraint

$$\frac{1}{2}\beta\beta'' - \frac{1}{4}\beta'^2 + k\beta^2 = 1.$$

The beam trajectory in the horizontal plane is then is described by the so called **beta function** $\beta(s)$ and the constant ϵ with the form

$$x(s) = \sqrt{\epsilon}\sqrt{\beta(s)}\cos(\phi(s) + \phi_0),$$

with

$$\phi(s) = \int_0^s \frac{d\sigma}{\beta(\sigma)}.$$

Liouville's theorem

We can re-write the constraint from Hill's equation as

$$\gamma(s)x^2(s) + 2\alpha(s)x(s)x'(s) + \beta(s)x'^2(s) = \epsilon,$$

where we define $\alpha(s) \equiv -\frac{1}{2}\beta'(s)$, $\beta(s) \equiv w(s)^2$ and $\gamma(s) \equiv \frac{1+\alpha^2(s)}{\beta(s)}$. This is the definition of the $x - x'$ phase ellipse from the equations of motion and Liouville's theorem states that the area of this phase ellipse remains constant in time. This theorem and the equations of motion do not strictly hold during acceleration for particles synchrotron radiation damping, the phase ellipse can shrink in these situations. The area of an ellipse with major and minor axes a, b has an area $A = ab\pi$, so we can find that the area of the phase space motion of a particle in an accelerator is $A = \pi\epsilon$. ϵ is also know as the Courant-Snyder invariat for a single particle. We can then draw the ellipse which is then defined for every point along the path s in an accelerator.
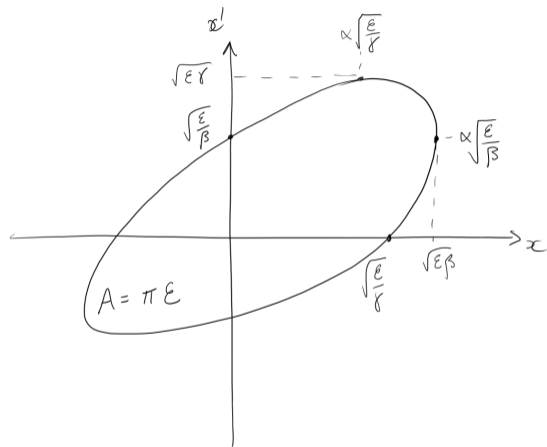
Phase ellipse

Figure 5: Phase ellipse of Courant-Snyder invariant in $x - x'$ at a single point s.

Twiss Matrix

Now let us construct a matrix that takes us from point 1 to point 2 in the machine

$$\begin{pmatrix} y(s_2) \\ y'(s_2) \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} y(s_1) \\ y'(s_1) \end{pmatrix} = \mathbf{M}_{12} \begin{pmatrix} y(s_1) \\ y'(s_1) \end{pmatrix}$$

We use $w = \sqrt{\beta}$ and $\phi = \frac{1}{\beta} = \frac{1}{w^2}$ and have

$$y = \sqrt{\epsilon} w \cos(\phi + \phi_0)$$
$$y' = \sqrt{\epsilon} w' \cos(\phi + \phi_0) - \frac{\sqrt{\epsilon}}{w} \sin(\phi + \phi_0)$$

We can construct two solutions, one with initial condition $\phi_0 = 0$ the so-called *cosine solution* $C(s)$, and one $\phi_0 = \pi/2$ the *sine solution* $S(s)$. We then can place these in the matrix equation and solve for a, b, c, d to find the matix elements.

Twiss Matrix cont.

Writing $\phi = \phi_2 - \phi_1$ the matrix elements are

$$\mathbf{M}_{12} = \begin{pmatrix} \frac{w_2}{w_1} \cos\phi - w_2 w_1' \sin\phi & w_1 w_2 \sin\phi \\ -\frac{1 + w_1 w_1' w_2 w_2'}{w_1 w_2} \sin\phi - \left(\frac{w_1'}{w_2} - \frac{w_2'}{w_1}\right) \cos\phi & \frac{w_1}{w_2} \cos\phi + w_1 w_2' \sin\phi \end{pmatrix}$$

If we now simplify the situation to where system is periodic from $1 \rightarrow 2$, then $w_1 = w_2 = w, w_1' = w_2' = w', \mu = \phi_2 - \phi_1$, the matrix becomes

$$\mathbf{M} = \begin{pmatrix} \cos\mu - ww' \sin\mu & w^2 \sin\mu \\ -\frac{1 + w^2 w'^2}{w^2} \sin\mu & \cos\mu + ww' \sin\mu \end{pmatrix}$$

Twiss Matrix cont.

Using the definition of the Twiss parameters from before we get α, β, γ (not to be confused with the relativistic β, γ!)

$$\alpha = -ww' = -\frac{\beta'}{2},$$
$$\beta = w^2,$$
$$\gamma = \frac{1 + (ww')^2}{w^2} = \frac{1 + \alpha^2}{\beta}.$$

The Twiss matrix can be simplified further to

$$\mathbf{M} = \begin{pmatrix} \cos\mu + \alpha\sin\mu & \beta\sin\mu \\ -\gamma\sin\mu & \cos\mu - \alpha\sin\mu \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

We can now construct a lattice of a series of elements with a matrix defined for each element. This is practically how accelerators and transfer lines are designed and their properties calculated.

Lattice

Practically the solutions to the matrix equations are calculated with computers.
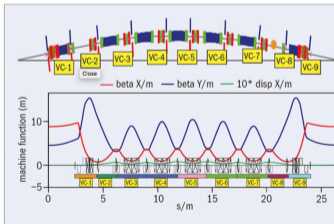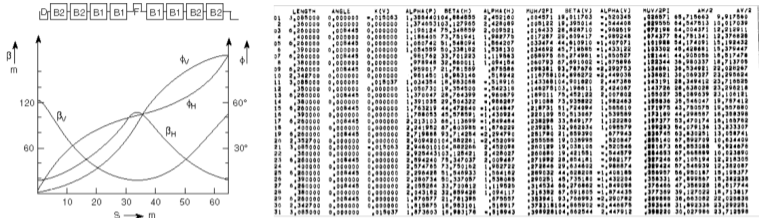
Figure 6: Twiss parameters as a function of s.

Combining elements

To calculate a trajectory through a series of elements $\mathbf{M}_i$ we just multiply the matrices together to get for example

$$\mathbf{X}_E = \mathbf{M}_{D4} \cdot \mathbf{M}_{Q3} \cdot \mathbf{M}_{D3} \cdot \mathbf{M}_{Q2} \cdot \mathbf{M}_{D2} \cdot \mathbf{M}_{Q1} \cdot \mathbf{M}_{D1} \cdot \mathbf{X}_0$$
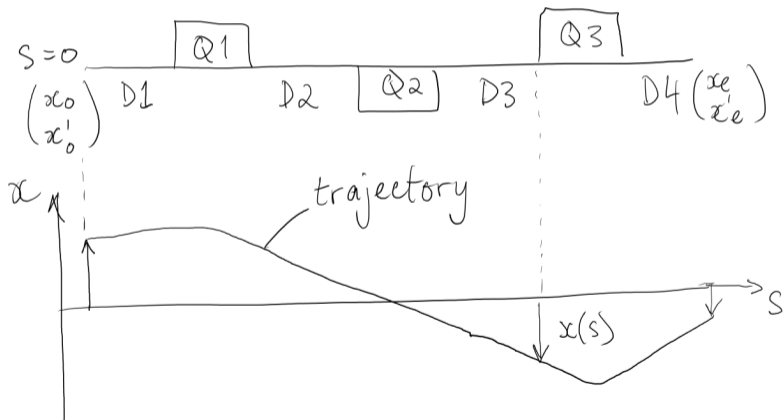
Focusing doublet

For a pair of thin lenses with focusing power f_1, f_2 with a drift space length L in between we get

$$\mathbf{M}_x^{1\to 2} = \begin{pmatrix} 1 & 0 \\ \frac{1}{f_2} & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{pmatrix} = \begin{pmatrix} 1 - \frac{L}{f_1} & L \\ -\frac{1}{f^*} & 1 + \frac{L}{f_2} \end{pmatrix}$$

where

$$\frac{1}{f^*} = \frac{1}{f_2} - \frac{1}{f_2} + \frac{1}{f_1 f_2}$$

For example when $f_1 = f_2$ we get focusing in both planes through the quadrupole doublet.

FODO latice example

We can construct a lattice with a series of horizontally focusing (F) and defocusing quadrupoles (D) spaced by drifts (O) to form a so called FODO cell
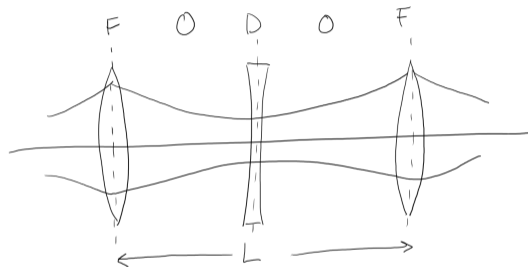
$$\mathbf{M}_{\text{FODO}} = \begin{pmatrix} 1 & \frac{L}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{L}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$$

$$\mathbf{M}_{\text{FODO}} = \begin{pmatrix} 1 - \frac{L}{2f} - \frac{L^2}{4f^2} & L + \frac{L^2}{4f} \\ -\frac{L}{2f^2} & 1 + \frac{L}{2f} \end{pmatrix}$$

Stability criteria

For a particle to follow a stable trajectory through N periods and k orbits we need the following product of matrices to not diverge

$$\{M(s)\}^{Nk}.$$

To check this we write out the eigenvalue problem for coordinates (y, y') as **Y** and Twiss matrix **M**(s) as

$$\mathbf{MY} = \lambda \mathbf{Y}.$$

The solutions are then

$$\det(\mathbf{M} - \lambda I) = 0,$$

so we get

$$\lambda^2 - \lambda(a + d) + 1 = 0.$$

Stability criteria cont.

We can find that the Twiss matrix has det $\mathbf{M} = 1$ and

$$\cos\mu = \frac{1}{2}\mathrm{Tr}\mathbf{M} = \frac{1}{2}(a+d),$$

then we get

$$\lambda = \cos\mu \pm i\sin\mu = e^{\pm i\mu}.$$

So for a non-exponential growth or decay μ must be real and so

$$|\frac{1}{2}\mathrm{Tr}\mathbf{M}| \leq 1,$$

and

$$|\lambda| = 1,$$

where λ is complex, $|a+ib| = \sqrt{a^2+b^2}$. So, to test stability of a Twiss matrix $\mathbf{M}$ we can compute these values numarically.

Equation for off-momentum particles

So far we have dealt with particles of the same momentum, now lets add an off-momentum particle with momentum deviation $\Delta p / p$. For simplicity we have only bends and no gradients, then equation of motion is

$$x'' + \frac{1}{\rho^2} x = \frac{1}{\rho} \frac{\Delta p}{p}.$$

We define a special trajectory $D(s)$ for which $\Delta p / p = 1$ which we call the dispersion function and we get

$$D''(s) + \frac{1}{\rho^2} D(s) = \frac{1}{\rho} \frac{\Delta p}{p}.$$

Then our new particle trajectory consider the possibility of off-momentum particles is

$$x(s) = x_0(s) + x_D = x_0(s) + D(s) \frac{\Delta p}{p}$$

Matrix for off-momentum particles

To account for this momentum deviation we add an extra term to our matrix to transform the particle motion in both planes and in momentum

$$
\begin{pmatrix} x(s) \\ x'(s) \\ z(s) \\ z'(s) \\ \Delta p/p \end{pmatrix} = M \cdot \begin{pmatrix} x_0 \\ x_0' \\ z_0 \\ z_0' \\ \Delta p/p \end{pmatrix}
$$

Since off-momentum particles will not have same the path length L of the reference orbit, they will have a path difference ΔL. We can define this relative path length change as a ratio of the relative momentum change as the **momentum compaction factor**

$$
\alpha_c = \frac{\Delta L/L}{\Delta p/p}
$$

Computer Codes

Real accelerators do not behave like Hill's equation, so we need better physics and computer models!

While it was possible in the 1950s and even later, to design an accelerator with pencil and paper, it is impossible today to design a beast like the LHC without the help of a tracking/design code.

– Etienne Forest, From Tracking Code to Analysis (2016).

Mark Oliphant, Birmingham, 1950s.

Mark Oliphant notebook extract, 1943.
University of Adelaide Oliphant archives.

M. Oliphant, The Acceleration of Particles to Very High Energies, Memo for UK Atomic Energy Directorate (1943).

The Synchrotron—A Proposed High Energy Particle Accelerator

EDWIN M. McMILLAN
University of California, Berkeley, California
September, 5, 1945

ONE of the most successful methods for accelerating charged particles to very high energies involves the repeated application of an oscillating electric field, as in the cyclotron. If a very large number of individual accelerations is required, there may be difficulty in keeping the particles in step with the electric field. In the case of the cyclotron this difficulty appears when the relativistic mass change causes an appreciable variation in the angular velocity of the particles.

The device proposed here makes use of a "phase stability" possessed by certain orbits in a cyclotron. Consider, for example, a particle whose energy is such that its angular velocity is just right to match the frequency of the electric field. This will be called the equilibrium energy. Suppose

McMillan, Phys Rev 68 p143 (1945)

Concerning Some New Methods of Acceleration of Relativistic Particles

V. VEKSLER
Lebedev Physical Institute of the Academy of Sciences, Moscow, U.S.S.R.
February 16, 1946

IN two papers[1,2] appearing in 1944 under the above title the author of the present letter pointed out two new principles of acceleration of relativistic particles which generalize the resonance method.

New possibilities for the resonance acceleration of particles in a constant magnetic field are described in the first of these papers, and the possibility of resonance acceleration in magnetic fields which increase with time is also noted.

This latter case is specially examined in the second paper. It is shown that phase stability automatically sets in if the time variation of the field is sufficiently small; relation between the amplitude of the variable electric fields and the rate of variation of the magnetic field is established.

It is also pointed out that the radiation losses in such acceleration do not violate phasing mechanism. Finally in a detailed paper[3] an accelerator of heavy particles based on a variation in frequency is analyzed.

Thus the foregoing papers cover completely the contents of the note by McMillan[4] in which no reference is made to my investigations.

Construction of a 30-Mev accelerator with varying magnetic field is now nearing completion at the Physical Institute of the Academy of Sciences, U.S.S.R.

[1] V. Veksler, Comptes Rendus (Doklady), Acad. Sci. U.S.S.R. **43**, No. 8, 444 IX (1944) (communicated April 25, 1944).
[2] V. Veksler, Comptes Rendus (Doklady), Acad. Sci. U.S.S.R. **44**, No. 9, 393 (1944) (communicated July 19, 1944).
[3] V. Veksler, J. Phys. (U.S.S.R.) **9**, No. 3, 153 (1945) (received March 1, 1945).
[4] E. McMillan, Phys. Rev. **68**, 143 (1945).

Veksler, Phys Rev 69 p244 (1946)

Marcus Laurence Elwin Oliphant (1901–2000)

Australian physicist
Inventor of the synchrotron
Pioneered centimeter radar and the atomic bomb

Mark Oliphant was an impressive individual, tall, with thick white hair. He spoke convincingly and energetically and in later life described himself as "a belligerent pacifist." Educated at Adelaide University, he joined Ernest Rutherford's group at the Cavendish Laboratory, Cambridge in 1927. He and Rutherford were the first to identify tritium and helium-3 produced by bombarding light nuclei with protons and deuterons.

By 1937 he was a Professor at Birmingham and, charged with overseeing Britain's coastal defenses, saw the clear need to use a radar wavelength much shorter than the 170 cm then current. His department set about developing a suitable power source and before long John Randall and Harry Boot from his department invented the magnetron. This was a device that made it possible for aircraft to carry their own radar and upon which the fate of the war hinged. He took this precious gift to the USA in 1941 where there were the resources to develop and mass produce it.

Andrew Sessler and Edmund Wilson, *Engines of Discovery – A Century of Particle Accelerators*, World Scientific, Singapore (2007).

The Best Tool

The best tool for optics design is your own brain.

- Trust but verify the results of a calculation.
- *A trades person never blames their tools.*
- Remember a useful design will need to be engineered someday, so take practical considerations into account with your optics design quite early on in the process. E.g. magnets probably can't be touching...
- Try to get to know the applicability and limits of the tool you use, example disclaimer:

Limitations of the beam TRANSPORT code:
For TRANSPORT the equation of motion is solved by applying a Taylor series up to second (or third) order and using the matrix formalism to compute the propagation of the beam through a beam line.
Therefore TRANSPORT calculations are usually describing a beam accurate enough in the paraxial approximation {sines and tangents of the angles can be replaced with the angles (valid up to about 100 mr or 5 degrees)}.
As long as the 5 first order sine- and cosine-functions (cx, sx, dx, cy and sy) and their derivatives are small as feasible through the used magnetic or electrostatic elements, then aberrations (2nd and higher order terms) remain reasonable small.
If above conditions are not fulfilled, then a ray-tracing program, which solves the equation of motion through 4th order Runge-Kutta integration should be used for checking the validity of the results computed with the beam TRANSPORT code.

MADX example description

From Todd Satogata:
There are many other codes available for beamline design, particle tracking, electromag-netic field calculations, plasma calculations, and other diverse areas of research in accelerator physics. MADX does some things extremely well (particularly optics design and matching), and some things reasonably well (tracking or pushing particles through magnets like in large accelerators). There are some things it does not do very well though:

- Acceleration and tracking simultaneously. (esme and BLonD are better longitudinal dynamics engines.)
- Not very good approximations for large excursions, particularly largeas found inFFAGs.
- Tracking through spatial descriptions of measured magnetic fields ("field maps": elegant and zgoubi are better at this).
- Very complicated magnet geometries (where field maps are usually better descriptions than multipole coefficients anyway).

It is likely that you have been exposed to some already and will be exposed to many moreover the course of your career.

Transport Codes

A convenient list is available on the Wikipedia Accelerator Code Page
`https://en.wikipedia.org/wiki/Accelerator_physics_codes`.
Here is a summary list of some of the maintained codes:

- MADX – CERN defacto standard code `https://mad.web.cern.ch/mad/`
- MATLAB Accelerator Toolbox – from SLAC, now maintained at atcollab
  `http://atcollab.sourceforge.net/`
- Elegant `https://www.aps.anl.gov/Accelerator-Operations-Physics/Software#elegant`
- OPA `https://ados.web.psi.ch/opa/`
- OPAL `https://gitlab.psi.ch/OPAL/src/wikis/home`
- Zgoubi – developed at Brookhaven `https://zgoubi.sourceforge.io/`, active user community
  `https://zgoubi-workshop.com/`
- G4beamline – hybrid accelerator and particle/nuclear physics code
  `http://www.muonsinternal.com/muons3/G4beamline`
- SIMION (commercial code) – `https://simion.com/` (Initially developed by Don McGilvery, my
  colleague at the Australian Synchrotron, for his PhD in 1978.)

<p style="text-align:center; color:red;">Choose the right tool for the right job!</p>

From Code to Commissioning

More realistic codes have enabled machines such as the LHC to be commissioned rapidly with high accuracy. There are also tools that are being developed to simulate commissioning which allow for better understanding machines and helping to foresee issues during the design phase.

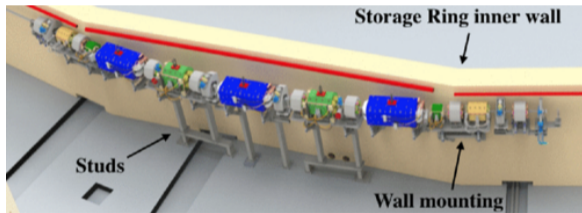- ALS-U accumulator ring commissioning tools, published October 2019
  https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.22.100702.
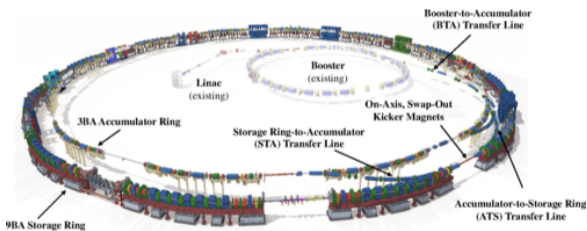
ALS-U new accumulator and storage rings.
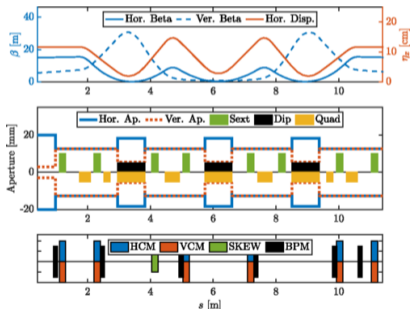
ALS-U AR optics for one sector.
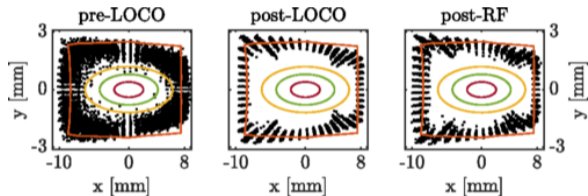
ALS-U AR mechanical design.
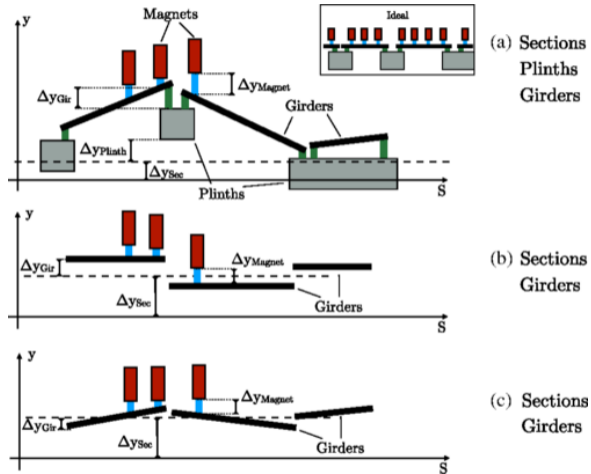
ALS-U AR misalignment model.

ALS-U AR Example
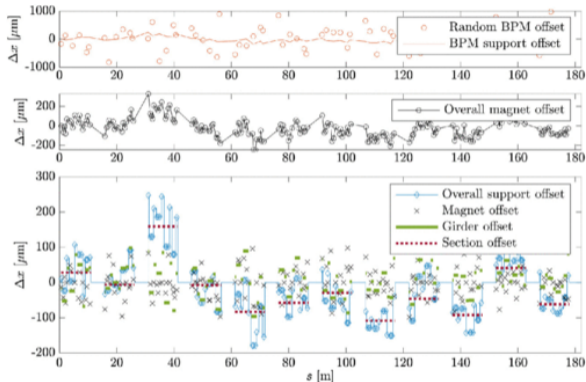
ALS-U AR possible offsets baased on mechanical design.
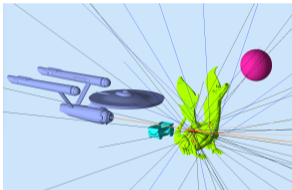

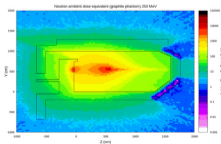ALS-U AR dynamic aperture improvements using the commissioning model.

Supplementary Codes

- GEANT4 – possibility to add many physics processes, not just EM fields, e.g. particle decay, say muon beams.
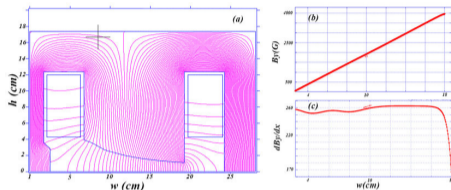 `https://geant4.web.cern.ch/`

- Fluka – radiation shielding considerations.
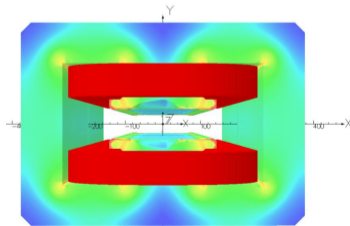 `http://www.fluka.org/`

- Poisson – 2D magnet calculations.

- Opera – 3D magnet calculations.

Resources

- Book to get started – Volker Ziemann, Hands-On Accelerator Physics Using MATLAB, CRC Press (2019). `https://www.crcpress.com/Hands-On-Accelerator-Physics-Using-MATLAB/Ziemann/p/book/9781138589940`
- Book with advanced details – Etienne Forest, From Tracking Code to Analysis, Springer (2016). `https://www.springer.com/gp/book/9784431558026`
- USPAS course material `https://uspas.fnal.gov/materials/materials-table.shtml`
- Example class Satogata and Peggs in 2019 `http://toddsatogata.net/2019-USPAS/`
- CAS courses `http://cas.web.cern.ch/` and CDS proceedings, search for CAS `https://cds.cern.ch/`
- Example class from Ziemann tutorial from CAS 2018 `http://ziemann.web.cern.ch/ziemann/teaching/cas/2018/`

Have fun designing your future collider!
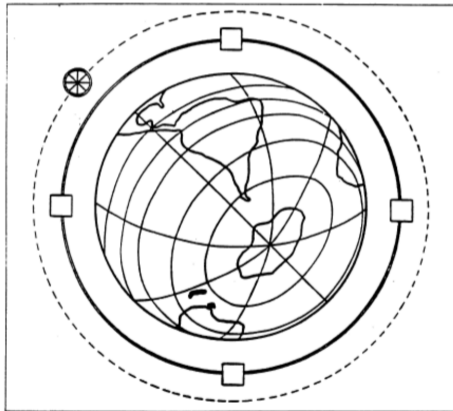
From a 1954 Slide by Enrico Fermi, University of Chicago Special Collections.