Introduction to Transverse Beam Dynamics

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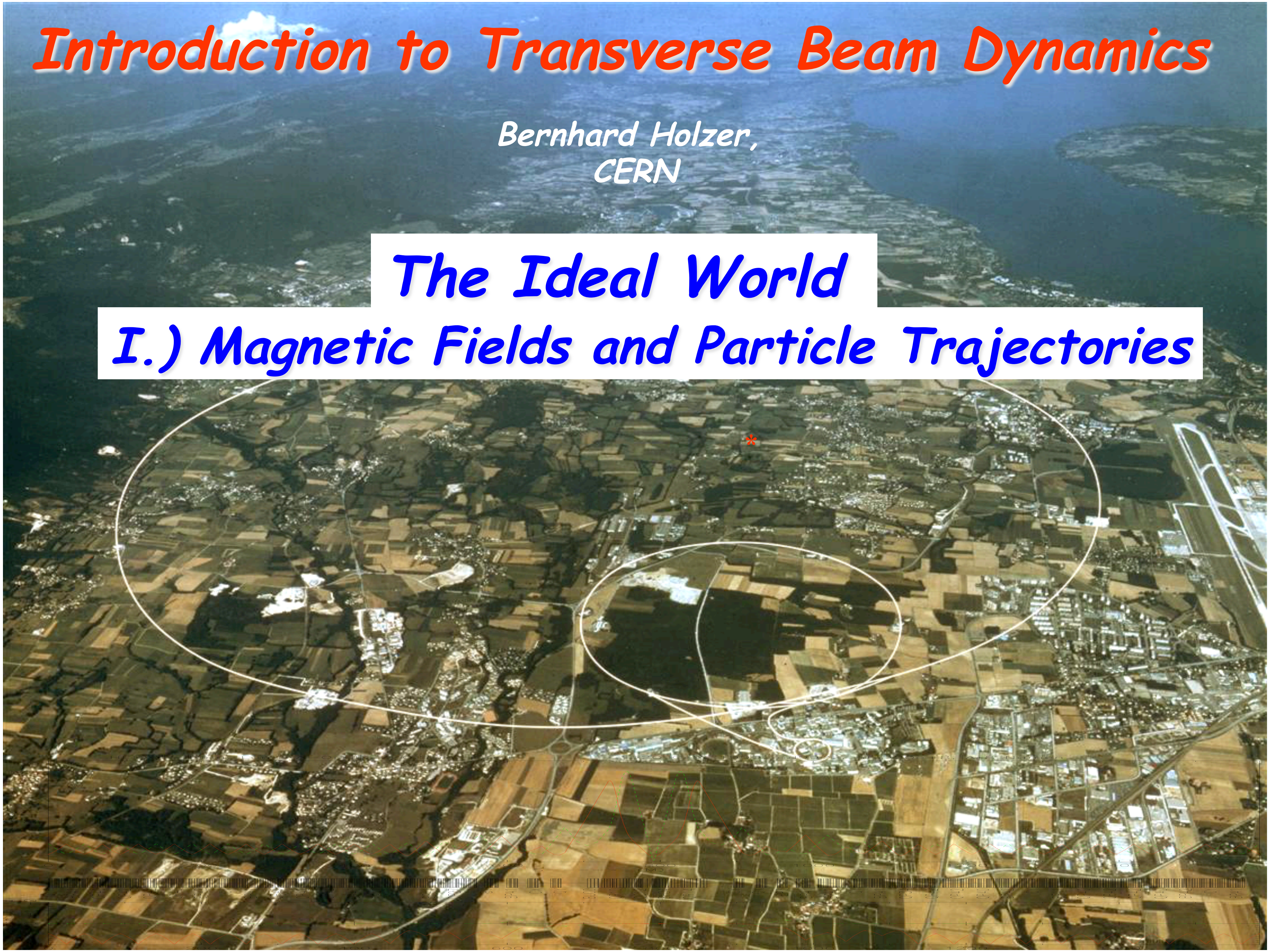
The Ideal World

I.) Magnetic Fields and Particle Trajectories



Luminosity Run of a typical storage ring:

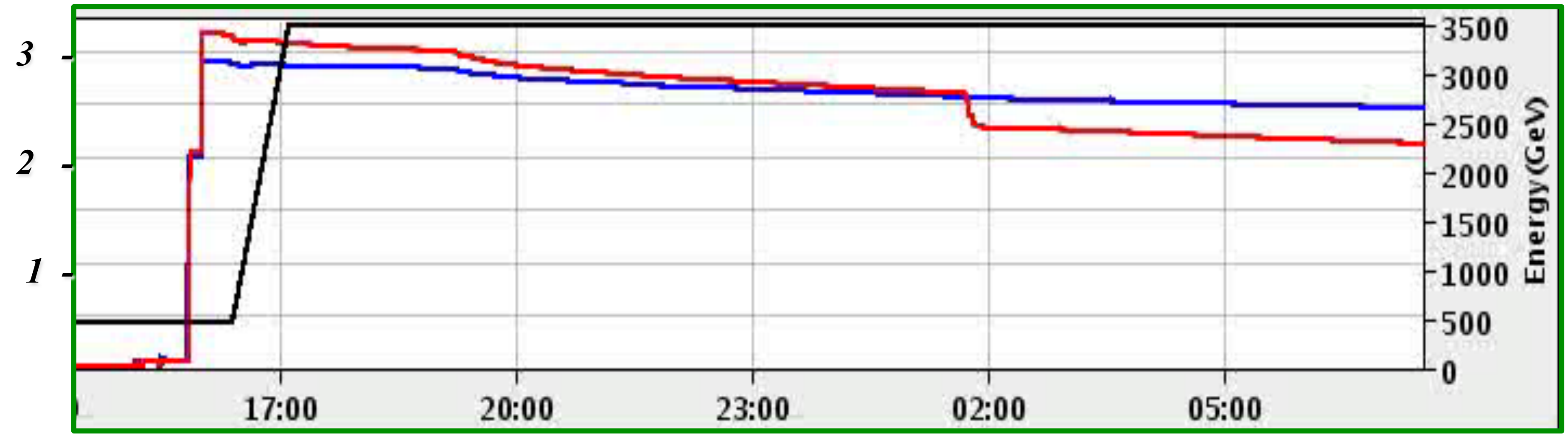
LHC Storage Ring: Protons accelerated and stored for 12 hours

distance of particles travelling at about $v \approx c$

$L = 10^{10}$-10^{11} km

... several times Sun - Pluto and back ♪

intensity (10^{11})



→ *guide the particles on a well defined orbit („design orbit")*

→ *focus the particles to keep each single particle trajectory within the vacuum chamber of the storage ring, i.e. close to the design orbit.*

Transverse Beam Dynamics:

0.) Introduction and Basic Ideas

„ ... in the end and after all it should be a kind of circular machine"

→ need transverse deflecting force

Lorentz force $$F = q\,(\cancel{\vec{E}} + \vec{v} \times \vec{B})$$

typical velocity in high energy machines: $$v \approx c \approx 3 * 10^8 \ \frac{m}{s}$$

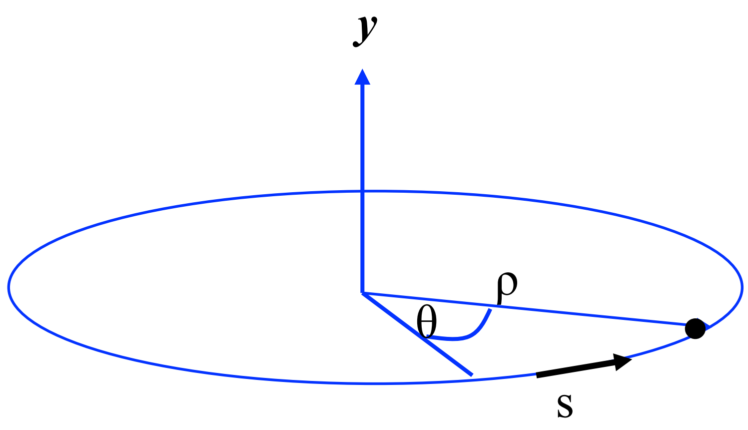
old greek dictum of wisdom:

if you are clever, you use magnetic fields in an accelerator wherever it is possible.

But remember: magn. fields act allways perpendicular to the velocity of the particle

→ only bending forces, → no „beam acceleration"

The ideal circular orbit



circular coordinate system

condition for circular orbit:

Lorentz force

$$F_L = e\,v\,B$$

centrifugal force

$$F_{centr} = \frac{\gamma\, m_0\, v^2}{\rho}$$

$$\frac{\gamma\, m_0\, \cancel{v^2}}{\rho} = e\,\cancel{v}\,B$$

$$\boxed{\frac{p}{e} = B\,\rho}$$

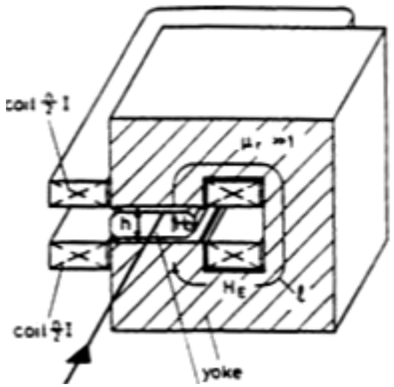
$B\,\rho =$ *"beam rigidity"*

1.) The Magnetic Guide Field

Dipole Magnets:

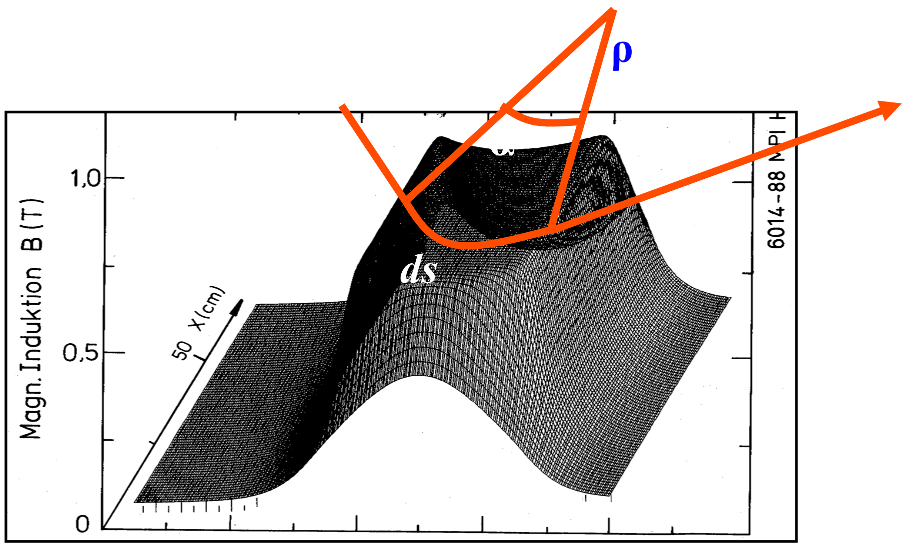
define the ideal orbit
homogeneous field created
by two flat pole shoes

$$B = \frac{\mu_0 \, n \, I}{h}$$



convenient units:

$$B = \left[T\right] = \left[\frac{Vs}{m^2}\right] \qquad p = \left[\frac{GeV}{c}\right]$$



field map of a storage ring dipole magnet

Normalise magnetic field to momentum:

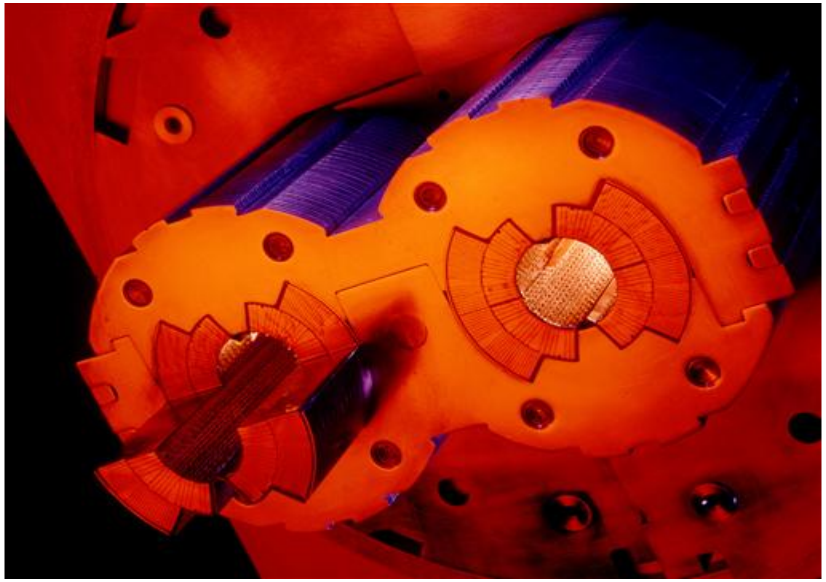
$$\frac{p}{e} = B\rho \longrightarrow \frac{1}{\rho} = \frac{e\,B}{p}$$

Example LHC:

$$B = 8.3\,T$$

$$p = 7000 \, \frac{GeV}{c}$$

The Magnetic Guide Field



$$\frac{1}{\rho} = e\,\frac{8.3\;{}^{\boldsymbol{Vs}}\!/_{\boldsymbol{m}^2}}{7000 * 10^9\;{}^{\boldsymbol{eV}}\!/_{\boldsymbol{c}}} = \frac{8.3\,\boldsymbol{s}\;\;3 * 10^8\;{}^{\boldsymbol{m}}\!/_{\boldsymbol{s}}}{7000 * 10^9\,\boldsymbol{m}^2}$$

$$\frac{1}{\rho} = 0.3\,\frac{8.3}{7000}\;{}^{1}\!/_{\boldsymbol{m}}$$

$\rho = 2.53\ \boldsymbol{km}$ → $2\pi\rho = 17.6\ km$

$\approx 66\%$

$\boldsymbol{B} \approx 1 \ldots 8\ \boldsymbol{T}$

rule of thumb:

$$\boxed{\frac{1}{\rho} \approx 0.3\,\frac{B[T]}{p[GeV/c]}}$$

„normalised bending strength"

2.) Quadrupole Magnets:

required: *focusing forces to keep trajectories in vicinity of the ideal orbit*

linear increasing Lorentz force

linear increasing magnetic field $B_y = g\,x \quad , \quad B_x = g\,y$

normalised quadrupole field:

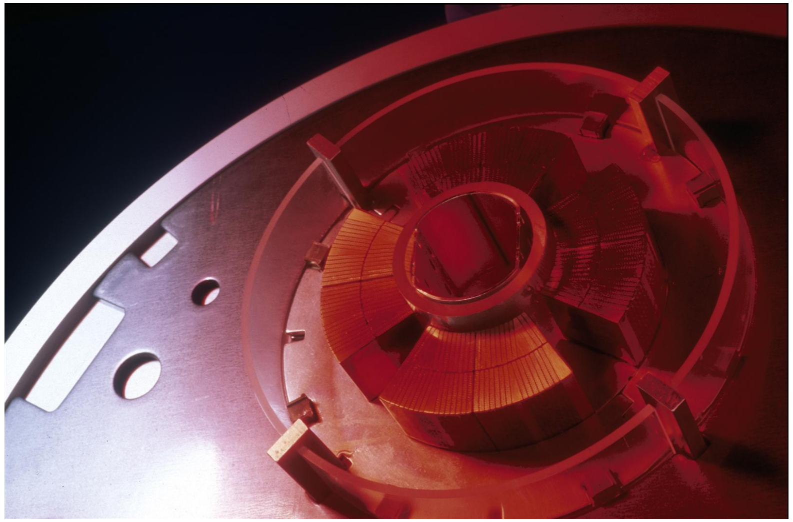
gradient of a quadrupole magnet:

$$g = \frac{2\mu_0 n I}{r^2}$$

$$\longrightarrow \quad k = \frac{g}{p/e}$$

simple rule:

$$\boxed{k = 0.3\,\frac{g(T/m)}{p(GeV/c)}}$$



LHC main quadrupole magnet

$$g \approx 25 \ldots 220\ \ T/m$$

what about the vertical plane:
... Maxwell

$$\vec{\nabla} \times \vec{B} = \cancel{\vec{j}} + \cancel{\frac{\partial \vec{E}}{\partial t}} = 0 \qquad \Rightarrow \qquad \frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y}$$

3.) The equation of motion:

Linear approximation:

* ideal particle → design orbit

* any other particle → coordinates x, y small quantities
$x,y \ll \rho$

→ magnetic guide field: only linear terms in x & y of B have to be taken into account

Taylor Expansion of the B field:

$$B_y(x) = B_{y0} + \frac{dB_y}{dx} x + \frac{1}{2!} \frac{d^2 B_y}{dx^2} x^2 + \frac{1}{3!} \frac{eg''}{dx^3} + \dots$$

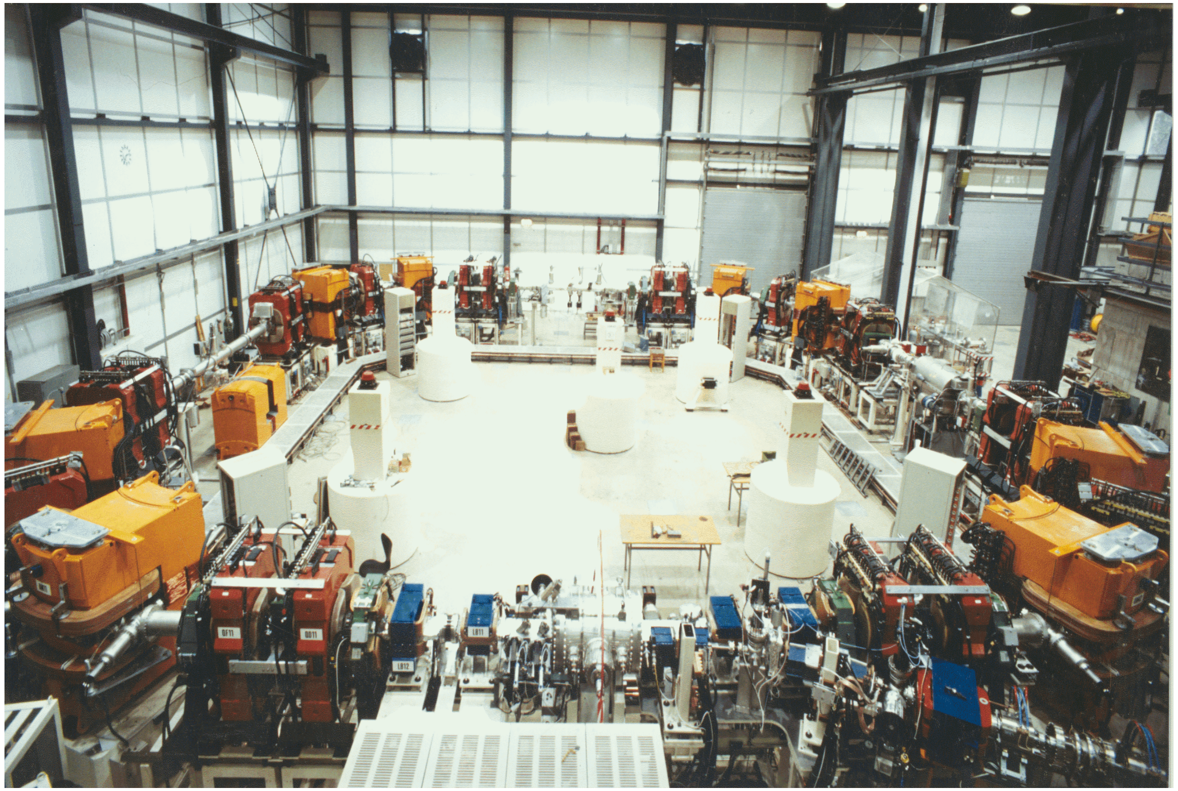
normalise to momentum
$p/e = B\rho$

$$\frac{B(x)}{p/e} = \frac{B_0}{B_0 \rho} + \frac{g * x}{p/e} + \frac{1}{2!} \frac{eg'}{p/e} + \frac{1}{3!} \frac{eg''}{p/e} + \dots$$

The Equation of Motion:

$$\frac{B(x)}{p/e} = \frac{1}{\rho} + k\,x + \cancel{\frac{1}{2!}m\,x^2} + \cancel{\frac{1}{3!}n\,x^3} + \ldots$$

only terms linear in x, y taken into account *dipole fields*
quadrupole fields



Separate Function Machines:

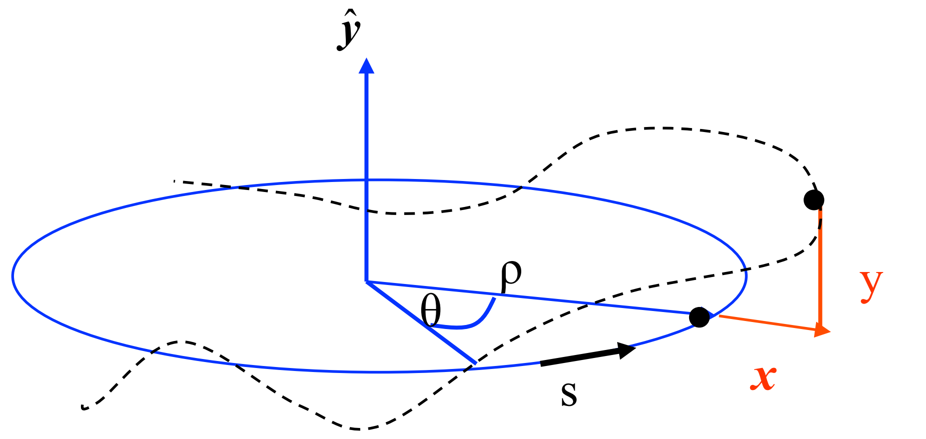
Split the magnets and optimise them according to their job:

bending, focusing etc

Example:
heavy ion storage ring TSR

* *man sieht nur dipole und quads → linear*

Equation of Motion:



Consider local segment of a particle trajectory
... and remember the old days:
(Goldstein page 27)

radial acceleration:

$$a_r = \frac{d^2\rho}{dt^2} - \rho\left(\frac{d\theta}{dt}\right)^2$$

general trajectory: $\rho \rightarrow \rho + x$

$$\boldsymbol{F = m\frac{d^2}{dt^2}(x+\rho) - \frac{mv^2}{x+\rho} = e\,B_y\,v}$$

Ideal orbit: $\rho = const, \quad \frac{d\rho}{dt} = 0$

Force: $F = m\rho\left(\frac{d\theta}{dt}\right)^2 = m\rho\omega^2$

$$F = mv^2/\rho$$

develop for small x:

$$x << \rho$$

$$m\frac{d^2x}{dt^2} - \frac{mv^2}{\rho}(1 - \frac{x}{\rho}) = eB_z v$$

guide field in linear approx.

$$B_z = B_0 + x\frac{\partial B_z}{\partial x}$$

$$m\frac{d^2x}{dt^2} - \frac{mv^2}{\rho}(1 - \frac{x}{\rho}) = ev\left\{B_0 + x\frac{\partial B_z}{\partial x}\right\}$$

independent variable: t → s

$$\frac{dx}{dt} = \frac{dx}{ds} * \frac{ds}{dt}$$

$$x' = \frac{dx}{ds}$$

$$x'' - \frac{1}{\rho}(1 - \frac{x}{\rho}) = \frac{eB_0}{mv} + \frac{exg}{mv}$$

$$x'' - \frac{1}{\rho} + \frac{x}{\rho^2} = -\frac{1}{\rho} + kx$$

$$x'' + x(\frac{1}{\rho^2} - k) = 0$$

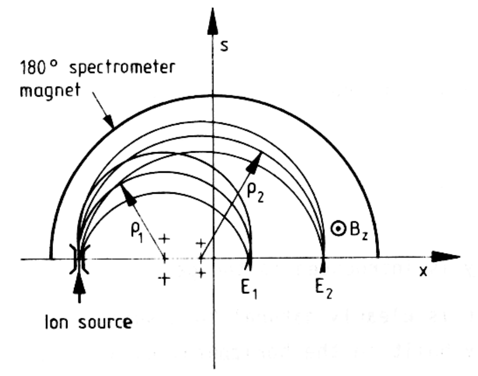
Remarks:

* *The Weak Focusing Term*

$$x'' + (\frac{1}{\rho^2} - k) \cdot x = 0$$

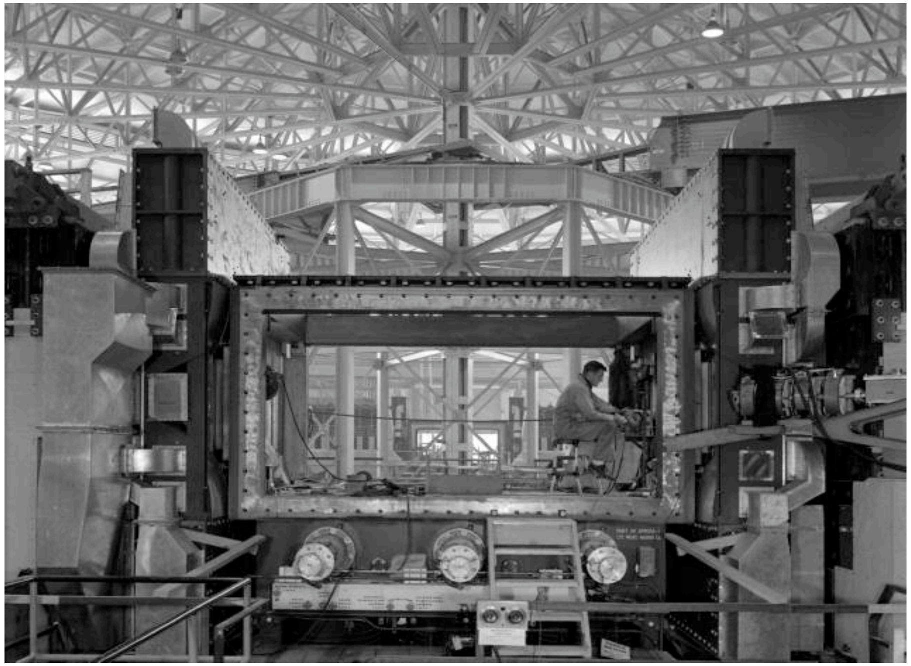
… there seems to be a focusing even without a quadrupole gradient ... but it is WEAK !

„weak focusing of dipole magnets“



Mass spectrometer: particles are separated according to their energy and focused due to the 1/ρ effect of the dipole

Don Edwards: ... This circumstance is illustrated in Fig. 4, in which an engineer is sitting at a desk within the vacuum chamber. The problem was a result of the weak focusing provided by the magnet systems.
The higher the energy, the larger ρ and the weaker the dipole focusing

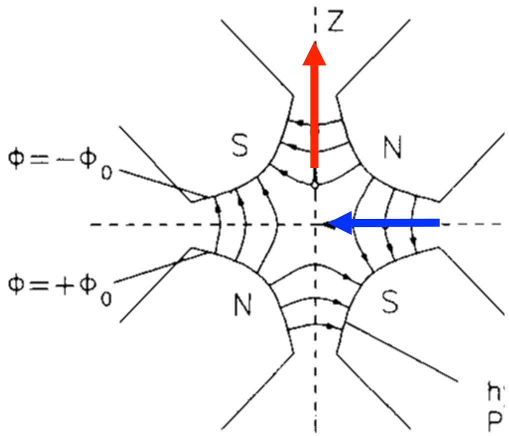


Bevatron, Berkeley

* * * vertical plane

Equation for the vertical motion:

$$z'' + k \cdot z = 0$$



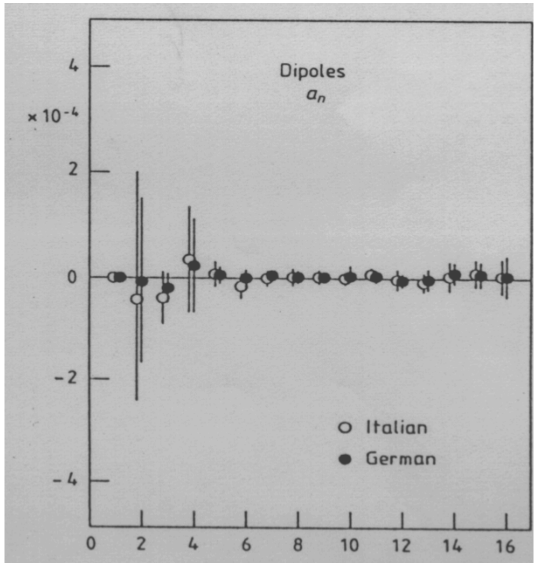
* * * keep it linear

Taylor Expansion of the B field:

$$B_y(x) = B_{y0} + \frac{dB_y}{dx} x + \frac{1}{2!} \frac{d^2 B_y}{dx^2} x^2 + \frac{1}{3!} \frac{d^3 B_y}{dx^3} x^3 + \dots$$

divide by the main field
to get the relative error contribution

→ definition of multipole coefficients.



Multipole contributions to the HERA s.c. dipole field

4.) Solution of Trajectory Equations

Define … hor. plane: $K = 1/\rho^2 - k$

… vert. Plane: $K = k$

$$\boldsymbol{x'' + K\,x = 0}$$

Differential Equation of harmonic oscillator … with spring constant K

Ansatz: $x(s) = a_1 \cdot \cos(\omega s) + a_2 \cdot \sin(\omega s)$

general solution: linear combination of two independent solutions

$$x'(s) = -a_1\omega \sin(\omega s) + a_2\omega \cos(\omega s)$$

$$x''(s) = -a_1\omega^2 \cos(\omega s) - a_2\omega^2 \sin(\omega s) = -\omega^2 x(s) \longrightarrow \omega = \sqrt{K}$$

general solution:

$$x(s) = a_1 \cos(\sqrt{K}s) + a_2 \sin(\sqrt{K}s)$$

determine a_1, a_2 by boundary conditions:

$$s = 0 \longrightarrow \begin{cases} x(0) = x_0 \quad , \quad a_1 = x_0 \\ x'(0) = x'_0 \quad , \quad a_2 = \dfrac{x'_0}{\sqrt{K}} \end{cases}$$

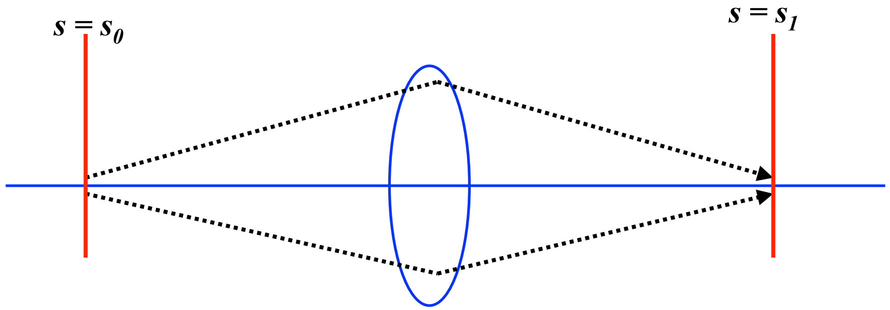
Hor. Focusing Quadrupole $K > 0$:

$$x(s) = x_0 \cdot \cos(\sqrt{|K|}s) + x'_0 \cdot \frac{1}{\sqrt{|K|}} \sin(\sqrt{|K|}s)$$

$$x'(s) = -x_0 \cdot \sqrt{|K|} \cdot \sin(\sqrt{|K|}s) + x'_0 \cdot \cos(\sqrt{|K|}s)$$

For convenience expressed in matrix formalism:

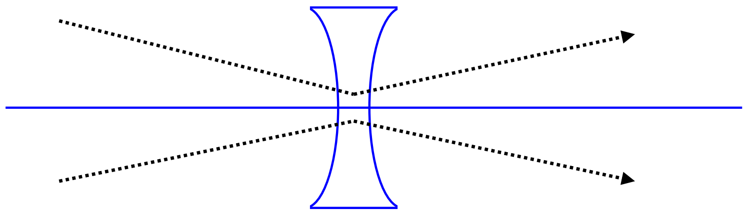
$$\begin{pmatrix} x \\ x' \end{pmatrix}_{s1} = M_{foc} * \begin{pmatrix} x \\ x' \end{pmatrix}_{s0}$$



$$M_{foc} = \begin{pmatrix} \cos(\sqrt{|K|}s) & \dfrac{1}{\sqrt{|K|}} \sin(\sqrt{|K|}s \\ -\sqrt{|K|} \sin(\sqrt{|K|}s) & \cos(\sqrt{|K|}s) \end{pmatrix}_0$$

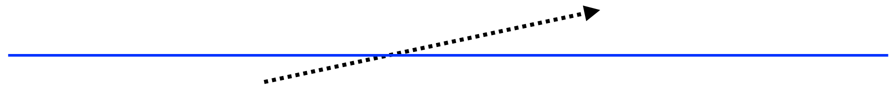
hor. defocusing quadrupole: ***K < 0***

$$M_{defoc} = \begin{pmatrix} \cosh\sqrt{|K|}\,l & \frac{1}{\sqrt{|K|}}\sinh\sqrt{|K|}\,l \\ \sqrt{|K|}\sinh\sqrt{|K|}\,l & \cosh\sqrt{|K|}\,l \end{pmatrix}$$



drift space: ***K = 0***

$$M_{drift} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}$$



! ***with the assumptions made, the motion in the horizontal and vertical planes are independent „ ... the particle motion in x & z is uncoupled“***

!! ***for all magnet matrices the condition det (M) =1 is fulfilled***
which means we are dealing with a conservative system

Thin Lens Approximation:

matrix of a quadrupole lens

$$M = \begin{pmatrix} \cos\sqrt{|k|}l & \frac{1}{\sqrt{|k|}}\sin\sqrt{|k|}l \\ -\sqrt{|k|}\sin\sqrt{|k|}l & \cos\sqrt{|k|}l \end{pmatrix}$$

in many practical cases we have the situation:

$$f = \frac{1}{kl_q} >> l_q$$

... focal length of the lens is much bigger than the length of the magnet

limes: $l_q \rightarrow 0$ ***while keeping*** $k\,l_q = const$

$$M_x = \begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix} \qquad M_z = \begin{pmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{pmatrix}$$

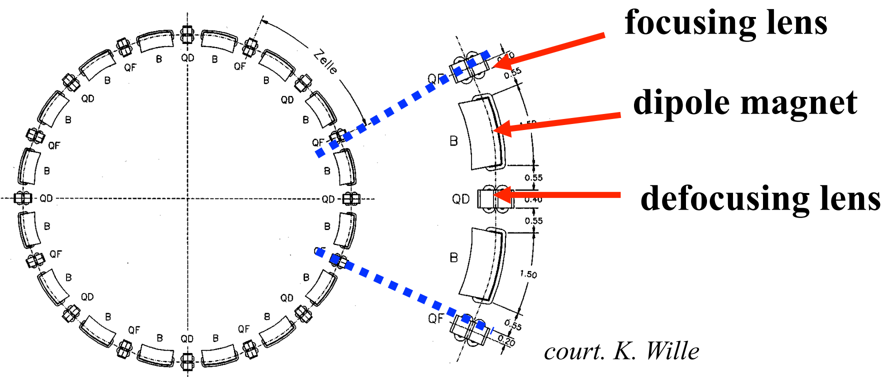
... useful for fast (and in large machines still quite accurate) „back on the envelope calculations" ... and for the guided studies !

Transformation through a system of lattice elements

combine the single element solutions by multiplication of the matrices

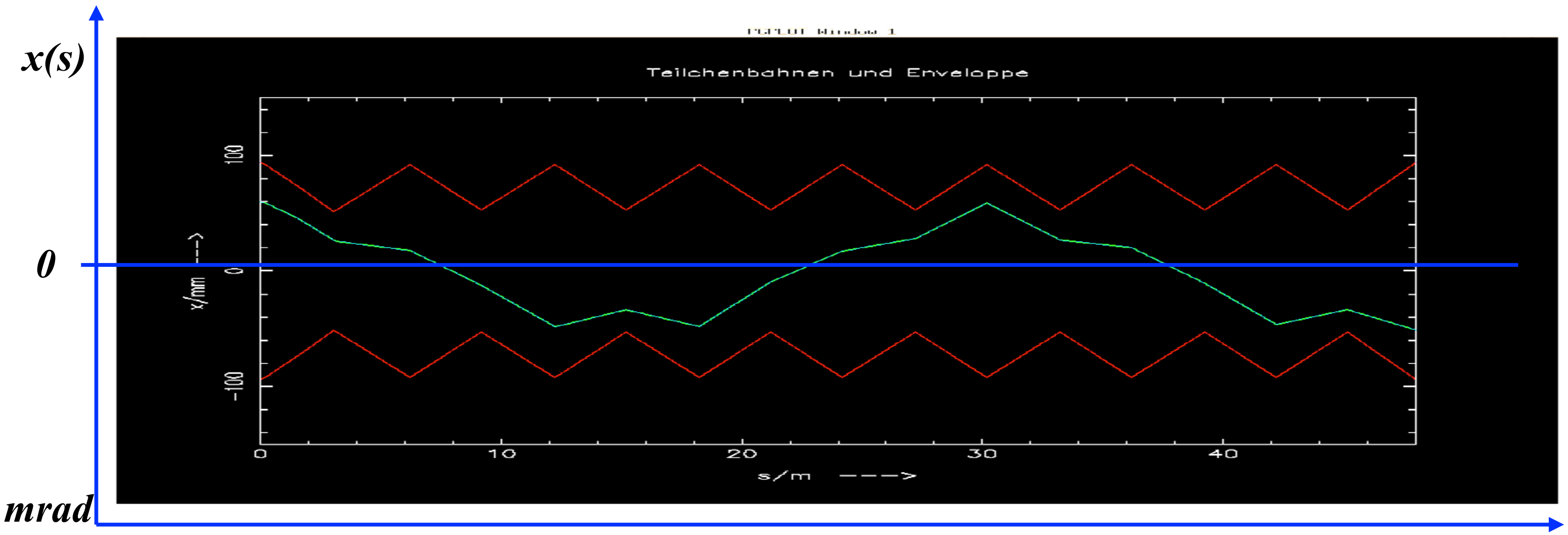
$$M_{total} = M_{QF} * M_D * M_{QD} * M_{Bend} * M_{D^*.....}$$

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{s2} = M(s_2, s_1) * \begin{pmatrix} x \\ x' \end{pmatrix}_{s1}$$



court. K. Wille

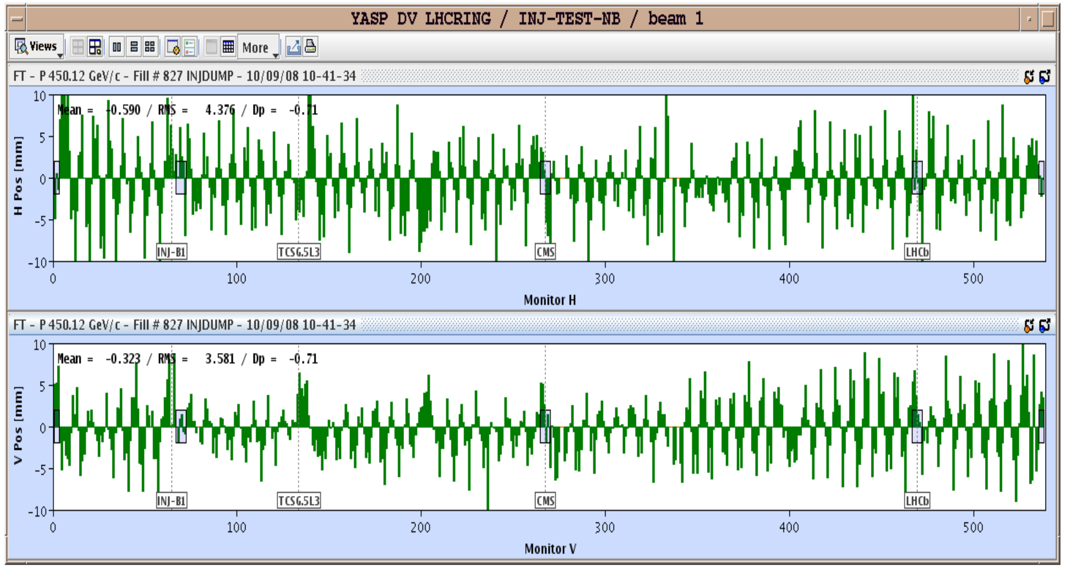
„C" and „S" = sin- and cos- like trajectories of the lattice structure, in other words the two independent solutions of the homogeneous equation of motion



typical values in a strong foc. machine:

$x \approx$ mm, $x' \leq$ mrad

5.) Orbit & Tune:



Tune: number of oscillations per turn

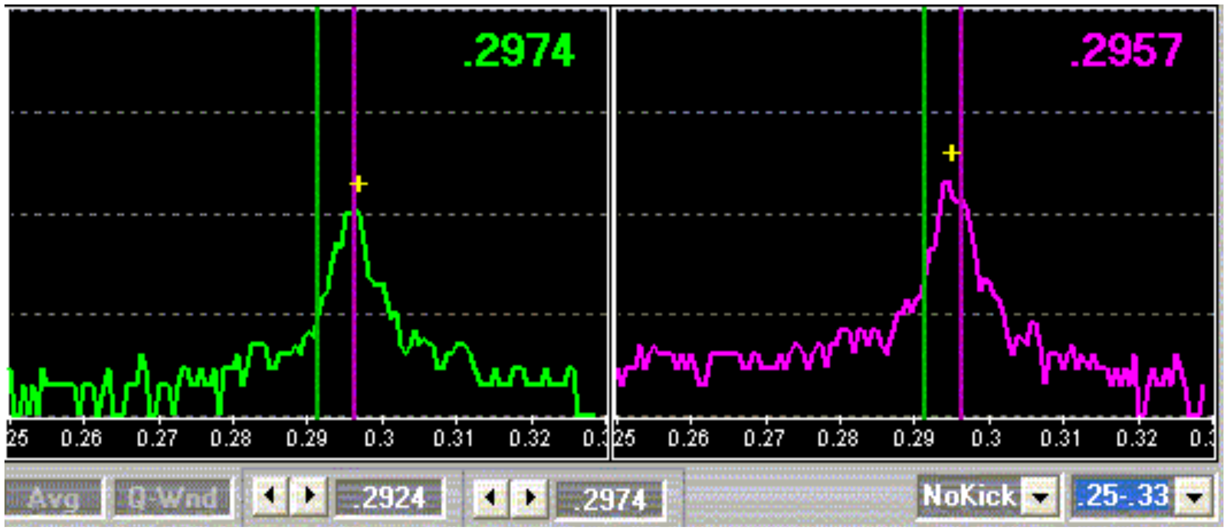
64.31
59.32

Relevant for beam stability:

non integer part

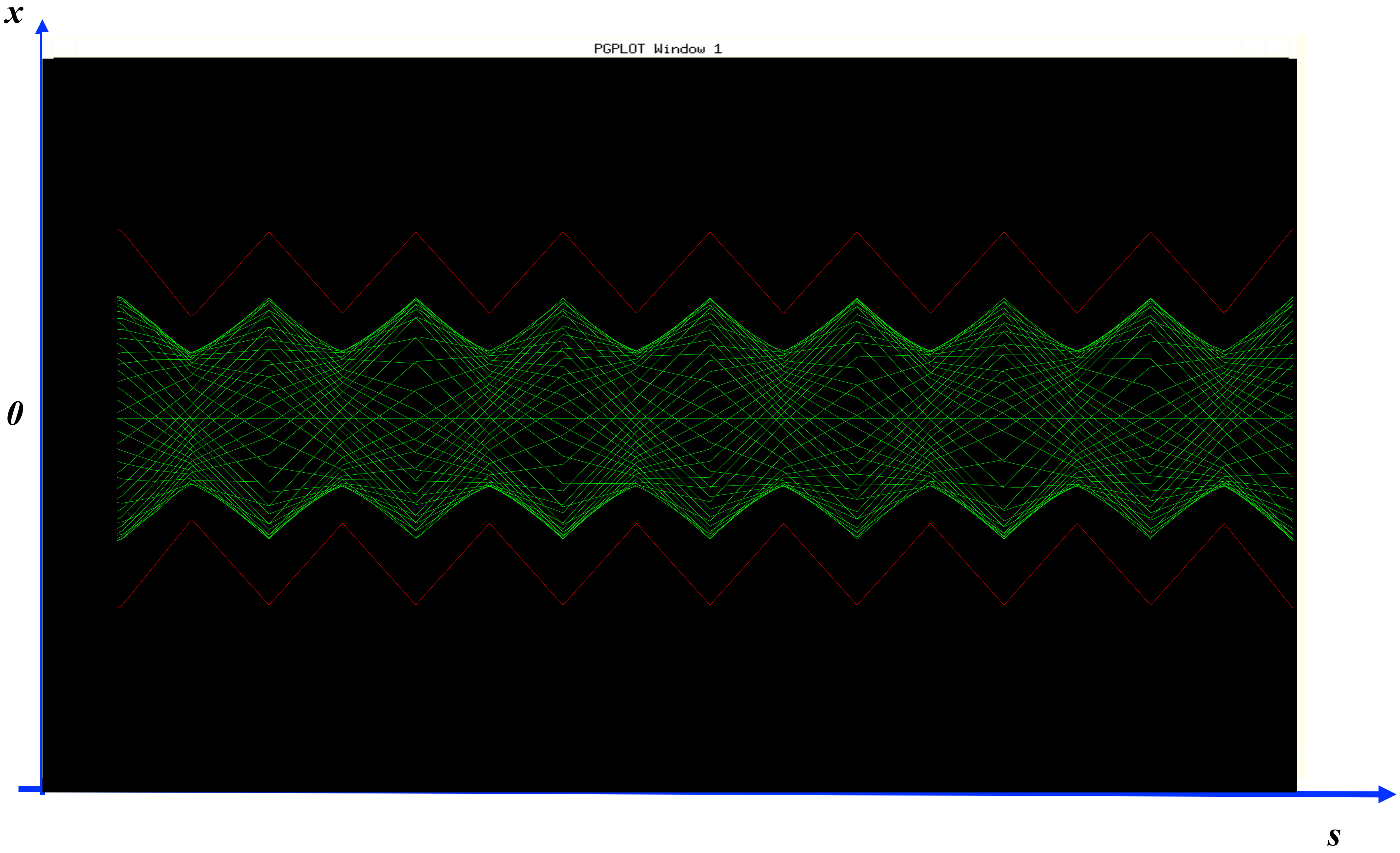
LHC revolution frequency: 11.3 kHz

$$0.31 * 11.3\,kHz = 3.5\,kHz$$



Question: ***what will happen, if the particle performs a second turn ?***

... or a third one or ... 10^{10} turns



Astronomer Hill:

differential equation for motions with periodic focusing properties
„Hill 's equation"

Example: particle motion with periodic coefficient

equation of motion: $$x''(s) - k(s)x(s) = 0$$

restoring force $\neq$ const,
k(s) = depending on the position s
k(s+L) = k(s), periodic function

we expect a kind of quasi harmonic oscillation: amplitude & phase will depend on the position s in the ring.

6.) The Beta Function

General solution of Hill´s equation:

(i) $$x(s) = \sqrt{\varepsilon}\sqrt{\beta(s)} \cdot \cos(\psi(s) + \phi)$$

ε, Φ = integration constants determined by initial conditions

β(s) periodic function given by focusing properties of the lattice ↔ quadrupoles

$$\beta(s + L) = \beta(s)$$

Inserting (i) into the equation of motion …

$$\psi(s) = \int_0^s \frac{ds}{\beta(s)}$$

Ψ(s) = „phase advance“ of the oscillation between point „0“ and „s“ in the lattice.
For one complete revolution: number of oscillations per turn „Tune“

$$Q_y = \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

7.) Beam Emittance and Phase Space Ellipse

general solution of Hill equation

(1) $$x(s) = \sqrt{\varepsilon}\,\sqrt{\beta(s)}\,\cos(\psi(s)+\phi)$$

(2) $$x'(s) = -\frac{\sqrt{\varepsilon}}{\sqrt{\beta(s)}}\left\{\alpha(s)\cos(\psi(s)+\phi)+\sin(\psi(s)+\phi)\right\}$$

from (1) we get

$$\cos(\psi(s)+\phi) = \frac{x(s)}{\sqrt{\varepsilon}\,\sqrt{\beta(s)}}$$

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

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

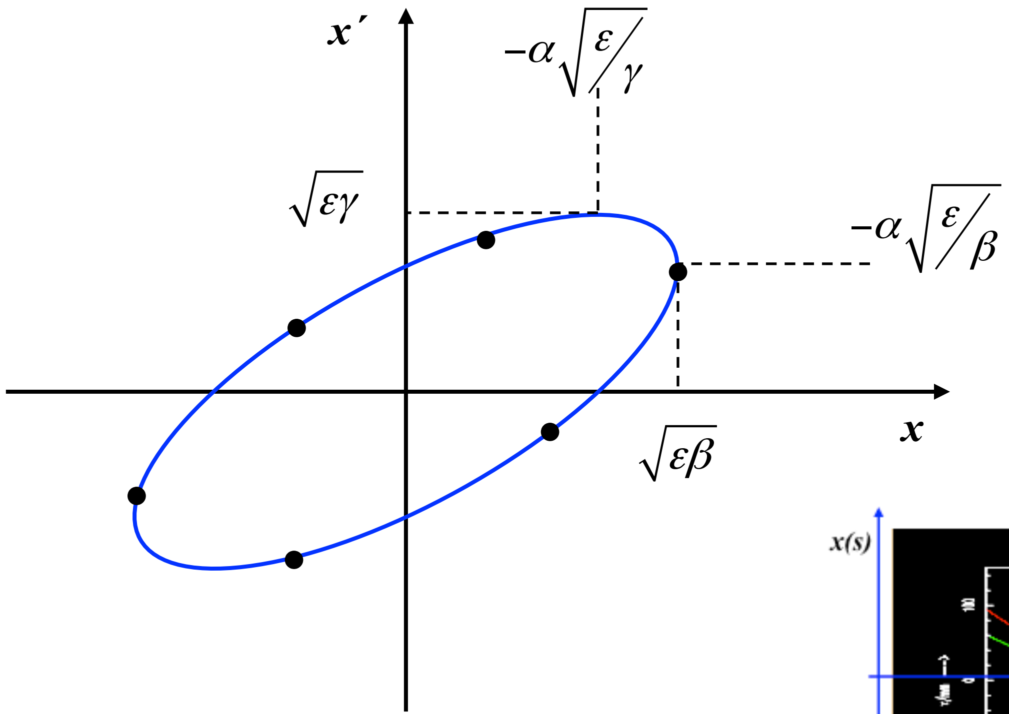
Insert into (2) and solve for ε

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

***** ε is a constant of the motion … it is independent of „s“*
***** parametric representation of an ellipse in the x x ‘ space*
***** shape and orientation of ellipse are given by α, β, γ*

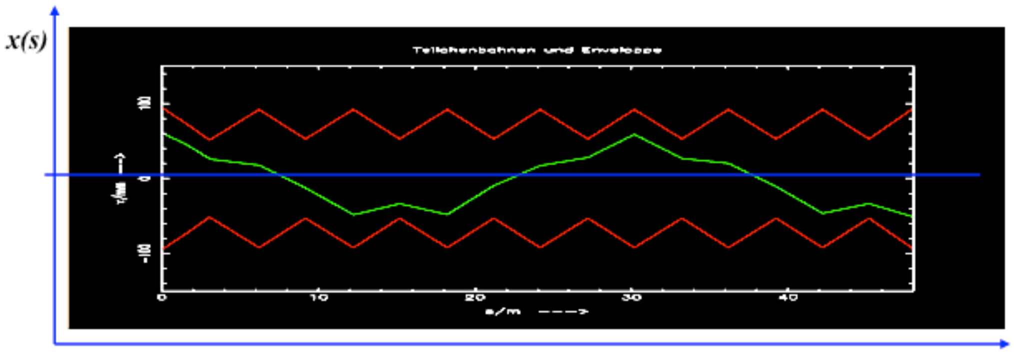
Beam Emittance and Phase Space Ellipse

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



***Liouville:** in reasonable storage rings*
area in phase space is constant.

$A = \pi{*}\varepsilon = const$



ε beam emittance = woozilycity of the particle ensemble, intrinsic beam parameter,
cannot be changed by the foc. properties.
Scientifiquely speaking: area covered in transverse x, x´ phase space … and it is constant !!!

Phase Space Ellipse

particel trajectory: $x(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}\cos\{\psi(s)+\phi\}$

max. Amplitude: $\hat{x}(s) = \sqrt{\varepsilon\beta}$ $\longrightarrow$ *x´ at that position …?*

… put $\hat{x}(s)$ *into* $\boldsymbol{\varepsilon = \gamma(s)\, x^2(s) + 2\alpha(s)x(s)x'(s) + \beta(s)\, x'^2(s)}$ *and solve for x´*

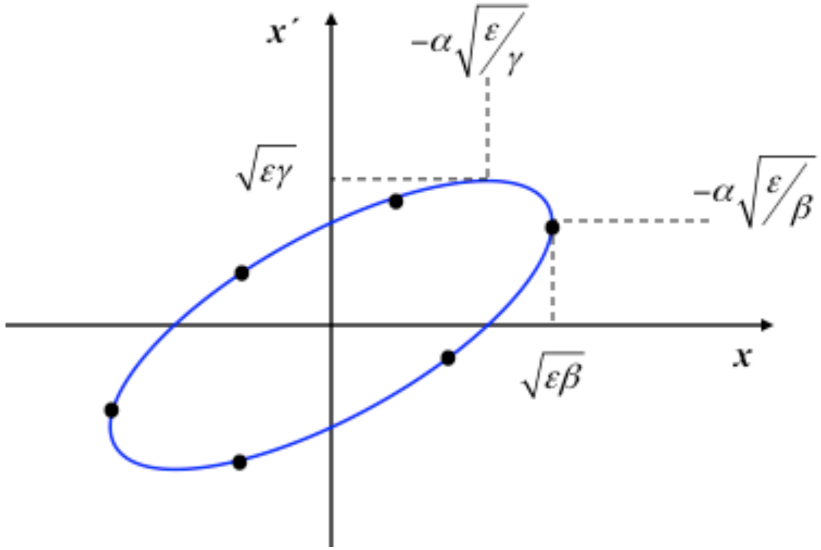
$$\varepsilon = \gamma \cdot \varepsilon\beta + 2\alpha\sqrt{\varepsilon\beta}\cdot x' + \beta x'^2 \longrightarrow x' = -\alpha \cdot \sqrt{\varepsilon / \beta}$$

and in the same way we obtain:

$$\hat{x}' = \sqrt{\varepsilon\gamma} \qquad x = \pm\alpha\sqrt{\varepsilon/\gamma}$$

* *A high β-function means a large beam size and a small beam divergence.*
  … et vice versa !!!
* *In the middle of a quadrupole β = maximum,*
  α = zero $x' = 0$ *… and the ellipse is flat*

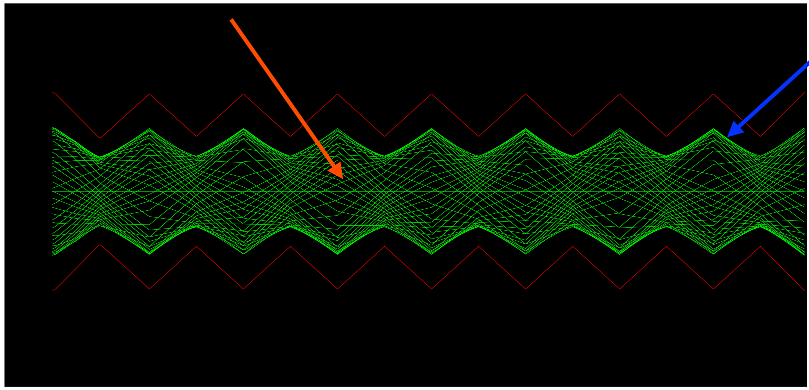
!



shape and orientation of the phase space ellipse depend on the Twiss parameters β α γ

Emittance of the Particle Ensemble:

$$x(s) = \sqrt{\varepsilon}\sqrt{\beta(s)} \cdot \cos(\Psi(s) + \phi) \qquad \hat{x}(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}$$

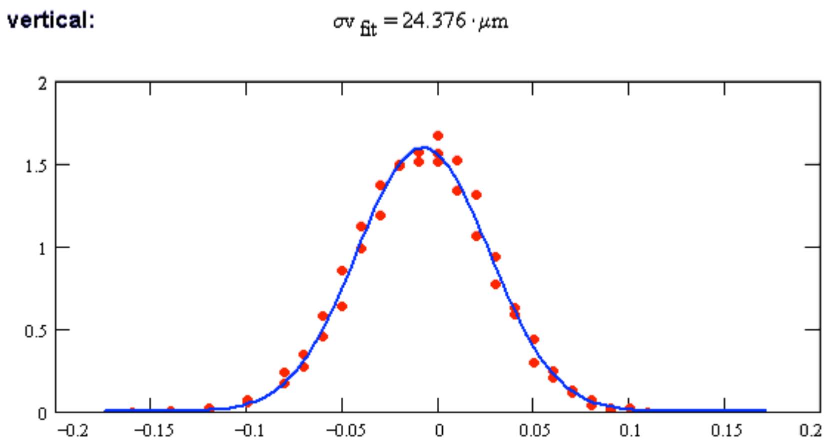


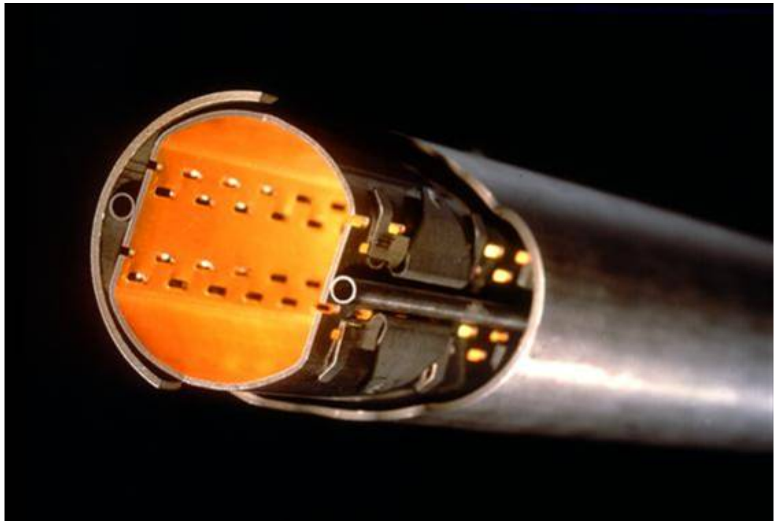
single particle trajectories, N ≈ 10 [11] per bunch

Gauß Particle Distribution:

$$\rho(x) = \frac{N \cdot e}{\sqrt{2\pi}\sigma_x} \cdot e^{-\frac{1}{2}\frac{x^2}{\sigma_x^2}}$$

particle at distance 1 σ from centre ↔ 68.3 % of all beam particles

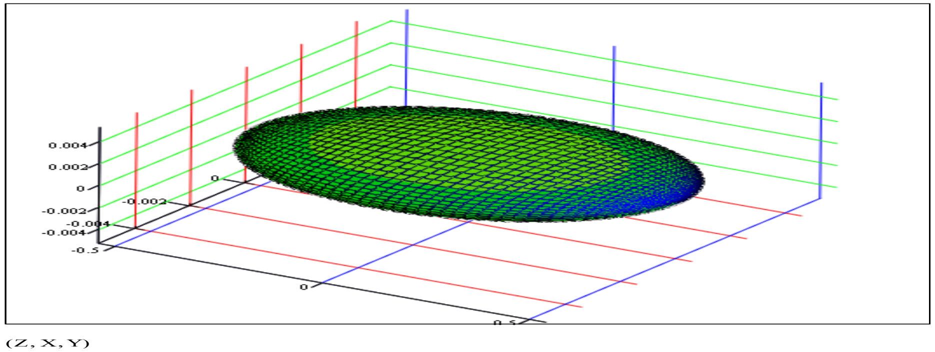




LHC: $\sigma = \sqrt{\varepsilon * \beta} = \sqrt{5*10^{-10}m*180m} = 0.3\,mm$

aperture requirements: $r_0 = 10 * \sigma$

Emittance of the Particle Ensemble:



particle bunch

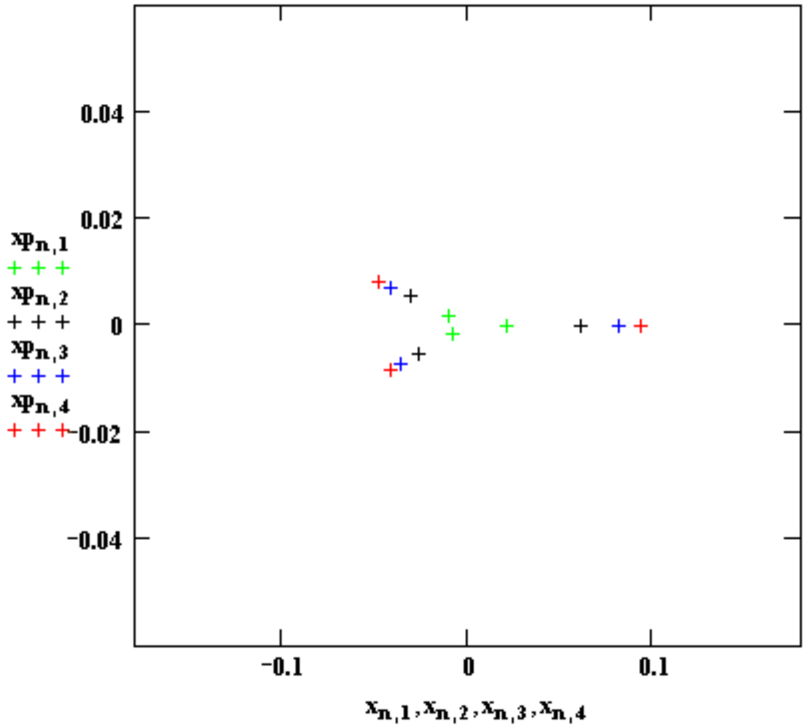
Example: HERA

beam parameters in the arc

$$\beta(x) \approx 80\, m$$

$$\varepsilon \approx 7 * 10^{-9}\ rad \cdot m \qquad (\leftrightarrow 1\,\sigma)$$

$$\sigma = \sqrt{\varepsilon \beta} \approx 0.75\ mm$$



8.) Transfer Matrix M

… yes we had the topic already

general solution of Hill´s equation

$$
\begin{cases}
x(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}\cos\{\psi(s)+\phi\} \\
x'(s) = \dfrac{-\sqrt{\varepsilon}}{\sqrt{\beta(s)}}\left[\alpha(s)\cos\{\psi(s)+\phi\}+\sin\{\psi(s)+\phi\}\right]
\end{cases}
$$

remember the trigonometrical gymnastics: sin(a + b) = … etc

$$x(s) = \sqrt{\varepsilon}\sqrt{\beta_s}\left(\cos\psi_s\cos\phi - \sin\psi_s\sin\phi\right)$$

$$x'(s) = \frac{-\sqrt{\varepsilon}}{\sqrt{\beta_s}}\left[\alpha_s\cos\psi_s\cos\phi - \alpha_s\sin\psi_s\sin\phi + \sin\psi_s\cos\phi + \cos\psi_s\sin\phi\right]$$

starting at point s(0) = s$_0$, where we put Ψ(0) = 0

$$
\left.
\begin{aligned}
\cos\phi &= \frac{x_0}{\sqrt{\varepsilon\beta_0}} \quad , \\
\sin\phi &= -\frac{1}{\sqrt{\varepsilon}}\left(x_0'\sqrt{\beta_0} + \frac{\alpha_0 x_0}{\sqrt{\beta_0}}\right)
\end{aligned}
\right\}
$$

inserting above …

$$x(s)=\sqrt{\frac{\beta_s}{\beta_0}}\left\{\cos\psi_s+\alpha_0\sin\psi_s\right\}x_0+\left\{\sqrt{\beta_s\beta_0}\sin\psi_s\right\}x_0'$$

$$x'(s)=\frac{1}{\sqrt{\beta_s\beta_0}}\left\{(\alpha_0-\alpha_s)\cos\psi_s-(1+\alpha_0\alpha_s)\sin\psi_s\right\}x_0+\sqrt{\frac{\beta_0}{\beta_s}}\left\{\cos\psi_s-\alpha_s\sin\psi_s\right\}x_0'$$

which can be expressed ... for convenience ... in matrix form

$$\begin{pmatrix} x \\ x' \end{pmatrix}_s = M \begin{pmatrix} x \\ x' \end{pmatrix}_0$$

$$M=\begin{pmatrix} \sqrt{\frac{\beta_s}{\beta_0}}\left(\cos\psi_s+\alpha_0\sin\psi_s\right) & \sqrt{\beta_s\beta_0}\sin\psi_s \\ \frac{(\alpha_0-\alpha_s)\cos\psi_s-(1+\alpha_0\alpha_s)\sin\psi_s}{\sqrt{\beta_s\beta_0}} & \sqrt{\frac{\beta_0}{\beta s}}\left(\cos\psi_s-\alpha_s\sin\psi_s\right) \end{pmatrix}$$

* ***we can calculate the single particle trajectories between two locations in the ring, if we know the α β γ at these positions.***
* ***and nothing but the α β γ at these positions.***
* ... **!**

*** *Äquivalenz der Matrizen***

11.) Résumé:

beam rigidity: $B \cdot \rho = p/q$

bending strength of a dipole: $\frac{1}{\rho}\left[m^{-1}\right] = \frac{0.2998 \cdot B_0(T)}{p(GeV/c)}$

focusing strength of a quadrupole: $k\left[m^{-2}\right] = \frac{0.2998 \cdot g}{p(GeV/c)}$

focal length of a quadrupole: $f = \frac{1}{k \cdot l_q}$

equation of motion: $x'' + Kx = \frac{1}{\rho}\frac{\Delta p}{p}$

matrix of a foc. quadrupole: $x_{s2} = M \cdot x_{s1}$

$$M = \begin{pmatrix} \cos\sqrt{|K|}l & \frac{1}{\sqrt{|K|}}\sin\sqrt{|K|}l \\ -\sqrt{|K|}\sin\sqrt{|K|}l & \cos\sqrt{|K|}l \end{pmatrix} , \qquad M = \begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix}$$

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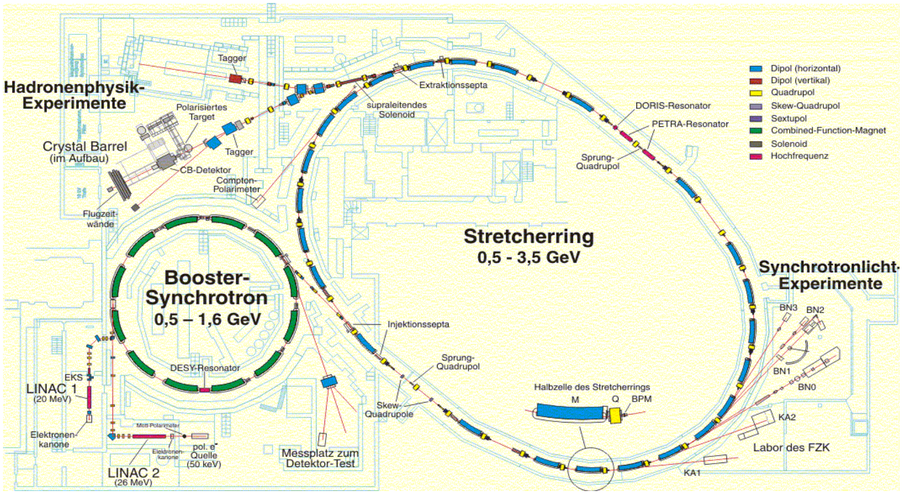
9.) Periodic Lattices

$$M = \begin{pmatrix} \sqrt{\frac{\beta_s}{\beta_0}}\left(\cos\psi_s + \alpha_0 \sin\psi_s\right) & \sqrt{\beta_s\beta_0}\,\sin\psi_s \\ \frac{(\alpha_0 - \alpha_s)\cos\psi_s - (1+\alpha_0\alpha_s)\sin\psi_s}{\sqrt{\beta_s\beta_0}} & \sqrt{\frac{\beta_0}{\beta s}}\left(\cos\psi_s - \alpha_s \sin\psi_s\right) \end{pmatrix}$$



DELTA Electron Storage Ring

„This rather formidable looking matrix simplifies considerably if we consider one complete revolution …"

$$\boldsymbol{M(s)} = \begin{pmatrix} \cos\psi_{turn} + \alpha_s \sin\psi_{turn} & \beta_s \sin\psi_{turn} \\ -\gamma_s \sin\psi_{turn} & \cos\psi_{turn} - \alpha_s \sin\psi_{turn} \end{pmatrix}$$

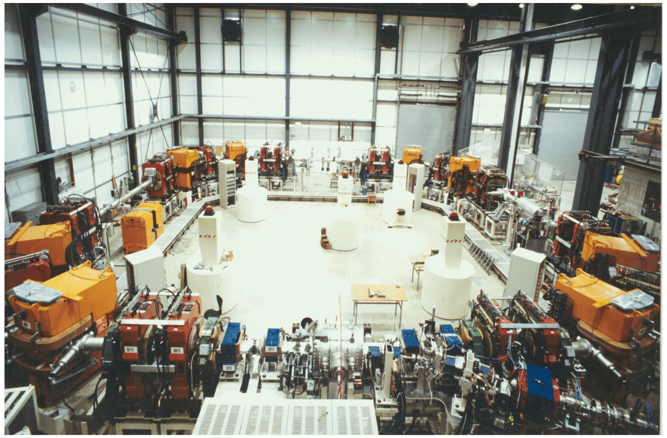
$$\psi_{turn} = \int_s^{s+L} \frac{ds}{\beta(s)}$$

ψ_{turn} = phase advance per period

***Tune:* Phase advance per turn in units of 2π**

$$Q = \frac{1}{2\pi}\oint \frac{ds}{\beta(s)}$$

Stability Criterion:



Question: ***what will happen, if we do not make too many mistakes and your particle performs one complete turn ?***

Matrix for 1 turn:

$$M = \begin{pmatrix} \cos\psi_{turn} + \alpha_s \sin\psi_{turn} & \beta_s \sin\psi_{turn} \\ -\gamma_s \sin\psi_{turn} & \cos\psi_{turn} - \alpha_s \sin\psi_{turn} \end{pmatrix} = \cos\psi \cdot \underbrace{\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}}_{1} + \sin\psi \underbrace{\begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix}}_{J}$$

Matrix for N turns:

$$M^N = (1 \cdot \cos\psi + J \cdot \sin\psi)^N = 1 \cdot \cos N\psi + J \cdot \sin N\psi$$

The motion for N turns remains bounded, if the elements of M^N remain bounded

$$\psi = real \quad \leftrightarrow \quad |\cos\psi| \le 1 \quad \leftrightarrow \quad Tr(M) \le 2$$

stability criterion …. proof for the disbelieving collegues !!

Matrix for 1 turn:

$$M = \begin{pmatrix} \cos\psi_{turn} + \alpha_s \sin\psi_{turn} & \beta_s \sin\psi_{turn} \\ -\gamma_s \sin\psi_{turn} & \cos\psi_{turn} - \alpha_s \sin\psi_{turn} \end{pmatrix} = \cos\psi \cdot \underbrace{\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}}_{\boldsymbol{I}} + \sin\psi \underbrace{\begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix}}_{\boldsymbol{J}}$$

Matrix for 2 turns:

$$\boldsymbol{M}^2 = (\boldsymbol{I}\cos\psi_1 + \boldsymbol{J}\sin\psi_1)(\boldsymbol{I}\cos\psi_2 + \boldsymbol{J}\sin\psi_2)$$

$$= \boldsymbol{I}^2 \cos\psi_1 \cos\psi_2 + \boldsymbol{IJ}\cos\psi_1 \sin\psi_2 + \boldsymbol{JI}\sin\psi_1 \cos\psi_2 + \boldsymbol{J}^2 \sin\psi_1 \sin\psi_2$$

now …

$$\boldsymbol{I}^2 = \boldsymbol{I}$$

$$\boldsymbol{I}\,\boldsymbol{J} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} * \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix}$$

$$\boldsymbol{J}\,\boldsymbol{I} = \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix} * \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix}$$

$$\boldsymbol{I}\,\boldsymbol{J} = \boldsymbol{J}\,\boldsymbol{I}$$

$$\boldsymbol{J}^2 = \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix} * \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix} = \begin{pmatrix} \alpha^2 - \gamma\beta & \alpha\beta - \beta\alpha \\ -\gamma\alpha + \alpha\gamma & \alpha^2 - \gamma\beta \end{pmatrix} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} = -\boldsymbol{I}$$

$$\boldsymbol{M}^2 = \boldsymbol{I}\cos(\psi_1 + \psi_2) + \boldsymbol{J}\sin(\psi_1 + \psi_2)$$

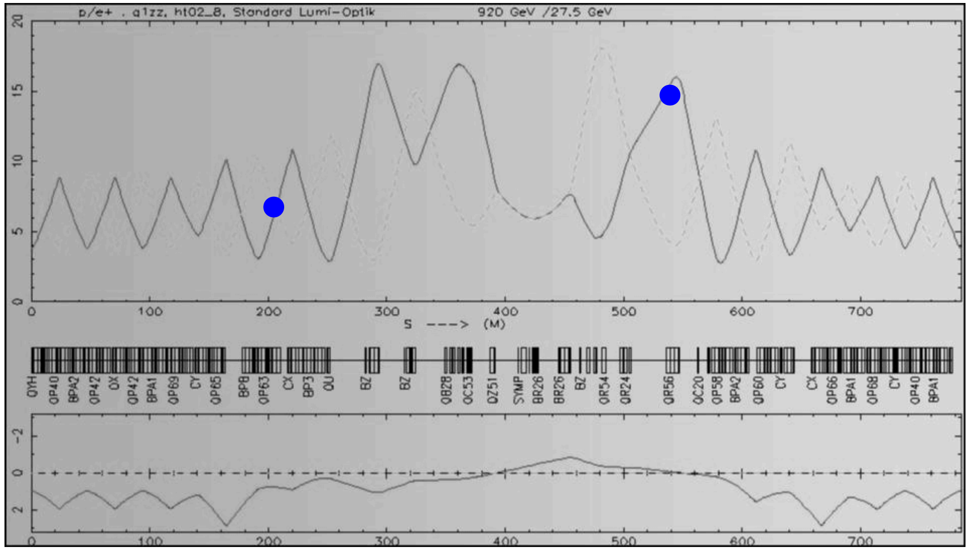
$$\boldsymbol{M}^2 = \boldsymbol{I}\cos(2\psi) + \boldsymbol{J}\sin(2\psi)$$

10.) Transformation of α, β, γ

consider two positions in the storage ring: s_0 , s

$$\begin{pmatrix} x \\ x' \end{pmatrix}_s = M * \begin{pmatrix} x \\ x' \end{pmatrix}_{s0}$$

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}$$



Betafunction in a Storage Ring

since ε = const (Liouville):

$$\varepsilon = \beta_s x'^2 + 2\alpha_s x x' + \gamma_s x^2$$

$$\varepsilon = \beta_0 x_0'^2 + 2\alpha_0 x_0 x_0' + \gamma_0 x_0{}^2$$

... remember W = CS´-SC´ = 1

$$\begin{pmatrix} x \\ x' \end{pmatrix}_0 = M^{-1} * \begin{pmatrix} x \\ x' \end{pmatrix}_s$$

$$M^{-1} = \begin{pmatrix} m_{22} & -m_{12} \\ -m_{21} & m_{11} \end{pmatrix}$$

$$\rightarrow \quad x_0 = m_{22} x - m_{12} x'$$

$$x_0' = -m_{21} x + m_{11} x'$$

... inserting into ε

$$\varepsilon = \beta_0 (m_{11} x' - m_{21} x)^2 + 2\alpha_0 (m_{22} x - m_{12} x')(m_{11} x' - m_{21} x) + \gamma_0 (m_{22} x - m_{12} x')^2$$

sort via x, x´and compare the coefficients to get ....

The Twiss parameters α, β, γ can be transformed through the lattice via the matrix elements defined above.

$$\beta(s) = m_{11}^2 \beta_0 - 2m_{11}m_{12}\alpha_0 + m_{12}^2 \gamma_0$$
$$\alpha(s) = -m_{11}m_{21}\beta_0 + (m_{12}m_{21} + m_{11}m_{22})\alpha_0 - m_{12}m_{22}\gamma_0$$
$$\gamma(s) = m_{21}^2 \beta_0 - 2m_{21}m_{22}\alpha_0 + m_{22}^2 \gamma_0$$

in matrix notation:

$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_{s2} = \begin{pmatrix} m_{11}^2 & -2m_{11}m_{12} & m_{12}^2 \\ -m_{11}m_{21} & m_{12}m_{21} + m_{22}m_{11} & -m_{12}m_{22} \\ m_{21}^2 & -2m_{22}m_{21} & m_{22}^2 \end{pmatrix} * \begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_{s1}$$

!

1.) this expression is important

2.) given the twiss parameters α, β, γ at any point in the lattice we can transform them and calculate their values at any other point in the ring.

3.) the transfer matrix is given by the focusing properties of the lattice elements, the elements of M are just those that we used to calculate single particle trajectories.

4.) go back to point 1.)

II.) Acceleration and Momentum Spread

The „ not so ideal world “

Remember:

Beam Emittance and Phase Space Ellipse:

equation of motion: $x''(s) - k(s)\, x(s) = 0$

general solution of Hills equation: $x(s) = \sqrt{\varepsilon}\,\sqrt{\beta(s)}\,\cos(\psi(s) + \varphi)$

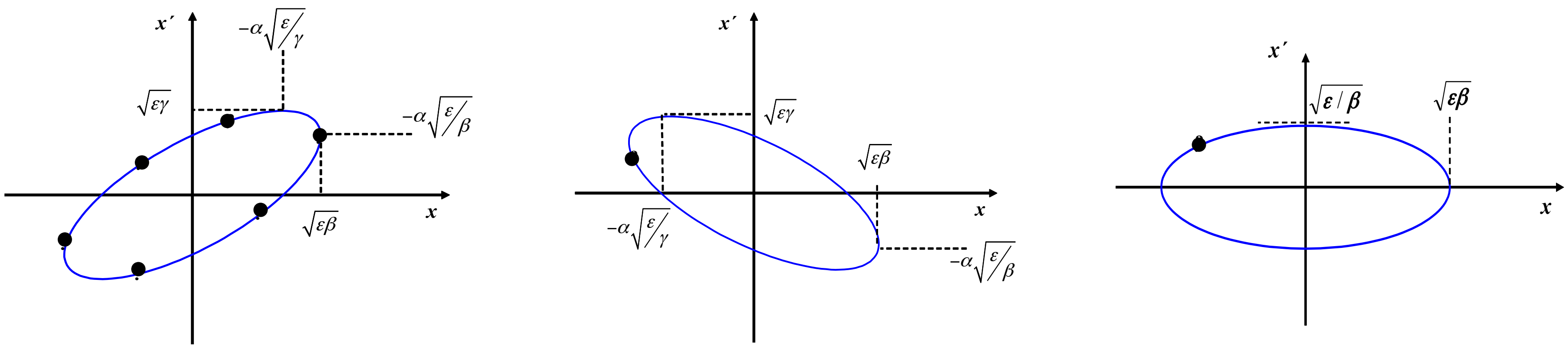
beam size: $\sigma = \sqrt{\varepsilon\beta} \approx \text{"}mm\text{"}$

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

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

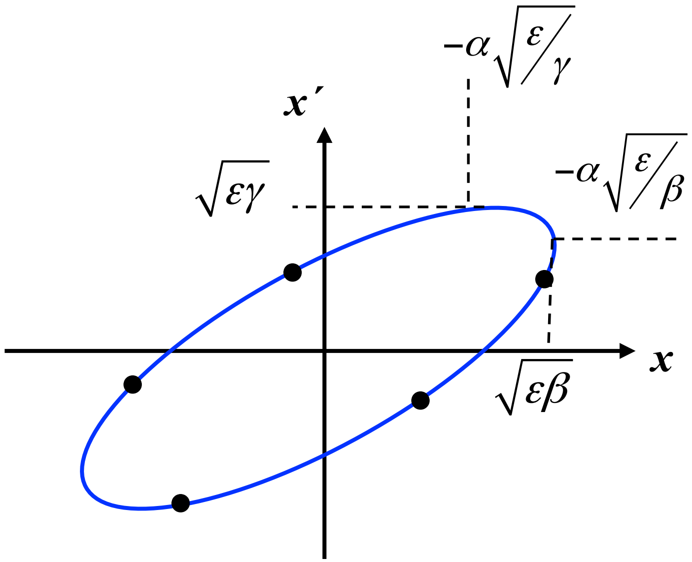
$$\gamma(s) = \frac{1+\alpha(s)^2}{\beta(s)}$$

** ε is a constant of the motion … it is independent of „s"*
** parametric representation of an ellipse in the x x ' space*
** shape and orientation of ellipse are given by α, β, γ*



11.) Liouville during Acceleration

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



Beam Emittance ***corresponds to the area covered in the x, x´ Phase Space Ellipse***

Liouville: ***Area in phase space is constant.***

But so sorry ... $\varepsilon \neq$ const !

Classical Mechanics:

phase space = ***diagram of the two canonical variables***

position & ***momentum***

x $\quad\quad$ p_x

$$p_j = \frac{\partial L}{\partial \dot{q}_j} \quad ; \quad L = T - V = kin.\,Energy - pot.\,Energy$$

According to Hamiltonian mechanics:
phase space diagram relates the variables q and p

$$q = position = x$$
$$p = momentum = \gamma m v = mc\gamma\beta_x$$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \quad ; \quad \beta_x = \frac{\dot{x}}{c}$$

Liouvilles Theorem: $\int p\,dq = const$

for convenience (i.e. because we are lazy bones) we use in accelerator theory:

$$x' = \frac{dx}{ds} = \frac{dx}{dt}\frac{dt}{ds} = \frac{\beta_x}{\beta}$$

where $\beta_x = v_x / c$

$$\int p dq = mc\int \gamma\beta_x dx$$

$$\int p dq = mc\gamma\beta\underbrace{\int x' dx}_{\varepsilon}$$

$$\boxed{\Rightarrow \quad \varepsilon = \int x' dx \propto \frac{1}{\beta\gamma}}$$

the beam emittance shrinks during acceleration $\varepsilon \sim 1/\gamma$

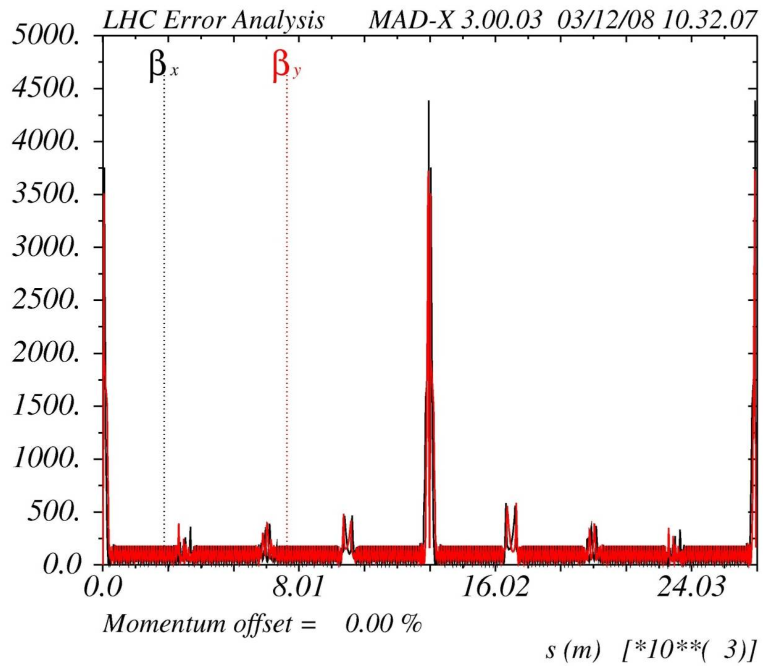
Nota bene:

1.) *A proton machine … or an electron linac … needs the highest aperture at injection energy !!!*
as soon as we start to accelerate the beam size shrinks as $\gamma^{-1/2}$ *in both planes.*

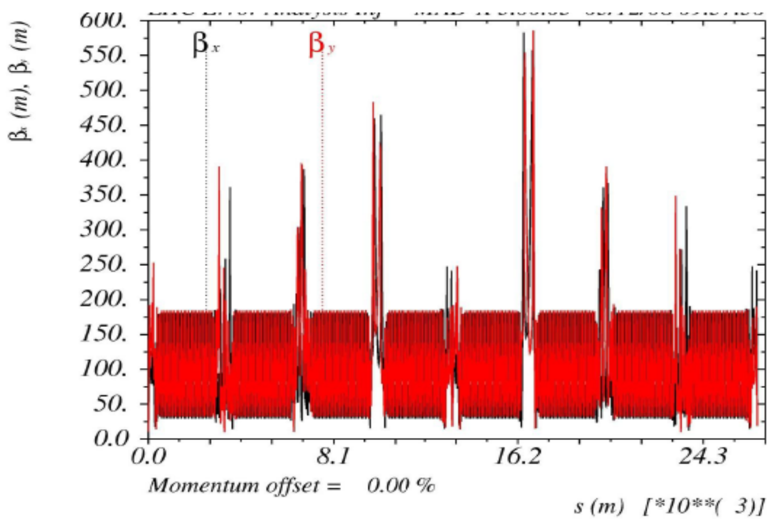
$$\sigma = \sqrt{\varepsilon\beta}$$

2.) *At lowest energy the machine will have the major aperture problems,*
→ *here we have to minimise* $\hat{\beta}$

3.) *we need different beam optics adopted to the energy:*
A Mini Beta concept will only be adequate at flat top.



LHC mini beta optics at 7000 GeV

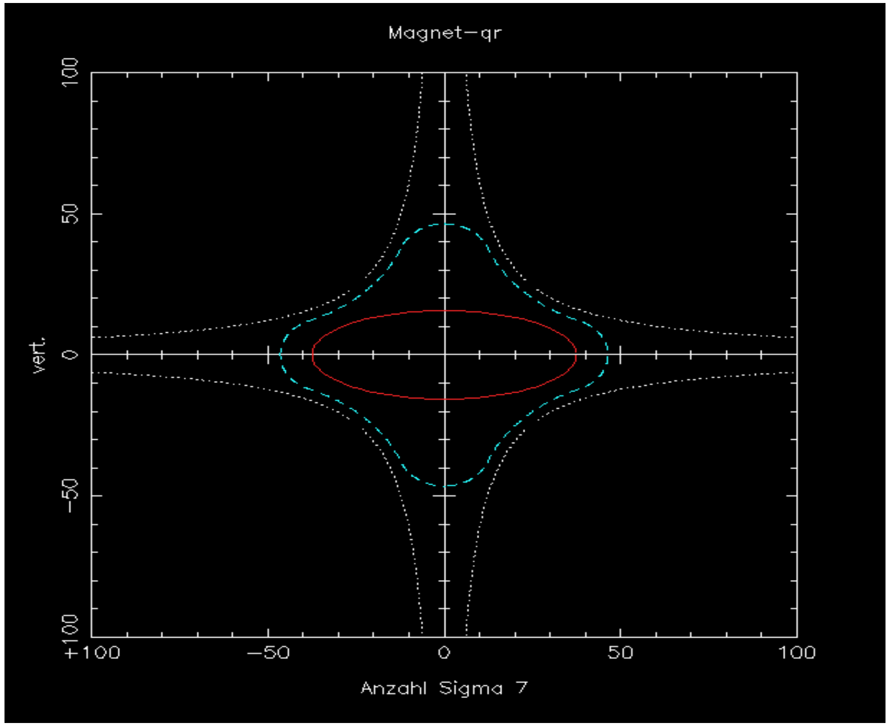


LHC injection optics at 450 GeV

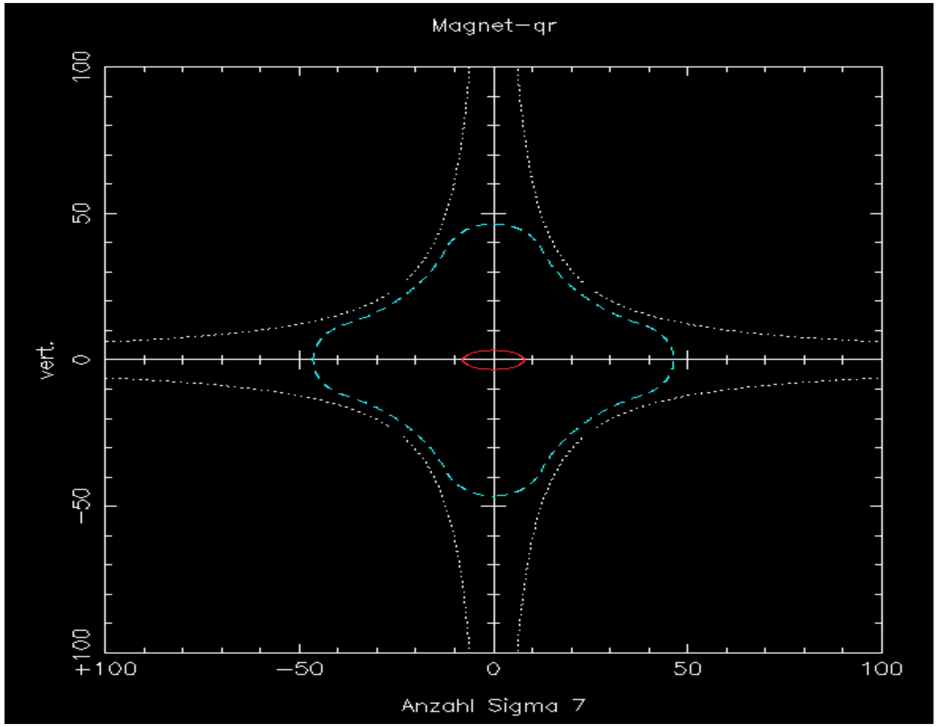
Example: HERA proton ring

injection energy: 40 GeV $\gamma = 43$
flat top energy: 920 GeV $\gamma = 980$

emittance $\varepsilon\,(40GeV) = 1.2 * 10^{-7}$
$\varepsilon\,(920GeV) = 5.1 * 10^{-9}$



7 σ beam envelope at E = 40 GeV



… and at E = 920 GeV

12.) The „ $\Delta p / p \neq 0$ “ Problem

A kind of ideal machine ...

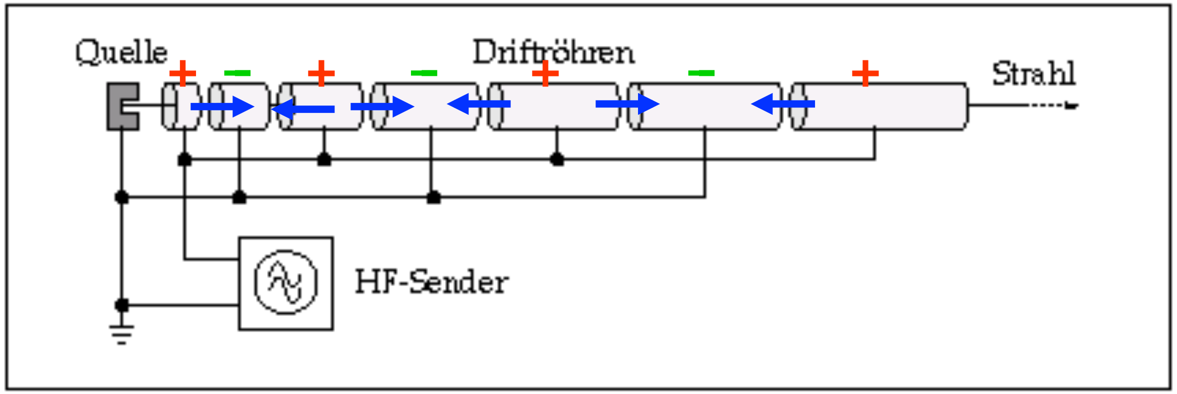
the Tandem Van-de Graaf

12.) The „ $\Delta p / p \neq 0$ “ Problem

Linear Accelerator

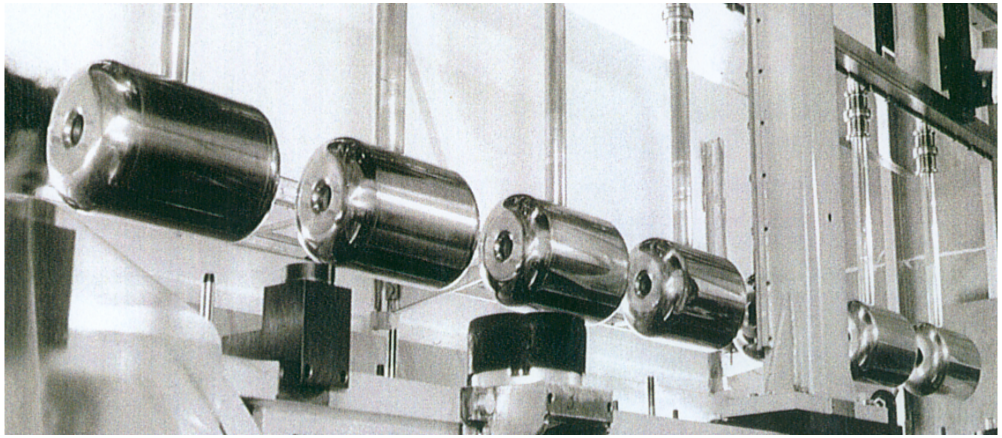
Energy Gain per „Gap“:

$$W = q\,U_0 \sin \omega_{RF} t$$

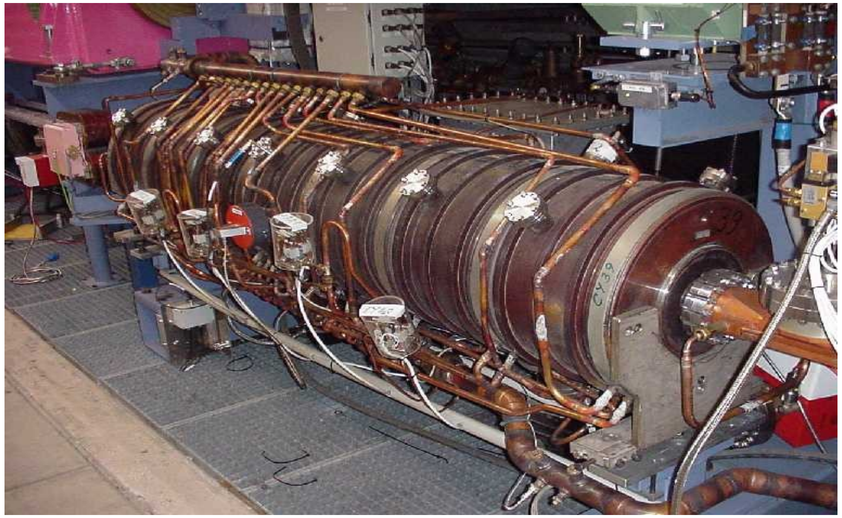


1928, Wideroe

drift tube structure at a proton linac



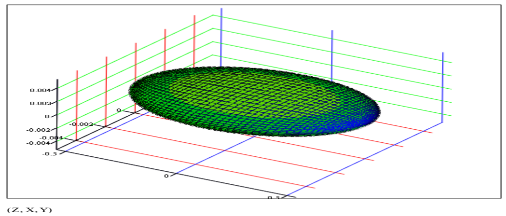
500 MHz cavities in an electron storage ring



* ***RF Acceleration:*** *multiple application of the same acceleration voltage; brillant idea to gain higher energies ... but* ***changing acceleration voltage***

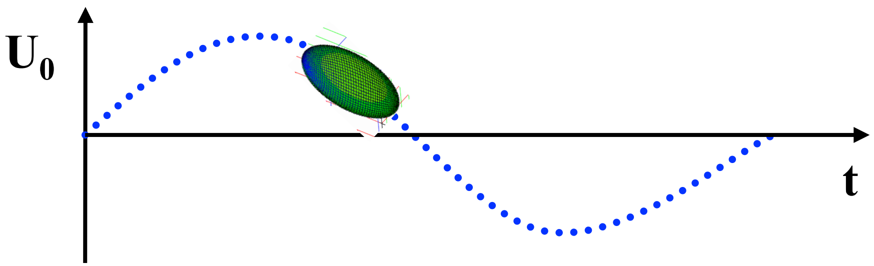
Problem: panta rhei !!!

(Heraklit: 540-480 v. Chr.)



Bunch length of Electrons ≈ 1cm

Example: HERA RF:



$$\lambda = 60\ cm$$

$$\left.\begin{aligned} \nu &= 500\,MHz \\ c &= \lambda\,\nu \end{aligned}\right\}\quad \lambda = 60\ cm$$

$$\sin(90^o) = 1$$

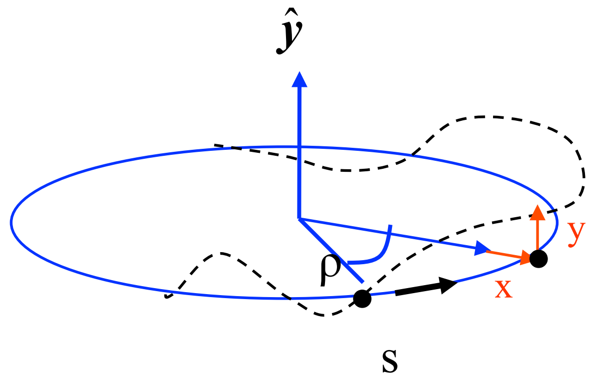
$$\sin(84^o) = 0.994$$

$$\frac{\Delta U}{U} = 6.0\ \ 10^{-3}$$

typical momentum spread of an electron bunch:

$$\frac{\Delta p}{p} \approx 1.0\ \ 10^{-3}$$

13.) Dispersion: trajectories for $\Delta p / p \neq 0$



***Force** acting on the particle*

$$F = m\frac{d^2}{dt^2}(x+\rho) - \frac{mv^2}{x+\rho} = e\,B_y\,v$$

***remember:** $x \approx mm$, $\rho \approx m$ … → develop for small x*

$$m\frac{d^2x}{dt^2} - \frac{mv^2}{\rho}(1-\frac{x}{\rho}) = eB_y v$$

***consider only linear fields, and change independent variable:** $t \rightarrow s$*

$$B_y = B_0 + x\frac{\partial B_y}{\partial x}$$

$$x'' - \frac{1}{\rho}(1-\frac{x}{\rho}) = \frac{e\,B_0}{mv} + \frac{e\,x\,g}{mv}$$

$p = p_0 + \Delta p$

… but now take a small momentum error into account !!!

Dispersion:

develop for small momentum error

$$\Delta p << p_0 \Rightarrow \frac{1}{p_0 + \Delta p} \approx \frac{1}{p_0} - \frac{\Delta p}{p_0^2}$$

$$x'' - \frac{1}{\rho} + \frac{x}{\rho^2} \approx \underbrace{\frac{e\ B_0}{p_0}}_{-\frac{1}{\rho}} - \frac{\Delta p}{p_0^2} eB_0 + \underbrace{\frac{xeg}{p_0}}_{k*x} - \underbrace{xeg\frac{\Delta p}{p_0^2}}_{\approx 0}$$

$$x'' + \frac{x}{\rho^2} \approx \frac{\Delta p}{p_0} * \underbrace{\frac{(-eB_0)}{p_0}}_{\frac{1}{\rho}} + k*x = \frac{\Delta p}{p_0} * \frac{1}{\rho} + k*x$$

$$x'' + \frac{x}{\rho^2} - kx = \frac{\Delta p}{p_0}\frac{1}{\rho} \quad \longrightarrow \quad x'' + x(\frac{1}{\rho^2} - k) = \frac{\Delta p}{p_0}\frac{1}{\rho}$$

***Momentum spread** of the beam adds a term on the r.h.s. of the equation of motion.*

*→ **inhomogeneous differential equation.***

Dispersion:

$$x'' + x\left(\frac{1}{\rho^2} - k\right) = \frac{\Delta p}{p} \cdot \frac{1}{\rho}$$

general solution:

$$x(s) = x_h(s) + x_i(s)$$

$$\begin{cases} x_h''(s) + K(s) \cdot x_h(s) = 0 \\ x_i''(s) + K(s) \cdot x_i(s) = \dfrac{1}{\rho} \cdot \dfrac{\Delta p}{p} \end{cases}$$

Normalise with respect to Δp/p:

$$D(s) = \frac{x_i(s)}{\Delta p / p}$$

Dispersion function D(s)

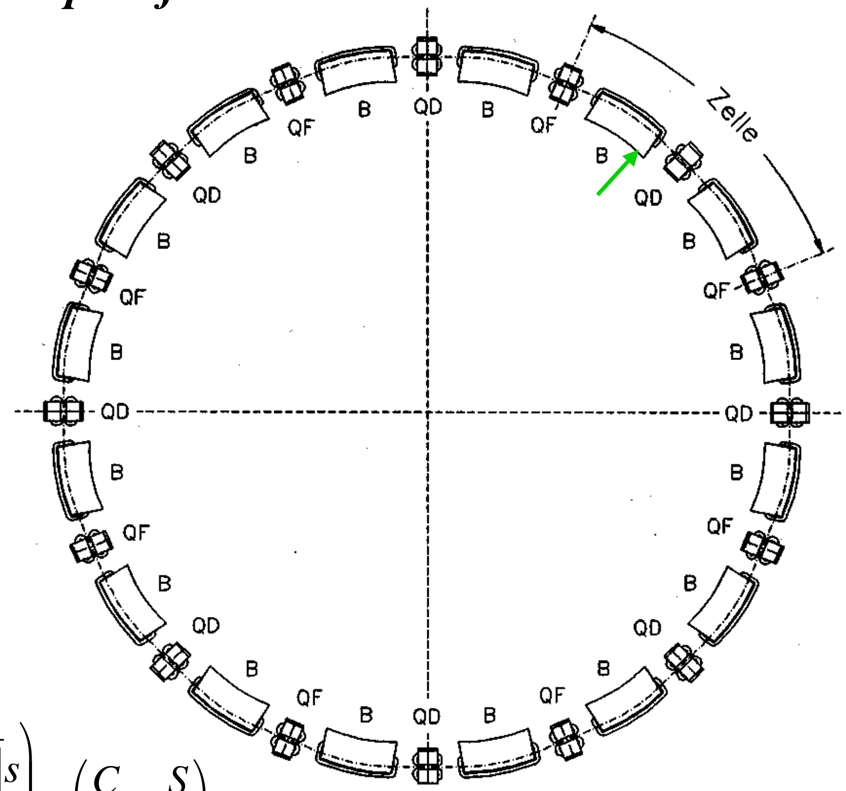
**** is that special orbit, an ideal particle would have for Δp/p = 1***

**** the orbit of any particle is the sum of the well known x_β and the dispersion***

**** as D(s) is just another orbit it will be subject to the focusing properties of the lattice***

Dispersion:

Example: homogenous dipole field



'bit for Δp/p > 0

$$= D(s) \cdot \frac{\Delta p}{p}$$

Matrix formalism:

e.g. matrix for a quadrupole lens:

$$M_{foc} = \begin{pmatrix} \cos(\sqrt{|K|}s & \frac{1}{\sqrt{|K|}}\sin(\sqrt{|K|}s \\ -\sqrt{|K|}\sin(\sqrt{|K|}s & \cos(\sqrt{|K|}s \end{pmatrix} = \begin{pmatrix} C & S \\ C' & S' \end{pmatrix}$$

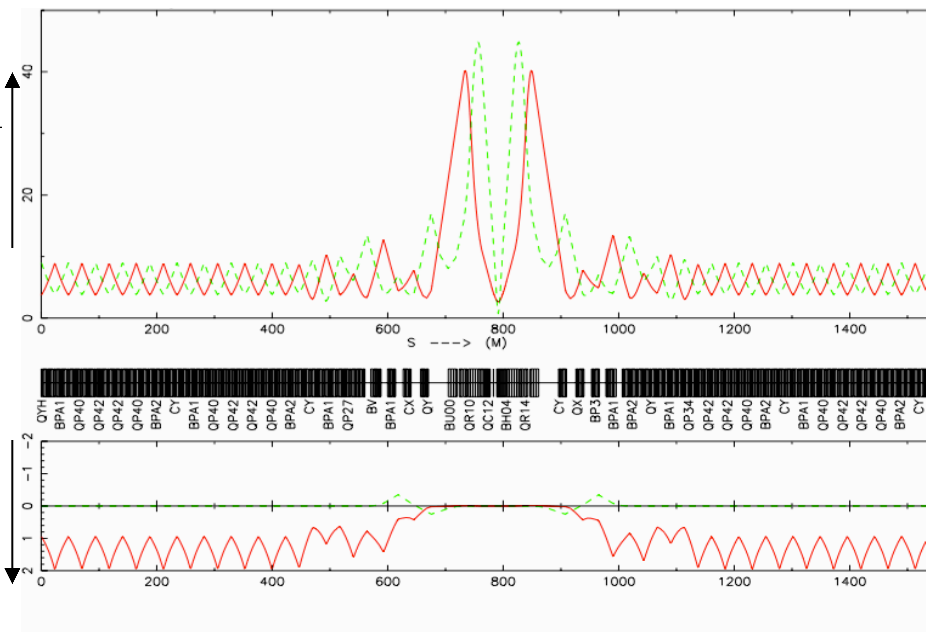
$$x(s) = x_\beta(s) + D(s) \cdot \frac{\Delta p}{p}$$

$$x(s) = C(s) \cdot x_0 + S(s) \cdot x_0' + D(s) \cdot \frac{\Delta p}{p}$$

$$\begin{pmatrix} x \\ x' \end{pmatrix}_s = \begin{pmatrix} C & S \\ C' & S' \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}_0 + \frac{\Delta p}{p} \begin{pmatrix} D \\ D' \end{pmatrix}$$

or expressed as 3x3 matrix

$$\begin{pmatrix} x \\ x' \\ \Delta p/p \end{pmatrix}_s = \begin{pmatrix} C & S & D \\ C' & S' & D' \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ x' \\ \Delta p/p \end{pmatrix}_0$$



Example HERA

$$\left.\begin{aligned} x_\beta &= 1 \dots 2\, mm \\ D(s) &\approx 1 \dots 2\, m \\ \Delta p/p &\approx 1 \cdot 10^{-3} \end{aligned}\right\}$$

Amplitude of Orbit oscillation
contribution due to Dispersion ≈ beam size
→ Dispersion must vanish at the collision point

!

Calculate D, D´

$$D(s) = S(s) \int_{s0}^{s1} \frac{1}{\rho} C(\tilde{s})\, d\tilde{s} - C(s) \int_{s0}^{s1} \frac{1}{\rho} S(\tilde{s})\, d\tilde{s}$$

(proof: see appendix)

Example: Drift

$$M_{Drift} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}$$

$$M_{Drift} = \begin{pmatrix} 1 & l & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$D(s) = S(s)\underbrace{\int_{s0}^{s1} \frac{1}{\rho} C(\tilde{s})\,d\tilde{s}}_{=0} - C(s)\underbrace{\int_{s0}^{s1} \frac{1}{\rho} S(\tilde{s})\,d\tilde{s}}_{=0}$$

Example: Dipole

$$M_{foc} = \begin{pmatrix} \cos(\sqrt{|K|}s) & \frac{1}{\sqrt{|K|}}\sin(\sqrt{|K|}s \\ -\sqrt{|K|}\sin(\sqrt{|K|}s) & \cos(\sqrt{|K|}s) \end{pmatrix}_0$$

$$\boldsymbol{K} = \frac{1}{\rho^2} \cancel{-k}$$

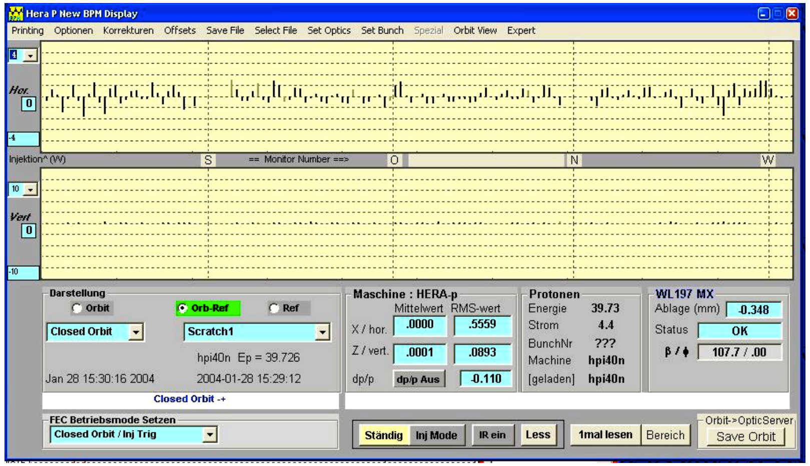
$$\boldsymbol{s} = \boldsymbol{l_B}$$

$$M_{Dipole} = \begin{pmatrix} \cos\frac{l}{\rho} & \rho\sin\frac{l}{\rho} \\ -\frac{1}{\rho}\sin\frac{l}{\rho} & \cos\frac{l}{\rho} \end{pmatrix} \quad \rightarrow$$

$$D(s) = \rho\cdot(1-\cos\frac{l}{\rho})$$

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

Dispersion is visible



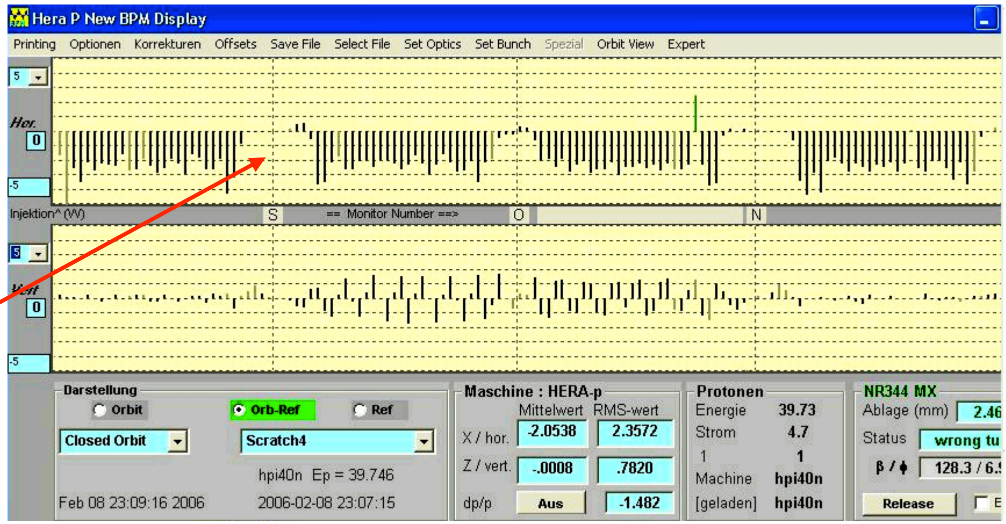
HERA Standard Orbit

HERA Dispersion Orbit

dedicated energy change of the stored beam

→ closed orbit is moved to a dispersions trajectory

$$x_D = D(s) * \frac{\Delta p}{p}$$

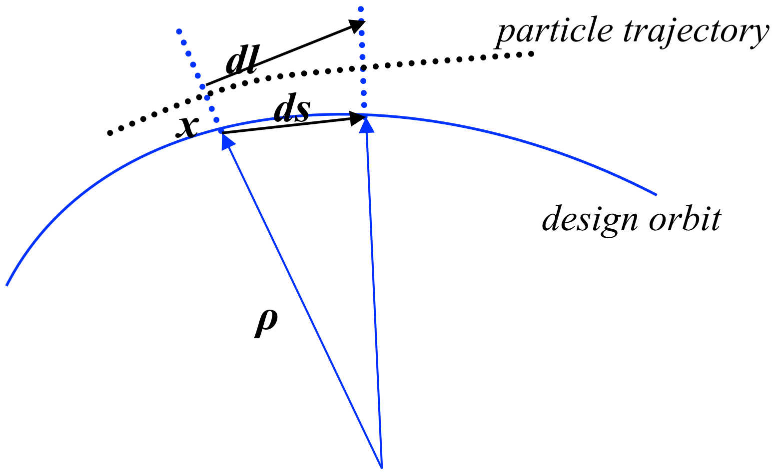


Attention: at the Interaction Points we require D=D′= 0

14.) Momentum Compaction Factor: α_p

The dispersion function relates the momentum error of a particle to the horizontal orbit coordinate and so it changes the length of the off - energy - orbit !!

particle with a displacement x to the design orbit
→ path length dl ...



$$\frac{dl}{ds} = \frac{\rho + x}{\rho}$$

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

circumference of an off-energy closed orbit

$$l_{\Delta E} = \oint dl = \oint \left(1 + \frac{x_{\Delta E}}{\rho(s)}\right) ds$$

remember:

$$x_{\Delta E}(s) = D(s)\frac{\Delta p}{p}$$

$$\delta l_{\Delta E} = \frac{\Delta p}{p} \oint \left(\frac{D(s)}{\rho(s)}\right) ds$$

**** The lengthening of the orbit for off-momentum particles is given by the dispersion function and the bending radius.***

Definition:

$$\frac{\delta l_\varepsilon}{L} = \alpha_p \frac{\Delta p}{p}$$

$$\rightarrow \alpha_p = \frac{1}{L}\oint\left(\frac{D(s)}{\rho(s)}\right)ds$$

For first estimates assume: $\frac{1}{\rho} = const.$

$$\int_{dipoles} D(s)\,ds \approx l_{\Sigma(dipoles)} \cdot \langle D \rangle_{dipole}$$

$$\alpha_p = \frac{1}{L}\, l_{\Sigma(dipoles)} \cdot \langle D \rangle \frac{1}{\rho} = \frac{1}{L}\, 2\pi\rho \cdot \langle D \rangle \frac{1}{\rho} \quad \rightarrow \quad \alpha_p \approx \frac{2\pi}{L}\langle D \rangle \approx \frac{\langle D \rangle}{R}$$

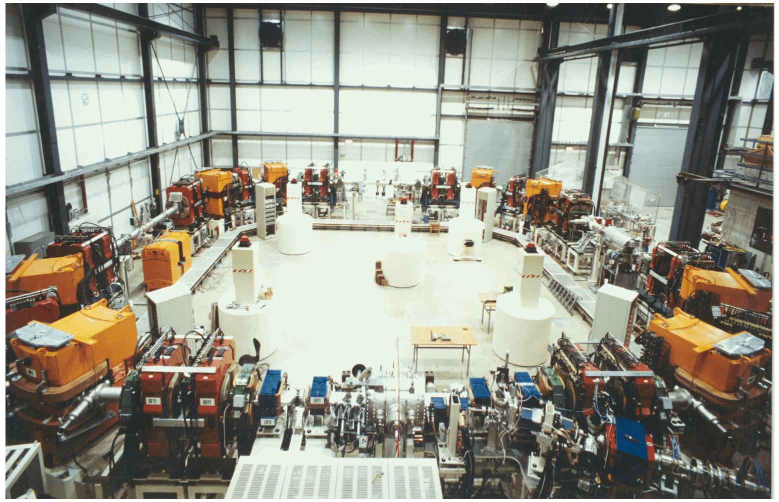
Assume: $v \approx c$

$$\rightarrow \quad \frac{\delta T}{T} = \frac{\delta l_\varepsilon}{L} = \alpha_p \frac{\Delta p}{p}$$

α_p combines via the dispersion function the momentum spread with the longitudinal motion of the particle.

15.) Gradient Errors

Matrix in Twiss Form



Transfer Matrix from point „0" in the lattice to point „s":

$$M(s) = \begin{pmatrix} \sqrt{\frac{\beta_s}{\beta_0}}(\cos\psi_s + \alpha_0 \sin\psi_s) & \sqrt{\beta_s \beta_0}\sin\psi_s \\ \frac{(\alpha_0 - \alpha_s)\cos(\psi_s - (1+\alpha_0\alpha_s)\sin\psi_s}{\sqrt{\beta_s\beta_0}} & \sqrt{\frac{\beta_0}{\beta_s}}(\cos(\psi_s - \alpha_0 \sin\psi_s) \end{pmatrix}$$

For one complete turn the Twiss parameters have to obey periodic bundary conditions:

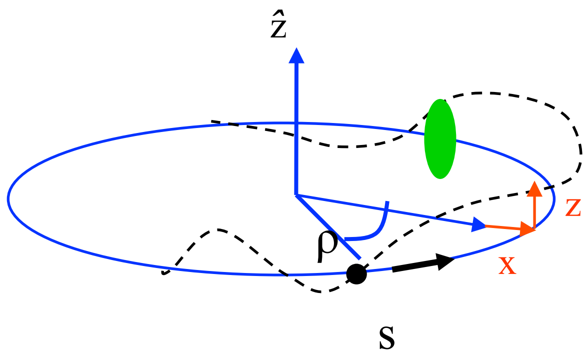
$$\beta(s+L) = \beta(s)$$
$$\alpha(s+L) = \alpha(s)$$
$$\gamma(s+L) = \gamma(s)$$

$$M(s) = \begin{pmatrix} \cos\psi_{turn} + \alpha_s \sin\psi_{turn} & \beta_s \sin\psi_{turn} \\ -\gamma_s \sin\psi_s & \cos\psi_{turn} - \alpha_s \sin\psi_{turn} \end{pmatrix}$$

Quadrupole Error in the Lattice

optic perturbation described by thin lens quadrupole

$$M_{dist} = M_{\Delta k} \cdot M_0 = \underbrace{\begin{pmatrix} 1 & 0 \\ \Delta k ds & 1 \end{pmatrix}}_{\text{quad error}} \cdot \underbrace{\begin{pmatrix} \cos\psi_{turn} + \alpha \sin\psi_{turn} & \beta \sin\psi_{turn} \\ -\gamma \sin\psi_{turn} & \cos\psi_{turn} - \alpha \sin\psi_{turn} \end{pmatrix}}_{\text{ideal storage ring}}$$



$$M_{dist} = \begin{pmatrix} \cos\psi_0 + \alpha \sin\psi_0 & \beta \sin\psi_0 \\ \Delta k ds(\cos\psi_0 + \alpha \sin\psi_0) - \gamma \sin\psi_0 & \Delta k ds\, \beta \sin\psi_0 + \cos\psi_0 - \alpha \sin\psi_0 \end{pmatrix}$$

rule for getting the tune

$$Trace(M) = 2\cos\psi = 2\cos\psi_0 + \Delta k ds \beta \sin\psi_0$$

Quadrupole error → Tune Shift

$$\boxed{\psi = \psi_0 + \Delta\psi} \longrightarrow \cos(\psi_0 + \Delta\psi) = \cos\psi_0 + \frac{\Delta k ds\, \beta \sin\psi_0}{2}$$

remember the old fashioned trigonometric stuff and assume that the error is small !!!

$$\cos\psi_0 \underbrace{\cos\Delta\psi}_{\approx 1} - \sin\psi_0 \underbrace{\sin\Delta\psi}_{\approx \Delta\psi} = \cos\psi_0 + \frac{k ds\, \beta \sin\psi_0}{2}$$

$$\Delta\psi = \frac{k ds\, \beta}{2}$$

and referring to Q instead of ψ:

$$\psi = 2\pi Q$$

$$\boxed{\Delta Q = \int_{s0}^{s0+l} \frac{\Delta k(s)\beta(s) ds}{4\pi}}$$

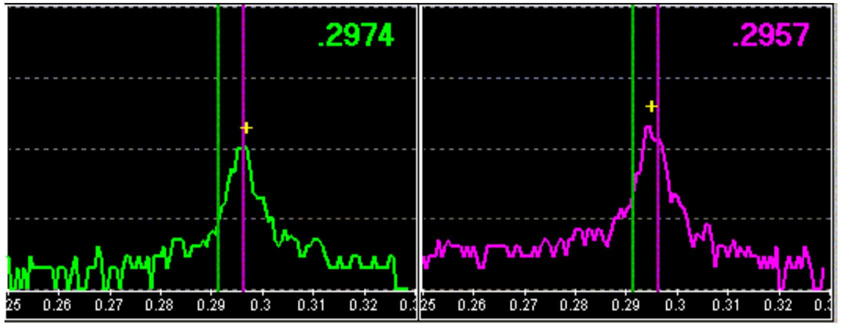
! the tune shift is proportional to the β-function at the quadrupole

!! field quality, power supply tolerances etc are much tighter at places where β is large

!!! mini beta quads: β ≈ 1900 m
arc quads: β ≈ 80 m

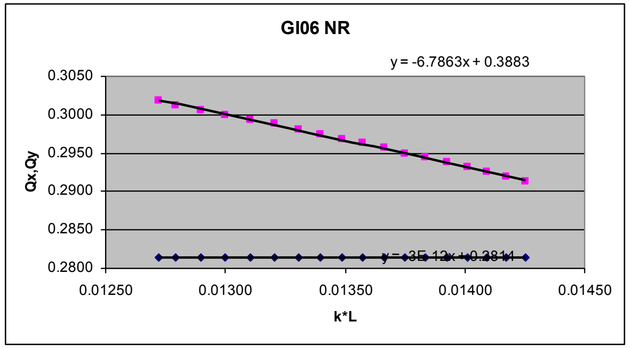
!!!! β is a measure for the sensitivity of the beam

a quadrupol error leads to a shift of the tune:



$$\Delta Q = \int_{s0}^{s0+l} \frac{\Delta k \beta(s)}{4\pi} ds \approx \frac{\Delta k l_{quad} \bar{\beta}}{4\pi}$$

Example: measurement of β in a storage ring:
tune spectrum



Without proof (CERN-94-01)
A quadrupole error will always lead to a tune shift, but in addition to a change of the beta–function.

$$\Delta\beta(s) = \frac{\beta(s)}{2\sin(2\pi Q)} \oint \beta(\tilde{s}) \Delta k(\tilde{s}) \cos(2\left|\psi(s) - \psi(\tilde{s})\right| - \pi Q)\, d\tilde{s}$$

As before the effect of the error depends on the β-function at the observation point as well as at the place of the error itself, on the error strength and there is again a resonance denominator

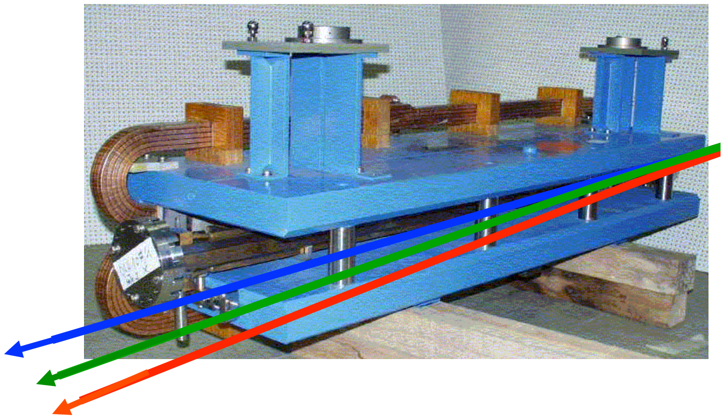
→ half integer tunes are forbidden.

16.) Chromaticity:
A Quadrupole Error for $\Delta p/p \neq 0$

Influence of external fields on the beam: *prop. to magn. field & prop. zu 1/p*

dipole magnet

$$\alpha = \frac{\int B\,dl}{p/e}$$



$$x_D(s) = D(s)\,\frac{\Delta p}{p}$$

focusing lens

$$k = \frac{g}{p/e}$$

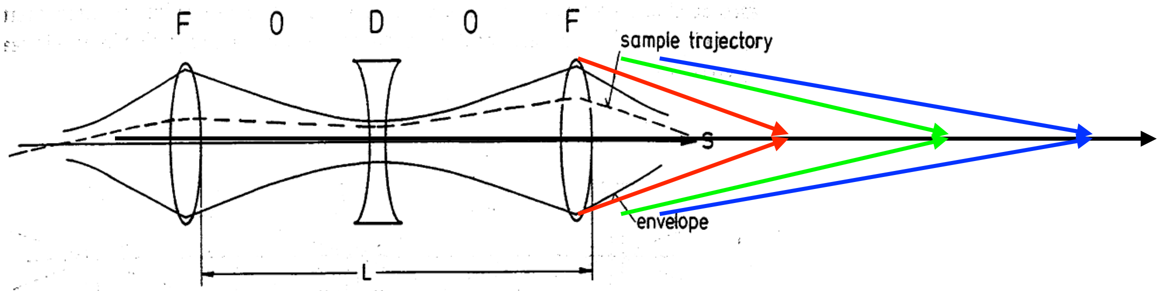


Figure 29: FODO cell

particle having ...

to high energy

to low energy

ideal energy

Chromaticity: Q'

$$k = \frac{g}{p/e} \qquad\qquad p = p_0 + \Delta p$$

in case of a momentum spread:

$$\boldsymbol{k = \frac{eg}{p_0 + \Delta p} \approx \frac{e}{p_0}\left(1 - \frac{\Delta p}{p_0}\right) g = k_0 + \Delta k}$$

$$\Delta k = -\frac{\Delta p}{p_0} k_0$$

… which acts like a quadrupole error in the machine and leads to a tune spread:

$$\boldsymbol{\Delta Q = -\frac{1}{4\pi} \frac{\Delta p}{p_0} k_0 \beta(s) ds}$$

definition of chromaticity:

$$\boldsymbol{\Delta Q = Q' \frac{\Delta p}{p} \quad ; \qquad Q' = -\frac{1}{4\pi} \oint k(s) \beta(s) ds}$$

… what is wrong about Chromaticity:

Problem: chromaticity is generated by the lattice itself !!

Q' is a number indicating the size of the tune spot in the working diagram,
Q' is always created if the beam is focussed
→ it is determined by the focusing strength k of all quadrupoles

$$Q' = -\frac{1}{4\pi} \oint \beta(s) k(s) ds$$

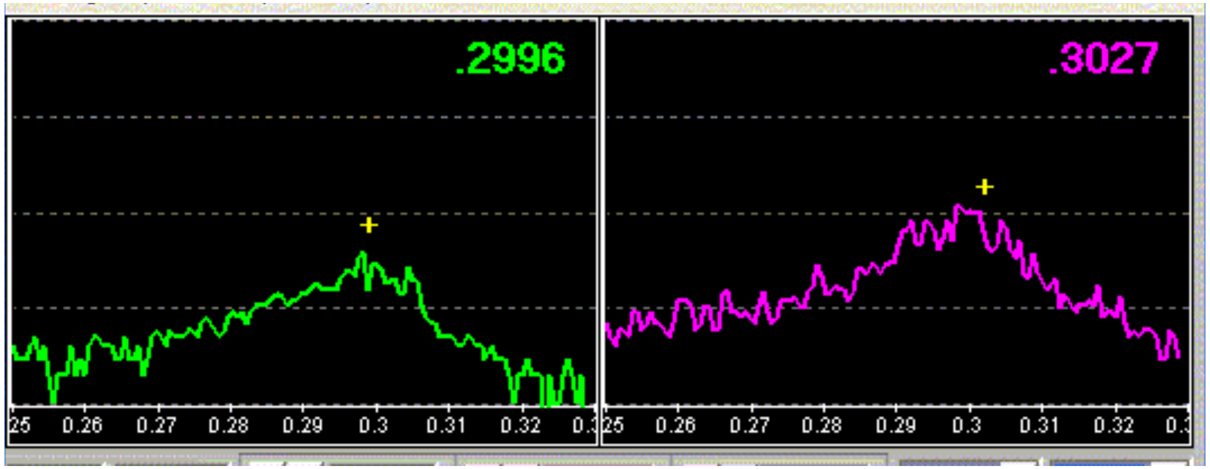
k = quadrupole strength
β = betafunction indicates the beam size … and even more the sensitivity of the beam to external fields

Example: LHC

$Q' = -250$
$\Delta p/p = +/- 0.2 \cdot 10^{-3}$
$\Delta Q = 0.256 \ldots 0.36$

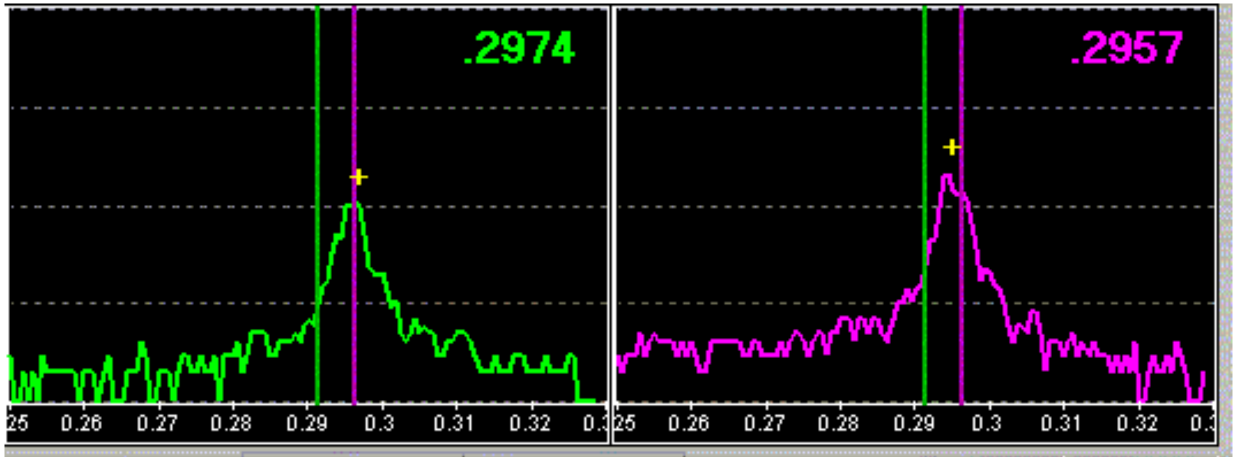
→ Some particles get very close to resonances and are lost

in other words: the tune is not a point
it is a pancake



Tune signal for a nearly uncompensated cromaticity (Q' ≈ 20)

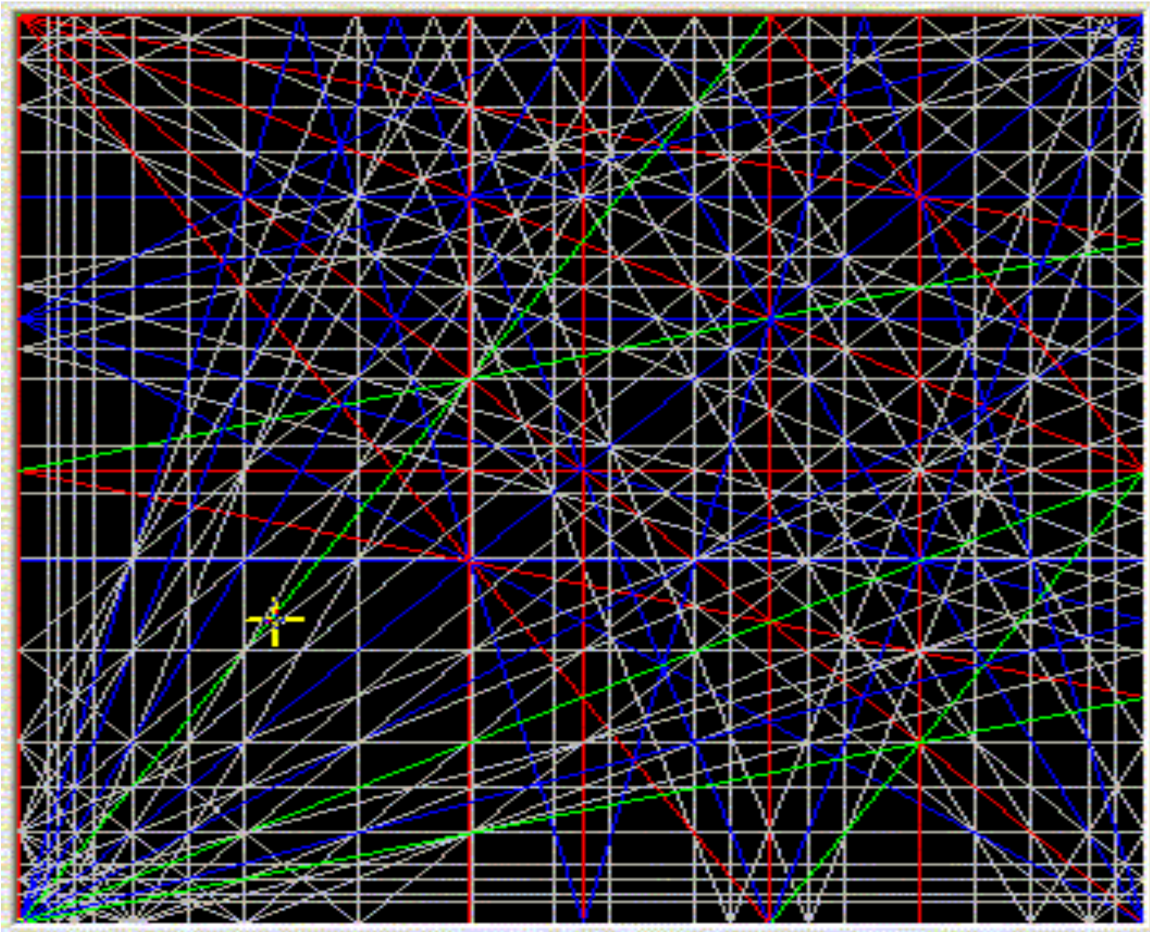
Ideal situation: cromaticity well corrected, (Q' ≈ 1)



Tune and Resonances

$$m*Q_x+n*Q_y+l*Q_s = integer$$

Tune diagram up to 3rd order



… and up to 7th order

Homework for the operateurs:
find a nice place for the tune
where against all probability
the beam will survive

Correction of Q'

1.) sort the particles acording to their momentum

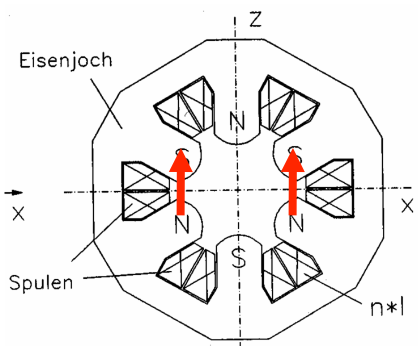
$$x_D(s) = D(s)\frac{\Delta p}{p}$$

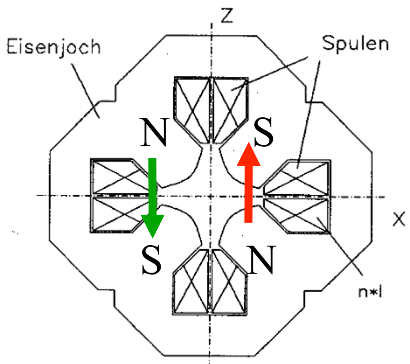
2.) apply a magnetic field that rises quadratically with x (sextupole field)

$$\left.\begin{aligned} B_x &= \tilde{g}xz \\ B_z &= \frac{1}{2}\tilde{g}(x^2 - z^2) \end{aligned}\right\} \qquad \frac{\partial B_x}{\partial z} = \frac{\partial B_z}{\partial x} = \tilde{g}x$$

linear rising „gradient":

Sextupole Magnets:





normalised quadrupole strength:

$$k_{sext} = \frac{\tilde{g}x}{p/e} = m_{sext}.x$$

$$k_{sext} = m_{sext}.D\frac{\Delta p}{p}$$

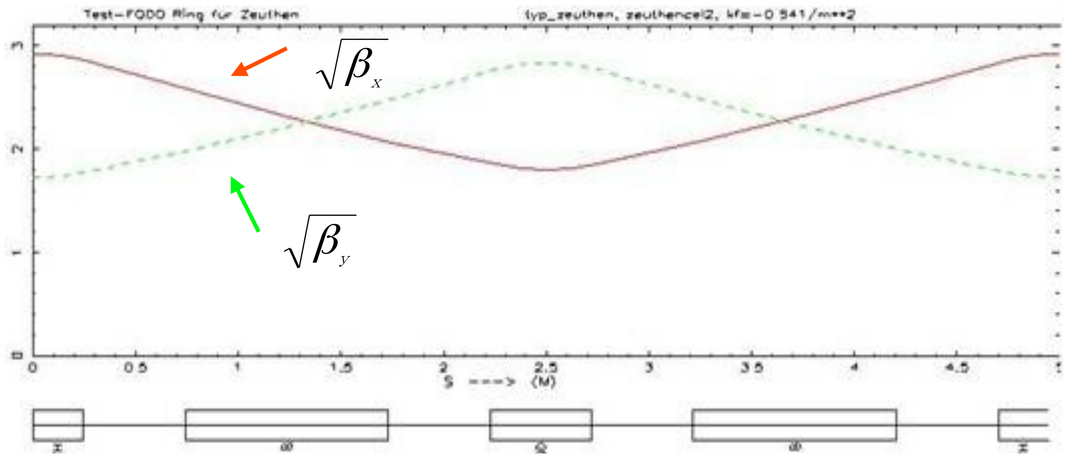
corrected chromaticity:

$$Q'_{cell\_x} = -\frac{1}{4\pi}\left\{ k_{qf}\hat{\beta}_x l_{qf} - k_{qd}\breve{\beta}_x l_{qd}\right\} + \frac{1}{4\pi}\sum_{F\,sext} k_2^F l_{sext} D_x^F \beta_x^F - \frac{1}{4\pi}\sum_{D\,sext} k_2^D l_{sext} D_x^D \beta_y^D$$

$$Q'_{cell\_y} = -\frac{1}{4\pi}\left\{ -k_{qf}\breve{\beta}_y l_{qf} + k_{qd}\hat{\beta}_y l_{qd}\right\} + \frac{1}{4\pi}\sum_{F\,sext} k_2^F l_{sext} D_x^F \beta_x^F - \frac{1}{4\pi}\sum_{D\,sext} k_2^D l_{sext} D_x^D \beta_y^D$$

Chromaticity in a FODO lattice

$$Q' = \frac{-1}{4\pi} * \oint k(s)\beta(s)\, ds$$



β-Function in a FoDo structure

$$\hat{\beta} = \frac{(1+\sin\frac{\psi_{cell}}{2})L}{\sin\psi_{cell}} \qquad \breve{\beta} = \frac{(1-\sin\frac{\psi_{cell}}{2})L}{\sin\psi_{cell}}$$

$$Q' = \frac{-1}{4\pi} N * \frac{\hat{\beta}-\breve{\beta}}{f_Q}$$

$$Q' = \frac{-1}{4\pi} N * \frac{1}{f_Q} * \left\{ \frac{L(1+\sin\frac{\psi_{cell}}{2}) - L(1-\sin\frac{\psi_{cell}}{2})}{\sin\mu} \right\}$$

using some TLC transformations ... ξ can be expressed in a very simple form:

$$Q' = \frac{-1}{4\pi} N * \frac{1}{f_Q} * \frac{2L \sin\frac{\psi_{cell}}{2}}{\sin\psi_{cell}}$$

$$Q' = \frac{-1}{4\pi} N * \frac{1}{f_Q} * \frac{L \sin\frac{\psi_{cell}}{2}}{\sin\frac{\psi_{cell}}{2} \cos\frac{\psi_{cell}}{2}}$$

remember ...

$$\sin x = 2 \sin\frac{x}{2} \cos\frac{x}{2}$$

$$Q'_{cell} = \frac{-1}{4\pi f_Q} * \frac{L \tan\frac{\psi_{cell}}{2}}{\sin\frac{\psi_{cell}}{2}}$$

putting ...

$$\sin\frac{\psi_{cell}}{2} = \frac{L}{4 f_Q}$$

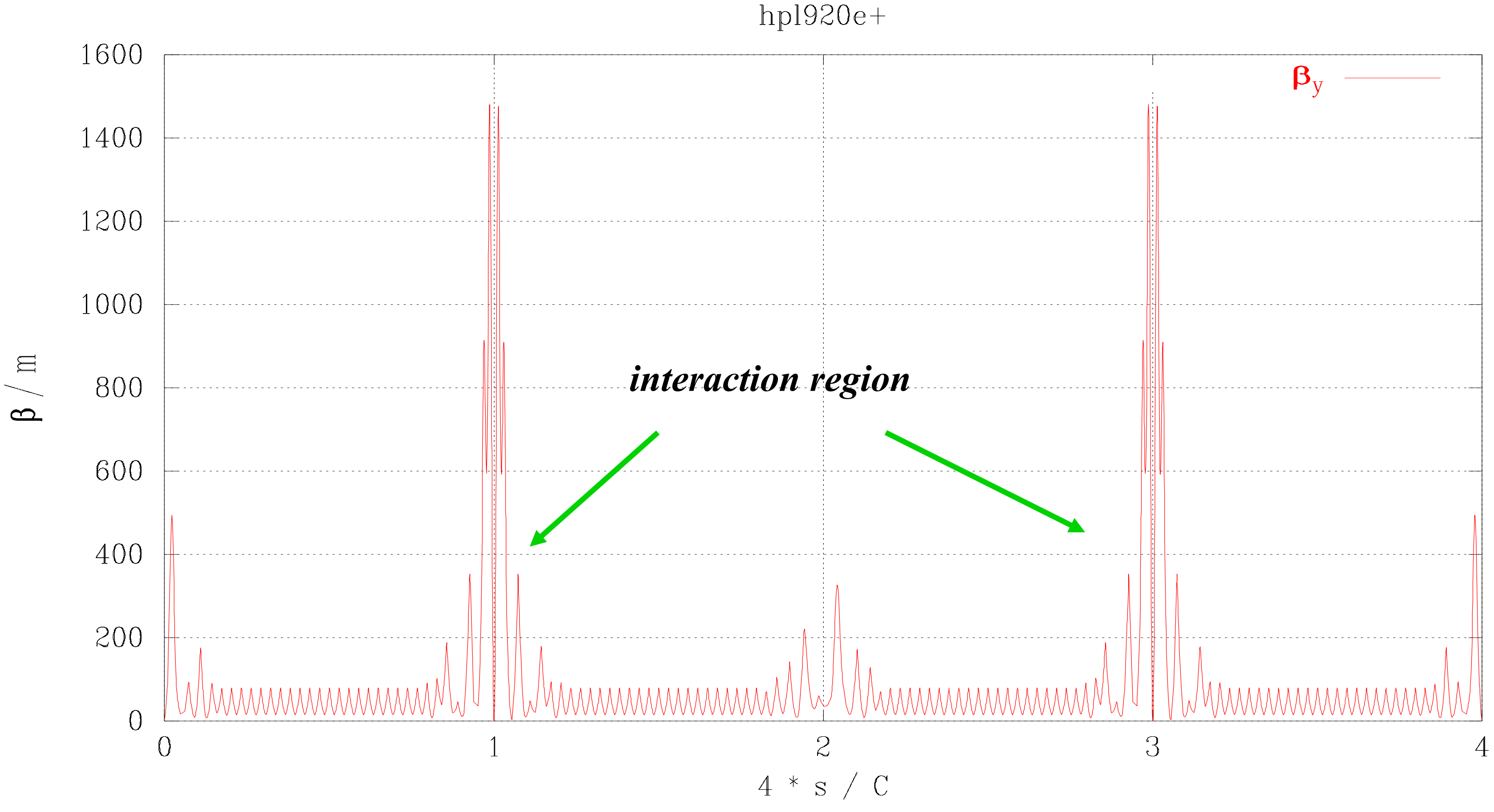
$$\boxed{Q'_{cell} = \frac{-1}{\pi} * \tan\frac{\psi_{cell}}{2}}$$

contribution of one FoDo Cell to the chromaticity of the ring:

Chromaticity

$$Q' = -\frac{1}{4\pi}\oint K(s)\beta(s)ds$$

question: main contribution to ξ in a lattice … ?



Dipole Errors / Quadrupole Misalignment

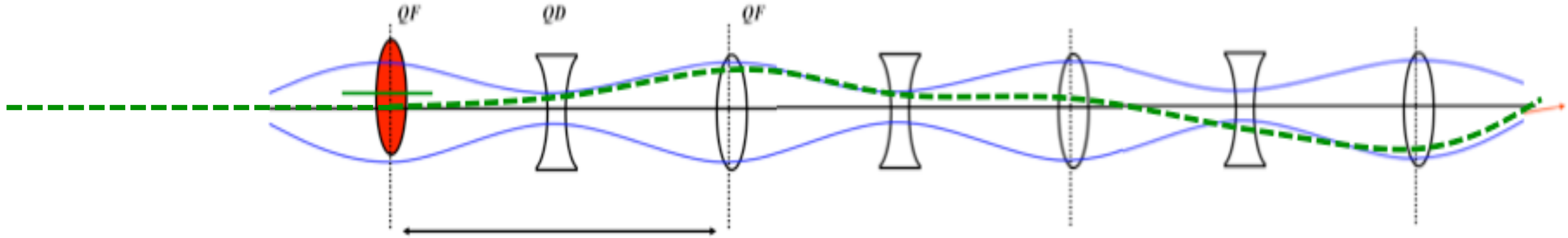
The Design Orbit is defined by the strength and arrangement of the dipoles.
Under the influence of dipole imperfections and quadrupole misalignments we obtain a "Closed Orbit" which is hopefully still closed and not too far away from the design.

Dipole field error: $$\theta = \frac{dl}{\rho} = \frac{\int B\,dl}{B\rho}$$

Quadrupole offset: $$g = \frac{dB}{dx} \rightarrow \quad \Delta x \cdot g = \Delta x \frac{dB}{dx} = \Delta B$$

misaligned quadrupoles (or orbit offsets in quadrupoles) create dipole effects that lead to a distorted "closed orbit"

normalised to p/e: $$\Delta x \cdot k = \Delta x \cdot \frac{g}{B\rho} = \frac{1}{\rho} \qquad \begin{pmatrix} x \\ x' \end{pmatrix}_i = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ x' \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{l}{\rho} \end{pmatrix}$$



In a Linac – starting with a perfect orbit – the misaligned quadrupole creates an oscillation that is transformed from now on downstream via

$$\begin{pmatrix} x \\ x' \end{pmatrix}_f = M \begin{pmatrix} x \\ x' \end{pmatrix}_i$$

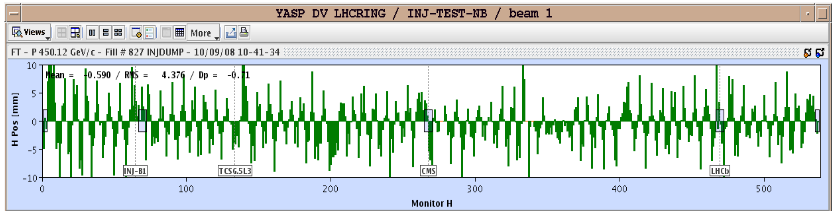
... and in a circular machine ??

we have to obey the periodicity condition.
The orbit is closed !! ... even under the influence of a orbit kick.

Calculation of the new closed orbit:
the general orbit will always be a solution of Hill, so ...

$$x(s) = a \cdot \sqrt{\beta}\cos(\psi(s) + \varphi$$

We set at the location of the error s=0, Ψ(s)=0
and require as 1st boundary condition:
periodic amplitude



$$x(s+L) = x(s)$$

$$\cancel{a} \cdot \sqrt{\cancel{\beta(s+L)}} \cdot \cos(\psi(s) + 2\pi Q - \varphi) = \cancel{a} \cdot \sqrt{\cancel{\beta(s)}} \cdot \cos(\psi(s) - \varphi)$$

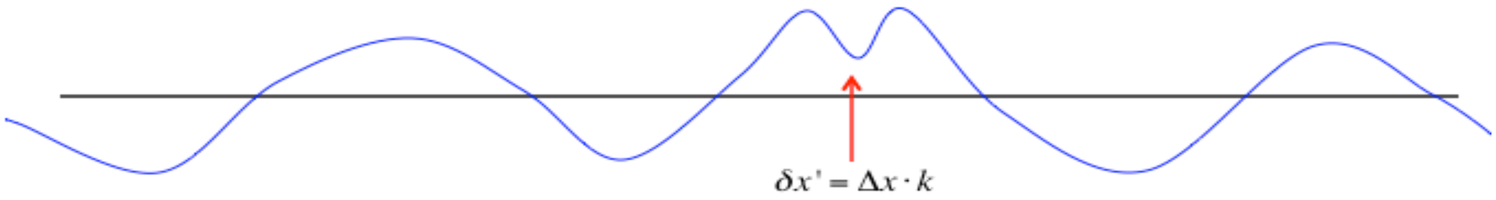
$$\cos(2\pi Q - \varphi) = \cos(-\varphi) = \cos(\varphi)$$

$$\boxed{\rightarrow \varphi = \pi Q}$$

$$\beta(s+L) = \beta(s)$$
$$\psi(s=0) = 0$$
$$\psi(s+L) = 2\pi Q$$

Misalignment error in a circular machine

2nd boundary condition: x' (s+L) + δx'= x'(s)
we have to close the orbit



$$x(s) = a \cdot \sqrt{\beta}\cos(\psi(s) - \varphi)$$

$$x'(s) = a \cdot \sqrt{\beta}\left(-\sin(\psi(s) - \varphi)\right)\psi' + \frac{\beta'(s)}{2\sqrt{\beta}} a \cdot \cos(\psi(s) - \varphi)$$

$$x'(s) = -a \cdot \frac{1}{\sqrt{\beta}}\left(\sin(\psi(s) - \varphi)\right) + \frac{\beta'(s)}{2\sqrt{\beta}} a \cdot \cos(\psi(s) - \varphi)$$

$$\psi(s) = \int \frac{1}{\beta(s)} ds$$

$$\psi'(s) = \frac{1}{\beta(s)}$$

boundary condition: x' (s+L) + δx'= x'(s)

$$-a \cdot \frac{1}{\sqrt{\beta(\tilde{s} + L)}}\left(\sin(2\pi Q - \varphi)\right) + \frac{\beta'(\tilde{s} + L)}{2\beta(\tilde{s} + L)}\sqrt{\beta(\tilde{s} + L)}\; a \cdot \cos(2\pi Q - \varphi) + \frac{\Delta\tilde{s}}{\rho} =$$

$$= -a \cdot \frac{1}{\sqrt{\beta(\tilde{s})}}\left(\sin(-\varphi)\right) + \frac{\beta'(\tilde{s})}{2\beta(\tilde{s})}\sqrt{\beta(\tilde{s})}\; a \cdot \cos(-\varphi)$$

Nota bene: refers $\tilde{s}$ to the location of the kick

Misalignment error in a circular machine

Now we use: $\beta(s+L) = \beta(s)$, $\varphi=\pi Q$

$$\frac{-a}{\sqrt{\beta(\tilde{s})}}\left(\sin(\pi Q\right)+\frac{\beta'(\tilde{s})}{2\beta(\tilde{s})}\sqrt{\beta(\tilde{s})}\, a\cdot\cos(\pi Q)+\frac{\Delta\tilde{s}}{\rho} \quad = \quad \frac{a}{\sqrt{\beta(\tilde{s})}}\left(\sin(\pi Q\right)+\frac{\beta'(\tilde{s})}{2\beta(\tilde{s})}\sqrt{\beta(\tilde{s})}\, a\cdot\cos(\pi Q)$$

$$\Rightarrow 2\,a\cdot\frac{\sin(\pi Q)}{\sqrt{\beta(\tilde{s})}}=\frac{\Delta\tilde{s}}{\rho} \quad \Rightarrow \quad a=\frac{\Delta\tilde{s}}{\rho}\cdot\sqrt{\beta(\tilde{s})}\,\frac{1}{2\sin(\pi Q)}$$

! this is the amplitude of the orbit oscillation resulting from a single kick

inserting in the equation of motion

$$x(s)=a\cdot\sqrt{\beta}\cos(\psi(s)+\varphi$$

$$x(s)=\frac{\Delta\tilde{s}}{\rho}\cdot\frac{\sqrt{\beta(\tilde{s})}\sqrt{\beta(s)}\cos(\psi(s)-\varphi)}{2\sin(\pi Q)}$$

! the distorted orbit depends on the kick strength,
! the local β function
! the β function at the observation point

!!! there is a resoncance denominator
→ watch your tune !!!

Misalignment error in a circular machine

For completeness:

if we do not set $\psi(s=0)=0$ *we have to write a bit more but finally we get:*

$$x(s)=\frac{\sqrt{\beta(s)}}{2\sin(\pi Q)}*\oint\sqrt{\beta(\tilde{s})}\,\frac{1}{\rho(\tilde{s})}\cos(|\psi(\tilde{s})-\psi(s)|-\pi Q)\,d\tilde{s}$$

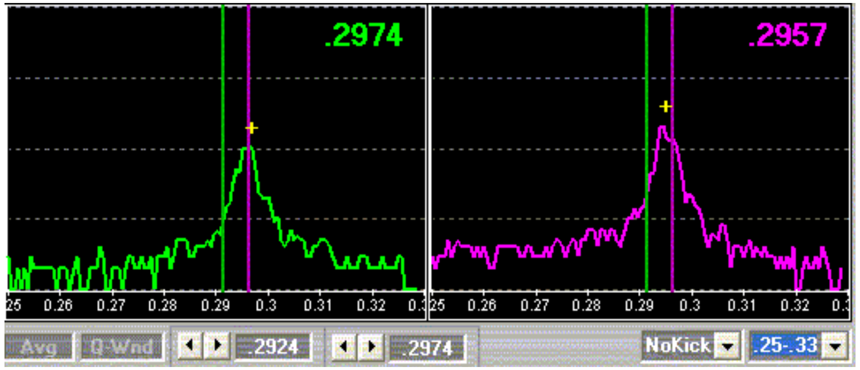
Reminder: LHC

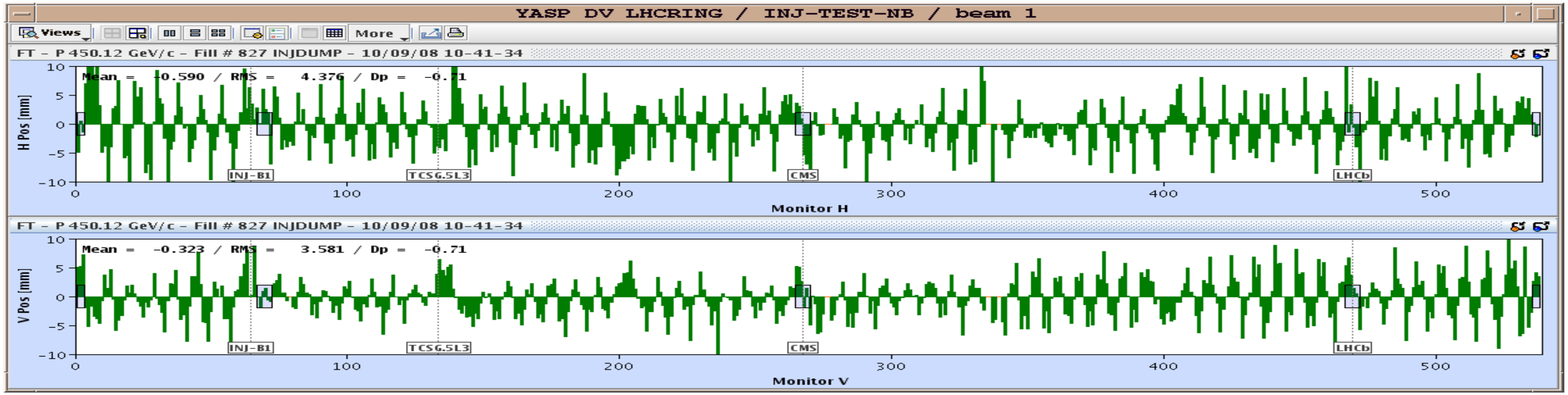
Tune: $Q_x = 64.31$, $Q_y = 59.32$

Relevant for beam stability:

non integer part

avoid integer tunes





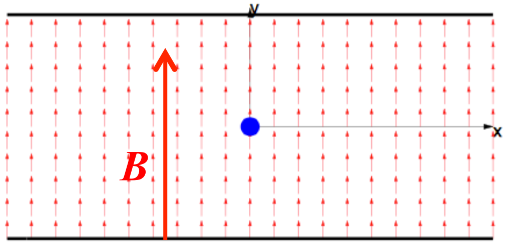
Quadrupole Rotation Errors

Short Resume until now:

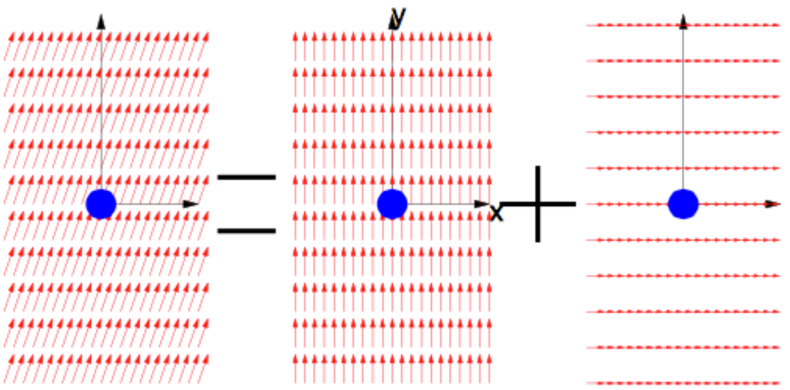
** Dipole field errors lead to closed orbit distortions*
** Quadrupole misalignments as well*
** Quadrupole gradient errors lead to tune shifts ΔQ and beta beats Δβ/β*

… and what does a roll angle error do ???

Dipole strength error:



An error in the strength of a main dipole causes a perturbation on the horizontal closed orbit.



A tilt error in a main dipole causes a perturbation on the vertical closed orbit.

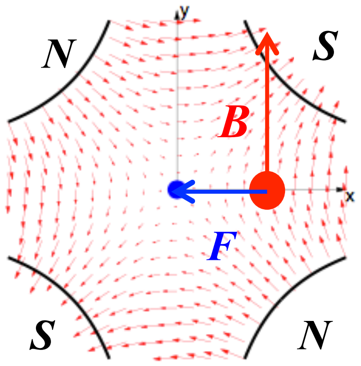
Dipole roll angle error

(court. pictures from R. Tomas)

Quadrupole Rotation Errors

quadrupole tilt errors lead to coupling of the transverse motions

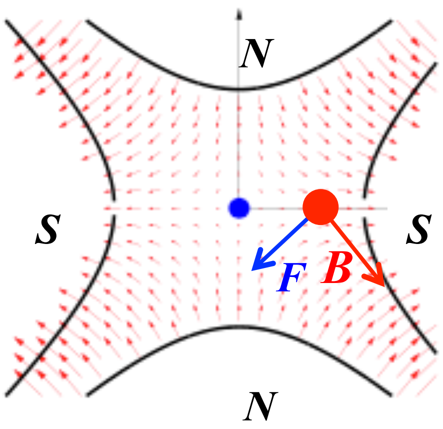
Standard quadrupol



Lorents Force:
$F_x = -kx$ and $F_y = ky$ making horizontal dynamics totally decoupled from vertical.

$$F = q(\vec{v} \times \vec{B})$$

Skew Quadrupole:

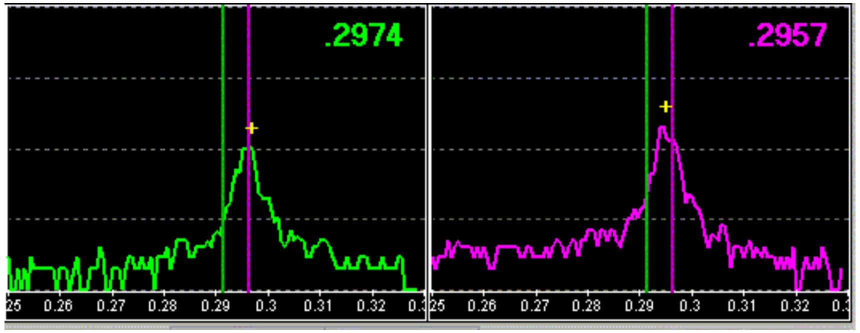


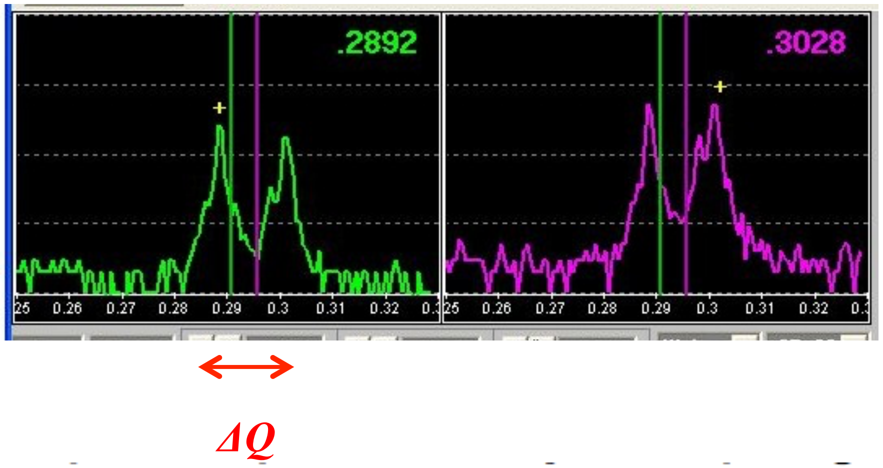
Lorents Force:
A horizontal offset leads to a horizontal and vertical component of the Lorentz force
-> to coupling between x and y plane

Quadrupole Rotation Errors

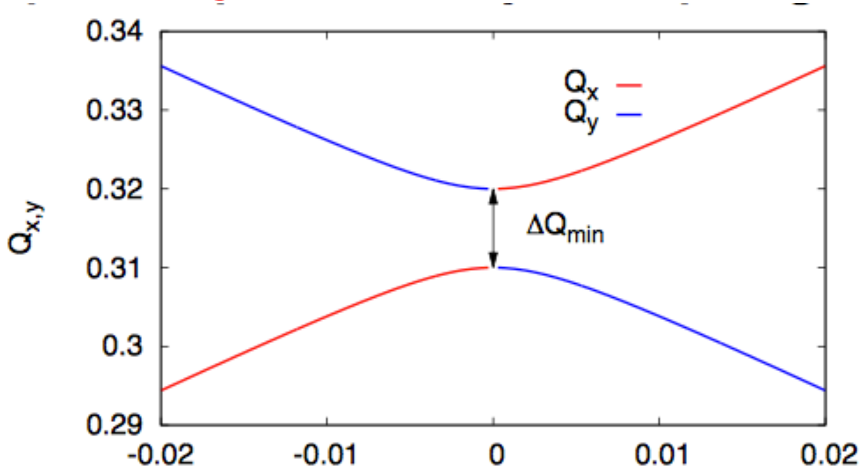
Observations on Beam:

Coupling makes it impossible to approach tunes below a certain ΔQ_{min} that depends on the tune and the coupling strength





observed tune as a function of the quadrupole strength "closest tune aproach"



Correction via dedicated skew quadrupoles in the machine

Resume´:

beam emittance:

$$\varepsilon \propto \frac{1}{\beta\gamma}$$

beta function in a drift:

$$\beta(s) = \beta_0 - 2\alpha_0 s + \gamma_0 s^2$$

… and for α = 0

$$\beta(s) = \beta_0 + \frac{s^2}{\beta_0}$$

particle trajectory for Δp/p ≠ 0
inhomogenious equation:

$$\boldsymbol{x}'' + \boldsymbol{x}\left(\frac{1}{\boldsymbol{\rho}^2} - \boldsymbol{k}\right) = \frac{\Delta \boldsymbol{p}}{\boldsymbol{p}_0}\,\frac{1}{\boldsymbol{\rho}}$$

… and its solution:

$$x(s) = x_\beta(s) + D(s)\cdot\frac{\Delta p}{p}$$

momentum compaction:

$$\frac{\delta l_\varepsilon}{L} = \alpha_{cp}\frac{\Delta p}{p} \qquad \alpha_{cp} \approx \frac{2\pi}{L}\langle D\rangle \approx \frac{\langle D\rangle}{R}$$

quadrupole error:

$$\Delta Q = \int_{s0}^{s0+l} \frac{\Delta K(s)\beta(s)ds}{4\pi}$$

chromaticity:

$$Q' = -\frac{1}{4\pi}\oint K(s)\beta(s)ds$$