Lattice Design in Particle Accelerators

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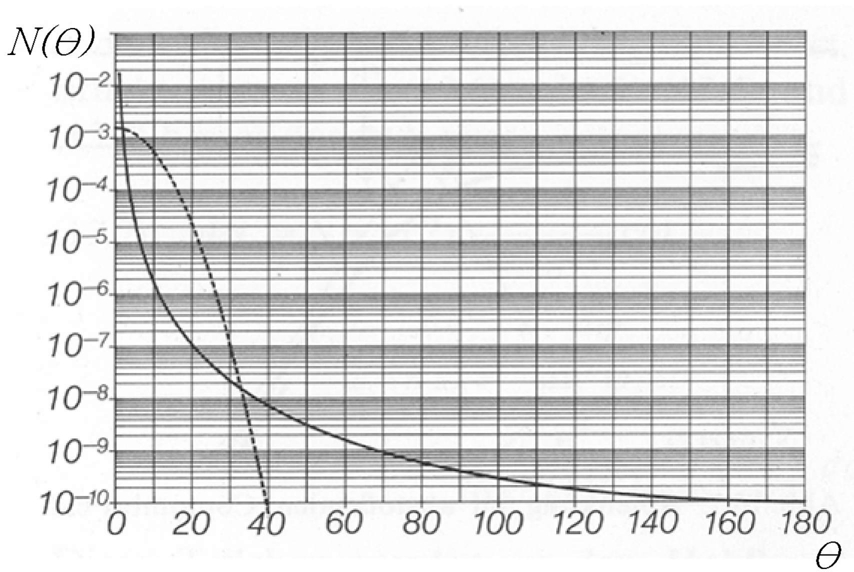
Historical note:

... Particle acceleration where lattice design is not needed

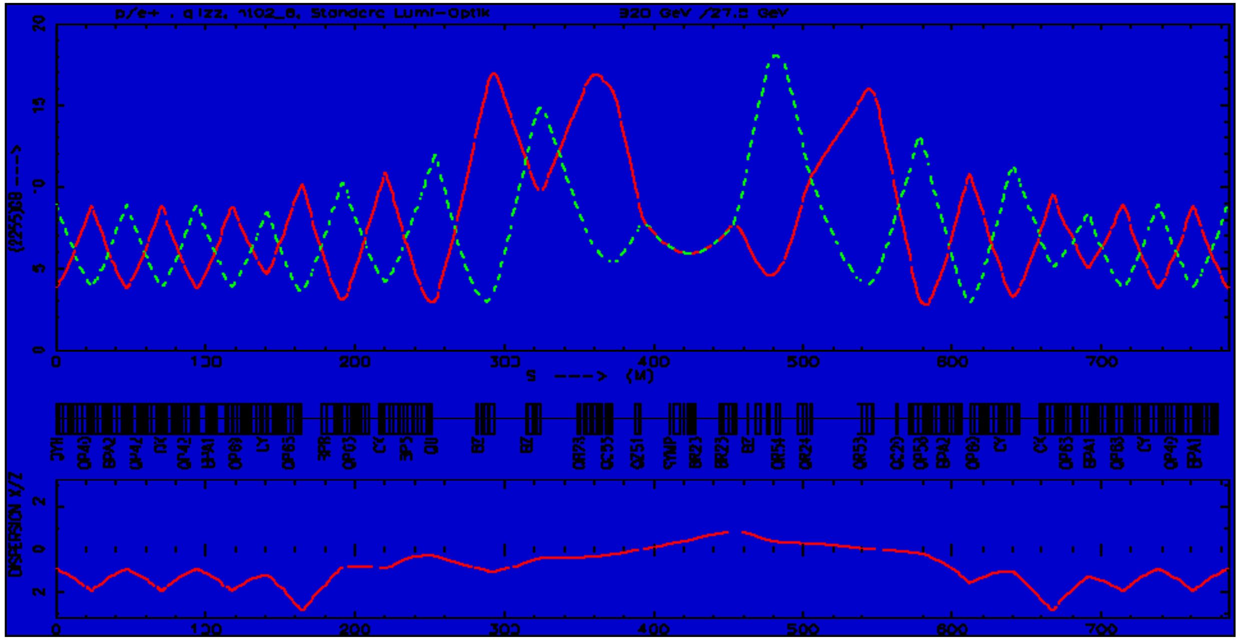
$$N(\theta) = \frac{N_i n t Z^2 e^4}{(8\pi\varepsilon_0)^2 r^2 K^2} * \frac{1}{\sin^4(\theta/2)}$$

Rutherford Scattering, 1906

Using radioactive particle sources:
α-particles of some MeV energy



Lattice design: design and optimisation of the principle elements of an accelerator ... *the lattice cells*



1952: Courant, Livingston, Snyder:

Theory of strong focusing in particle beams

Lattice Design: *„… how to build a storage ring"*

High energy accelerators → circular machines

somewhere in the lattice we need a number of dipole magnets,
that are bending the design orbit to a closed ring

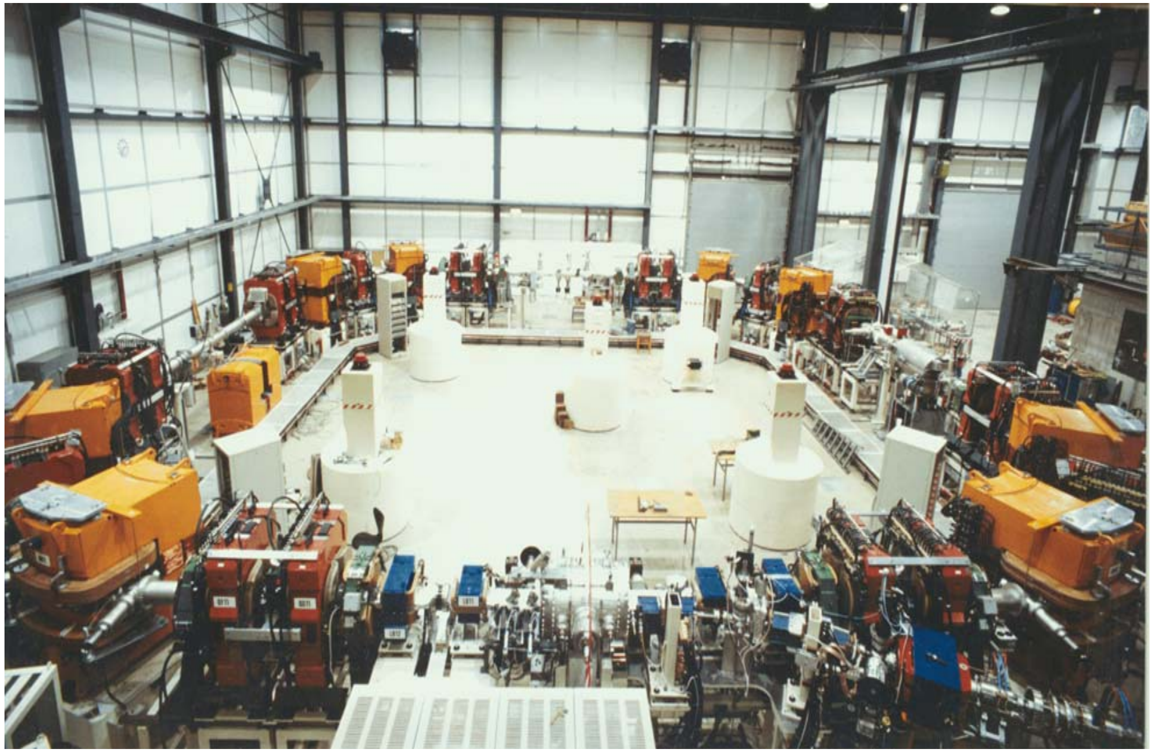
Geometry of the ring:

centrifugal force = Lorentz force

$$e * v * B = \frac{m v^2}{\rho}$$

$$\rightarrow e * B = \frac{m v}{\rho} = p / \rho$$

$$\boxed{\rightarrow B * \rho = p / e}$$



Example: heavy ion storage ring TSR
8 dipole magnets of equal bending strength

p = momentum of the particle,
ρ = curvature radius

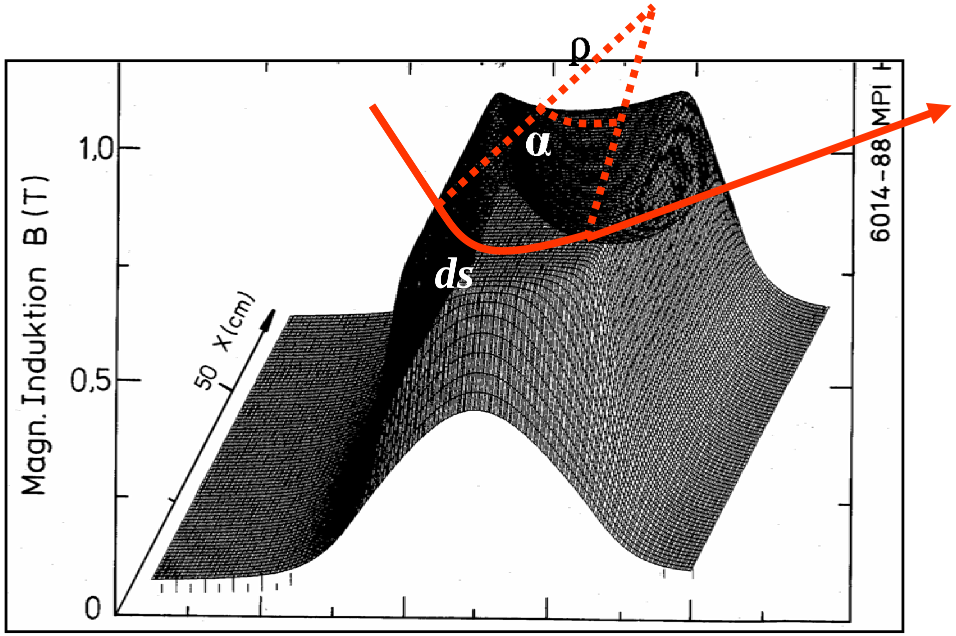
Bρ= beam rigidity

Circular Orbit:

„… defining the geometry“

$$\alpha = \frac{ds}{\rho} \approx \frac{dl}{\rho}$$

$$\alpha = \frac{B * dl}{B * \rho}$$



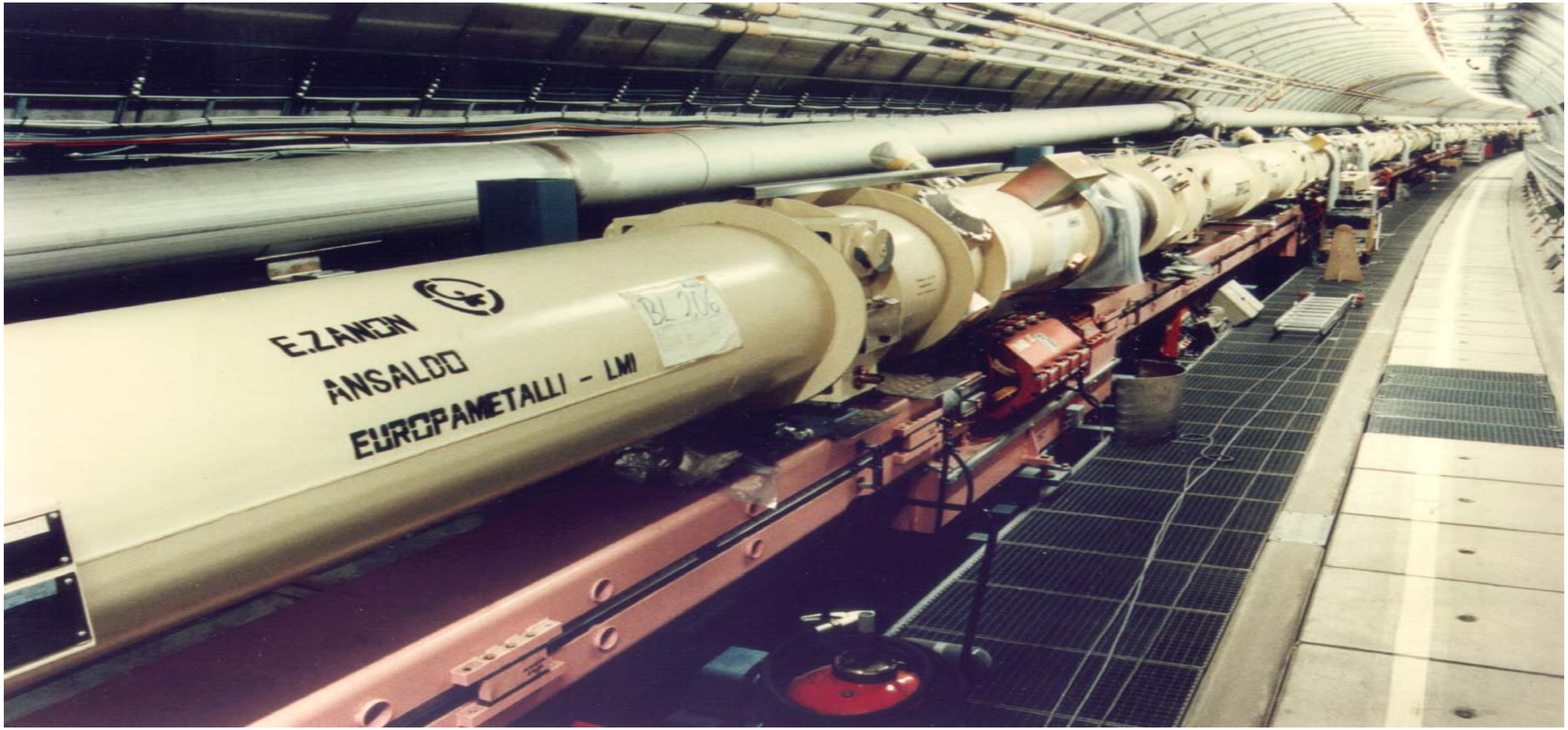
field map of a storage ring dipole magnet

The angle swept out in one revolution must be 2π, so

… for a full circle $$\alpha = \frac{\int B dl}{B * \rho} = 2\pi \quad \rightarrow \quad \int B dl = 2\pi * \frac{p}{q}$$

Nota bene: $\frac{\Delta B}{B} \approx 10^{-4}$ ***is usually required !!***

Example HERA:



920 GeV Proton storage ring
dipole magnets N = 416
l = 8.8m
q = +1 e

$$\int B dl \approx N * l * B = 2\pi\ p / q$$

$$B \approx \frac{2\pi * 920 * 10^9 eV}{416 * 3 * 10^8 \frac{m}{s} * 8.8m * e} \approx 5.15\ Tesla$$

Focusing forces and particle trajectories:

Equation of motion

$$x'' + K * x = 0$$

$K = -k + 1/\rho^2$ **hor. plane**

$K = k$ **vert. plane**

dipole magnet: $\dfrac{1}{\rho} = \dfrac{B}{p/e}$

quadrupole lens: $k = \dfrac{g}{p/e}$

focal length: $f = \dfrac{1}{k*l}$

Example: HERA Ring:

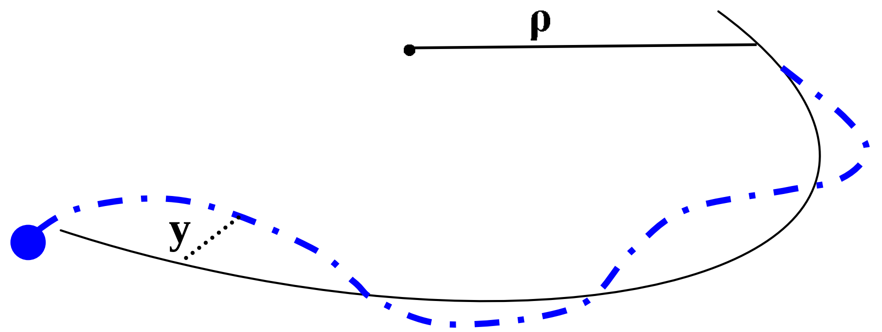
Circumference: $C_0 = 6335$ m
Bending radius: $\rho = 580$ m
Quadrupol Gradient: G= 110 T/m

→ $k = 33.64*10^{-3}/m^2$
→ $1/\rho^2 = 2.97*10^{-6}/m^2$

! ***For estimates in large accelerators the weak focusing term $1/\rho^2$ can in general be neglected***

„… single particle trajectories“

$$y'' + K * y = 0$$



Solution for a focusing magnet

$$y(s) = y_0 * \cos(\sqrt{K} * s) + \frac{y'_0}{\sqrt{K}} * \sin(\sqrt{K} * s)$$

$$y'(s) = -y_0 * \sqrt{K} * \sin(\sqrt{K} * s) + y'_0 * \cos(\sqrt{K} * s)$$

Or written more convenient in matrix form:

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

Matrices of lattice elements

Hor. focusing Quadrupole Magnet

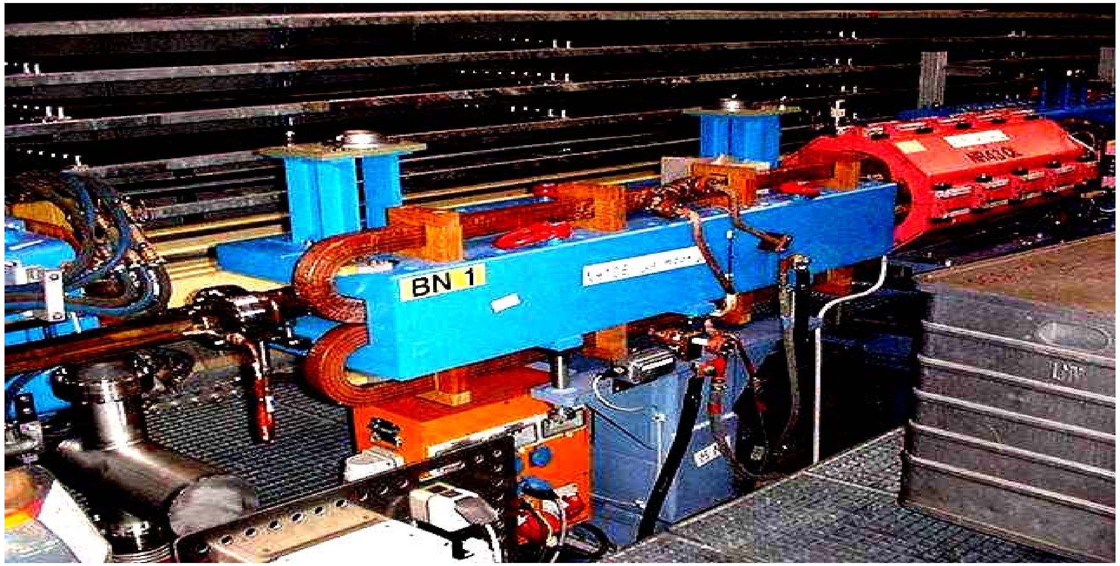
$$M_{QF} = \begin{pmatrix} \cos(\sqrt{K}*l) & \frac{1}{\sqrt{K}}\sin(\sqrt{K}*l) \\ -\sqrt{K}\sin(\sqrt{K}*l) & \cos(\sqrt{K}*l) \end{pmatrix}$$

Hor. defocusing Quadrupole Magnet

$$M_{QD} = \begin{pmatrix} \cosh(\sqrt{K}*l) & \frac{1}{\sqrt{K}}\sinh(\sqrt{K}*l) \\ \sqrt{K}\sinh(\sqrt{K}*l) & \cosh(\sqrt{K}*l) \end{pmatrix}$$

Drift space

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



$$M_{lattice} = M_{QF1} * M_{D1} * M_{QD} * M_{D1} * M_{QF2} \ldots$$

Periodic Lattices

In the case of periodic lattices the transfer matrix can be expressed as a function of a set of periodic parameters α, β, γ

$$M(s) = \begin{pmatrix} \cos\mu + \alpha_S \sin\mu & \beta_S \sin\mu \\ -\gamma_S \sin\mu & \cos(\mu) - \alpha_S \sin\mu \end{pmatrix}$$

$$\mu = \int_s^{s+L} \frac{dt}{\beta(t)}$$

μ = phase advance per period:

For stability of the motion in periodic lattice structures it is required that

$$|trace(M)| < 2$$

In terms of these new periodic parameters the solution of the equation of motion is

$$y(s) = \sqrt{\varepsilon} * \sqrt{\beta(s)} * \cos(\Phi(s) - \delta)$$

$$y'(s) = \frac{-\sqrt{\varepsilon}}{\sqrt{\beta}} * \{\sin(\Phi(s) - \delta) + \alpha \cos(\Phi(s) - \delta)\}$$

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

$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_S = \begin{pmatrix} C^2 & -2SC & S^2 \\ -CC' & SC'+S'C & -SS' \\ C'^2 & -2S'C' & S'^2 \end{pmatrix} * \begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_0$$

Question: „ What does that mean ???? "

... and here starts the lattice design !!!

Most simple example: drift space

$$M = \begin{pmatrix} C & S \\ C' & S' \end{pmatrix} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}$$

particle coordinates

$$\begin{pmatrix} x \\ x' \end{pmatrix}_l = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} * \begin{pmatrix} x \\ x' \end{pmatrix}_0 \quad \rightarrow \quad \boxed{\begin{aligned} x(l) &= x_0 + l * x_0' \\ x'(l) &= x_0' \end{aligned}}$$

transformation of twiss parameters:

$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_l = \begin{pmatrix} 1 & -2l & l^2 \\ 0 & 1 & -l \\ 0 & 0 & 1 \end{pmatrix} * \begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix}_0$$

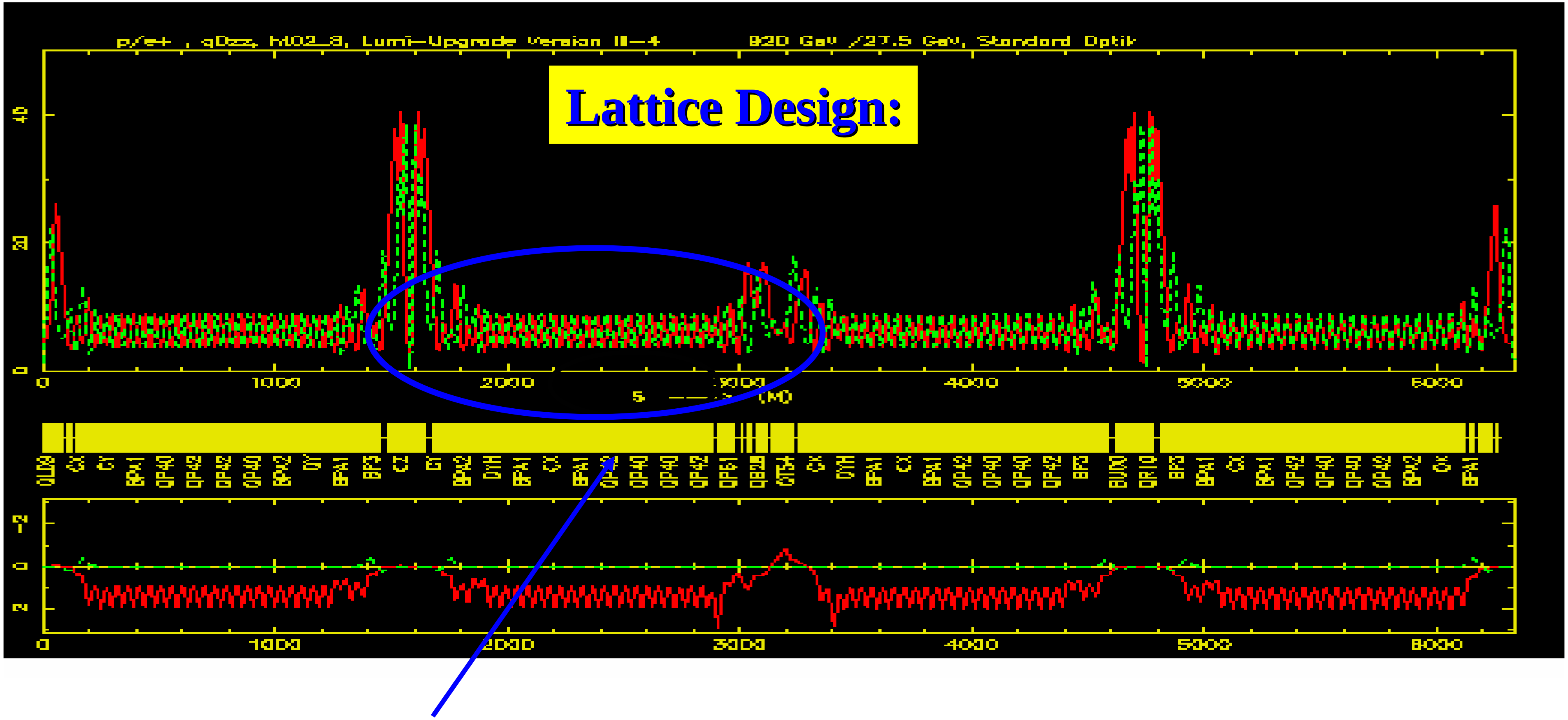
$$\boxed{\beta(s) = \beta_0 - 2l * \alpha_0 + l^2 * \gamma_0}$$

Stability ...?

$$trace(M) = 1 + 1 = 2$$

→ ***A periodic solution doesn‘t exist in a lattice built exclusively out of drift spaces.***

Lattice Design:



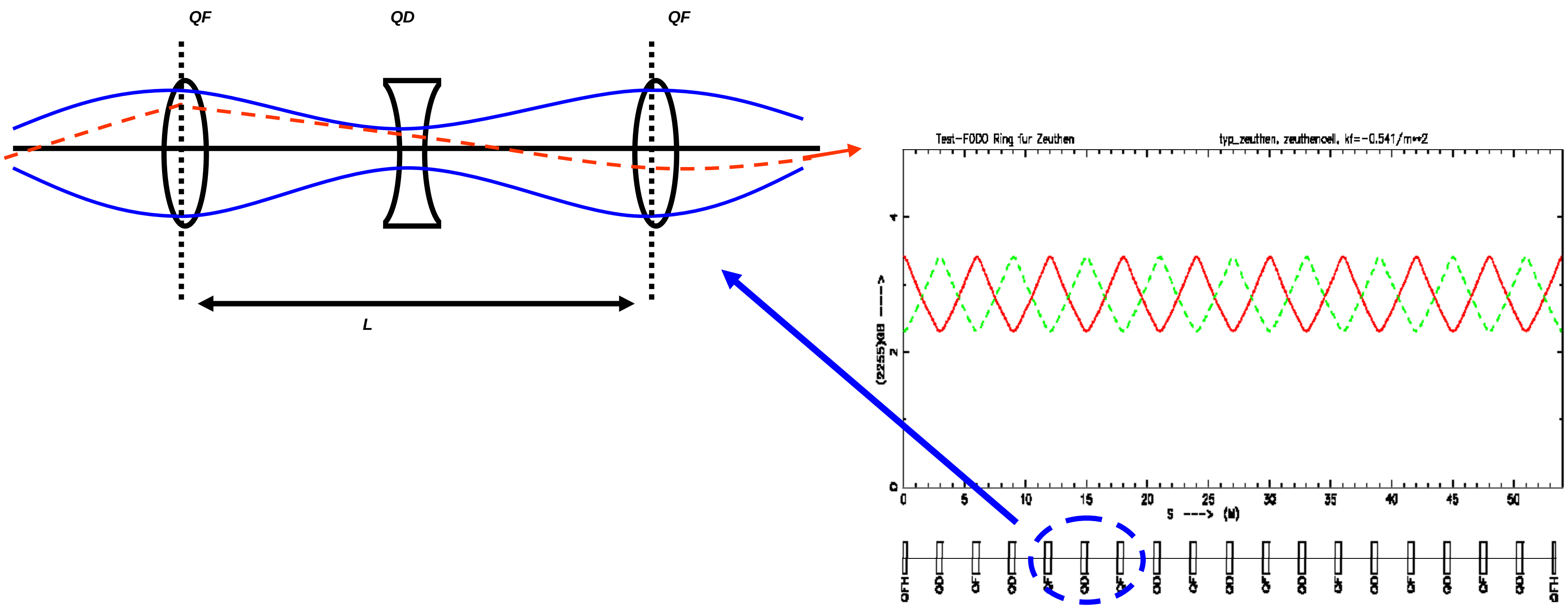
Arc: regular (periodic) magnet structure:

bending magnets → define the energy of the ring
main focusing & tune control, chromaticity correction,
multipoles for higher order corrections

Straight sections: drift spaces for injection, dispersion suppressors,
low beta insertions, RF cavities, etc....
... and the high energy experiments if they cannot be avoided

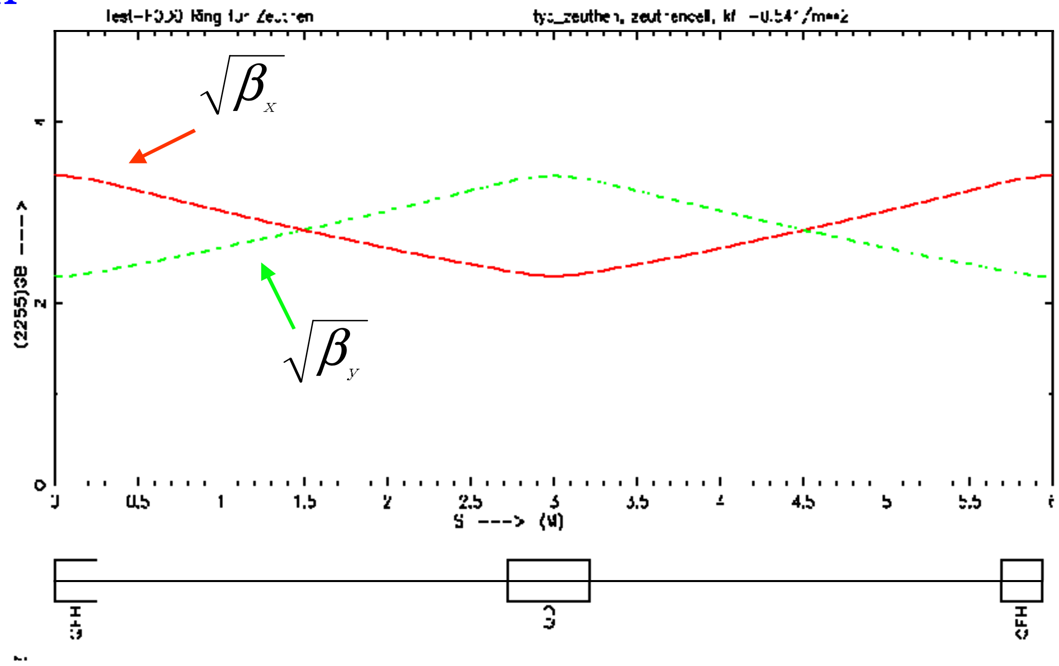
The FoDo-Lattice

A magnet structure consisting of focusing and defocusing quadrupole lenses in alternating order with nothing in between.
(Nothing = elements that can be neglected on first sight: drift, bending magnets, RF structures ... and especially experiments...)



Starting point for the calculation: in the middle of a focusing quadrupole
Phase advance per cell $\mu = 45°$,
→ calculate the twiss parameters for a periodic solution

Periodic solution of a FoDo Cell



Output of the optics program:

Nr	Type	Length	Strength	β_x	α_x	φ_x	β_z	α_z	φ_z
		m	1/m2	m		$1/2\pi$	m		$1/2\pi$
0	IP	0,000	0,000	11,611	0,000	0,000	5,295	0,000	0,000
1	QFH	0,250	-0,541	11,228	1,514	0,004	5,488	-0,781	0,007
2	QD	3,251	0,541	5,488	-0,781	0,070	11,228	1,514	0,066
3	QFH	6,002	-0,541	11,611	0,000	0,125	5,295	0,000	0,125
4	IP	6,002	0,000	11,611	0,000	0,125	5,295	0,000	0,125

QX= 0,125 QZ= 0,125

$$0.125 * 2\pi = 45°$$

Can we understand, what the optics code is doing?

matrices

$$M_{QF} = \begin{pmatrix} \cos(\sqrt{K} * l_q) & \frac{1}{\sqrt{K}} \sin(\sqrt{K} * l_q) \\ -\sqrt{K} \sin(\sqrt{K} * l_q) & \cos(\sqrt{K} * l_q) \end{pmatrix} , \qquad M_{Drift} = \begin{pmatrix} 1 & l \\ 0 & 1_d \end{pmatrix}$$

strength and length of the FoDo elements

K = +/- 0.54102 m^{-2}
lq = 0.5 m
ld = 2.5 m

The matrix for the complete cell is obtained by multiplication of the element matrices

$$M_{FoDo} = M_{qfh} * M_{ld} * M_{qd} * M_{ld} * M_{qfh}$$

Putting the numbers in and multiplying out ...

$$M_{FoDo} = \begin{pmatrix} 0.707 & 8.206 \\ -0.061 & 0.707 \end{pmatrix}$$

The transfer matrix for 1 period gives us all the information that we need !

1.) is the motion stable?

$$trace(M_{FoDo}) = 1.415 \rightarrow \quad < 2$$

2.) Phase advance per cell

$$M(s) = \begin{pmatrix} \cos\mu + \alpha\sin\mu & \beta\sin\mu \\ -\gamma\sin\mu & \cos(\mu) - \alpha\sin\mu \end{pmatrix} \rightarrow$$

$$\cos(\mu) = \frac{1}{2} * trace(M) = 0.707$$

$$\mu = arc\cos(\frac{1}{2} * trace(M)) = 45°$$

3.) hor β-function

$$\beta = \frac{M(1,2)}{\sin(\mu)} = 11.611 \ m$$

4.) hor α-function

$$\alpha = \frac{M(1,1) - \cos(\mu)}{\sin(\mu)} = 0$$

Can we do it a little bit easier ?

We can: … the „thin lens approximation“

Matrix of a focusing quadrupole magnet:

$$M_{QF} = \begin{pmatrix} \cos(\sqrt{K} * l) & \frac{1}{\sqrt{K}} \sin(\sqrt{K} * l) \\ -\sqrt{K} \sin(\sqrt{K} * l) & \cos(\sqrt{K} * l) \end{pmatrix}$$

If the focal length *f* is much larger than the length of the quadrupole magnet,

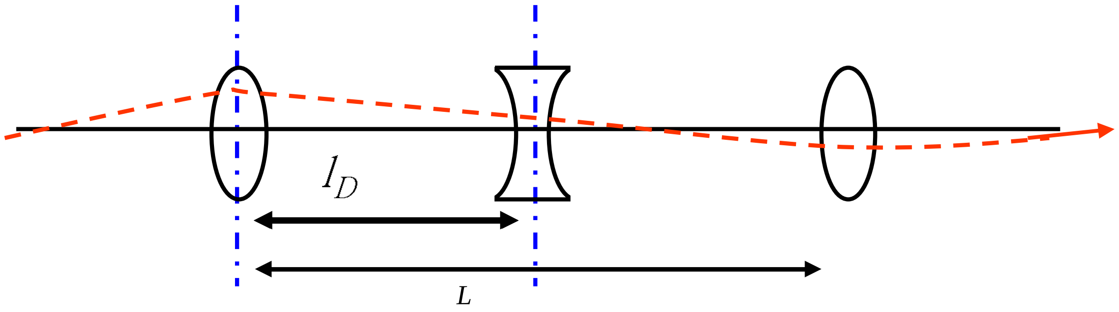
$$f = \frac{1}{kl_Q} >> l_Q$$

the transfer matrix can be aproximated using

$$kl_q = const, \quad l_q \to 0$$

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

FoDo in thin lens approximation



$$l_D = L/2,$$
$$\tilde{f} = 2f$$

Calculate the matrix for a half cell, starting in the middle of a foc. quadrupole:

$$M_{halfCell} = M_{QD/2} * M_{lD} * M_{QF/2}$$

$$M_{halfCell} = \begin{pmatrix} 1 & 0 \\ 1/\tilde{f} & 1 \end{pmatrix} * \begin{pmatrix} 1 & l_D \\ 0 & 1 \end{pmatrix} * \begin{pmatrix} 1 & 0 \\ -1/\tilde{f} & 1 \end{pmatrix}$$

$$M_{halfCell} = \begin{pmatrix} 1 - l_D/\tilde{f} & l_D \\ -l_D/\tilde{f}^2 & 1 + l_D/\tilde{f} \end{pmatrix}$$

for the second half cell set f → -f

FoDo in thin lens approximation

Matrix for the complete FoDo cell:

$$M = \begin{pmatrix} 1+{l_D}/{\tilde f} & l_D \\ -{l_D}/{\tilde f^2} & 1-{l_D}/{\tilde f} \end{pmatrix} * \begin{pmatrix} 1-{l_D}/{\tilde f} & l_D \\ -{l_D}/{\tilde f^2} & 1+{l_D}/{\tilde f} \end{pmatrix}$$

$$M = \begin{pmatrix} 1-\frac{2l_D^2}{\tilde f^2} & 2l_D(1+\frac{l_D}{\tilde f}) \\ 2(\frac{l_D^2}{\tilde f^3}-\frac{l_D}{\tilde f^2}) & 1-2\frac{l_D^2}{\tilde f^2} \end{pmatrix}$$

Now we know, that the phase advance is related to the transfer matrix by

$$\cos\mu = \frac{1}{2} trace\ \ (M) = {1}/{2} * (2-\frac{4l_D^2}{\tilde f^2}) = 1-\frac{2l_D^2}{\tilde f^2}$$

After some beer and with a little bit of trigonometric gymnastics

$$\cos(x) = \cos^2({x}/{2}) - \sin^2(x/2) = 1-2\sin^2({x}/{2})$$

we can calculate the phase advance as a function of the FoDo parameter …

$$\cos(\mu) = 1 - 2\sin^2(\mu/2) = 1 - \frac{2l_D^2}{\tilde{f}^2}$$

$$\sin(\mu/2) = l_D / \tilde{f} = \frac{L_{Cell}}{2\tilde{f}}$$

$$\sin(\mu/2) = \frac{L_{Cell}}{4f}$$

Example:

45-degree Cell

$L_{Cell} = l_{QF} + l_D + l_{QD} + l_D = 0.5m+2.5m+0.5m+2.5m = 6m$

$1/f = k*l_Q = 0.5m*0.541\ m^{-2} = 0.27\ m^{-1}$

$$\sin(\mu/2) \approx \frac{L_{Cell}}{4f} = 0.405$$

$$\rightarrow \mu \approx 47.8^\circ$$

$$\rightarrow \beta \approx 11.4m$$

Remember:

Exact calculation yields:

$$\mu = 45^\circ$$

$$\beta = 11.6m$$

Stability in a FoDo structure

SPS Lattice

$$M_{FoDo} = \begin{pmatrix} 1-\frac{2l_D^2}{\tilde{f}^2} & 2l_D(1+\frac{l_D}{\tilde{f}}) \\ 2(\frac{l_D^2}{\tilde{f}^3}-\frac{l_D}{\tilde{f}^2}) & 1-2\frac{l_D^2}{\tilde{f}^2} \end{pmatrix}$$

Stability requires: $trace(M) < 2$

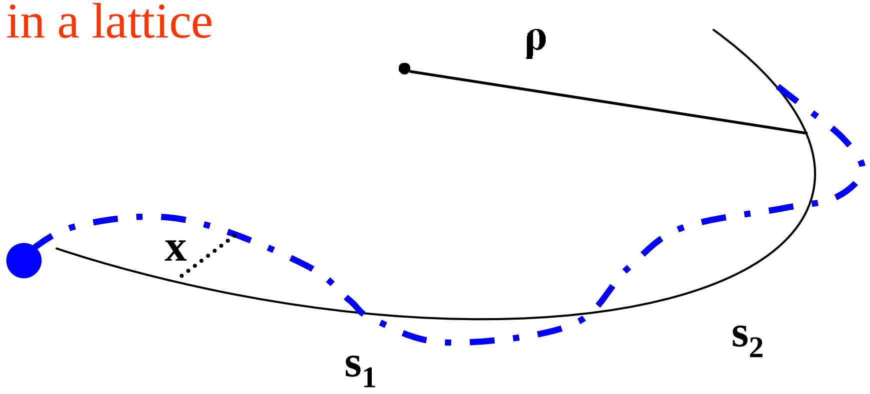
$$trace(M) = \left| 2-\frac{4l_D^2}{\tilde{f}^2} \right| < 2$$

$$\rightarrow f > \frac{L_{cell}}{4}$$

For stability the focal length has to be larger than a quarter of the cell length !!

Transformation matrix in terms of the Twiss parameters

Transformation of the coordinate vector (x,x´) in a lattice



$$\begin{pmatrix} x(s) \\ x'(s) \end{pmatrix} = M_{s1,s2} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

General solution of the equation of motion

$$x(s) = \sqrt{\varepsilon * \beta(s)} * \cos(\phi(s) + \varphi)$$

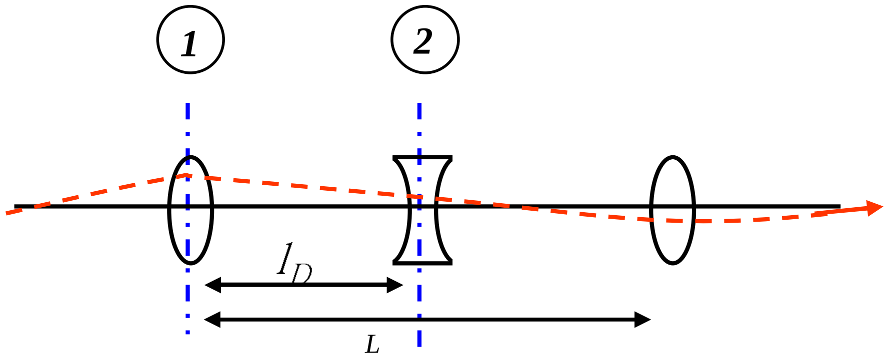
$$x'(s) = -\sqrt{\varepsilon / \beta(s)} * \{\alpha(s)\cos(\phi(s)+\varphi) + \sin(\phi(s)+\varphi)\}$$

Transformation of the coordinate vector (x,x´) expressed
as a function of the twiss parameters

$$M_{1\to 2} = \begin{pmatrix} \sqrt{\dfrac{\beta_2}{\beta_1}}(\cos\phi_{12} + \alpha_1 \sin\phi_{12}) & \sqrt{\beta_2\beta_1}\sin\phi_{12} \\ \dfrac{(\alpha_1 - \alpha_2)\cos\phi - (1+\alpha_1\alpha_2)\sin\phi_{12}}{\sqrt{\beta_2\beta_1}} & \sqrt{\dfrac{\beta_2}{\beta_1}}(\cos\phi_{12} - \alpha_2\sin\phi_{12}) \end{pmatrix}$$

Transfer matrix for half a FoDo cell:

$$M_{halfCell} = \begin{pmatrix} 1 - {l_D}/{\tilde f} & l_D \\ -{l_D}/{\tilde f^2} & 1 + {l_D}/{\tilde f} \end{pmatrix}$$



Compare to the twiss parameter form of M

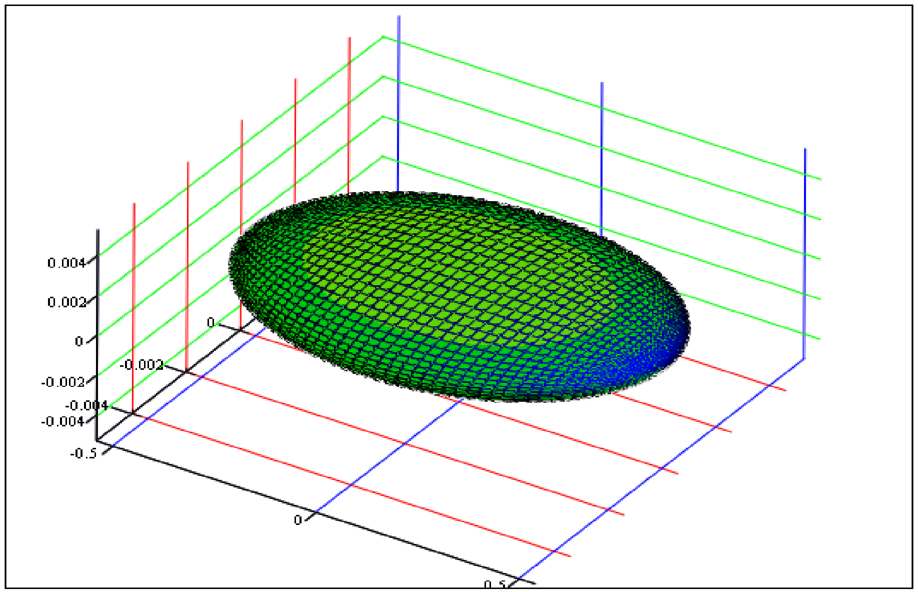
$$M = \begin{pmatrix} \sqrt{\frac{\beta_1}{\beta_2}}(\cos\phi_{12} + \alpha_2 \sin\phi_{12}) & \sqrt{\beta_1\beta_2}\sin\phi_{12} \\ \frac{(\alpha_1 - \alpha_2)\cos\phi_{12} - (1 + \alpha_1\alpha_2)\sin\phi_{12}}{\sqrt{\beta_1\beta_2}} & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\phi_{12} - \alpha_2 \sin\phi_{12}) \end{pmatrix}$$

In the middle of a foc (defoc) quadrupole of the FoDo we allways have $\alpha = 0$, and the half cell will lead us from β_{max} to β_{min}

$$M = \begin{pmatrix} C & S \\ C' & S' \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\check\beta}{\hat\beta}}\cos\frac{\mu}{2} & \sqrt{\hat\beta\,\check\beta}\sin\frac{\mu}{2} \\ \frac{-1}{\sqrt{\hat\beta\,\check\beta}}\sin\frac{\mu}{2} & \sqrt{\frac{\hat\beta}{\check\beta}}\cos\frac{\mu}{2} \end{pmatrix}$$

Solving for β_{max} and β_{min} and remembering that …. $\sin\frac{\mu}{2} = \frac{l_D}{\tilde{f}} = \frac{L}{4f}$

$$\left.\begin{aligned} \frac{S'}{C} &= \frac{\hat{\beta}}{\check{\beta}} = \frac{1+l_D/\tilde{f}}{1-l_D/\tilde{f}} = \frac{1+\sin\frac{\mu}{2}}{1-\sin\frac{\mu}{2}} \\ \frac{S}{C'} &= \hat{\beta}\,\check{\beta} = \tilde{f}^{\,2} = \frac{l_D^2}{\sin^2\frac{\mu}{2}} \end{aligned}\right\} \rightarrow \quad \begin{aligned} \hat{\beta} &= \frac{(1+\sin\frac{\mu}{2})L}{\sin\mu} \quad ! \\ \check{\beta} &= \frac{(1-\sin\frac{\mu}{2})L}{\sin\mu} \quad ! \end{aligned}$$



(Z, X, Y)

The maximum and minimum values of the β-function are solely determined by the phase advance and the length of the cell.

Longer cells lead to larger β

typical shape of a proton bunch in the HERA FoDo Cell

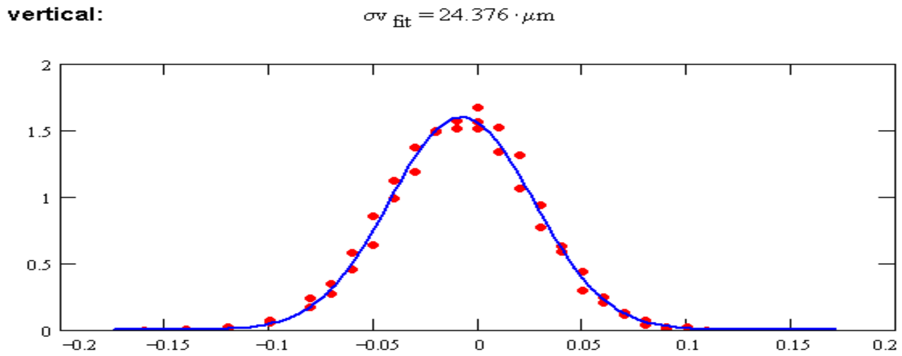
Beam dimension:

Optimisation of the FoDo Phase advance:

In both planes a gaussian particle distribution is assumed, given by the beam emittance ε and the β-function

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

HERA beam size

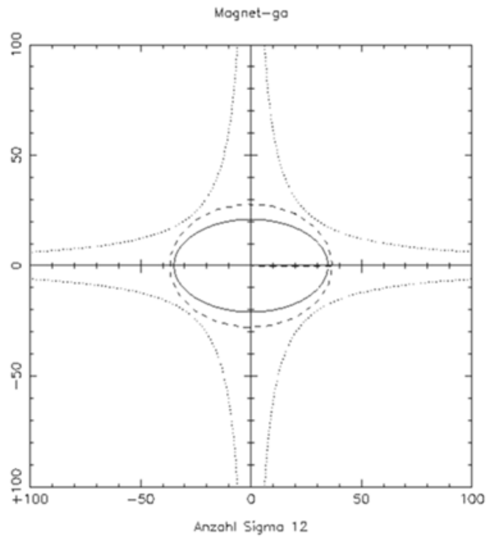


In general proton beams are „*round*" in the sense that

$$\varepsilon_x \approx \varepsilon_y$$

So for highest aperture we have to minimise the β-function in both planes:

$$r^2 = \varepsilon_x \beta_x + \varepsilon_y \beta_y$$



typical beam envelope, vacuum chamber and pole shape in a foc. Quadrupole lens in HERA

Optimising the FoDo phase advance

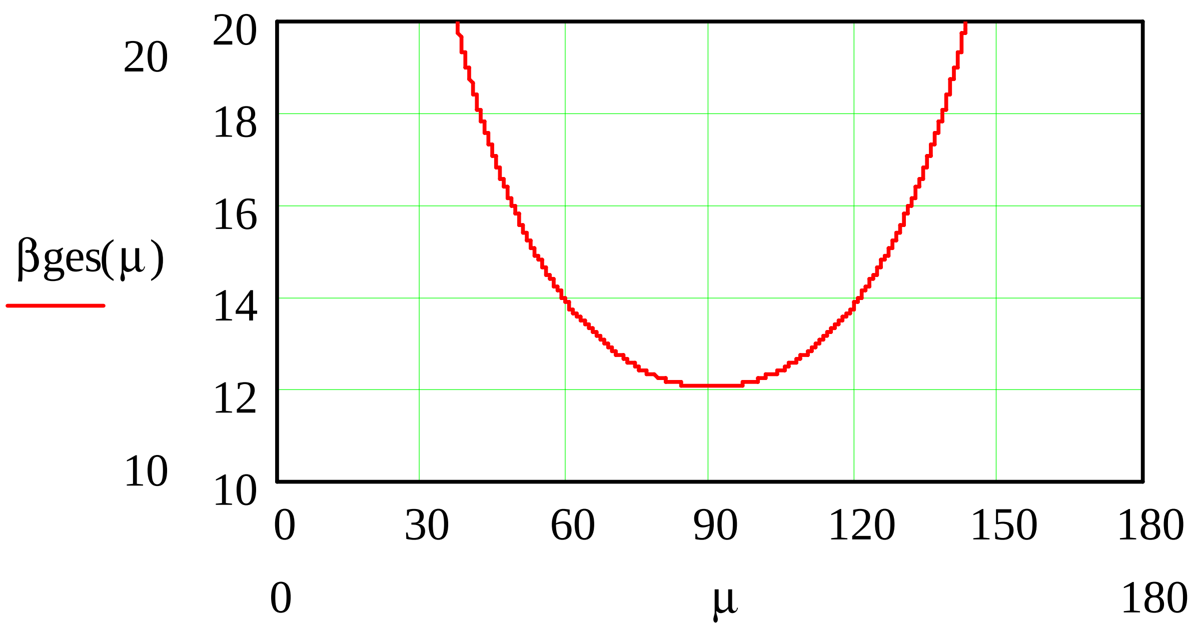
$$r^2 = \varepsilon_x \beta_x + \varepsilon_y \beta_y$$

search for the phase advance μ that results in a minimum of the sum of the beta's

$$\hat{\beta} + \check{\beta} = \frac{(1+\sin\frac{\mu}{2}) * L}{\sin\mu} + \frac{(1-\sin\frac{\mu}{2}) * L}{\sin\mu}$$

$$\hat{\beta} + \check{\beta} = \frac{2L}{\sin\mu}$$

$$\frac{d}{d\mu}\left(2L / \sin\mu\right) = 0$$



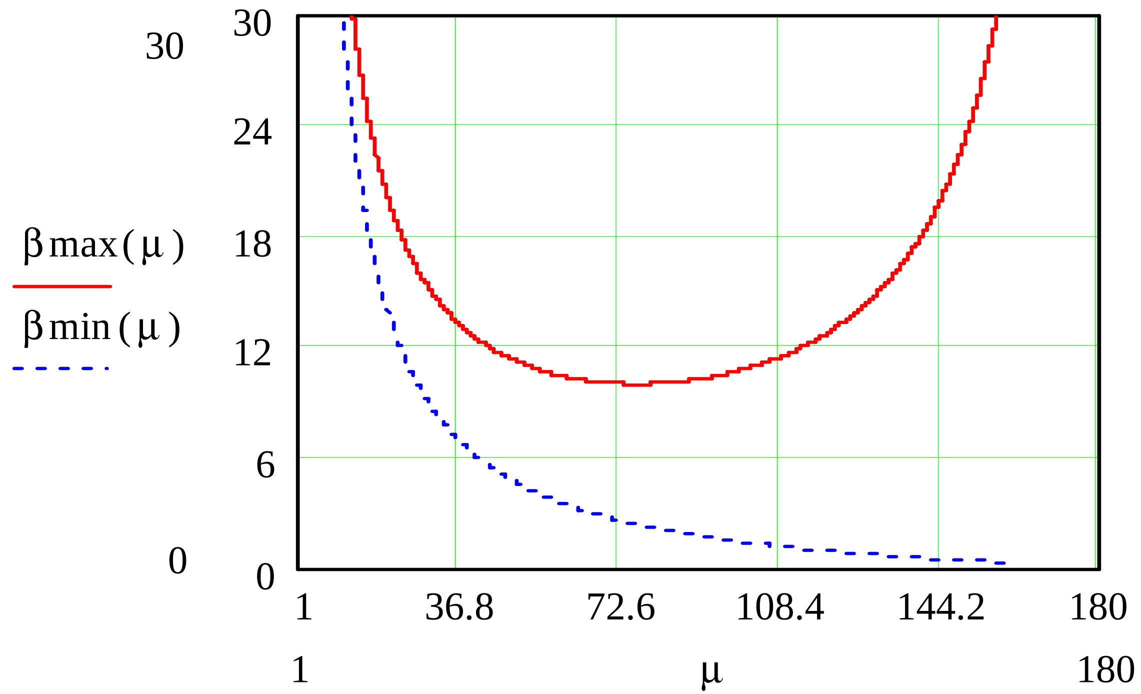
$$\frac{L}{\sin^2\mu} * \cos\mu = 0 \rightarrow \mu = 90°$$

Electrons are different

electron beams are usually flat, $\varepsilon_y \approx 2$ - $10\ \%\ \varepsilon_x$

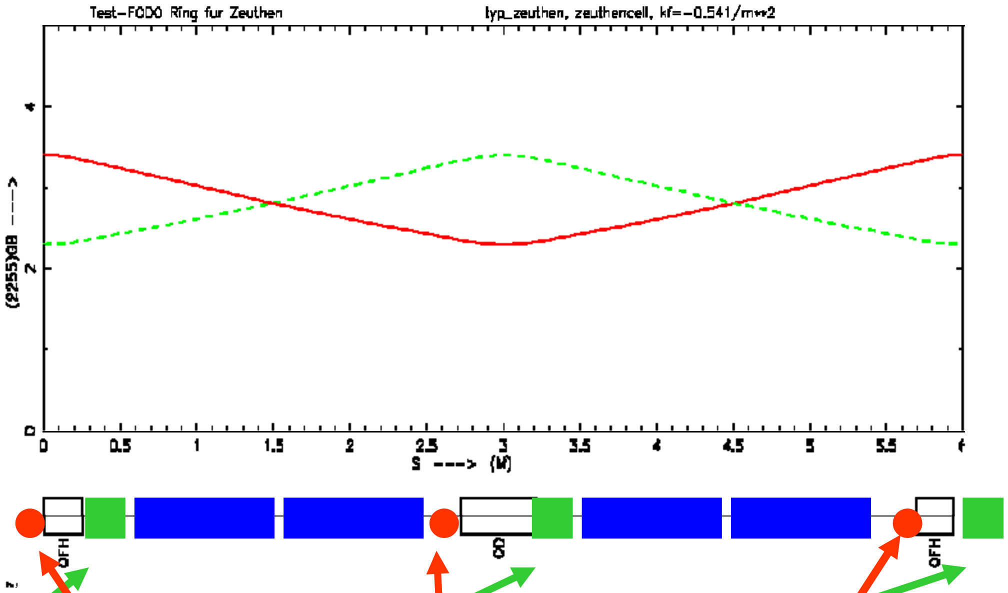
→ *optimise only* β_{hor}

$$\frac{d}{d\mu}(\hat{\beta}) = \frac{d}{d\mu}\frac{L(1+\sin\frac{\mu}{2})}{\sin\mu} = 0 \rightarrow \mu \approx 76°$$



red curve: β_{max}
blue curve: β_{min}
as a function of the phase advance μ

Orbit distortions in a periodic lattice



field error of a dipole/distorted quadrupole

$$\rightarrow \delta(mrad) = \frac{ds}{\rho} = \frac{\int B ds}{p/e}$$

the particle will follow a new closed trajectory, the distorted orbit:

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

*** the orbit amplitude will be large if the β function at the location of the kick is large**
$\beta(\tilde{s})$ **indicates the sensitivity of the beam → here orbit correctors should be placed in the lattice**

*** the orbit amplitude will be large at places where in the lattice β(s) is large → here beam position monitors should be installed**

Orbit Correction and Beam Instrumentation in a storage ring

Elsa ring, Bonn

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Resumé:

1.) Dipole strength:

$$\int B ds = N * B_0 * l_{eff} = 2\pi \frac{p}{q}$$

l_{eff} effective magnet length, N number of magnets

2.) Stability condition:

$$Trace(M) < 2$$

for periodic structures within the lattice / at least for the transfer matrix of the complete circular machine

3.) Transfer matrix for periodic cell

$$M(s) = \begin{pmatrix} \cos\mu + \alpha(s)\sin\mu & \beta(s)\sin\mu \\ -\gamma(s)\sin\mu & \cos(\mu) - \alpha(s)\sin\mu \end{pmatrix}$$

α,β,γ depend on the position s in the ring, μ (phase advance) is independent of s

4.) Thin lens approximation:

$$M_{QF} = \begin{pmatrix} 1 & 0 \\ \frac{1}{f_Q} & 1 \end{pmatrix} \qquad f_Q = \frac{1}{k_Q l_Q}$$

focal length of the quadrupole magnet $f_Q = 1/(k_Q l_Q) >> l_Q$

5.) Tune (rough estimate):

$$\mu = \int_s^{s+L} \frac{dt}{\beta(t)}$$

Tune = phase advance
in units of 2π

$$Q := N * \frac{\mu}{2\pi} = \frac{1}{2\pi} * \oint \frac{ds}{\beta(s)} \approx \frac{1}{2\pi} * \frac{2\pi \bar{R}}{\bar{\beta}} = \bar{R} / \bar{\beta}$$

$\bar{R}$, $\bar{\beta}$ average radius
and β-function

$$Q \approx \frac{\bar{R}}{\bar{\beta}}$$

6.) Phase advance per FoDo cell

(thin lens approx)

$$\sin\frac{\mu}{2} = \frac{L_{Cell}}{4 f_Q}$$

L_{Cell} length of the complete FoDo cell, f_Q focal length of the quadrupole, μ phase advance per cell

7.) Stability in a FoDo cell

(thin lens approx)

$$f_Q > \frac{L_{Cell}}{4}$$

8.) Beta functions in a FoDo cell

(thin lens approx)

$$\hat{\beta} = \frac{(1+\sin\frac{\mu}{2})L_{Cell}}{\sin\mu} \qquad \check{\beta} = \frac{(1-\sin\frac{\mu}{2})L_{Cell}}{\sin\mu}$$

L_{Cell} length of the complete FoDo cell, μ phase advance per cell

Conclusion:

* *„the arc“ of a storage ring is usually built out of a periodic sequence of single magnet elements eg. FoDo sections*

* *a first guess of the main parameters of the beam in the arc is obtained by the settings of the quadrupole lenses in this section*

* *we can get an estimate of the beam parameters using a selection of „rules of thumb“*

Usually the real beam properties will not differ too much from these estimates and we will have a nice storage ring and a beautifull beam and everybody is happy around.

And then someone comes and spoils it all by saying something stupid like installing a tiny little piece of detector in our machine …

INSERTIONS