Linear

Imperfections

CAS Frascati November 2008

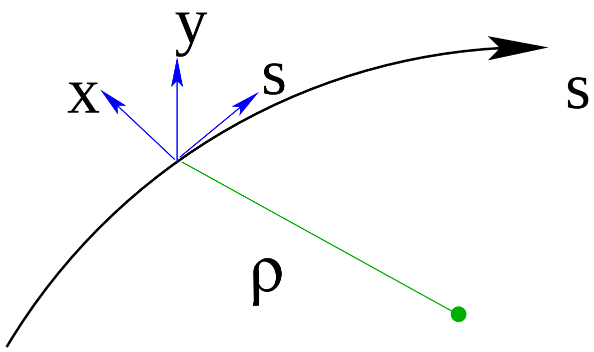
Oliver Bruning / CERN AP−ABP

Linear Imperfections

- equation of motion in an accelerator
  - → Hills equation
  - → sine and cosine like solutions
  - → closed orbit
  - → sources for closed orbit perturbations
- dipole perturbations
  - → closed orbit response
  - → dispersion orbit
  - → integer resonances
  - → BPMs & dipole correctors
- quadrupole perturbations
  - → one−turn map & tune error
  - → beta−beat
  - → half−integer resonances
- orbit correction
  - → local orbit bumps

Variable Definition

Variables in moving coordinate system:



$$x' = \frac{d}{ds}\,x$$

$$\frac{d}{dt} = \frac{ds}{dt}\cdot\frac{d}{ds} \longrightarrow x' = \frac{p_x}{p_0}$$

$\frac{ds}{dt}$: v

Hill's Equation:

$$\frac{d^2x}{d\,s^2} + K(s)\cdot x = 0; \qquad K(s) = K(s+L);$$

$$K(s) = \begin{cases} 0 & \text{drift} \\ 1/\rho^2 & \text{dipole} \\ 0.3\cdot\dfrac{B[T/m]}{p[GeV]} & \text{quadrupole} \end{cases}$$

Perturbations:

$$\frac{d^2x}{d\,s^2} + K(s)\cdot x = G(s); \qquad G(s) = \frac{F(s)_{Lorentz}}{v\cdot p_0}$$

Sinelike and Cosinelike Solutions

- system of first order linear differential equations:

$$\vec{y} = \begin{pmatrix} x \\ x' \end{pmatrix} \longrightarrow \vec{y}\,' + \begin{pmatrix} 0 & 1 \\ K & 0 \end{pmatrix} \bullet \vec{y} = 0$$

$K = \text{const} \longrightarrow$

$$\vec{Y}_1(s) = \begin{pmatrix} \sin(\sqrt{K}\bullet s) \\ \sqrt{K}\bullet\cos(\sqrt{K}\bullet s) \end{pmatrix} \qquad \vec{Y}_2(s) = \begin{pmatrix} \cos(\sqrt{K}\bullet s) \\ -\sqrt{K}\bullet\sin(\sqrt{K}\bullet s) \end{pmatrix}$$

- initial conditions:

$$\vec{Y}_1(0) = \begin{pmatrix} Y_1 \\ Y_1' \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad \text{and} \quad \vec{Y}_2(0) = \begin{pmatrix} Y_2 \\ Y_2' \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

- general solution: $\vec{y}(s) = a\bullet\vec{Y}_1(s) + b\bullet\vec{Y}_2(s)$

- transport map: $\vec{y}(s) = \underline{M}(s - s_0)\bullet\vec{y}(s_0)$

with: $$= \begin{pmatrix} \cos(\sqrt{K}\bullet[s-s_0]) & \sin(\sqrt{K}\bullet[s-s_0]) \\ -\sqrt{K}\bullet\sin(\sqrt{K}\bullet[s-s_0]) & \sqrt{K}\bullet\cos(\sqrt{K}\bullet[s-s_0]) \end{pmatrix}$$

Sinelike and Cosinelike Solutions

Floquet theorem:

$$\vec{Y}_1(s) = \begin{pmatrix} \sqrt{\beta(s)} \bullet \sin(\phi(s)+\phi_0) \\ [\cos(\phi(s)+\phi_0) + \alpha(s)\bullet\sin(\phi(s)+\phi_0)]/\sqrt{\beta(s)} \end{pmatrix}$$

$$\vec{Y}_2(s) = \begin{pmatrix} \sqrt{\beta(s)} \bullet \cos(\phi(s)+\phi_0) \\ -[\sin(\phi(s)+\phi_0) + \alpha(s)\bullet\cos(\phi(s)+\phi_0)]/\sqrt{\beta(s)} \end{pmatrix}$$

$$\beta(s) = \beta(s+L); \quad \phi(s) = \int \frac{1}{\beta}\, ds; \quad \alpha(s) = -\frac{1}{2}\beta'(s)$$

´sinelike´ and ´cosinelike´ solutions:

$$\vec{C}(s) = a \bullet \vec{Y}_1(s) + b \bullet \vec{Y}_2(s) \qquad \vec{S}(s) = c \bullet \vec{Y}_1(s) + d \bullet \vec{Y}_2(s)$$

with: $\vec{C}(s_0) = \begin{pmatrix} C(s_0) \\ C'(s_0) \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $\vec{S}(s_0) = \begin{pmatrix} S(s_0) \\ S'(s_0) \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

→ one can generate a transport matrix in analogy to the case with constant K(s)!

Sinelike and Cosinelike Solutions

´sinelike´ and ´cosinelike´ solutions:

$$\vec{S}(s) = \begin{pmatrix} \sqrt{\beta(s)\beta(s_0)} \bullet \sin(\phi(s)+\phi_0) \\ \sqrt{\beta(s_0)} \bullet [\cos(\phi(s)+\phi_0) + \alpha(s) \bullet \sin(\phi(s)+\phi_0)] / \sqrt{\beta(s)} \end{pmatrix}$$

$$\vec{C}(s) = \begin{pmatrix} \sqrt{\beta(s)} \bullet [\cos(\phi(s)+\phi_0) + \alpha(s_0) \bullet \sin(\phi(s)+\phi_0)] / \sqrt{\beta(s_0)} \\ -(1+\alpha\alpha_0) \bullet [\sin(\phi(s)+\phi_0) + (\alpha_0 - \alpha) \bullet \cos(\phi(s)+\phi_0)] / \sqrt{\beta\,\beta_0} \end{pmatrix}$$

transport map from s_0 to s: $\vec{y}(s) = \underline{M}(s, s_0) \bullet \vec{y}(s_0)$

with: $\underline{M} = \begin{pmatrix} C(s) & S(s) \\ C'(s) & S'(s) \end{pmatrix}$

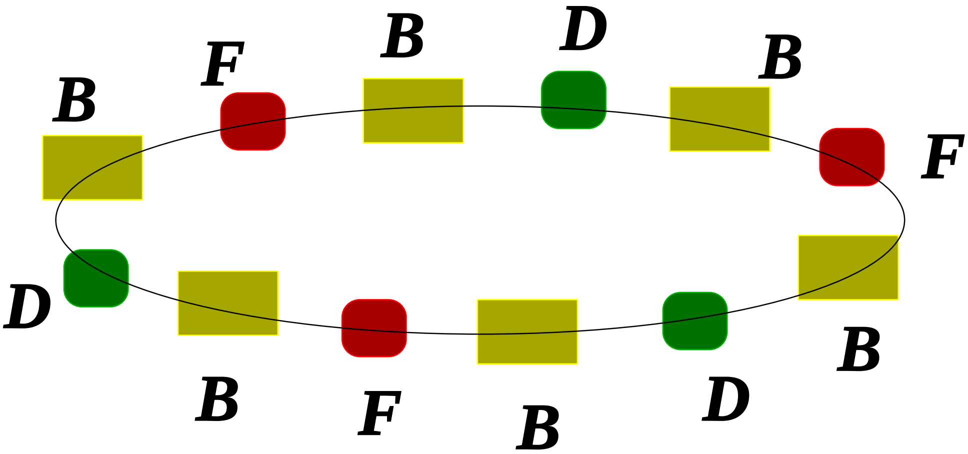
transport map for $s = s_0 + L$:

$$\underline{M} = \underline{I} \bullet \cos(2\pi Q) + \underline{J} \bullet \sin(2\pi Q)$$

$$\underline{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \underline{J} = \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix}; \quad \gamma = [1+\alpha^2] / \beta$$

Closed Orbit

- **particles oscillate around an ideal orbit:**



- **additional dipole fields perturb the orbit:**

- error in dipole field

- energy error

$$\alpha = \frac{l}{\rho} = \frac{q \cdot B \cdot l}{p + \Delta p} \approx \left(1 - \frac{\Delta p}{p}\right) \cdot \frac{q \cdot B \cdot l}{p}$$

- offset in quadrupole field

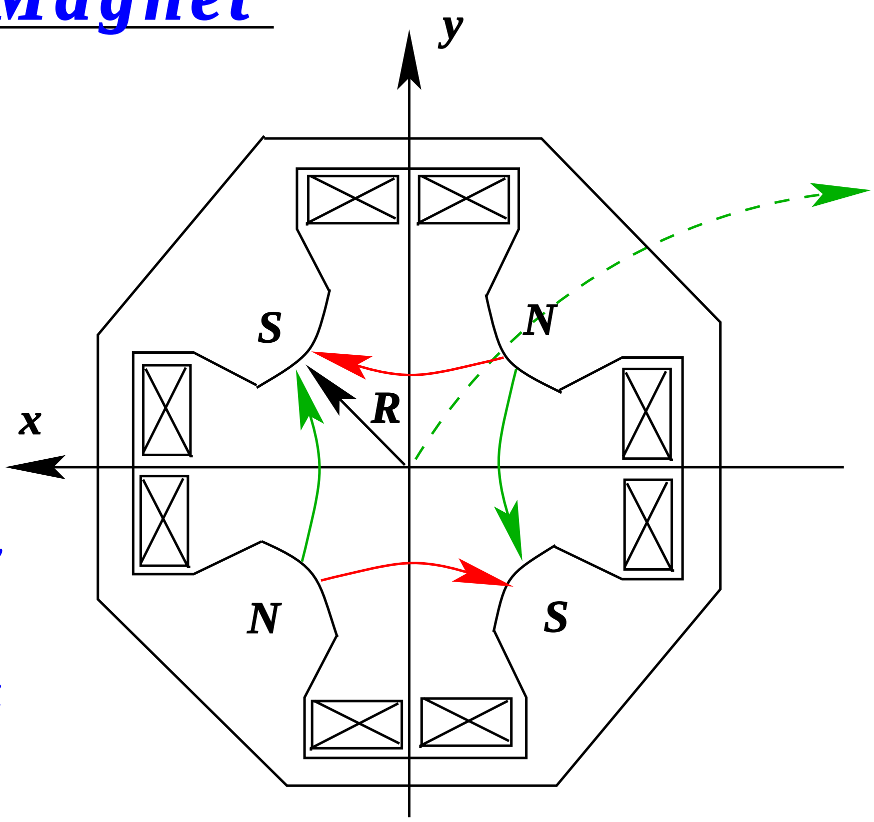
$$B_x = g \cdot y \qquad\qquad B_x = g \cdot \tilde{y}$$

$$B_y = g \cdot x \qquad x = x_0 + \tilde{x} \longrightarrow B_y = \underbrace{g \cdot x_0}_{\text{dipole component}} + g \cdot \tilde{x}$$

Quadrupole Magnet

$$B_x = g \cdot y$$

$$B_y = g \cdot x$$



$$F_x = -q \cdot v \cdot B_y$$

$$F_y = q \cdot v \cdot B_x$$

$$\frac{d^2x}{d\,s^2} + K(s) \cdot x = G(s); \qquad G(s) = \frac{F(s)_{Lorentz}}{v \cdot p_0}$$

normalized fields:

dipole: $$k_0(s) = 0.3 \cdot \frac{B_0[T]}{p_0[GeV]}$$

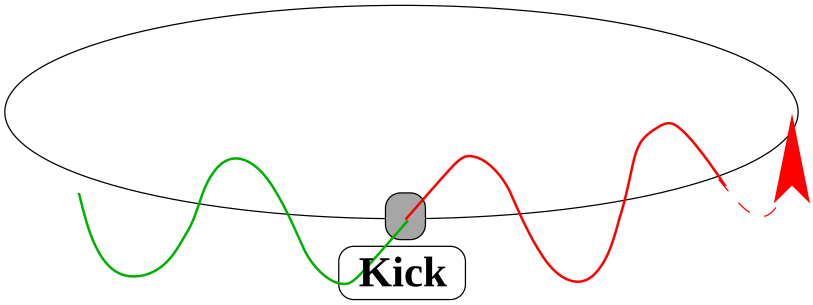
quadrupole: $$k_1(s) = 0.3 \cdot \frac{g_0[T/m]}{p_0[GeV]}$$

quadrupole misalignment: $$\Delta k_0(s) = 0.3 \cdot \frac{g[T/m]}{p[GeV]} \cdot x_0$$

Dipole Error and Orbit Stability

Q: number of β−oscillations per turn

Q = N

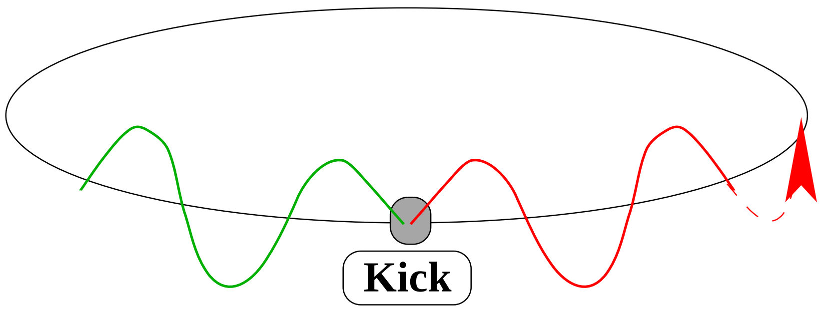


the perturbation adds up

amplitude growth and particle loss

watch out for integer tunes!

Q = N + 0.5



the perturbation cancels after each turn

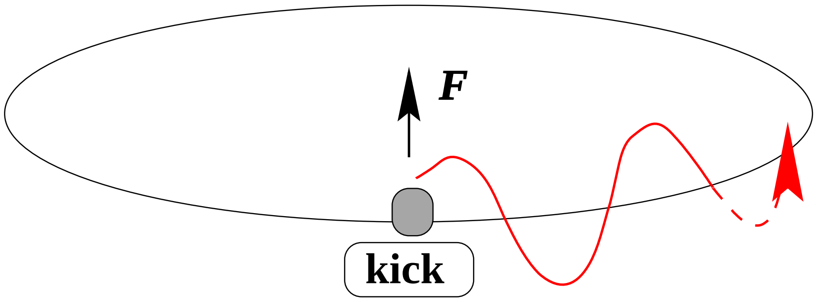
Quadrupole Error and Orbit Stability

Quadrupole Error:

→ orbit kick proportional to beam offset in quadrupole

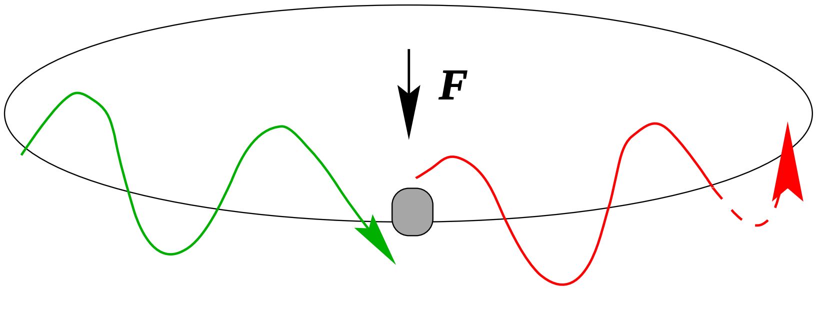
$Q = N + 0.5$

1. Turn: $x > 0$



→ amplitude increase

2. Turn: $x < 0$



→ amplitude increase

→ watch out for half integer tunes!

Sources for Orbit Errors

- ***Quadrupole offset:***
  - ***alignment*** ***+/- 0.1 mm***
  - ***ground motion***
    - ***slow drift***
    - ***civilisation***
    - ***moon***
    - ***seasons***
    - ***civil engineering***
- ***Error in dipole strength***
  - ***power supplies***
  - ***calibration***
- ***Energy error of particles***
  - ***injection energy (RF off)***
  - ***RF frequency***
  - ***momentum distribtion***

Example Quadrupole Alignment inLEP

Transversal tilt dispersion of the 3278 dipoles	σ = ± 0.34 mrd
Vertical dispersion of the 784 quadrupoles (with respect to the smoothing polynomial)	σ = ± 0.65 mm

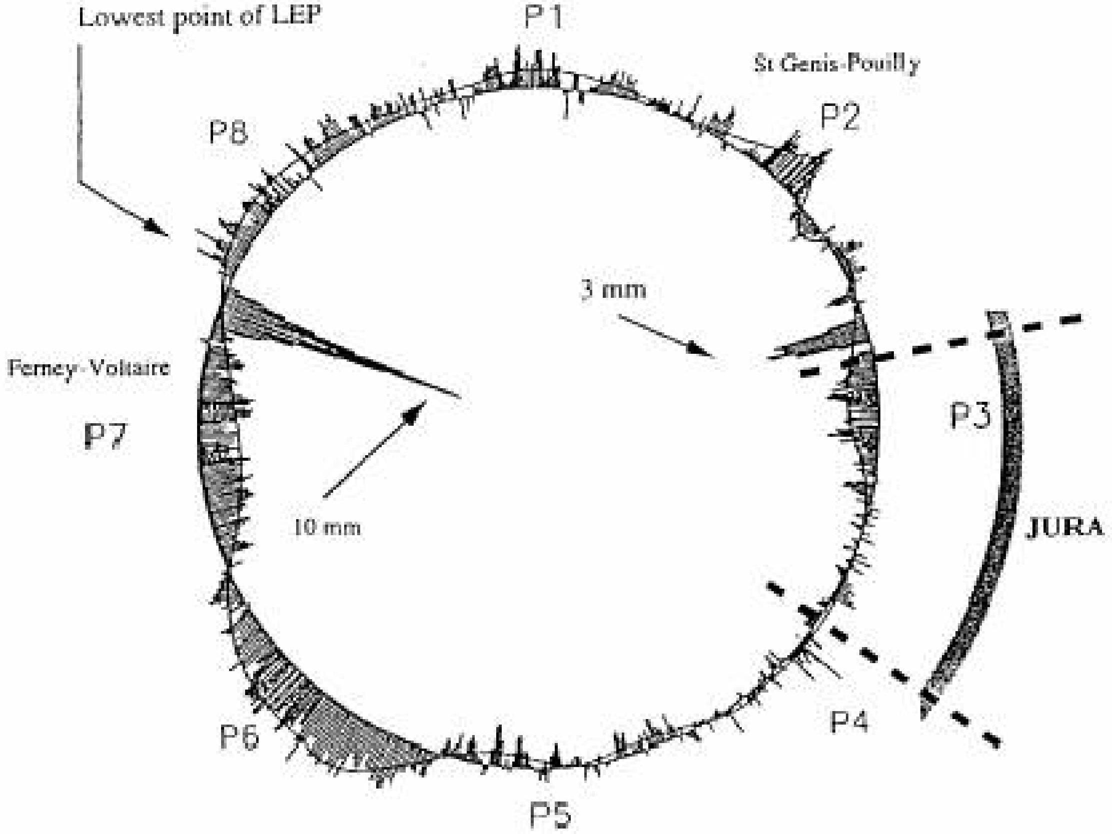


Figure 1 : observed status, end 1992

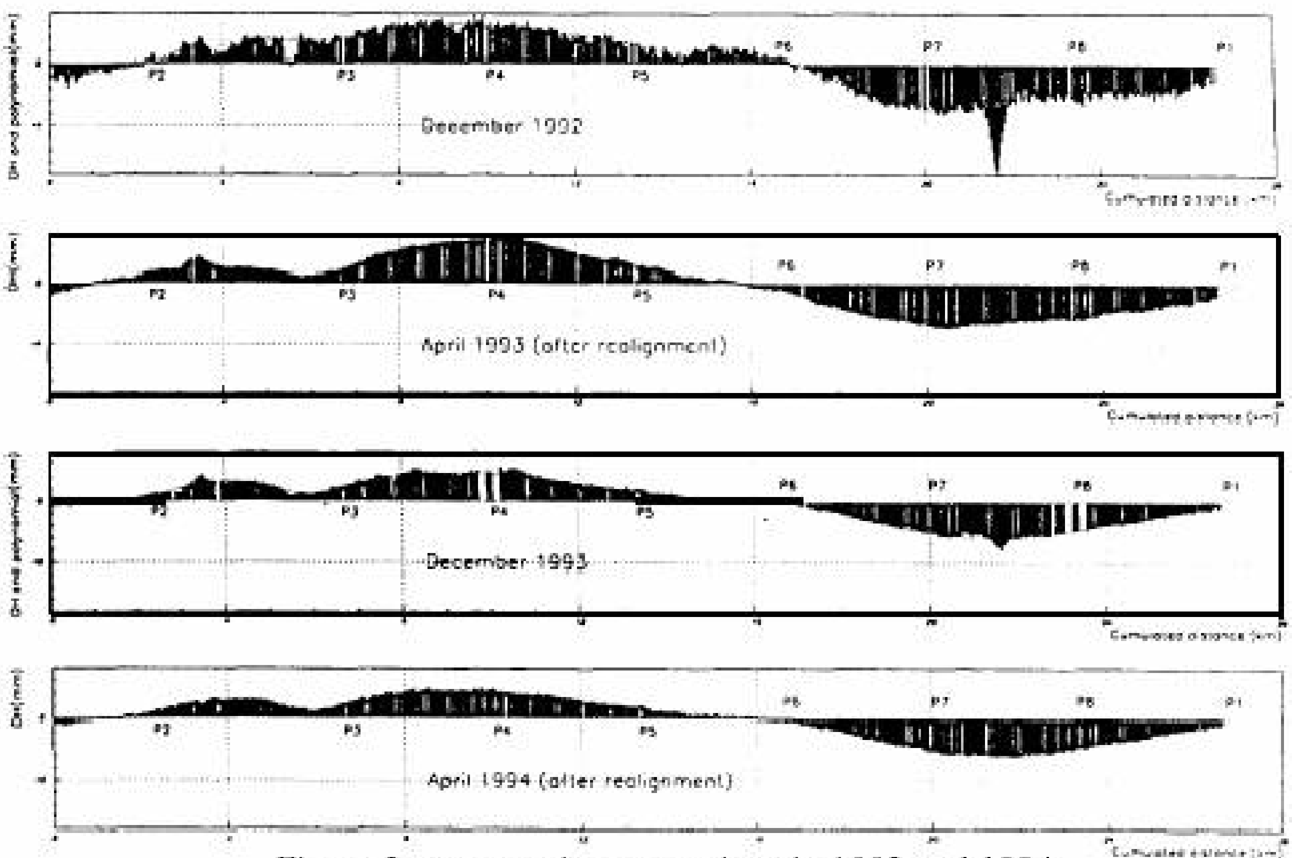


Figure 2 : progressive corrections in 1993 and 1994

Problems Generated by Orbit Errrors

- **injection errors:**
  - aperture → beam losses
  - filamentation → beam size

- **closed orbit errors:**
  - x−y coupling
  - aperture
  - energy error
  - field imperfections
  - dispersion → beam size at IP
  - beam separation

Aim:

$\Delta x,\ \Delta y < 4$ mm

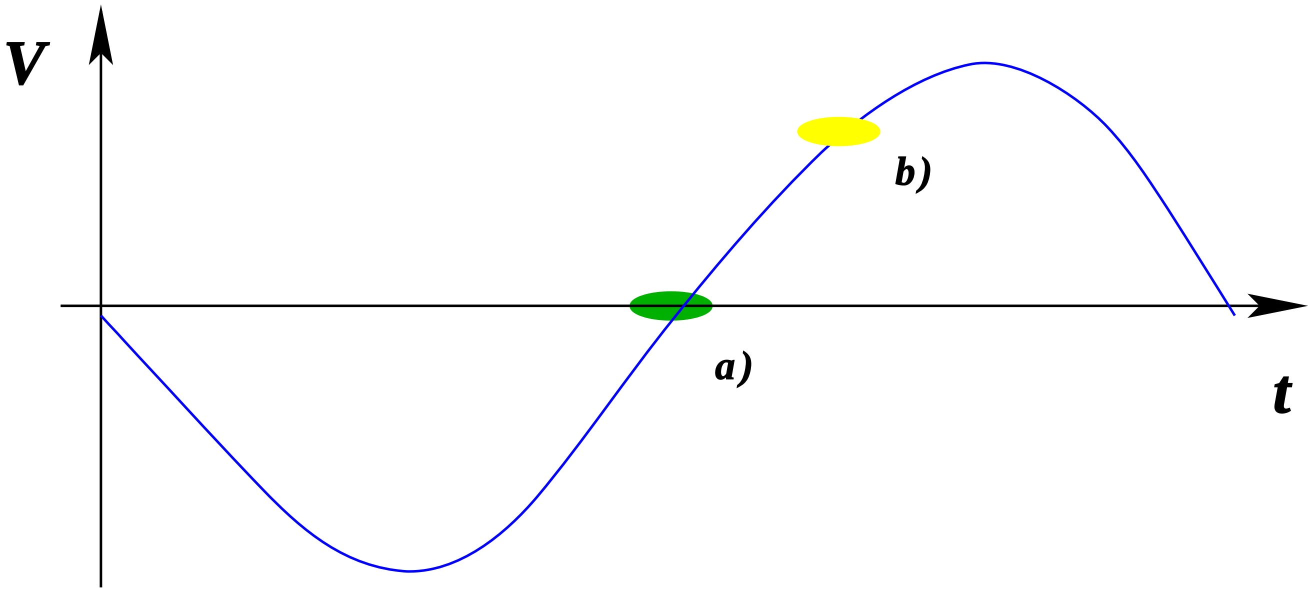
rms < 0.5 mm

→ beam monitors and orbit correctors

Synchrotron:

→ **the orbit determines the particle energy!**

assume: L > design orbit



→ **energy increase**

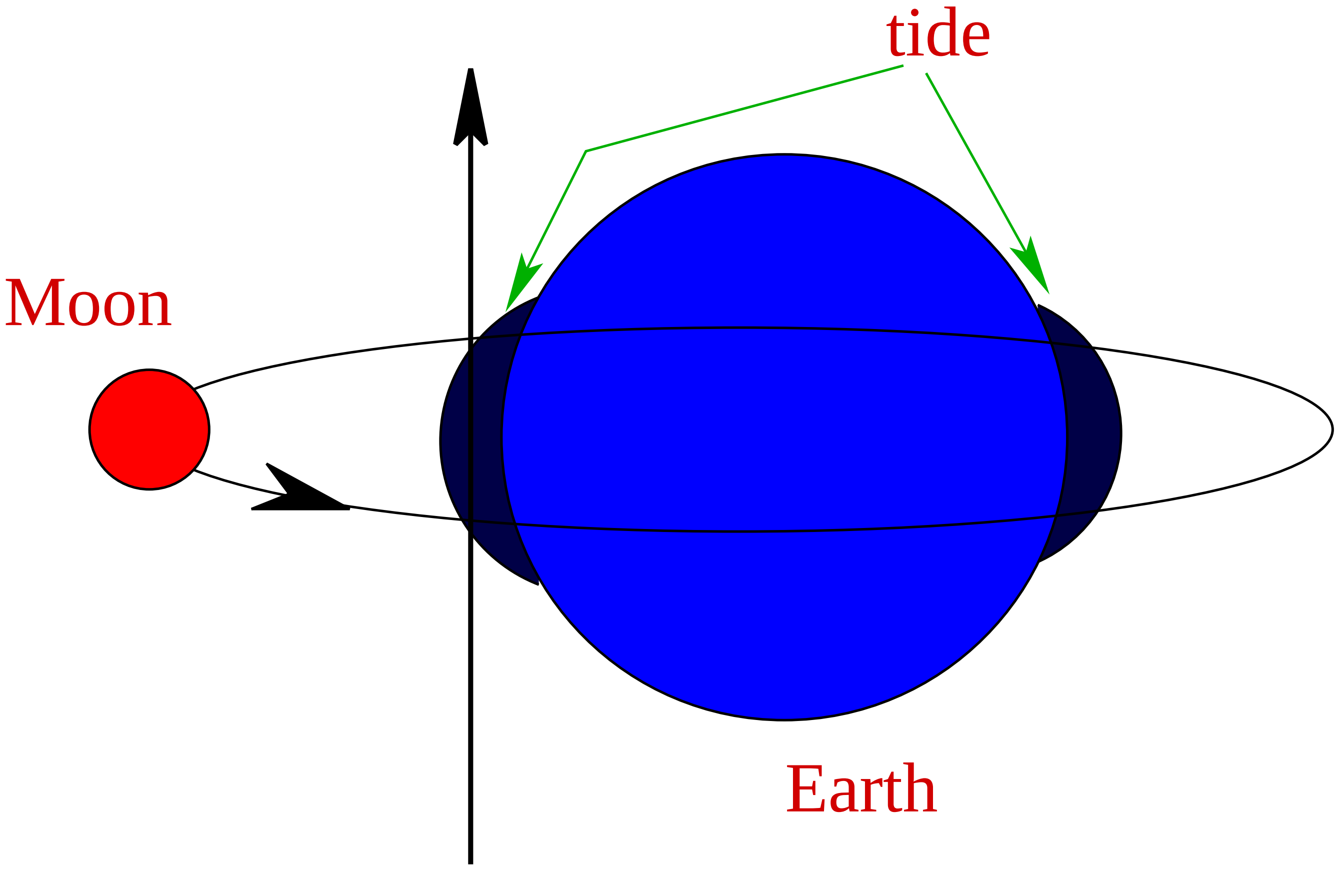
Equilibrium:

$$f_{RF} = h \cdot f_{rev}$$

$$f_{rev} = \frac{1}{2 \cdot \pi} \cdot \frac{q}{m \cdot \gamma} \cdot B$$

→ **E depends on orbit and magnetic field!**

tidal motion of the earth:



orbit and beam energy modulation:

$$f_{mod} = 24\ h;\ 12\ h$$

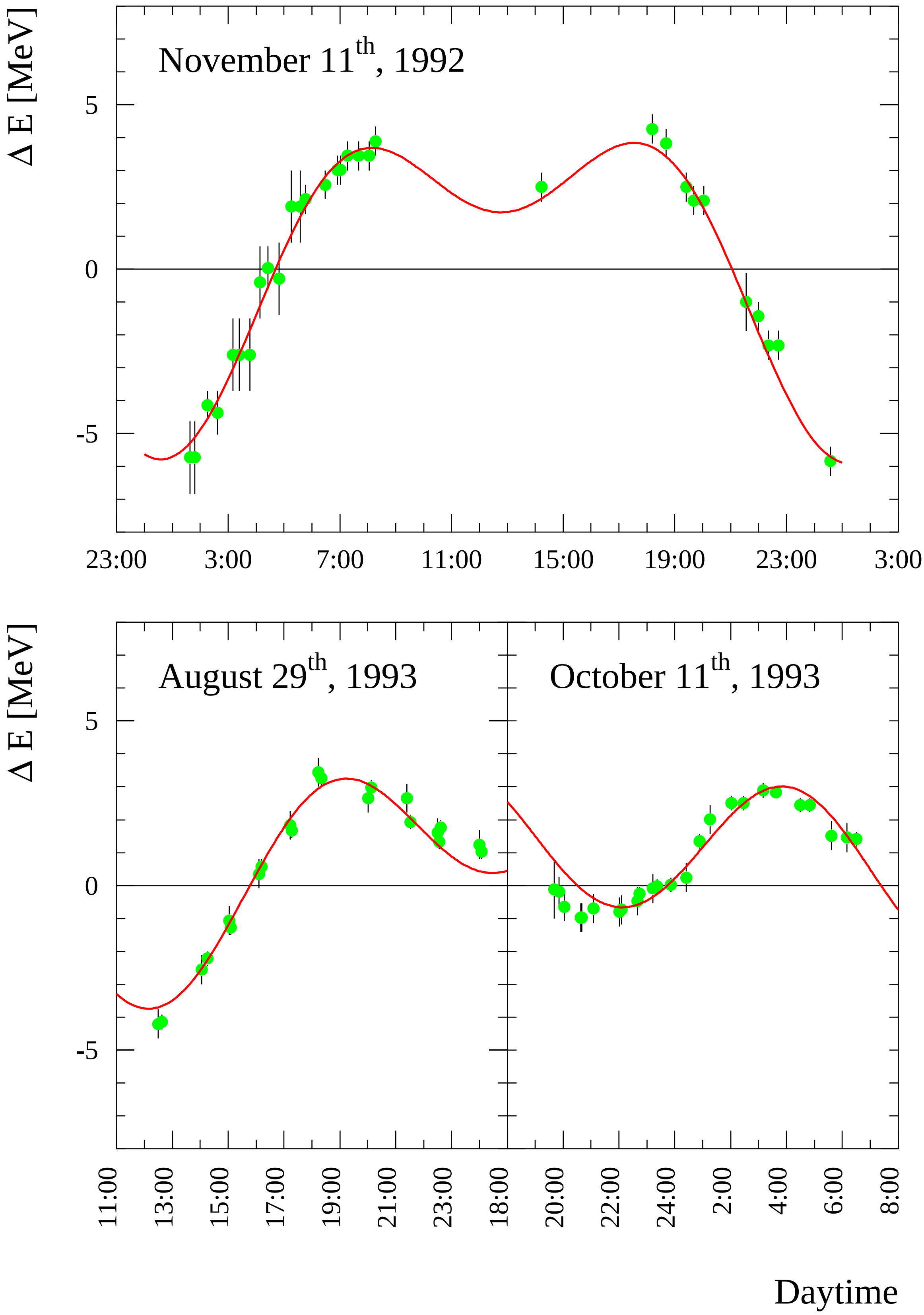
$\rightarrow$ $\Delta E \approx 10\ MeV$

$\approx 0.02\%$

aim: $\Delta E \lesssim 0.003\%$

$\rightarrow$ ***requires correction!***

energy modulation due to tidal motion of earth

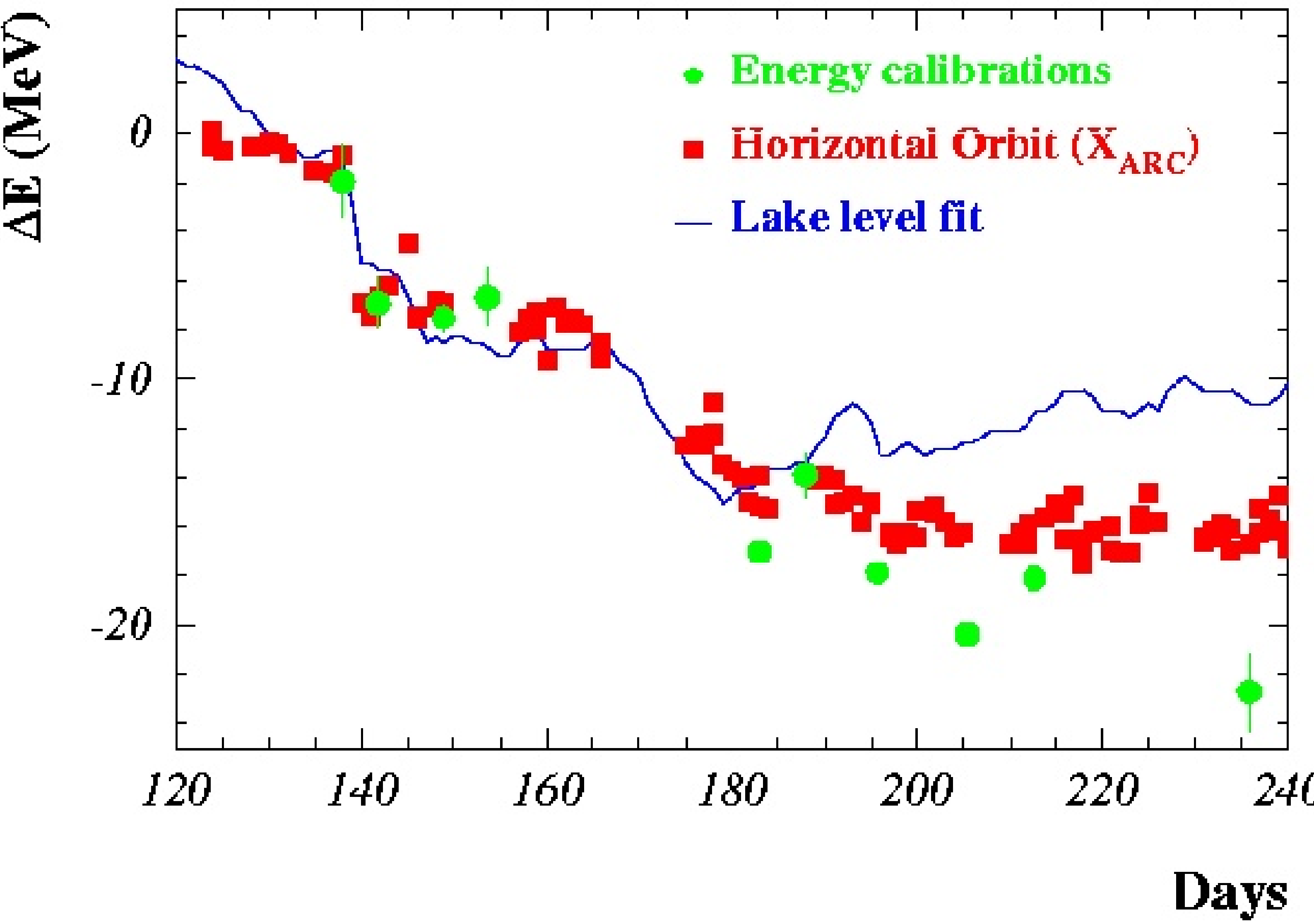


→ $\Delta E \approx 10$ MeV

energy modulation due to lake level changes

changes in the water level of lake Geneva change the position of the LEP tunnel and thus the quadrupole positions

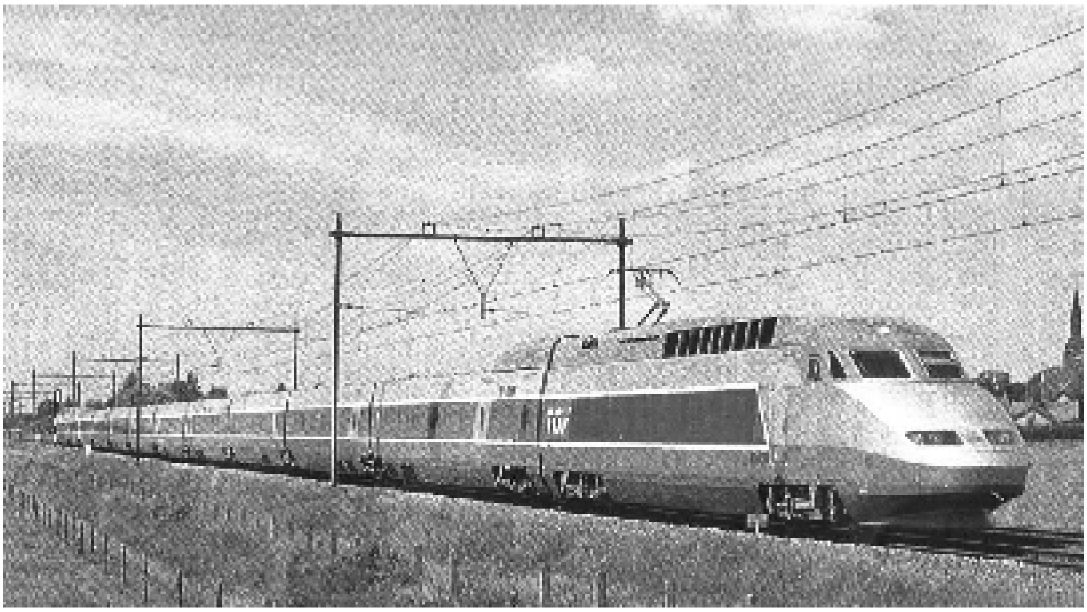
→ orbit and energy perturbations

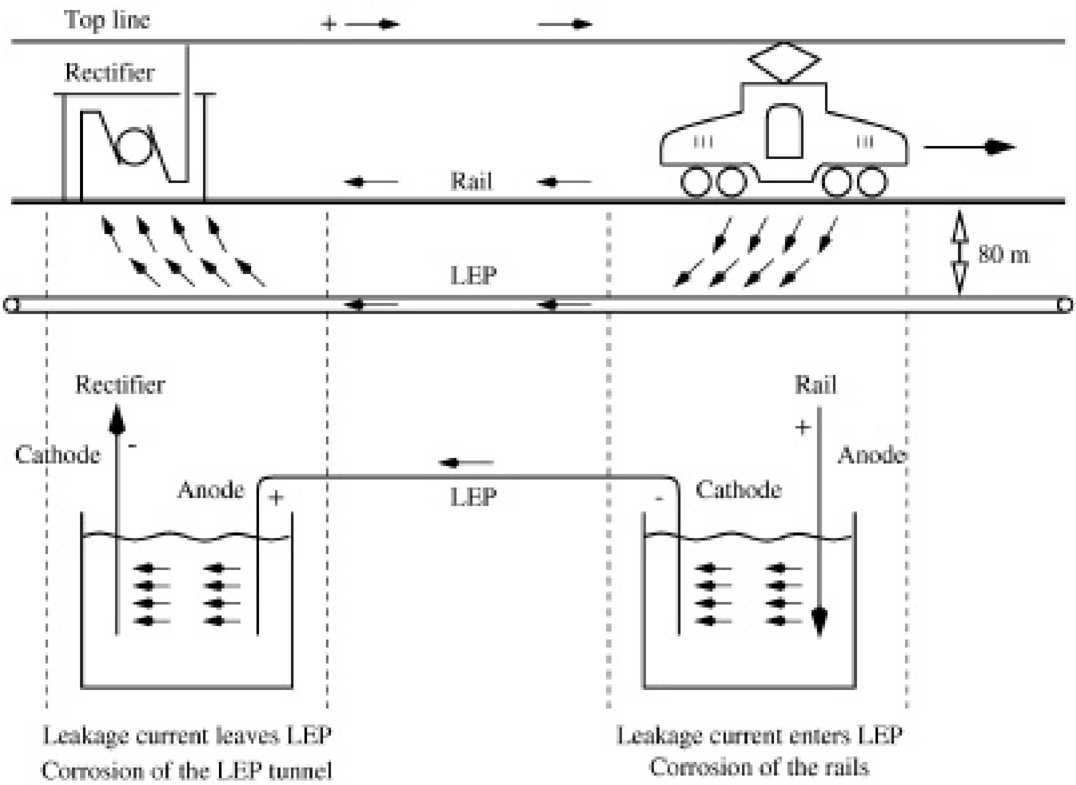


→ $\Delta E \approx 20\ MeV$

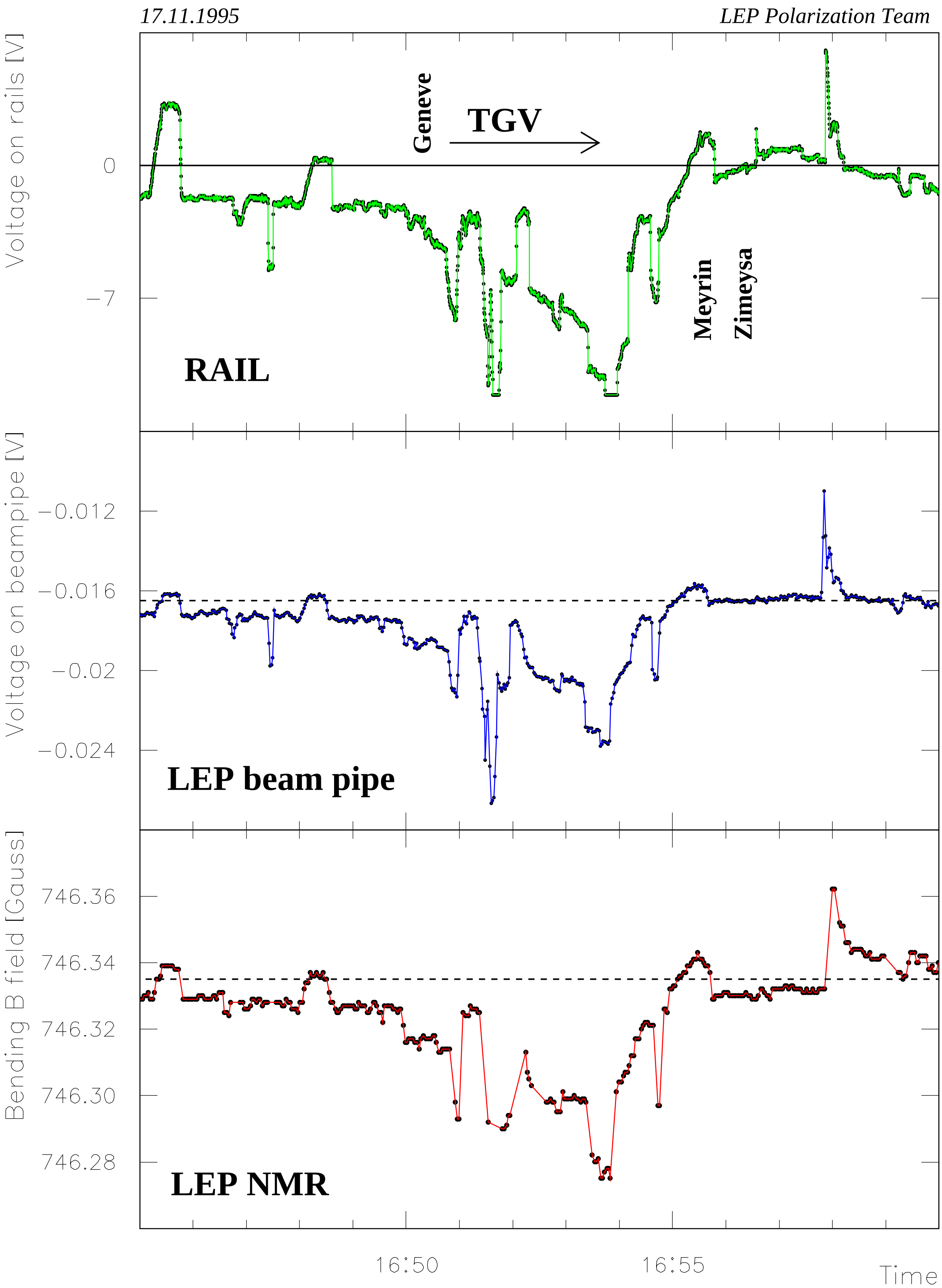
- energy modulation due current perturbations in the main dipole magnets

- TGV line between Geneva and Bellegarde





correlation of NMR dipole field measurements with the voltage on the TGC train tracks



ΔE ~ 5 MeV for LEP operation at 45 GeV

ground motion due to human activity

quadrupole motion in HERA−p (DESY Hamburg)

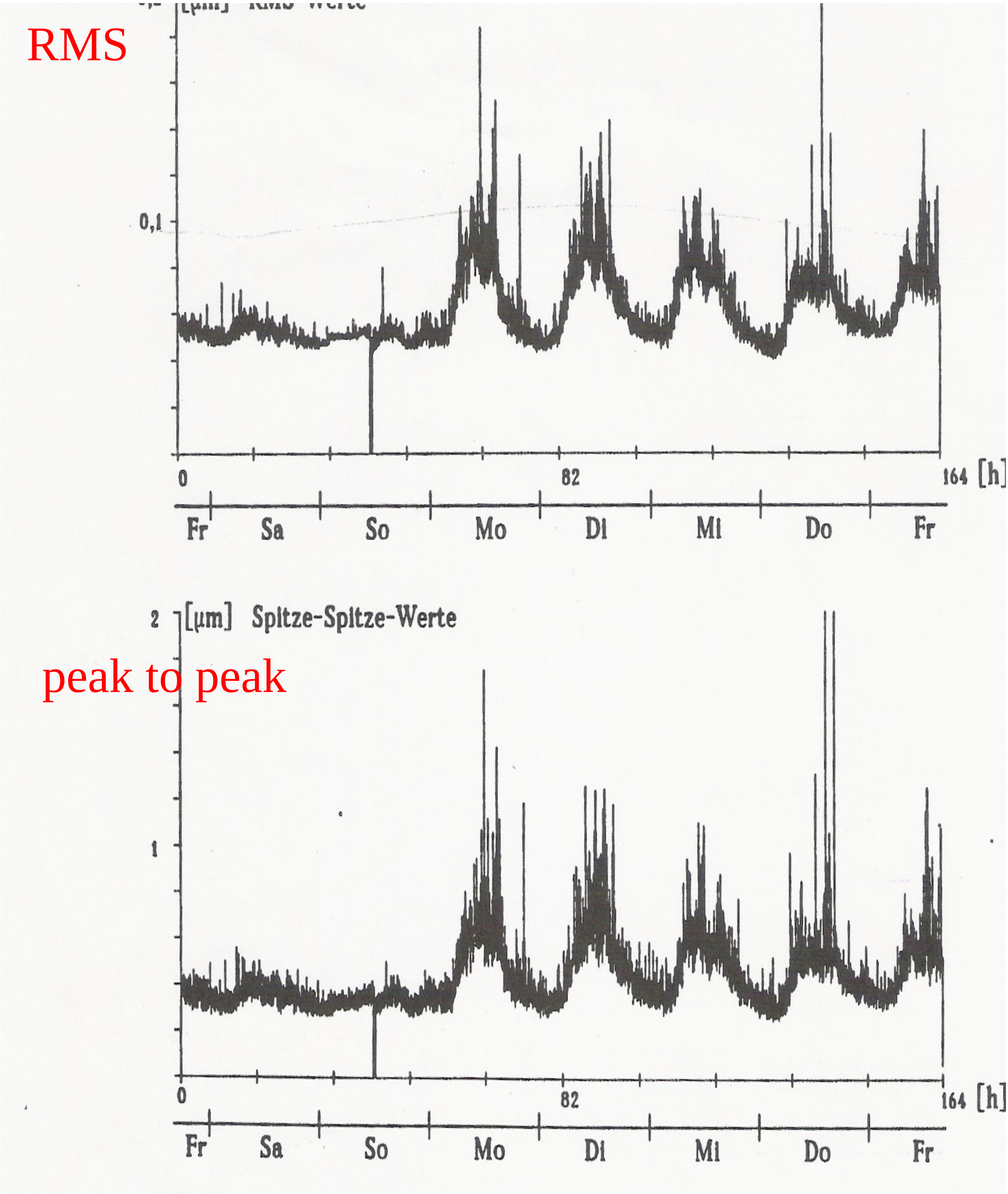


Abb. 3.13 Zeitabhängigkeit der Bodenbewegung
oben RMS-Werte
unten Spitze-Spitze-Werte

Closed Orbit Response

inhomogeneous equation:

$$\frac{d^2x}{d\,s^2} + K(s) \cdot x = G(s); \qquad G(s) = \Delta k_0(s)$$

$$\vec{y}' + \begin{pmatrix} 0 & 1 \\ K & 0 \end{pmatrix} \cdot \vec{y} = \vec{G}; \quad \vec{G} = \begin{pmatrix} 0 \\ G \end{pmatrix}$$

$$\vec{y}(s) = a \cdot \vec{S}(s) + b \cdot \vec{C}(s) + \vec{\psi}(s)$$

we need to find only one solution!

variation of the constant:

$$\vec{\psi}(s) = c(s) \cdot \vec{S}(s) + d(s) \cdot \vec{C}(s)$$

Closed Orbit Response

variation of the constant in matrix form:

$$\vec{\psi}(s) = \underline{\phi}(s) \bullet \vec{u}(s); \quad \text{with}$$

$$\underline{\phi}(s) = \begin{pmatrix} C(s) & S(s) \\ C'(s) & S'(s) \end{pmatrix}$$

substitute into differential equation:

$$\longrightarrow \quad \underline{\phi}(s) \bullet \vec{u}\,'(s) = \vec{G}(s)$$

$$\longrightarrow \quad \vec{u}(s) = \int_{s_0}^{s} \underline{\phi}(t)^{-1} \bullet \vec{G}(t)\, dt$$

$$\longrightarrow \quad \vec{y}(s) = a \bullet \vec{S}(s) + b \bullet \vec{C}(s) + \underline{\phi}(s) \bullet \int_{s_0}^{s} \underline{\phi}(t)^{-1} \bullet \vec{G}(t)\, dt$$

Closed Orbit Response

periodic boundary conditions:

$$\vec{y}(s) = a \cdot \vec{S}(s) + b \cdot \vec{C}(s) + \underline{\phi}(s) \cdot \int_{s0}^{s} \underline{\phi}(t)^{-1} \cdot \vec{G}(t)\, dt$$

with

$$\vec{y}(s) = \begin{pmatrix} x(s) \\ x'(s) \end{pmatrix}; \quad x(s) = x(s+L); \quad x'(s) = x'(s+L)$$

→

periodic boundary conditions determine coefficients a ***and*** b

→

$$x(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi \cdot Q)} \cdot \int_{s0}^{s0+circ} \sqrt{\beta(t)} \cdot G(t)\, \cos[\phi(t) - \phi(s) - \pi Q]\, dt$$

Closed Orbit Response

Example: particle momentum error

normalized dipole strength: $$k_0(s) = 0.3 \cdot \frac{B[T]}{p[GeV]}$$

$$k_0(s) = \frac{1}{\rho(t)} - \frac{1}{\rho(t)} \cdot \frac{\Delta p}{p_0} \longrightarrow G(t) = \frac{1}{\rho(t)} \cdot \frac{\Delta p}{p_0}$$

$$x(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi \cdot Q)} \cdot \oint \sqrt{\beta(t)} \cdot G(t) \cos[|\phi(t) - \phi(s)| - \pi Q]\, dt$$

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

with

$$D(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi \cdot Q)} \cdot \oint \frac{\sqrt{\beta(t)}}{\rho(t)} \cdot \cos[|\phi(t) - \phi(s)| - \pi Q]\, dt$$

$\longrightarrow$ **Dispersion Orbit**

Orbit Correction

- the orbit error in a storage ring with conventional magnets is dominated by the contributions from the quadrupole alignment errors

- orbit perturbation is proportional to the local β-functions at the location of the dipole error

  → alignment errors at QF cause mainly horizontal orbit errors

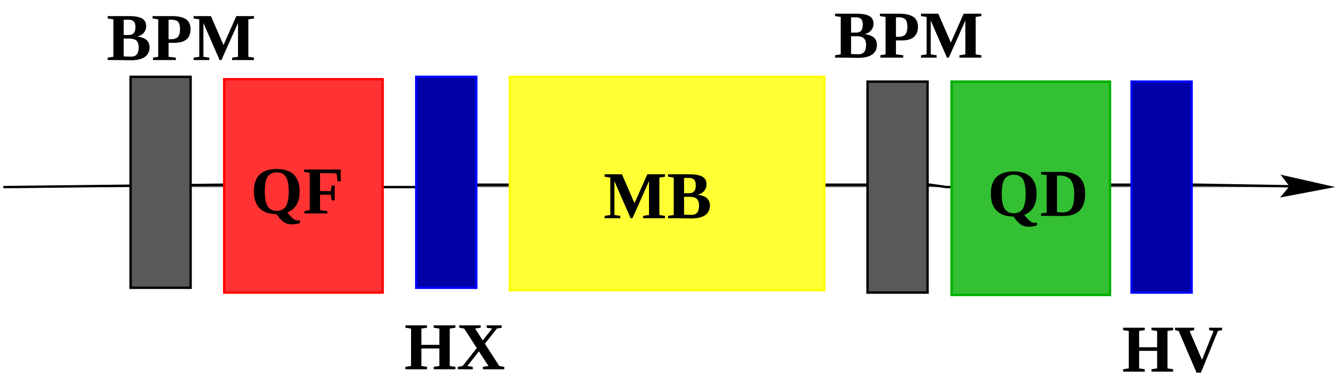
  → alignment errors at QD causes mainly vertical orbit errors

Orbit Correction

- aim at a local correction of the dipole error due to the quadrupole alignment errors

→ place orbit corrector and BPM next to the main quadrupoles

→ horizontal BPM and corrector next to QF
vertical BPM and corrector next to QD



→ **orbit in the opposite plane?**

relative alignment of BPM and quadrupole?

LEP Orbit

Horizontal Orbit:

- **beam offset in quadrupoles:**
  - → Lake Geneva
  - → moon

→ energy error

Vertical Orbit:

- **beam offset in quadrupoles**
- **beam separation**

→ orbit deflection depends on particle energy

→ vertical dispersion [D(s)]

$$\sigma_y = \sqrt{\varepsilon \cdot \beta_y + \delta_y^2 \cdot D^2}$$

→ **small vertical beam size relies on good orbit**

- 1994: 13000 vertical orbit corrections in physics

Quadrupole Gradient Error

one turn map:

can be generated by matrix multiplication:

$$\longrightarrow \quad \vec{z}_{n+1} = \underline{M} \bullet \vec{z}_n \qquad \vec{z} = \begin{pmatrix} x \\ x' \end{pmatrix}$$

and can be expressed in terms of the C and S solutions

$$\underline{M} = \underline{I} \bullet \cos(2\pi\, Q) + \underline{J} \bullet \sin(2\pi\, Q)$$

$$\underline{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \underline{J} = \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix}; \quad \gamma = [1 + \alpha^2\ ] / \beta$$

remember: $\cos(2\pi\, Q) = \frac{1}{2}\, \text{trace}\, \underline{M}$

$\longrightarrow$ the coefficients of: $\dfrac{\underline{M} - \underline{I} \bullet \cos(2\pi\, Q)}{\sin(2\pi\, Q)}$

provide the optic functions at s_0

Quadrupole Gradient Error

- ***transfer matrix for single quadrupole:***

$$m_0 = \begin{pmatrix} 1 & 0 \\ -k_1 \cdot l & 1 \end{pmatrix}$$

- ***matrix for single quadrupole with error:***

$$m = \begin{pmatrix} 1 & 0 \\ -[k_1 + \Delta k_1] \cdot l & 1 \end{pmatrix}$$

- ***one turn matrix with quadrupole error:***

$$M = m \cdot m_0^{-1} \cdot M_0$$

trace M

$$\longrightarrow$$

$$\cos(2\pi Q) = \cos(2\pi Q_0) - \frac{1}{2} \beta \cdot \Delta k_1 l \cdot \sin(2\pi Q_0)$$

Quadrupole Gradient Error

- ***distributed perturbation:***

$$\cos(2\pi Q) = \cos(2\pi Q_0) - \frac{\sin(2\pi Q_0)}{2} \cdot \oint \beta \cdot \Delta k_1 ds$$

$$\longrightarrow \boxed{\Delta Q = \frac{1}{4\pi} \cdot \oint \beta \cdot \Delta k_1 ds}$$

- ***chromaticity:*** $k_1 = \frac{e \cdot g}{p}$

momentum error $\longrightarrow$ $\Delta k_1 = -k_1 \cdot \frac{\Delta p}{p}$

$$\Delta Q = -\frac{1}{4\pi} \cdot \oint \beta \cdot k_1 ds \cdot \frac{\Delta p}{p}$$

$$= \xi \cdot \frac{\Delta p}{p}$$

β − *Beat*

quadrupole error:

$\longrightarrow$ $\vec{z}_{n+1} = \underline{M} \bullet \vec{z}_n$ $\qquad \underline{M} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}$

with

$$\underline{M} = \underline{I} \bullet \cos(2\pi \ Q) + \underline{J} \bullet \sin(2\pi \ Q)$$

$$\underline{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \underline{J} = \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix}; \ \gamma = [1 + \alpha^2 \ ] / \beta$$

$\longrightarrow$ calculate: $\dfrac{m_{12}}{\sin(2\pi Q)}$

$$\Delta\beta(s) = \frac{\beta(s)}{2 \sin(2\pi \bullet Q)} \bullet \int_{s0}^{s0+circ} \beta(t) \bullet \Delta k(t) \ \cos[2[\phi(t) - \phi(s)] - 2\pi \ Q] \ dt$$

$\longrightarrow$

β − beat oscillates with twice the betatron frequency

Local Orbit Bumps I

deflection angle:

$$\theta_i = \int_{\text{dipole}} G_i(t)\, dt = \frac{0.3 \bullet B_i[T] \bullet l}{p[GeV]}$$

trajectory response:

[no periodic boundary conditions]

$$\longrightarrow \quad x(s) = \sqrt{\beta_i\, \beta(s)} \bullet \theta_i \bullet \sin[\phi(s) - \phi_i]$$

$$\longrightarrow \quad x'(s) = \sqrt{\beta_i / \beta(s)} \bullet \theta_i \bullet \cos[\phi(s) - \phi_i]$$

Local Orbit Bumps II

- ***closed orbit bump:***

compensate the trajectory perturbation with

additional corrector kicks further down stream

→ closure of the perturbation within one turn

→ local orbit excursion

→ possibility to correct orbit errors locally

→ closure with one additional corrector magnet

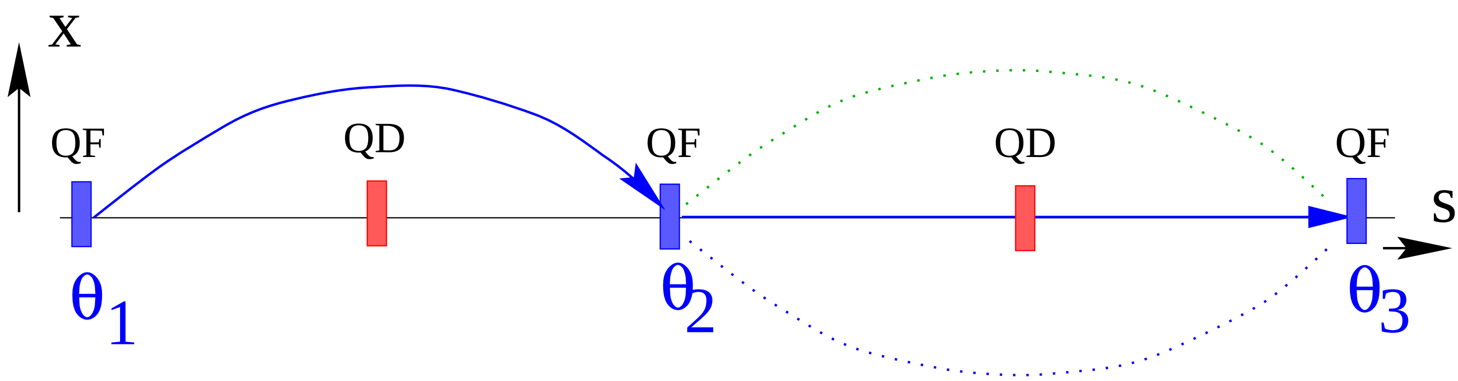
→ π - bump

→ closure with two additional corrector magnets

→ three corrector bump

Local Orbit Bumps III

- **π - bump:** (quasi local correction of error)



$$\rightarrow \quad \theta_2 = \frac{\sqrt{\beta_1}}{\sqrt{\beta_2}} \cdot \theta_1$$

- **limits / problems:**

→ closure depends on lattice phase advance

→ requires 90^o lattice

→ sensitive to lattice errors

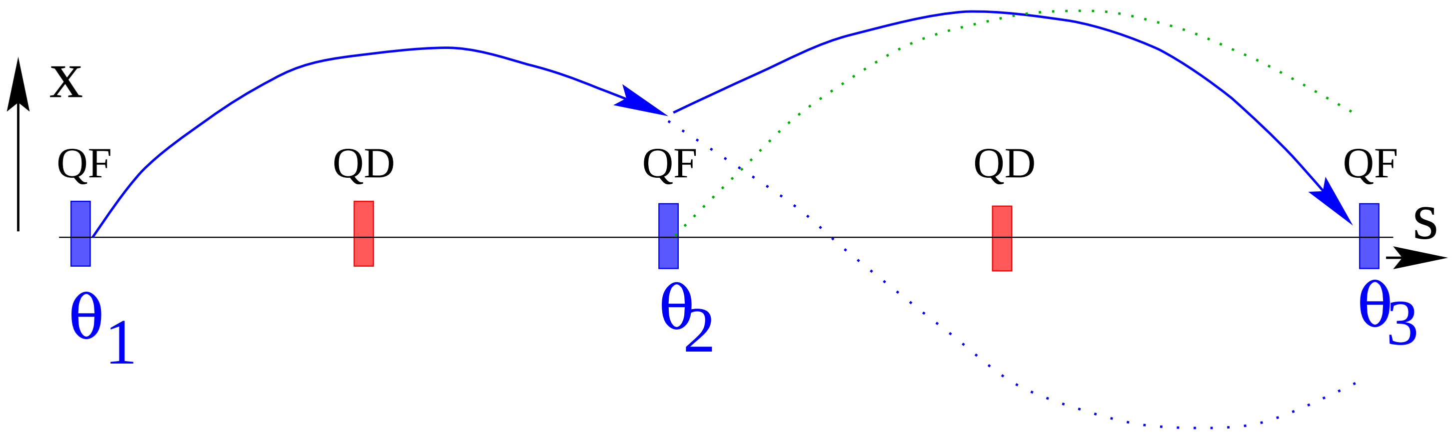
→ requires horizontal BPMs at QF and QD

→ sensitive to BPM errors

→ requires large number of correctors

Local Orbit Bumps IV

3 corrector bump: (quasi local correction of error)



$$\theta_2 = -\frac{\sqrt{\beta_1}}{\sqrt{\beta_2}} \cdot \frac{\sin(\Delta\phi_{3-1})}{\sin(\Delta\phi_{3-2})} \cdot \theta_1$$

$$\theta_3 = \left(\frac{\sin(\Delta\phi_{3-1})}{\tan(\Delta\phi_{3-2})} - \cos(\Delta\phi_{3-1}) \right) \cdot \frac{\sqrt{\beta_1}}{\sqrt{\beta_3}} \cdot \theta_1$$

- works for any lattice phase advance
- requires only horizontal BPMs at QF

limits / problems:

- sensitive to BPM errors
- large number of correctors
- can not control x'

Summary Linear Imperfections

- avoid machine tunes near integer resonances:
  - → they amplifies the response to dipole field errors
  - → a closed orbit perturbation propagates with the betatron phase around the storage ring
  - → discontinuities in the derivative of the closed orbit response at the location of the perturbation
- avoid storage ring tunes near half−integer resonances:
  - → they amplifies the response to quadrupole field errors
  - → betafunction perturbations propagate with twice the betatron phase advance around the storage ring
- integral expressions are mainly used for estimates
  numerical programs mainly rely on maps
  - → closed orbit = fixed point of ´1−turn´ map
  - → dispersion = eigenvector of extended ´1−turn´ map
  - → tune is given by the trace of the ´1−turn´ map
  - → twiss functions are given by the matrix elements