BEAM BASED ALIGNMENT

Beam Based Alignment tests at COSY

March 19, 2018 | Tim Wagner, on behalf of the JEDI Collaboration |

COSY

Cooler Syncrotron

- Circumference: 184 m
- Provides polarized protons and deuterons
- Maximum momentum: 3.65 GeV/c
- Intensity: 10^9 to 10^{10} particles
- Electron cooling
- Spin manipulators

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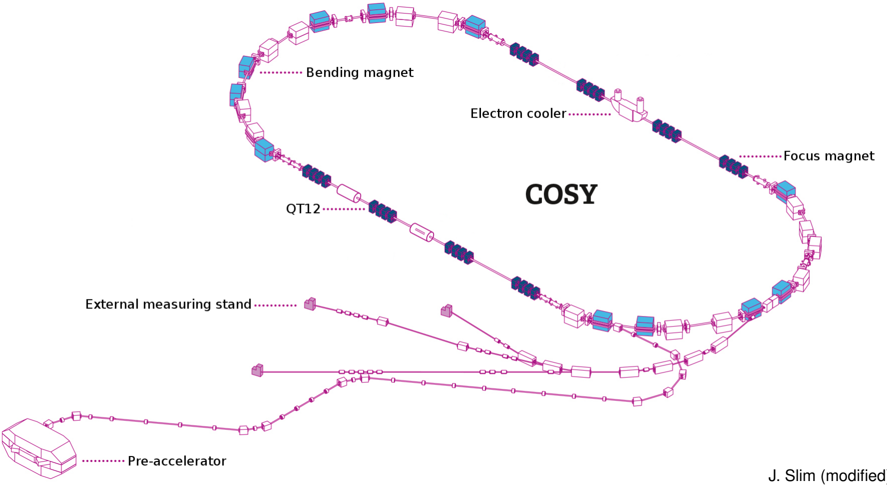
COSY

Cooler Syncrotron



J. Slim (modified)

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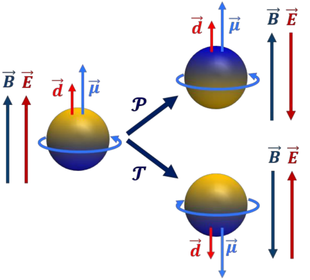
ELECTRIC DIPOLE MOMENT (EDM)

- Permanent EDMs of light hadrons are $\mathcal{T}$- and $\mathcal{P}$-violating
- $\mathcal{CPT}$ theorem $\rightarrow \mathcal{CP}$ violation
- Measure EDMs of charged particles in storage rings
- $d_{Neutron} < 3 \times 10^{-26}\,\mathrm{e} \cdot \mathrm{cm}$
- $d_{Proton} < 5 \times 10^{-24}\,\mathrm{e} \cdot \mathrm{cm}$
- $d_{Deuteron} = ?$

$$\vec{d} = \eta \cdot \frac{q}{2mc} \vec{S}$$



V. Schmidt

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

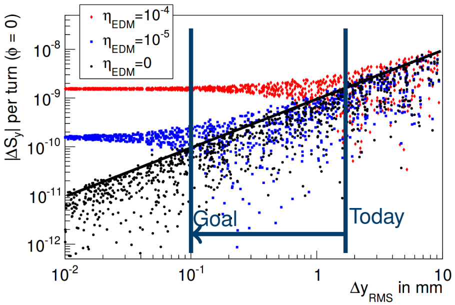
$$\mathcal{P} : \mathcal{H} = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

$$\mathcal{T} : \mathcal{H} = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

BEAM BASED ALIGNMENT

Why is it needed?

- For an EDM measurement the orbit has to be as good as possible
- Orbit RMS should be lower than 100 µm
  $\rightarrow$ Orbit Control
- Orbit Control corrects the beam to the BPM zero position



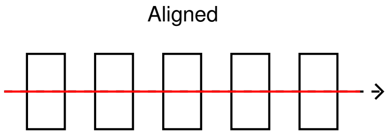
M.Rosenthal, PhD Thesis (modified)

- Goal is to go central through all magnets (i.e. quadrupoles)
- Thus BPM to quadrupole offset has to be known
  $\rightarrow$ Beam Based Alignment

BEAM BASED ALIGNMENT

How does it work?

- Use beam to optimize the beam position
- Vary quadrupole strength
- Observe orbit change
- Try to minimize the orbit change



BEAM BASED ALIGNMENT

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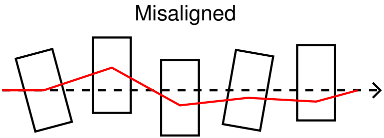


BEAM BASED ALIGNMENT

How does it work?

- How does the orbit change when varying the quadrupole strength?

$$\Delta x(s) = \left(\frac{\Delta k\, x(\bar{s})\, l}{B\rho}\right)\left(\frac{1}{1 - k\frac{l\beta(\bar{s})}{2B\rho\tan\pi\nu}}\right) \times \frac{\sqrt{\beta(s)}\sqrt{\beta(\bar{s})}}{2\sin\pi\nu}\cos(\phi(s) - \phi(\bar{s}) - \pi\nu)$$

- Not possible to calculate $x(\bar{s})$ due to lack of precise knowledge of all other parameters

BEAM BASED ALIGNMENT

How does it work?

- Use the following merit function

$$f = \frac{1}{N_{\text{BPM}}} \sum_{i=1}^{N_{\text{BPM}}} \left(x_i(+\Delta k) - x_i(-\Delta k)\right)^2$$

$$f \propto (\Delta x)^2 \propto (x(\bar{s}))^2$$

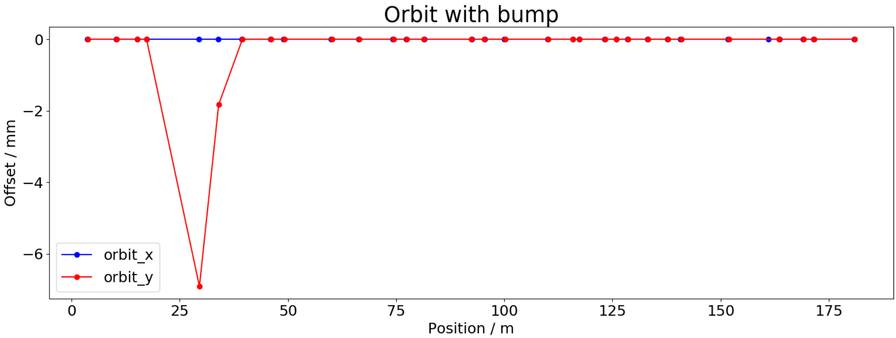
- By finding the minimum the optimal beam position can be found

SIMULATION

- Simulation of COSY done with MAD-X
- Option 1: Generate a bump inside the quadrupole
- Option 2: Move the quadrupole
- Vary the quadrupole strength
- Obseve the effect on the orbit
- Calculate the optimal position

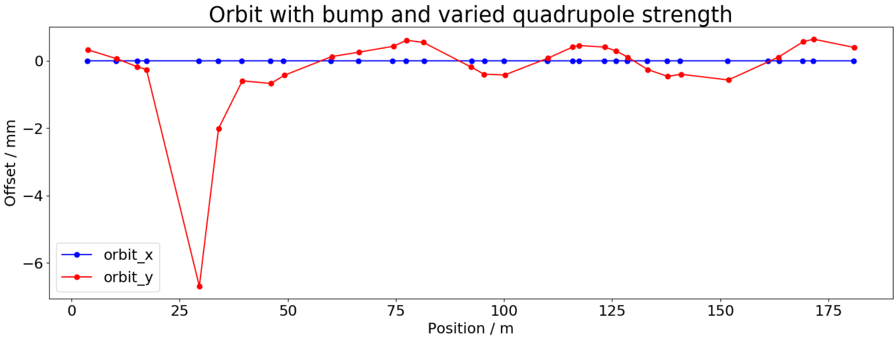
SIMULATION

Example Bump



SIMULATION

Example Bump



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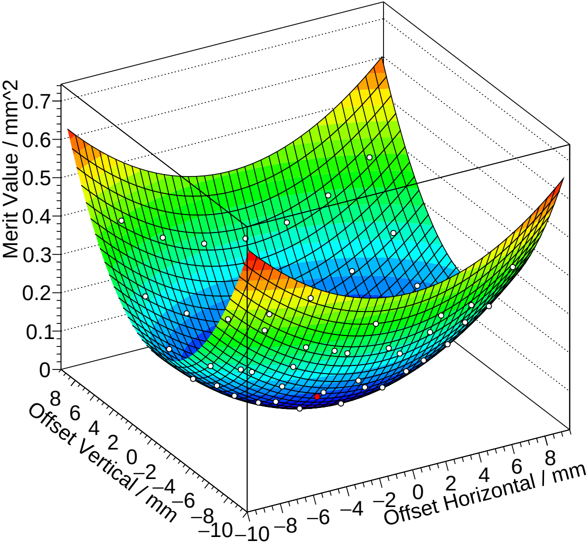
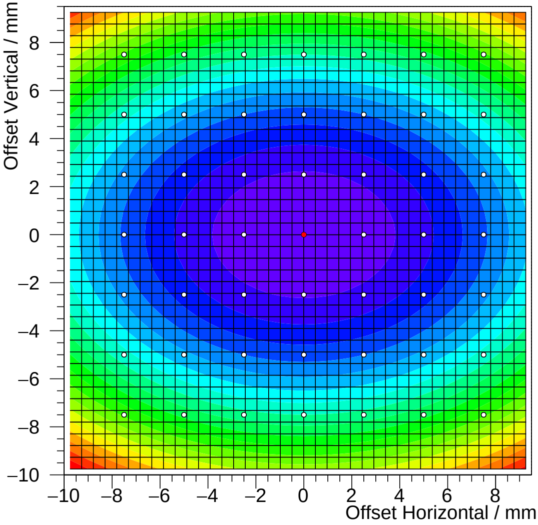
SIMULATION

Option 1 - Apply Bump



SIMULATION

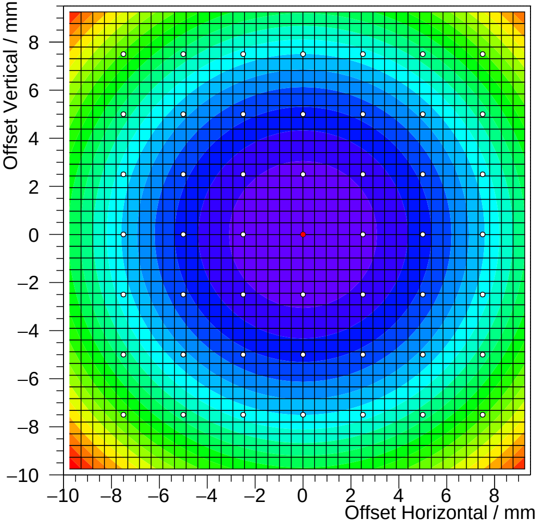
Option 1 - Apply Bump



- Asymmetric due to imperfect bumps
- Different slopes of the beam for horizontal and vertical direction

SIMULATION

Option 2 - Move Quadrupole



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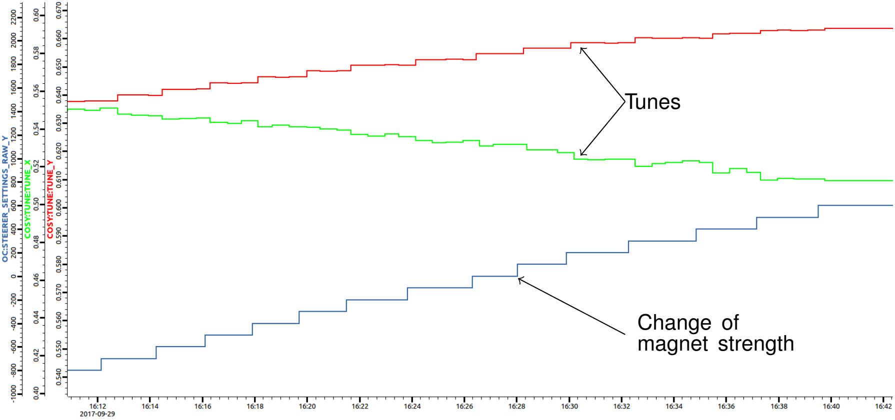
MEASUREMENT

- Quadrupoles are powered in families of four
- On the poles of quadrupole QT12 the additional coils of the steerer BLW04 were recabled to work as a quadrupole

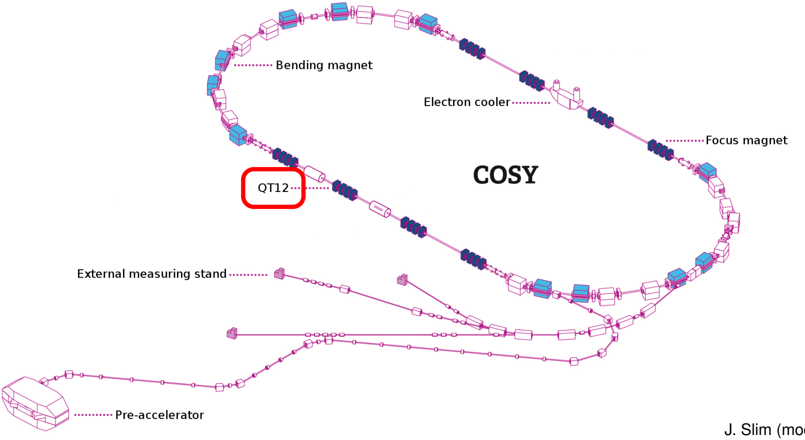
MEASUREMENT

Quadrupole behavior



MEASUREMENT

Location of QT12



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COSY scetch with position of quadrupole QT12 indicated

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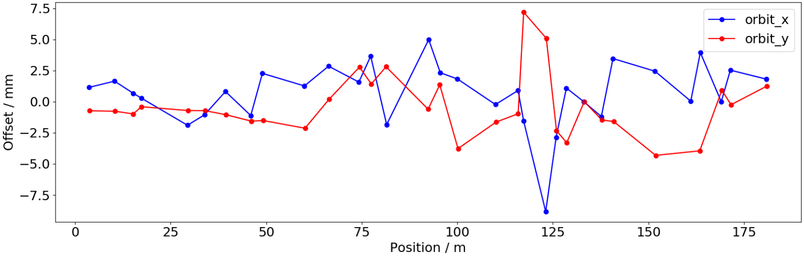
MEASUREMENT

- Quadrupoles are powered in families of four
- On the poles of quadrupole QT12 the additional coils of the steerer BLW04 were recabled to work as a quadrupole
- Effectively the strength of quadrupole QT12 can be varied
- Local bumps applied at the position of the quadrupole
- Measured effect on orbit upon varying the quadrupole strength

MEASUREMENT

Orbit



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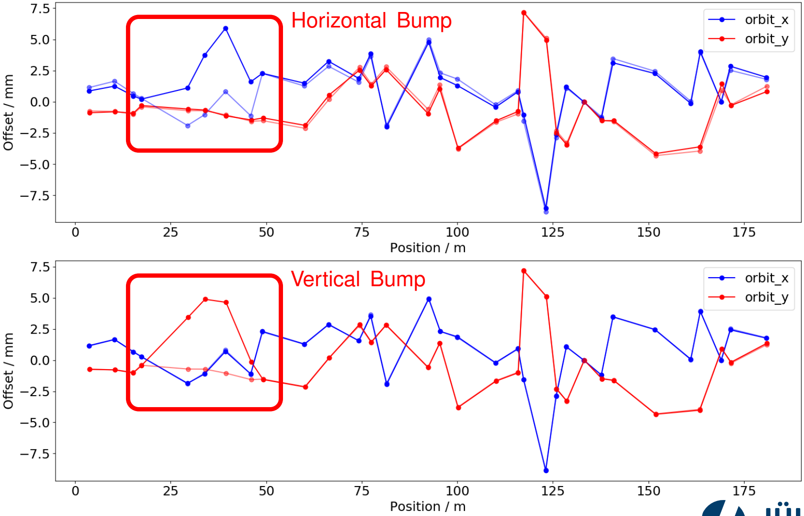
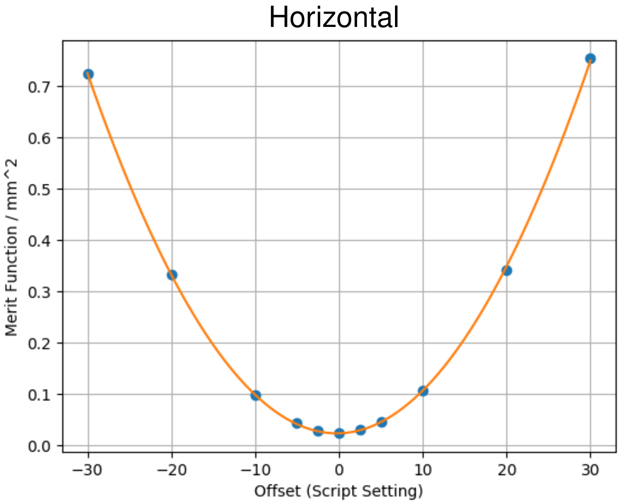
MEASUREMENT

Orbit

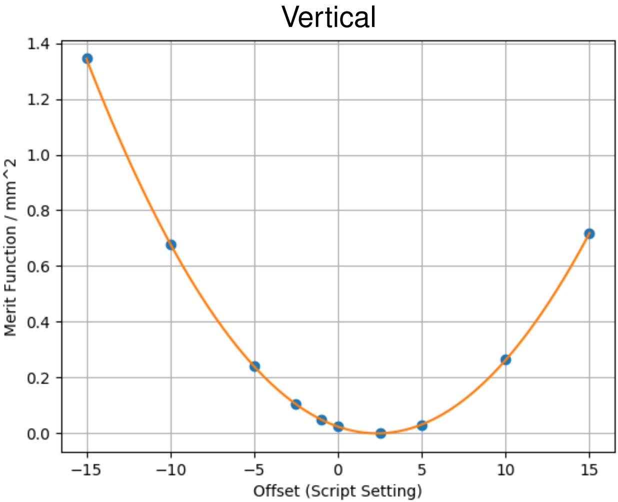


RESULTS

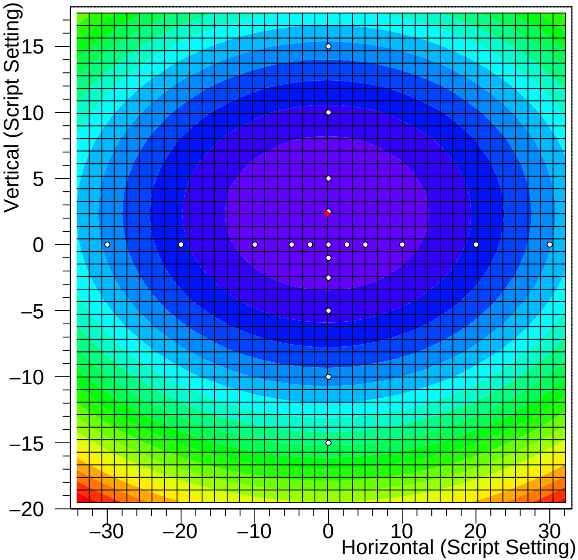


Horizontal
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Merit Function / mm^2
−30
−20
−10
0
10
20
30
Offset (Script Setting)

RESULTS


Vertical
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Merit Function / mm^2
−15
−10
−5
0
5
10
15
Offset (Script Setting)

RESULTS



Vertical (Script Setting)
15
10
5
0
−5
−10
−15
−20
−30
−20
−10
0
10
20
30
Horizontal (Script Setting)

RESULTS

	Optimal Position	in mm
Horizontal	-0.255 ± 0.028	-1.98 ± 0.01
Vertical	2.329 ± 0.011	1.15 ± 0.01

- Optimal position given in script setting
- The values in mm are the BPM 6 readings nearby

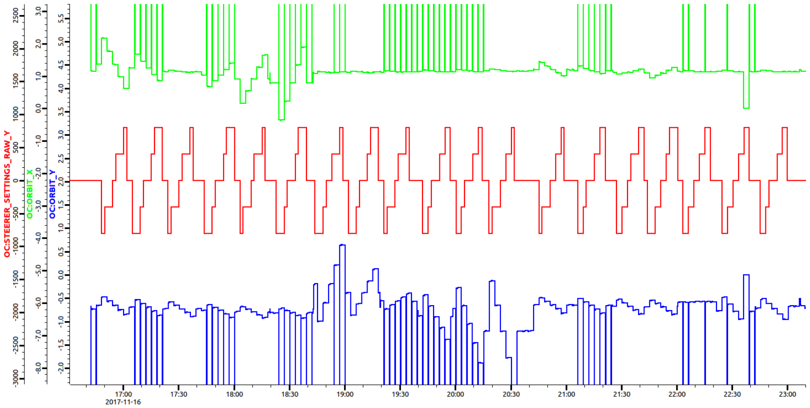
SUMMARY & OUTLOOK

- Beam based alignment works
- The change of the magnet strength with additional coils works
- Optimal beam position inside the quadrupole could be determined to be (-1.98 ± 0.01) mm horizontally and (1.15 ± 0.01) mm vertically

- Additional quadrupole magnets need to be changed to be individually controlled
- Measurement all along the ring to obtain quadrupole to BPM offsets

Backup

MEASUREMENT SCREENSHOT



Screenshot of the measurement. In red the change of the magnet strength is shown and in green and blue an example for a bpm reading. For each scan a different beam position was used.

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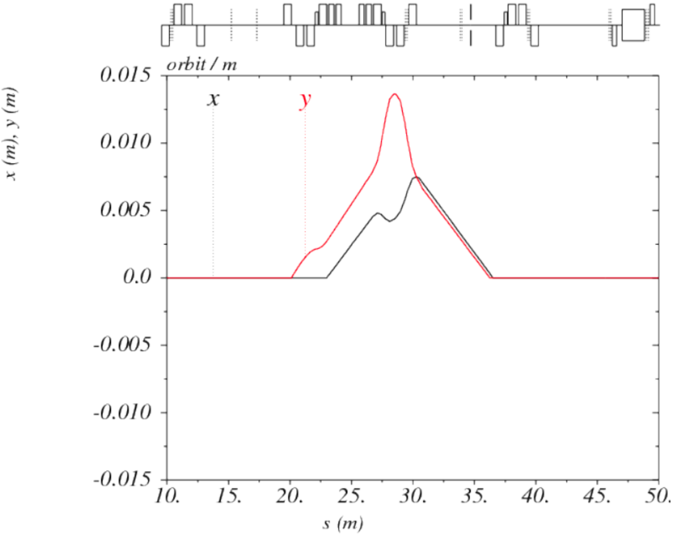
SIMULATION: BUMP



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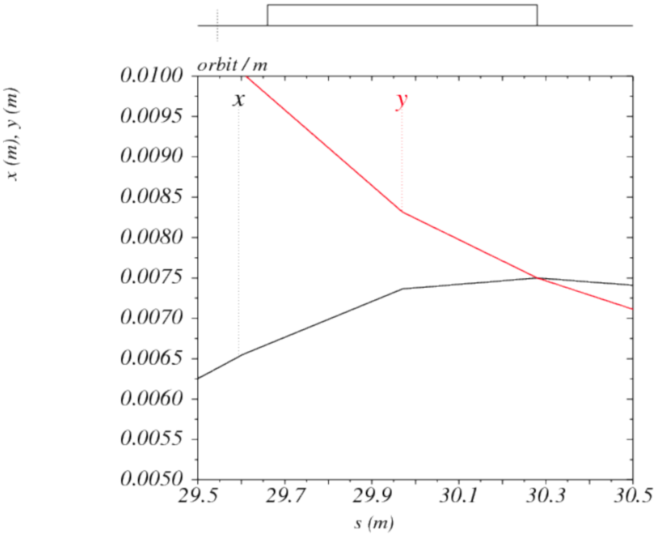
SIMULATION: BUMP



BEAM BASED ALIGNMENT

Derivation of formula for orbit change

$$\Delta x(s) = \left(\frac{\Delta k \cdot x(\bar{s}) l}{B\rho}\right) \left(\frac{1}{1 - k \frac{l\beta(\bar{s})}{2B\rho \tan \pi\nu}}\right) \frac{\sqrt{\beta(s)}\sqrt{\beta(\bar{s})}}{2 \sin \pi\nu} \cos(\phi(s) - \phi(\bar{s}) - \pi\nu)$$

- Δx = orbit change
- s = measurement position
- $\bar{s}$ = position of quadrupole
- Δk = change of quadrupole strength
- $x(\bar{s})$ = position of beam inside the quadrupole
- β = beta function
- ν = tune
- ϕ = betatron phase
- k = quadrupole strength
- l = length of quadrupole
- $B\rho$ = magnetic rigidity of the beam

BEAM BASED ALIGNMENT

Derivation of formula for orbit change

- Start with effect of a dipole kick θ on the orbit.

$$\Delta x(s) = \theta \times \frac{\sqrt{\beta(s)}\sqrt{\beta(\bar{s})}}{2\sin\pi\nu}\cos(\phi(s) - \phi(\bar{s}) - \pi\nu)$$

$$\theta = \frac{\Delta Bl}{B\rho}$$

- To first order a beam offset inside a quadrupole sees a change in quadrupole strength as a dipole kick.
- The change of the tune, beta function and betaton phase are effects of second order and can be neglected.

BEAM BASED ALIGNMENT

Derivation of formula for orbit change

- Quadrupole magnetic field is $B = kx$, thus

$$\Delta B = (k + \Delta k)(x + \Delta x) - kx = \Delta kx + \Delta xk + \mathcal{O}(\Delta k \Delta x)$$

- Combine the equations with $\bar{s} = s$ to get

$$\Delta x = \frac{(\Delta kx + \Delta xk)l}{B\rho} \frac{\beta}{2\sin \pi\nu} \cos \pi\nu$$

- and solve for Δx.

$$\Delta x = \Delta kx \frac{\frac{\beta l}{2B\rho \tan \pi\nu}}{1 - \frac{\beta l}{2B\rho \tan \pi\nu}}$$

BEAM BASED ALIGNMENT

Derivation of formula for orbit change

- With that calculate ΔB

$$\Delta B = \Delta k x \frac{1}{1 - k \frac{\beta l}{2B\rho \tan \pi\nu}}$$

- and insert that into the equation for θ and $\Delta x(s)$.

$$\Delta x(s) = \left(\frac{\Delta k \cdot x(\bar{s}) l}{B\rho} \right) \left(\frac{1}{1 - k \frac{l \beta(\bar{s})}{2B\rho \tan \pi\nu}} \right) \frac{\sqrt{\beta(s)}\sqrt{\beta(\bar{s})}}{2 \sin \pi\nu} \cos(\phi(s) - \phi(\bar{s}) - \pi\nu)$$