Closed Orbit Correction

Theme study problem no. 2

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The Given Problem

Closed orbit correction

Start from the lattice of Exercise 3 and assume random misalignments of the quadrupoles of r.m.s. 0.1 mm in the horizontal and 0.2 mm in the vertical plane. Calculate the expected r.m.s. orbit and verify with MAD-X. Add the necessary equipment to be able to correct the closed orbit in both planes. Estimate first the maximum necessary strength of the orbit correctors assuming a maximum quadrupole displacement of 1 mm. Use MAD-X to correct the orbit in both planes. What is the effect of the correction on the dispersion? Now remove the correction and repeat the exercise by adding a skew quadrupole. Power the skew quadrupole until you start to see the coupling between the horizontal and vertical orbits. Perform again the MAD-X orbit correction and compare the results with the uncoupled case.

Step Zero

Closed orbit correction

Start from the lattice of Exercise 3 and assume random misalignments of the quadrupoles of r.m.s. 0.1 mm in the horizontal and 0.2 mm in the vertical plane. Calculate the expected r.m.s. orbit and verify with MAD-X. Add the necessary equipment to be able to correct the closed orbit in both planes. Estimate first the maximum necessary strength of the orbit correctors assuming a maximum quadrupole displacement of 1 mm. Use MAD-X to correct the orbit in both planes. What is the effect of the correction on the dispersion? Now remove the correction and repeat the exercise by adding a skew quadrupole. Power the skew quadrupole until you start to see the coupling between the horizontal and vertical orbits. Perform again the MAD-X orbit correction and compare the results with the uncoupled case.

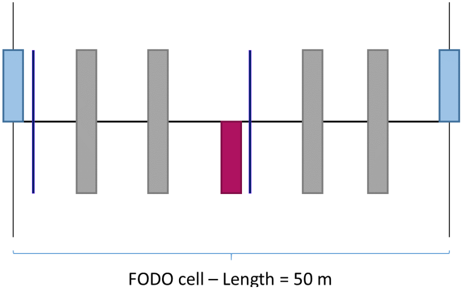
Step Zero: A quick recap of Exercise 3

Our machine:

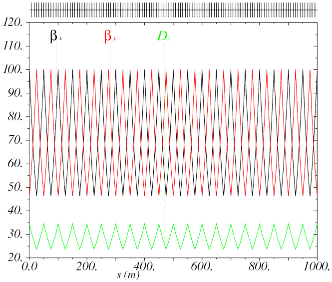
- Circumference of 1000 m
- 20 FODO cells
- Sextupoles for correcting chromaticity

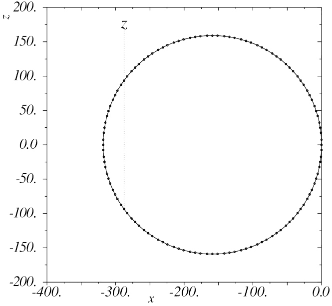
Designed for:

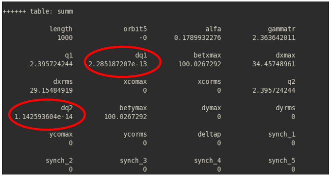
- Proton beams with energy of 20 GeV



Step Zero: Results from Exercise 3







++++++ table: summ

length	orbit5	alfa	gammatr
1000	-0	0.1789932276	2.363642011
q1	dq1	betxmax	dxmax
2.395724244	-2.285187207e-13	100.0267292	34.45748961
dxrms	xcomax	xcorms	q2
29.15484919	0	0	2.395724244
dq2	betymax	dymax	dyrms
1.142593604e-14	100.0267292	0	0
ycomax	ycorms	deltap	synch_1
0	0	0	0
synch_2	synch_3	synch_4	synch_5
0	0	0	0

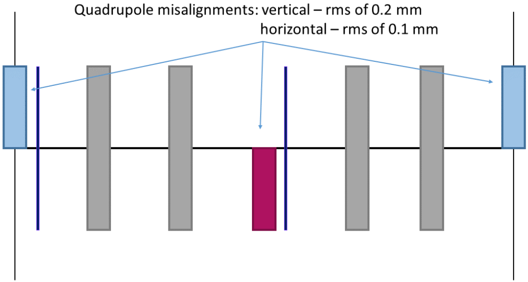
Step One

Closed orbit correction

Start from the lattice of Exercise 3 and assume random misalignments of the quadrupoles of r.m.s. 0.1 mm in the horizontal and 0.2 mm in the vertical plane. Calculate the expected r.m.s. orbit and verify with MAD-X. Add the necessary equipment to be able to correct the closed orbit in both planes. Estimate first the maximum necessary strength of the orbit correctors assuming a maximum quadrupole displacement of 1 mm. Use MAD-X to correct the orbit in both planes. What is the effect of the correction on the dispersion? Now remove the correction and repeat the exercise by adding a skew quadrupole. Power the skew quadrupole until you start to see the coupling between the horizontal and vertical orbits. Perform again the MAD-X orbit correction and compare the results with the uncoupled case.

Step One: Introduce alignment errors in quadrupoles

Misalign quadrupoles of each FODO cell randomly

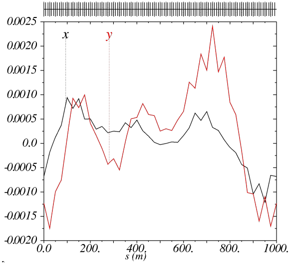


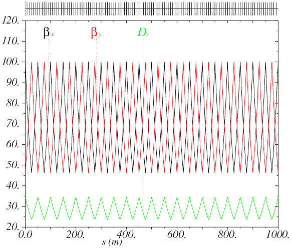
In MADX:

```
eoption,seed=62989;
select,flag=error,pattern="q.*";
ealign,dx:=tgauss(3.0)*0.1*1.0e-3,dy:=tgauss(3.0)*0.2*1.0e-3;
```

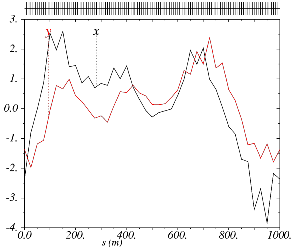
Step One: Changes due to misalignments

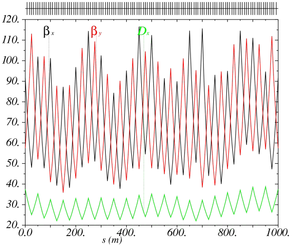
Misalignments on the order of 0.1 mm



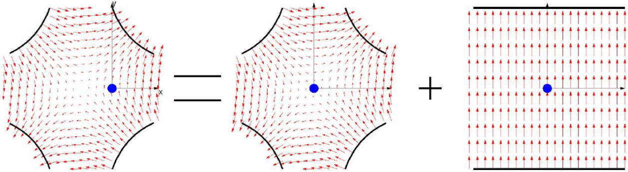


Misalignments on the order of 100 mm





Understanding what's going on...



An offset quadrupole is seen as a centered quadrupole plus a dipole.

Recap of transverse beam dynamics - H. Schmickler

Bigger are the misalignments, stronger will be the additional dipole kicks.

$$F_x = -k_q x \quad | \quad F_y = -k_q y$$

Step Two

Closed orbit correction

Start from the lattice of Exercise 3 and assume random misalignments of the quadrupoles of r.m.s. 0.1 mm in the horizontal and 0.2 mm in the vertical plane. Calculate the expected r.m.s. orbit and verify with MAD-X. Add the necessary equipment to be able to correct the closed orbit in both planes. Estimate first the maximum necessary strength of the orbit correctors assuming a maximum quadrupole displacement of 1 mm. Use MAD-X to correct the orbit in both planes. What is the effect of the correction on the dispersion? Now remove the correction and repeat the exercise by adding a skew quadrupole. Power the skew quadrupole until you start to see the coupling between the horizontal and vertical orbits. Perform again the MAD-X orbit correction and compare the results with the uncoupled case.

Step Two: Calculation of RMS value for the closed orbit

$$CO(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi Q)} \sum_i \sqrt{\beta_i}\theta_i \cos(\pi Q - |\phi(s) - \phi_i|)$$

with:

$$RMS\left(\sum_i \sqrt{\beta_i}\theta_i \cos(\pi Q - |\phi(s) - \phi_i|)\right) = \sqrt{\bar{\beta}}\theta_i^{RMS}\sqrt{2N_Q}$$

$$\theta_i^{RMS} = \text{ strength of kick } = x_{disp}^{RMS} K_Q L_Q$$

$$RMS(CO(s)) = \frac{\bar{\beta}}{2\sin(\pi Q)} x_{disp}^{RMS} K_Q L_Q \sqrt{2N_Q}$$

Step Two: RMS value of closed orbit

Calculated RMS value:

$$x^{RMS} = 4.4 \times 10^{-4} m$$
$$y^{RMS} = 8.8 \times 10^{-4} m$$

Confirmation with MADX:

$$x^{RMS} = 4.9 \times 10^{-4} m$$
$$y^{RMS} = 10.1 \times 10^{-4} m$$

```
++++++ table: summ

         length             orbit5               alfa            gammatr
           1000                 -0       0.1789930965        2.363642876

             q1                dq1            betxmax              dxmax
    2.395717531   -6.902595533e-06        100.0428412        34.45870438

          dxrms             xcomax             xcorms                 q2
     29.3087879     0.001277501335    0.0004947344599        2.395749048

            dq2            betymax               dymax              dyrms
 1.462626543e-05         100.039852      0.00241113148     0.001013606388

         ycomax             ycorms             deltap            synch_1
 0.002515516812     0.001012452211                  0                  0

        synch_2            synch_3            synch_4            synch_5
              0                  0                  0                  0
!plot, haxis=s, vaxis=betx, bety, dx, colour=100;
```

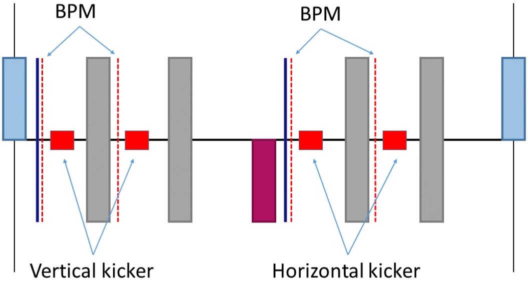
Step Three

Closed orbit correction

Start from the lattice of Exercise 3 and assume random misalignments of the quadrupoles of r.m.s. 0.1 mm in the horizontal and 0.2 mm in the vertical plane. Calculate the expected r.m.s. orbit and verify with MAD-X. Add the necessary equipment to be able to correct the closed orbit in both planes. Estimate first the maximum necessary strength of the orbit correctors assuming a maximum quadrupole displacement of 1 mm. Use MAD-X to correct the orbit in both planes. What is the effect of the correction on the dispersion? Now remove the correction and repeat the exercise by adding a skew quadrupole. Power the skew quadrupole until you start to see the coupling between the horizontal and vertical orbits. Perform again the MAD-X orbit correction and compare the results with the uncoupled case.

Step Three: Inserting monitors and correctors

Beam position monitors and kickers were inserted in each FODO cell for misalignment corrections.



Step Four

Closed orbit correction

Start from the lattice of Exercise 3 and assume random misalignments of the quadrupoles of r.m.s. 0.1 mm in the horizontal and 0.2 mm in the vertical plane. Calculate the expected r.m.s. orbit and verify with MAD-X. Add the necessary equipment to be able to correct the closed orbit in both planes. Estimate first the maximum necessary strength of the orbit correctors assuming a maximum quadrupole displacement of 1 mm. Use MAD-X to correct the orbit in both planes. What is the effect of the correction on the dispersion? Now remove the correction and repeat the exercise by adding a skew quadrupole. Power the skew quadrupole until you start to see the coupling between the horizontal and vertical orbits. Perform again the MAD-X orbit correction and compare the results with the uncoupled case.

Step Four: Estimation of maximum kicker strength

Calculation for max. displacement of 1.0 mm:

$$\theta_i^{MAX} = x_{disp}^{MAX} K_Q L_Q$$

$$\theta_i^{MAX} = 0.0294 \quad \text{mrad}$$

Confirmation with MADX:

$$\theta_i^{MAX} = 0.0294 \quad \text{mrad} \checkmark$$

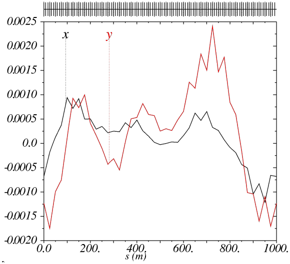
Step Five

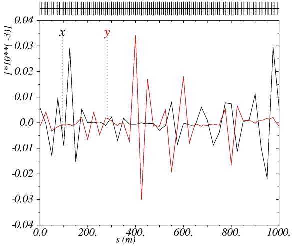
Closed orbit correction

Start from the lattice of Exercise 3 and assume random misalignments of the quadrupoles of r.m.s. 0.1 mm in the horizontal and 0.2 mm in the vertical plane. Calculate the expected r.m.s. orbit and verify with MAD-X. Add the necessary equipment to be able to correct the closed orbit in both planes. Estimate first the maximum necessary strength of the orbit correctors assuming a maximum quadrupole displacement of 1 mm. Use MAD-X to correct the orbit in both planes. What is the effect of the correction on the dispersion? Now remove the correction and repeat the exercise by adding a skew quadrupole. Power the skew quadrupole until you start to see the coupling between the horizontal and vertical orbits. Perform again the MAD-X orbit correction and compare the results with the uncoupled case.

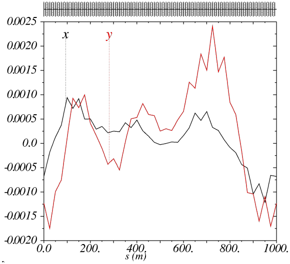
Step Five: Correction with BPMs & kickers (MICADO)

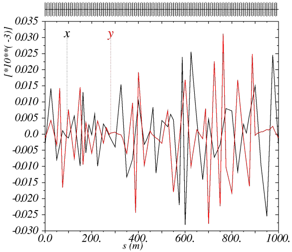
2 BPMs & 2 kickers per cell ($CO-X_{RMS}$ & $CO-Y_{RMS} \approx 10^{-6}$)





4 BPMs & 4 kickers per cell ($CO-X_{RMS}$ & $CO-Y_{RMS} \approx 10^{-6}$)





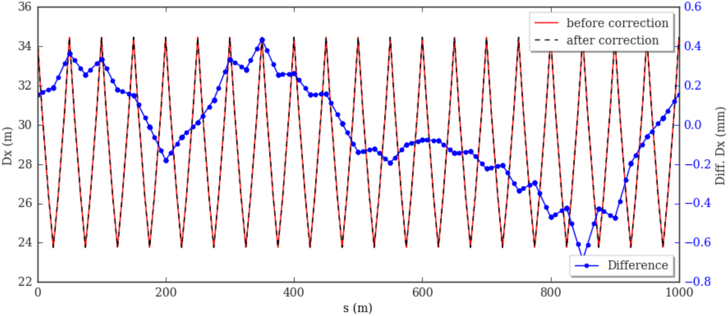
Step Six

Closed orbit correction

Start from the lattice of Exercise 3 and assume random misalignments of the quadrupoles of r.m.s. 0.1 mm in the horizontal and 0.2 mm in the vertical plane. Calculate the expected r.m.s. orbit and verify with MAD-X. Add the necessary equipment to be able to correct the closed orbit in both planes. Estimate first the maximum necessary strength of the orbit correctors assuming a maximum quadrupole displacement of 1 mm. Use MAD-X to correct the orbit in both planes. What is the effect of the correction on the dispersion? Now remove the correction and repeat the exercise by adding a skew quadrupole. Power the skew quadrupole until you start to see the coupling between the horizontal and vertical orbits. Perform again the MAD-X orbit correction and compare the results with the uncoupled case.

Step Six: Effect of alignment corrections on dispersion

The dispersion (Dx) changes only a little due to alignment corrections. The change is negligible.



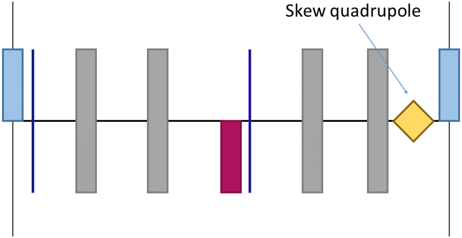
Step Seven

Closed orbit correction

Start from the lattice of Exercise 3 and assume random misalignments of the quadrupoles of r.m.s. 0.1 mm in the horizontal and 0.2 mm in the vertical plane. Calculate the expected r.m.s. orbit and verify with MAD-X. Add the necessary equipment to be able to correct the closed orbit in both planes. Estimate first the maximum necessary strength of the orbit correctors assuming a maximum quadrupole displacement of 1 mm. Use MAD-X to correct the orbit in both planes. What is the effect of the correction on the dispersion? Now remove the correction and repeat the exercise by adding a skew quadrupole. Power the skew quadrupole until you start to see the coupling between the horizontal and vertical orbits. Perform again the MAD-X orbit correction and compare the results with the uncoupled case.

Step Seven: Adding a skew quadrupole

BPMs and Kickers were switched off and a skew quadrupole was added in each FODO cell.



Quadrupole tilt: 0.2 rad. (11.46 deg.)

Step Eight

Closed orbit correction

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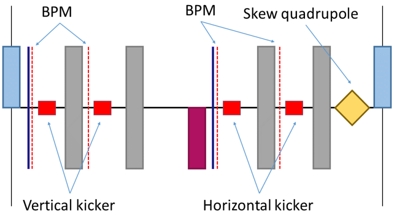
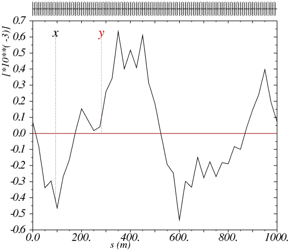
Step Eight: Coupling b/w hor. & ver. planes

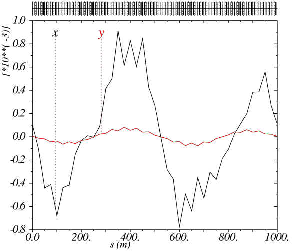
By adding a skew quadrupole, we obtain a coupling between the x and y planes. Introducing a misalignment in x automatically introduces an error in y.



Without skew quads.



With skew quads.



Step Nine: The last step

Closed orbit correction

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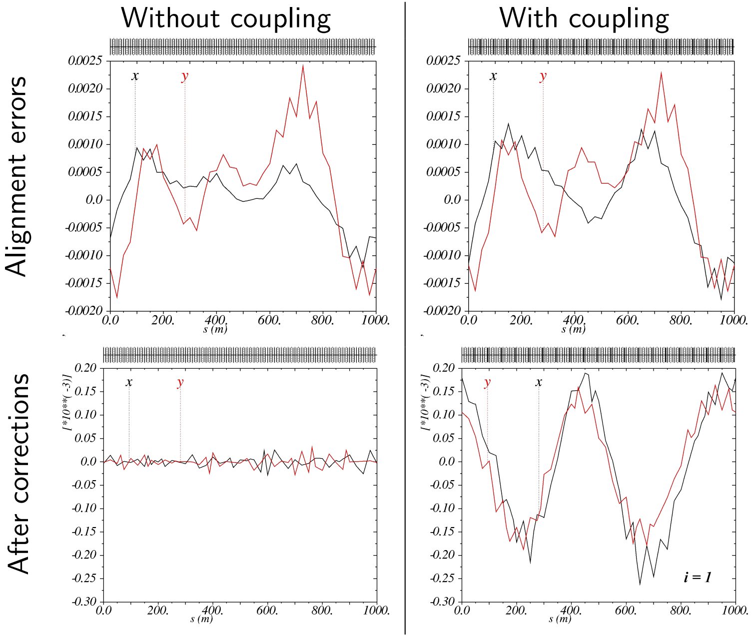
Step Nine: MAD-X orbit correction comparison



Any questions/comments?