Emittance preservation techniques in a linear accelerator

Obligatory Exercise, FYS4550/9550, Fall 2016

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1 Description

In this project the students will design a small linear accelerator, with similar structure to the ones to be used in a linear electron-positron collider. In order to generate enough luminosity, the beams in a linear collider must be very small at the interaction point. This implies that both the beam focusing (beta function) and the beam quality (emittance) must be very small. Preservation of very small beam emittance all the way to the interaction point is one of the key challenges in linear collider design.

The students will investigate the deterioration of beam emittance as the lattice elements are misaligned. The students will apply two different steering techniques and investigate how the emittance preservation is improved by applying these techniques. The two steering techniques to be studies are 1-to-1 steering and dispersion-free steering.

The project can be performed in groups of one, two or three students.

2 Reading list

I "Experimental demonstration of a global dispersion-free steering correction at the new linac test facility at SLAC", A. Latina et al. (http://journals.aps.org/prstab/pdf/10.1103/PhysRevSTAB.17.042803)

II "Estimates of emittance dilution and stability in high-energy linear accelerators", T.O. Raubenheimer (http://journals.aps.org/prstab/pdf/10.1103/PhysRevSTAB.3.121002)

III "A dispersion-free trajectory correction technique for linear colliders", T.O. Raubenheimer & R.D. Ruth (http://www.sciencedirect.com/science/article/pii/016890029190403D)

IV "A Study of the Beam Physics in the CLIC Drive Beam Decelerator", E. Adli (http://inspirehep.net/record/887068/files/CERN-THESIS-2010-024.pdf)

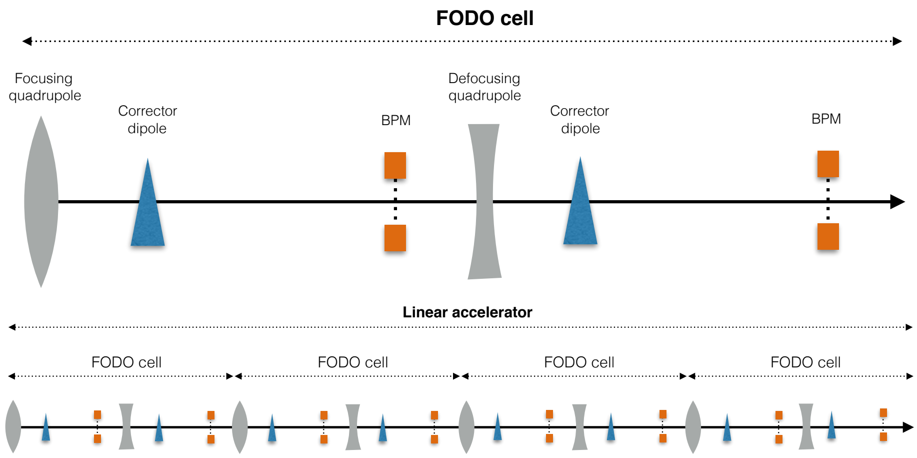

Figure 1: Schematic of the MADX accelerator lattice, consisting of 4 FODO-cells. There are 8 quadrupoles, 8 beam position monitors (BPM) and 8 corrector dipoles.

3 Requirements

Students must have access to the accelerator optics code MADX. We have provided auxiliary scripts in MATLAB format. The recommended language for analysis is therefore MATLAB. However, script languages similar to MATLAB, like Octave or Python may be used (some modification to the provided scripts is required).

4 Exercises

4.1 Linear collider emittance requirements

1. What are the beam parameters of the Compact Linear Collider (CLIC), at the interaction point (3 TeV version)?
2. Describe, briefly, some of the most important sources of emittance growth in the CLIC main linac.

4.2 Twiss parameters and emittance

1. What is the relation between geometric emittance ϵ and normalized emittance ϵ_N? How do they change as the beam is accelerated?
2. What is the relation between the phase space variables $(x,\, x')$ and the Twiss parameters $(\beta_x,\, \alpha_x,\, \gamma_x)$?
3. Write down expressions for the Twiss parameters and the geometric emittance of a beam with a discrete number of particles N and phase space $\{x_n,\, x'_n\}$.

4.3 Emittance growth

In the rest of the exercise we will simulate a beam with the following parameters:

- 1 GeV electrons
- 10 μm rad normalized emittance in both planes
- 1% rms relative energy spread
- 1000 particles to represent the beam (or more for higher accuracy)
- We assume that the beam charge is so small that collective effects are insignificant. In this case the results do not depend on beam charge.

The provided MADX script tracks this particle beam through the lattice shown in Figure 1. The particle beam is matched to the entrance of the FODO lattice. Note that MADX must be executed after every parameter change. You might also need to run `addpath('get','set')` to access the predefined MATLAB functions.

1. Get the scripts running and track a beam [`runMADX()`].
2. Load the initial beam with MATLAB [`getInitialBeam()`]. The beam is characterized by the 6D phase space distribution (x, x', y, y', z, σ_E/E).
3. Calculate the rms normalized emittance of the input beam from the phase space distribution. Verify that your number coincide with the input parameters (10 μm rad). Expect a relative error of order $1/\sqrt{N}$, where N is the particle number, due to statistical fluctuation.
4. Calculate the TWISS parameters (β_x, β_y, α_x, α_y) for the input beam. Verify that this is the same as the FODO-matched solution (as printed in the MADX output). Again, expect a relative error around $1/\sqrt{N}$.
5. A beam position monitor (BPM) measures the centroid of the beam position ($\bar{x}$, $\bar{y}$). Plot the beam orbit ($\bar{x}$, $\bar{y}$ vs. s) as measured in the BPMs, using [`getBPMreadings()`].
6. Introduce quadrupole misalignments [`setQuadMisalignments()`], with a 1 mm rms offset. Plot the new BPM orbit.
7. How is the dispersion function of an accelerator beam line defined? Calculate the dispersion function by first tracking a beam with the nominal energy, then by tracking a beam with a slightly different energy. Compare the dispersion you have calculated with the dispersion as printed in the MADX output file (`plots.ps`).
8. Set the energy spread in the input beam to zero [`setEnergySpread()`]. Plot the relative emittance growth ($\Delta\epsilon/\epsilon$) at the end of the lattice as a function of quadrupole misalignment (ranging from 0 to 2 mm).
9. Introduce an energy spread (1% rms). Replot emittance growth as function of quadrupole misalignment.
10. Explain the observed emittance growth for 0% and 1% energy spreads.

11. Change the quad strength (k) of the FODO-cells [`setQuadStrength()`]. What effect does this have and why? Is there a change in emittance growth?

12. (Optional) Attempt to estimate the emittance growth due to dispersion analytically. First, estimate the emittance increase in a beam, with a given beta function, as function of the dispersion. Then, estimate the dispersion growth in a lattice for a given rms quadrupole misalignment. Section VIII b in Reference II has detailed derivation of how emittance growth due to misalignments may be calculated in a more rigorous manner (however, we do not expect you to derive the equations in Reference II as part of this exercise).

4.4 Correction algorithms

Reference IV describes the 1-to-1 steering (Section 5.5.3) and dispersion free steering (Section 5.5.4) techniques. We will assume noise-free/ideal BPMs ($w_0 = 0$ in Reference IV Eq. (5.28)), and keep the energy spread of the beam at 1%. Note that it is sufficient to work in one plane, e.g. x only.

1. Correct the beam orbit by adjusting the corrector magnets [`setKickers()`] according to 1-to-1 steering (use `getResponseMatrix()` to calculate the response matrix). Plot uncorrected and 1-to-1 corrected BPM orbits.

2. Plot emittance growth vs. quadrupole misalignment for both uncorrected and 1-to-1 steered orbits.

3. Introduce BPM misalignments [`setBpmMisalignments()`] (1 mm rms). Replot uncorrected and 1-to-1 corrected BPM orbits.

4. Replot emittance growth vs. quadrupole misalignment for both uncorrected and 1-to-1 steered orbits. Explain the effect of BPM misalignments.

5. Dispersion-free steering (DFS) can be used to find an orbit that gives less emittance growth than steering through the centers of the BPMs. Correct the beam orbit by adjusting the corrector magnets according to dispersion-free steering (still with quadrupole and BPM misalignments). Plot uncorrected and DFS corrected BPM orbits.

6. Plot emittance growth vs. quadrupole misalignment for both uncorrected and DFS corrected orbits.

7. Plot emittance growth vs. BPM misalignment for uncorrected, 1-to-1 and DFS corrected orbits. Explain the observed behavior.

8. (Optional) The BPM signals in the MADX simulation have no noise, except the effects of representing a beam with only 1000 particles. Add simulated noise to the BPM signals, to represent a finite BPM resolution. You can do this either by using MADX commands, or "by hand" in your MATLAB scripts. Comment on how the BPM resolution influences the results of the dispersion free steering.