JUAS'22 Accelerator Design Workshop: Exercises

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1 Timetable

JUAS slots with lectures introducing the mini-workshop:

- Thursday, 27 January, 14:15 to 17:00
- Friday, 28 January, 14:15 to 17:00

JUAS slots to work on exercise set:

- Monday, 31 January, 13:15 to 15:00
- Tuesday, 1 February, 13:15 to 15:00
- Wednesday, 2 February, 13:15 to 15:00
- Thursday, 3 February, 13:15 to 15:00
- Friday, 4 February, 13:15 to 16:00

$\Longrightarrow$ finish presentation slides for your group until the exam.

Exam: marked presentations follow during the morning on Monday, 7 February. Every group will present their results to the jury. Slides should be prepared such that students working on other aspects of the machine could understand: selected groups will repeat their presentation during the workshop conclusion (afternoon at 13:00).

2 Introduction

The goal of this mini-workshop is to apply the knowledge gained during this school to a realistic problem. The task is to design a particle accelerator with certain specifications and boundary conditions. The idea is to gain experience how such a big task is tackled and organised. There are ten groups of three to four students each. We assigned three topics, that look at the same problem from slightly different angles and with different emphasis.

Scope: design a top factory for precision measurements. Design a particle collider for precision measurements of the top quark mass at the $t\bar{t}$-threshold. The circumference must not exceed 100 km and the maximum synchrotron radiation power is limited to 50 MW per beam. Per year at least 100000 $t\bar{t}$ pairs should be produced for sufficient statistics.

3 Topic III: Lattice Design

3.1 Exercise summary

1. Design basic cell according to beam requirements
2. Implement a MAD-X model of your basic cell, close the ring and calculate SR integrals and equilibrium beam parameters
3. Include dispersion suppressors and straight sections to your model and match optics
4. Include RF cavities and calculate equilibrium beam parameters with MAD-X
5. Optional: include mini-beta insertion and match optics.

3.2 Exercises

This group focuses on the lattice design of a new accelerator. A lattice is being developed to match a pre-defined set of requirements.

1. Assume following boundary conditions:
   (a) Beam energy: $E = 175\,\mathrm{GeV}$
   (b) Horizontal equilibrium emittance: $\epsilon_x = 1.3\,\mathrm{nm\,rad}$
   (c) Damping partition number: $J_x = 1$
   (d) A maximum circumference of $100\,\mathrm{km}$
   (e) Maximum synchrotron radiation power: $P = 50\,\mathrm{MW}$ per beam
   (f) The basic cell should have the same phase advance in both planes.
2. Design of basic arc cell
   (a) What lattice type do you choose for your basic cell, and why?
   (b) What phase advance per cell do you choose, and why?
   (c) Think about the layout of your basic cell: cell length, length of magnetic elements, dipole filling factor. *Hint:* start with a cell length in the range from $50\,\mathrm{m}$ to $60\,\mathrm{m}$.
   (d) Calculate the bending angle for your dipoles in order to match the required equilibrium emittance. The equilibrium emittance can be approximately calculated using following equation:

$$\epsilon_x = \frac{C_\mathrm{q}}{J_x}\gamma^2\theta^3 F \tag{1}$$

   $C_\mathrm{q} = \frac{55}{32\sqrt{3}}\frac{\hbar c}{m_0 c^2} = 3.832 \times 10^{-13}\,\mathrm{m}$, $J_x \approx 1$ is the damping partition number, γ the Lorentz factor, and θ the bending angle of all dipole magnets in a half-cell. For a FODO cell with phase advance μ the factor F can be written as

$$F_\mathrm{FODO} = \frac{1}{2\sin\mu}\frac{5 + 3\cos\mu}{1 - \cos\mu}\frac{L}{l_\mathrm{B}}. \tag{2}$$

   L is the cell length and l_b is the length of all dipole magnets in the cell.
   (e) Calculate the quadrupole strength k_1 using

$$\sin\left(\frac{\mu}{2}\right) = \frac{L}{4f} \qquad \text{and} \qquad \frac{1}{f} = k_1 L_Q \tag{3}$$

   where L_Q is the length of the quadrupole magnets.

(f) Define the elements and the basic cell in MAD-X. Set up an MAD-X environment (define beam etc.) and implement your basic cell using thick lenses. Advice: Use sequences, not lines! Check the tunes in the TWISS summary table. Do they fit your expectation?

(g) Match the phase advance of your basic arc cell. Compare the maximum and minimum values of beta functions and dispersion of MAD-X to the analytically calculated values.

(h) Match the chromaticity of your basic arc cell to zero. Can you explain why the sextupole strengths for the "defocusing" sextupole are larger than for the "focusing" one?

(i) Build a full ring with your basic cells. How many cells do you need to close the ring? Do the tunes fit your expectation? Check if the ring is closed (`SURVEY` command).

```
survey;
value, table(survey,yourSequence$END,theta);
```

(j) Calculate the synchrotron radiation integrals (`TWISS, chrom;`). Proceed to calculate equilibrium emittance and energy loss per turn and compare to the requirements.

3. Dispersion suppressors and straight sections

   (a) Design a dispersion suppressor section for your storage ring and implement it in MAD-X. What scheme do you use and why? Why is it not possible to use the identical section on both sides of an arc?

   (b) Define a straight cell for the straight sections.

   (c) Define matching sections for the beginning ("MSL") and the end ("MSR") of your straight sections. Why do you need matching sections? How many parameters do you need to match? How many degrees of freedoms (=quadrupoles) do you need? Match the optics.

   (d) Include straight sections at four places in your ring.

   (e) Observe tunes and chromaticities. Do they match your expectation? Re-match tunes and chromaticities.

   (f) Calculate and save the synchrotron radiation integrals of your storage ring for analytical calculations later

4. RF sections

   (a) Estimate the total RF voltage which is needed to compensate the synchrotron radiation energy loss. The energy gain in the cavity is given by

$$U = eV_{\mathrm{RF}} \sin\left(2\pi(\phi - hf_0 t)\right), \tag{4}$$

   where ϕ is the phase lag ("synchronous phase"), h the harmonic number of the ring, and f_0 the cavity frequency.

   (b) Define a straight cell and straight section that contains RF cavities.

   (c) Switch on radiation and observe tunes and chromaticities. Can you explain what happens?

   (d) Observe the transverse orbit. Can you explain the pattern you see?

   (e) Calculate equilibrium beam parameters with the MAD-X `EMIT` command and compare them to the analytical values from the calculation using the synchrotron radiation integrals calculated above.

   (f) How many particles and bunches can you fill into the rings before you reach the limit of synchrotron radiation power?

5. If time permits: mini-beta insertions

   (a) Calculate the required values for β^* or get them from colleagues (groups working on the general parameters topic I).

   (b) Include two mini-beta insertions into your model and match the optics.

   (c) How do you distribute the mini-beta insertions and why?