Preface

The purpose of this tutorial is to think about a Conceptual Design Study (CDS) for a proposed new machine.
A few performance parameters are given and the basic building blocks for this machine with a feasible and realistic layout and related parameters should be defined. The necessary knowledge is acquired from the lectures as the school proceeds. Of course a formal, unique solution to this exercise does not exist. There will be many alternative solutions for such a design. It is rather expected to discuss the arising issues with other participants, tutors and lecturers during the school to arrive at a proposal.
The main objectives are to touch upon the strategies how the different steps and exercises are attacked and how the material of the lectures is put into practice. Some steps in the design build upon previous steps.
During the final tutorial session just before the end of the school the outcome and possible difficulties and other issues can be discussed in the small tutorial groups together with a tutor.

General comments:

- Please choose "reasonable" parameters as input for the thoughts and computations. Take into account implications for engineering (geometry and symmetry).
- Not for all systems the details have to be worked out, an educated estimate is sufficient (and even encouraged). A concept for further required studies should be established.

  Organize yourself within small groups to work on the specific topics.

Outline

The design should follow different stages, divided into topics. Several of the topics can be worked out independently (not all of them), while others depend on previous deliberations.

1. General considerations
   - Layout and choice of the machine
2. Basic systems, beam dynamics and components:
   - Bending, layout and dipoles
   - Focusing, Quadrupoles
   - RF system (frequency, frequency swing, ...)
3. Machine performance:
   - Luminosity
   - Synchrotron radiation
   - Multiparticle effects
4. Overall layout:
   - Injector chain
5. Operational considerations:
   - Instrumentation and diagnostics
   - Control of machine parameters

1 Topic 1a (Lattice I):

1.1 Problem:

Consider a machine for proton-proton collisions (collider) :

- Circumference C = 60 km, Centre of Mass Energy 40 TeV
- Energy at Injection 4 TeV
- Maximum β in the arc $\approx$ 300 m in <u>both</u> planes
- Length of available dipoles 10 m

Find a consistent set of parameters assuming it is made only of FODO cells, using only the given constraints.
Ignore the need for insertions at this stage.
First assume that the focusing and defocusing quadrupoles have the same strengths.

- Parameters to estimate (recommendation $\Rightarrow$ in this order): m
  - A first estimate for the strengths of dipoles
  - Maximum and minimum β in the arc
  - Phase advance per cell
  - Length and number of cells
  - Tunes of the machine
  - Number of dipoles per cell
  - Optional: chromaticity, momentum compaction (α_c) and average $\bar{\beta}$

Remark: please use reasonable numbers, i.e. ring should have an integer number of cells, not a fraction of a cell etc., take into account possible periodicity to make your life simple (e.g. 4, 6, 8, ..).

Reminder:
For a FODO cell with phase advance ϕ and a cell length L we have for the maximum and minimum β within the cell (see lecture on transverse dynamics):

$$\hat{\beta} \;=\; L \;\cdot\; \frac{1 + sin(\phi/2)}{sin(\phi)} \;=\; L_{1/2} \;\cdot\; \frac{1 + sin(\phi/2)}{sin(\phi/2) \cdot cos(\phi/2)} \tag{1}$$

and

$$\check{\beta} \;=\; L \;\cdot\; \frac{1 - sin(\phi/2)}{sin(\phi)} \;=\; L_{1/2} \;\cdot\; \frac{1 - sin(\phi/2)}{sin(\phi/2) \cdot cos(\phi/2)} \tag{2}$$

2 Topic 1b (Lattice II):

2.1 Problem:

For discussion, calculation not needed:

(a): In exercise 1a we have assumed that the strengths of focusing and defocusing quadrupoles are the same.

- What happens if they are different, e.g. defocusing quadrupoles are 0.5% weaker and the focusing quadrupoles 0.5% stronger ?
- Is it possible ?
- Can you think of a reason (or reasons) to do that ?

Please discuss with colleagues, lecturers and tutors, try an estimate.

(b): How can you compute and control the beam emittance with the optical parameters ?

Consider two cases:

1. With protons like in our case
2. What changes for electrons ?

3 Topic 2 (RF system):

3.1 Problem:

Consider the previous pp collider and design a RF system:

- Assume an acceleration from 4 to 20 TeV in 10 minutes
- r.m.s. bunch length $\sigma_s = 0.06$ m
- use exact speed of light for calculations: 299792458 m/s

Find a consistent and realistic set of parameters to fulfill the given constraints.

- Parameters to find:
  - RF frequency
  - Harmonic number
  - Frequency change during acceleration (hint: look at lecture on relativity), how to realize it ?
  - Energy gain per turn per proton during acceleration
  - Minimum RF voltage

4 Topic 3 (luminosity):

4.1 Problem:

Hint: For this exercise please use the simplified luminosity formula introduced in the lecture "Introduction to Accelerators". The intricate subtleties, technical details and problems are discussed in a dedicated lecture towards the end of the school.
As a reminder, the formula is:

$$L = \frac{kN_1N_2f}{4\pi\sigma_x\sigma_y}$$

with:
k: number of colliding bunches
N_1, N_2: particles per bunch
f: revolution frequency
σ_x, σ_y: horizontal and vertical beam sizes

Consider a pp collider with the following constraints:

- Minimum distance between bunches 15 m (to allow space for experiments)
- Maximum beam power 500 MJ
- Number of collisions per bunch crossing (μ) not larger than 4
- Hints:
  - define luminosity per bunch
  - total cross section at 40 TeV is $\approx$ 80 mbarn ($\approx 80\ 10^{-27}$ cm^2)

Find a consistent set of parameters to obtain the required luminosity within the given constraints.

- Parameters to find:
  - Number of bunches
  - Luminosity
  - Number of protons per bunch
  - Possible parameters for β^* and ϵ_n (reasonable guesses, there are many possible solutions)

5 Topic 4 (Geometrical aperture):

5.1 Problem:

Consider the previous pp collider and re-assess the parameters:

- Maximum beam size in the arc: r.m.s. 0.5 mm

Find a consistent set of parameters to obtain the required constraints.

- Parameters to find:
  - Maximum emittance ϵ_n
  - Related β^*

These constraints will complete the set of parameters needed for the previous exercise.

6 Topic 5 (Synchrotron radiation):

6.1 Problem:

Consider the previous pp collider and evaluate effect of synchrotron radiation:

- Parameters to find:

  Energy loss per turn per proton

  Power loss per proton (in W)

  Power loss for full beam (in W)

7 Topic 6 (Collective effects):

Collective effects may limit the machine performance. Discuss and/or estimate effects in the collider at top energy:

(a) Is the direct space charge an issue ? What is the effect on the beam ? Can it also be useful ?

(b) The impedances of the machine can be complex. What are the effects of the real and the imaginary part ? Can the imaginary part be measured ? If yes, what can be a possibility ?

(c) To stabilize the beam, chromaticity might have to be controlled, what should be the sign of the chromaticity:

   (c1) At injection energy ?

   (c2) At top energy ?

   (c3) When do we have to change the sign ?

8 Topic 7 (Accelerator chain):

The protons cannot be accelerated from rest energy (particle source !) to the final energy in a single accelerator.
Please discuss the following issues, where possible, make rough estimates:

- What are the limitations to the energy range of a proton accelerator ?
- How would a possible chain look like ?
- Propose a chain with energy range and accelerator type
- What are implications for the parameters for the collider ?

9 Topic 8 (Operational considerations):

The operational needs to be considered from the first design and defines some of the specifications.

1. Machine control:

Discuss how some critical parameters can be controlled.

- (a) Orbit:
  - How can it be measured ?
  - Which elements can be used to control it ?
  - How many of these elements would you suggest ?
- (b) Tune:
  - How can it be measured ?
  - How can the horizontal tune be changed (vertical should be kept as it is) ?
- (c) Chromaticity:
  - How can it be measured ?
  - Which elements can be used to control it ?
  - How many of these elements would you suggest ?

2. Machine optimization:

A requirement from experiments: 10 events per run for a process with a cross-section of 0.385 pbarn.

Assuming previous parameters and an exponential decay of the luminosity with a lifetime (1/e) of $\tau = 15$ hours, what is the required length T_r of a run ?
This is required as input for the design of auxiliary systems, such as cooling, vacuum, machine protection ...