Notes for CAS IET Erice Case Study Course 2017

Lepton Case Studies:

A. Design a top-up injection system for an high-energy circular collider, e.g. FCC-ee
B. Design an injection system for a synchrotron light source, e.g. SLS

Hadron Case Studies:

C. Design an injection system for an high-energy circular collider, e.g. FCC-hh
D. Design a fast extraction system for an high-energy circular collider, e.g. FCC-hh

A: Design a top-up injection system for an high-energy circular collider, e.g. FCC-ee

FCC-ee, a 100-km-scale electron-positron collider, aims at very high luminosity and thus necessitates top-up injection to comply with short beam lifetime due to fast and continuous particle losses arising from collisions. The injection scheme must be highly robust, including a requirement of high injection efficiency ideally 100%. A full energy booster, which accelerates injection beams to the collider beam energy, is to be installed into the same tunnel as the collider.

Table of basic parameters:

Four operation modes are foreseen in FCC-ee at various beam energies (45.6, 80, 120 and 175 GeV/beam). The horizontal emittance of the stored beam scales with the beam energy, i.e. $\varepsilon_h \propto E^2$. Therefore, the most difficult case for the injection would be the operation mode with 175 GeV beams with the largest horizontal emittances and the highest magnetic rigidity. We may look into the injection for the 175 GeV operation mode. The injection is challenged by small dynamic aperture, which is limited by the tight optics at the interaction points. The parameters relevant to the injection design are listed below. Some parameters for the 45.6 GeV operation mode are also show for failure scenario considerations.

Parameter	**Typical value**
Circumference [m]	100 km
Beam energy [GeV]	175 (45.6)
Number of bunches / beam	81 (30180)
Bunch population	1.7e11 (1.0e11)
Horizontal emittance, rms [nm]	1.3
Energy spread of Collider/Booster beam, rms [%]	0.17/0.14
Peak luminosity [10^{34} cm^{-2} s^{-1}]	1.3
Beam lifetime [h]	~1
Dynamic aperture	15σ at nominal energy
Momentum acceptance	±2% (5σ dynamic aperture at δ=±2%)
Number of beams	2 (Electron and Positron)*

* The collider consists of two symmetric rings. Therefore, an injection design for electron beam is also valid for positron beam.

Injection straight:

In the collider ring, about 1.5 km straight section is available for the injection.

A-1: Overview and injection scheme

1) How often should top-up injection be repeated to reasonably suppress the integrated luminosity loss?

Note: Luminosity $\propto N_{e^+}N_{e^-}$, and Number of particle $N(t) = N_0 e^{-(t/\tau)}$

2) Consider the conventional injection scheme
3) What are the ring optics parameters (Beta function and Dispersion) required or suitable for the injection?
    a. Assume that the septum thickness is 3~5 mm.
    b. Assume that beta function can be arbitrarily set between 10 m ~ a few km. This assumption is justified for the long straight section available.
       (Normalised dispersion Dispersion/sqrt(Beta) may be limited to <0.05 $m^{-1/2}$ in case where Synchrotron phase space injection is applied.)
    c. What are the optimum parameters for the injection beam?

A-2: Hardware considerations

1) What are the requirements for kickers and septa? Connected to A-1 (1)
2) Design kickers and/or septa
3) Discuss stored beam stability vs. kicker stability

A-3: Failure scenario considerations (if time permits)

1) What is the stored energy of the beams in the collider?
2) Is the stored energy critical or not for failure scenario?
3) Discuss failure scenarios:
    i. List possible failures, what happens if kickers fail for example, where the injection and stored beams go then, etc.

B: Design a top-up injection system for a light source, e.g. SLS

Top-up injection is highly important for light sources to achieve maximum and constant photon beam flux. At the same time, the highest beam stability is achieved when the thermal load is kept constant with a constant electron beam current; photons emitted around the ring dissipate energy to the accelerator components.

Table of basic parameters:

The parameters of SLS relevant to the injection design are listed below.

Parameter	**Typical value**
Circumference [m]	288
Beam energy [GeV]	2.4
Beam current [mA]	400~402
Number of bunches / beam*	390 (out of 480 rf buckets)
Hor./Ver. emittance, rms [nm]	5.5/0.01 (Energy spread ~0.1%)
Injection beam horizontal emittance [nm]	9
Beam lifetime [h]	8
Dynamic aperture [mm]	~15
Septum thickness [mm] / length [m] / field [T]	3 / 0.8 / ~0.9
Length of injection straight [m]	~10
Hor. beta function in the middle of straight section [m]	4.5
Hor./Ver. betatron tune	20.43 / 8.74

* Top-up injection is performed bunch by bunch, and thus the number of bunches may not be relevant.

Injection scheme:

SLS has been in operation with a top-up injection based on the conventional injection scheme. Although the injection components are well tuned and the disturbance to the stored beam is minimized to about 10 μm, applying multipole kicker injection to SLS would be an interesting option. The septum currently installed will be reused.

B-1: Overview and injection scheme

1) Consider to apply multipole kicker injection scheme within the straight section of 10 m
2) Find kicker specifications:
   i. *Assume to use a sextupole kicker*
   ii. *How much is the required kick angle? Take into account the stored and injection beam sizes, and the septum thickness.*

Note: Beta function is represented as $\beta(s) = \beta_0 + \frac{s^2}{\beta_0}$ in the straight section, where s is the distance from the centre of straight section ($\beta = \beta_0, \alpha = 0$). Assume the same Twiss parameters for the injection and stored beam for now.

iii. *Compute the magnetic field corresponding to the kick angle at the injection beam and at the magnet pole. Note: the field depends on the transverse position x in sextupole kicker.*

B-2: Tracking the injection beam:

1) The injection beam may be significantly (de)focused by the kicker field (feed-down). Evaluate the change of the injection beam (Change in Twiss parameters and Beam shape in the phase space).
   i. *Sextupole kicker field is described as $B_y = \frac{S}{2}x^2$, where x is the distance from the magnetic axis. For the injection beam going through the kicker off-axis x_0, $B_y = \frac{S}{2}(x_i + x_0)^2 = \frac{S}{2}({x_i}^2 + 2x_i x_0 + {x_0}^2)$, where x_i is the distance from x_0. As seen, the second term is proportional to x_i, and thus it acts as a quadrupole giving (de)focusing to the injection beam. The third term obviously corresponds to the dipole kick necessary for injection.*

2) The kicker field may not decay in one revolution. Track the injection beam for few turns and see whether the residual kicks at the following turns are harmful or not.
   i. *Note: (Linear) beam transport from Location 1 to 2 can be described by a transfer matrix*

$$\begin{pmatrix} x_2 \\ x'_2 \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\mu + \alpha_1 \sin\mu) & \sqrt{\beta_1\beta_2}\sin\mu \\ \frac{\alpha_1-\alpha_2}{\sqrt{\beta_1\beta_2}}\cos\mu - \frac{1+\alpha_1\alpha_2}{\sqrt{\beta_1\beta_2}}\sin\mu & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\mu + \alpha_2 \sin\mu) \end{pmatrix} \begin{pmatrix} x_1 \\ x'_1 \end{pmatrix}$$

where α, β are Twiss parameters at Location 1 or 2 (subscript), and μ is the phase advance between Location 1 and 2. For one turn in a ring, $\beta_1 = \beta_2$, $\alpha_1 = \alpha_2$ and $\mu = 2\pi Q$ with Q being the betatron tune.

3) (*If time permits*) The (de)focusing from the feed-down may be compensated by adjusting the Twiss parameters of the coming injection beam. Investigate if the transport line from the booster to the storage ring can provide an optimum set of parameters.

B-3: Hardware design

1) Design a sextupole or octupole kicker:

i. *Description about a sextupole kicker is found in http://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.13.020705*
ii. *Note: There are field computation tools available, e.g. Poisson from LANL.*

2) Design a nonlinear kicker *(if time permits)*:
   i. *The feed-down issue, B-2 (2), may be mitigated if the kicker field profile includes a flat part, i.e. nonlinear kicker. A kicker with 8 conductors realizes an octupole-like field profile around the axis with a flat part outside.*
   ii. *Note: When the kicker length is much longer than the transverse dimension, the field computed with Ampere's law is a good approximation. Try to optimize the position of conductors to realise a flat part in the field profile.*

C: Design an injection system for an high-energy circular collider, e.g. FCC-hh, for the two HEB injector options under consideration

One of the critical systems for a future 100 TeV centre-of-mass (c.m.) circular-collider is the fast beam injection that needs to accurately and safely inject the batches of beam from the 25 ns buckets in the High Energy Booster (HEB) injector to the 25 ns buckets in the collider. The most important considerations in the design of such a system are the delivery precision, the collider filling factor and the machine protection during the injection process. The baseline is to re-use LHC for injection at 3.3 TeV.

Table of basic parameters:

These parameters are based on the present FCC-hh design study:

Parameter	**HEB@LHC**
HEB extraction energy [TeV]	3.3
HEB ramp up/down rate [T/s]	0.03
HEB circumference [km]	26.7
Collider/HEB bunch spacing [ns]	25
FCC collider circumference [km]	100
c.m. Energy [TeV]	100
Bunch population [10^{11}]	1.0
Transverse emittance, normalized rms [μm]	2.2
Collider aperture (full Ø) [mm]	50
Number of collider beams	2
Collider filling pattern	Discuss with FCC beam dump team!

Assumptions:

In the collider ring, about 1.4 km straight section is available to house one injection and an experiment. 700 m is available for the injection system. Assume that the radius of the quadrupole cryostats are 500 mm. In addition, it is assumed that the maximum transferred beam energy is about 5 MJ. Assume that it takes approximately 3 minutes per beam in injectors to fill the HEB, before acceleration, and that the beam is prepared with particle free gaps corresponding to the 5 MJ transfer limit in mind.

C-1: Overview and injection schemes

1) How many bunches can be transferred per injection?
2) Propose a layout for the fast injection system (sketch + parameters):
    a. Assume that the septum thickness is ~15 mm.
    b. Assume that the beta function can be arbitrarily set between 10 m and a few km (dedicated insertion) and that dispersion can be neglected.
    c. What are the optimum parameters (layout, kick angles)?

i. *What are the integration and aperture constraints? Connected to C-2.*
ii. *Is the septum deflecting in the same plane as the kicker?*
iii. *Will a kick enhancement quadrupole help, i.e. will a quad be placed between kicker and septum? Should it be a QD or QF? What aperture does it need?*
iv. *Could an injection bump be useful to reduce the kicker strength?*

3) Work out the minimum collider filling time (both beams). Does this seem OK? How could this be speeded up?

C-2: Hardware considerations:

1) What are the requirements for kickers and septa?
    i. *Dynamic operational range*
    ii. *Rise-time and flat-top length: what is the impact on filling factor?*
    iii. *Flat-top ripple and field quality: how flat does the waveform need to be, is field quality of septum important? What about any post-injection pulse ripple?*
    iv. *Aperture: what ingredients go into the aperture needed at injection? How exact does the delivery from the transfer line need to be? What performance aspects are affected by this?*
2) List failure scenarios, their consequences and propose mitigation solutions in your design
    a. *kicker not firing: kicker erratic firing, kicker partial firing, wrong injected beam energy, …*
    b. *How can you protect against these?*
3) Design kickers, septa and protection devices:
    i. *Integration constraints: is the beam coming from the inside or outside, can you ensure the injection equipment and trajectory avoids conflicts? Don't forget there are 2 circulating beams!*
    ii. *How should the kicker and septum be powered, and why?*
    iii. *Where should physical protection devices be located and what do they need to accomplish?*

C-3: Lower energy injection (if time permits):

1) How would the design and overall performance differ if the injection energy were reduced to 1.3 TeV, with beam coming from a 6.9 km circumference injector that can ramp at 0.5 T/s?

D: Design a fast extraction system for an high-energy circular collider, e.g. FCC-hh

One of the biggest challenges in the construction of a future 100 TeV centre-of-mass (c.m.) circular-collider is the design of an extraction system that can safely remove and dump both beams, each containing many GJ of kinetic energy, at any moment during the operation of the collider and within one turn. The most important considerations in the design of such a system are machine protection and reliability and guaranteeing safe extraction at all times and therefore at all energies.

Table of basic parameters:

These parameters are based on the FCC-hh design study but can be used with some artistic license:

Parameter	**Typical value**
c.m. Energy [TeV]	100
Dipole field [T]	16
Arc filling factor	0.80
Injection energy [TeV]	Discuss with injection team!
Peak luminosity [10^{34} cm^{-2} s^{-1}]	5.0
Bunch spacing [ns]	25
Filling pattern and injection kicker rise-time	Discuss with injection team!
Bunch population [10^{11}]	1.0
Transverse emittance, normalized rms [μm]	2.2
Aperture (full) [mm]	50
Number of beams	2

Extraction straight:

In the collider ring, about 1.5 km straight section is available for extraction. Assume that the radius of the quadrupole cryostats are 500 mm.

D-1: Overview and extraction scheme

1) Propose a layout for the fast beam dump extraction system:
   a. Assume that the septum thickness is ~ 25 mm
   b. Assume that the beta function can be arbitrarily set between 10 m and a few km (dedicated insertion region) (dispersion can be neglected)
   c. What are the optimum parameters?
      i. *What are the integration and aperture constraints? Connected to D-2.*
      ii. *Will a kick enhancement quadrupole (QD) help, i.e. will a quad be placed between kicker and septum?*
      iii. *What are the implications for the aperture of the QD?*
      iv. *Could an extraction bump be useful to reduce the kicker strength? Explore its design features.*

D-2: Hardware considerations:

1) What are the requirements for kickers and septa?
   i. *Dynamic operational range*
   ii. *Rise-time and abort gap: what is the impact on luminosity?*
   iii. *Flat-top ripple and field quality: how flat does the waveform need to be, is field quality of septum important?*
   iv. *Aperture: check emittance at injection with teams working on Case Study C.*
2) Design kickers and septa:
   i. *Integration constraints: extract to inside/outside, extraction up/down, can you ensure the extraction equipment and trajectory avoids conflicts? Don't forget there are 2 beams!*
   ii. *How should these devices be powered, and why? Connected to D-3 below.*
3) Discuss the extraction beam line and design a dilution system:
   i. *What optics is needed, if any?*
   ii. *How can you keep adjacent bunches spaced by >2 mm?*

D-3: Failure scenario considerations (if time permits):

1) What is the stored energy of the beams in your collider?
2) List failure scenarios, their consequences and propose mitigation solutions in your design.
   i. *E.g. kicker failure: erratic triggering, missing kicker, wrong voltage etc.*