PC Assignments

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Storage Ring Design Guidelines

The exercise during this week will guide you through basic steps (unfortunately not all, the time is too short) of storage ring design.

First set your goals for synchrotron light source. Decide on beam energy, beam current, number/length of insertion straight sections, rough circumference of the ring. At this point you may ask yourself, how do I make the right decision with my limited experience? Most probably, you will make the “wrong” decision or “not so right” decision. That is fine, nobody makes the right decision at the beginning of a design effort. That’s the point where the iterations start. You start with some parameters, use them for your designs and when you get into some problems (physical, technical or financial) you let the rest of the design group know and you all discuss which and how to alter the basic design parameters to get to realistic and affordable solutions. In this school, never mind “affordable” since we do not perform a cost estimate, but you may make here and there certain choices purely on an economic basis if there are no physical or technical reasons to go one or another way.

With these general guidelines start your first storage ring design effort. To simulate somewhat economic constraints the design should be within the following boundaries:

- Beam energy between 1.3 and 3 GeV (choose energy to meet desired radiation characteristics)
- Ring circumference no more than 150 m (VUV ring) or 300 m (x-ray ring) : smaller is better, but do include the desired number of insertion straight sections and consider the desired small beam emittance
- The total length of bending magnets should be between 25 and 30% of circumference
- Beam current no more than 300 mA (try to meet your goals with the least current)
- Maximum bending magnet field is 1.5T
- Maximum pole tip field in quadrupoles is 1.0T
- Maximum pole tip field in sextupoles is 0.5T
- Always keep at least 20 cm between magnets as space for magnet coils!
- At least 4 straight sections available for insertion magnets
- Length of insertion straight sections no more than 3m
- Maximum pumping speed per pump be 1000 lt/sec.
- Place pumps only where there is at least 15 cm of magnetfree space available.

To obtain a high brightness synchrotron radiation source you want to design the ring for a small beam emittance. The emittance scales like E^2 and φ^3, where φ is the deflection angle of each bending magnet. Therefore, many lattice cells with small deflection per unit results in a small emittance, but at the price of a large circumference.

Design goals for a VUV ring may be:

- Keep rf power below about 300 kW
- Bending magnet radiation: critical energy 1 keV or more
- Wiggler magnet radiation: critical energy 1 keV or more
- Undulator radiation: should cover a photon energy spectrum (use up to 7th order) up to about 2 keV.

Design goals for an x-ray ring:

- Keep rf-power below about 600 kW
- Bending magnet radiation: critical energy 5 keV or more
- Wiggler magnet radiation: critical energy 10 keV or more
- Undulator radiation:should cover a photon energy spectrum (use up to 7th order) up to about 10 keV.

*** Use <u>Beam Optics</u> program for exercise 1 to 4 and
<u>Synchrotron Radiation</u> program for exercise 5 to 8. ***

Exercise 1: Design quadrupole doublet focusing

1.1 Design a quadrupole focusing doublet such that the focal point in both the horizontal and vertical plane is 3 m from the end of the second quadrupole.
Choose your own quadrupole length.
What is the focal length, defined by f=1/(k*l), for each quadrupole?
Here, k is the quadrupole strength and l the quadrupole length, respectively.

1.2 Choose a different value for the distance between both quadrupoles and find again the focal point at a distance of 3 m from the second quadrupole.
(a) What are the individual quadrupole focal lengths now?
(b) Are they longer or shorter?
(c) How do the focal lengths scale with quadrupole distance?

Exercise 2: Design storage ring

2.1 Design on a few basic storage ring parameters and goals: VUV or x-ray ring, energy (the beam energy should meet your desired radiation characteristic)., approximate circumference, number/length of unit cells and insertion straight sections. Before you start working on the computer make a sketch of the ring cell (sequence of quadrupoles and bending magnets depending on your choice of lattice). Then also sketch the whole ring showing cells, insertion straight sections, number of superperiods.

2.2 Use PC program to design your ring (You may start building your own lattice (FODO) or use a lattice cell from a low energy ring and modify to get high energy ring).

a.) Determine bending magnet parameters: length, bending radius, field (keep field less than 1.5 Tesla !), choose aperture (see 2.2d).

b.) Determine quadrupole parameters: length, strengths, choose aperture radius (see 2.d), max. pole tip field (keep pole tip field to less than 1.0 Tesla !). If not consider the aperture radius at this point, you may use maximum gradient for quadrupole magnets of 20 Tesla/m.

c.) General ring parameters: circumference, number of superperiods, number of insertion straight sections, length of insertions.

d.) Determine magnet apertures: assume you want the ring acceptances to be at least 50 mm*mrad horizontally and 20 mm*mrad vertically. Further assume an extra allowance of ± 5mm for orbit distortion and ± 5mm for the vacuum chamber thickness. Or use the requirement that emittance(ε_x) should be smaller than 20 nm.

e.) Beam optics parameters: plot/list betatron functions and dispersion function for one superperiod, ring tunes.

2.3 Start Report: import magnet list, betatron functions, plot of betatron function with magnet lattice (*.wmf file) into WORD. Add some text describing your goals and choices and what the numbers and plots mean.

Exercise 3: Design storage ring (Cont.)

3.1 We must correct for chromatic aberrations of the focusing structure. This is done by inserting sextupoles where the dispersion is nonzero. The degree of aberration in storage rings is measured in terms of natural chromaticity which is always negative. Insert sextupoles, SF's and SD's into the lattice to correct the natural chromaticity to +1.0 in both planes.

3.2 Sextupoles are nonlinear elements causing potential problems on particle stabilities at large amplitudes. The range of stability is determined by particle tracking.

a.) Track individual particles starting with increasing horizontal amplitudes and track for 1000 turns. Watch the phase space trajectories evolve from a pure elliptical shape to a distorted shape and eventually to instability. Track particles with negative as well as positive amplitudes and record the limiting amplitudes.

b.) Do the same for vertical oscillation, but use only positive amplidutes. Motion and limits are symmetric in the vertical plane. Check it out!

c.) Finally start with a finite horizontal amplitude within the stability range and vary the vertical amplitude.

d.) Create a an x-y-plot showing the amplitudes at which the particle oscillation becomes unstable. The range of stability is called the dynamic aperture of the ring. Compare this stability range with the acceptance of the ring. The dynamic aperture should be larger than the physical aperture. Note: you cannot compare apertures (in mm) you must compare emittances/acceptances. The acceptance of a ring is equal to the largest emittance a beam may have to just fit through the vacuum chambers. To determine the physical acceptance of the ring evaluate the expressions $A^2_{x,y}/\beta_{x,y}$ (A and β are the aperture/betafunction in the vertical or horizontal plane) wherever the betatron function reaches a maximum. For each plane, the smallest of these numbers is the acceptance (bottle neck) of the storage ring.

Exercise 4: RF-system, ultra-high vacuum and beam lifetime

4.1 Beam life time: In group discussions define the total desired beam life time.

a.) Determine required design parameters to reach the desired beam lifetime. Such parameters are: energy acceptance, transverse acceptance/aperture, vacuum pressure, rf-voltage.

b.) Specify the minimum horizontal and vertical acceptance required and translate into apertures for magnet design.

c.) The minimum energy acceptance determines the minimum rf-voltage requirement.

d.) Specify vacuum pressure requirements based on the desired beam lifetime.

4.2 RF-system:

a.) Determine the total synchrotron radiation power required by synchrotron radiation from bending magnets and wiggler/undulator magnets magnets.

b.) Determine the number of required rf-cavities to meet the following goals and boundaries: each cavity shall not absorb more than about 50 kW of rf-power due to wall losses;

c.) the cavities must compensate the energy loss due to synchrotron radiation and provide for the desired energy acceptance as specified by beam lifetime calculations(bremsstrahlung, Touschek effect, quantum lifetime).

d.) What is the total rf-power required? How much goes into the beam and how much is heating in the cavities?.

4.3 Vacuum System:

a.) Assume for simplicity an average vacuum chamber radius equal to the aperture requirement found from beam lifetime calculations and assume you have that same aperture all around the machine.

b.) Place vacuum pumps at appropriate locations around the ring and calculate the average pressure. Adjust pumping speed and pump locations to reach an average pressure as required by beam lifetime estmates (elastic and inelastic scattering).

c.) If you cannot reach the desired pressure then increase vacuum chamber aperture and communicate this change to the magnet design and beam lifetime group.

Exercise 5: Synchrotron radiation from bending magnets

5.1 Specify radiation characteristics from bending magnets. From the ring design the beam energy, current and bending magnet field is known. Use these parameters to determine the characteristics of bending magnet radiation:

a.) What is the total radiation power from each bending magnet and for the total ring?

b.) Calculate the radiation power density in units of (watt/mrad). Use the a vertical opening angle of $2/\gamma$ and calculate the power density in units of (Watt/mm^2) at an experimental station 10m away from the source.

c.) Determine spectral radiation characteristics of bending magnet radiation:

d.) What is the critical photon energy?

e.) Estimate at what photon energy (round off to an integer multiple of the critical photon energy) the spectral intensity has dropped down to about 1% of the maximum.

f.) Calculate the photon spectrum and specify the useful photon energy range, that is the spectral range for which the intensity is at least 1% of the maximum intensity.

g.) Suppose, for your experiment you are interested in 8keV radiation within a bandwidth of 1e-4. The beam line has a horizontal acceptance of 5mrad. What is the photon flux at your experiment?

h.) Assume a 1:1 imaging from the source to the experiment. Calculate for a photon energy equal to the critical photon energy the photon flux density at the experiment. Choose the optimum source location within the bending magnet

5.2 Photon beam polarization

a.) What is the plane of polarization for bending magnet radiation?

b.) For a photon energy of 0.1*ε_crit and 0.5*ε_crit determine the photon flux for π-mode radiation as a function of observation angle.

Exercise 6: Synchrotron radiation

In a low energy storage ring the bending magnet radiation often does not provide enough intensity at hard x-rays. More x-rays can be obtained if, for example, a bending magnet is replaced by a superconducting magnet providing the same deflection angle. Assume operation of your x-ray ring at 1.0 GeV to simulate a low energy ring.

a.) Consider a maximum field of 6 Tesla for the superconducting magnet. What is the length of the magnet? Calculate the total synchrotron radiation power from this magnet. Determine the critical photon energy.

b.) Calculate the photon flux spectrum and compare with the original bending magnet spectrum. How does the spectral intensity scale at low and high photon energies.

c.) Determine the storage ring energy that would give you the same spectral width of the radiation from regular bending magnets.

Exercise 7: Wiggler magnet radiation

7.1 Specify radiation characteristics from an wiggler magnet. From the ring design the beam energy and current is known. Use these parameters to determine the characteristics of wiggler radiation:

a.) Specify parameters for a wiggler magnet which would fit into a straight section of your ring.

b.) Define a permanent magnet wiggler (period length, field) with the boundary condition that the gap must be large enough to let the beam go though (plus 1mm for vacuum chamber).

c.) The critical photon energy should be as high as possible.

d.) What is the field strength of your wiggler magnet, its period length and number of periods?

7.2 Determine spectral radiation characteristics of wiggler magnet radiation:

a.) What is the critical photon energy?

b.) Calculate the total radiation power from this wiggler. With a vertical opening angle of $2/\gamma$ and a horizontal opening angle given by the beam deflection in the wiggler magnet calculate the power density (W/mm^2) at the experiment 10 m away from te wiggler magnet.

c.) Determine the photon spectrum and specify the useful photon energy range, that is the spectral range for which the intensity is at least 1% of the maximum intensity. Compare with bending magnet radiation. Describe advantages of wiggler radiation if any.

Exercise 8: Undulator radiation

8.1 Specify radiation characteristics from an undulator magnet. From the ring design the beam energy and current is known. Use these parameters to determine the characteristics of undulator radiation:

a.) Given the length of a straight section in your ring and the vertical aperture required by beam and vacuum chamber specify an undulator magnet for a strength parameter of at least K=2.0. Determine length and number of periods, field and gap.

b.) For which value (within 10%) of the undulator strength parameter K is the intensity of the fundamental radiation a maximum.

c.) Calculate the maximum transverse oscillation amplitude of the beam while passing through the undulator magnet.

d.) What is the horizontal and vertical-opening angle of the radiation?

8.2 Determine spectral radiation haracteristics of undulator radiation:

a.) Determine the fundamental wavelength of undulator radiation as a function of gap aperture. How far can you vary the wavelength by varying the undulator gap?

b.) Plot the line spectrum for say K=0.5,1.0 and 2.0

c.) Considering all harmonics up to 7th order, plot the photon beam brightness as a function of undulator gap. Does the undulator cover a continuous spectrum at these harmonics?