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Machine physics

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Abstract. The figures of merit for synchrotron radiation storage rings are discussed. The machine functions, defining the particle beam characteristics, are then overviewed. Some lattice configurations, optimised for synchrotron storage rings are then presented. The talk will also touch some problems and solutions related to particle beam stability and lifetime.

1. Introduction.

The aim when designing synchrotron radiation rings is to match the ring properties to those of the emitted synchrotron radiation (SR). During the evolution of synchrotron radiation sources, that is the magnet structures emitting SR, these goals have changed. For the first generation of synchrotron radiation rings, which mostly consist of high energy physics rings, dipole magnets are used as SR sources and the optimisation is constrained by the existing design. The second generation of SR rings still use the dipole magnets as main SR sources, but the electron (or positron) beam is optimised for SR uses.

The third generation sources are using special insertion devices, undulators and wigglers as SR sources and these devices introduce new challenges in the machine design.

We can only scratch slightly on the surface of machine physics during this talk. A more detailed description can be found in for instance ref 1.

2. Figures of merit.

There are mainly two properties characterising a SR source. The first is the flux defined as

$$\Phi = \frac{N_f}{0.1\%, mrad} \quad (\text{photons}/(s, 0.1 \% \text{ energy spread, mrad horizontally}))$$

The brilliance B is the peak flux density in phase space

$$B = \frac{N_f}{0.1\%, mm^2, mrad^2}$$

The flux is a function of electron current and electron energy only. When calculating the brilliance we have to take into account the phase space defined by the diffraction properties and that given by the electron beam emittance.

Other figures of merit for a SR ring are electron beam lifetime, spatial stability, ring reliability and ease of operation.

3. Specification goals.

3.1 Spectral region.

For a dipole source, the critical wavelength where intensity is close to maximum, is given by

$$\lambda_c = \frac{18.6}{E^2 B} \text{ (\AA)} \text{ where } E \text{ is the electron energy in GeV and } B \text{ the magnet field in T.}$$

We should thus choose the electron energy to cover the photon spectral region of interest, but a too high electron energy might induce unnecessary heat problems and a too high ring cost. We must also take into account that a large bending magnet radius will put the optical elements further away which will reduce the opening angle for a given optical element size.

The use of insertion devices and then especially undulators puts even tighter boundary conditions on the electron energy. The spectral region is given by the undulator period and its magnet field. The total flux is proportional to the number of undulator periods. The latter is strongly dependent on the minimum undulator gap allowed in the machine.

As a consequence of this, the optimisation process of a third generation storage ring for SR is heavily dependent on the evolution of the insertion devices. A ring optimised for an undulator minimum gap of 40 mm, which was a conservative value some years ago, is certainly quite different from a ring optimised for a 10 mm gap, which is used and discussed today.

3.2 Matching.

The photon angular spread defined by diffraction can generally be approximated for gaussian distributions to

$$\sigma'_{ph} = \sqrt{\frac{\lambda}{2L}} \text{ where } \sigma' \text{ is the RMS angular spread, } \lambda \text{ the emitted light wavelength and } L \text{ the source length.}$$

The diffraction relation for gaussian distributions

$$\sigma_{ph} \sigma'_{ph} = \frac{\lambda}{4\pi} \text{ yields the apparent source size } \sigma_{ph} = \frac{1}{\pi} \sqrt{\frac{\lambda L}{8}}$$

The electron beam phase space area or emittance $\varepsilon = \sigma_e \sigma'_e$ should thus preferably be less than $\frac{\lambda}{4\pi}$. If this is the case, the source is called diffraction-limited. This demand is so far difficult to fulfil, especially for shorter wave-lengths.

Even if the electron beam emittance is smaller than $\frac{\lambda}{4\pi}$, we need to match the phase space form of the electron beam emittance to that induced by diffraction. The mismatch between these phase-space forms for a dipole source is seen in fig. 1, where L is in the mm range which gives σ_{ph} in the μm range while the electron beam size is orders of magnitudes larger. For an undulator, with L in the meter region, σ_{ph} is some order of magnitude larger which yields a better match to the electron beam size. This fact plus the larger number of emitting sources explain the high brilliance attainable from an undulator in a low emittance storage ring.

Fig. 1. Photon and electron beam emittances in phase space.

4. Magnet lattice.

4.1 Betatron motion.

A ring magnet lattice consists mainly of dipole magnets which recirculate the electron beam and magnet lenses, quadrupole magnets. These lenses will force the stored particles to oscillate around a reference orbit. If we smear out the focusing evenly around the ring, we should obviously get a harmonic oscillation for a certain particle

$$x(\Psi) = C \sin(K\Psi + \Phi)$$

where C is the oscillation amplitude, K is the wave number, Ψ the azimuth angle in the ring and ϕ a phase angle.

In a real machine, we have piece-wise constant focusing lenses. A solution to the particle motion can then be described as

$$x(s) = C\sqrt{\beta(s)} \sin(Q\Psi(s) + \Phi)$$

$\beta(s)$ is now a modulating function, s the coordinate in the reference orbit direction and Q is the betatron wave number defining the number of oscillations the particle will execute during one turn in the machine. Ψ is now not exactly the azimuth angle but is generally rather close to it. The angle between the particle motion and the reference orbit is achieved by differentiating x with respect to s

$$x'(s) = \frac{dx(s)}{ds}$$

In phase space x x' the particle will now describe an ellipse when moving in the ring . The oscillation amplitudes for the particles in the beam will have a gaussian distribution. The particle with the RMS amplitude will have its motion described by

$x(s) = \sqrt{\varepsilon\beta(s)} \sin(Q\Psi(s) + \Phi)$ where ε defining the oscillation amplitude is the area (divided by π) of the phase space ellipse and is called the electron beam emittance.

We have two directions of oscillations, the radial and vertical ones, so we now have two β functions.

One example of the β functions is seen for the MAX I ring for one cell in fig. 2. We can thus read the beam size variations around the machine. One peculiarity is that the β function is at maximum at focusing lenses and minimum at defocusing ones. Since the sign of focusing is changing when going from radial to vertical motion, the beam size has a horizontal maximum where the vertical size is at minimum and vice versa.

Fig. 2. Beta and dispersion (eta) functions for a double bend achromat.

4.2 Dispersion.

A particle with a higher energy than the nominal one will have a larger bending radius in a dipole magnet field. An achromatic bend is seen in fig. 3. A particle with a higher energy is entering the first dipole magnet from the left on the reference axis. This particle is then deflected less than the nominal one in this magnet but will then enter a focusing quadrupole which will deflect the particle inwards the machine. By symmetrical reasons, the particle will, after the second dipole transit, be situated on the reference orbit again.

Fig. 3. Double bend achromat showing particles of high, nominal and low energy.

The function, describing the position of an off-energy particle with a momentum deviation $\Delta P/P = 1$, is called the dispersion function η and this is also seen in fig. 2.

5. Radiation damping and beam emittance.

As we have seen above, the particles stored in the ring execute oscillations around a reference orbit. Let's first look for the radiation damping in the vertical direction as seen in fig. 4.

An oscillating particle will emit a photon in a dipole magnet. The recoil of the photon will have one longitudinal component retarding the particle and one vertical component damping the vertical oscillation. The longitudinal recoil will be replaced by the accelerating cavity while the vertical recoil component will damp the oscillation.

Fig. 4. Vertical and radial damping.

The situation is somewhat more complicated in the radial direction. Let us look at fig. 4 where we assume that a particle of nominal energy on the reference orbit emits a photon in a bending magnet. Apart from the damping mechanism described for the vertical case above, the particle will now suddenly have another equilibrium orbit introduced by its changed energy and the present non-zero dispersion. The introduced oscillation amplitude equals the particle distance to the new equilibrium orbit.

This mechanism is in fact responsible for the equilibrium emittance in a storage ring. We can also see that a large dispersion in the bending magnets introduces large oscillation amplitudes and thus a larger emittance.

6. Decreasing the electron beam emittance.

The chase is now for smaller dispersion functions in the bending magnets in order to decrease the particle beam emittance and thus increase the brilliance. The first thing is of course to enlarge the number of achromats to get a small dispersion in the bending magnets. The smaller the bending angle of the bending magnet, the smaller the dispersion. We can also lower the electron beam energy and get a smaller recoil. The emittance is in fact scaling like

$$\varepsilon \propto E^2 / N^3$$

where E is the electron energy and N the number of bending magnets.

We can, however, not push this scheme to far. The reason for this is chromaticity corrections. A particle of higher energy will experience a weaker focusing in the quadrupole lenses and should thus get a lower betatron wave number Q . The chromaticity

$$\xi = \frac{dQ}{dP / P}$$

will then be negative which will excite the head-tail instability. We correct the chromaticity by introducing nonlinear lenses, sextupole magnets, at places with non-zero dispersion as seen in fig. 3. The particle position is here energy-dependent and the nonlinear sextupole lens can then compensate the betatron Q -value.

For small dispersion functions, we need stronger sextupoles and this will make the lattice more unstable, the dynamic aperture is reduced. This mechanism is one factor limiting the possibility to reach small remittances.

7. One lattice example.

The machine functions of the MAX II ring is seen in fig 5. First, we notice that the cell is not strictly an achromat. The dispersion function is not zero at the long straight sections. The reason for this is that the mean dispersion in the bending magnets (where the emittance is defined) can be minimised by allowing dispersion at both dipole ends. We can in principle adjust the dispersion to zero in the middle of the bending magnet which should effectively double the number of dipoles compared to the conventional double achromat example and thereby reducing the emittance a factor of eight.

Fig. 5. MAX II beta and eta functions.

An other feature is that no sextupoles are seen in the lattice. The sextupoles are integrated into the quadrupole lenses by a special machining of the magnet iron surfaces. This yields an optimum sextupole distribution with a large momentum acceptance and a large dynamic aperture paired with a compact and cheap magnet lattice. Since we simultaneously restrict the tuning flexibility, we have to carefully calculate the lattice characteristics prior production.

8. Performance limitations.

Even if we in principal know the way to diffraction-limited emittances, there are a number of hinders blocking the road.

One is money. Decreasing the particle emittance means a larger number of magnets to decrease the dispersion. The machines tend to be big and costly.

A second is dynamic stability. As we increase the sextupole strengths, we reduce the dynamic aperture. This causes a reduction of beam life-time and increases the aligning problems.

A third is the possibility to effectively keep the beam position inside a fraction of the beam size. As we reduce the beam size, we have to position the beam more exactly. If the experiments should be able to benefit from the smaller beam size, then the effective emittance seen by the user should not be diluted by beam motions.

We are also aiming at high mean currents. This means high maximum current and a life-time which is long compared to the injection time.

The maximum current in a storage ring is often quoted as a very important figure of merit. However, high currents are often inducing various instabilities, beam drifts and increased beam sizes, so the counting rate at the experiment is not always proportional to the current.

For the production of SR, we have two possible kinds of particles, electrons and positrons. Electrons offer a potential well in which ions, created by the particle beam hitting rest-gas molecules, can be trapped. These trapped ions will disturb the electron beam with a beam blow-up and a shorter beam life-time as a consequence.

Also small particles, ionised either by synchrotron radiation or directly by the electron beam, can be trapped resulting in electron beam-losses.

Positrons offer the guarantee of ion and trapped particle free operation, but are rare and expensive. At some big labs, positron production is already existing for other purposes. The ion trapping problem has however been managed at a number of synchrotron radiation labs using electron beams. A suitable current density modulation is then introduced in the ring. For some electron distributions, the ion motion in the beam becomes unstable and the electron beam is thus cleared from ions.

The particle trapping is now being investigated ²⁾. Under some circumstances, the effect of trapped particles is serious, at other labs very little is seen.

Electron operation needs some careful precautions to eliminate ion trapping. Each school has its arguments. There are many factors which should be taken in account for an optimum choice like if positrons already are available, injection time versus beam life-time, economical priorities between ring equipment and beam-lines, sensibility to micro-losses etc.

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