A pure insertion device synchrotron light source utilizing the MBA-optics

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Abstract: The pure insertion device (PID) lattice is a novel concept for a synchrotron light source, where all possible light ports are irradiated by insertion devices. Up to 40% of the ring circumference is available for insertion devices. The lattice has been obtained by giving up the constraint of zero dispersion in the straight sections. However, for many SR experiments, the resulting reduction in brilliance is not of importance. An application of the PID structure for a 3 GeV storage ring is presented and discussed. With 202 m of circumference and an emittance of 14 nm.rad, it has 24 straight sections of over 3m each. Tracking studies show excellent dynamic properties of the lattice.

1. INTRODUCTION

Third generation synchrotron radiation storage ring are characterized by an optics which minimizes the emittance in order to obtain a high brilliance. However, there are many experiments, where only the total photon flux integrated over the angular acceptance of the beam line is important, as long as the beam spot size is smaller than the sample size. Most common X-ray beamlines, which use only mirrors for focussing, don't reduce the spot size below 1 mm² because of manufacturing tolerances.

Those experiments would still profit from the high fluxes provided by insertion devices, but they are usually placed at bending magnet sources, because the number of insertion devices is limited. In this paper we present a storage ring which circumvents these limitations by joining and extending two existing ideas[1]: building a lattice which allows one ID per bending magnet (SuperACO) and which has non-zero dispersion in all straight sections in order to reduce the emittance (Grenoble).

The expense of having dispersion also in the straight sections does not affect the aforementioned type of experiments. The big advantage is that now up to 40% of the ring circumference can be used for insertion devices. This design is therefore ideal for small storage rings with many similar experimental methods being utilized at the same time.

2. CONSEQUENCES OF A HIGH BRILLIANCE DESIGN

The design of a high-brilliance storage ring starts by minimizing the emittance. The formulae for calculating the emittance of a storage ring with isomagnetic bending magnets – neglecting any effect due to insertion devices – can be summarized as:

$$\epsilon = C_q \gamma^2 \frac{\langle H \rangle_{\text{mag}}}{J_x \rho_0} \quad (1.1)$$

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where $C_q = 3.8 \cdot 10^{-13}$ m is a constant, γ is the relativistic factor, J_x is the horizontal partition number, ρ_0 is the bending radius of the bending magnets, $\langle \rangle_{\text{mag}}$ denotes averaging over the length of the bending magnets only and

$$H = \gamma \eta^2 + 2\alpha \eta \eta' + \beta \eta'^2 \quad (1.2)$$

The emittance scales in general with the square of the energy and the third power of the bending magnet's deflection angle.

The optics influences the emittance via the partition number J_x , which is unity for a pure dipole field and via the H-function (eq.1.2), which is determined by the shape of the horizontal betatron (β) and dispersion (η) functions within the bending magnets only. Low emittances can be reached if the $\beta(s)$ and $\eta(s)$ have a minimum there. Hence to reach the lowest emittance, a storage ring should have a lattice which provides a shape of the horizontal betatron and dispersion functions as represented in figure 1b in all dipole magnets. However, conventional design considerations forbid this. A light source includes undulators and wigglers and at the position of these insertion devices, in the long straight sections, the dispersion has to be zero. This requires a matching of the Twiss functions to the desired values within the straight sections.

Figure 1: Twiss functions in a bending magnet which minimize the H-function for a nondispersive entrance (a) and in the general case (b). The expressions for the optimum values of the Twiss functions and the minimum emittances are shown.

The zero dispersion can be matched only if the straight section is on the left side of the dipole in figure 1a. Two of these dipoles with one quadrupole in between form the double bend achromat (DBA) structure [2]. Implicit to the DBA structure is the requirement that the phase advance of the horizontal betatron oscillation from the beginning of the first to the end of the second dipole has to be π . This is only possible if the distance between both dipoles is very large [3] or there are at least two more quadrupoles in between the dipoles, as for the ELETTRA design [4].

Be it either way, the constraint of dispersionless straight sections results in two disadvantages, which we aim to avoid with our proposed lattice:

- the minimum of eq. 1.1 can not be reached by almost an order of magnitude
- only up to 20% of the ring circumference is available to insertion devices, the rest is used up to provide suitable optics

The disadvantages remain also for other types of lattices, where the lowest emittance was obtained, such as the modified quadrupole bend achromat[5,6,7] and the modified multiple bend achromat (MBA).

The lattice of the modified MBA structure has been described in detail elsewhere[8,9]. It consists of several unit cells accompanied on each side by a matching section followed by a straight section. The matching sections assure that the dispersion is zero in the straight sections and that the beta-functions can

be set to the requirements of either undulators (high beta) or wigglers (low beta). The unit cell is composed of a defocussing bending magnet and a focussing and a defocussing quadrupole. The low emittance is obtained because the dipoles in the matching section deflect by a smaller angle than the ones in the unit cell.

3. THE PURE INSERTION DEVICE (PID) LATTICE

Both aforementioned disadvantages can be avoided if a ring is composed only of unit cells of the modified MBA lattice with one straight section between each pair of unit cells. Although there is a small dispersion in the straights which contributes to a slightly broader beam, this is partially compensated for by a smaller emittance. A less tight lattice allows for up to 40% of the circumference to be used for insertion devices.

Figure 2: A bird's eye view of the storage ring with 24 IDs. Inserted are the horizontal (full line) and vertical (dashed) beta functions and the dispersion multiplied by 10 (dashed-dotted). All units in meters.

As an example, we present a 3 GeV light source for material science, with similar characteristics of the radiation as a previously proposed light source ROSY[7]. The ring has a 24 - fold symmetry (figure 2). The unit cell consists of one bending magnet with a superimposed defocussing gradient and two quadrupoles on each side of the bending magnet. In principle, one quadrupole on each side is sufficient to obtain the low emittance. The second quadrupole has been added to allow for greater flexibility and in particular for the compensation of linear tune shifts by insertion devices. Such a unit cell is small, therefore it doesn't unnecessarily increase the total circumference. In addition, the partition number J_x is larger than 1 which reduces the emittance further.

Since the phase advance in one unit cell is rather small, there are no many choices for the tunes in order to avoid resonances within both the unit cell and the complete ring. The two quadrupoles, Q1 and Q2, were used to fix the horizontal and vertical tunes of the unit cell to 0.38125 and 0.2625 respectively. The total tunes were thus 9.15 and 5.70.

The optics shown in figure 2 are a good compromise between low emittance and reasonably long straight sections. A longer straight section or a shorter bending magnet would have given more space for IDs but would have also increased the emittance. With a total circumference of 202 m and straight sections with space for insertion devices, each up to 3 m long, over 35% of the circumference is used. The emittance

could have been reduced further by increasing the index of the bending magnet, but then the strengths of the quadrupoles would have become too high.

3.1. The characteristics of the optics

The emittance for the presented optics is 14 nm.rad, the relative energy spread is $1.7 \cdot 10^{-3}$. The beta functions in the straight section are rather low in both planes, which is particularly suited for wigglers. Assuming 10% coupling between planes, the beam sizes due to the emittance are 260 μm and 65 μm r.m.s. in the horizontal and vertical plane, respectively. The dispersion increases the horizontal r.m.s. to 740 μm , which is still smaller than a typical beam line spot size. All damping times are around or below 5 ms and the natural chromaticities are small (-8 horizontal and -15 vertical). The sextupoles are placed in well decoupled regions and have very modest strengths. One is superimposed on the outer quadrupole, the other one is next to the bending magnet.

The results of tracking one particle over 100 turns through the ring are shown in figure 3a. No harmonic sextupoles were necessary to compensate the nonlinearities of the chromatic sextupoles. The tracking has been performed using the computer code RACETRACK [10]. The dynamic aperture is large and the tune shifts with momentum and amplitude are small. Thus the overall dynamic properties of the lattice are very promising.

In order to investigate the behaviour of the lattice with insertion devices, a worst case was studied, where all 24 straight section were occupied by wigglers with 30 periods of 10.2 cm and a magnetic field on axis of 1.5 T. The dynamic aperture was initially reduced to zero. But just by using the two quadrupoles to compensate the integral tunes back to the original values, the dynamic aperture was practically reestablished (figure 3b) proving the flexibility and the good dynamic properties of the lattice.

Figure 3: the dynamic aperture for energy deviations from -4% to +4% without IDs (a) and with 24 wigglers (b).

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