A Lattice Design to Reach the Theoretical Minimum Emittance for a Storage Ring.

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Abstract

The theoretical minimum emittance (TME) for a storage ring is given if both the horizontal betatron and the dispersion function have a minimum in the middle oft the bending magnet and furthermore meet special values. In most of the storage rings the emittance is a factor 2 to 5 higher as the TME-value. The TME can be reached with a new type of lattice composed of combined function bending magnets and a quadrupole doublet at each side following by a drift space of 2 to 3 m: DRIFT / Q(d) / Q(f) / BENDING / Q(f) /Q(d) / DRIFT. With a 20 degree bending magnet it is possible to reach an emittance down to 9 nmrad at 3 GeV (which is only 14 % higher as the TME-value). With a circumference of 250m and 18 unit cells (20 degree bending magnet) it is possible to use up to 50 % of the circumference for the installation of insertion devices. With a 10 degree bending magnet (3GeV) it is possible to reach an emittance of 1.5 nmrad

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1 INTRODUCTION

In recent years, electron storage rings have frequently been used as light sources for research in atomic, molecular, condensed matter and solid state physics, chemistry, cell biology etc. For many experiments, it is desirable to use high brilliance light, which requires a small emittance of the beam. In most cases the radiation from undulators will be used. Because the efficiency of a light source goes with the beam ports it is worthwhile to install a large number of undulators or have a large percentage of the circumference free for the installation of insertion devices. Also for the next generation of colliders one needs electron storage rings which small emittances as daemping rings. In this case the emittance should be around 0.5 nmrad, hence one order of magnitudes smaller as the 3rd. generation light sources.

The horizontal emittance of a electron storage ring is given by [1]:

$$\varepsilon_{x0} = c_q \cdot \gamma^2 \frac{\langle \mathcal{H} \rangle_{dipol}}{J_x \cdot \rho} \tag{1}$$

where $C_q = 3.84 \cdot 10^{-13}\ m$,$J_x$ is the damping partition number, and $\langle \mathcal{H} \rangle$ is the average over the dipole functions,

$$\langle \mathcal{H} \rangle = \gamma_x \cdot \eta_x^2 + 2 \cdot \alpha_x \cdot \eta_x \cdot \eta_x' + \beta_x \cdot {\eta_x'}^2 \tag{2}$$

where γ, α and β are the Courant Snyder betatron amplitude functions, $\eta(x)$ and $\eta'(x)$ are the dispersion function, respectively its derivative. Storage rings [2] are build up with different magnet structures: FODO, DBA, TBA etc. The emittance of each structure can be expressed as:

$$\varepsilon_{x0} = K \cdot \frac{1}{3 \cdot 4 \cdot \sqrt{15}} \cdot C_q \cdot \gamma^2 \cdot \frac{1}{J_x} \cdot \varphi^3 \tag{3}$$

where φ is the deflection angle of the bending magnet and K is a so called quality factor for each structure.Most of the synchrotron light sources uses DBA- or TBA structure. For the DBA-structure the theoretical K-value is 3 and for the FODO structure around 100. The K- value of the TBA structure is in the near of the DBA-lattice. The real K-values reached within these machines are a factor 2 to 5 higher as the theoretical one [2]. ELETTRA has with K=4 the smallest deviation to the theoretical emittance. From the theoretical point of view the theoretical minimum emittance (TME) has a K-value equal 1. But so far there doesn't exist any machine with the TME-structure [3],[4],[5],. The K-value of the lattice influenced the cost of the machine very match. With a wanted emittance ε_{x0}, the number of bending magnets and also the circumference is proportional to $(K/\varepsilon_{x0})^{1/3}$. Hence it is worthwhile looking for a machine design with a TME - structure.

2 TME - LATTICE

The theoretical minimum emittance is according to fig.1 given [5], when the $\beta(x)$ as well as the dispersion function reach in the middle of the bending magnet a minimum and meet the required values $\beta(0)$ and $\eta(0)$

$$\beta_x(0) = \frac{1}{2 \cdot \sqrt{15}} \cdot L \qquad \eta_x(0) = \frac{L^2}{24 \cdot \rho}$$
$$\varepsilon_{x0} = C_q \cdot \gamma^2 \cdot \frac{1}{J_x} \cdot \frac{1}{3 \cdot 4\sqrt{15}} \cdot \varphi^3 \tag{4}$$

The principle layout of the magnetic lattice build up with a TME- structure is given in fig.2. Within the unit cells (U) one has the TME-structure. The matching (M) sections performs the matching of the machine functions to the required values within the straight sections (the location of the insertion devices) and to keep the dispersion function zero. The last point can only be done with a bending magnet in the matching section. But one has to take care that this bendings will not destroy the emittance given by the TME-structure. As a rough rule the bendings in the matching section should have half of the angle as that one within the TME-structure.

In order to get a TME-lattice one has to add adjacent to the bending magnet of fig.1 quadruples for fitting the machine functions at the symmetry point to: $\alpha_x = \alpha_y = 0$

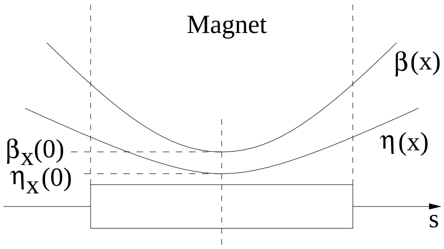

Figure 1: Behavior of the machine functions at a bending magnet to reach the theoretical minimum emittance.

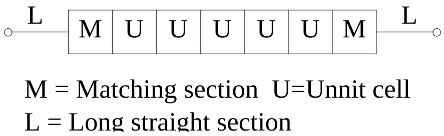

Figure 2: Scheme for building up a lattice with a TME-structure

and $\eta'_x = 0$. The symmetry point is in fig.2 the transition between the unit cells. For the matching one has to use first a horizontal focusing and than a vertical focusing quad. The lattice for the TME-structure, including the behavior of the machine functions is given in fig.3, for a 20 degree bending magnet. Here one uses a combined function bending magnet in order to increase the partition function J_x and to reduce the emittance. To get a minimum emittance for a 20 degree bending magnet with a radius of 7.148 m the optimized conditions are:

$$\beta_x(0) = 0.322\, m/rad \;\; and \;\; \eta_(0) = 0.0363\, m \qquad (5)$$

In fig.3 $\beta_x(0)$ and $\eta_x(0)$ have exactly these values. For the example in fig.3 one gets a TME-emittance of 7.85 nm*rad including a partition function of $J_x = 1.53$. The emittance according to the lattice is $9.07\, nm \cdot rad$. Hence the K-value is 1.15. Which means that the TME-value has more or less been reached.

The reason for getting the TME-emittance follows from fig.3. The TME-emittance is determined by the $\beta_x(0)$ and the $\eta_x(0)$ value in the middle of the bending magnet. Already for a 20 degree bending magnet $\eta_x(0)$ is near zero ($0.0363\, m$). That means the phase advance from cell to cell

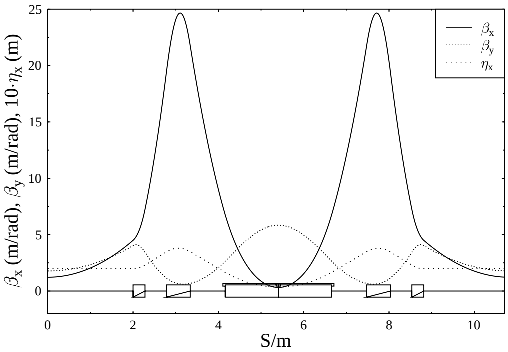

Figure 3: Layout of a TME-Structure with the bending magnet in the middle and a quadrupole doublet at each side.

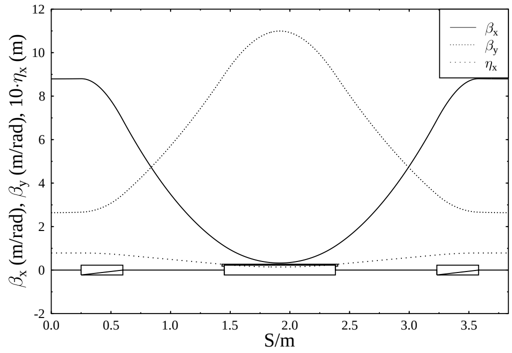

Figure 4: Lattice of a simplified TME-structure

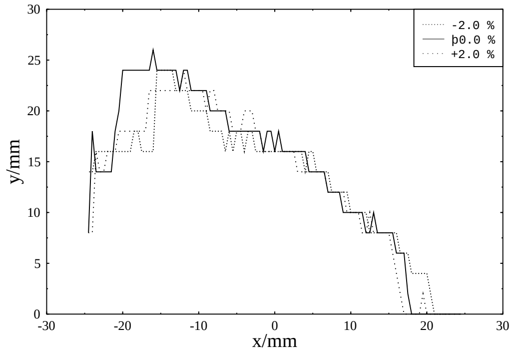

Figure 5: Dynamic aperture for the lattice of fig.4

has to be around $1.5 \cdot \pi$. To get such a high value one has to focus the β_x-function at the symmetry point to another minimum, as shown in fig.3. The dynamic aperture for this case are $A_x = 118\, mm \cdot mrad$ and $A_y = 351\, mm \cdot mrad$, which are quite large for storage rings.

Reducing the deflection angle to 10 degrees with a radius of 10 m, the starting values are $\beta_x(0) = 0.255$ and $\eta_x(0) = 0.0127$ resulting in a TME-emittance of $1.51\, nm/J_x$. In our design we reached an emittance of $1.6\, nmrad$ with $J_x = 1.906$. That means a K-value of 2. The reason for this deviation is the small phase advance from cell to cell ($1.17 \cdot \pi$). By increasing this, one gets a smaller emittance.

For a bending angle of 5 degree the TME-emittance is $0.29\, nm \cdot rad$. With a lattice according to fig.3 we reached a value of $0.32\, nm \cdot rad$, which means a K-value of K=1.8

3 SIMPLIFIED TME-STRUCTURE

For the reduction of costs it is possible to simplify the TME - structure in a way, that it exist only of 3 elements: a combined function bending magnet, and a horizontal focusing quad at each side. The lattice of this structure for a 5 degree bending magnet is given in 4. The dynamic aperture for this lattice is presented fig.5 Because there isn't a minimum of the $\beta_(s$ function at the symmetry point the k-value increases to 3 to 4, but the are smaller as for the DBA- or TBA- structure. The simplified TME-structure has been used for some machines [6].

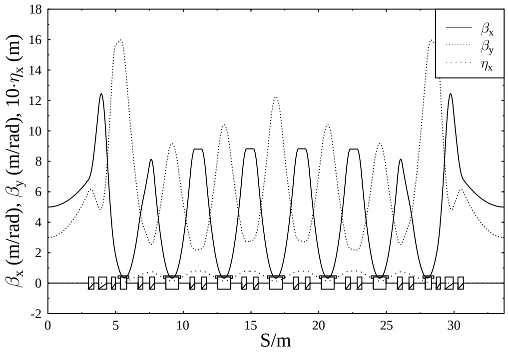

Figure 6: Lattice for a Diffraction Limited light Source.

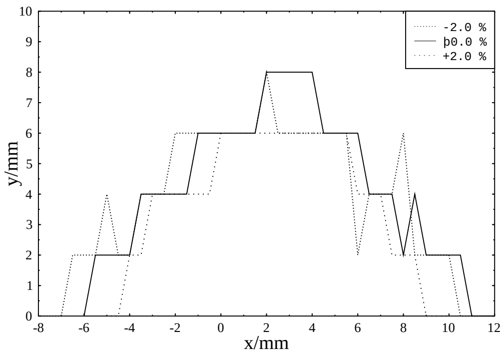

Figure 7: Dynamic aperture for the lattice of fig.6

4 APPLICATION OF THE TME-STRUCTURE

4.1 3rd. Generation Light source

The main parameters for a 3 rd. generation light source are the emittance, the length of the straight sections and the percentage of the circumference which can be used for the installation of insertion devices. With a TME-structure according to fig.3 and taking a deflection angle of 15 degree the emittance for a 3 GeV machine is in the range of 5 nmrad, a typical value for a 3 rd. generation light source. The circumference of such a machine is around 308 m. The dynamical aperture is Ax= and Ay= quite large. The authors of this paper gave this structure the name PID (Pure Insertion Device) [7],[8].

4.2 Diffraction Limited light Source

The next generation of synchrotron light sources should have an emittance in the range of 0.5 nmrad in order to reach the brilliance for a diffraction limited light source and to get a higher amount of coherent radiation from the undulators. With the simplified TME-structure we worked out the lattice for a 0.5 nmrad emittance machine. First results have been presented at the PAC 95 [9] and the workshop of the next generation light sources art the ESRF [10].

4.3 Daemping Ring for a Linear Collider

The next generation of linear colliders will use a linac to accelerate the electrons up to 200 - 500 GeV. For the wanted high luminosity one has to accelerate in the linac short bunches, which will be produced in the daemping rings. To meet the required values, the emittance of the daemping ring has to be around 0.7 nmrad. With a simplified TME-structure it is possible to reach this value. In fig.6. the lattice and the machine function within a unit cell are presented. The dynamic aperture is given in fig.7.

5 CONCLUSION

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