Design of a Diffraction Limited Light Source (DIFL)

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Abstract:

Three synchrotron light source of the third generation have been commissioned (ESRF, ALS and ELETTRA). All machines have reached their target specifications without any problems. Hence it should be possible to run light sources with a smaller emittance, higher brilliance and emitting coherent radiation. A first disign of a Diffraction Limited Light Source has been performed. It is a 3 GeV storage ring with a modified multiple bend achromat (MBA) optics as a lattice leading to a normalized emittance of $\varepsilon_x = 0.5$ nmrad. The novel feature of this lattice is the use of horizontally defocussing bending magnets with different bending angles to keep the radiation integrals low. The circumference is 400 m including 12 straight sections with a lenght of 6 m. The dynamical behaviour should allow to store a beam of 100 mA with a lifetime larger 5 hours.

I. Introduction

The most important factor for synchrotron radiation users is the brilliance which is mainly determined by the cross-section of the beam and given by the square root of the emittance multiplied with the betatron function. However, even at zero emittances the phase space of the radiation from an undulator itself is finite due to diffraction effects. The corresponding emittance of the light beam is given by $\varepsilon_{phot} = \lambda/4\pi$, with λ being the wavelength at the peak flux. A light source is called diffraction limited if the emittance of the electron beam is smaller than that of the photon beam.

For a 3 GeV light source, the typical undulator radiations peaks at a wavelength of around 1 nm, or energy 1.2 keV, respectively. This means that for a diffraction limited light source, the emittance would have to be below 0.08 nm·rad.

The third generation light sources ALS, ESRF and ELETTRA have been commissioned in record times and are running very well and reliable. This proves that it should be possible to obtain a horizontal emittance which is an order of magnitude below the present one of these machines, i.e. around 0.5 nm·rad. With a coupling of 1%, the corresponding vertical emittance is 5 pm·rad. The diffraction limited emittance would thus be between the two vaules.

It is interesting to note that damping rings for the next generation electron-positron colliders have a similar emittance and a similar particle energy [1]. They can be kept much more compact, however, because the light sources need a larger circumference to accomodate straight sections for insertion devices.

2. Obtaining a Low Emittance

The optics influences the emittance via the partition number J_X, which is unity for a pure dipole field and via the H-function:

$$H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta\eta'^2$$

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. In order to get the desired shape of the Twiss funktions in a unit cell a bending, a focussing and a defocussing magnet are needed. This can be achieved with four quadrupoles and a dipole with the deflecting angle φ [2] or by two qudrupoles and a bending magnet with a superimposed quadrupole strenge to focus the beam vertically [3],[4]. 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. To get the smallest emittance the bending magnet with in the matching section must have a deflection angel around $\varphi/2$ [4],[5].

3. The Concepts of the MBA Lattice

The lattice of a multiple bend achromat (MBA) structure can be described as a set 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 dipoles within the unit cells have a deflection angle of φ, whereas the ones in the matching section deflect by $\varphi/2$.

The unit cell with a defocussing bending magnet has a threefold advantage:

1) the number of magnets per achromat is reduced;
2) the partition number J_X is larger than 1 and thus reduces the emittance;
3) the length of the cell is small, therefore reducing the total circumference.

The circumference of such a machine containing five unit cells within an achromat which performs an overall deflection of 30 degrees would be around 400 m.

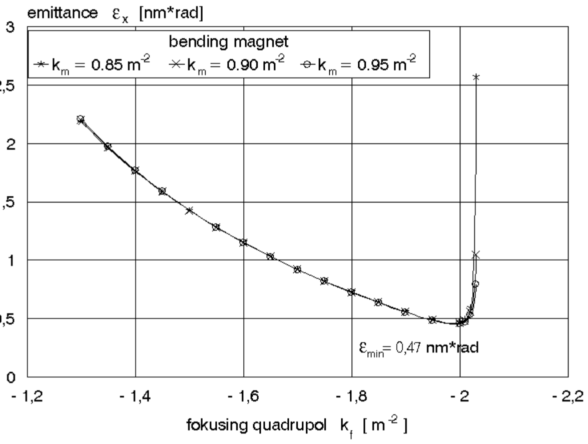

Fig. 1: The emittance of the DIFL unit cell as function of the focussing quadrupole strength at different defocussing strengths of the bend.

Accepting reasonable magnetic field strengths for the bending magnets determines more or less the length of the magnets. The only two free parameters which can be varied to minimize the emittance are the strength of the focusing quadrupole and the quadrupole strength of the bending magnet. Therefore it is easy to find the optimal setting (figure 1), resulting in an emittance of 0.47 nm·rad. The shape of the Twiss functions within a unit cell is shown in figure 2.

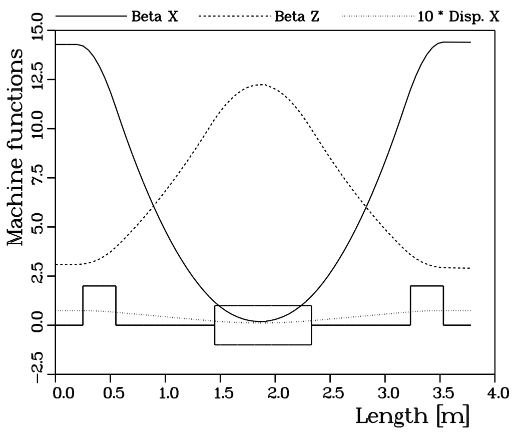

Fig. 2: The course of the machine functions within a unit cell.

The performance of the achromat is mainly determined by the unit cell. Its characteristics are given by the factors: emittance, partition number, working point, chromaticities and momentum compaction factor. The optimisation of the lattice is therefore first done on a hypothetical ring consisting of 72 unit cells. From figure 1 one can see, that the minimal emittance depends very weakly on the defocussing strength of the bend. Therefore it can be chosen such as to find an optics with a large dynamic aperture by keeping the total tune away from dangerous resonances. The results of tracking one particle over 100 turns through the hypothetical ring are shown in figure 3. Only chromatic sextupoles have been used. The tracking has been performed using the computer codes RACETRACK [6] and BETA [7]. The dependence on the particle momentum is negligeable.

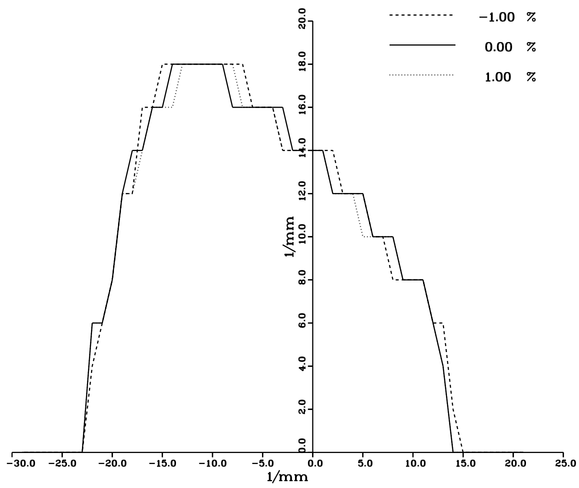

Fig. 3 The dynamic aperture of the MBA lattice composed of unit cells only.

The dynamic aperture is particularly large if one considers that it extends from -296 to 160 times the beam width in the horizontal plane and to +/-3680 times the beam height (at 1% coupling) in the vertical plane. Thus the overall dynamic properties of the MBA lattice are very promising.

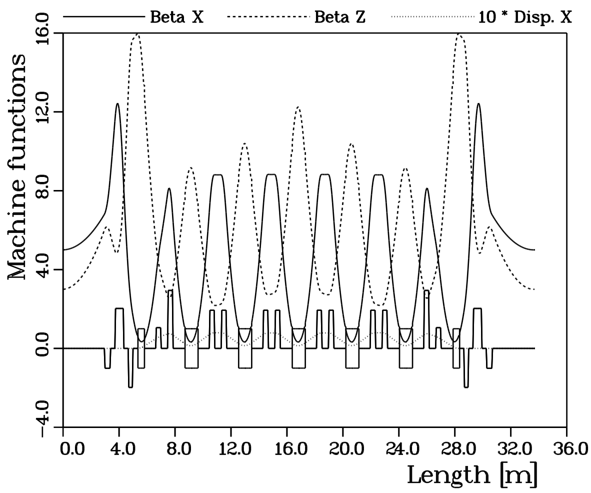

Fig. 4 The optical functions for one achromat of the DIFL lattice. Indicated are the position and sizes of bending magnets and quadrupoles. All units are in meters.

4. THE DIFL LATTICE

In the realistic lattice, twelve straight sections of 6m length each are introduced, leaving sufficient space for insertion devices. Four quadrupoles and a 2.5 degree bending magnet compose the matching section to set the dispersion to zero and the horizontal and vertical beta functions in the straight sections to the desired values (figure 4).

With the matching, the emittance is increased by the presence of the outer two magnets from 0.47 nm rad to 0.56 nm rad. Assuming 1% coupling between planes, the beam sizes $\sigma_{x,y}$ are 54 µm and 4 µm in the horizontal and vertical plane, respectively. All damping times are around or below 9 ms, the relative energy spread is 8 10^{-4}, and even the natural chromaticities are not too large (-77 horizontal and -37 vertical).

Unfortunately, the dynamic aperture is reduced once the optics composed of unit cells only is modified to allow for dispersion-free straight sections.

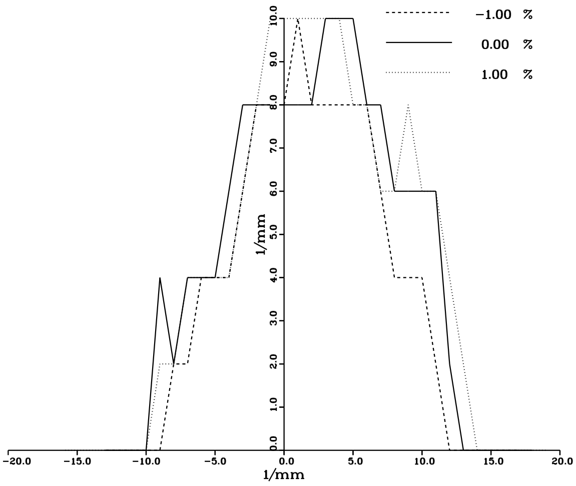

Fig. 5 The dynamic aperture of the DIFL lattice.

Even after reoptimizing the optics, the largest dynamic aperture obtained is 10 mm horizontally and 8 mm vertically (figure 5), certainly creating a challenge for the injection into the ring but not rendering the optics unfeasible, because once the injected beam is damped to the natural emittance, the dynamic aperture still corresponds to more than 100 times the beam size in both planes. This should be sufficient to accomodate Touschek scattering given that the dispersion is also quite small.

The plot of the tune shift with amplitude (figure 6) reveals that indeed the dynamic aperture vanishes due to the rapid change of the tune. With proper sextupole arrangements we hope to increase the dynamic aperture to larger values.

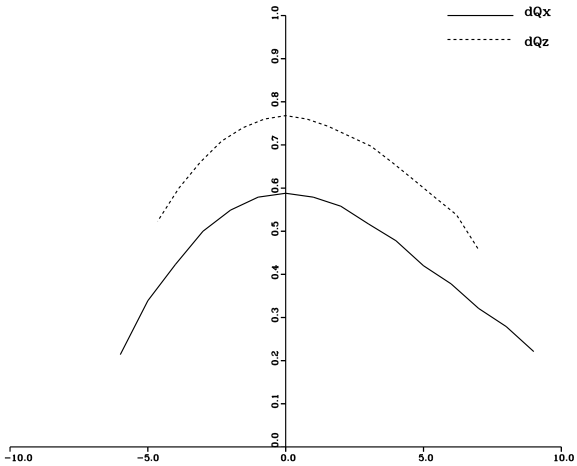

Fig. 6 The tune shift with amplitude of the DIFL lattice.

5. CONCLUSIONS

The presented multiple bend achromat (MBA) lattice provides a mean to obtain significantly lower emittances than with conventional DBA or TBA lattices. The advantages of the modified lattice are the small contribution of the outer magnets bending to the emittance, a large horizontal partition number which further reduces the emittance, a small number of quadrupole magnets, a short unit cell and good dynamic properties with only chromatic sextupoles. The scheme of the MBA optics can be applied to small compact rings as well as for the design of a diffraction limited light source.

6. REFERENCES

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