Nuclear Instruments and Methods in Physics Research A 770 (2015) 98–112

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Compact low emittance light sources based on longitudinal gradient bending magnets

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ARTICLE INFO

Article history:
Received 30 June 2014
Received in revised form
29 September 2014
Accepted 1 October 2014
Available online 13 October 2014

Keywords:
Lattice design
Ultralow emittance
Light source
Damping ring
Longitudinal gradient magnet

ABSTRACT

The horizontal emittance of a storage ring beam can be reduced below the theoretical minimum of a given magnet structure if a variation of the longitudinal field is introduced in the bending magnets. The optimum longitudinal field variation for the generation of the lowest emittance has been calculated numerically – and analytically for different classes of simple functions: exponential-, power-, hyperbolic- and step-function. Constraints have been introduced for the maximum field and the minimum beta function in the magnet. The distribution of the deflection angles to the different magnet types has been optimized. The optimization results have been applied to an exemplary design of a lattice for a light source with limited circumference as for instance the Swiss Light Source.

1. Introduction

The horizontal emittance in a storage ring is given by the equilibrium between quantum fluctuation and radiation damping and solely defined by the magnet structure and the energy. Radiation sources are targeting for small emittances in order to enhance the brilliance of the emitted light which is inversely proportional to the emittance. In lattices composed from many identical cells, each containing one bending magnet (BM), the emittance scales with the third power of the bending angle per cell and becomes minimal if the beam is properly horizontally focused in the BM. Optimum beam parameters can be calculated to realize the so-called theoretical minimum emittance (TME), which is the lowest possible emittance for a lattice cell containing a homogeneous BM.

Recent progress in accelerator technology, in particular coating of narrow vacuum chambers with non-evaporable getter (NEG) films, allowed the beam pipe dimensions and the magnet apertures to be reduced. Thus magnet gradients can be increased and magnet lengths can be reduced correspondingly, such that a larger number of lattice cells can be accommodated within a given ring circumference, and the bending angle per cell is correspondingly decreased. This is the winning concept of the multi-bend achromat (MBA) lattices [1] as first exploited by the MAX IV 3 GeV storage ring design [2], and subsequently leading to designs for fully diffraction limited X-ray sources like PEP-X [3]. Upgrades of existing storage rings at ESRF [4], ALS [5] and other places follow the same concept and plan for the exchange of the storage ring lattice by a low emittance MBA-ring while maintaining the source points of the beam lines.

In a lattice of limited circumference a low-aperture MBA lattice alone is insufficient to reach very low emittance. Installation of damping wigglers as common means for emittance reduction is impeded by lack of space. But the horizontal emittance can be reduced below the TME of a given magnet structure by introducing a longitudinal variation of the magnetic field in the BM. This option has not yet been fully exploited before. In addition, the radiation from the high field region of such a BM could well serve hard X-ray dipole beam lines. The double feature of emittance reduction and hard X-ray production, which makes the concept of a longitudinal gradient superbend (LGSB) attractive in particular for compact storage rings at moderate beam energy, will be elaborated in this paper.

After giving an historical overview on previous work and recalling the basic equations, we will derive the general expressions for the minimum emittance and the related integrals for arbitrary longitudinal variations of the magnetic field. A numerical optimization of the field profile will suggest classes of simple functions to be used for an analytic optimization. The effectiveness of four different field representations is compared under realistic conditions, i.e. the preservation of the deflection angle and the limitation of the magnetic field value to a technically manageable upper limit. Numerical evaluations are accompanying the analytical results. Finally a draft design for a compact low emittance storage ring lattice based on these magnets is elaborated.

http://dx.doi.org/10.1016/j.nima.2014.10.002
0168-9002/

2. Historical overview on longitudinal gradient bends

The first documented idea has been published in 1992 at the Low Emittance Workshop at SLAC [6], where it was stated that the emittance can be reduced below the value for constant magnetic field, if a longitudinal variation of the magnetic field is introduced which generates a third power of the inverse bending radius out of phase with the Courant Snyder Function. A first assessment to this idea has been made in [7]: an empirical analysis was made there under the assumption that the bending magnet field has the approximate form $b/(1+as)^m$. An analytical solution was derived for the minimum emittance, whereas the integrals forming the minimum emittance were solved numerically. The same field model was then further analyzed in [8]. In [9], a step-function bend was considered for a possible upgrade of the ESRF lattice. A comprehensive analysis of longitudinal field variation was presented in [10] with analytical solutions for an exponential field variation and a polynomial approach whereas the latter could only be optimized numerically. A superbend composed from two dipoles of different field strength was analyzed in [11]. A thorough and very general analysis of the minimum emittance from dipoles with transverse or longitudinal gradients was performed in [12], in particular a symmetric dipole with a step-function variation of the field was analyzed in detail. This study was continued by numerical optimization of field profiles of bending magnets fulfilling different functions in a lattice [13]. Complete lattice cells containing dipoles of step-function or trapezoidal field variation were optimized in [14]. A step-function dipole is included in the design of the SIRIUS storage ring to provide hard X-rays for users while also reducing the emittance by 10% [15]. The dispersion suppressor magnets in the hybrid-7BA (seven bend achromat) lattice of the ESRF upgrade lattice are designed as longitudinal gradient dipoles based on permanent magnets [16].

3. Basic equations and definitions

3.1. Equilibrium emittance

The natural horizontal equilibrium emittance ϵ_{xo}, the rms relative energy spread σ_δ and the radiated energy per turn ΔE in a flat storage ring lattice are given in practical units by

$$\epsilon_{xo}[\mathrm{m\cdot rad}] = C_q\gamma^2\frac{I_5}{I_2-I_4},$$
$$\sigma_\delta^2 = C_q\gamma^2\frac{I_3}{2I_2+I_4},\quad \Delta E[\mathrm{keV}] = \tilde{C}_\gamma\gamma^4 I_2, \tag{1}$$

with γ the Lorentz factor, the constants

$$C_q = 3.83\cdot10^{-13}\ \mathrm{m},\quad \tilde{C}_\gamma = 9.60\cdot10^{-13}\ \mathrm{keV},$$

and the radiation integrals

$$I_2=\oint b^2\,ds,\quad I_3=\oint|b|^3\,ds,\quad I_4=\oint\eta b(b^2+2k)\,ds,\quad I_5=\oint|b|^3\mathcal{H}\,ds, \tag{2}$$

with $b(s)=1/\rho(s)=(e/p)B(s)$ the orbit curvature, i.e. the inverse bending radius ρ, with e the electron charge, p the electron momentum and B the vertically oriented bending field. $k[>0]$ is the [horizontally] focusing BM gradient and $\mathcal{H}$ the dispersion's betatron amplitude,

$$\mathcal{H}=\gamma\eta^2+2\alpha\eta\eta'+\beta\eta'^2, \tag{3}$$

with β, $\alpha=-\beta'/2$, $\gamma=(1+\alpha^2)/\beta$ the horizontal Courant–Snyder parameters and η, η' the dispersion and its derivative.

3.2. Symmetric and achromat bending magnets

Special considerations are given to the two most common implementations of a BM as sketched in Fig. 1: A symmetric bending magnet (SBM) has zero slopes of optical functions on one side and thus can be appended to its mirror image, thus forming a BM of double bending angle 2Φ with a symmetry point in its center. It is used inside an MBA arc or as center bend in a triple bend achromat (TBA) lattice. An achromat bending magnet (ABM) has zero dispersion on one side. It is also called dispersion suppressor and used at the ends of an MBA arc and for double bend achromat (DBA) lattices. The initial conditions at $s=0$ are given by

$$\text{SBM}\quad \alpha_o=0\quad \eta_o'=0 \tag{4}$$

$$\text{ABM}\quad \eta_o=0\quad \eta_o'=0 \tag{5}$$

3.3. Minimum emittance for the homogeneous bending magnets

It results from Eq. (1) that the most efficient and elegant way to achieve a low emittance is the minimization of the I_5 integral. An increase of I_2 is limited due to high synchrotron radiation losses, and a manipulation of I_4 is limited by the requirement to preserve longitudinal damping and to get a low energy spread. Minimization of I_5 requires a horizontal focus in each bending magnet, and a small bending angle, such that the dispersion cannot grow to large values. In this case I_5 and with it the emittance scale cubically with the angle per bending magnet. For an iso-magnetic lattice containing short, gradient-free homogeneous BMs of identical type, calculation of the TME is straightforward and gives the well-known formula [17]:

$$\epsilon_{xo}[\mathrm{m\cdot rad}] = \frac{C_q\gamma^2}{J_x}\frac{\Phi^3}{12\sqrt{15}}\cdot\begin{cases}8 & \text{(SBM)}\\ 3 & \text{(ABM)}\end{cases}\quad \text{with } J_x = 1-\frac{I_4}{I_2} \tag{6}$$

the horizontal damping partitioning number. Since we defined the SBM as a *half* magnet as shown in Fig. 1, an unfamiliar factor 8 appears in the emittance formula. Appending the SBM to its mirror image doubles the angle without changing the TME. Due to the cubic scaling of the TME with angle the factor 8 cancels, and a mirrored SBM, as commonly considered, provides a three times lower TME than an ABM of the same angle.

Eq. (6) requires exact matching of the beam parameters at $s=0$:

$$\beta_o=\frac{L}{\sqrt{15}}\quad\text{and}\quad\eta_o=\frac{\Phi L}{6}\quad\text{(SBM)}, \tag{7}$$

$$\beta_o=\frac{6L}{\sqrt{15}}\quad\text{and}\quad\alpha_o=\sqrt{15}\quad\text{(ABM)}. \tag{8}$$

In case of the ABM it is sometimes more convenient to express the matching conditions by the minimum beta function and the position of its focus inside the magnet:

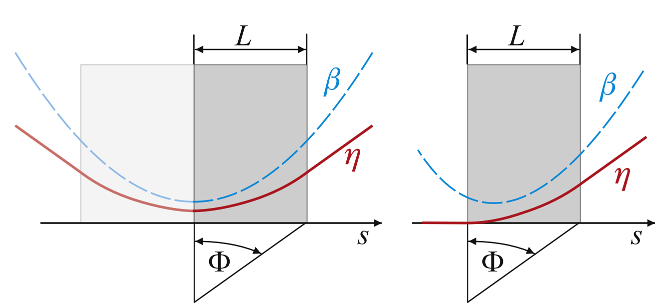

Fig. 1. Symmetric bending magnet (SBM, left) and achromat bending magnet (ABM, right).