Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

The anti-bend cell for ultralow emittance storage ring lattices

Q1 A. Streun *

Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

ARTICLE INFO

Article history:
Received 7 October 2013
Received in revised form
13 November 2013
Accepted 15 November 2013

Keywords:
Lattice design
Ultralow emittance
Light source
Damping ring
Reverse bend
Inverse bend

ABSTRACT

A small bending magnet of negative deflection, called anti-bend, can be used to reduce the equilibrium emittance of a periodic lattice cell by providing the proper matching of the dispersion function to the theoretical minimum emittance (TME) condition. With an anti-bend deflection angle of about −10% of the main bending magnet angle, a factor of 2 lower emittance can be achieved. Integration of horizontal focusing into the anti-bend leads to an economic half-quadrupole magnet design, which allows us to adjust the damping partitions conveniently for further emittance reduction. The use of the anti-bend cell (ABC) is exemplified by the draft design of a compact storage ring with very low emittance and options for short pulse operation.

1. Introduction

Recent progress in the design of electron storage rings leads to a reduction of the natural equilibrium emittance by 1–2 orders of magnitude, shifting the scale from some nm rad down to 10–100 pm rad range. This process is based on the "multibend achromat miniaturization cycle" as pioneered by the MAX IV storage ring design [1]: the use of a multibend achromat (MBA) lattice with very many bending magnets of small deflection angle and correspondingly small values of the dispersion function allowed a significant reduction of vacuum chamber diameters from previous 60–80 mm down to about 20–30 mm while maintaining the required energy acceptance. Concurrently techniques for NEG coating of narrow chambers had been established to realize ultra high vacuum conditions in simple chamber geometries. Smaller vacuum chambers allow magnets with smaller gaps and correspondent higher gradients and reduced lengths. The miniaturization of magnets in turn allows one to accommodate more cells in a given circumference, thus closing the cycle.

Considering one periodic cell in a MBA lattice, realization of the lowest possible emittance, called "theoretical minimum emittance" (TME), requires appropriate matching of the horizontal beta function and the dispersion. However, matching both simultaneously leads to a long cell with overstrained optics, which practically is never realized. Instead all lattice designs back down and allow for a factor of 3–6 larger emittance in favor of relaxed optics.

This paper will demonstrate how anti-bends, also called inverse bends or reverse bends, i.e. bending magnets of negative deflection angle, can be used to disentangle the matching of beta function and dispersion in the TME cell (TMEC). The resulting anti-bend cell (ABC) provides about a factor of 2 lower emittance with less side-effects compared to other methods gaining factors of 2 like Robinson wigglers for manipulation of damping partitions or fully coupled beam for distributing the natural emittance horizontally and vertically.

In the past, this concept had been explored for reduction of damping times and emittance in colliders [2] and damping rings [3]. Anti-bends have been employed previously in isochronous lattices for manipulation of the momentum compaction factor [4]. This measure was also considered for positron damping rings to increase the RF acceptance [5]. Application to light sources had already been suggested in Ref. [2], however the lattice cells proposed there used rather low cell tunes and large anti-bend angles for the main purpose of damping time reduction. This paper will explore cells at higher tune with anti-bends of relatively small deflection angle in order to achieve the lowest emittance for given storage ring circumference and without substantial increase of radiated power.

2. The theoretical minimum emittance cell

Numerous derivations, e.g. Ref. [6], can be found for the equilibrium emittance of an isomagnetic storage ring lattice composed of

* Tel.: +41 563103688; fax: +41 563103151.
E-mail address: andreas.streun@psi.ch

0168-9002/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2013.11.064

cells of deflection angle $\Phi \ll 1$. In practical units, the emittance of an iso-magnetic flat lattice is given by

$$\varepsilon\ [\mathrm{pm\ rad}] = \frac{7.8}{J_x}(E\ [\mathrm{GeV}])^2(\Phi\ [^\circ])^3\frac{F}{12\sqrt{15}} \tag{1}$$

with E being the beam energy and J_x the horizontal damping partition. The TME condition is realized for $F=1$ and requires for the horizontal beta function ($\beta=\beta_x$) and the horizontal dispersion (η) at the dipole center

$$\beta_o^{\mathrm{TME}} = \frac{1}{2\sqrt{15}}D, \quad \eta_o^{\mathrm{TME}} = \frac{hD^2}{24} \tag{2}$$

with D being the dipole magnet length and $h=1/\rho$ its curvature. An example for an ideal TMEC is shown in Fig. 1.

Defining dimensionless parameters characterizing detuning from the ideal TME conditions,

$$b := \frac{\beta_o}{\beta_o^{\mathrm{TME}}}, \quad d := \frac{\eta_o}{\eta_o^{\mathrm{TME}}}, \quad F := \frac{\varepsilon}{\varepsilon^{\mathrm{TME}}} \tag{3}$$

ellipse equations are obtained for the iso-emittance contours in the (b,d)-diagram of Fig. 2,

$$\tfrac{5}{4}(d-1)^2 + (b-F)^2 = F^2 - 1 \tag{4}$$

and the corresponding cell phase advance is given by straight lines

$$\tan\frac{\mu}{2} = \frac{6}{\sqrt{15}}\frac{b}{(d-3)}. \tag{5}$$

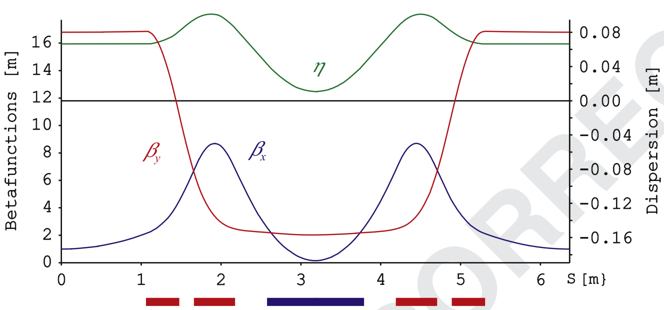

Fig. 1. Example for an ideal TMEC based on a 12° center dipole. To fulfil matching conditions for horizontal beta function and dispersion results in a horizontal cell tune of 0.79° or 284.5° phase advance.

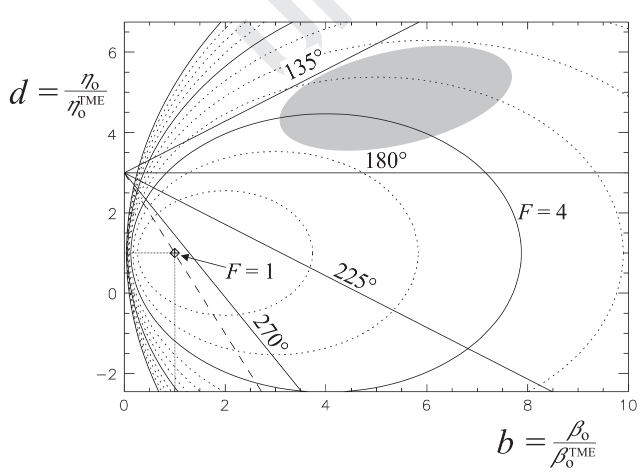

Fig. 2. Normalized emittance F as a function of beta function and dispersion at the midpoint of a detuned TMEC normalized to their minimum values, which are marked by the diamond symbol at $F=b=d=1$. The elliptic iso-emittance contours correspond to integer values up to $F=12$, where $F=4$, 8, 12 are solid, others dotted. The solid lines correspond to annotated values of the cell phase advance, the dashed line to 284.5°. The shaded area indicates the range of operation for usual lattice cells.

The ideal TMEC shown in Fig. 1 fulfills both conditions $b=d=1$, which requires a secondary focus and with additional drift spaces at the cell ends and strong quadrupoles, resulting in a very high phase advance of 284.5°. Due to these complications, lattice cells are usually designed to work in the shaded region of Fig. 2 at cell phases advances well below 180°, taking into account a larger emittance of $F \approx 3$–6.

3. The anti-bend cell

Fig. 2 indicates that emittance is relatively tolerant to larger beta function ($b>1$) but grows fast if the condition $d=1$ is relaxed. Looking at Fig. 1 obviously the appropriate matching of dispersion results in an over-focusing of the beta function. Thus a low emittance cell with relaxed beta function and correspondingly reduced phase advance could be realized, if the missing focusing of dispersion can be provided by other means. This problem can be solved by the anti-bend: the kick on the dispersion function by an anti-bend of angle $-\psi$ is given by

$$\Delta\eta' = -\sin\psi. \tag{6}$$

Fig. 3 displays an exaggerated sketch of the corresponding lattice cell: the quadrupoles at the ends provide beta-matching for a moderate phase advance but insufficient dispersion matching. The anti-bend provides additional dispersion matching to meet the $d=1$ criterion while virtually not affecting the beta functions. The half-deflection angle ϕ of the center bending magnet of course has to be increased to maintain the cell deflection Φ, i.e. $\phi = \Phi/2 + \psi$. Since emittance scales cubically with the magnet bending angle, see Eq. (1), this will increase the emittance. Further, the anti-bend itself does not fulfill at all the conditions for low emittance, since beta function and dispersion are both large at its location. However, both detrimental effects will be overcompensated by the gain from proper dispersion matching.

A simplified analytical model is established by considering the half-cell from Fig. 3 with half- center dipole of length c, angle ϕ, anti-bend dipole of length a, angle ψ in distance l and of an ideal, thin quadrupole directly attached to the exit of the anti-bend. Due to the fact that symmetry derivatives are zero in the cell center: $\alpha_o = \eta_o' = 0$. Ignoring any focusing from the pure dipoles with small deflection angles, the thin quadrupole is the only focusing element. Thus the beta function propagates like in a drift space, and the full cell phase advance is given by

$$\mu = 2\int_o^L \frac{ds}{\beta_o + s^2/\beta_o} = 2\arctan\left(\frac{L}{\beta_o}\right) \tag{7}$$

with $L = c+l+a$ defining the half-cell length. The transfer matrix of the half-cell is the product of the drift L and the thin quadrupole of focal length f, and f follows from the constraint for periodic

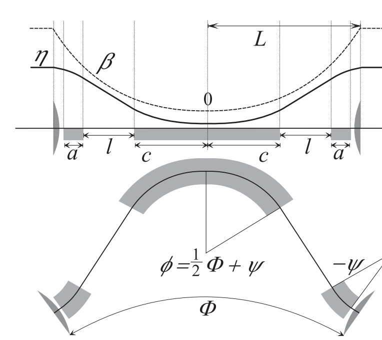

Fig. 3. Schematics of the anti-bend cell, see the text for explanation.