IMPROVING EMITTANCES IN EXISTING STORAGE RINGS BY DEFOCUSING DIPOLES*

C. E. Mayes†, L. Gupta, G. H. Hoffstaetter, V. O. Kostroun, A. A. Mikhailichenko
CLASSE, Cornell University, Ithaca, NY 14853, USA

Abstract

Designs for ultimate storage rings (USRs) typically employ two strategies to lower the emittances: 1) adding more bending magnets, and 2) using only focusing quadrupole magnets, with additional defocusing in the bending magnets. In an existing storage ring, the first strategy is precluded because the number of bends is typically fixed, but the second strategy could be used at modest expense. With the CESR storage ring as an example, we show how this is possible and propose an optics that reduces its emittance by more than a factor of 20. Furthermore, such an upgrade would could be installed incrementally without any long dark-time period.

INTRODUCTION

In an isomagnetic ring without insertion devices, the minimum possible horizontal emittance is given approximately by

$$\epsilon_x = (1/\mathcal{J}_x)\, C_q\, \gamma^2\, \theta^3\, \mathcal{F}, \tag{1}$$

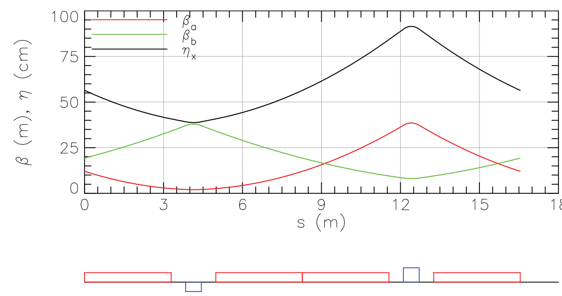
where $C_q \equiv 55\hbar/\left(32\sqrt{3}mc\right)$, m is the mass of the particle, γ is the relativistic factor, θ is the angle for a single dipole magnet, and $\mathcal{J}_x \approx 1$ is the horizontal damping partition number. The factor $\mathcal{F}$ depends on the arrangement of focusing magnets surrounding the bends. This factor bounded below the theoretical minimum emittance (TME) factor $\mathcal{F}_{\mathrm{TME}} = (12\sqrt{15})^{-1}$ [1].

When designing a new ring, the θ^3 scaling in Eq. 1 is a powerful incentive to use numerous short dipole magnets in every arc section. Furthermore, the circumference of the ring can be kept small if the space between dipole magnets contains only a single horizontally focusing quadrupole magnet, and a horizontally defocusing quadrupole field is added to the dipole magnets. This has the additional advantage that the dispersion and the horizontal beta functions tend to be minimal within the dipoles. These are the strategies used in the now under construction Max IV [2] facility and the PEP-X design study (for which $\mathcal{F}/\mathcal{J}_x \approx 5.7\,\mathcal{F}_{\mathrm{TME}}$) [3].

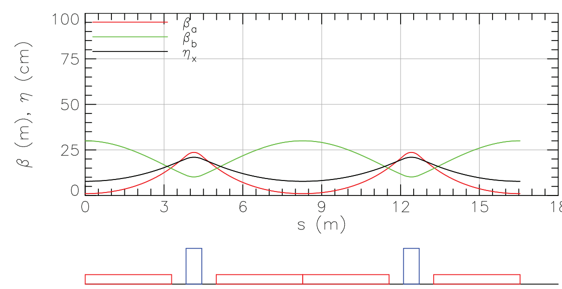
FODO UPGRADE CONCEPT

When upgrading an existing accelerator, it may not be desirable or economical to change the baseline arrangements of bend and straight sections in the ring, precluding a change in bend angles. However, upgrading the focusing in the dipole magnets can achieve a much better emittance.

* Supported by NSF award DMR-0807731
† christopher.mayes@cornell.edu



(a) Existing FODO (idealized) with $\epsilon_x = 22\,\mathrm{nm}$.

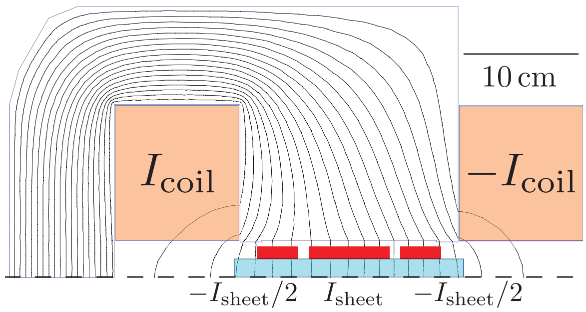


(b) Upgrade with horizontally defocusing bends and $\epsilon_x = 1\,\mathrm{nm}$

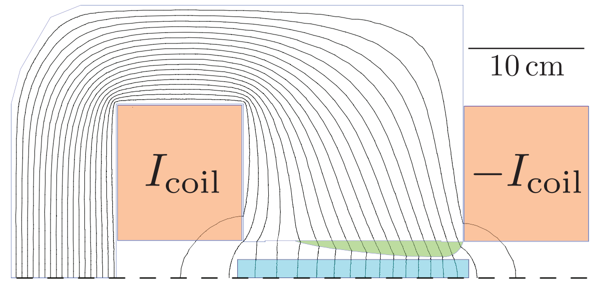
Figure 1: Idealized CESR arc cell optics for a 5.3 GeV electron beam, centered on the 6.574 m long dipole magnet (red) with a bending radius of 87.89 m (corresponding to about $4.29°$). The drift between dipole magnets is 1.7 m, with a 0.6 m quadrupole magnet (blue) in the center. Figure 1a shows optics for the existing magnet configuration. Figure 1b is the same geometry, but with an additional horizontally defocusing quadrupole moment in the dipole magnets ($k_1 = -0.06/\,\mathrm{m}^2$, corresponding to about 1 T/m at this energy).

For a concrete example, we will take the case of the Cornell Electron Storage Ring (CESR), which was originally built to operate at 8 GeV for e^+e^- collisions [4]. Since its completion 1979, CESR has been continuously upgraded and now serves as the Cornell High Energy Synchrotron Source (CHESS) for hard x-rays, and the CESR Test Accelerator (CESR-TA) for ILC damping ring and low emittance beam tuning studies [5].

Like many colliders, CESR's magnetic lattice is primarily built out of focusing-defocusing (FODO) cells, with single quadrupole and sextupole magnets between all of the dipole magnets. An idealized model of a typical cell is described in Fig. 1. Optimizing for emittance only, the existing magnets for such a cell would be able to realize the solution shown in Fig. 1a with an emittance corresponding to



(a) Current sheets (red) with $I_{\rm coil} = 5274$ A and $I_{\rm sheet} = 1900$ A.



(b) Wedge (green) and $I_{\rm coil} = 3795$ A.

Figure 2: Two concepts for upgrading a 0.2 T dipole magnet to have an additional 1 T/m defocusing quadrupole field. This is achieved in the magnet in Fig. 2a by adding current sheets around the vacuum chamber area (shaded in blue). The center sheet is 70 mm wide and 10 mm high. Alternatively, the magnet in Fig. 2b achieves the same fields by adding steel wedges to the magnet poles. The magnetic fields for these magnets are shown in Fig. 3. These magnets are mirror symmetric about the horizontal dashed line, and are modeled with the 2D finite element code `FEMM` [6].

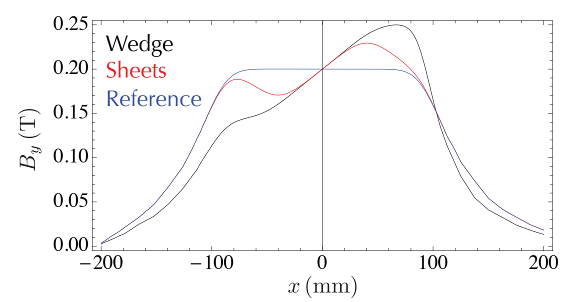
the factor $\mathcal{F}/\mathcal{J}_x \approx 60\,\mathcal{F}_{\rm TME}$. With upgraded dipole magnets, the solution in Fig. 1b would have a vastly improved emittance with factor $\mathcal{F}/\mathcal{J}_x \approx 3\,\mathcal{F}_{\rm TME}$. Essentially the vertical focusing in the dipole magnets keeps the vertical beta function under control and allows the quadrupole magnets to tightly focus the horizontal beta function and dispersion through the bend, minimizing the radiation integral that contributes to the emittance. All particle simulations and optics calculations were preformed using the software library *Bmad* [7].

DIPOLE UPGRADE CONCEPTS

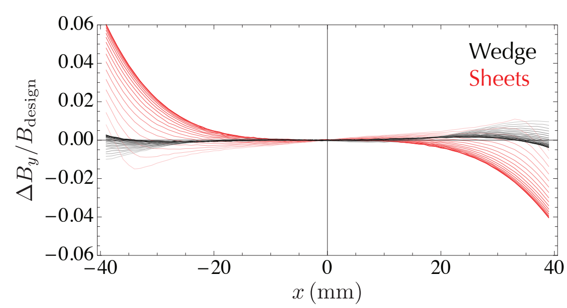
Adding pure multipole moments to magnets is a simple matter for an accelerator simulation code, whereas a physical concept must demonstrate good field quality in the region of the beam, and allow for some degree of tunability beyond the needs of the design lattice. Two concepts for adding quadrupole fields to the existing CESR dipole magnets are shown in Fig. 2. These fields correspond to the needs of the optics in Fig. 1b.

The concept in Fig. 2a has wide current sheets above and below the vacuum chamber with current $I_{\rm sheet}$ traveling through each of the central sheets. Alone, the central sheets would provide a quadrupole field and a dipole field [8]. To maintain the design dipole field, the current in each of the coils $I_{\rm coil}$ would have to be further adjusted. In the case of CESR, it is desirable that the fields due to the current sheets be decoupled from the fields due to the coils, and this is easily accomplished by adding additional return current sheets to the sides of the central sheets. Such a configuration also minimizes the stray field outside the magnet. If each current sheet constructed from 8.8×8.8 mm square, hollow (7 mm ID) copper conductor, we estimate the power to be about 6.4 kW per magnet. For a 15 C change in bulk water temperature, the coolant flow is in the few gpm range, and the pressure drop across each sheet is several psi.

Alternatively, the concept in Fig. 2b shows how steel wedges could be added to the magnet poles to the same effect, transforming the magnet into a traditional ‘combined function’ magnet. The shape of the wedge has been numerically optimized for field quality. Fields and errors for both concepts are shown in Fig. 3.



(a) On-axis fields. The reference field is for the magnet in Fig. 2a with $I_{\rm sheets} = 0$.



(b) Relative deviations from design vertical field, in vertical steps of 1 mm out to 16 mm. Darker lines are closer to the central axis.

Figure 3: Vertical magnetic fields for the two magnet concepts shown in Fig. 2. The relative deviation from the design vertical field $\Delta B_y/B_{\rm design}$ is better (smaller) for the wedge, primarily because the wedge shape has been numerically optimized for quality.

ISBN 978-3-95450-122-9

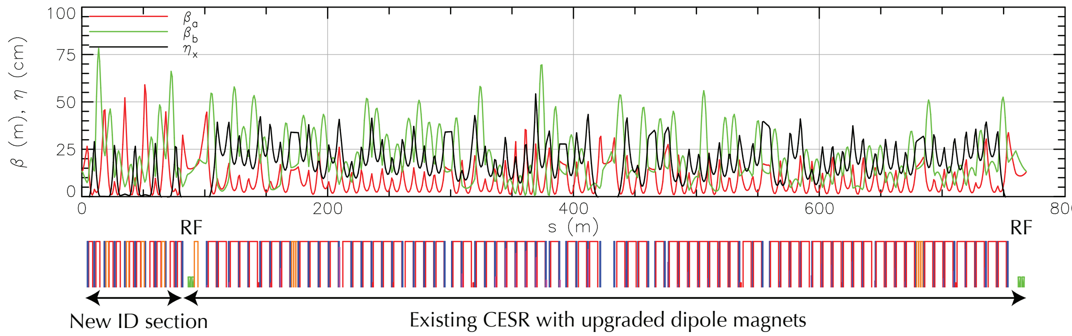


Figure 4: Optics for the realistic CESR layout, incorporating upgraded dipole magnets. A new insertion device (ID) section is discussed in Ref. [9]. The 75 sextupole magnets have been independently optimized to correct the chromaticities, limit the chromatic beta beat, and expand the dynamic aperture. This solution has $\epsilon_x = 2.5\,\mathrm{nm}$.

REALISTIC CESR LATTICE

For a realistic upgrade, we have applied the optics concept in Fig. 1b to a lattice that represents the existing CESR layout, with the addition of a new insertion device (ID) section (discussed in Ref. [9]). Figure 4 shows the linear optics for one possible solution, with some parameters shown in Table 1. This solution has $\epsilon_x = 2.5\,\mathrm{nm}$, which corresponds to a factor $\mathcal{F}/\mathcal{J}_x \approx 6.7\,\mathcal{F}_{\mathrm{TME}}$. For reference, CESR with its current FODO lattice can store emittances as low as 50 nm, but regular CHESS operation uses a 130 nm beam.

As noted in Ref. [3], a major difficulty with USR designs is that they tend to have very large negative natural chromaticities. Because the horizontal dispersion is often kept small, the sextupole magnets required to correct these chromacities are much stronger than those needed in a typical FODO lattice. Strong sextuples tend to restrict the beam's dynamic aperture, and must be carefully optimized.

Because of the many idiosyncrasies in the realistic CESR layout, there are no simple symmetries to choose families of sextuples. Therefore the 75 sextupole magnets have been independently optimized to correct the chromaticities and limit the chromatic beta beat. Furthermore, the dynamic aperture has been optimized for directly, a scan of which is shown in Fig. 5. The strongest sextupole moment is $k_2 = 35/\,\mathrm{m}^2$, which is about $600\,\mathrm{T}/\mathrm{m}^2$ at our design energy.

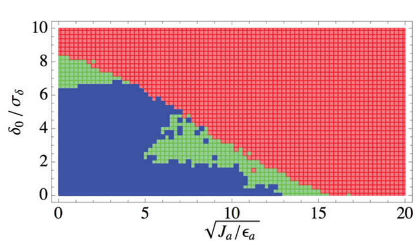


Figure 5: Dynamic aperture scan, starting with a particle with initial a-mode amplitude J_a, and initial relative momentum deviation δ_0. The axes are normalized by the emittance ϵ_a and energy spread σ_δ. Green is a survival with the RF and SR off, blue is survival with the RF on and SR on, and red is a loss, after 10,000 turns.

CONNECTION TO THE CORNELL ERL

The Cornell Energy Recovery Linac (ERL) project, described in detail in Ref. [10], is a revolutionary concept for a synchrotron radiation (SR) lightsource. The baseline design incorporates the existing CESR lattice as a return arc which degrades the excellent linac-quality emittance present just before the arc. The upgrade described here would overcome this limitation.

Table 1: Parameters Corresponding to the Optics in Fig. 4.

Parameter	Symbol	Value	Unit
Energy	$\mathcal{E}$	5.3	GeV
Circumference	$\mathcal{C}$	768.4	m
Tunes	Q_x, Q_y	26.401, 10.161	1
Emittance	ϵ_x	2.5	nm
Damping numbers	$\mathcal{J}_x, \mathcal{J}_y$	2.3, 1.0	1
Natural chromaticities	ξ_{x0}, ξ_{y0}	-43.3, -31.0	1

REFERENCES

[1] S.Y. Lee, *Accelerator Physics*, (Singapore: World Scientific, 1999), 439.

[2] S.C. Leemann et al., Phys. Rev. ST-AB **12**, 120701 (2009).

[3] Y. Cai et al., Phys. Rev. ST-AB **15**, 054002 (2012).

[4] K. Berkelman, *A Personal History of CESR and CLEO*, (Singapore: World Scientific, 2004).

[5] http://www.lepp.cornell.edu

[6] D.C. Meeker, Finite Element Method Magnetics, Version 4.2 (11Apr2012 Build), http://www.femm.info

[7] D. Sagan, *Bmad Reference Manual* http://www.lepp.cornell.edu/~dcs/bmad

[8] A. A. Mikhailichenko, CLASSE Note: CBN 13-4

[9] D. Rubin et al., TUPME066, these proceedings.

[10] G. H. Hoffstaetter, S. Gruner, and M. Tigner, eds., Cornell ERL Project Definition Design Report (2011) http://erl.chess.cornell.edu/PDDR