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

\[ \epsilon_x = \left(1/J_x\right) C_q \gamma^2 \theta^3 F, \]

where \( C_q \equiv 55h/(32\sqrt{3}mc) \), \( m \) is the mass of the particle, \( \gamma \) is the relativistic factor, \( \theta \) is the angle for a single dipole magnet, and \( J_x \approx 1 \) is the horizontal damping partition number. The factor \( F \) depends on the arrangement of focusing magnets surrounding the bends. This factor bounded below the theoretical minimum emittance (TME) factor \( F_{\text{TME}} = (12\sqrt{15})^{-1} \) [1].

When designing a new ring, the \( \theta^3 \) 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 \( F/J_x \approx 5.7 F_{\text{TME}} \) ) [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.

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...
the factor $F/J_x \approx 60 F_{\text{TME}}$. With upgraded dipole magnets, the solution in Fig. 1b would have a vastly improved emittance with factor $F/J_x \approx 3 F_{\text{TME}}$. 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 performed 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 $I_{\text{sheet}}$ 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 $I_{\text{coil}}$ 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 x 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.
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 $\epsilon_x = 2.5 \text{nm}$, which corresponds to a factor $F/J_x \approx 6.7 F_{\text{TME}}$. 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 chromaticities 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 $k_2 = 35/\text{m}^2$, which is about 600 T/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 $\delta_0$. The axes are normalized by the emittance $\epsilon_a$ and energy spread $\sigma_\delta$. 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.

<table>
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<tr>
<th>Parameter</th>
<th>Symbol</th>
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</tbody>
</table>

REFERENCES

[8] A. A. Mikhailichenko, CLASSE Note: CBN 13-4
[9] D. Rubin et al., TUPME066, these proceedings.