CESRc as a Test Facility for the International Linear Collider

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It has been proposed that in 2008 the present Cornell Electron Storage Ring (CESR) will be converted to a test facility for the International Linear Collider (ILC) damping rings. This facility, CesrTF, will allow for preliminary studies in low-emittance beams in addition to studying properties of electron clouds within the wigglers. It is necessary to examine these properties prior to the transition, preferably using the present CESRc layout or a very close variant thereof. Several possible lattices have been examined involving similar parameters to those of the CesrTF facility.

I. INTRODUCTION

The CESR storage ring is unique in that it is the only wiggler-dominated ring presently operational. Aside from scaling, it is similar in design to the proposed damping rings for the International Linear Collider (ILC). Additionally, the proposed wigglers to be used in the ILC will be modeled after the current CESRc wigglers. For these reasons, CESR is an ideal facility to test equipment before the ILC undergoes construction. It has been proposed that in 2008 CESR will be converted explicitly to a test facility for the ILC. This facility, CesrTF, will be used to explore properties within the wigglers, such as the Electron-Cloud Effect (ECE), and to gain experience in running a damping ring at low-emittance specifications.

Within a factor of π, emittance is the cross-section of the beam in phase-space. It will be crucial for the ILC to have ultra-low emittance in order to reduce the beam size, increasing luminosity and collision rates at the interaction point. When the CesrTF layout was designed it was optimized for low-emittance operation. When implemented, it will require a rearrangement of the ring to place the wigglers in zero-dispersion regions, in addition to the removal of the CLEO detector. Optimizations on versions of the CesrTF lattice have been completed, providing target emittance values of approximately $\epsilon_x \approx 2$nm, $\epsilon_y \approx 5$–10pm.

The Electron-Cloud Effect occurs when radiated photons or charged particles strike the chamber walls. In doing so, the particles may excite other electrons and cascade into an electron cloud. When a positron beam passes through the chamber, these electrons will be drawn toward the center of the beam-pipe and disrupt the beam optics. In a wiggler-dominated ring this will impair the pursuit of ultra-low emittance such as that desired by the ILC damping rings. The ILC damping ring emittance goals are on the order of 0.8nm in the horizontal and 2.0pm in the vertical [1]. In order to achieve these ultra-low emittance values, it is necessary to further understand ECE and its suppression within the wigglers.

Although the conversion to the CesrTF configuration will not occur until 2008, it will be possible to use the present configuration (CESRc) to examine phenomena such as ECE and its suppression within the wigglers, and allow researchers to gain experience in operating the ring under similar conditions to CesrTF, while leaving the CLEO detector in place.

II. WIGGLER-DOMINATED STORAGE RINGS

Because CESR is wiggler-dominated, the lower bound on the emittance is determined by parameters within the wiggler regions. For any wiggler-dominated ring where the wigglers are in zero-dispersion regions, the minimum horizontal emittance achievable becomes [2]

$$\epsilon_x \approx C_q \frac{\gamma^2}{J_x} \frac{8\beta_x}{15 k_p^2 \rho_w^3}, \tag{1}$$

where $C_q = 3.8319 \times 10^{-13}$m, γ is the relativistic factor, J_x is the horizontal damping partition number, β_x refers to the oscillation envelope Twiss parameter, k_p is inversely related to the wiggler period, and ρ is the bending radius. By placing the wigglers within a region of zero dispersion, we ensure that the trajectory changes as the particles emit synchrotron radiation, and hence the emittance growth is minimized. It is useful to note that when the wigglers are placed within regions of zero dispersion the emittance is proportional to the beta function. At an operating energy of 2.0GeV in the present CESRc configuration, the lower theoretical limit for horizontal emittance becomes $\epsilon_x \approx 1.4$nm.

One of the primary uses for having wigglers in a storage ring is for radiation damping. Because there is some inherent dispersion of the beam, not all particles will be on-energy at all times. Bending magnets cause the electrons to emit synchrotron radiation and lose momentum. When the electrons reach the RF cavities, additional momentum is applied explicitly in the forward direction. The bending magnets will continue to decrease the momentum in all coordinates on each pass, bringing the electrons closer to an equilibrium at the ideal on-energy trajectory. This process, known as radiation damping, acts as a cooling effect on the transverse momentum of the beam. In a normal storage ring this effect takes place mostly in the bending magnets; however, in a wiggler-dominated ring (such as CESR or the proposed ILC damping rings), the damping primarily occurs within the wigglers themselves, increasing the rate at which the damping occurs.

The CESRc layout presently has 12 wigglers installed, located in four groups of three along the arcs with the groups being East–West symmetric. It has been determined that it is possible to create zero-dispersion regions within two of these groups, and another zero-dispersion region is readily created at the North Interaction Point. The CesrTF lattice will therefore maintain the two groups of wigglers already in potential zero-dispersion regions and relocate the remaining two triplets of wigglers to the North IP. To simulate this in the modified CESRc lattice, the wigglers in nonzero-dispersion regions were disabled. A zero-dispersion region was also enforced at the North IP.

One significant difference between the proposed changes to CESRc and the CesrTF facility is the CLEO detector. The CLEO detector has many magnets that introduce coupling, including permanent magnet quadrupoles that cannot be disabled. The designs for CesrTF assume that CLEO will eventually be removed, but until then the detector will remain in place. Configurations are being explored where the variable CLEO elements have been reduced or completely disabled. The primary configuration being investigated has kept the solenoid and coupling elements at full current.

III. TAO

When generating the modified CESRc lattices, it is necessary to intentionally distort or otherwise modify the optics in order to achieve certain desired constraints on the system. The primary utility used during this part of the optimization process was Tao [6], a software package based on the Bmad accelerator library [7]. Tao allows the user to simulate an accelerator or storage ring and optimize the optics in such a way to achieve desired parameters. To scan for global minima fulfilling these parameters, the Differential Evolution (DE) optimizer was utilized. When the global minima were located, a second optimizer, the Levenburg–Marquardt (LM) algorithm, was used to determine more localized minima within these regions.

The primary constraints applied in these optimizations were: dispersion within the wigglers and at the North IP; on the beta functions; constraining the tunes; and decreasing the coupling of the transverse coordinates. The latter two will be discussed in following sections.

In addition, Tao allows the user to plot various functions and parameters of the lattice. Graphs of the beta functions and dispersion were useful in minimizing these parameters within specific regions. Plots for the CesrTF and CESRc lattices (Figure 1) show similar optics parameters have been achieved.

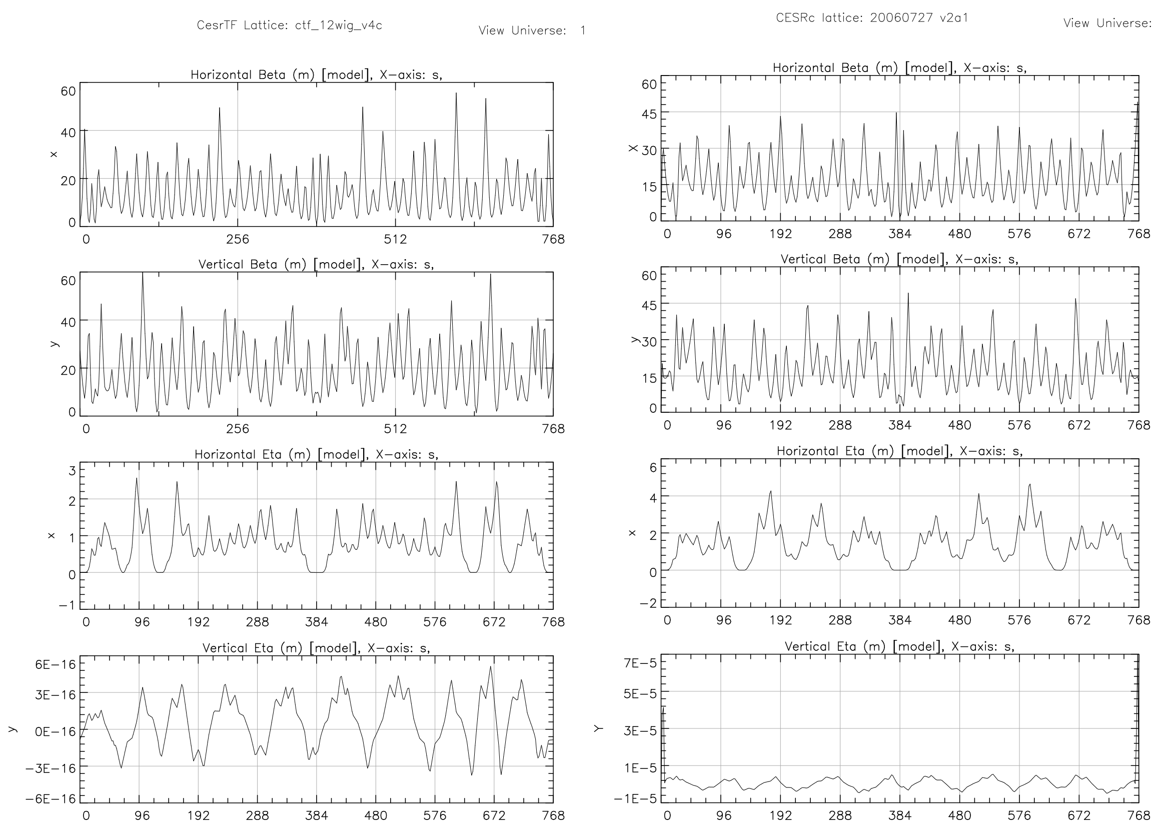

FIG. 1: Outputs from Tao for CesrTF [4] (left) and an optimized CESRc variant [5] (right). Plots of beta (top) and dispersion (bottom) are included for both. Important features include: beta functions held under 60m, zero dispersion in the wiggler regions and RF cavities (in addition to the North IP, in the CESRc layout), and beta functions minimized in the wiggler regions. (Recall that in regions of zero dispersion, the emittance is proportional to the beta function)

IV. TUNE SCANS

The tune, Q, is defined to be [3]

$$Q = \frac{1}{2\pi} \oint \frac{ds}{\beta(s)} \tag{2}$$

This value defines the number of betatron oscillations the beam undergoes in each coordinate during each pass through the accelerator. This property is directly controlled by the quadrupole elements in the lattice.

The Q value can be decomposed into two components, the integer tune and the fractional tune, which can be analyzed separately. The integer tunes are mostly chosen based on the strength of the quadrupoles. High quadrupole strength will result in a high integer tune, which should in turn theoretically lead to a smaller lower-bound on emittance generated by the bends. The integer tune is most easily adjusted by modifying the QTune groups of the lattice. QTune groups are simply groups of quadrupoles whose strength adjustments have been linked together in order to make changes in the horizontal and vertical tunes easier. In the present CESRc lattice, integer tunes of 10 in the horizontal, 9 in the vertical are used; in the proposed CesrTF facility, integer tunes of 14 in the horizontal, 9 in the vertical are being explored.

It is important to take care when choosing the fractional tunes for the lattice. If the fractional tunes in the horizontal and vertical coordinates are too close to each other the coordinates will become coupled, thus causing a large increase in vertical emittance. To prevent this from occurring, a minimum separation in the fractional tunes is generally imposed (a typical scale would be ≈ 0.04). There is also a possibility of resonance if a simple fractional tune is used (for example, 0.5, or 0.25). Any inherent imperfections in the lattice will compound quickly after the beam makes several revolutions through the ring, and the beam will likely lose stability and strike the beam-pipe. For this reason, simple fractional tunes are avoided.

To assist in choosing suitable fractional tunes, a tune scan is performed. A tune scan is a process that tracks particles and identifies regions where the beam size increases due to resonance or coupling effects. The output assists in choosing an ideal coordinate in the fractional tune plane to operate at while minimizing the risk of resonance. Figure 2 shows tune scan plots for both the CesrTF and primary modified CESRc lattices.

V. SEXTUPOLE OPTIMIZATIONS AND DYNAMIC APERTURE

Much like an optical system, the focusing effects of the quadrupoles result in chromatic aberrations due to particles being slightly off-energy. The energy dependence of quadrupole focusing is corrected by sextupole magnets. These magnets correct the focal length for off-momentum particles. These magnets are intentionally placed in regions of nonzero dispersion, where particles of different momenta are sorted transversely. The focusing strength of the sextupole magnets increases linearly with respect to the horizontal displacement; therefore, more focusing will occur on particles that are further off-energy. By optimizing the distribution and strengths of the sextupoles, one can minimize the chromatic aberrations that naturally occur from quadrupole focusing. The sextupole optimizations were achieved using standard CESR utilities [8].

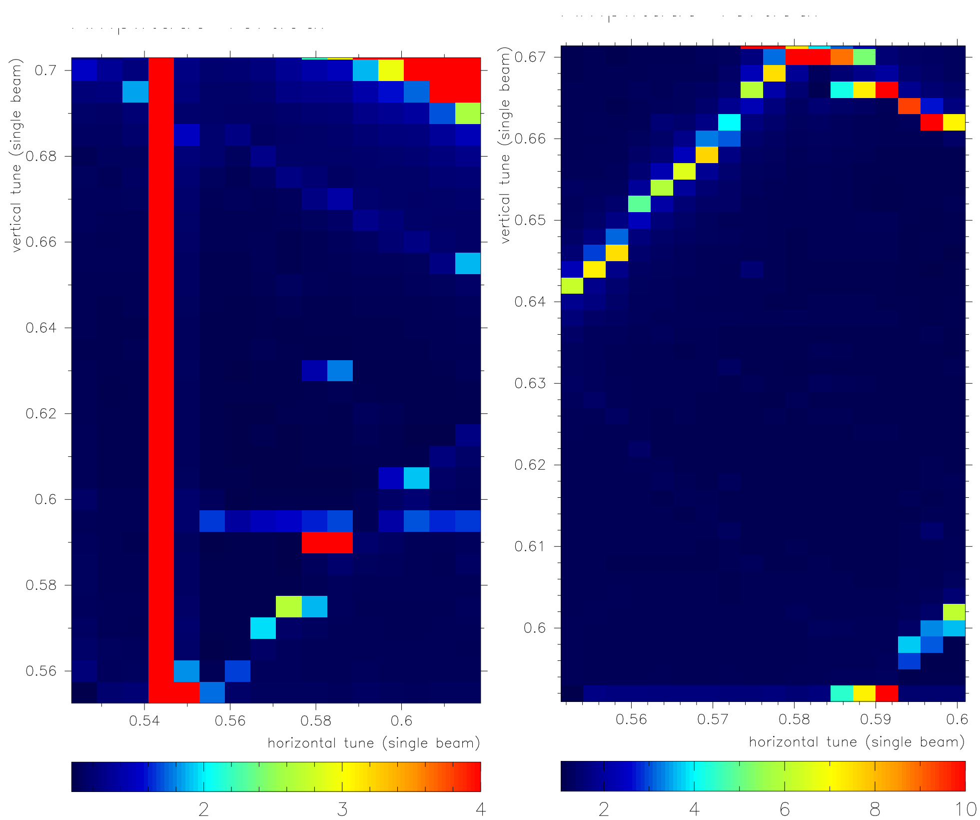

FIG. 2: Tune scans performed for CesrTF [4] (left) and an optimized CESRc variant [5] (right). Regions that are red indicate resonance, whereas regions that are blue are more stable. In these cases, fractional tunes of $Q_x(fract) = .572$, $Q_y(fract) = .615$ for the CesrTF lattice, and $Q_x(fract) = .580$, $Q_y(fract) = .630$ for the CESRc lattice.

Once the particle beam has been stabilized for both on-energy and off-energy particles, the actual dynamics of the beam may be examined. When sextupoles are introduced into the storage ring the beam becomes inherently unstable outside a certain range in phase-space. The region in phase-space in which the beam is stable is defined as the dynamic aperture. It is not possible to solve for the dynamic aperture analytically; rather, numerical methods must be used. In this case a standard CESR utility was used for particle tracking, measuring how far off-energy and off-axis a particle would have to be before it was lost. Figure 3 shows the dynamic aperture studies performed on both the proposed CesrTF lattice and the primary modified CESRc lattice.

VI. CONCLUSIONS

A brief summary of the base CesrTF and modified CESRc lattices has been included as Table I.

There is some uncertainty in the vertical emittance that will be possible using this modified lattice. The lowest coupling that CESR has achieved is 0.5%, but the facility is not presently capable of measuring the range of emittance theoretically possible according to this optimization. The vertical emittance will likely be dominated by magnet errors, therefore a more reasonable estimate would be $\epsilon_y > 100$pm.

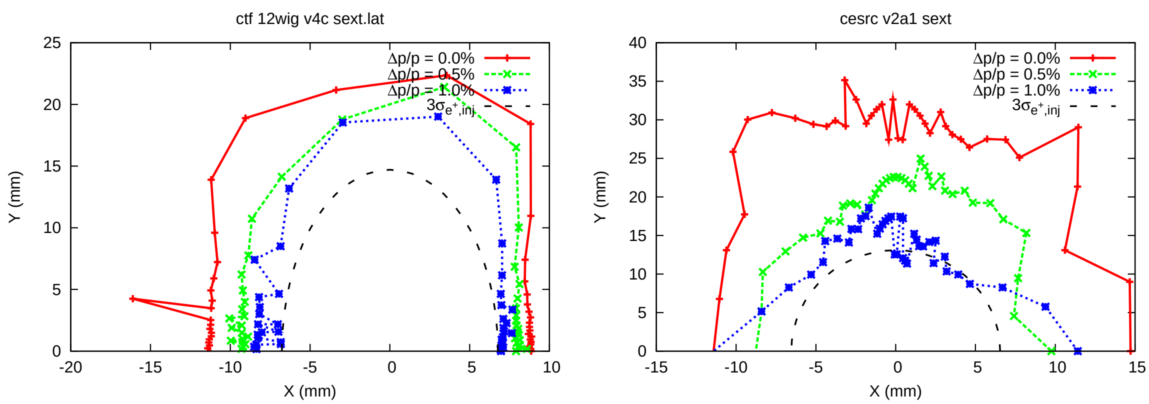

FIG. 3: Dynamic Apertures for CesrTF [4] (left) and an optimized CESRc variant [5] (right). The red line denotes particles that are exactly on-energy, green are particles 0.5% off-energy, and blue are particles 1.0% off-energy. The outlines mark where in the cross-section the particles are lost, showing the dynamic aperture. The black dashed line is a simulated injection cross-section, at 3σ. From this it is evident that the dynamic apertures in both of these lattices are reasonable for particles that are 1% off-energy.

TABLE I: A summary of parameters achieved in the CesrTF and base modified CESRc lattice optimizations.

Lattice	$\epsilon_x (nm)$	ϵ_y (pm)
ILC Design	0.8 nm	2.0 pm
CesrTF	2.0 nm	5–10 pm
Present CESRc	100–200 nm	500–1000 pm [9]
Modified CESRc	6.5 nm	?

The results that are theoretically achievable using the present CESRc lattice look promising. It appears that it will be possible to achieve horizontal low-emittance parameters within a factor of 3.5 of CesrTF, even with the coupling effects from the CLEO solenoid and compensating elements.

The next stage is to investigate reducing the current in the CLEO solenoid and coupling elements, ideally to the point where the main solenoid has been deactivated. The coupling elements will remain on at some degree due to the pair of permanent magnet tilted quads within CLEO, which cannot be deactivated or removed at this time. Optimizations on this variant are currently underway, with the main CLEO solenoid at 10% current.

Other variations that are currently being explored include an increased horizontal integer tune. Presently CESRc operates with a horizontal integer tune of 10, whereas CesrTF will operate at 14. Lattices based on CESRc with integer tunes of 11 and 14 with the CLEO detector in-place are presently being optimized for low-emittance. Versions of these two lattices with the CLEO solenoid disabled will also be considered in the future, when optimizations have been completed on the higher integer-tune lattices.

VII. ACKNOWLEDGMENTS

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[1] CESR wiki, Damping Ring Configuration Recommendation, available at https://wiki.lepp.cornell.edu/ilc/pub/Public/DampingRings/ConfigStudy/DRConfigRecommend.pdf
[2] Internal memo, M. Palmer
[3] K. Wille, "The Physics of Particle Accelerators," p. 101, Oxford University Press, 2000
[4] CesrTF lattice version v4c.
[5] CESRc lattice version v2a1, with new fractional tunes.
[6] Tao documentation, available at http://www.lns.cornell.edu/∼dcs/bmad/tao.html
[7] Bmad documentation, available at http://www.lns.cornell.edu/∼dcs/bmad/
[8] Sextupole optimizations completed by Mike Forster.
[9] Based on the lowest coupling achieved by CESR, at 0.5%.