CESR-C: A WIGGLER-DOMINATED COLLIDER*

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Abstract

CESR-c operates with twelve 2.1 Tesla wigglers that account for 90% of the synchrotron radiation with beam energy in the range of 1.8 to 2.1 GeV. The wigglers reduce the radiation damping time from 0.5 seconds to 50 milliseconds.

The carefully designed wigglers restrict neither physical nor dynamic aperture of the storage ring though both quadrupole and sextupole distributions must be tailored to compensate the primary optics effects of the wigglers. Colliding beam performance limits are determined by the numerous parasitic beam-beam interactions in the single ring. Several approaches taken to mitigate these limiting effects are described herein.

The CESR-c wigglers are an excellent match to the requirements for future damping rings. Flexible optics, extensive infrastructure, and resource expertise, form an effective test bed for assessment and solution of damping ring issues such as electron cloud and ion effects, and exploring ultra-low emittance beams.

INTRODUCTION

CESR – a Brief History

The Cornell Electron Storage Ring CESR has been in operation since 1978 and has been extensively described in previous publications. [1,2] The storage ring has a circumference of 768 m and was unique at the time of construction in that all quadrupoles and sextupoles are independently controllable. While initially motivated by the geometry of the ring, incorporating bending magnets with bending radii covering the range of 33 to 140 m., this flexibility in optics has proven to be essential to the many successful upgrades throughout CESR's history.

A succession of upgrades includes permanent magnet, and later superconducting quadrupoles for small beta interaction region optics, superconducting RF cavities, and operation with up to 45 bunches per beam in a single vacuum chamber. [3] The upgrade from a single bunch to multiple bunches per beam prompted an upgrade to the linac injector to deliver to CESR multiple high intensity, full energy bunches each 60 Hz injection cycle.

As many as 45 bunches in each beam circulate in a single vacuum chamber for colliding beam physics, arranged in up to 9 trains of 5 bunches each. Undesired, or parasitic, collisions are prevented by the horizontal "pretzel" orbit as shown in Figure 1. Often other bunch patterns are found to be advantageous. E.g., leaving out a train to form an ion clearing gap or reducing the number of bunches per train to provide better separation and increase charge per bunch for the same parasitic beam-beam limitation.

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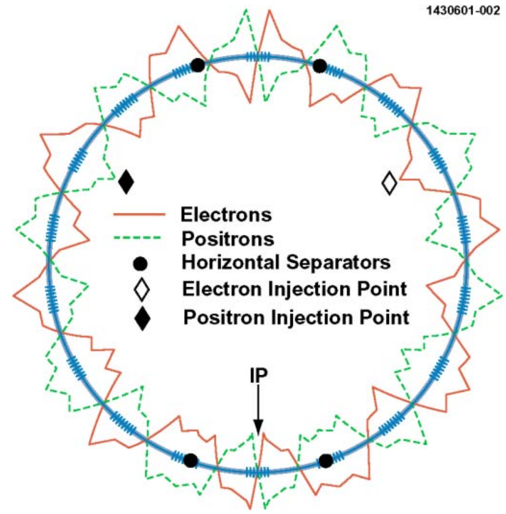

Figure 1: Schematic layout of CESR with pretzel orbits

CESR carried out very productive studies using the decay of B mesons for many years while delivering record luminosities. However, the advent of the spectacularly successful asymmetric B factories at SLAC and KEK prompted the realignment of CESR's capabilities to other physics realms. The ability to use a state-of-art detector, well characterized by years of observing B decays, along with record luminosities in the Charm regime has proven to be a very productive combination.

Producing Charm mesons requires operation of the storage ring at a fraction of the original 8 GeV design maximum energy. The need for enhanced damping to sustain the high currents and beam-beam space charge limits was quickly realized, and strong wiggler magnets, providing 90% of the synchrotron radiation power, were the primary accelerator upgrade task.

Energy Dependent Effects

The luminosity of electron-positron colliders often scales as E_0^4 but the exact exponent depends on the measures taken to mitigate loss of luminosity as the energy is lowered. Other colliding beam storage rings have operated over an energy range comparable to CESR-c, but none had previously been able to modify the damping time as drastically as was proposed for CESR-c. The natural E_0^{-3} dependence would produce a damping time at 1.9 GeV of over 500 ms. This can be reduced by a factor of 10 by the strong wiggler magnets. In addition, the transverse beam emittance would decrease by a factor E_0^2 (~ 8). The energy scaling of beam dynamics effects is determined by the rigidity of the beam, the radiation damping rates, and the quantum excitation effects of radiation. Choosing the correct weight to place on each of these effects is key to accurately projecting operating parameters.

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LOW ENERGY CONSIDERATIONS

Accelerator Physics

Insight into the physical processes determining the luminosity of an e+-e- collider is frequently found through equation 1:

$$L = 2.17 \times 10^{32} (1+r) \frac{n_b i_b E_0 \xi_y}{\beta_y^*} \quad (1)$$

where L is the luminosity in cm^{-2}-s^{-1}, i_b (A) the current per bunch, n_b the number of bunches per beam, E_0 (Gev) the beam energy, ξ_y the vertical beam-beam space charge parameter, and β_y^* (m) the vertical focusing function at the interaction point.

Beyond the explicit linear energy dependence shown here, ξ_y is found to vary as damping time $\delta_y^{0\to -1}$. Bunch current (i_b) limits can have a wide range for energy dependency according to the primary limiting phenomenon while the number of bunches will have a weak, if any, dependence. The optics at the interaction point may benefit from lower energy if limited by magnet strengths. Injection rates usually depend on damping time, affecting integrated luminosity.

The added transverse acceleration in wiggler magnets is the most effective means to control radiation damping. (Changing damping partition numbers has also been used but is limited to changes ~x2.) In a ring where synchrotron radiation is primarily from wiggler magnets (which we will call "wiggler dominated") the scaling of several important machine parameters with wiggler length and magnetic field is summarized:

Damping time	Horizontal Emittance	Energy spread
$\tau \propto \frac{1}{L_W B_W^2}$	$\varepsilon_X \propto B_W H_W$	$\frac{\sigma_E}{E_0} \propto \sqrt{B_W}$

where B_w is the peak magnetic field in the wigglers, L_w the total length of such wigglers, and H_w the normalized dispersion at the wiggler(s), or "emittance function" and is controllable over a wide range via optics manipulations.

While wigglers can offer effective control of damping time and emittance as beam energy is decreased, there is an unavoidable penalty in beam energy spread, reducible only by installing longer lengths of lower field wigglers. In addition, there are well known optical effects of wigglers; some are intrinsic, others are from field non-uniformities. [4,5].

Wiggler design

Several parameters must be chosen for the wigglers:

1) Technology
2) Peak magnetic field
3) Individual and total length
4) Period of field variation
5) Width of poles
6) Number of poles (odd and even have quite different properties).
7) Pole gap

The choice of these parameters has been previously described [6,7]. Table 1 gives a summary of the CESR-c wiggler parameters.

Table 1: CESRc Wiggler Parameters

Parameter	**Value**
Technology	Superferric
Peak Field	1.7-2.1 T
Wiggler Length	1.3 m
Number of wigglers	12
Field period (2x pole length)	40 cm
Transverse width of poles	23 cm
Number of poles	6-20 cm, 2-10 cm, 2-5 cm
Pole gap	7.6 cm
Operating current (2.1 T)	185 A
S.C. wire operating margin	50%

Optics Implications of Strong Wigglers

The systematic focusing effects from the CESR-c wigglers must be compensated by adjustments to the optics. CESR optics, both linear and non-linear, are calculated using a variety of optimization techniques [8] using tracking to compute a matrix of partial derivatives. In this framework it is straight forward to insert wiggler transfer functions obtained by symplectic integration through a fit to a 3-D field map of the wigglers. Both linear and third order (octupole-like) vertical focusing properties of the wigglers must be compensated in optics design with solutions dependent on numbers and placement of wigglers.

Other Low Energy Effects

Several other effects in low energy operation of CESR were potential concerns.

The multipole components of arc magnets were measured and found to be comparable to operation at 5.3 GeV where we have had extensive operating experience.

Superconducting interaction region quadrupoles were installed 2 years before low energy operation began, replacing permanent magnet (vertical focusing) and iron-copper (horizontal focusing) quadrupoles. The operational characteristics of this new IR configuration were not confirmed at the previous performance level.

Six electrostatic separators form an integral part of the guide field to maintain separation at the multiple parasitic crossings. Any nonlinear fields will scale with beam energy so these elements are not, by themselves, likely to be an increased liability at low energies.

Injector emittance will increase – both from the reduced adiabatic damping and from passage through two windows and a length of Helium gas. The Coulomb scattering cross section increases as $(Z/E_0)^2$. The Titanium windows were replaced with Beryllium to reduce the emittance growth, which nevertheless increased from 0.12 (5.3 GeV) to 0.6 (1.9 GeV) $\times 10^{-6}$ m-rad.

Finally, with the planned 45 bunches per beam, there are 89 parasitic crossings for each bunch. These effects will be described in detail since, in the final analysis, they set the performance limit of CESR-c.

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COMMISSIONING EXPERIENCE

Beam Based Wiggler Characterization

The wigglers for CESR-c operation were installed in three stages. A single wiggler was installed to make preliminary assessments of field quality in September, 2002. During July, 2003, 5 additional wigglers were installed to provide sufficient damping for initial low energy engineering runs. The last 6 wigglers were added in June, 2004 to provide full damping and allow more symmetric optics. Each wiggler introduces vertical focusing sufficient to cause an increase in Q_y of 0.1 of an integer, requiring significant changes in optics for each configuration. Approximately 90% of the synchrotron radiation power is in the wigglers.

Beam-based measurements were made to confirm the level of non-linearities introduced by the wigglers. The principle technique used was to measure betatron tune as a function of beam position in the wigglers. Good agreement with calculated values was found.[9]

Measured radiation damping rates were close to expected values, as were single beam instability limits. We compared only longitudinal damping rates since transverse stability has a significant influence from ion or electron cloud effects.

Single Beam Characteristics

Single bunch charge limits have not been extensively explored but are greater than 15 mA/bunch (2.4×10^{11} e^-/bunch). Total currents in a single beam of 150 mA have been stored. Both are well above beam-beam limits.

Both fast ion (electrons) and electron cloud (positrons and electrons) effects have been studied in CESR. [10] For the most part the impact of these effects on colliding beam performance has not been isolated from the stronger parasitic beam-beam effects discussed below.

"Slow" ion effects were seen in electron lifetime when first attempts were made to store (nearly) equally spaced trains of electrons (9 trains of 5 bunches each). Acceptable beam lifetime was obtained by leaving out one or two trains of electron bunches. Hints of this effect had been seen at 5.3 GeV after vacuum interventions. Studies of electron cloud and ion effects in CESR with wigglers in operation are in progress.

Colliding Beam Performance

The design CESR-c parameter list assumed that, beyond explicit energy scaling, most performance related parameters would primarily be a function of radiation damping rates. Luminosity performance from 2003 to mid-2007 is shown in Figure 2, and best achieved parameters are shown in Table 2. (Most of the gaps in luminosity are periods of dedicated photon science operation at 5.3 GeV.)

Several different optics solutions were tried during this period with only modest success in improving luminosity. The peak luminosity of $\sim7\times10^{31}$ cm^{-2}-sec^{-1} was achieved only through talented and intensive hands-on tuning, often with some effort to recover from a break in running. While peak luminosity appears to be relatively constant over the past 2 years, improvements in injection and efficiency have made modest increases in integrated luminosity. The reasons for the discrepancy between planned and achieved performance are generally understood and are discussed below.

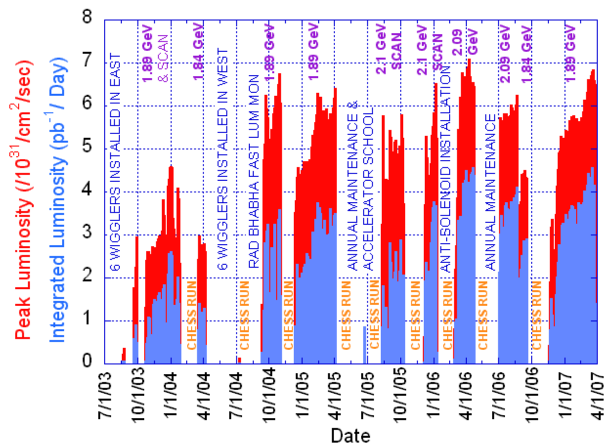

Figure 2: CESR-c peak and integrated luminosity delivered to CLEOc with configuration changes, beam energy, and dedicated photon physics (CHESS) periods.

Table 2: CESR-c design and actual parameters compared.

Beam Energy [GeV]	Achieved 5.3	Design 1.88	Achieved 1.88	Achieved 2.09
Luminosity [$\div10^{30}$]	1250	300	65	73
i_b [mA/bunch]	8.0	4.0	1.9	2.6
I_{Beam} [mA]	370	180	75	65
ξ_y	0.06	0.04	0.024	0.03
ξ_x	0.03	0.036	0.028	0.035
σ_E/E_0 [$x10^3$]	0.64	0.81	0.86	0.86
$\tau_{x,y}$ [ms]	22	55	50	50
B_W [Tesla]	-	2.1	2.1	1.9
β_y^* [cm]	1.8	1.0	1.15	1.3
ε_x [nm-rad]	220	220	140	125

Several features of CESR-c complicate any modeling of beam dynamics:

- The "pretzel" orbits used to separate the counter-rotating beams create separate optics for the two beams due to sextupoles and higher order multipoles.
- The special focusing properties of the wigglers require accurate maps to be adequately modeled for the pretzel orbits, and the localized radiation effects should be properly treated.
- Coherent beam-beam effects from up to 89 parasitic crossings cause the optics to be strongly current dependent.

Programs to adequately model the beam dynamics are complex and were not available in the initial design stages. Thus the scaling of many parameters to lower energy relied on approximate formulae and experiences at other colliders.

Once a comprehensive model and analysis software [11] were available, many analysis techniques could be applied. The code employs a weak-strong beam-beam model with periodic renormalization of the strong beam. Since the simulations are usually run with 500 macro particles in the weak beam the results are better indicators of luminosity performance than of beam lifetime. Benchmark results are shown in Figure 3.

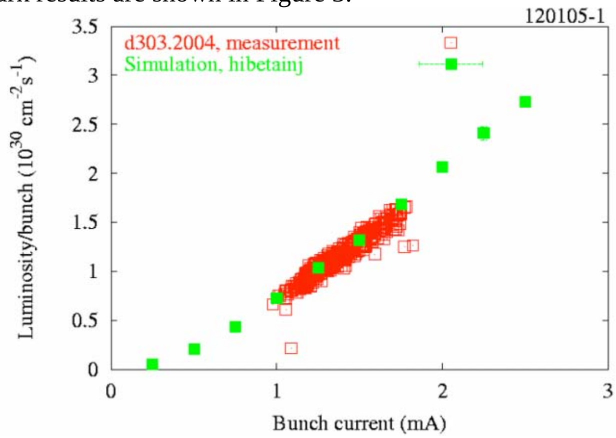

Figure 3: Comparison of simulated and measured CESR-c luminosity

Several "experiments" in the simulation were done and found the following changes in specific luminosity in the 2-3 mA/bunch range:

- Wiggler non-linearities were turned off *- no change*
- Low field wigglers creating similar damping times were distributed uniformly around the arc – *better performance but comparable to that predicted by changing only energy spread and synchrotron tune (Q_s) resulting from lower field wigglers and momentum compaction.*
- Turn off pretzel and parasitic crossings - *<10% increase*
- Turn off CLEO solenoid and coupling compensation – *50% increase in specific luminosity*
- Add anti-solenoid to IR coupling compensation – *25-30% increase in specific luminosity*
- Reduce Q_s or reduce bunch length to ½ nominal – *comparable results – higher bunch current without particle loss, 1.8x luminosity at 3 mA/bunch, ξ_v increases from 0.03 to 0.055.*

These simulations and machine physics experiments identified several components limiting performance.

Beam current limits: Ion effects required leaving out one train of bunches to create an ion-clearing gap, reducing the maximum number of bunches from 45 to 40. Empirical tuning has at times suggested running with as few as 3 bunches per train (24 bunches). Parasitic beam-beam effects reduce both beam lifetime and injection efficiency above 80 mA per beam.

CLEO-c solenoid compensation: We found that the compensation of horizontal-vertical coupling from the CLEO-c solenoid has a strong energy-dependent component. Anti-solenoids were constructed and installed to improve these chromatic effects. Results are discussed below.

Synchrotron tune / bunch length: It is well known that betatron phase modulation from synchrotron oscillations can reduce luminosity performance. Simulation studies indicate that this is the dominant limitation to luminosity performance. This is partially a side-effect of the wigglers since their high peak fields increase the beam energy spread roughly three-fold, requiring high RF dV/dt to control bunch length. The pretzel requirements restrict options to reduce the momentum compaction. To date no practical option for mitigation of this effect has been found.

Other than the effects of large energy spread discussed above, the wigglers have not been implicated in CESR-c performance limitations.

Performance Improvement Efforts

The work to improve beam current and beam-beam limits may be divided into four general areas. Once all 12 wigglers were installed, several variations in optics were tried. These include interaction point beta functions, injection point beta and dispersion functions, some variation in betatron tunes, alternate compensation schemes for the CLEO solenoid field, variations in RF voltage and frequency, and different tuning knobs providing orthogonal adjustment of accelerator parameters. As mentioned above, momentum compaction changes are very difficult because of the bunch separation requirements of the pretzel orbits.

A second thrust has been to calculate, measure and compensate the parasitic beam-beam effects by massaging of betatron phases to minimize interaction of the beams at parasitic crossings. Beta-beats as high as 40% arise from the parasitic beam-beam interactions. (Separation criteria constrain optics so all parasitic crossings tend to add in phase but with large bunch-to-bunch variations.) Figure 4 shows calculated maximum horizontal beta vs. opposing beam current for a train of 4 bunches.

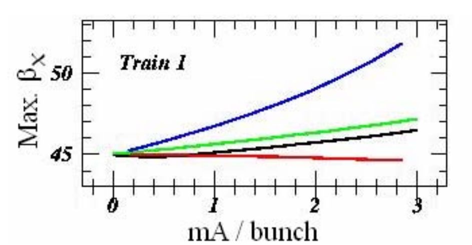

Fig. 4: Maximum β_x in arc for 4 bunches from parasitic beam-beam effects vs. opposing beam bunch current.

Using CESR's individually settable quads, closed beta bumps can be calculated that compensate for the linear tune shift effects of each cluster of parasitic crossings. [12] It is straight forward to extend this compensation to the primary beam-beam interaction also. Experience with this compensation has been mixed. Some machine studies measurements show improvement in injection and beam lifetime, but finding direct evidence of luminosity gains resulting from the bbi compensation has proven elusive.

The third program has been to add anti-solenoids next to the CLEO detector to reduce the energy dependence of the solenoid compensation. The magnet layout around the detector is shown in Figure 5.

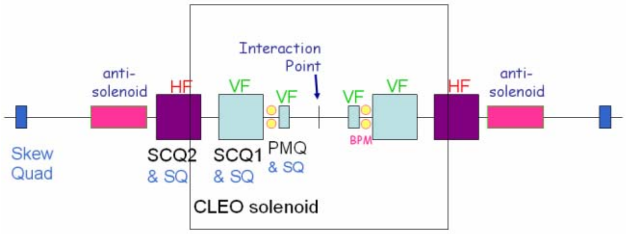

Figure 5: Interaction Region layout with anti-solenoids.

Comparing runs at similar energies before and after installation of the anti-solenoids shows a 13% increase in luminosity and nearly 30% increase in ξ_v. Backgrounds were lower and beam lifetime better. Results in succeeding runs have been inconsistent. Improved optics solutions employing anti-solenoids are being explored.

The fourth factor is consistently responsible for the last 20-30% in performance. Dedicated and talented tuning by an experienced operator has always been a critical component. This is particularly so in multi-bunch CESR where the pretzel orbits' contributions to optics and the strong current dependence of local optics introduced by the parasitic crossings create complex and changing conditions. Single beam or single bunch tuning have been found to be of limited use to actual, full current conditions. Work to find improved solutions continues.

CESR AS A FLEXIBLE TEST BED

CESR's flexibility in optics, powerful injector, high quality wiggler magnets, and decades of experience developing instrumentation and manipulating optics make a powerful and versatile test bed for accelerator R&D.

The individual control of all quadrupoles and all sextupoles gives complete flexibility in linear and non-linear optics design, and also facilitates beam based diagnostics.

A comprehensive collection of optics design and modeling tools with real-time link to the accelerator control system makes it possible to do optics correction and adjustments in minutes rather than hours or days. The beam diagnostics complement the optics capabilities effectively.

With the use of low impedance super conducting RF cavities, the primary source of narrow band impedance in CESR is in the six electrostatic separators. This number will be reduced to two after CLEO-c running is done and is expected to raise significantly the current thresholds for beam instabilities.

Finally the capability to quickly inject full energy multiple bunches of both electrons and positrons permits experiments to be conducted in short lifetime (Touschek scattering limited) conditions. A companion paper [13] describes in detail the potential for detailed R&D relevant to high performance damping rings.

SUMMARY AND ACKNOWLEDGEMENTS

CESR-c with its 14 meters of strong wigglers has increased the world sample of events in the 3770 to 4170 MeV mass range by more than fifteen-fold in less than four years. Performance limitations have been primarily due to parasitic beam-beam effects. The wigglers have performed effectively with no discernable negative effects other than the expected increase in beam energy spread.

CESR is extremely powerful and flexible as a test bed for accelerator R&D, well positioned to provide experimental corroboration of designs for future damping rings and storage rings.

This work was made possible by the dedicated efforts of the staff at Wilson Lab. The operators and operations group have worked tirelessly to understand and improve CESR-c as a colliding beam storage ring. The talented technical support staff has provided quality construction and maintenance of accelerator components.

Finally I would like to remember the leadership and foresight of former director Boyce McDaniel whose initiative to make CESR a multi-bunch machine paved the way to the successes we have enjoyed.

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