

1.1 Colliding Beams at the Cornell Electron Storage Ring CESR

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1.1.1 Introduction

The electron-positron collider CESR was constructed as an upgrade to the Cornell Electron Synchrotron in the late 1970's, originally designed to operate at 16 GeV center of mass with a maximum luminosity of $1 \times 10^{32} \text{ cm}^{-2}\text{-sec}^{-1}$. [1] The parameter list specified a single 100 mA (1.5×10^{12} e-) bunch in each beam and beam-beam parameters of 0.06 in each plane. The fortuitous discovery of the Upsilon family of resonances at FNAL quickly focused activities at CESR in the 9.4-11 GeV c.m. regime. Eventually the excess design energy was traded for increased beam currents to push toward higher luminosity.

After a description of the beginnings of CESR we cover the main elements of change throughout its history as a collider. These include multi-bunch operation, optics development, and the transition to Charm physics, CESR-c. The development of several critical systems also plays a critical role in improvements and upgrades. These are covered in 1.1.5 Development of Accelerator Systems.

The primary chapters are:

- 1.1.1 Introduction
- 1.1.2 The Foundations of CESR
- 1.1.3 Multibunch Operation
- 1.1.4 Optics
- 1.1.5 Development of Accelerator Systems
- 1.1.6 CESR-c
- 1.1.7 Performance Overview
- 1.1.8 Acknowledgements
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1.1.2 The Foundations of CESR

1.1.2.1 Initial CESR Configuration

Constraints on the initial layout of CESR drove several design decisions that would prove central to later successes in luminosity achievements. In fact, throughout the

development of CESR as a collider the hardware infrastructure has been an essential component to advances in performance.

The CESR collider was constructed as an upgrade to the existing “10 GeV Synchrotron” on the edge of the Cornell University campus. The ring had to share a 10 foot diameter tunnel with the synchrotron and provide space for two high energy physics (HEP) experiments. Since the synchrotron was close to circular, providing sufficient space for large experimental detectors required some significant manipulations to bending magnet configuration, inserting long drift sections (also to provide space for RF cavities) followed by small radius bends. Next, low field bends were required adjacent to the high energy physics detectors to control synchrotron radiation background. Furthermore, the RF sections of the synchrotron introduced interruptions to a uniform radius in the tunnel layout at several locations.

The two HEP detectors were located 180° apart in azimuth. A large detector (CLEO) with 1.5 T solenoid field, and optimized for particle detection was located in the larger interaction region in the main laboratory building. 15 m underground the CUSB (Columbia-Stony Brook) detector located at the symmetry point incorporated a lead-glass calorimeter for spectroscopy measurements. The CUSB detector was considerably smaller with no magnetic field at the beam line.

This geometry made the concept of a standard cell difficult to hold, and the need to manipulate optics functions to control the emittance generated in the high field bends caused the number of quadrupole families to grow week-by-week during the design stage. When the number of families reached 18 with pressure for more, the magnet power supply plan was reviewed and, with the introduction of a relatively inexpensive, high precision power supply concept [2] and high impedance coil configuration, the decision was made to power quadrupoles individually. It was natural to do the same for the sextupoles.

The concept of no quad families, and no standard cell led to alternate approaches in optics design. Rather than the conventional path of standard cells, matching sections, and inserts, global optimization algorithms had to be developed that could control optics functions at each quadrupole and the interaction points, including effects of the high field bends on beam emittance.

The former 10 GeV synchrotron was retained as part of the injector chain with a circumference of 60/61 times that of CESR. This feature permitted simultaneous acceleration and injection into CESR of many bunches within each (60 Hz) acceleration cycle.

1.1.2.2 Initial CESR Performance

First beams were stored on April 2, 1979 with first measured luminosity on August 14 of that year. [1] For the reasons outlined below, beam-beam performance was initially mediocre, around $3 \times 10^{30} \text{ cm}^{-2}\text{-sec}^{-1}$ with beam-beam parameters ~ 0.02 . Low beta optics (10 cm β^*_{ν}) for the CLEO IR were replaced with “mini-beta” optics (3 cm β^*_{ν}) in 1981, resulting in luminosity increasing to $1.2 \times 10^{31} \text{ cm}^{-2}\text{-sec}^{-1}$. In implementing the mini-beta optics, space for compensating solenoids (to cancel the effects of the 1.5 T experimental solenoid field) became occupied by quadrupoles, requiring alternative compensation schemes to be developed (see 1.1.4 Optics).

With the geometrical constraints described above, the optics were a compromise at best. The proximity of the RF cavities to high field bends prevented achieving zero dispersion in the cavities. It also proved impossible to have zero dispersion at both

interaction points, resulting in a compromise, in hindsight with near worst case from a beam-beam dynamics viewpoint. Beam currents were limited by beam-beam effects with sudden losses when attempting to collide above the current limit (likely exacerbated by slow turn-off of electrostatic separators used for injection).

Reaching maximum current was a tenuous endeavor with the low current gun initially used. Multiple bunches were injected into the storage ring, then re-injected into the synchrotron where they “caught up” with an accreting bunch in the storage ring and were then again transferred to the storage ring. The 60/61 ratio of circumferences was chosen to facilitate this coalescing operation. In April, 1983 the low charge electron gun was replaced with a high charge gridded gun and new pre-acceleration optics and pre-bunchers, [3] providing sufficient charge to create and inject positrons into CESR without the need for coalescing.

Having struggled with what were at the time the conventional means for improving performance with only modest success, effort turned toward the less conventional directions, particularly those that could take advantage of CESR’s special infrastructure.

1.1.3 Multibunch Operation

1.1.3.1 CESR’s Adaptability to Multiple Bunches

While CESR was conceived as a single bunch per beam, two interaction region (IR) collider, a chance discussion between director B.D. McDaniel and his son during the December, 1981 holiday break turned thoughts toward additional circulating bunches. The difficult task of separating beams at parasitic collision points in the arcs was met by a “pretzel” orbit configuration cooked up by R. Littauer that winter. [4].

Higher currents resulting from multiple bunches could be handled by the vacuum system since the operating energy was well below the design energy of the storage ring, reducing synchrotron radiation power per unit current to 20% of an 8 GeV beam.

The Pretzel separation scheme employs closed orbit distortions propagating around the arcs with phase advance tailored to place the anti-nodes at parasitic crossing points. Four electrostatic separators created multiple wavelength closed orbits on each side of the diametrically opposed interaction points. With an integer horizontal tune of 9.39 it was possible to separate 6 parasitic crossings on each half of the ring, accommodating up to 7 bunches in each beam, though initial operation used 3 bunches per beam with uniform spacing.

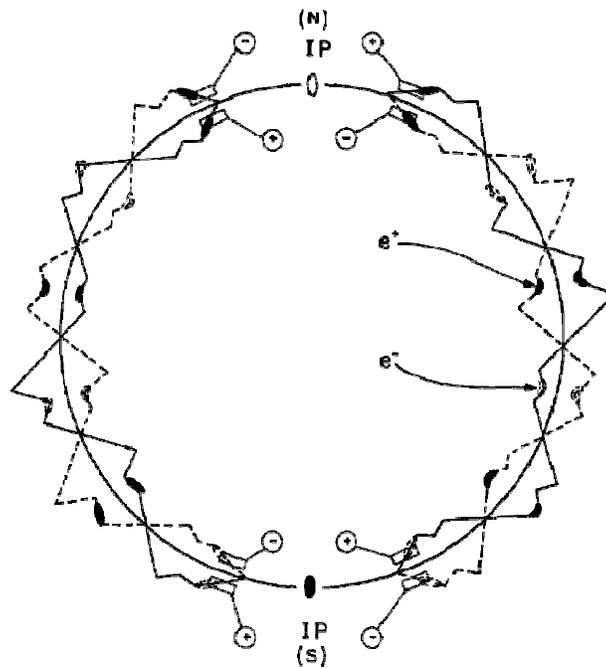


Figure 1: Early Pretzel orbits in CESR in anti-symmetric configuration.

Separation in the horizontal plane only was chosen to avoid complications from coupling introduced by vertical closed orbits in sextupoles. It was felt that dealing with the 1 dimensional optics distortions from the horizontal displacements in sextupoles was easier than fixing vertical coupling. Thus the electron beam and positron beam could have different optics functions, and even different coupling from skew-sextupole components. This and several other constraints on the optics (injection, interaction point, equal damping partition numbers etc.) leaned heavily on the flexibility of the individual quadrupole and sextupole powering scheme. A discussion of these constraints and solutions may be found in the next section.

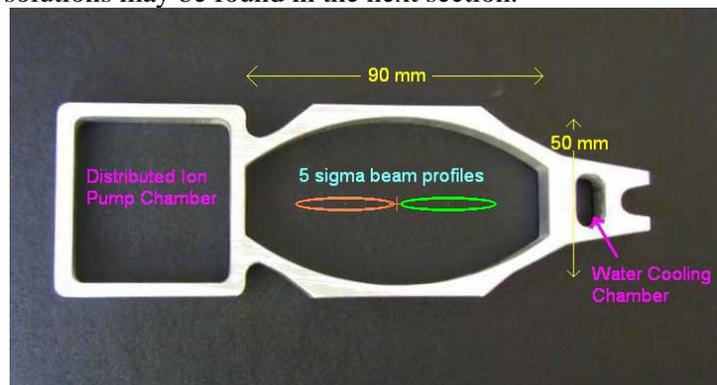


Figure 2: Separated beams in CESR vacuum chamber

The injection process in CESR achieves stacking primarily in horizontal betatron phase space. The effective horizontal aperture is reduced by the electro-magnetic field of the counter-rotating bunches. This reduction is current dependent and ultimately imposes a current limit for two-beam operation. None the less, optics solutions and

Careful tuning have allowed injection to currents limited by beam-beam effects. Injection of multiple bunches (up to 45 in later configurations) is more effective than injecting a single bunch since the full energy synchrotron used in the injector chain is capable of accelerating 20 or more bunches on each injection cycle. When well tuned, filling rates of more than 150 mA/minute for electrons and 50 mA/minute for positrons are achievable.

1.1.3.2 Initial Experience with Multi-bunch Operation

Detailed design and engineering occupied the staff for most of 1982, leading to a test of a prototype electrostatic separator in early December, 1982. Four horizontal electrostatic separators were installed in CESR by mid-June, 1983. To make space for the two separators on the North half of the ring, a dipole magnet on each side had to be removed and the adjacent dipoles strengthened and moved to preserve geometry and orbit path length. (Repositioning the dipoles required carving into the tunnel wall in several places!) Three bunches per beam were used initially since only that number of bunches has perfectly uniform spacing as determined by the RF numerology. The first luminosity with three bunches per beam was measured on June 21. That Summer roughly half of scheduled operating time was devoted to machine studies to make multi-bunch operation work.

The optics effects from the separated trajectories were indeed substantial and a deep appreciation for control of optics parameters, particularly orbit control, vertical dispersion and coupling, developed during the following months. The pretzel scheme in fact embodied some of the most difficult effects of both single and two ring colliders. The electrons and positrons are in distinct rings as far as details of optics are concerned, yet the ability to correct them independently is limited. It was only in September that the luminosity with 3 bunches per beam passed that with a single bunch.

The first year's experience with pretzels is well documented in reference [4]. With the separate orbits for positrons and electrons, to be brought together at two interaction points (IP), there are many opportunities to introduce differential orbit perturbations causing misalignment at the IP's. Both symmetric and anti-symmetric pretzels were evaluated, finding the anti-symmetric pattern reduces tune differences (though independent control of tunes was later exploited for injection optimization) and lateral separation at the IP's. Isochronous pretzel orbits were also important for good performance, especially so because of the finite dispersion at the IP's.

With the finite horizontal aperture a good deal of optics optimization effort is put into "Pretzel efficiency" or the ratio between weighted minimum separation provided at parasitic crossing points to peak closed orbit excursion. As experience accumulated, more attention was turned to differential vertical orbit and differential coupling effects. In order to achieve these, and later other, conditions the ability to tailor the sextupole distribution without constraints of hard-wired families was extensively exploited.

As previously mentioned, several months of intensive studies passed before the break-even performance was reached with 3 bunches in each beam. High energy physics operation with three bunches started on October 21, 1983. After a year the 3-bunch luminosity reached $2.6 \times 10^{31} \text{ cm}^{-2}\text{-sec}^{-1}$, or 60% higher than that achieved with a single bunch. Because of the ability to inject multiple bunches in each injection cycle, the daily integrated luminosity followed closely the gains in peak luminosity.

1.1.3.3 From 3 to 7 Bunches

Since this pretzel configuration was designed to accommodate 7 bunches per beam, this was an obvious next step. During initial operation results were encouraging. However, after a few weeks of operation with increasing currents the RF cavity main power window failed. [5] (At this time a 14-cell copper RF cavity was in use.) After a second similar failure an intensive study was undertaken, resulting in modification of the cylindrical window structure to eliminate a trapped higher-order mode (HOM). A corona ring formed an effective edge-coupled waveguide around the circumference of the window. Fields from the HOM's initiated a discharge, then aggravated by the fundamental power fields to sputter metal onto the window. Removing the corona ring solved the problem.

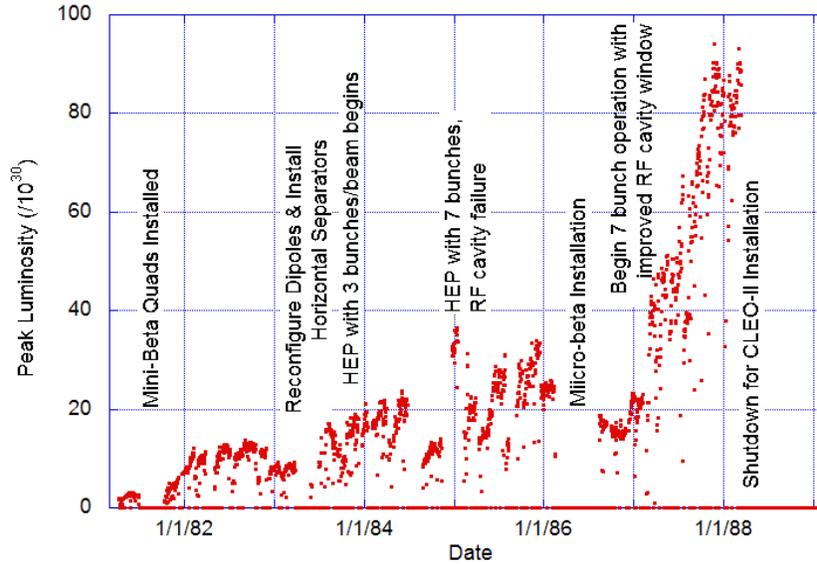


Figure 3: CESR Peak Luminosity 1981 to the CLEO-II installation shutdown in June, 1988. Most extended low luminosity periods reflect lower energy runs.

During the limited operation between window failures the peak luminosity reached $3.7 \times 10^{31} \text{ cm}^{-2}\text{-sec}^{-1}$, adding confidence that we were on the right track. Finally in December, 1986 a cavity with modified window was installed. Meanwhile in July, 1986 CESR started operation with a “micro-beta” IR optic employing permanent magnet quadrupole focusing beginning only 62 cm from the IP. Operation with three bunches did not yield an immediate luminosity increase, partly because of a run at lower energy on the Y(3S) resonance. However, after 7 bunch operation was resumed in February, 1987 at 5.3 GeV and without the current limit imposed by the RF cavity windows, the luminosity increased rapidly, reaching $9 \times 10^{31} \text{ cm}^{-2}\text{-sec}^{-1}$ by December, 1987. This was achieved with 73 mA per beam distributed in 7 bunches. The vertical beam-beam parameter was saturated at 0.017, [6] the low value likely due to high dispersion in the interaction points. The value of β_v^* was 2 cm, comparable to the bunch length. A scan of performance vs. β_v^* suggested that maximum luminosity (but not maximum beam-beam parameter) would be achieved when $\beta_v^* \sim \text{bunch length}$. [7]

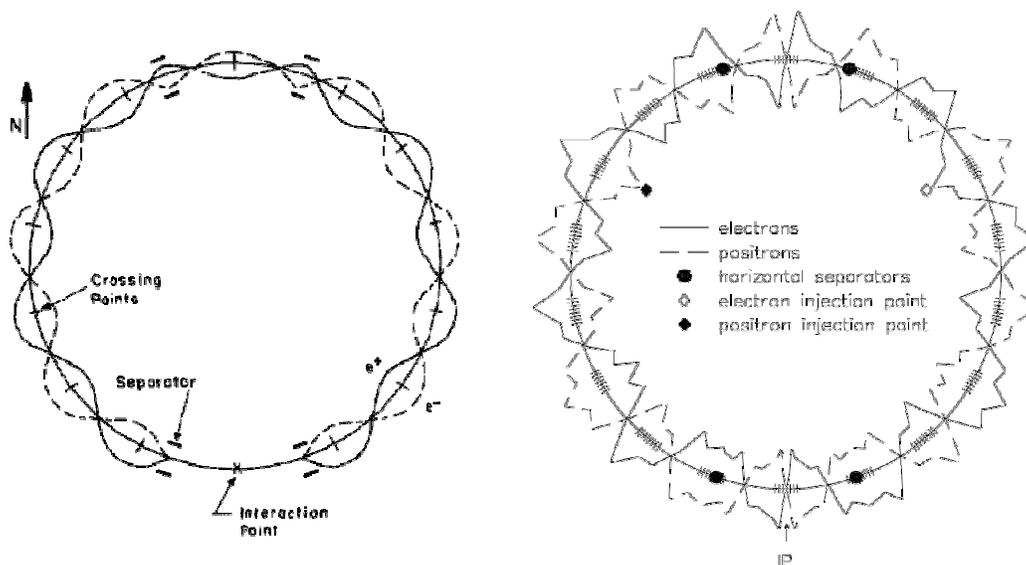


Figure 4: Single IR and Bunch Train / Crossing Angle Pretzel Orbits

1.1.3.4 Beyond 7

Encouraged by the success with 7 bunches, thoughts turned to schemes to add more bunches. Placing separators very close to the (now single) IP was studied but the technical difficulties were extreme, so this option was side lined while others were examined. A “Delta-E” option was studied extensively – by creating anisochronous pretzels the two beams could be given different energies, possibly allowing magnetic separation, at least partially.[8] A well thought out proposal by R. Meller [9] to substitute trains of closely spaced bunches for the individual bunches, separating the resulting parasitic crossings near the IP by a small crossing angle won out in the end.

Nearly 2 years of studies followed before implementing a bunch train with crossing angle for HEP. Degradation of crossing angle luminosity for a single bunch was measured [10] and calculations of resonances performed [11]. There were also distractions such as the transition from two IP’s to a single IP along with optics opportunities to improve beam-beam performance, transition from 14 cell to 5 cell CESR RF cavities, feedback kickers installed and feedback system commissioned, separators with lower HOM impedances installed, etc. All of these improvements likely contributed to a gradual climb in performance from 0.9 to $2.8 \times 10^{32} \text{ cm}^{-2}\text{-sec}^{-1}$, or $0.28/\text{nb}/\text{sec}$ in 7 bunch, single IP operation. By February, 1994 tests with crossing angle collisions had progressed sufficiently to start HEP operation with 9 bunches (1 bunch per “train”) and a crossing angle at the IP. In November a second bunch was added in each train 28 ns behind the first. While 9 bunch luminosity didn’t quite attain the best 7 bunch levels, with 18 bunches per beam the luminosity quickly climbed beyond , reaching $0.33/\text{nb}/\text{sec}$ just before a shutdown for CLEO upgrade work and modified IR optics beginning in April, 1995.

After the shutdown continual tuning and optimization of conditions resulted in a gradual increase in luminosity to $0.48/\text{nb}/\text{s}$ in March, 1998 (Figure 5) when a third bunch was added to each of the 9 trains followed by a fourth in November. Over the holiday break, with uninterrupted running and tuning, the luminosity reached

0.75/nb/sec. Later conversion to S.C. RF cavities, addition of longitudinal feedback plus much tuning would lead to a peak luminosity of 1.3 /nb/sec, at that time a world record for colliders by a wide margin. Beam currents had increased to 380 mA per beam with 45 bunches, or 9 trains of 5 bunches each.

1.1.3.5 *Il primo, Il contorno, Il dolce*

While multi-bunch with pretzel was the main dish during this period, the dinner could not have been completed without many other changes to the configuration of CESR and its injector. Upgrades to the RF system to handle the higher currents and lower parasitic mode impedances was essential – first from 14 cell copper to 5 cell copper, then to single cell super conducting cavities. Wide band feedback systems in all 3 dimensions were developed and commissioned over this period. The transition to single IR with zero dispersion and horizontal tunes above and close to the half-integer broke through the 0.025 beam-beam tune shift limit, eventually exceeding 0.06. Several upgrades to the IR improved the ability to compensate coupling and errors, and lowered the natural chromaticity.

While having the right hardware is the basis, persistent and focused tuning is just as essential to realize peak performance. This is evident from the slow yet steady increases in performance between major hardware changes.

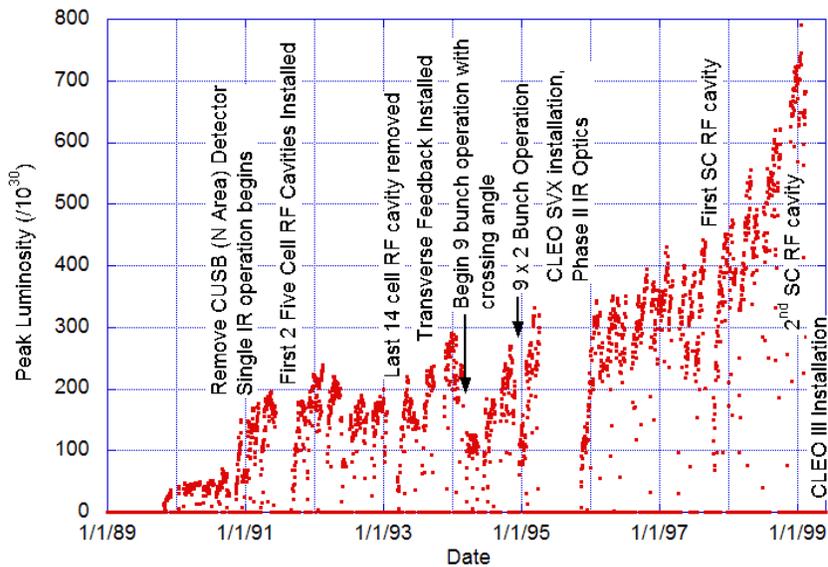


Figure 5: CESR peak luminosity from 1990 through 1998. The cyclic patterns, particularly evident in the later years, result from shutdown recovery or energy or equipment changes.

1.1.4 Optics

1.1.4.1 *Two interaction regions*

With two interaction regions and pretzeled orbits designed to accommodate 7 bunches/beam, CESR operated with both horizontal and vertical tunes just below the half integer. The difference in fractional tunes ($Q_h - Q_v$) was less than 0.15, so that it was straightforward to tune onto the coupling resonance to diagnose global coupling. The integer part of the horizontal tune was 9 to satisfy the constraints imposed by the horizontal separation scheme, 3 full wavelengths in each arc between each separator pair, and then a bit more than 1.5 wavelengths from the east separator, through the IR to the west separator.

The separators in the east and west arcs were powered with anti symmetric voltages so that sextupole feed down would contribute symmetrically to pretzel dependence of tune shift and β^* . The two family sextupole distribution, while enough to adjust horizontal and vertical chromaticity, was extended to four families with a degree of freedom to correct differential phase advance through the arcs.

Multibunch operation began with 3 bunches/beam. The sophisticated control system software that allowed for automatic filling of multiple bunches had not yet been developed and the procedure depended on an alert operator and reliable hardware. Each bunch experienced a unique set of parasitic interactions during injection and once stored and so each was characterized by a different injection efficiency and lifetime. Luminosity depends on the total current that can be brought into collision with acceptable lifetime, and the acceptable lifetime decreases with filling time. A consequence of our determination to optimize performance, operation was by definition on the edge. Only after many months tuning and iterating optics and beam parameters were we finally able to exceed with three bunches per beam the luminosity that we had achieved with a single bunch.

1.1.4.2 *Micro-Beta*

In the mid 80's the mini-beta interaction region was amended with the addition of a 1.2m long permanent magnet final focus quadrupole. The front end of the magnet was only 60cm from the interaction point. The outer radius of the quadrupole was a mere 15cm, so it fit neatly inside the CLEO drift chamber. With a focusing strength $k=0.86/m^2$, it was a factor of two stronger than any other quadrupole in CESR and allowed us to achieve $\beta^*_v < 15mm$ with corresponding peak vertical β less than 100m. The lower limit on β^* was imposed not from optical concerns about aperture or chromaticity but rather by the finite bunch length.

In order to cover that CESR continue to be capable of running on all of the Upsilon resonances, from 4.7GeV/beam for the 1S to 5.6 GeV/beam for the 5S, an electromagnetic trim quad was located just beyond the end of the permanent magnet. A wide aperture horizontally focusing quadrupole completed the final focus.

1.1.4.3 *7-bunches/beam*

We proceeded to 7 bunch operation with some trepidation in view of the higher power that would necessarily be transmitted through the cylindrical of our 14 cell RF cavities. Indeed within the first several weeks of 7 bunch operation, a ceramic window

gave way and until the two 14 cell cavities were replaced by four 5 cell structures, beam current and luminosity was RF limited.

Meanwhile we had yet to significantly increase the specific luminosity, i.e., the luminosity per unit average beam current. The beta functions at the interaction point were typically 15 mm vertically and 100cm horizontally and horizontal dispersion was about 1m. Contribution of emittance and energy spread to the horizontal beam size were roughly equal. The synchro-betatron coupling due to the finite dispersion likely limited the achievable beam-beam tune shift. But the increased beam width allowed a corresponding increase in the beam-beam limiting current.

1.1.4.4 Single IR – head on collisions

With the conclusion of the CUSB experimental program in 1988, the CESR optics were reinvented. The low beta optics in the CUSP interaction region were normalized, and the horizontal separators were powered with east-west symmetric voltages, so that the closed horizontal orbit distortion extended from just east of the CLEO IR, through the east arc, north area, and west arc to the west of the CLEO IR. With 7 bunches in each beam, there would be horizontal separation at all of the 13 parasitic crossing points, including that point diametrically opposite the remaining IR where beams would collide head-on. The vertical separators just beyond the final focus of the single interaction point, and that had been used during injection were removed. We took advantage of the available space by lengthening the permanent magnet quadrupole from 120 to 150cm (having recovered 30cm from each of the magnets coming out of the CUSB IR) and rearranging the electromagnet trims. The phase advance between the horizontal separators to either side of the IR was very nearly 1.5 wavelengths. By turning them off, the pretzel extended around the entire circumference of CESR, providing separation at all 14 crossing points, a circumstance well suited to injection of electrons with a full load of positrons already stored.

In the single IP configuration with symmetric separation, the horizontal tune was reduced from 9.4 (just below the half integer) to 8.57, just above. The vertical tune was increased from 9.37 to 9.6. No longer constrained to maintain symmetry of optical parameters at two interaction points, we were able to zero the dispersion at the single IP. With $\beta^*_v = 18\text{mm}/1\text{m}$, we were able to increase the limiting beam-beam vertical tune shift parameter to over 0.04, nearly twice what we had achieved in the two IP operation.

The east-west symmetric pretzel effectively separated the electron and positron bunches at all of the parasitic collision points, but the cancellation of sextupole nonlinearities that arose naturally with the antisymmetric pretzel no longer obtained. A considerably more sophisticated algorithm for designing the sextupole distribution was required. All of the 76 sextupoles are independently powered, affording an enormous phase space of possibilities. The distribution was chosen to minimize pretzel amplitude dependence of twiss parameters at the IP, and tunes. Chromaticity was constrained and the local chromatic function was minimized and the dynamic aperture was optimized by minimizing the amplitude dependence of the full turn Jacobian matrix. Knobs were designed to tune chromaticity and “tonality,” that is the electron – positron tune difference.

1.1.4.5 *Crossing angle – bunch trains*

As long as we insisted that the beams collide head-on, the bunches in each beam were necessarily approximately evenly spaced, and the total number N was limited to be less than $C/2d$, where C is the circumference and d the distance from the IP to the horizontal separator. But in 1990, R. Meller suggested that if we were prepared to tolerate a small horizontal crossing angle that we could store trains of closely spaced bunches. At the parasitic crossings in the interaction region, at a distance s from the IP, where s is less than the distance to the first focusing element, the beams would be horizontally separated by $x=s\times\theta$. θ is the crossing angle. He argued that the required crossing angle was less than the width/length of the beam, and thus not likely to have a significant impact on beam-beam dynamics. We developed optics with an integer tune of 10 that could accommodate nine evenly spaced trains with as many as 5 bunches in each train. The bunch spacing within the trains was limited to multiples of 14ns, the smallest integral multiple of linac, synchrotron and storage ring RF periods. The IR quadrupoles would be modified for increased aperture for reliable HEP operation. J. Hylas discovered that by crossing the synchro-betatron line $2Q_H - Q_S = n$ and operating very close to the half integer, ($Q_H=10.51$) that it was possible to increase vertical beam-beam parameter to in excess of 0.06.

1.1.4.6 *CESR-c optics*

Outgunned by the B-factories at SLAC and KEK, CLEO physicists began to think about charm. Having replaced the permanent magnet final focus quadrupole with a superconducting-permanent magnet hybrid, the the charm threshold was well within the energy reach of the CESR guide field. The complication with operation at the lower energy (1.9 GeV vs. 5.3 GeV) was that the radiation damping time would increase 20-fold to about $\frac{1}{2}$ second. At high energy, we injected at 60Hz, allowing a damping time between each injection cycle. A 2 Hz injection rate would make filling times unacceptably long. Furthermore lepton colliders, CESR included, depend on radiation damping to tame instabilities, wash out the effects of beam-beam nonlinearities, and otherwise dissipate high Q resonances.

A. Mikhailichenko designed a superferric damping wiggler with peak field of 2.1T. Eventually a dozen of these 1.3m long wiggler magnets were installed in CESR. In total, the wiggler radiation at 1.9GeV beam energy was 10 times that of all the rest of the bending magnets combined, thus reducing the radiation damping time to a tolerable 50ms. The wigglers featured a wide pole in order to preserve field uniformity over the full width of the vacuum chamber, consistent with the aperture requirements of the pretzel configuration. The very long wiggler period of 40cm was chosen to minimize the inherent third order nonlinearities. Finally, the CESR optics were again modified, this time to exploit the wiggler field to generate a sufficiently high horizontal emittance., as well as separation at 89 parasitic crossing points.

The damping wigglers provided a means to reduce damping time and increase horizontal emittance at low energy. Evidenced by extensive tracking studies and machine experiments, wiggler non-linearity had no significant impact on dynamic aperture or beam-beam performance. But one unavoidable consequence of depending on very high and localized magnetic fields to generate radiation damping was an increased energy spread. In order to preserve a sufficiently short bunch, it was necessary to operate at a high synchrotron tune ~ 0.1 . The combination, further

compromised by our solenoid compensation scheme, limited the achievable beam-beam tune shift.

1.1.4.7 Solenoid compensation

The CLEO experimental solenoid operated at 1.5T with a length that corresponded to a rotation of about 6 degrees for a 5 GeV beam. Compensation with anti-solenoids was abandoned with the introduction of so-called mini-beta focusing so that the final focus quadrupoles could be placed closer to the IP. The IR quadrupoles were mounted so that they could be rotated about the beam axis. Three antisymmetric couplers are required to compensate the coupling of horizontal to vertical motion through a solenoid, the vertically focusing IR quads, the horizontally focusing IR quads, and then a pair of skew quads outside the IR. The skew quad was necessarily beyond the first bend and it generated some vertical dispersion at the IP. Additional arc skew quads were included in order to minimize the coupling of dispersion. The rotation angles of the IR quads were adjusted remotely by means of stepper motors. Tuning was tedious, mostly because the rotation mechanism did not provide for a reliable retreat. And colliding beam conditions were extraordinarily sensitive to residual coupling.

With the micro- β upgrade, in which the 1.5m long permanent magnet was installed as the final focus quadrupole, the permanent magnet quad as well as the vertical trim and the horizontal quads were rotatable, eliminating the need for additional skew quads to complete the compensation, and possibility of generating vertical dispersion.

Finally, in the IR with the superconducting/ permanent magnet hybrid final focus, the quadrupoles were all deployed at a fixed angle of rotation, and skew quad trim windings were used to adjust for energy and optical variations. A characteristic of this compensation scheme was a significant energy dependence, an effect exacerbated by the large energy spread associated with the damping wigglers. Superconducting anti-solenoids were added just beyond the final focus quads in an only partially successful attempt to ameliorate this effect. (As a retro-fit, there was no space closer to the IP.) In retrospect, the anti-solenoids would have been more effective superimposed directly over the superconducting quadrupoles, obviating the need for skew quad trim windings. Such an arrangement would have very significantly reduced the energy dependence of the compensation.

1.1.5 Development of Accelerator Systems

1.1.5.1 CESR RF

As mentioned above, the developments in the CESR RF system played an essential role in the performance increases. The original RF cavities were designed for high shunt impedance to efficiently provide the voltage necessary to sustain 8 GeV beams of 100 mA. Besides the afore-mentioned window problem, the 14 cell cavities were a poor match to the lower voltage operating conditions in CESR during the mid-1980's. While the beam currents were initially smaller than design (~60 mA/beam in early 7 bunch operation) the bunches were passing through the cavity closer together and the bunch length was much shorter than at 8 GeV, exciting more higher order modes in the cavities. In order to reduce both the fundamental and HOM RF power passing through

each window and provide a better match to high currents, the two 14-cell cavities were replaced by four 5-cell cavities between October 1991 and February 1993.

Meanwhile the development of super-conducting cavities, an activity at Cornell since the 1960's, had reached a stage of a practical cavity system for high current storage rings. The rationale for super-conducting RF is not to save mains power (the cryogenic equipment running 24/7 uses most of the savings in RF transmitter power) but to reduce the shunt impedance of HOM's, significantly reducing the demands on feedback systems. Because of the very low wall losses, the cavity shape can be smoothed and the resulting loss of accelerating mode shunt impedance is not a serious penalty. Beam tests indicated that the copper RF cavities were a significant impedance contribution to a low longitudinal instability threshold. [12] Even as the last 5-cell copper cavities were being installed, construction was starting on the super-conducting replacement.

The first super-conducting cavity was installed in September, 1997, the first to be installed in a storage ring for long term use. After some initial problems such as multipacting in window and coupling waveguide, the cavity operated quite well. Lessons learned were applied to the succeeding cavities with resulting smoother installation and commissioning experiences. [13] As seen in Figure 5, the slope of luminosity changed markedly after just one half of the copper RF cavities were replaced. Today the SC RF cavities continue to perform well for both photon science (400 mA total, 5.3 GeV) and accelerator physics studies requiring high gradient at low currents.

1.1.5.2 Injection

The availability of a full energy, long pulse injector has been essential to maintaining an integrated luminosity increase close to the peak luminosity increase. The high current gridded gun installed in April, 1983 allowed direct acceleration and injection into the storage ring. Its flexible bunch pattern has been very useful in filling the bunch trains.

Until September, 1985, separate optics for injection and colliding beams were still being used. After modification of injection "beam bump" magnets to shorten their pulse length, and with careful tuning, top-up injection became practical, saving time consuming lattice changes and producing more stable conditions.

When the "micro-beta" IR was installed in 1986 the vertical separators in the IR used for injection had to be removed. By unbalancing the horizontal separators used for multi-bunch operation, sufficient separation could be created in the horizontal plane to allow efficient injection.

In late 1988 the electron transport line from linac to synchrotron was upgraded to handle the full 300 MeV from the linac, producing more stable and higher current beams captured by the synchrotron. Addition of electronic beam position monitors in the linac and new prebuncher cavities led to more stable and reproducible conditions.

With multi-bunch operation, the beam dynamics of injection became more complex. Capture efficiencies when the opposing beam was at full current were reduced to 20-30% even in the best conditions, and could be 5-10% in bad. This was especially true for the low energy operation in the CLEO/CESR-c era. Often the ability to inject would determine the beam current. Different bunch distributions in the trains were tried with varying success. Despite significant effort to find better conditions and compensate the

parasitic beam-beam effects [14], no good solution, other than empirical tuning skills, was found to effectively cure these limits.

1.1.5.3 Instrumentation & Tuning

Beam diagnostic instrumentation has played a critical role in commissioning optics and identifying sources of faults and beam losses. A good orbit measurement system is of course essential. Both horizontal and vertical measurement at every quadrupole, plus the ability to calibrate offsets using modulation of the local quadrupole have proven valuable. The technique of exciting an eigenmode of the betatron motion and recording phase and amplitude data on the position monitors to measure both phase advance and coupling has been extensively used to quickly measure and correct these parameters.

Fast signal recording to circular buffers to identify parameter variations causing beam loss has been essential to finding problems with electrostatic separators, RF control systems, and magnet power supplies.

Installation of a high rate radiative Bhabha luminosity monitor in 2004 aided tuning in the lower luminosity conditions of CESR-c operation. [15]

Finally, dedicated tuning has been responsible not only for the last 10-20% in performance, but also in identifying problems and finding new operating conditions. The source of an anomalous impedance affecting positron beams was associated with the sputter ion vacuum pumps by an extremely dedicated operator. This same operator found a much improved operating point near the half-integer resonance. First hand knowledge and feeling for a machine's response to parameter changes will always play an important role in the operation of these complex devices.

1.1.6 CESR-c

1.1.6.1 Motivation and some basics

As previously mentioned, while CESR had very productive years studying B meson decays with world-record luminosity, the arrival of the two asymmetric B factories at SLAC and KEK suggested that CESR's flexibility could better serve other areas of elementary particle physics. 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.

Twelve 2.1 T wigglers, each 1.3 m in length can reduce the transverse damping time at 1.9 GeV from over 500 to 50 ms and control the transverse emittance within a desirable range. The wigglers were designed considering pretzel orbits, i.e., with a wide good field region initially evaluated by particle tracking through 3-D wiggler fields. [16, 17]

Such strong magnets are not without undesirable effects of course. There is an uncontrollable increase in energy spread from the high magnetic fields. Wigglers have strong focusing, both linear and non-linear, in the vertical plane only, making it difficult

to simply compensate with adjacent quadrupoles. Depending on the field quality, there may be non-linear terms in both planes due to magnetic field changes at large displacements from the centerline.

Other challenges to low energy operation come from the change in beam rigidity and different operating range of magnets, separators, and kickers. One concern was the two windows and a length of Helium gas separating the storage ring vacuum from the synchrotron. 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.

With the planned 45 bunches per beam, there are 89 parasitic crossings for each bunch. These effects proved to be the major focus of efforts to improve CESR-c performance.

1.1.6.2 Commissioning Experience & Performance

CESR operated at low energy from August, 2003 until March, 2008. Once the first wigglers were installed in the ring, beam-based measurements were made to determine 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. Reasonable agreement with calculated values was found [18] and longitudinal damping rates and single-beam stability limits were both close to expected values.

One of the first issues found was that slow ion effects caused us to leave out one or two trains of bunches in order to destabilize the ions. This of course would be a factor in the achievable luminosity. Hints of this effect had been observed at 5.3 GeV in a vertical beam instability for a week or two following a vacuum intervention.

While single beam current limits were in excess of 150 mA, comparable to the 180 mA in the original parameter list, with counter-rotating beams the injection efficiency dropped quickly above approximately 80 mA per beam. In addition, the beam-beam parameter usually saturated around 0.026 with best achieved around 0.03. Maximum luminosity recorded was 0.075/nb/sec (7.5×10^{31} cm⁻²-sec⁻¹ in more conventional units) though constant tuning was required to maintain luminosity above 0.06/nb/sec. While well below target values, the delivered luminosity was well above that of previous machines at these energies. This, along with the capabilities and experience of the CLEO detector and collaboration, resulted in publication of more than 100 papers, with analysis and reporting continuing through 2009. Recently the CLEO collaboration submitted for publication their 500th paper covering data taken since 1979.

In the final analysis the current limits during CESR-c operation were primarily caused by parasitic beam-beam interactions. Their effects had been inadequately assessed during the design stage, partly buoyed by the successful operation at higher beam energies. An important limit on specific luminosity likely comes from the very high synchrotron frequency required to control bunch length given the additional energy spread from the 1.9 to 2.1 T wigglers that accounted for 90% of the synchrotron radiation power. Other than this, no other detrimental effects from the damping wigglers has been identified.

Many of these conclusions have been supported by a detailed computer simulation providing particle tracking with both main and parasitic beam-beam interactions, local energy effects, high order field maps through the wigglers, as well as the usual nonlinear elements. [19] Software development was not sufficiently advanced at the design stage to utilize many of the detailed features used in later analyses.

The parasitic beam-beam interactions give each bunch its own optics functions dependent on the charges in counter-rotating bunches. These effects were strong enough that it was necessary to have two slightly different (empirically adjusted) optics for injecting from zero current and high current topping off injection. Differences in focusing effects caused bunches within a single train to have peak beta values varying up to 20%. Several attempts [14] were made to partially compensate these effects but were unable to produce measureable improvement in practice.

As described above, the beam energy spread from the wigglers aggravates the chromatic effects of the CLEO solenoid compensation. In January, 2006 compensating solenoids were installed in the IR, taking over most of the compensation from the skew quad components previously used. The following run showed a 25% increase in specific luminosity, but lower current limit due to poorer injection conditions. Tuning was easier and backgrounds lower (though backgrounds were not an operational issue during CESR/CLEO-c operations). This improvement was smaller in succeeding runs however.

The large (~ 0.1) synchrotron tune has been identified as an important factor limiting specific luminosity. Pretzel constraints on the horizontal tune severely limit control of the momentum compaction. Simulations, both with artificially low synchrotron tune and reduced bunch length suggest that the beam-beam parameter would climb from 0.03 to 0.055 when either is reduced to half nominal values. However, we were not able to find a practical option to mitigate this effect.

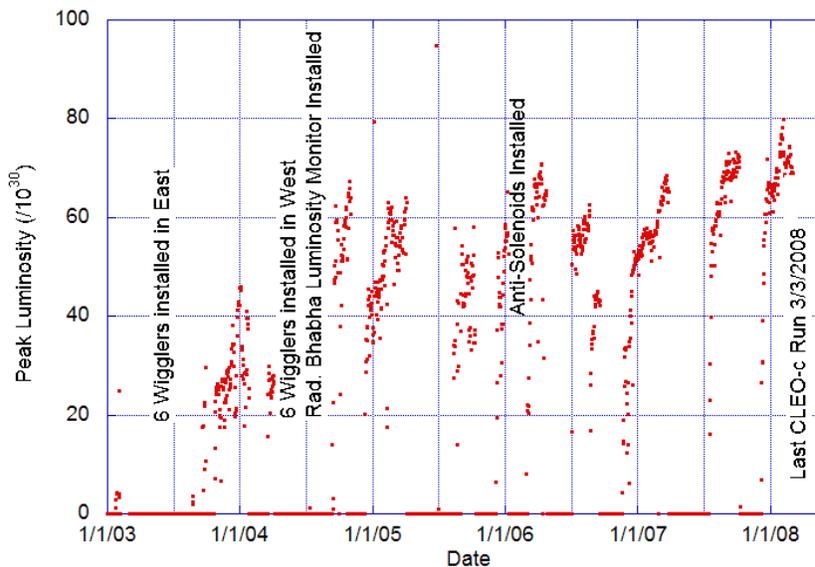


Figure 6: Peak Luminosity during CESR-c Operation. Gaps in data are either CHES dedicated runs or machine shutdown periods.

CESR-c performance relied heavily on expert knowledge and tuning to maintain and improve performance, even more so than higher energy operation, in part because of the variation of conditions with current and bunch-to-bunch.

1.1.7 Performance Overview

The growth from a luminosity of 0.003/nb/sec reached in initial configuration 20 months after startup to nearly 1.3/nb/sec achieved with 45 bunches per beam, micro-beta IR, SC RF cavities, and numerous other changes is a remarkable and detailed story of continuous perseverance and resourcefulness that is representative of the accelerator community. The table below lists performance parameters reported at conferences in the period from 1987 through 2007, capturing the upgrade and changes in the growth period from 1988 through 2002.

Table 1: CESR parameters as reported at accelerator conferences.

Date	Luminosity /nb/sec	Cur/beam mA	XiV	RF
7/2007	0.075	75(7x4)	.03 (1.9 GeV)	4-scrf
6/2002	1.25	370 (9x5)	0.06	4-scrf
5/2001	1.1	310 (9x4)	0.065	4-scrf
5/1999	0.83	225 (9x4)	0.05	2-5cell, 2-scrf
6/1998	0.56	200 (9x3)	0.044	3-5cell, 1-scrf
5/1997	0.41	180 (9x2)	0.04	4-5cell
6/1996	0.35	160 (9x2)	0.04	4-5cell
5/1995	0.33	160 (9x2)	0.036	4-5cell
3/1994	0.29	112 (7x1)	0.04	4-5cell
5/1993	0.25	100(7x1)	0.04	1-14cell,2-5 cell
5/1991	0.18	82(7x1)	0.028 (1 IP)	2-14cell
5/1989	0.09	73(7x1)	0.017 (2 IP)	2-14cell
5/1987	0.025	37(3x1)	0.018 (2 IP)	1-14cell
5/1985	0.026	37(3x1)		1-14cell

1.1.8 Acknowledgements

The list of people who have contributed to the development of CESR over the years is long and extends outside the Cornell laboratory to collaborators, visitors, and those who have engaged in stimulating conversation with members of the CESR operations team. This is a list too large to include here, and with great risk of leaving out important contributors. However, we do wish to explicitly mention a few whose contributions have been pivotal.

- Boyce D. (Mac) McDaniel, Laboratory Director at the time of CESR's conception, worked tirelessly to secure funding and guide the project through construction and the early years. He gave the initial push to go beyond a single bunch after a holiday conversation with his son, being challenged to explain why we could NOT put additional bunches in CESR. In his retirement years Mac kept in touch with the laboratory, his last project being to put precision, yet simple rotators on North area quads to test the Möbius machine concept. We miss him greatly.
- Maury Tigner, former director and present Chair of CLASSE Directorate, tirelessly managed the design, construction and commissioning of CESR and conceived the positron coalescing scheme that was critical to obtaining funding and saw CESR through the first few years of operation.
- Al Abashian and Marcel Bardou of the NSF Physics Division in the late 1970's had the vision of CESR and provided unwavering support leading to NSF approval of the project in 1977.
- Raphael Littauer conceived and developed the Pretzel scheme to successfully separate the counter-rotating beams. He has conceived the basic designs of many critical diagnostic systems, including the first beam position monitor processing and betatron phase measurement schemes for CESR.
- Bob Meller designed the ultra-stable timing systems used in CESR and made a convincing argument for a crossing angle / bunch train configuration to go beyond the 7 bunches per beam of the initial Pretzel scheme.
- John Hylas coupled intimately to CESR through thousands of hours of tuning and noting responses and correlations. He continually challenged the machine physicists to make good their theories of beam dynamics and tuning. John rescued the machine from performance minima on many occasions and could always coax an extra 10-15% in performance.

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