CESR* Luminosity Upgrades and Experiments

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Abstract

The Cornell Electron Storage Ring (CESR) has provided over 2.5 fb^{-1} integrated luminosity on the Υ(4S) resonance and nearby continuum, facilitating measurements of B meson decays. In order to seek out rarer events, the luminosity of the storage ring must maintain a geometric growth. The luminosity upgrade program of CESR provides this growth capability while utilizing many of the developments in technology and accelerator physics required for later upgrade to an asymmetric B factory. All upgrades incorporate approximately the same per-bunch parameters as in CESR's present operation. The next step in the upgrade replaces the individual bunches with "bunch trains," or closely spaced groups of bunches treated as a single bunch by the pretzel separation secheme. The higher beam currents will require improvements to the RF, vacuum, feedback, and injector systems. Separation at the parasitic interaction points near the main interaction point is provided by a small horizontal crossing angle. Machine experiments have been conducted to determine criteria for separation at parasitic crossings and measure the effects of small crossing angles on beam-beam dynamics, as well as study other topics related to the upgrade program.

I. INTRODUCTION

Since the commissioning of CESR in 1979, the CLEO and CUSB experiments at Cornell have been a primary source of experimental data on B meson decays. Several of the important observations first made at CESR are:

- Υ(4S) resonance
- First evidence for B mesons
- $b \to c$ decays
- First measurement of B mass
- $b \to u$ decays
- $B^0 \to \psi K_S$
- higher order loop decays of B mesons
- $B^0 \to \pi^+\pi^-$

where the last four processes provide direct evidence for the existance of cp violation and channels for its observation in B decays.

The primary goal of the laboratory is the detailed exploration of B meson decays, and particularly the characterization of cp violation. At this time the most direct path appears to be through neutral B decays which requires the relativistic boost of an asymmetric collider. Thus the CESR B asymmetric B factory is the principal goal of the laboratory.

As much of the technology required for an asymmetric B factory is related to the large beam currents and closely spaced bunches, also needed for upgraded CESR operation, carrying out an upgrade program for CESR is a conservative yet timely approach to an asymmetric B factory. Accordingly we have planned a phased upgrade to CESR which will provide increased luminosity to satisfy near term physics needs, will establish a solid technical basis for CESR B operation, and will be compatible with the commissioning of CESR B as soon as possible after approval.

II. PRESENT CESR STATUS

The CESR facility has been described in detail in several documents [1,2,3,4]. The accelerator facility is located on the side of a small valley, providing convenient access to the accelerator tunnel which is approximately 15 m below the surface level. The storage ring and former 12 GeV electron synchrotron share a 3.3 m diameter tunnel with a circumference of 768 m. A 300 MeV linac provides a 2.5 μs long stream of bunches to the synchrotron which accelerates these bunches to as much as 8 GeV. Thus full energy injection of nearly all bunches stored in one beam in CESR is possible.

The storage ring itself is capable, in principle, of operating from 3 to 8 GeV. However, because of the strong interest in B physics, performance has been optimized in the range of 4.7–6.0 GeV beam energy. Independent power supplies[5] for the 102 quadrupoles and 84 sextupoles provide great flexibility in optics implementation which has proven invaluable for both operations and machine studies.

CESR operates with a single interaction point (accomodating the CLEO detector) and 7 bunches per beam. The bunches collide head-on, but electrons and positrons follow separate (horizontal) closed orbits for approximately 88% of the circumference to provide separation at the 13 parasitic crossing points. These orbits, or "pretzels," are extablished by 4 electrostatic separators. A schematic plan view showing the pretzel orbits is shown in Figure 1.

A list of the principal operating characteristics of CESR may be found in Table 1 (later in this document). Several parameters merit special note.

We have found by extensive machine studies [6] that, while the vertical beam-beam parameter, ξ_V, falls as β^*_V approaches the bunch length, σ_l, the best luminosity (proportional to ξ_V / β^*_V) is found when $\beta^*_V \approx \sigma_l$.

β^*_V itself is less than 2.0 cm. Beam size and chromaticity are limited by the use of 1.22 m long permanent magnet quads

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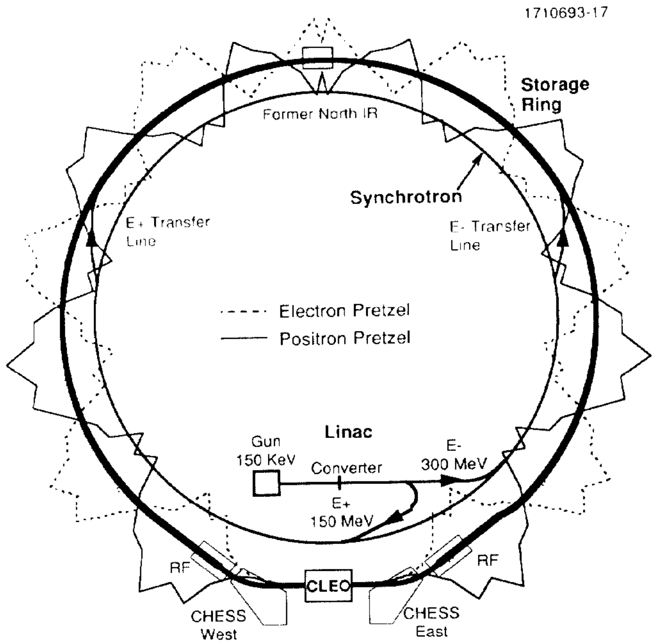

Figure 1. Schematic layout of CESR and injector complex. Prezel orbits for 7 bunch operation are superimposed on the CESR ring.

with a gradient of approximately 15 T/m. Energy flexibility is provided by an adjacent electromagnetic quad.

The charge per bunch is modest, minimizing blowup of vertical emittance by the beam-beam effect. During machine studies with 1 bunch/beam, up to $3x10^{11}$ e/bunch have been collided.

The vertical beam-beam parameter, ξ_V, reaches 0.04 during high energy physics. ξ_H is also around 0.04 during physics runs, and somewhat higher during single bunch machine studies.

III. Upgrade Path

The luminosity of a colliding beam machine is often parameterized in terms of total beam current and factors determining the luminosity per bunch:

$$L = 2.17\,(1{+}r)\,E_{beam}\frac{\xi_V}{\beta_V^*}\;I_{beam} \qquad (1)$$

where L is luminosity in units of 10^{32} cm^{-2}-s^{-1}, r is the beam aspect ratio at the ip, E_{beam} the beam energy (GeV), ξ_V the beam-beam parameter, β_V^* the vertical focussing function at the i.p. (m), and I_{beam} the current per beam (A).

Here E_{beam} is determined by the physics and we will continue to use flat beams (r small) to avoid background problems and optics designs which are difficult to impliment. Of the remaining three parameters, we choose to concentrate initially on increasing total beam current, I_{beam}. After looking at the accelerator physics and engineering problems associated with each of these three parameters, we feel that the largest potential gain lies in the total beam current. Short of a breakthrough in understanding of the beam-beam effect, ξ_V is unlikely to be increased much beyond 0.06, and may be adversely affected by changes made in β_V^* or I_{beam}. Reducing β_V^* will requre reducing the bunch length proportionately. These changes will increase chromaticity (Q'), RF voltage requirements, and higher order mode (HOM) losses, all of which are undesirable and, in turn, affect limits on ξ_V and I_{beam}.

Having chosen to increase I_{beam}, there remains the decision of how to distribute the additional current. The HOM losses, at constant bunch length, scale as I_{bunch} x I_{beam}, so these will increase as I_{beam}^2 if the current per bunch is increased, but only as I_{beam} if we increase the number of bunches and keep the bunch current constant. A more fundamental limit results from beam-beam effects. The horizontal beam-beam parameter, ξ_H, increases linearly with I_{bunch}. In the case when ξ_V has reached a saturation limit, the vertical emittance increases with bunch current, causing the beam lifetime to decrease (and often the detector background to increase) beyond some limiting current. For these reasons we choose to increase the number of bunches in CESR.

Assuring sufficient separation of counter-rotating bunches at all parasitic crossing points is the most fundamental consideration in planning the distribution of additional bunches. The most obvious option is to increase the number of "loops" in the pretzel orbit shown in Figure 1 by increasing the horizontal betatron tune, Q_H. This option results in stronger sextupoles which reduces the dynamic aperture of the machine and increases the difficulty of balancing optics distortions from the off-center orbits of the pretzel through the sextupoles. An increase from 7 to 12 bunches per beam may be possible by this approach.

A more attractive option [7] is to use each pretzel loop to separate multiple parasitic crossings. This leads to grouping the additional bunches in "trains." Thus several trains of 2 to 5 bunches each could be separated using a pretzel scheme resembling that currently used. We have studied options capable of accomodating as many as 45 bunches per beam arranged in 9 trains, each with 5 bunches.

There is an additional complication with this approach. The closely spaced bunches in each train create parasitic crossings very close to the main interaction point (i.p.), posing a difficult separation problem. The bunches could be separated at these parasitic crossings if a small crossing angle is used at the i.p. The pretzel orbits near the IR are shown for both present (7 bunch) layout and for a bunch train with crossing angle layout (9x3 bunches) in Figure 2.

IV. Upgrade Plan

We are following a phased approach to the CESR luminosity upgrade. There are several reasons for this. Operational reliability is maximized by relatively short shutdowns to install hardware for each phase and the option to go back to a previous configuration is available. We get practical experience with equipment and optics configurations with fewer bunches and lower currents before adding the complications of more parasitic crossings and higher currents. The beam current is increased gradually, accommodating the

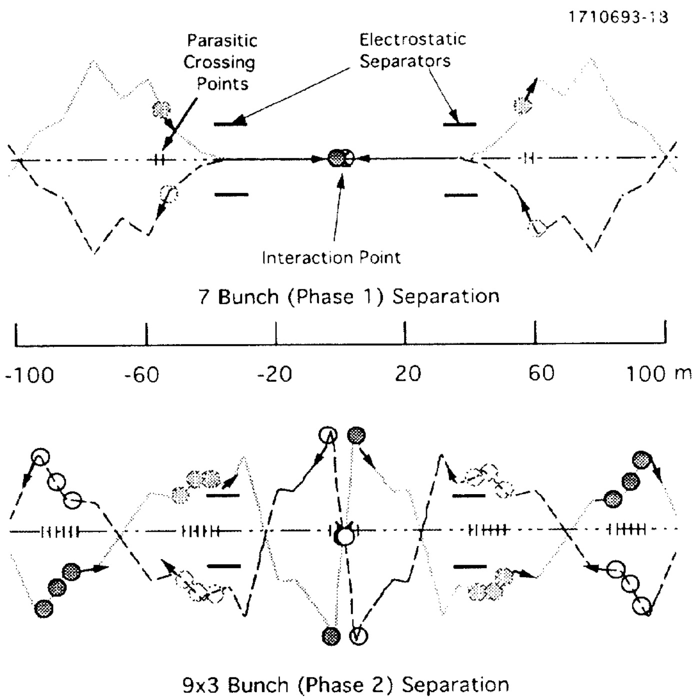

Figure 2. Pretzel separation plan near the IR. The present 7 bunch lauout is shown in the top view. The 9x3 bunch train with a ±2.5 mr horizontal crossing angle is shown in the bottom view. The scales' aspect ratio is highly distorted.

conditioning of RF cavities and separators into the schedule. The gradual increase of current is also compatible with systematic identification and replacement of any individual vacuum system components which exhibit excessive HOM losses.

The present configuration of CESR is identified as Phase I of the luminosity upgrade plan. The major components of Phase I are: 1) conversion from 2 to 1 interaction point, 2) upgrade of the linac instrumentation to increase its intensity and reliability, and 3) replacement of the original 14 cell RF cavities with 5 cell cavities of similar geometry. The orginal RF cavities in CESR were designed for 100 mA/beam maximum current. The new 5-cell "Mk III" cavities are designed for 300 mA/beam. The measured peak luminosity in this configuration is 2.5 x 10^{32} cm^{-2}-s^{-1} and maximum beam current is ≈100 mA/beam.

Phase II equipment construction has been approved and commissioning will take place in early 1994 at the same time as the CLEO inner detector will be upgraded by the installation of a silicon strip vertex detector. [8] 27 bunches per beam will circulate in 9 bunch trains. The bunch spacing within a train will be 28 ns or 14 CESR RF wavelengths.

Several pieces of accelerator equipment will be replaced or modified:

- New electrostatic separators will be installed which are expected to have 1/3 the HOM losses of the present ones.
- Vacuum chambers and pumps within ±15 m of the i.p. are being replaced to maintain particle backgrounds at present levels even with 3x increase in beam current.
- A wideband transverse feedback system has been tested in CESR which will provide bunch-by-bunch feedback in both planes with bunch spacings as low as 10 ns.
- The master timing system will be replaced with a system that will accomodate all likely combinations of bunch spacing.
- A new gun modulator has been installed which will provide bunches at full charge (10^{11} e-) at a spacing of 14 ns.
- The IR quadrupoles will be reconfigured to provide more horizontal aperture to accomodate the ±2.5 mr crossing angle pretzel orbits during injection.
- The CHESS beam stops and windows for wiggler lines are being upgraded to handle the higher beam power.

The design luminosity in the Phase II configuration is 6 x 10^{32} cm^{-2}-s^{-1} at a current of 300 mA/beam.

A comparison of the parameters for Phase I and Phase II is made in Table 1. We use a conservative value of 0.03 for ξ_V although we expect to eventually reach 0.04 as is our present experience. Note also that the emittance and current per bunch are lower in Phase II operation.

Table 1. Principal parameters for current CESR operation (Phase I) and upgade operation in 1994 (Phase II)

Parameter	Phase I	Phase II	Units
E_0	5.30	5.30	GeV
Peak Luminosity	0.25	0.6	$10^{33}cm^{-2}$-sec^{-1}
n_b (bunches/beam)	7	9x3	
r (aspect ratio at i.p.)	0.014	0.023	
N	2.24	1.75	10^{11}e/bunch
i_b (current/bunch)	14.0	11.0	mA
I_{Beam} (current/beam)	0.10	0.30	Amps
ξ_v (beam-beam param.)	0.04	0.03	
ξ_h " " "	0.04	0.04	
$2\pi R$ (circumference)	768.43	768.43	m
σ_h^* (beam size at i.p.)	550	430	μm
σ_v^* " " " "	8	10	μm
β^*_h (focus funct at i.p.)	1.00	1.00	m
β^*_v " " " "	18	17	mm
σ_l (bunch length)	18	17	mm
ε_h (emittance)	3.0	1.9	$x10^{-7}$m
α_p (momentum comp.)	1.54	1.13	$x10^{-2}$
Q_s (synchrotron tune)	0.06	0.055	
Q_h (betatron tune)	8.57	10.57	

The bunch train concept can be taken to the beam current limit of the CESR vacuum chamber, estimated to be around 500 mA/beam at 5.3 GeV. In order to handle the total storage ring current of 1 ampere, many components will have essentially the same specifications as for the CESR-B asymmetric B factory [9]. Therefore, to a large extent, the two programs have identical R&D agenda. The principal components for both projects are:

- Single cell superconducting RF cavities will be required to handle the very high currents and maintain low beam impedance. The design is identical for both upgrade or CESR-B.
- Copper vacuum chambers with high pumping speeds from NEG and TiSP pumps will be needed in the hard-bend regions of CESR. In CESR-B the whole vacuum system will be of a similar design.
- Some arc vacuum chamber components will be replaced in CESR to accept 1A of total stored current. The design for these components will again be similar to those in CESR-B.
- CESR Phase III interaction region uses both permanent-magnet and superconducting technologies for the first vertically focussing quads. CESR-B uses a superconducting quad with compensating solenoids.
- CESR will use a ±2.5 mr uncompensated crossing angle, while CESR-B will use a ±12 mr crab compensated crossing angle.

With 500 mA/beam in 45 bunches, the luminosity will be between 1 and 2 x 10^{33} cm^{-2}-s^{-1} depending on the extent to which ξ_V and β_V^* can be further optimized. CESR-B will reach 3 x 10^{33} cm^{-2}-s^{-1} with 0.87 A in the 8 GeV beam and 2 A in the 3.5 GeV beam.

V. Upgrade R&D Activities

There is no operational experience with bunch trains and a small horizontal crossing angle in existing or past e^+-e^- storage rings. Therefore it is necessary to understand the accelerator physics aspects of this mode of operation through analytic methods, computer simulation, and machine experiments. We will discuss several of the accelerator experiments at CESR in the remainder of this report.

Some of the recent areas of experimental study are:

- Single beam stability of bunch trains in CESR
- Comparison of injection performance with a computer model [10]
- Dynamic aperture and beam-beam performance with small β_V^* and large Q_H. [11]
- Ion and dust trapping phenomena [12,13]
- Comparison of measured with simulated detector background from both synchrotron radiation and lost particles [14]
- Beam-beam effects with a crossing angle [15]
- Long range beam-beam interaction and separation criteria for optics design [16]

The last two of these will be discussed in more detail below.

A. Crossing Angle

The independently controlled quadrupoles and sextupoles in CESR make it possible to use the pretzel electrostatic separators to create a horizontal crossing angle at the i.p. Adjustment of separator voltages causes a horizontal separation at the i.p. for injection. The crossing angle may be adjusted from 0 to ±2.8 mrad.

These experiments were carried out with the 1.5 tesla experiment solenoid turned on to eliminate the overhead of ramping the solenoid and readjusting compensation. Since a crossing angle of 2.5 mr is over 5 times the rms angular spread from natural beam emittance, the sensitivity to errors in compensation the relevant coupling terms is increased a comparable amount. Effects such as this are usually removed by operator tuning over periods of several days to weeks. This was not possible in the limited time available for machine studies.

ξ_V was calculated from Bhabha scattering measurements for different crossing angles. The results appear in Figure 3. Part of the ≈15% drop at -2.5 mrad is from the orbit distortion as can be seen in the square points representing magnetically induce orbit distortions (which result in head-on collisions but with orbit distortions of comparable magnitude). Most of the remaining drop is probably a result of imperfections in the solenoid compensation as described above.

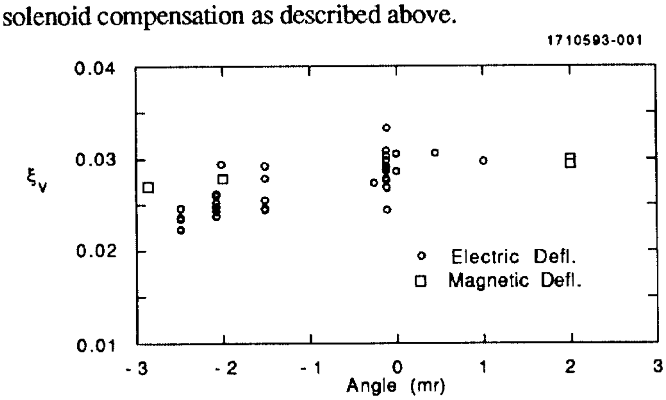

Figure 3. ξ_V vs. horizontal crossing angle. The data represented by square markers were taken using a magnetic orbit distortion without crossing angle.

Beam lifetime is also important for integrated luminosity. A sensitive measurement of lifetime effects may be made by inserting a movable aperture or "scraper" into the vacuum chamber and recording beam lifetime as a function of its position. Measurements in the vertical plane show no influence of crossing angle on particle distribution. In the horizontal plane some effect may be seen (Figure 4), but small changes in betatron tune cause the crossing angle induced blow up to disappear (11 mA, Q_H=8.59). More detailed studies [17] of resonances and crossing angles confirm the picture that the primary effect of a small crossing angle is to drive isolated resonances which are avoidable with proper choice of operating point.

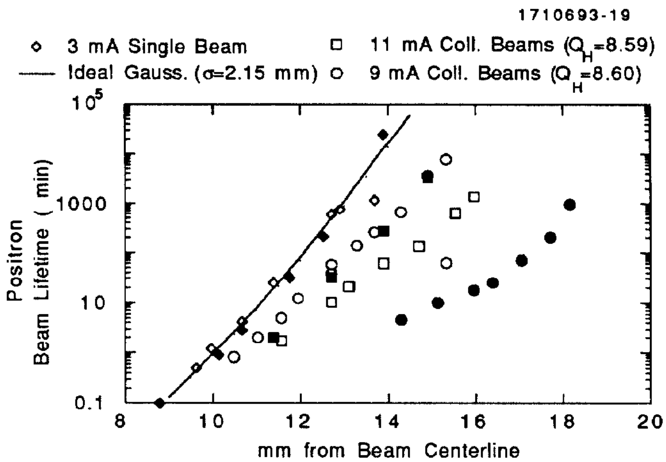

Figure 4. Beam lifetime due to movable aperture for single and colliding positron beams. The result for an ideal gaussian charge distribution is shown by the solid line. The open points were measured with head-on collisions, the solid points were measured with ±2 mrad crossing angle.

B. Long Range Beam-Beam Effects

We have had experience at CESR with no parasitic crossings (single bunch operation), and n=4, 12, and 13 parasitic crossings with 3 and 7 bunches per beam. The required separation between beams has increased more slowly than $\sqrt{n}$, which would be expected if the effects of the crossings added but were uncorrelated. However, with the possibility of 89 parasitic crossings and tightened optics constraints, a better understanding of the relevant physics and an analytic formulation of separation criteria for optics optimization is needed.

While initial measurements at CESR suggested a "hard-core" model of the parasitic interaction (counter-rotating beam acted like a scraper), using a fixed limit on the long range tune shift experianced by a zero-amplitude particle fit the current dependence of separation better. (All measurements were done for a beam lifetime of 60-100 minutes.) However, the appropriate value of tune shift varied from one crossing point to another.

Recently a phenomenological approach has been taken to finding an appropriate separation criterion. Measurements of separation vs. beam current were made in 11 different configurations. Several plausible forms of separation criteria were used to fit the data. Finally the residual scatter about the fit curve was reduced to an r.m.s. spread. The aforementioned criteria were among the worst fits. Several scaling relations were found which had about half the r.m.s. scatter. These are discussed in detail in another paper in this conference[16].

VI. Conclusion

A. Summary

The demands of the high luminosity colliders and "factories" being planned today will push many of the older accelerator design techniques close to, and possibly beyond their limits. Innovation and a systematic design approach coupling analytic, simulation, and experimental techniques is the most effective way to answer these challenges.

CESR is not only an effective physics production machine, but is also an ideal platform for carrying out experiments in accelerator physics. An optimum size and the flexibility offered by independant magnet control contribute to these qualities.

The upgrade described here will assure a continuation of the past trend in CESR luminosity (doubling every two years) and address many of the issues of asymmetric B factories.

B. Acknowledgements

The dedicated technical staff and accelerator operations group made the impressive performance record of CESR possible. All members of the accelerator operations group contributed to the measurements described here. Several members of the CLEO collaborating institutions have been very active in accelerator development areas; their capable help is gratefully acknowledged.

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