HIGH LUMINOSITY OPERATION OF THE CORNELL ELECTRON STORAGE RING

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Summary

The High Energy Physics (HEP) performance of CESR has improved by a factor of 2.5 since the beginning of 7 bunch operation in February, 1987. In addition to the gains provided by multiple bunches, other improvements, including very low beta ("Micro-Beta") insertions and increased injection rates, have played a role in these advances. Presently performance is limited by sparking in the horizontal separators used in multiple bunch operation. Since performance is current, not beam-beam, limited, optimum luminosity is obtained by lowering β_v^* to 0.9 times the bunch length.

CESR Overview

CESR is an electron-positron collider operating in the 9.4–12 GeV/c c.m. range since October, 1979. A detailed description of the facility may be found in references [1,2,3]. While CESR was originally designed to operate over an range of 4 to 8 GeV beam energy, the intense interest in b physics has narrowed our operating range to 4.7 through 6 GeV. A list of parameters pertinent to recent performance is given in Table 1.

Table 1. - CESR Operating Parameters:

Max beam energy	6 GeV
Circumference	768 m
No. Interaction Regions	2
Injector	150 MeV linac, full energy fast cycling synchrotron
Filling time	20 minutes
Peak luminosity/IR	1×10^{32} cm^{-2}sec^{-1}
Current / beam	7 x 10.5 mA at run start
Energy Spread $\Delta E/E$	0.6×10^{-3} @ 5.3 GeV
Transverse emittance	H: 0.16 mm-mrad V: 0.010 mm-mrad
Bunch Length	0.017 m
β functions at IP	H= 1.0 m V= 0.015 m
Dispersion at IP	H= 0.5 m
Beam size at IP	H= 0.6 mm V= 0.011 mm
Dipole bending radii	87.89 m (standard), 31.65 m, 140.63 m
RF power budget (10.5 mA /bunch, 7 bunches e+, 7 bunches e-, 5.3 GeV)	P_{Cu} = 300 kW P_{rad} = 150 kW P_{hom} = 50 kW

Several unique features of CESR are primarily responsible for its recent performance: multiple bunch operation, a very low β_v at the interaction point, and a flexible multiple bunch full energy injector. The references cited with each section below give detailed descriptions of their respective topics.

Multi-bunch [4,5]

After 4 years of operation as a single bunch machine, 4 electrostatic separators (deflecting the beam in the horizontal plane) were installed in early 1983 to separate the electrons and positrons at the additional parasitic crossing points created by the circulation of additional bunches. There is no crossing angle in the interaction regions. Separation was not done in the vertical plane because of the lower tolerance to misalignment at the main interaction points and skew quad fields introduced by passing through sextupoles off center vertically. Individual control of all quad and sextupole currents has been crucial for compensation of lattice errors and optical effects created by the separated horizontal closed orbits.

The CESR lattice and separator layout permit operation with 1, 3, 5, or 7 bunches per beam. Initially 3 bunch operation was chosen to let us learn to manage the storage ring without worrying about higher currents and slower injection. The first 7 bunch operation resulted in the failure of several RF cavity windows because of higher order mode fields near the window. A modification of the window structure was necessary to permit reliable 7 bunch operation.

Micro-Beta [6,7]

The narrow range of operating energies of CESR permit the use of permanent magnet quadrupoles to provide a high gradient field in a small space without significant interaction with the 1 tesla experiment solenoid field. The Samarium-cobalt quads start 0.6 meters from the interaction point and are 1.2 meters in length. A gradient of 15 tesla/m provides a k of -0.84 at 5.3 GeV. Adjacent vertically focussing electromagnetic quads provide optics flexibility for operation from 4.7 to 6 GeV beam energy.

Injection [8]

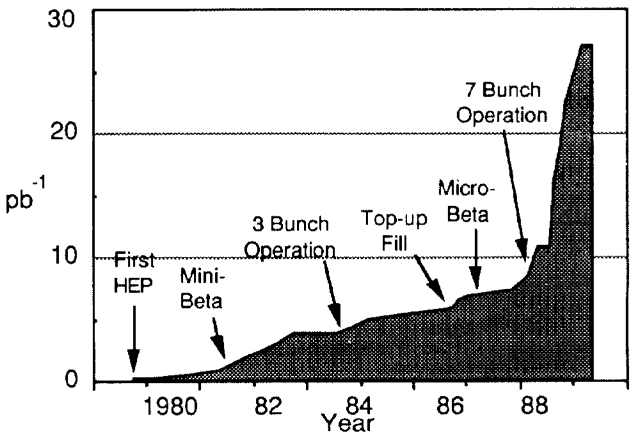
Full energy injection into CESR is accomplished by a fast cycling synchrotron with a circumference exactly 60/61 that of CESR. Up to 6 bunches (limited by kicker magnet fall time) are accelerated simultaneously in the synchrotron. A high current ($10^{11}e^-$/bunch) grid modulated gun provides the flexibility in bunch spacing required for even filling of all 7 bunches in CESR.

Filling is done using the same storage ring optics as colliding beams to minimize overhead in the filling process. This also helps in keeping the positrons remaining at the end of each run from one cycle to the next, effectively cutting positron filling time in half ("top-up" filling cycle). Electrons are dumped at the end of each run to improve positron injection efficiency.

High Energy Physics Performance

Several upgrades to CESR over its 8 years of operation have lead to increased performance. Invariably several months to a year are required after installation to learn how to effectively utilize a particular improvement. One measurement of the luminosity capability of a collider is the maximum integrated luminosity actually achieved during a given period, for example, 1 week. This quantity is plotted over the life of CESR in Figure 1 along with installation dates of several major upgrades.

Figure 1 - Luminosity Capability of CESR (pb^{-1} / week)



The effectiveness of various upgrades on accelerator productivity is clearly evident. 3 bunch operation, for example, resulted in little immediate increase in luminosity capability. The transition from 3 to 7 bunch operation, however, provided a large gain in a relatively short period. Luminosity-per-bunch performance suffers in going to the CESR multi-bunch configuration, but further increases in number of bunches in that configuration are not

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accompanied by a significant additional penalty. In another example, top-up filling gave a relatively small, but immediate, improvement in performance.

Peak luminosity during recent high energy physics running is shown in Figure 2. Here again, the learning curve has a time constant of about a year. Benefits of both micro-beta (installed in March, 1986) and 7 bunch running were realized during the last half of 1987.

Monthly integrated luminosity for the last 2 years of CESR operation is shown in Figure 3. (High energy physics running was interrupted in March, 1988 for dedicated accelerator studies and a major shutdown to upgrade the CLEO detector.) While 7 bunch operation resulted in an immediate increase in peak luminosity, the longer filling time required for the higher currents and equipment reliability problems caused average luminosity to increase more slowly. Figure 3 also shows unscheduled down time, both total and that due to RF and separator systems only. Many beam losses due to sparking in RF cavities and separators lowered average luminosity during the first 6 months of 7 bunch operation. Continuous running at higher currents and optimization of tuning by accelerator operators were eventually rewarded by improved duty cycle. The increased down time in January, 1988 was due to a series of vacuum leaks in one cavity (possibly related to high current running).

Filling time, measured from stopping to starting data acquisition by the experiment detectors, was between 15 and 30 minutes by the end of this period with average times around 20 minutes.

During a typical high energy physics run the vertical beam-beam tune shift parameter is saturated around .017 as shown in Figure 4. Luminosity is falling linearly with current in these conditions.

The micro-beta insertions in CESR permit lowering vertical ß* to less than 1.5 cm without causing aperture problems or excessive chromaticity. The beam bunch length in CESR is 1.7 cm (limited by excessive chromaticity. The beam bunch length in CESR is 1.7 cm (limited by RF cavities and higher order mode dissipation) resulting in significant change in ß_v and beam envelope over the collision region[9]. As ß* is decreased, luminosity increases less than linearly, background rates increase, and maximum current (as determined by beam lifetime)decreases.[10] Machine studies at CESR suggest the optimum value for ß* is around 1.5 cm under present conditions where bunch current is limited to 10-11 mA (Figure 5). The maximum current was limited by beam lifetime. The maximum luminosity was that achieved in 2 shifts of machine studies. If luminosity were beam-beam limited, best performance would be realized at a somewhat larger vertical ß*.

Performance Limitations

Several phenomena limit CESR's performance at or close to present levels ($1 \times 10^{32} \text{cm}^{-2}\text{sec}^{-1}$ peak luminosity and around 4 pb^{-1}/day).

Horizontal Separator Sparking keeps CESR luminosity at $1 \times 10^{32} \text{cm}^{-2}\text{sec}^{-1}$. Four horizontal electrostatic separators operating at a gradient of 16 kv/cm establish different closed orbits for electrons and positrons. Under colliding beam conditions a spark in one separator often results in immediate beam loss. They are processed to 140% of operating field and have a very low rate of breakdown without stored beam; however, sparking frequency increases rapidly with stored currents above 14x9 mA and any increase of DC voltage while beam is present.[11] (We have found that higher beam currents require greater separation between electrons and positrons due to growing exponential tails on the horizontal beam distribution, thus higher separator DC voltage.)

Figure 2- Peak Luminosity per IR

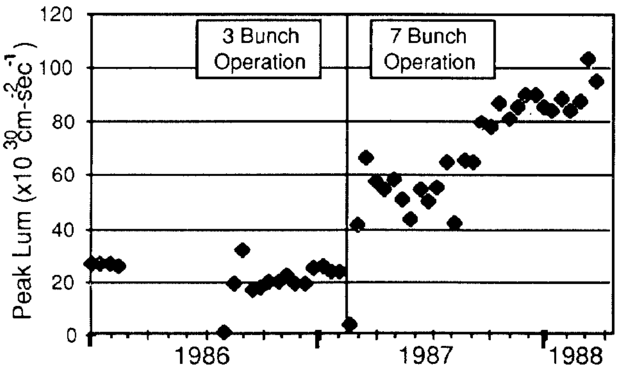


Figure 3. - Monthly Integrated Luminosity, Unscheduled Down Time, and RF and Separator Down Time

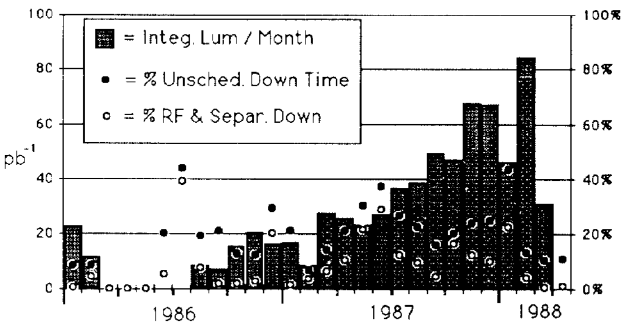


Figure 4 - Luminosity and Vertical Tune Shift Parameter vs. Bunch Current for CESR Fill Number 88.70.2

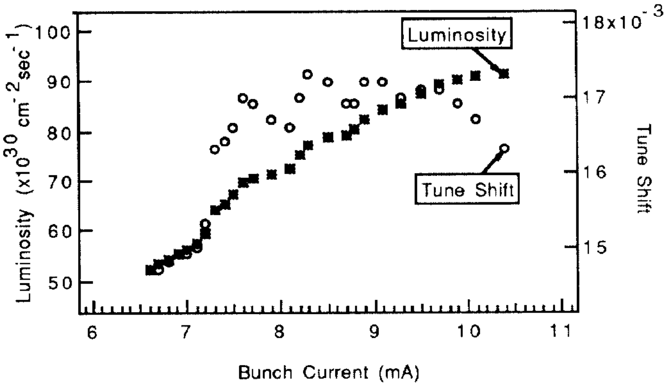
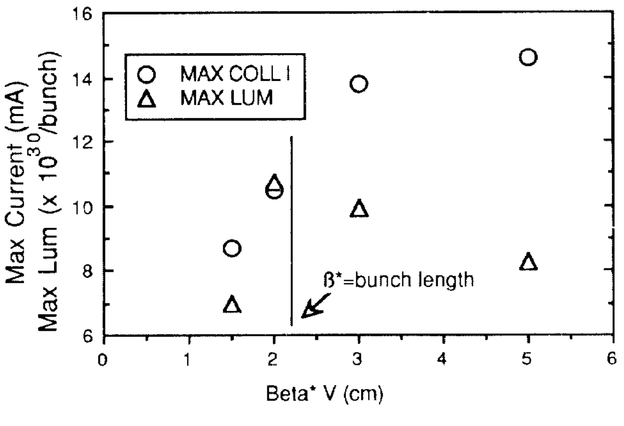


Figure 5 - Maximum Current and Luminosity vs ß*(v)



Modifications to the separators to improve their high voltage design and permit processing to higher voltages are underway. Improvement to the vacuum environment is also planned.

RF Cavity Sparking has limited beam currents in the past and would do so again at 1 to 1.5 times the present current. This breakdown phenomenon seems to respond favorably to conditioning or processing the cavities with moderate RF excitation and large stored beam currents. Conventional processing establishes fields only in the fundamental accelerating mode. Bunched beams excite higher modes into the GHz range at considerable levels - approximately 20 kW per 14 cell cavity. These fields are capable of initiating multi-pacting action.

Additional RF cavities are being built with improved vacuum characteristics and 5 instead of 14 cells per cavity[12]. The new cavities, in combination with intensive beam conditioning, are expected to give reliable service at higher currents.

Beam-Beam Effects will impose a limit at $1.4 \times 10^{32} cm^{-2} sec^{-1}$ because of increased beam size both vertically and horizontally. Estimates for this limit are made by analysis of data from beam scraper measurements.

Options to raise this limit are 1)increase the beam-beam tune shift limit, 2) increase the number of bunches, 3) find conditions to reduce the growth of exponential beam tails, and 4) increase the storage ring aperture. The first three options are being studied.

Higher Order Mode Heating in a few vacuum chamber components will limit luminosity at $1.5\text{-}2 \times 10^{32} cm^{-2} sec^{-1}$. These include vertical scrapers, some ceramics (no longer used), and random vacuum chamber flanges.

Since the number of troublesome components is small, this limit can be approximately doubled by a moderate effort to replace or cool the lossy pieces.

The Vacuum System's ability to pump gas desorbed from the chamber wall by synchrotron radiation may impose a limit between 2 and $4 \times 10^{32} cm^{-2} sec^{-1}$. This is an approximate estimate based on extrapolation of vac-ion pump currents in CESR. The response of pump currents to beam is not understood, however.[13] Furthermore we have found that the pressure rise per mA of beam current is reduced as ampere-hours accumulate at higher beam currents. With some modification, the present vacuum system should not prevent operation at $5 \times 10^{32} cm^{-2} sec^{-1}$.

Performance Improvements

An extensive upgrade program is underway to improve the performance of the present CESR ring ("CESR Plus" [14]). The major features of this program address the limitations discussed above and will 1) eliminate one interaction point to increase the tune shift limit and add optics flexibility, 2) increase the number of bunches from 7 to 14, and 3) make injector improvements to reduce filling time to ≈6 minutes even with the expected 4x increase in current. New RF cavities and horizontal separators, better suited for the large beam currents than the present devices, are being constructed. The number of electrostatic separators in the storage ring is being reduced from 8 to 3, and higher order mode properties are being improved. These changes are expected to give a x4-x5 increase in average luminosity in the next 3 years.

Acknowledgements

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