CESR PLUS

D. L. Rubin for the CESR Operations Group*
Laboratory of Nuclear Studies , Cornell University , Ithaca, NY 14853

The Cornell Electron Storage Ring operates with seven bunches per beam and $11ma$ per bunch to yield a peak luminosity of $1 \times 10^{32} cm^{-2}s^{-1}$ at each of two interaction points. An electrostatic orbit distortion separates the beams at the 12 parasitic crossings. The beam-beam limited luminosity can be significantly increased by reducing the number of interaction points to one. The fraction of a radiation damping time per collision at the remaining interaction point is thereby doubled. Because one of two sets of low beta optics can be removed, the integer part of the horizontal tune can be increased to 13 from 9 permitting operation with fourteen bunches per beam, and the beam width at the single interaction point can be enhanced. Currents of about $300ma$/beam will be required to operate the upgraded machine at its beam-beam limit. The reconfigured storage ring with a beam-beam limited luminosity in excess of $5 \times 10^{32} cm^{-2}s^{-1}$ and the associated upgrade of the single beam current carrying capability are described.

Introduction

The upgrade of the CESR luminosity involves an increase in the beam-beam current limit and then a corresponding increase in the single beam current carrying capability. We begin by considering the dependence of beam-beam limited luminosity on the machine parameters and follow with a discussion of the single beam limits.

The storage ring luminosity is given by

$$L = \frac{fN\gamma}{2r_e\beta^*} n_b \xi_v \qquad (1)$$

where f is the revolution frequency, N the number of particles per bunch, n_b the number of bunches, and β^* the focusing parameter at the interaction point. The beam-beam tune shift parameter $\xi_v = 2r_e/\gamma\beta^* D$ where $D = N/(4\pi\sigma_x\sigma_y)$ is the charge per unit of cross sectional area. σ_x and σ_y are the horizontal and vertical dimensions of the bunch.

To raise the beam-beam limited luminosity there are four distinct options that we must consider as indicated by (1)including:

1. Reducing the interaction point focusing parameter β^*,
2. Increasing the critical charge density or maximum tune shift,
3. Increasing the width of the bunch at the interaction point,
4. Adding more bunches.

Guided by the enumerated options we consider the optimization of the luminosity in CESR.

Focusing Parameter β^*

The vertical focusing function at the CESR interaction points is $\beta^* = 1.5cm$. The low β^* is achieved without degrading physical or dynamic apertures by placing the permanent magnet final focus quadrupoles very near to the interaction point. Equation (1), which indicates that the luminosity grows inversely with β^*, is valid in the limit of a zero length bunch. We observe in CESR with a bunch length of $1.7cm$ that the tune shift limit at $\beta^* = 1.5cm$ is lower than for $\beta^* = 3.0cm$.[1]

While the bunch length can be reduced by an increase in the RF accelerating gradient, or a decrease in the momentum compaction, in CESR it is limited by the machine impedance. At high currents wake fields excited in the vacuum chamber and the RF cavities can effect a bunch lengthening, and the threshold will fall with the length of the bunch. Head tail, as well as bunched beam stability thresholds fall if the momentum compaction is reduced. And the total higher order mode loss increases since the high frequency component of the bunch spectrum is enhanced as the bunch shrinks in length. Then there are more modes with finite shunt impedance. Without a very different RF system, shorter bunches and lower β^* are not accessible.

Tune Shift Limit

In CESR the bunches collide twice per revolution. If we eliminate one of the collisions we expect to attain a higher critical charge density at the remaining interaction point.[2] [3] With each beam-beam collision, the nonlinear forces can excite resonances that distort the phase space or couple horizontal or longitudinal motion into the vertical dimension. If the charge density is high then the forces are strong and the increasing vertical amplitudes blow up the beam and the tune shift saturates. During the time between collisions, synchrotron radiation leads to a damping of the amplitudes and a randomization of the particle betatron phases. If the number of high energy photons that is radiated per collision is increased then a higher charge density is tolerable.

The detailed dependence of the maximum tune shift on the radiation damping per collision is not well established. Various models of the beam-beam interaction indicate that the tune shift limit scales with the square root of the damping decrement.[4] [5] The damping decrement is defined as the fraction of a radiation damping time per beam-beam collision.

An experiment was performed with the CESR to measure the saturated tune shift parameter in a single interaction point configuration versus the standard two IP mode.[6] A quadrupole lattice was developed that exploited the existing multibunch separators to differentially displace the beams in one of CESR's two interaction regions. We measured a value of 0.021 for the saturated tune shift parameter in the configuration with collisions at a single interaction point as shown in Fig. 1. For simplicity a single bunch was stored in each beam. By contrast we measure $\xi_v = 0.017$ when there are two collisions per revolution. Our two interaction point measurement is with single bunches per beam but horizontal separators powered in a manner consistent with multibunch operation. The experiment yielded a 20% increase in the critical charge density.

Note that the luminosity scales as the square of the critical current density. If with tuning we can attain the increase in saturated tune shift predicted by the simple models, ($\frac{\Delta\xi_v}{\xi_v} = \sqrt{\frac{\Delta\delta}{\delta}}$), the beam-beam limited luminosity will double with the elimination of one collision per turn.

---

* Work supported by the National Science Foundation.

CH2669-0/89/0000-1837$01.00©1989 IEEE

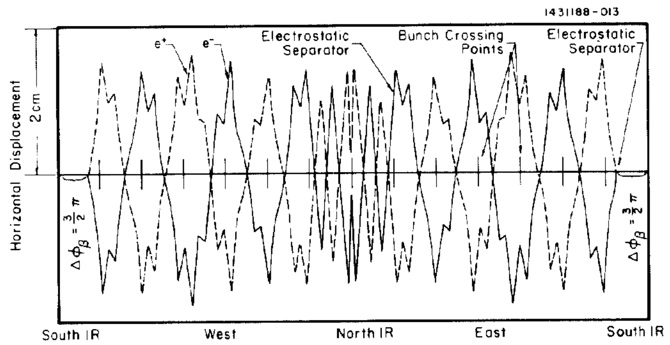

Fig. 1. The closed orbits for electrons and positrons are indicated by the solid and dashed lines respectively. The beams are separated at 13 of the 14 crossing points characteristic of 7 bunch per beam operation, including one of the low beta interaction regions.

Beam Width

Since the tune shift depends on the charge per unit area it is possible to increase the number of particles in the bunch without changing the tune shift parameter if the horizontal beam size is increased. For fixed ξ_v the luminosity scales linearly with bunch charge. Therefore $L \sim \sigma_x$. The width of the beam is due to the invariant emittance ϵ and the energy spread , σ_E, so that $\sigma_x = \sqrt{\epsilon\beta_x^* + \eta^2(\sigma_E/E)^2}$. η is the dispersion function.

A nonzero dispersion at the interaction point leads to a correlation between horizontal displacement and energy offset in the beam beam kick, and the collision couples transverse and longitudinal degrees of freedom. It is preferable to enhance the beam width by an increase in the emittance.[5] But the emittance is a global property of the lattice and it is limited by the smallest aperture in the machine. In the case of CESR the aperture is most restricted in the arcs where the beams are horizontally separated to accomodate multiple bunches. If we increase the emittance we find that we cannot maintain sufficient separation within the physical aperture. We are thus forced to consider a nonzero dispersion.

The storage ring has historically operated in the regime of nonzero dispersion. During single bunch operation the beam width of $920\mu m$ was established in a lattice with $\epsilon_x = 2.4 \times 10^{-7} m - rad$, $\beta_x^* = 1.2m$, and $\eta^* = 1.1m$. In the multibunch optics, $\sigma_x = 550\mu m$, $\beta_x^* = 1m$, and $\eta^* = 0.55m$. In each case the dispersion contributes less than half of the beam width. We propose a restoration of the dispersion to nearer $1m$ without a corresponding increase in the emittance to yield as much as a 1.5 fold increase in the width. A quadrupole lattice with a dispersion of $1.1m$ that satisfies constraints imposed by multibunch operation in a one interaction region configuration exists.

Measurements of the saturated tune shift in a high dispersion lattice suggest that the critical charge density may be degraded[7] if $\eta^*(\sigma_E/E) \geq \epsilon\beta^*$. When the horizontal size of the beam is dominated by energy dispersion the simple scaling of luminosity with beam width may breakdown, perhaps due to the synchro-betatron coupling. While the technique might in principle yield as much as a 50% increase in the beam-beam current limit, we conservatively estimate that dispersion enhancement will account for no more than a 10 – 20% gain in luminosity. More studies are required to evaluate the optimum dispersion for CESR.

More Bunches

The number of bunches per beam is constrained by the distance of the horizontal separator from the interaction point and in a machine with a single vacuum chamber by the number of horizontal betatron wavelengths around the ring.

Electrostatic Separators

A parasitic crossing of the electron and positron bunches occurs at a distance equal to one-half of the bunch spacing from the interaction point. The beams must be separated before they have traveled the length $S/2$ and the horizontal separator is necessarily located something less then $S/2$ from the IP. For CESR this implies relocating the horizontal separator nearer the IP.

At present CESR operates with 4 pairs of electrostatic separators. The two horizontal pairs serve to prevent collisions at the $2n_b - 2$ parasitic crossing points. A vertical separator is located at each end of each IR. The vertical separators are used exclusively during the injection process. Since the number of interaction points will be reduced by one, one pair of vertical separators is removed immediately. Further since there are $1\frac{1}{2}$ betatron wavelengths between the horizontal separators that surround the remaining interaction point, as noted in Fig. 1, we find that by powering a single pair of separators symmetrically east and west that the beams can be separated at all $2n_b$ crossings. The beams are then brought into collision with the second pair of horizontal separators. All four vertical separators are rendered obsolete, significantly reducing the machine impedance and making space available very near the IP for horizontal separators.

During most recent running, CESR luminosity was limited by sparking in the horizontal separator tanks. Typically as the beam current is increased it is necessary to raise the voltage in order to maintain adequate separation at the parasitic crossing points. The combination of the higher order mode RF fields and high DC voltage effectively limit the beam current. But the separators are expected support significantly higher currents in the upgraded machine. To that end the high voltage feedthroughs have been redesigned and are being rebuilt with higher quality insulators.

High Tune

The separation of electron and positron beams at s is given by

$$\Delta x(s) = 2k\sqrt{\beta_k\beta(s)}\sin(\phi(s) - \phi_k),$$

where β_k and ϕ_k are the β-function and phase at the location of the electrostatic kick, k. The bunches are most efficiently displaced if the crossing points are an odd integer number of half wavelengths from the separator. If there are n_b bunches in the beam then there are $p = 2n_b - n_{IP}$ parasitic crossing points and necessarily of order p half wavelengths. In a lattice consistent with 14 bunches per beam the integer part of the horizontal tune is 13. The closed orbit for a 14 bunch lattice is shown in Fig. 2.

CESR presently operates with an integer tune of 9 in both horizontal and vertical dimensions. An increase of the horizontal tune to 13.4 dramatically reduces the average dispersion around the ring and strong sextupoles are required to compensate the chromaticity. But the elimination of an interaction

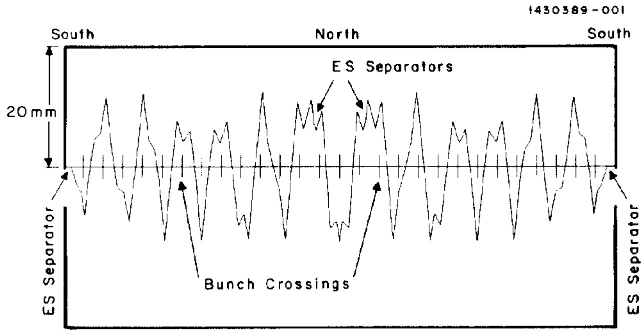

Fig. 2. The closed orbit for electrons is indicated. The positron orbit is the reflection about the undisplaced trajectory. The beams are separated at 27 of the 28 crossing points that occur with 14 bunches per beam and a single collision point.

region significantly reduces the chromaticity and the demands on the sextupoles. We find that the horizontal chromaticity suffers a net increase of 10% while the vertical chromaticity actually decreases by 30% in the high tune single IR machine as compared to the tune of 9, two IR configuration. The sextupoles are nevertheless stronger than in the tune of 9 lattice due to the reduced dispersion in the arcs, but not as strong as in an experimental tune of 11 lattice that yielded good luminosity and tune shift.[8] We will further exploit the normalization of IR optics to introduce additional sextupole magnets and thereby effect a reduction in all sextupole strengths.

Parasitic crossings and differential orbits

As noted above, large numbers of bunches per beam imply many parasitic crossings and a long range beam-beam effect. We observe that with increasing beam currents, higher separator voltages are required to preserve tune shift and beam lifetime. Doubling the number of bunches doubles the number of parasitic crossings and the horizontal aperture may limit bunch charge.

Magnet errors and nonlinear elements effect the separated beams differentially.[9] We observe a $10 - 20\%$ degradation in luminosity in collisions of single bunches if the electrostatic closed orbit distortion is applied. In the low current limit no further degradation is observed as more bunches are added to each beam.[10] The effects of the parasitic crossings appear near the beam-beam limit.

Beam-Beam Limit

The implications of the upgrades described above for the beam-beam limit and beam and bunch current are summarized in the table. Note that in the present configuration the current is single beam rather than colliding beam limited. The limit is associated with the electrostatic separators and is expected to be eliminated with the upgrade of the hardware. Measurements indicate that the beam-beam limited current is 20% beyond the present single beam limit imposed by the separators and is so indicated in the table.

	ξ_v	Lum	I_B	I_{TOT}
→ Beam Beam Limit		1.2	1.2	1.2
$2 \rightarrow 1$ IP	$\sqrt{2}$	2	$\sqrt{2}$	$\sqrt{2}$
$7 \rightarrow 14$ bunches	1	14/7	1	14/7
$\sigma_x \rightarrow 1.1\sigma_x$	1	1.1	1.1	1.1
Total	$\sqrt{2}$	5.3	1.9	3.8

Table 1. Indicated in each column is the factor by which the tune shift limit, luminosity, bunch current and total current are expected to increase as a result of the change in operating conditions. The change in horizontal beam size σ_x, is due to a 20% increase in dispersion.

If we can learn to exploit all of the projected increase in the beam-beam limit we attain a luminosity in excess of $5 \times 10^{32} cm^{-2} s^{-1}$.

Single Beam Limits

In order to operate the reconfigured machine at the beam-beam limit we need to store high current beams of multiple bunches. RF power adequate to restore losses to synchrotron radiation and higher order parasitic modes must be provided. Synchrotron radiated power scales linearly with beam current and higher order mode power as the square of the charge per bunch. Instability thresholds depend on the impedance of the vacuum chamber and the coupling of the beam to high Q parasitic modes.

Ring Impedance

There are two 14-cell 500MHz RF cavities in CESR at present and they account for about 2/3 of the dissipated higher order mode power. The remaining 1/3 is associated with the 4 vertical and 4 horizontal electrostatic separators. The vertical separators are removed in the upgraded machine and the two 14-cell RF cavities replaced with four 5-cell cavities. The net decrease in the impedance is about 50%.

With seven bunches per beam and $11ma$/bunch the radiated power is $90kW$ and the higher order mode power is $39kW$. If the reconfigured machine is operated at the beam-beam limit the synchroton radiation accounts for $324kW$ and the higher order modes $202kW$ per beam.

As noted, a single 14-cell RF cavity provides adequate accelerating voltage but insufficient power to support $300ma$/beam as required by the upgrade. The corresponding HOM loss is about $7kW$/cell. In a high current, low energy machine like CESR it is advantageous to minimize the number of cells. A large fraction of the RF power is dissipated in higher order modes in each cell, and the associated impedance reduces the single beam stability thresholds. The demand on the system in the upgraded machine will be just over $1MW$ and we propose to satisfy that demand with four 5-cell cavities. The fundamental power at each of the four cylindrical windows is then $250 - 300kW$. A window of similar design has been operated for an extended period of time at an incident power level of $360kW$. The total of 20 cells can sustain the $5 - 7MeV$ accelerating voltage, while presenting a somewhat smaller impedance to the beam than exists at present. The new cavities have been designed and are being built.[11]

Strong Head Tail

The short range wakefield induces a current dependent tune shift and a strong head-tail instability. The associated impedance is determined by a measure of the dependence of the betatron tune on the bunch current .[12] The instability appears when the tune shift approaches the synchrotron tune. $I_{max} = \frac{\Delta I}{\Delta f_v} f_s$. We measure $\frac{\Delta f_v}{\Delta I} = 234 Hz/ma$.[13] The projected maximum current is over $100ma$. In fact a single bunch instability is observed at $28ma$. Apparently a more subtle phenomonon limits the single beam current than the minimal strong head tail. If we nevertheless suppose that the limit scales as the impedance we can expect a current threshold above $42ma$ in the machine with the four 5-cell RF cavities installed.

A consequence of the higher horizontal tune is a reduction of the momentum compaction factor by about $30 - 50\%$. The effect is to lower the bunch lengthening threshold. Unfortunately we have no direct measure of bunch length as a function of beam current. But we have stored a $35ma$ bunch in a high tune lattice[14] . At the time of the measurement there was a single 14 cell RF cavity in the ring in addition to the eight electrostatic separators for a total impedance roughly equivalent to that anticipated in the upgraded machine.

Multiple bunch limit

Multibunch and multi-turn instabilities can arise if the beam couples to high Q parasitic modes in the vacuum system. With the removal of 8 cells of RF cavities, and four vertical separators, the coupling of such modes will decrease whereas the loading (Q) will remain unaffected. But the higher bunch currents imply a greater stored energy will reside in all nonzero coupling modes.

A transverse mode that appears with seven bunch/beam operation was stabilized with a broad band feedback. The system is being upgraded to accomodate 14 bunches per beam. Single beams of 14 bunches with currents in excess of $12ma$/bunch have been stored without active feedback. The current was limited by heating, either by higher order modes or x-rays, of a ceramic section of the vacuum chamber.[15]

We may find it very difficult to store the $20ma$ per bunch required to reach the beam-beam limit as indicated in Table 1. But no fundamental obstacle to high currents has been identified.

Conclusion

It is clear that a substantial increase in the CESR luminosity beyond the performance achieved to date is possible. Attaining the gains that are in principle available to us presents a very significant challenge especially in terms of storing the high currents required. In addition the beam-beam dynamics are likely to be very different in a machine with high dispersion and a single interaction point. But there appear to be no fundamental problems and the benefits to the high energy physics are obvious.

Acknowledgements

Thanks are due the entire CESR operations group for the many measurements of the beam-beam and single beam phenomona and to Don Hartill, Dave Rice and Stu Peck for helping to develop and implement the concept of the upgrade. Thanks to Bob Siemann for helping me to appreciate and understand single beam instabilities.

REFERENCES

1) D.Rice,CON 87-3

2) Keil and Talman, Particle Accelerators, 1983 Vol. 14 pp.109-118

3) J. T. Seeman, Nonlinear Dynamics Aspects of Particle Accelerators Proceedings, Sardinia, 1985

4) D.L.Rubin, CON 87-12

5) A.W.Chao, Proceedings of the Third Annual U.S. Summer School on High Energy Accelerators, Upton and Stony Brook, New York, 1983, ed. M.Month, P.F.Dahl and M.Dienes, pp.236-238

6) D.L.Rubin, CON 88-6

7) CESR Log 77, pp.151-160, and Log 78, pp.6-40, April, 1988

8) CESR Log 75, pp. 37-44, September, 1987

9) R. Littauer, Proceedings of the 12th International Conference on High-Energy Accelerators, Fermilab, 1983, p. 161.

10) D.L.Rubin, Proceedings of the UCLA Workshop Linear-Collider $B\bar{B}$ Factory, January, 1987, ed. D.Stork

11) S. Greenwald, proceedings this conference

12) P. Wilson, Proceedings of the Fermilab Summer School on the Physics of High Energy Particle Accelerators, Fermilab, July, 1981, ed. M.Month, R.A.Carrigan, and F.R.Huson, pp.536-537

13) CESR Log 77, p.159, April, 1988

14) CESR Log 78, p.112, June, 1988

15) CESR Log 77, p.149, April, 1988