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Observation of the Beam-Beam Limit in CESR*

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Summary

CESR has produced e^+e^- collisions for high energy physics in the very productive Υ region (4.7 to 5.7 GeV per beam) since the fall of 1979. The peak luminosity recorded during physics data taking over that period is shown in Fig. 1. The dramatic increase in the luminosity has resulted from the reduction of β_y* from 11 cm to 3 cm, an increase in σ_x*, and increases in the vertical aperture. Furthermore, observations of the beam-beam interaction show that the luminosity increases as the square of the beam current at low currents and linearly with current at high currents. These observations are consistent with a vertical beam size which is constant at low currents and increases linearly at high currents. A linearly increasing vertical beam size implies a constant vertical tune shift. The luminosity and the beam lifetime are limited by non-gaussian tails which reach the physical aperture of CESR.

Standard Luminosity and Tune Shift Equations

The luminosity L is given by[1]

$$L = \frac{I^2}{4\pi e^2 f \sigma_x^* \sigma_y^*} \qquad (1)$$

where I is the beam current, e the electron charge, f the revolution frequency, and σ_x* and σ_y* the horizontal (x) and vertical (y) gaussian beam sizes at the crossing point. The beam-beam tune shifts are given by

$$\xi_y = \frac{I r_e \beta_y^*}{2\pi e f (\sigma_x^* + \sigma_y^*)\sigma_y^* \gamma} \qquad (2)$$

$$\xi_x = \frac{I r_e \beta_x^*}{2\pi e f (\sigma_x^* + \sigma_y^*)\sigma_x^* \gamma} \qquad (3)$$

where γ is the electron energy divided by its rest mass, $r_e = 2.82 \times 10^{-13}$ cm, and β_x* and β_y* are the horizontal and vertical betatron functions at the crossing point. Eqn. (1) and (2) can be combined to give

$$L = \frac{I \gamma \xi_y}{2 e r_e \beta_y^*} \qquad (4)$$

assuming $\sigma_x^* \gg \sigma_y^*$ (well satisfied at CESR).

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Description of CESR

CESR has been described elsewhere[2,3,4], but briefly it has a 768 m circumference, two interaction regions (IR), one bunch per beam, typical peak betas and etas in the bends of 36 m and 4 m, respectively, and vacuum chamber dimensions of 90 mm by 50 mm (appropriately larger in the IRs). A 5.2 GeV particle loses 1 MeV per turn and has a transverse damping time of 27 msec. A single bunch is ribbonlike, has a 2 cm length (σ), and has no instabilities to well over 30 milliamperes.

Minibeta insertions were installed in the summer of 1981 allowing β_y* to be lowered from 11 cm to 4 cm. In order to install the mini-beta insertion in the south detector, the solenoid compensators had to be removed. The compensation is now performed with three antisymmetric pairs of skew quadrupoles[5] and works quite well for the present 3 m long - 10 Kg solenoidal field. The removal of the restricting vertical synchrotron radiation masks near the IRs in December 1981 and March 1982 has allowed β_y* to be reduced to 3 cm.

Under operating conditions the orbit is typically flattened to 0.5 mm rms and the spurious vertical dispersion and global horizontal- vertical coupling carefully minimized. The diagnostic equipment is described in Ref. 6.

Observations of Nonzero η_x* Lattices

The four lattices used for experimental physics from June 1981 through March 1983 are reviewed here. They have similar tunes and have a range of β_y* from 3 cm to 11 cm. One is a pre-minibeta lattice. The parameters of these lattices are listed in Table I. The generation of these lattices is an involved process dealing mainly with the optimization of the natural beam size.[7] The choice of tunes is crucial because acceptable regions shrink dramatically near the maximum beam current causing gradually increasing backgrounds and decreasing beam lifetime. At the present tunes synchrobetatron side bands of $Q_x = Q_y$, $Q_x = 1/3$,

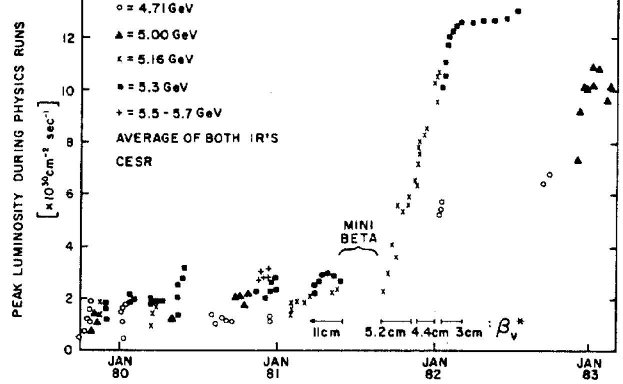

Fig. 1 Peak luminosity since CESR turnon.

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Table I Parameters for four physics and one η_x*=0 CESR lattices.[a]

Lattice	N9932B.9A1	G9932B.9A0	E99XX6.9A0	L3538.002	L88330.9A0
Date used	Feb82-Mar83	Dec81-Jan82	Nov-Dec 81	June 81	March 82
Q_x / Qy	9.39/9.37	9.39/9.37	9.39/9.38	9.42/9.37	8.41.8.38
IR-Q1 Distance(m) (N/S)	1.9/2.2	1.9/2.2	2.2	3.6	1.9/2.2
ε_x (mm-mrad)	0.244	0.168	0.145	0.104	0.230
β_x* (m)	1.25	1.2	1.3	3.45	1.6
η_x* (m)	1.1	0.8	0.59	1.28	0.0
β_y* (cm)	3.0	4.4	5.15	11.25	3.7
σ_x* (mm)	0.87	0.65	0.56	0.97	0.61
σ_y*max (μm)	20	29.6	33	45.7	17
σ_y* min (μm)	<10	<11	<19	<24	<11
ξ_{xmax}	0.020	0.022	0.023	0.020	0.025
ξ_{ymax}	0.021	0.027	0.036	0.030	0.031
I_{max} (mA)	18	13.9	12.1	11.8	10
L_{max} (x10^{30} $cm^{-2}sec^{-1}$)	15	8.0	6.3	2.5	7.7
Min. Vert. Clearance[b]	26	23	24	23	35
Extent of Tail (% of Aper.)[c]	92	96	94	83	--
Peak nb^{-1} /day/IR	600	320	280	120	--

a) σ_E/E = 0.00060, Q_s = 0.05, E = 5.2 GeV.
b) Tightest vertical half aperture divided by σ_{ymax} at that aperture (number of σ).
c) Vertical scraper position at the highest current for a definite reduction of beam lifetime.

Q_y = 1/3, $2Q_x + Q_y$ = 1, and others are important

A comparison of the luminosity versus current of the four nonzero η_x* lattices is shown in Fig. 2. At low currents L is proportional to I^2, specifically measured for β_y* = 4.4 cm and 3 cm. At high currents L α I for all four lattices. The maximum values of L and I are recorded in Table I. Often during the course of a fill L will fall faster than I and the accelerator operator must make adjustments involving Q_x, Q_y, and the skew quadrupoles to restore it.

The motivation for studying the luminosity experimentally is to determine the current dependence of the transverse beam dimensions. Since no evidence has been seen at CESR from either the optical scanner or the radial scrapers of a change in the radial beam size with current, we assume here that σ_x* is a constant determined by the lattice. As a result ξ_x will increase linearly with I assuming σ_x* >>σ_y*.

Conversely, σ_y* and ξ_y vary strongly with current. They can be determined from the L

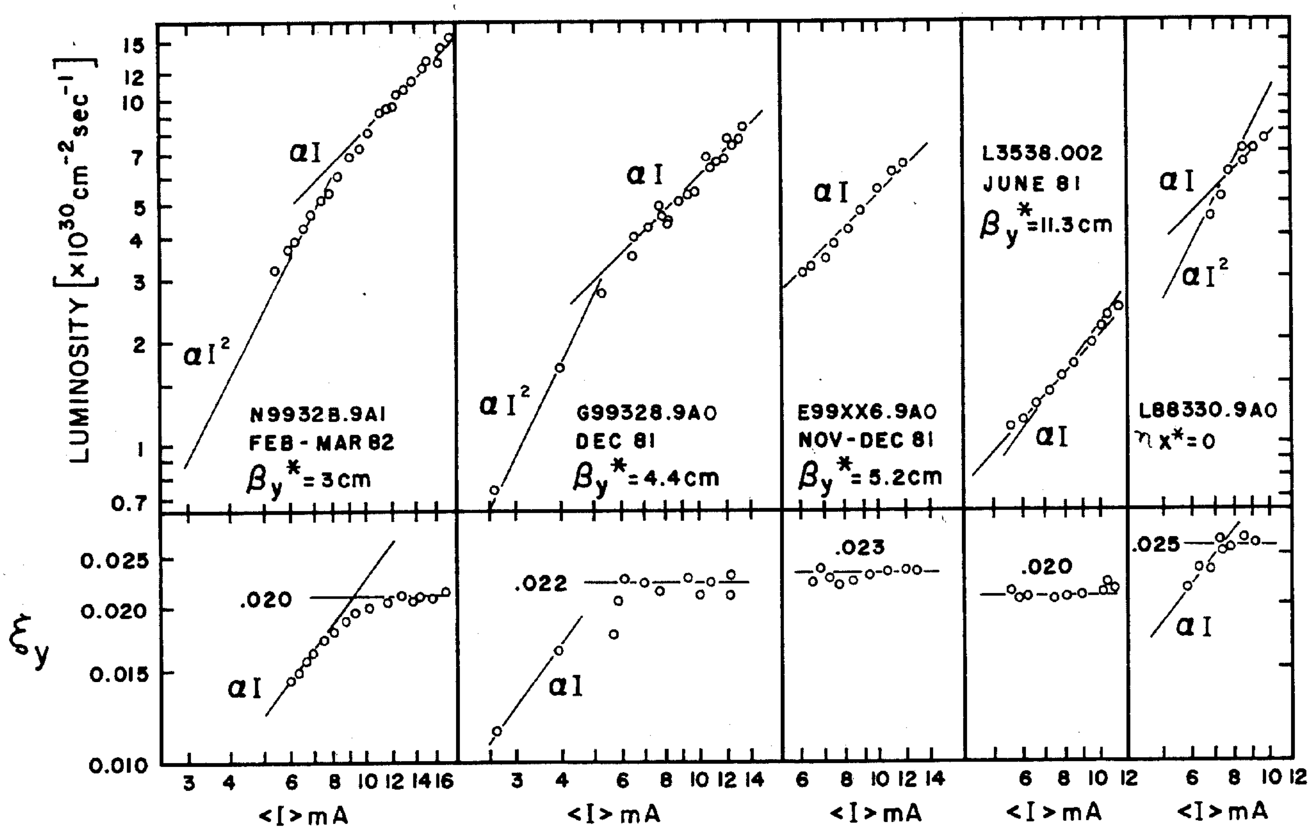


Fig. 2 Luminosity and ξ_y vs current for four physics and one η_x*=0 lattices at CESR.

vs I data and Eqns. (1) and (4). ξ_y is plotted versus current in Fig. 2. Note that above a current of 5 to 8 mA ξ_y is constant, which implies that σ_y^* increases linearly with current. The calculated maximum vertical beam size σ_y^* max (see Table I) is at least two times the natural or low current size.

Further evidence that the vertical beam only is enlarged comes from the beam-beam tune shifts seen on the spectrum analyzer.[8,9] The measured shifts for the lattice N9932B.9A1 are plotted versus current in Fig. 3a. Note that the horizontal shift is linear in the current but that the vertical shift saturates above 11 mA. Since the horizontal shift does not saturate, σ_x^* remains a constant. Therefore, if the vertical shift saturates then σ_y^* must be proportional to I, in agreement with the luminosity measurements. The optical synchrotron radiation scanners (Fig. 3b) also show that the vertical core of the beam enlarges linearly with current at high current.

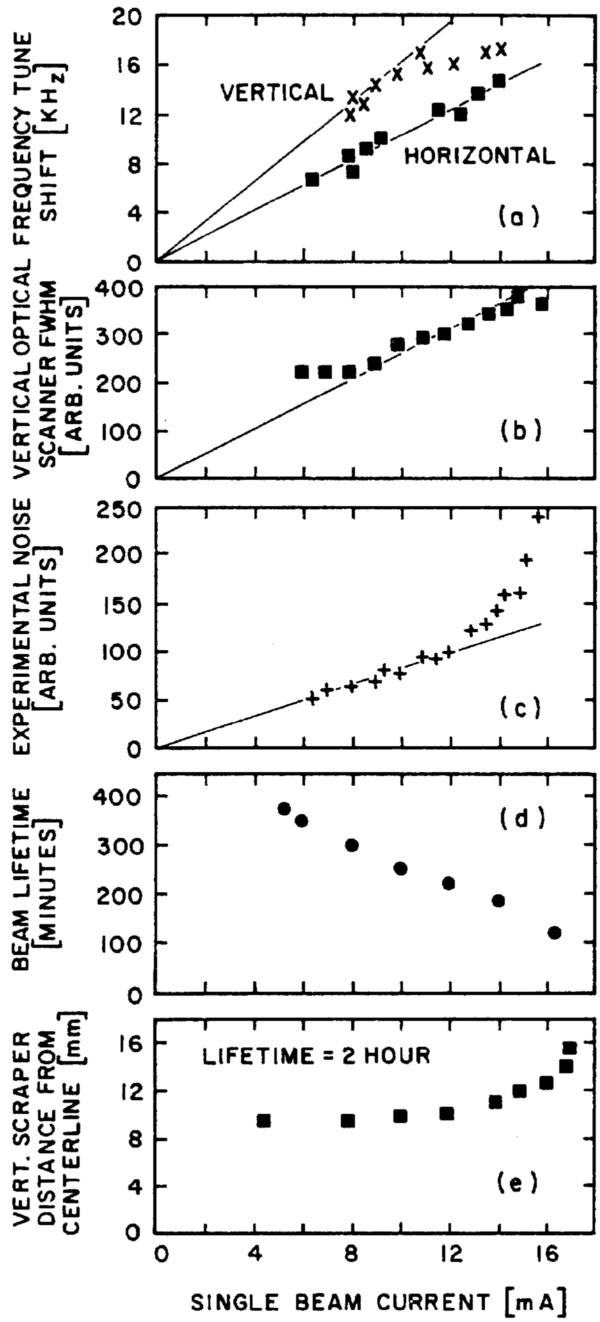
The luminosity and vertical beam size can not increase indefinitely with current. Several observations indicate that non-gaussian tails of the beams limit the current. The experimental background is plotted versus current in Fig. 3c and is linear with current at low currents but increases dramatically at high currents. The beam lifetime (Fig. 3d) decreases with current and is reduced to under two hours at the peak current. Both data suggest that a substantial fraction of the beams is very near the physical aperture of CESR at high currents.

How nongaussian the beams are at high currents can be determined by translating the maximum vertical beam size as determined by the luminosity to the tightest aperture using the vertical beta function.[10] The results of the calculations are recorded in Table I and show that the beam clearance is 23 to 26 beam sigma. Clearly, large nongaussian tails are present. The vertical scrapers can be used to track, say, the two hour lifetime 'edge' of the beam as a function of current throughout a fill. (See Fig. 3e) These preliminary measurements indicate that the tail grows roughly in proportion to the core of the beam. Several studies are underway to more precisely measure the transverse particle distribution (for example see Ref. 11).

A comparison of the peak luminosities in Table I reveals that the luminosity has increased faster than $1/\beta_y^*$. This is because σ_x^* has been increased using ε_x and η_x^* allowing more current to be stored and thus a higher luminosity.

Observations of a Zero η_x^* Lattice

The minibeta $\eta_x^*=0$ lattice which has produced the highest luminosity is discussed here. The parameters of this lattice are listed in Table I and the observations are shown in Fig. 2. The peak vertical tune shift is higher but the peak luminosity is lower than the best $\eta_x^* > 0$ lattice. The luminosity grows as I^2 at low currents and as I at high currents, but measurements[7] of the vertical and horizontal tune shifts as seen on the spectrum analyzer show that both tune shifts saturate above about 8 mA. Also, the horizontal shifted peak is observed to be very excited near the half integer. These data can be explained if both σ_y^* and σ_x^* grow as $I^{1/2}$. More information on this and other $\eta_x^*=0$ lattices is in Ref. 7.



Single Beam Current
Fig. 3 Measurements of N9932B.9A1 vs current.

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