Observation of the dynamic beta effect at the Cornell Electron-Positron Storage Ring with the CLEO detector

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Using the silicon strip detector of the CLEO experiment operating at the Cornell Electron-Positron Storage Ring (CESR), we have observed that the horizontal size of the luminous region decreases in the presence of the beam-beam interaction from what is expected without the beam-beam interaction. The dependence on the bunch current agrees with the prediction of the dynamic beta effect. This is the first direct observation of the effect. [S1063-651X(98)02501-X]

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In a high energy colliding beam storage ring when two beams of oppositely charged particles pass through each other there is an attractive force between them. Under certain circumstances this beam-beam interaction can lead to a reduction in the transverse beam size at the interaction point. This ''dynamic beta'' effect is potentially important since a smaller beam size corresponds to a higher luminosity.

The dynamic beta effect has been long predicted [1]. It has been observed indirectly through its effect on luminosity at Cornell Electron-Positron Storage Ring (CESR) [2]. This paper describes a direct observation of the reduction in beam size due to the effect. The dynamic beta effect is analyzed by modeling the beam-beam interaction as a linear focusing lens. This focusing alters the beta, β, around the ring. The beta with the beam-beam interaction can be given in terms of the ''unperturbed'' β_0^*, the beta at the interaction point. For the horizontal

$$\frac{\beta_{x0}^*}{\beta_x^*} = \sqrt{1 - (2\pi\xi_x)^2 + 2(2\pi\xi_x)\cot(2\pi Q_{x0})}, \qquad (1)$$

where Q_{x0} is the unperturbed horizontal tune and ξ_x is the beam-beam parameter

$$\xi_x \equiv \frac{\beta_{x0}^* N r_e}{2\pi\gamma\sigma_x^*(\sigma_x^* + \sigma_y^*)}, \qquad (2)$$

where N is the number of particles per bunch ($N = 1.61 \times 10^{10}$ times the bunch current in mA at CESR), r_e is the classical electron radius (2.82×10^{-15} m), γ is the relativistic factor (1.04×10^4 at CESR), and the σ^*'s are the horizontal (x) and vertical (y) beam sizes at the interaction point. Note that the σ^*'s are dependent upon the β^*'s in the above equations. Equation (1) makes it clear that if the tune is just above the half integer resonance there is a sharp reduction in β^*. This decreases the size of a single beam at the interaction point, given by $\sigma^* = \sqrt{\beta^*\epsilon}$ where ϵ is the emittance. The strength of the linear lens and therefore the reduction in β^* become larger with increases in the bunch current.

CESR is a particularly good place to observe the dynamic beta effect. Table I gives some of CESR's parameters and CESR is described in full detail elsewhere [3]. The bunch current is large, over 8 mA, generating a large beam-beam interaction. There is also a large range of bunch currents during normal CESR operations as the beam lifetime is about 3 h and the typical fill lasts 75 min. The collisions studied here have bunch currents ranging from 4 to 8 mA. In the horizontal direction the CESR lattice has a tune just above the half integer contributing to a large dynamic beta effect. In the vertical direction the tune is not close to the half integer and thus dynamic beta effects are much smaller on the vertical size of the beam.

The CLEO detector has been described in detail elsewhere [4]. A recent addition is a silicon strip vertex detector [5], which is crucial to the observation of the dynamic beta effect. This consists of three layers of silicon wafers arrayed in an octagonal geometry around the interaction point. The first measurement layer is at a radius of 2.3 cm and the wafers are read out on both sides by strips, which are perpendicular to each other. The readout strips have a pitch of about 100 μm and with charge sharing the detector has an intrinsic per point resolution of better than 20 μm in both the plane transverse to the beam, the xy plane, and in the direction parallel to the colliding beams, called z.

We observe the luminous region with events of the type $e^+e^- \rightarrow$hadrons, which are defined as events with more than two charged tracks and four or more significant energy deposits in the electromagnetic calorimeter. All the data are taken with electron-positron collisions with a center of mass energy equal to or just below the mass of the $\Upsilon(4S)$ resonance. We try to form a vertex from all the tracks in the event that have hits in at least two of the three layers of the silicon in both the xy plane and z direction. Those tracks with a contribution to the vertex chi-square of over two per degrees of freedom are removed as being unlikely to share a common vertex with the other tracks. This procedure is iterated until all such tracks are removed. Finally the probability of the vertex chi-squared must be greater than 10%. Vertices formed from two or more tracks give three-dimensional points in space that are used to determine the size of the luminous region. A total of 77 327 such vertices are found and used for these measurements.

For each discrete fill of CESR the average position is found in the vertical and horizontal directions. There are occasional large shifts in this average fill position that result from tuning CESR for backgrounds or luminosity with the introduction of closed orbit distortions through the interaction region. These fill averages are subtracted from all the points of the fill to correct for these shifts in the average

TABLE I. Operational parameters of CESR. IP denotes interaction point.

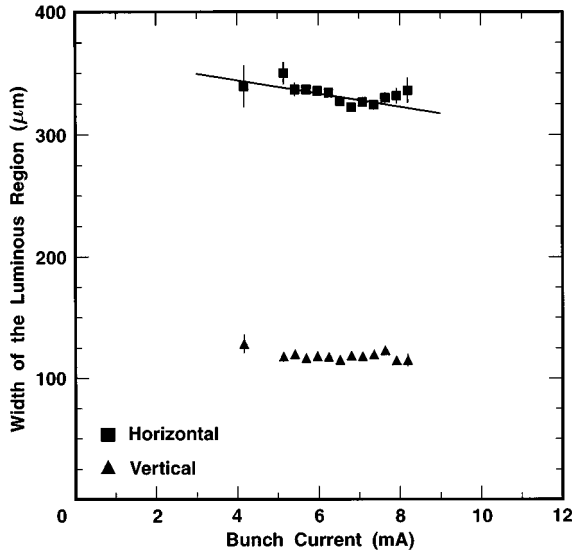| Parameter	Symbol	Value
Energy	E	5.29 GeV
Unperturbed horizontal beta at the IP	β_{x0}^*	1.38 m
Unperturbed vertical beta at the IP	β_{y0}^*	1.89 cm
Unperturbed horizontal emittance	ϵ_{x0}	2.11×10^{-7} m
Unperturbed vertical emittance	ϵ_{y0}	2.12×10^{-9} m
Bunch length	σ_z	1.87 cm
Horizontal integer tune	Q_x	10.540
Vertical integer tune	Q_y	9.630
Transverse damping time	τ_{damp}	10 000 turns

FIG. 1. The observed width of the luminous region in the horizontal and vertical directions as a function of the bunch current. Also shown is the line from the fit to the horizontal widths described in the text.
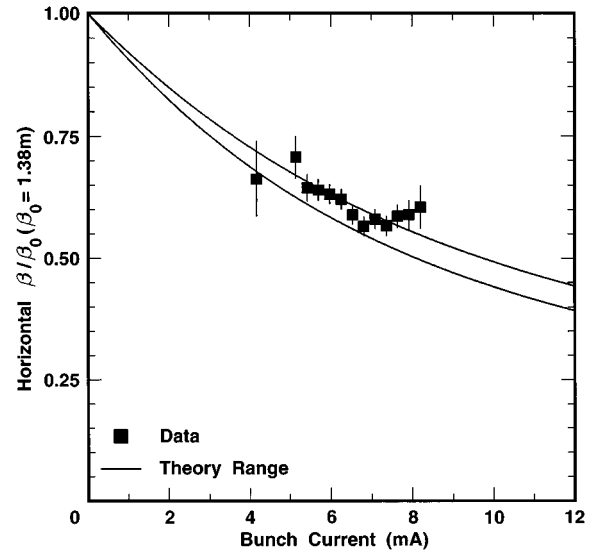

FIG. 2. The horizontal beta as a function of bunch current. Note that the error on β_{x0}^* of 5% of its value is not included in the error bars on the data.

position of luminous region. We have looked for changes in the average beam position during the course of a fill and can discern none.

The distribution of these positions in the horizontal and vertical directions is binned and then fit to a flat function, to account for vertices not resulting from beam-beam collisions, plus a Gaussian shape. The width of this Gaussian is taken as the observed width of the luminous region.

Another useful feature of the CESR lattice for the observation of the dynamic beta effect is the disparity of the beam size between the horizontal and vertical directions. Without considering the effect of the beam-beam interaction the Gaussian width of the beam in the horizontal direction is $\sigma_{0x}^*=540$ μm. In the vertical direction $\sigma_{0y}^*\approx10$ μm. Note that when the two beams collide they create a luminous region, which is the overlap of the two colliding beams. The size of this luminous region is a factor of $\sqrt{2}$ smaller than the single beam size.

Figure 1 shows the observed width of the luminous region in the horizontal and vertical directions as a function of the bunch current. The vertical width of around 120 μm is much larger than the expectation of $10/\sqrt{2}=7$ μm. Studies with a Monte Carlo based simulation of hadronic events in the CLEO detector indicate that the vertical width of the luminous region, which is observed to be much larger than the expectation, is actually a measure of the resolution on the luminous region in the x-y plane. Note that there are observations of strong beam-beam effects on the vertical beam size [6]. Also note that the bunch length is similar to the vertical size of the luminous region; thus there is an appreciable ''hourglass'' effect [7] in the vertical direction. These effects, and any vertical dynamic beta effects, have no impact on this observation as our resolution is much larger than the vertical size of the luminous region.

The observed horizontal width is as small as 320 μm which is smaller than the expected unperturbed value of $540/\sqrt{2}=380$ μm. Interpreting the observed vertical width as

the resolution implies an underlying horizontal width of the luminous region of $\sigma_{x\mathcal{L}}=295$ μm, which is much below the expected unperturbed value.

If we fit the observed vertical width as a function of the bunch current to a line the width is seen to be independent of the bunch current. This is expected if the vertical width is dominated by the resolution. A linear fit to the horizontal width as a function of bunch current has a negative slope of -5.4 ± 1.6 μm/mA. Both the observation of a significantly smaller than expected horizontal width of the luminous region in the presence of the beam-beam interaction and a significant dependence of the horizontal width on the bunch current are evidence of the dynamic beta effect.

To compare with the prediction of the dynamic beta effect we extract the horizontal beta from the width of the luminous region. We use a resolution of 118 ± 10 μm. This is from a fit to the vertical distribution independent of bunch current with the error dominated by a 10 μm jitter introduced by the correction for the average fill position. The horizontal emittance is calculated using the theoretical lattice with a thin quadrupole at the IP to simulate the beam-beam interaction. Variations in the quadrupole strength due to variations in the beam current lead to variations in the Twiss parameters around the ring. This variation leads to variation of the radiation integrals and hence to a variation of the emittance [2]. The emittance is parametrized by $\epsilon_x=(1.96\times10^{-7}+1.46\times10^{-9}I_{bunch}+5.15\times10^{-12}I_{bunch}^2)$ m, where I_{bunch} is the bunch current in mA. We have checked this calculation of the horizontal emittance using $e^+e^-\rightarrow\mu^+\mu^-$ events observed with CLEO. They give $\epsilon_x=(1.87\pm0.65)\times10^{-7}$ m, where the error is dominated by the resolution on the angle between the two muons. Then using $\beta_x^*=\sigma_{x\mathcal{L}}^2/2\epsilon_x$ we calculate β_x^* as a function of the bunch current as shown in Fig. 2. The β_{x0}^* of 1.38 ± 0.07 m is taken from a single beam measurement using the observed phase advance through the interaction region.

The theory curves shown in Fig. 2 also include the small effect of the beam-beam interaction at parasitic crossings away from the interaction point where the beams are separated by a pretzel orbit. This effect serves to lower β_x^* by about 10% at a bunch current of 12 mA and is essentially linear from no effect at zero bunch current. The range of the theory comes from the observed variation in the fractional integer tune from 0.537 to 0.544 from fill to fill.

In conclusion, we have directly observed the dynamic beta effect at CESR with the silicon strip detector of the CLEO experiment. We have seen that the horizontal size of the luminous region is smaller than expected when there is a beam-beam interaction, and that it decreases in size with increasing bunch current as the dynamic beta effect predicts. When we extract the horizontal beta as a function of the bunch current it is seen to agree very well with the expectation of the dynamic beta effect. This is the first direct observation of this effect.

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