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## OBSERVATION OF BEAM-BEAM DEFLECTIONS AT THE INTERACTION POINT OF THE SLAC LINEAR COLLIDER\*

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## ABSTRACT

We report the first direct observation of the electromagnetic deflection of high energy electron and positron beams as they pass each other with small impact \_\_parameters. Measurements of the deflection amplitude are found in agreement with theoretical expectations. This phenomenon, which is sensitive both to the relative position of the two beams and to their transverse sizes, has been used successfully to optimize and maintain collisions at the interaction point of the SLAC Linear Collider.

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\* Work supported by the U.S. Department of Energy under contracts DE-AC02-86ER40253, DE-AC02-84ER01112, and DE-AC03-76SF00515. The SLAC Linear Collider<sup>1</sup> (SLC) is a novel electron-positron accelerator designed to operate with center-of-mass energies around the mass of the neutral intermediate vector boson ( $Z^{\circ}$ ). The frequency of collisions in linear colliders is limited by power considerations to a few hundred Hertz, typically two or three orders of magnitude lower than in storage rings. At these frequencies, achieving interaction rates useful for physics requires focusing the beams to transverse sizes of at most a few microns, and then establishing and maintaining collisions between beams with impact parameters smaller than the beam sizes themselves. One technique which has been proposed<sup>2</sup> for this purpose is based on measuring the deflections produced in the beam trajectories by the coherent electromagnetic interaction between the beam bunches as they pass near or through each other at the interaction point (IP).

In this letter we report the first observation of beam-beam deflections, which constitutes a crucial step in establishing the viability of the linear collider concept. After deriving the predicted properties of the phenomenon and their dependence on beam parameters, we describe the technique used to measure the deflections. We then turn to a discussion of the experimental results, and conclude with an outline of possible refinements in applying beam-beam deflections to luminosity optimization in linear colliders.

When two oppositely charged, relativistic beams pass each other, they feel an attractive impulse as a result of their electromagnetic interaction. The resulting deflection in their trajectory is given by  $\theta = tan^{-1} (p_t/p) \approx (p_t/p)$ , where  $p_t$  is the transverse momentum imparted to one bunch as it passes through the field of the other bunch, and p is the longitudinal momentum of the bunch.

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Consider the deflection of a single "probe" particle in the field of an oppositely charged "target" bunch of  $N_t$  particles, each with charge q, having a Gaussian charge distribution. In the rest frame of the target bunch, we may write its charge distribution as:

$$G(x,y,z,\sigma_x,\sigma_y,\sigma_z) = \frac{N_t q}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp\left\{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}\right\} \quad . \tag{1}$$

The transverse electric field of the bunch is given by:<sup>3</sup>

$$E_{x,y} = -\frac{\partial}{\partial x,y} \left[ \frac{N_t q}{\sqrt{\pi} \ 4\pi \ \epsilon_0} \int_0^\infty dt \ \frac{\exp\left\{-\frac{x^2}{t+2\sigma_x^2} - \frac{y^2}{t+2\sigma_y^2} - \frac{z^2}{t+2\sigma_z^2}\right\}}{\left(t+2\sigma_x^2\right)^{1/2} \ \left(t+2\sigma_y^2\right)^{1/2} \ \left(t+2\sigma_z^2\right)^{1/2}} \right]$$
(2)

We now solve for the transverse momentum in x and y:

$$p_{x,y} = \int_{\Delta_{\tau}} q E_{x,y} d\tau = \frac{-2N_t q^2 \Delta_{x,y}}{4\pi \epsilon_0 c} \int_0^\infty dt \; \frac{\exp\left\{-\frac{\Delta_x^2}{t+2\sigma_x^2} - \frac{\Delta_y^2}{t+2\sigma_y^2}\right\}}{\left(t+2\sigma_{x,y}^2\right) \; \left(t+2\sigma_x^2\right)^{1/2} \; \left(t+2\sigma_y^2\right)^{1/2}} \;, \tag{3}$$

where  $\Delta_{\tau}$  is the length of time the probe charge is in the field of the beam and  $\Delta_{x,y}$ is the offset between the probe charge and the center of the bunch. To obtain the right-hand side of Eq. (3), we have made the substitution  $c\tau = z$  and performed the integration over z. Equation 3 is valid when disruption effects, where the beams induce size changes in each other during collision, are negligible. If we now transform to the laboratory rest frame,  $p_{x,y}$  remains unchanged,  $p \approx m_e \gamma c$ , and:

$$-\frac{1}{\theta_{x,y}} = \frac{-2r_e N_t \Delta_{x,y}}{\gamma} \int_0^\infty dt \; \frac{\exp\left\{-\frac{\Delta_x^2}{t+2\sigma_x^2} - \frac{\Delta_y^2}{t+2\sigma_y^2}\right\}}{\left(t+2\sigma_{x,y}^2\right) \; \left(t+2\sigma_x^2\right)^{1/2} \; \left(t+2\sigma_y^2\right)^{1/2}} \quad , \quad (4)$$

where  $r_e$  is the classical radius of the electron.

For the realistic case of a probe beam with a Gaussian charge distribution a convolution with the expression obtained for the deflection of a single particle must be done:

$$\langle \theta_{x,y} \rangle = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dx dy \; \tilde{G} \left( x - \bar{x}_p, y - \bar{y}_p, \sigma_{p,x} \sigma_{p,y} \right) \; \theta_{x,y} \quad , \tag{5}$$

where  $\langle \theta_{x,y} \rangle$  is the average deflection angle of the probe bunch (*i.e.* the deflection of the center of gravity of the bunch). The density distribution of the probe beam is  $\tilde{G}$ , where  $\bar{x}_p(\bar{y}_p)$  is the center and  $\sigma_{p,x}(\sigma_{p,y})$  is the standard deviation in the x(y)direction. If we assume that the two beam spots are erect ellipses in the transverse plane, then<sup>4</sup>

$$\langle \theta_{\boldsymbol{x},\boldsymbol{y}} \rangle = \frac{-2r_e N_t \Delta_{\boldsymbol{x},\boldsymbol{y}}}{\gamma} \int_0^\infty dt \; \frac{\exp\left\{-\frac{\Delta_{\boldsymbol{x}}^2}{(t+2\Sigma_{\boldsymbol{x}}^2)} - \frac{\Delta_{\boldsymbol{y}}^2}{(t+2\Sigma_{\boldsymbol{y}}^2)}\right\}}{\left(t+2\Sigma_{\boldsymbol{x},\boldsymbol{y}}^2\right) \; \left(t+2\Sigma_{\boldsymbol{x}}^2\right)^{1/2} \; \left(t+2\Sigma_{\boldsymbol{y}}^2\right)^{1/2}} \quad , \tag{6}$$

where  $\Delta_x(\Delta_y)$  is now the distance between beam centers and  $\Sigma_x^2 = \sigma_{p,x}^2 + \sigma_{t,x}^2$   $\neg(\Sigma_y^2 = \sigma_{p,y}^2 + \sigma_{t,y}^2)$  is the sum of the squares of the probe and target beam sizes. The integration in this expression can be performed analytically if we assume that  $\Sigma_x = \Sigma_y = \Sigma$  (this includes the case of round probe and target beams). With  $\Delta = (\Delta_x^2 + \Delta_y^2)^{1/2}$  the result is:

$$\langle \theta_{x,y} \rangle = \frac{-2r_e N_t \Delta_{x,y}}{\gamma \Delta} \left( \frac{1 - \exp\left\{ -\frac{\Delta^2}{2\Sigma^2} \right\}}{\Delta} \right) \quad . \tag{7}$$

Equation 7 shows, as expected, that there is no deflection either when the beams are far from each other or when they are exactly centered. The maximum deflection for round beams occurs when the impact parameter is approximately 1.6  $\Sigma$ . During its start up phase, the SLC ran with typical beam intensities of slightly less than  $1 \times 10^{10}$  particles/pulse, and transverse beam sizes at the IP of approximately 5  $\mu$ m, so the maximum deflections seen in this data should be about 35  $\mu$ rad. At these sizes and intensities disruption effects are expected to be negligible.

We used four beam position monitors (BPMs), two on either side of the IP, to determine the beam deflection at the IP. These BPMs<sup>5</sup> are captured between quadrupole magnet pole pieces due to space limitations (Fig. 1). The four electrodes in each BPM are carefully impedance-matched and are read out on both ends into custom-designed electronics.<sup>5</sup> This allows us to measure the vertical and horizontal positions of both beams on the same machine pulse, even though the beams are separated by less than 30 nsec in the BPMs closest to the IP. The pulseto-pulse resolution of these BPMs is measured to be better than 10  $\mu$ m for beam intensities of ~ 5 × 10<sup>9</sup> particles/pulse, and is expected to improve further as SLC beam intensities increase.

Measuring positions in two BPMs on both sides of the IP independently defines incoming and outgoing beam trajectories at the IP. The information from all four BPMs is used in four separate linear fits which yield the beam position, the incoming beam angle, and the beam deflection angle (all evaluated at the IP) in each plane for both beams on a single beam pulse.<sup>6</sup> While the positions and angles of the beams at the IP are observed to be stable on a pulse-by-pulse basis to a fraction of the measured beam size and angular divergence (typically several hundred  $\mu$ rad), fluctuations of this magnitude in the outgoing beam angle can still be several times larger than the expected maximum deflection. Fitting directly for the difference between the outgoing and incoming angles of a given beam effectively decouples any angular motion of the incoming beam from the deflection angle measurement. This can also be shown to reduce any static misalignments in the BPMs to a constant offset of the measured deflection angle,<sup>6</sup> which can be ignored for our applications.

In practice, the deflection angles for both beams are measured as a function of the impact parameter as one beam is swept across the other in either the horizontal or the vertical-direction. These beam scans are accomplished using small air-core dipole magnets (Fig. 1), which can increment the beam position, between machine pulses, with a resolution of 0.05  $\mu$ m. Since the beams deflect each other very little when they are far apart, they must first be brought to within a few beam radii of each other. This has been done by steering the beams, one at a time, onto carbon filaments with radii comparable to the beam size, which are inserted into the center of the beam pipe at the IP.<sup>7,8</sup> These filaments produce secondary emission and bremsstrahlung signals proportional to the fraction of the beam intercepted. The filaments, which are primarily used to measure and optimize transverse beam sizes, stay retracted during deflection measurements.

To get the information necessary to precisely center the beams, one beam is scanned past the other, typically over a range of  $\pm 40 \ \mu m$  in 2  $\mu m$  steps. The BPM signals are read out on each pulse, processed, and stored by a microcomputer until the scan is finished. The microcomputer also sets and reads back the current in the air-core dipole magnets used to position the beams. When the scan is finished, the microcomputer sends the scan data to a VAX-8800 computer on which the data is analysed and displayed. The results of a typical positron beam scan in xare shown in Fig. 2. The deflection angles parallel ( $\langle \theta_x \rangle$ ) and perpendicular ( $\langle \theta_y \rangle$ ) to the scan direction as a function of the scanned beam's distance from its original position are shown in Figs. 2(a) and 2(b), respectively. The errors on the points are derived assuming a position resolution of 15  $\mu$ m for the individual BPMs. For approximately round beams, the data are expected to be described by Eq. (7). For real-time beam centering, the data were fitted using Eq. (7) for the in-plane deflection curve, assuming the beams were aligned in the scanned direction, and by a Gaussian<sup>9</sup> for the out-of-plane curve. As can be seen by the curves shown in Fig. 2, the data is consistent with these approximate functional forms, with the maximum out-of-plane deflection occurring at the zero-crossing of the in-plane deflection curve.

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Figure 3 shows a scan with one of the largest maximum deflections measured to date. After centering the beams in x, the  $e^+$  beam was scanned past the  $e^$ beam in the y direction. The beam sizes measured prior to this scan using the carbon filaments were  $\sigma_x = 7.2 \ \mu m$ ,  $\sigma_y = 3.9 \ \mu m$  for the electron beam;  $\sigma_x =$  $4.9 \ \mu m$ ,  $\sigma_y = 3.9 \ \mu m$  for the positron beam. The curve derived using these measured beam sizes as input to Eq. (6) overlays the data. The beam currents, which provide a multiplicative normalization, were adjusted to give the best fit and were found to be consistent with currents measured by other means. The agreement between data and theory indicates that beam-beam deflections are well understood and reliably measured.

Beam-beam deflections are a powerful tool for luminosity optimization at the SLC. Positioning the scanned beam on the zero-crossing of the deflection curve aligns the beams to a small fraction of the beam size. This has been the primary method used to steer the SLC beams into collision. In most cases, the beam spots at the interaction point are approximately round, so that meaningful fits to the

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deflection data using the form of Eq. (7) can be made. These immediately yield estimates of the beam sizes and intensities. In the future, pulse-to-pulse sampling of the beam deflection will be made in a feedback microcomputer which will be used to compensate for any slow drifts of the beams relative to each other.

Beam-beam deflections may also be used to minimize the spot size at the IP. Small changes in beam size are signalled by measurable changes in the slope of the deflection curve through the zero-crossing point. This is demonstrated in Fig. 4, which shows the predicted dependence of the slope on the size of the  $e^-$  beam in x for several different  $e^+$  beam radii. The electron beam size in y is assumed fixed near its optimal value.

The relationship between the slopes of the deflection curves and the luminosity is:<sup>10</sup>

$$L = \frac{Nf\gamma}{4\pi r_e} \left( S_x + S_y \right) \quad , \tag{8}$$

where  $S_x$  and  $S_y$  are the slopes of the deflection curves measured with separate x and y scans after the beams have been centered. The repetition rate of the collider is f. An independent measurement of the number of particles, N, in the deflected beam is also required. The advantage in using the slopes is that they can be accurately measured even when the beams are not round. Optimal luminosity can be achieved by adjusting the focus of the beams to obtain the maximum slopes. Once this has been established, it can be monitored by checking the slopes periodically with short scans across the zero-crossing point.

In conclusion, we have presented measurements of the deflections of high-energy electron and positron beams as they pass by each other. These measured deflections agree with theoretical expectations. We have discussed how the deflections have been used to steer micron-sized beams into collision, and how they will be used for spot size optimization at the SLC.

Although it is impossible to acknowledge individually the efforts of the many people who brought the SLC into operation, we would like to thank the staff of the Stanford Linear Accelerator Center and the numerous scientists from other institutions who have worked on this project, and without whose invaluable contributions the observations described in this paper could not have been made. We also would like to thank G. B. Bowden, J.-C. Denard, A. Gromme, J.-L. Pellegrin, and M. Ross, who were responsible for the BPM system. The performance of these devices was critical for the results presented here.

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## FIGURE CAPTIONS

- Fig. 1. Schematic of beamline components relevant to the beam-beam deflection measurement.
- Fig. 2. A beam-beam deflection scan of the  $e^+$  beam relative to its initial position showing (a) the in-plane deflection, and (b) the out-of-plane deflection. The  $e^-$  beam intensity was about  $7 \times 10^9 e^-$ /pulse, and both beams were approximately round with  $\sigma = 7 \mu m$ . The beams were approximately 10  $\mu m$  apart in the out-of-plane direction during this scan. The data are consistent with these parameters.
- Fig. 3. An  $e^+$  beam deflection scan in y after alignment in x. The curve overlaying the data is a theoretical calculation using as input the beam sizes as measured by the wire filaments.
- Fig. 4. The expected slope of the in-plane deflection curve at the zerocrossing point as a function of the  $e^-$  beam  $\sigma_x^-$  with a fixed  $\sigma_y^$ of 1.5  $\mu$ m. The solid curve corresponds to a round  $e^+$  beam with  $\sigma^+ = 1.5 \ \mu$ m, the dashed to  $\sigma^+ = 3.0 \ \mu$ m and the dotted to  $\sigma^+ = 6.0 \ \mu$ m. The target beam intensity for these calculations was  $1 \times 10^{10}$ .

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Fig. 2



Fig. 3



Fig. 4