First Observation of Beamstrahlung

G. Bonvicini, E. Gero, R. Frey, and W. Koska
University of Michigan, Ann Arbor, Michigan 48109

C. Field and N. Phinney
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

A. Minten
CERN, CH-1211, Geneva 23, Switzerland
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Collisions of electron and positron bunches at the interaction point of the linear collider at SLAC have led to the first detected emission of beamstrahlung. This radiation, caused by the collective electromagnetic fields of one beam deflecting particles of the other, is a potential tool for optimizing collisions in linear colliders.

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With the advent of the linear collider¹ as a tool for the study of high-energy elementary particle physics, there has developed a strong interest in the physics of the beams in such machines. Of particular interest is the interaction point (IP), where the two beams must be brought to superimposed foci, with transverse sizes in the micron range or smaller. New methods are needed for the measurement and monitoring of these beams in collision. We describe here the first observation of beamstrahlung—an electromagnetic radiation from the collision of the beams. The phenomenon promises to be a valuable operating tool for linear colliders and very-high-energy storage rings.²

There is a considerable body of theoretical work on beamstrahlung in the literature, covering various energy regimes and beam parameters,³ and the topic continues to develop at a lively pace. It has not been possible to observe the radiation, however, until the Stanford Linear Collider (SLC) at SLAC began to collide high-energy electron and positron beams with exceptionally intense focal spots. For the data reported here, typical beam energies were 46 GeV (Lorentz factor $\gamma=9\times 10^4$), with bunches of about 10^{10} electrons and 6×10^9 positrons. At collision, the bunches were approximately Gaussian along all three axes, with rms length about $750\text{ }\mu\text{m}$, and transverse rms sizes typically below $5\text{ }\mu\text{m}$.

The magnetic fields around one of these dense bunches can approach 10 T. Consequently, each particle trajectory is deflected (equally by the magnetic and electric fields), and emits synchrotron radiation. It is this radiation which is termed beamstrahlung. Until conditions are such that its energy is comparable with the energy of the beam, it may, as in this Letter, be treated classically.

The charge-density distributions of each beam have Gaussian lengths λ , and, in the simplified case of round cross sections, Gaussian radius σ . N is the bunch population, and subscripts 1 and 2 refer, respectively, to the

beam whose radiation is being calculated and to the target beam. The impact parameter between beam centers is d . The energy radiated is

$$U_1 = \frac{8}{3\sqrt{\pi}} \frac{N_1 N_2^2 r_e^3 m c^2 \gamma^2}{\sigma_1^2 \lambda_2} F,$$

$$F = \int_0^\infty \frac{1}{x} (1 - e^{(-B^2 x^2)})^2 e^{-(x^2 + l^2)} I_0(2lx) dx.$$

Here, r_e is the electron classical radius, m is its mass, c is the velocity of light, B is σ_1/σ_2 , and l is $d/\sqrt{2}\sigma_1$. The transverse spatial integral F , involving the modified Bessel function I_0 , in general is evaluated numerically.

The energy scale of synchrotron radiation is characterized by the “critical energy”⁴ E_c . In beamstrahlung, there is a range of critical energies. An expression for the energy-weighted mean critical energy is

$$\langle E_c \rangle = \left(\frac{6}{\pi} \right)^{1/2} \left(\frac{N_2 r_e^2 m c^2 \gamma^2}{\alpha \sigma_1 \lambda_2} \right) \frac{G}{F},$$

$$G = \int_0^\infty \frac{1}{x^2} (1 - e^{(-B^2 x^2)})^3 e^{-(x^2 + l^2)} I_0(2lx) dx,$$

where α is the fine-structure constant. G is also evaluated numerically. In the work reported here, $\langle E_c \rangle$ has been in the range 10–15 MeV.

Since the emission of the γ rays is tangential with microradians to the emitting trajectory,⁵ the radiation forms a neutral beam with the same angular divergence as the charged beam, broadened by the range of angles through which the charged beam is deflected during the collision.

At the SLC interaction point, beam bunches collide at a rate of up to 120 Hz, and so each collision can be observed individually. The bunches leaving the interaction point travel approximately 38 m before magnetic dipoles deflect the charged beams by approximately 1° . At 41

m along both e^+ and e^- beam lines there is sufficient separation between the charged and neutral trajectories to permit the installation of a detector for the γ rays. However, the radiation environment, particularly the synchrotron radiation from the nearby dipole with potentially 10^3 rads per pulse and a critical energy of 2.3 MeV, strongly influenced the design and operation of the detectors, which are described in detail elsewhere.⁶ For γ -ray energies $E \gg E_c$, the synchrotron (and beamstrahlung) spectrum falls as $E^{-1/2} \exp(-E/E_c)$, and so an energy threshold in the range of 20–30 MeV suppresses a synchrotron-radiation and other low-energy backgrounds while retaining sensitivity to some of the beamstrahlung. This has been accomplished by using a plate to convert approximately 3% of the γ rays to e^+e^- pairs, and using a gas Čerenkov counter to measure the flux of $e^\pm$ above the Čerenkov threshold. In practice, synchrotron-radiation backgrounds have been too small to measure, even when thresholds were tested as low as 16 MeV.

The Čerenkov counters measure the amount of light from individual tracks within their energy and geometric acceptance, and this is not proportional to the total

beamstrahlung energy. With the help of a Monte Carlo study, the response of the counter has been tabulated for a set of spectra characterized by values of $\langle E_c \rangle$. Thus an evaluation of $\langle E_c \rangle$ and U from the expressions above allows the yield of the counter to be interpolated and scaled for the beam parameters of interest.

The counters are also used for measuring bremsstrahlung from fine-carbon-fiber targets inserted at the IP to probe the size and shape of the beam spots.⁷ The signal is normally amplified in this case by placing a 3.3-radiation-length converter plate in front of the counter. For purposes of this Letter, the bremsstrahlung signals afford a calibration for the counters—the digitized pulse height is measured for a known flux of bremsstrahlung γ rays. The sensitivity for the lower-energy beamstrahlung spectrum is then inferred with the help of the electron-photon shower code EGS.⁸

One of the actions carried out in studying and tuning the colliding beams involves steering one beam spot across the other in steps typically of $2 \mu\text{m}$. Between steps, the beams are held stable for a selected number of pulses, frequently three, to allow data from these pulses to be averaged. The influence of their fields is strong

FIG. 1. (a) Response of the two counters as the positron beam spot is stepped at $2\text{-}\mu\text{m}$ intervals across the electron spot, with three pulses averaged at each step. Pedestal subtraction and $e^\pm$ intensity corrections have been made. The symbol diameter represents the uncertainty from the digitizer least count, averaged for three pulses. (b) The same data folded about the common mid-point. The continuous curves are the best representation of the data as defined in the text. For the dashed curves, the electron bunch radius is increased by 10%.

enough that the beams deflect each other, and results from beam position monitors are used to measure the deflections and set the steering for head-on collisions.⁹

An illustration is given in Fig. 1(a) of the signals obtained from the counters as the position beam spot was stepped vertically across the electron spot. The step size was 2 μm , and the results were averaged for three pulses between steps. The peaks rising a few counts above the signal digitizer (analog-to-digital converter) pedestal levels, which have been subtracted, indicate that radiation was detected along both beam lines only while the beam bunches were in very close proximity. Signals like this have been seen during numerous beam scans. With well focused beams the radiation is consistently detectable.

There has been nothing similar to the characteristic appearance of the intensity peaks in several months of operation with single beams. Occasionally there are backgrounds, both from the nearby showering of off-axis beam particles, and from a flux of higher-energy neutrals in the beam pipe from more distant beam scraping. However, when only one beam is present, such backgrounds are not sensitive to positioning it at the micron level, and are not seen when the beam is well focused and steered, as in this work. As a test, one beam was stopped far upstream, and the radiation from the remaining beam immediately ceased. The radiation clearly comes from a true beam-beam interaction, and at least for the conditions of this test, remaining single-beam backgrounds were at least an order of magnitude lower in amplitude.

The radiation has also been observed with the 3.3-radiation-length additional converter in front of the detector. The signal was attenuated by about 25%. Had it been caused by a high-energy background, the signal would have been amplified by up to a factor of 100, depending on the energy of the rays. A background originating from synchrotron radiation—with its energies below a few MeV—would be strongly attenuated by the converter. The observed decrease in signal is, however, consistent with what would be expected for the tail of a beamstrahlung spectrum just above the Čerenkov threshold of 25 MeV.

As discussed in detail in Ref. 6, the counters are capable of estimating the angular distribution of the incident radiation in the horizontal plane for radiation from the electron beam, and in the vertical plane for emission from the positron beam. This is obtained from the distribution of signals among the photomultiplier tubes. To date, however, the beamstrahlung yields have been small, and the contribution of electronic noise and least-count sensitivity to the results from individual channels has been relatively large. Nonetheless, a single measurement has been made of the vertical angular divergence of the positron beam. The result, 251 ± 25 μrad , lies within the range measured using bremsstrahlung during beam tuning operations a few hours before

and after the beamstrahlung measurement.

A more quantitative examination of the results of some of the scans has been attempted. Fluctuations are to be expected from pulse-to-pulse intensity changes of the charged beams. Corrections for this have already been made in Fig. 1(a). The resulting plots show some remaining fluctuations, and also a tendency for left-right asymmetry. Asymmetries can be produced by beams with substantial ellipticity whose major axes are in the neighborhood of 45° askew, and where the scan passes to one side of the exact head-on position. Studies with beam deflections and with carbon fibers suggest that these circumstances are unusual. On the other hand, the effect can simply be explained by a drift in the beam transverse dimensions in the range of 5% during the scan, with possibly a contribution from intrinsic asymmetry in the beam spots. Other measuring techniques do not exclude this. To compensate partially for such effects, we fold the scan results about the common midpoint of the positron and electron peak. In Fig. 1(b) are shown the results of folding the data of Fig. 1(a).

These folded peaks are characterized simply by amplitude and width. The first moment about zero beam separation is used as the width parameter. We then attempt to reproduce these observed width and amplitude values using beamstrahlung calculations as outlined above, in the approximation that the beam cross sections are round. We look for beam intensities, lengths, and radii which lead to good agreement with the data.

As is seen in the equations above, the variation of beamstrahlung emission with distance between the beams is given by the factors F and G . These depend only on the beam radii, and so we can first determine the radii from the observed widths of the beamstrahlung peaks. Then we obtain values for intensities and lengths which give agreement between calculation and data for both peak amplitudes from each scan.

Results are illustrated in Fig. 1(b). The solid curves are the best representation found for these data. In this and other cases, the charged-beam intensities needed for the curves agree with values from beam-line monitors within their uncertainty of $\pm 15\%$. The bunch lengths required for agreement with the data have also been consistent in the cases tried, close to 0.5 mm for positrons and 0.82 for electrons. The extent to which uncertainties in intensity and width (considered below) affect the length values was treated by a Monte Carlo correlation analysis, giving a length uncertainty of ± 0.21 mm. The results are consistent with electron bunch lengths of 0.54 ± 0.06 mm measured near the start of the linac,¹⁰ although trajectory-path-length differences may modify the length slightly before the IP is reached, and small variations with time may also occur. In summary, beamstrahlung yields appear to be consistent with theory, the dominant uncertainties being those on the charged-beam parameters.

The beam radii required in the calculations to make the first moments agree with the data generally have fallen within 7% of the values from carbon-filament scans made within an hour or so of the beam scans. The exception is the electron beam of Fig. 1, which, at $3.7\text{ }\mu\text{m}$, is 26% narrower than the carbon-fiber result, probably because of a change in beam conditions. The positron bunch radius was $4.1\text{ }\mu\text{m}$. The effect of a 26% difference may be judged from the figure, in which the dashed curves are calculated for an electron beam only 10% wider than the best value. (With the wider beam, it was necessary to shorten the bunch length to compensate for the 40% loss in intensity.) Although it was the electron beam whose width was altered, the dominant effect is on the emission from positrons. The calculations show that, over a broad range of beam radii of interest at SLC, the first moment remains within the range 1.45 to 1.75 times the *target* beam width. This simplifies the interpretation of the results of scans used to monitor changes in the colliding beams.

In the scans we have examined, there are occasional differences in shape between data and calculation. These can be large enough that our confidence in the width measurement does not yet extend below uncertainties of 10%. They may be associated with ellipticity in the beams, for which an analysis should include major and minor axis $e^\pm$ beam dimensions (instead of radii), and the angles of both ellipses relative to the scan direction. In order to determine the extra geometrical parameters, a set of scans must be made along at least three directions, a procedure which remains to be tested in future SLC operation. It may be concluded, however, that the technique is ready for development as a nondestructive monitor of beam profiles. Performance should improve as beam intensity increases, into the range where carbon-filament probes could not survive.⁷

A most important part of the work of obtaining the beamstrahlung signal was the effort of the people, too numerous to mention individually, who have worked hard to develop the SLC beams, both improving the collisions and reducing the background radiation. Particularly we thank J. Ballam and W. Kozanecki for their continual support and interest. This work was supported by the United States Department of Energy Contracts No. DE-AC03-76SF00515 and No. DE-AC02-76ER01112.

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