Problems in Measuring Micron Size Beams

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Summary: Measurements of the beam sizes at the SLAC linear collider are made using probes of carbon filament, and also using the beams to probe each other. Some of the difficulties encountered in implementing these techniques are discussed.

Beam tuning and accelerator physics at the collision point of the linear collider at the Stanford Linear Accelerator Center requires the measurement of the transverse dimensions of the beams. Techniques to perform this task must be appropriate for the range of beam conditions encountered. To date:

Beam energy	46 GeV
Bunch population	2×10^{9} - 2×10^{10}
Bunch length	0.5 - 1 mm
Bunch width	> 2.5 μm .

An increase of a factor of 2.5 in the bunch population, and a reduction by 30-40% in width are anticipated and the measuring systems have to allow for this.

Two approaches to width measurement have been followed. The use of a fine filament was the first of these, but, because of limitations in the beam intensity a filament can handle, an alternative approach using the beams to measure each other is coming into use. Some of the problems of these two schemes will be discussed in turn.

The use of wires to measure beam sizes is, of course, a well established procedure. The wire may be swept across the beam or *vice versa*. Spatial resolution can be achieved by using a step size (or an equivalent sampling rate) that is small compared with the dimensions of the beam. Even in the SLC range of 1-10 microns this is straight forward. There may be other criteria, however. The radiation from the probe, under beam bombardment, must be acceptable for the equipment around it -- for example, the elementary particle physics detector, which at present is the MARK II at the SLC. This means that the SLC probe must be of minimum mass, and low Z. It must be a conductor to prevent catastrophic electrical discharges. Most serious of all, the heating from ionization energy loss in the probe must be taken into account.

Carbon seems to meet these criteria better than any other conductor, although there are ceramics which are reputed to have a higher temperature range. The use of filaments with diameter less than the beam size has the added advantage that the temperature gradient from a heated spot is close to 1-dimensional -- along the filament -- and so internal rupturing stresses are eliminated.

Approximately 40% of the ionization energy loss escapes in the form of delta rays from fibers of diameter 4-35 microns. The remaining energy, deposited in 3 psec, leads to "instantaneous" thermal expansion. A shock wave results, and the extension "trough" following the wave would exceed the tensile strength of the carbon if the temperature pulse were above 2200°C. It must be said that the thermal and mechanical properties of the material are not well known in this range, and all numbers estimated here are quite inexact. However, this means that there is a risk of failure of the fibers for bunches of 10^{10} or more, with RMS widths of 3μm. Should the filament survive this, melting would occur at something like 1.7×10^{10} for a 3μm beam width. Note that the failure is a single pulse effect at SLC. The hot spot on the filament, hardly longer than it is wide, cools within tens of microseconds by conduction along the fiber.

We turn now to the methods of obtaining the beam signal from the fibers. Only two processes give signals strong enough for use at SLC -- surface emission and Bremsstrahlung. We consider surface emission first.

The fields around the focussed SLC bunches are very strong, and they induce a "mirror" charge at the surface of the fiber. The dipole field at the surface is complicated and difficult to calculate, but has a typical magnitude in the range of kilovolts. On the other hand, the most prolific surface emission process, secondary emission, yields an electron energy spectrum in the range of volts. The electrons which escape are those which, energized by the passing beam particle, under normal circumstances have enough range to pass the surface. In a conductor, only a surface layer 50 nm or so thick contributes. There are two points to notice.

First, tracks close to the edge of a filament free their ionization energy close to the surface, and so are accompanied by an increase in secondary emission -- a $1/\cos\theta$ effect, where θ is the normal angle of incidence of the track.

The second point is that the surface dipole <u>suppresses</u> secondary emission from an SLC electron beam. On the other hand, it clears away the emission from a positron beam, overcoming any space charge limitation which is often a factor in secondary emission. What

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is left from an electron beam is delta rays. These are products of "close encounters", and have a broad energy spectrum extending up to half the beam energy. Most of these with enough range to escape can also overcome the surface dipole. But the delta ray emission is an order of magnitude weaker than secondary emission. In addition, the efficiency profile of a fiber is quite different for delta rays than for secondary emission. This may be seen in Fig.1, where the performance of a 35 micron fiber for similar positron and electron beams, approximately 10 microns wide RMS, are compared. Although the electron beam was about 3 times as intense as the positron beam, its signal is half as large. The lines in the figure represent the profiles expected for secondary and delta ray emission respectively.

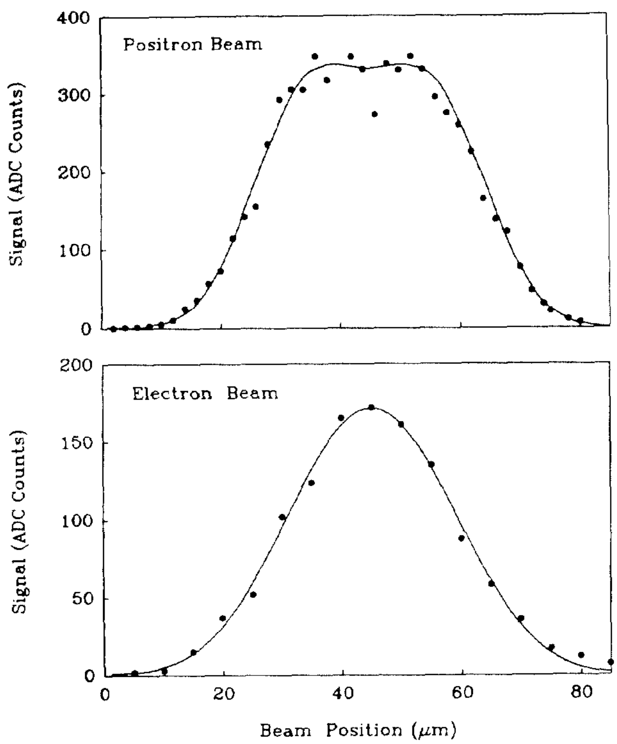

Fig.1. Profiles of beams of equal sizes with a 35 μm fiber: top -- secondary emission from a positron beam; bottom -- delta ray emission from an electron beam.

Summarizing surface emission, the effective width of a filament for a positron beam is different than that for an electron beam. Additionally the signal from the electron beam is small, decreases as the square of the fiber radius, and is difficult to extract from the R/F noise from the beam in the case of small fibers. Fortunately, another effect is easier to apply -- Bremsstrahlung.

As the beam trajectories penetrate a fiber, Bremsstrahlung gamma rays are emitted within 10 μrad, with a spectrum falling inversely with their energy, and a mean energy of about 7 GeV. These gamma rays travel with the charged beam until it is deflected by a dipole. At SLC, this occurs at about 40 meters from the collision point. A gamma ray detector[1] has been placed at this location in both positron and electron lines. The counters cover a divergence cone of ± 1 mrad from the collision point. It will be evident through this note that retaining access to the zero degree region for the installation of detectors has considerable value for colliders.

Of course, the counter must survive the synchrotron radiation from the dipole immediately upstream, which can reach 1000 rads per pulse with a critical energy of 2.3 MeV. Backgrounds from the beam scraping on collimators, where the gamma energies average 4 MeV, can also be bothersome. Backgrounds are the principal problem of this method, and they are overcome by applying an energy threshold, and designing the detector with massive, labyrinthine shielding. The threshold is applied as follows. A plate is used to convert some of the gammas into electron-positron pairs, which then enter a Cherenkov counter. Those tracks with energy above 25 MeV emit light, which is collected by a shielded periscopic optical system, and converted into electronic signals by photomultiplier tubes. Of course, it is vital to avoid scintillating material, including the gas, and to construct the exposed optics to withstand the extreme radiation levels.

In Fig.2 is an example of the performance of a counter with a 7 micron fiber[2]. The beam width was 2.7 μm, which was folded with the fiber diameter to appear as 3.22 ± 0.08 μm. The performance with a 4 micron fiber is illustrated in Fig.3, where the beam width was 3.1 μm, and is resolved as 3.3 ± 0.17 μm. The fiber diameters have been measured to $\pm 8\%$ for the 4 μm fibers, and $\pm 5\%$ for the 7 μm fibers now installed. We project that this will be adequate to allow beam widths as narrow as 1.5 μm to be measured within 5% and 10% respectively by the two sizes.

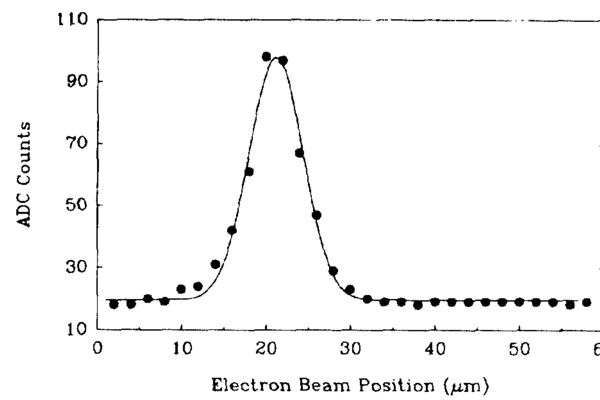

Fig.2. Bremsstrahlung beam profile from a 7 μm fiber.

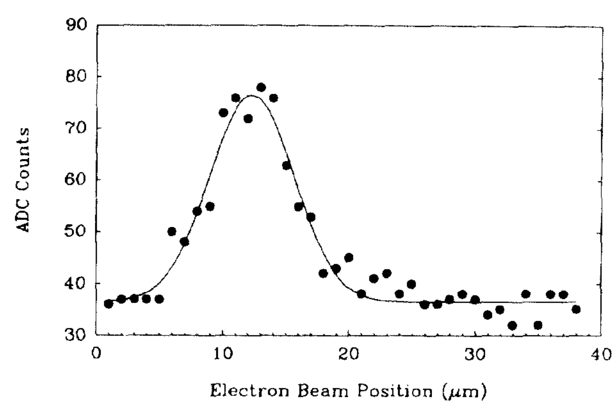

Fig.3. Bremsstrahlung beam profile from a 4 μm fiber.

However, a bunch of this size would be fatal for a filament if its population were much above 2.5×10^9. As a consequence, we now discuss our experiences with non-solid probes.

Cross sections for e^+-e^- interaction channels are too small to be of value for tuning or monitoring the SLC beams. (A possible exception to this is the radiative Bhabha scattering process which adequate in rate, but which, within the bounds of present technology, is masked by the beamstrahlung process to be discussed below.) On the other hand, the collective electric and magnetic fields of a bunch at the interaction point are strong enough to have macroscopic consequences for the opposing bunch. The radial electric field of a (round) bunch increases from zero at the center to reach a maximum at about 1.5 Gaussian radii, and thereafter tends to fall off inversely with radius. The deflecting effects of the magnetic and electric fields are equal, and during SLC development, peak fields could approach 100 kGauss, over millimeter lengths.

There are some obvious consequences of the effect. Opposing beam bunches will be deflected towards each other's axis, proportionally to the field strength encountered. Thus, outside the Gaussian structure of the bunch, the size of the deflection will vary inversely with separation between the centers. When the bunches are overlapping, the deflection will depend on an overlap of the two offset Gaussian shapes, with zero deflection at zero offset, and maximum deflection at a separation of $\pm$(1-2) Gaussian widths. More exactly, where $\langle\theta\rangle$ is the mean deflection angle, N the bunch population, d the offset between beams, σ the Gaussian radius, the subscripts 1 and 2 refer to the two beams, r_e is the classical radius of the electron, and γ is the Lorentz factor,

$$\langle\theta_1\rangle = -\frac{2r_e N_2}{\gamma\, d}\left[1-\exp\left\{\frac{-d^2}{2\left[\sigma_1^2+\sigma_2^2\right]}\right\}\right]$$

Additionally, conservation of transverse momentum means that the ratio of the size of the deflections of the two beams is the inverse of the ratio of the bunch populations.

This effect is in use at SLC[3], principally as a means of enforcing head-on collisions. One of the beams is steered in (typically) 2 micron steps across the position of the other at the collision point. A number of pulses, frequently three, are averaged at each position before the next step is taken using an air core magnet so that the move is accomplished between pulses. The positions of both beams are measured both ingoing and outgoing, using a specially designed beam position monitor system[4], with resolutions in the range of 10 µm for beam intensities used to date. A trajectory fit for each beam determines the deflection angle. An example of the measurement of deflections during one of these beam "scans" is shown in Fig.4. The major point of importance to this discussion comes from the width parameter of the Gaussian in the deflection formula above. The width of the deflection curves depends on the quadrature sum of the widths of the two bunches, which can therefore be established without a solid probe.

More information is available, however. The trajectory deflections give rise to a synchrotron-type radiation, termed beamstrahlung, which has been detected at SLC, and is being developed as a beam tuning tool.

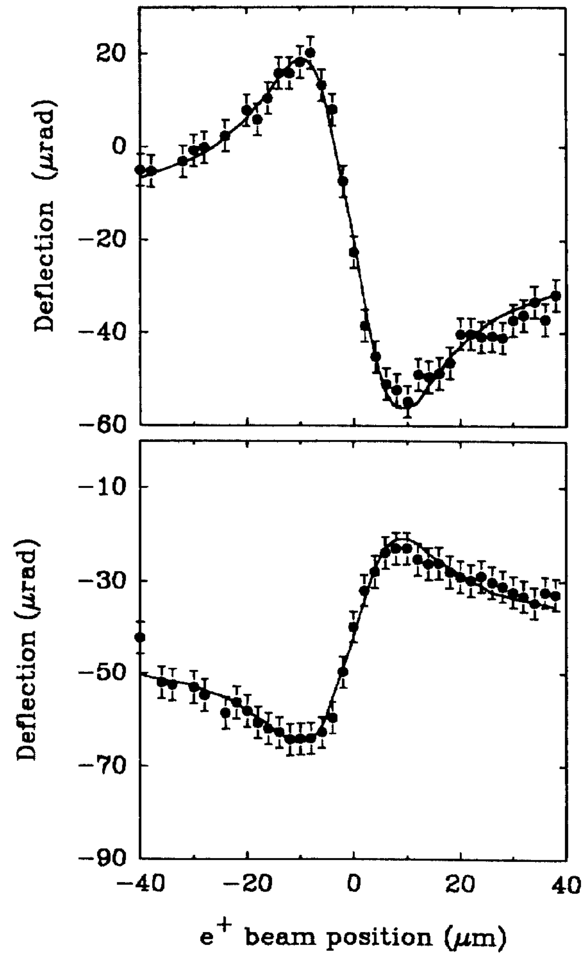

Fig.4. Deflections of the positron (top) and electron (bottom) beams against the position of the positron beam.

The beamstrahlung, like Bremsstrahlung, is emitted sharply forward, and is intercepted by the gamma ray counters described above. The signal from the counters during the deflection scan just described is shown in Fig.5. Gamma emission is seen clearly while the beams are overlapping. An expression for the energy yield of beamstrahlung is:

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

$$F=\int_0^{\infty}\frac{1}{x}\left(1-\exp\left[-B^2x^2\right]\right)^2 \exp-\left[x^2+l^2\right] I_0(2lx)\,dx\ .$$

In these expressions, the length of the bunch is λ , B is the ratio of widths of emitting to target bunches, l is the separation between the beams in units of $\sqrt{2}\sigma_1$, and I_0 is a modified Bessel function. An expression for the energy weighted mean critical energy has a similar form, and the integrals, which are transverse spatial integrals, must, in general, be evaluated numerically.

it is worth noting that the beam populations and lengths appear only as normalizing factors. The dependence on the offset between beams involves only transverse spatial parameters.

Of course, the beamstrahlung signal can only be estimated after the results of these

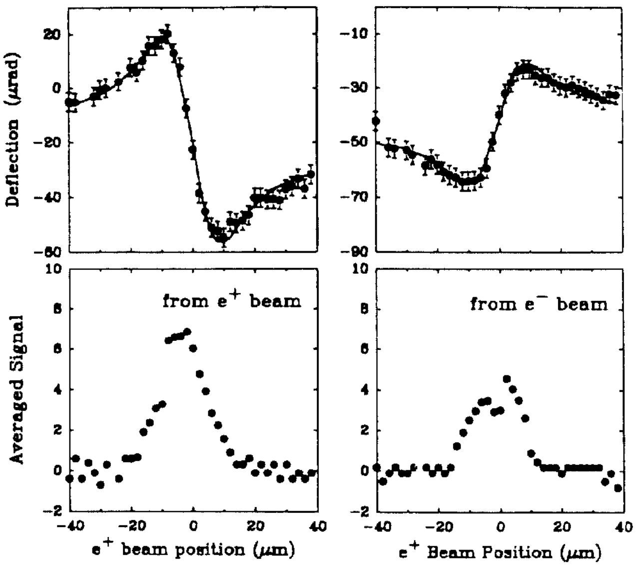

Fig.5. Beamstrahlung emission compared with beam deflection.

expressions are extended by the pair production and Cherenkov light generation functions of the gamma ray counter described above.

The principal difficulty with the weak beamstrahlung signal lies in its low average critical energy. During SLC development, this value rarely rose above 10 MeV, compared with the 2.3 Mev of the synchrotron radiation from the dipoles upstream of the counter. Fig.6 illustrates the overlap of the spectra, and the need to impose a threshold in the range of 25 MeV.

Results of calculations (solid lines) of two scans are compared in Fig.7 with data (points). The data have been folded about the mid-point to reduce the effect of fluctuations on the weak signals. A good representation of the data is generally achieved, and the parameters required for a good fit are typically within a few percent of values estimated by filament scans made within an hour or so of the deflection scan, and with beam intensity measurements. There is agreement also with a length measurement made near the beginning of the accelerator, although the uncertainty is considerably larger in this case.

The principal feature to emphasize is that the width of the beamstrahlung emission peak is controlled in good approximation only by the transverse dimensions of the beams[5]. Further, the two peak widths, taken together, determine the values of the two beam radii. The "target" bunch width dominates the effect. Over a wide range of SLC beam conditions, we calculate that the first moment of the folded beamstrahlung peak lies in the range of 1.45 to 1.75 times the target beam RMS width.

Non-invasive measurements of the beam transverse dimensions are evidently becoming practical. However, the complications of the general case of elliptical beams with major axes askew to the beam axes are still under study. A full treatment will require the coupled analysis of beam scans made in at least three directions. On the other hand, the SLC design is for beams close to round at the collision point, and, even during development work, this approximation is frequently adequate.

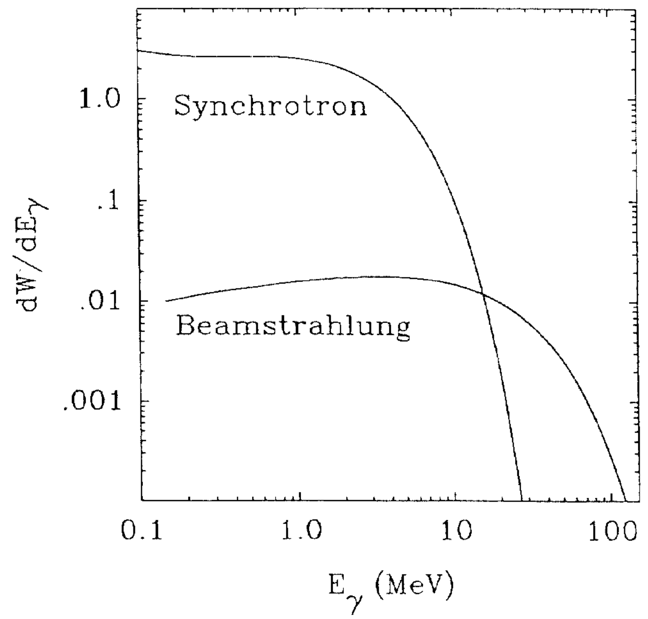

Fig.6. Synchrotron radiation and typical beamstrahlung spectra compared.

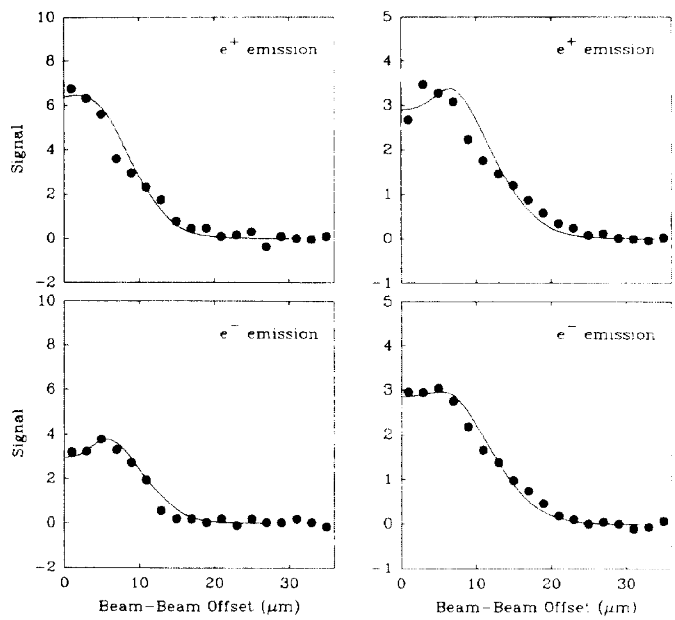

Fig.7. Comparison of beamstrahlung profiles (points) folded about the center, for two beam scans, and calculated profiles (lines).

I wish to acknowledge the people listed in the references who have made major contributions to one or more aspects of the work described here. There were others, too numerous to mention, who have worked with the SLC to develop the systems and the clean beam conditions which allowed the equipment to operate as well as it has done.

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