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BEAM-BEAM DEFLECTIONS AS AN INTERACTION POINT DIAGNOSTIC FOR THE SLC*

P. BAMBADE AND R. ERICKSON

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

Abstract

A technique is described for non-destructive measurement and monitoring of the steering offset of the electron and positron beams at the interaction point of the SLC, based on using stripline beam-position monitors to measure the centroid of one beam as it is deflected by the opposing beam. This technique is also expected to provide diagnostic information related to the spot size of the micron-size beams.

1. Introduction

The electromagnetic force acting between two intense colliding beams of oppositely charged particles will cause them to be deflected in passing by an angle that depends on the offset between the bunches, and the distribution of charge within the bunches. This deflection, measurable with nondestructive techniques, is expected to be the key to the final steering of the e^+e^- beams in the SLC. More generally, the beam-beam deflection phenomenon is a measurable manifestation of the collision of micron-size beams and is applicable to any large future linear collider.

In an e^+ e^- storage ring with a purely magnetic guide field, the counter-rotating beams follow exactly the same central trajectory and thus head-on collisions are unavoidable. There is no a priori reason why this should be true in linear colliders, however. In any linear collider, including the SLC, the opposing beams must be actively steered into collision guided by some observable that is sensitive to the impact parameter. Using state-of-the-art strip-line beam position monitors (BPMs), it may be possible to direct the two beams independently to the intended interaction point with an accuracy of perhaps 100 μm. In order to achieve acceptable luminosity with the SLC, the beams must be steered to within about one beam radius (about 2 μm) of each other. It is in this regime, far below the resolution limits of single-beam diagnostic devices, that the beam-beam deflection is strongest.

2. Basic Formulae

The angular deflection produced by the interaction of an SLC beam with the electromagnetic field of its colliding partner can be estimated analytically in the simplified case of two round Gaussian beams (see Fig. 1). Realistically, the beams are not expected to be round and gaussian until the final focus optical tuning is completed, a procedure that requires that the beams be colliding. A two-dimensional parametrization for the collision of two beams with transverse distributions of arbitrary flatness and orientation is given in Ref. 1.

The deflection of a single particle of charge e, passing at an offset $\triangle$ from the centroid of an oppositely charged Gaussian distribution, is given by:

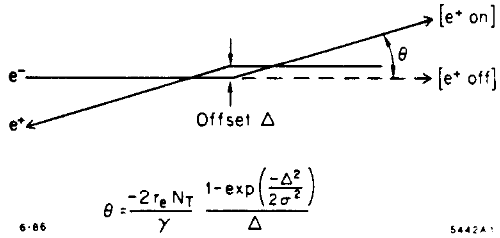

Fig. 1. The trajectory of each beam is deflected by the opposing beam passing at an offset $\triangle$.

$$\theta(\triangle) = \frac{-2r_e N_T}{\gamma} \; \frac{1 - \exp[-\triangle^2/2\sigma^2]}{\triangle} \quad , \qquad (1)$$

where r_e is the classical radius of the electron, γ the relativistic E/m factor, N_T the number of particles and σ the RMS transverse size of the Gaussian distribution.

When the beams pass with offsets large compared to their transverse sizes, they see each other as point charges and (1) is a good approximation for their mutual deflection. When colliding with a small offset, the finite sizes of the beam distributions must be taken into account. This can be done by convoluting (1) with the distribution of the opposing beam. The result of such a calculation, carried out in the limit of small $\triangle$, is expressed in terms of a form factor which reduces the average deflection:

$$F(R) = \frac{Ln(1+R^2)}{R^2} \qquad (2)$$

Here R is the ratio of the transverse sizes of the two beams.

Deflection versus offset is plotted in Fig. 2 for 50 GeV beams consisting of 5×10^{10} particles, with transverse spot sizes σ of 2, 5, and 10 μm. 10 μm is the estimated size of the beams at the SLC interaction point before optical corrections are made. Magnet setting errors and misalignments contribute to this estimate. By adjusting the final focus corrector magnets, σ can be reduced to about 2 μm. The above form factor has been incorporated in the curves as a multiplying reduction factor, assuming in each case $R = 1$.

3. Deflection Detection

Several methods have been studied for detecting and measuring the beam-beam deflections. The most obvious is to use a pair of BPMs stradling the interaction point. If the drift length "lever arm" is long enough, a deflection at the I.P. will result in a measurable position shift at the BPM. The power of this method can be greatly enhanced by suppressing the opposing beam on some pulses and watching the measured beam jump back to its undeflected position. To make this possible, a pair of special pulsed magnets, the "single-beam dumpers",

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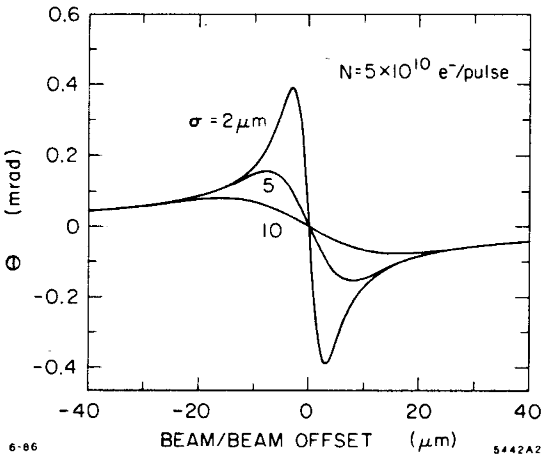

Fig. 2. The deflection angle Θ as a function of offset $\triangle$, plotted for three spot sizes.

will be provided upstream of the final focus to kick either beam out of the transport system on command.

In principle, the beam-beam deflection can also be observed with conventional screen profile monitors located in the paths of the outgoing extracted beams as they are transported to the dumps. In the SLC, such measurements will be possible in the vertical dimension only. Deflections in the horizontal plane will be obscured by the momentum dispersion introduced by the extraction septum magnets. As part of a planned upgrade for the north extraction line,[2] it will be possible to cancel the dispersion with additional magnets to enable deflection measurements in both the horizontal and vertical dimensions. In any case, position measurements in the extraction lines provide essentially no information about the absolute position of either beam near the I.P., because of the large number of magnets, traversed by the outgoing beam before reaching the extraction line. However, relative position shifts can be measured using devices in the extraction lines in conjunction with the single-beam-dumpers mentioned above to give a useful measure of the deflection at the I.P.

Another approach is based on detecting beamstrahlung radiation. This is the name given to the synchrotron radiation emitted by each beam as it is deflected by the other. The angular distribution of this radiation, strongly peaked forward in the direction of the outgoing beam, can be measured with a suitable detector along a line of sight but quite distant from the interaction point.[3]

4. Application to Steering and Tuning Procedures

A three-step tuning procedure is envisioned:

1. Initial beam finding: One beam – designated the "target" in this case – is momentarily suppressed with a single-beam dumper while position measurements are made on the "probe" beam. In this way, the shift induced by the target beam can be determined. When the offset between the beams is large, the magnitude of the shift is inversely proportional to the offset and its sign tells in which direction to steer. This can be seen by taking the limit of (1) for large $\triangle$:

$$\theta(\triangle) \simeq \frac{-2r_e N_T}{\gamma} \frac{1}{\triangle} . \qquad (3)$$

2. Beam centering: Scanning the target across the probe and recording a plot similar to Fig. 2 for the probe will facilitate optimal steering of the two beams. The zero-deflection symmetry point in Fig. 2 is reached when the beams are perfectly centered.
3. Spot size tuning: Taking the limit of (1) for small $\triangle$ and multiplying by the form factor (2) gives:

$$\theta(\triangle) \simeq \frac{-r_e N_T}{\gamma} \frac{\triangle}{\sigma^2} F(R) . \qquad (4)$$

The slope of the deflection of the probe beam near the zero-deflection symmetry point is inversely proportional to the cross-sectional area of the target. By differentiating (1), it can be seen that the deflection is maximum for offsets of about 1.6 standard deviations of the target distribution, and that the maximum deflection scales as the inverse of the transverse spot size:

$$\theta_{max} = 0.451 \frac{2r_e N_T}{\gamma} \frac{1}{\sigma} . \qquad (5)$$

A relative measure of spot size can thus be obtained by scanning one beam across the other as in Step 2 above. Guided by these measurements, an operator can adjust optical elements of the transport system to minimize this final spot size.

The procedures described here are based on relative measurements of the outgoing beam position at locations where the angular deflection produced in the collision leads to a transverse position shift. Many of the BPMs in the outgoing transport system have suitable phase shifts from the IP to be used for this purpose. The best locations, however, are in the final optical transformer quadrupoles, where the β-functions reach their largest values, thereby magnifying the deflections the most, and where dispersion is negligible, (which minimizes confusion with energy variations). Three BPMs, near quadrupoles Q1, 3 and 4, are planned for this purpose[3] (Fig. 3). Each has an effective optical lever arm of about 3 meters. Position shifts corresponding to a wide range of IP parameters can be resolved at these locations.

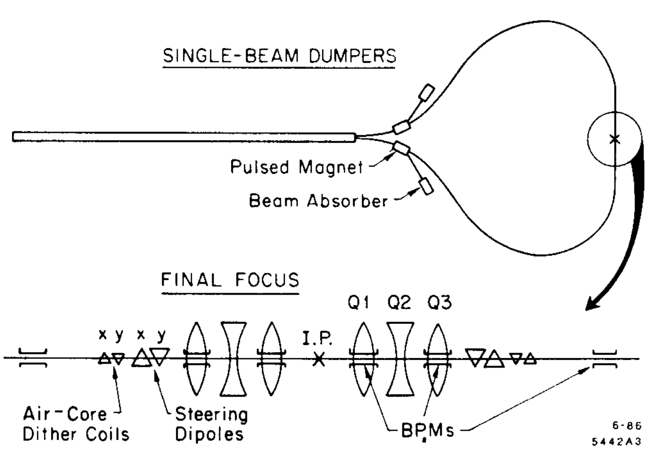

Fig. 3. Schematic of beamline components relevant to the deflection technique.

The useful range of these techniques, i.e., the maximum offset that still gives a measurable deflection, is limited only by the ability of the BPM to resolve beam centroid movements. For example, assume the BPM near Q1 can resolve the centroid position of a single bunch of 5×10^9 particles to a level of 20 μm. It will then be possible to detect relative beam-beam offsets up to a maximum of:

$$\Delta(\mu\mathrm{m}) \quad \simeq \quad 40 \ \frac{N_T}{5 \times 10^9} \quad . \tag{6}$$

For larger beam currents, it may be possible to do better than the limit indicated in (6), because the BPM resolution also improves with increasing current. By chopping one beam off and on using the single beam dumpers and averaging over many pulses, the resolution can be improved further. Although marginal at low intensity, this beam finding technique should bridge the gap between the usual orbit matching methods which rely on absolute BPM accuracy to steer the beams independently to the IP, and techniques based on luminosity-related signals, such as beamstrahlung,[4] disruption imaging,[2] and the Bhabha scattering rate.

5. Dynamic Errors and Corrections

It is expected that even when the static crossing errors have been corrected as described above, the two beams will not remain centered on each other without an active feedback system. Many sources of drift and jitter that could cause the beams to wander at the IP have been identified. In most cases, these effects can be minimized with careful attention to relevant hardware designs. Magnet power supplies, for example, must be well regulated, and support structures must be rigid. Natural ambient ground vibrations at frequencies above 1 Hz have been shown[5] to be negligible, although some local man-made vibration sources such as reciprocating pumps could cause problems if not isolated. On a slower time scale, thermal effects will cause mechanical support structures to expand, and power supplies to drift enough to adversely effect the luminosity unless steering corrections are made. Studies of feedback schemes for the SLC have focused on simple and relatively slow algorithms, although the BPM electronics, control system, and other key components are being built to allow pulse-by-pulse feedback to accommodate faster or more complex schemes.

A simple feedback algorithm for correcting relatively slow drifts is based on automatically suppressing one beam periodically using the single beam dumper. Of course, the luminosity would be sacrificed on these occasional pulses, but they would enable a steering correction to be computed from the measured position shifts of the outgoing beam. Because each measured deflection can correspond to two possible offsets, the operation has to be carried out frequently enough to ensure that the actual offset does not drift outside the domain of the IP, bounded by the deflection maxima, in the time between updates. This approach is probably adequate to track the thermal expansion of support structures and other mechanical effects.

An approach that does not require sacrificing any beam pulses would be to excite small "dither coil" dipoles (Fig. 3) in a pre-programmed way to induce small periodic offsets at the IP, with an amplitude of a fraction of a standard deviation. In this way, one beam can be made to trace out a pattern such as a small circle at the IP. The deflections of the opposing beam will then project the same pattern at the BPM. When the offset between the beams corresponds to a point on a steeply rising positive slope in Fig. 2 (beyond the 1.6 σ peak on either side), the projection is a magnified image of the dither pattern. When the offset is less than 1.6 σ, the projection is an inverted image of the dither pattern. Synchronous position measurement would then allow a determination of whether the beams were colliding within or beyond 1.6 standard deviations of each other. If necessary, a correction could be applied to bring them back to within one σ. The sign of the deflection would indicate the direction in which to steer. In both these algorithms, corrections are applied using steering correctors immediately upstream of Q3.

Acknowledgements

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