Limitations of Interaction-Point Spot-Size Tuning at the SLC*

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At the Stanford Linear Collider (SLC), the interaction-point spot size is minimized by repeatedly correcting, for both beams, various low-order optical aberrations, such as dispersion, waist position or coupling. These corrections are performed about every 8 hours, by minimizing the IP spot size while exciting different orthogonal combinations of final-focus magnets. The spot size itself is determined by measuring the beam deflection angle as a function of the beam-beam separation. Additional information is derived from the energy loss due to beamstrahlung and from luminosity-related signals. In the 1996 SLC run, the typical corrections were so large as to imply a 20–40% average luminosity loss due to residual uncompensated or fluctuating tunable aberrations. In this paper, we explore the origin of these large tuning corrections and study possible mitigations for the next SLC run.

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Abstract

At the Stanford Linear Collider (SLC), the interaction-point spot size is minimized by repeatedly correcting, for both beams, various low-order optical aberrations, such as dispersion, waist position or coupling. These corrections are performed about every 8 hours, by minimizing the IP spot size while exciting different orthogonal combinations of final-focus magnets. The spot size itself is determined by measuring the beam deflection angle as a function of the beam-beam separation. Additional information is derived from the energy loss due to beamstrahlung and from luminosity-related signals. In the 1996 SLC run, the typical corrections were so large as to imply a 20–40% average luminosity loss due to residual uncompensated or fluctuating tunable aberrations. In this paper, we explore the origin of these large tuning corrections and study possible mitigations for the next SLC run.

1 INTRODUCTION

During the last two runs of the Stanford Linear Collider, typical vertical interaction-point (IP) spot sizes at nominal bunch populations (~4 x 10^10 particles per bunch) were about 35% larger than expected from the linac emittances, energy spread and IP angular divergences. Recent evidence suggests that a large part of this discrepancy might be attributed to imperfect or inadequate IP spot-size tuning. In this paper, we present some of the evidence and outline possible solutions for the next SLC run.

2 SPOT-SIZE CORRECTIONS

The spot size at the SLC interaction point (IP) is routinely optimized by correcting the most important low-order aberrations, such as waist shift, dispersion and skew coupling, for either beam. The aberrations are corrected by exciting orthogonal linear combinations of quadrupoles and/or skew quadrupoles (so-called 'knobs'), measuring the spot size for different, typically 5–7 knob values, and adjusting each knob to the best value.

Consider one aberration as an example. For different values of the knob correcting this aberration, the convoluted horizontal or vertical spot size of the two beams at the IP is inferred from beam-beam deflection scans [1], i.e., from the measured deflection angle as a function of beam-beam separation. The optimum correction is computed by fitting a parabola to the square of the spot size as a function of the knob value. A correction is applied by setting the knob to the minimum of this parabola. The same procedure is then repeated for another aberration.

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cal waist position, dispersion and skew coupling that were applied during the 1996 SLC run. The rms corrections appear to be larger than the typical measurement resolution, indicated by dotted lines.

If an IP aberration is not fully corrected, the spot size will be larger than the nominal value. For the three most critical aberrations, the increase of the vertical spot size $\Delta \sigma_y$ due to imperfect correction is given by

$$\Delta \sigma_y = \left\{ \begin{array}{ll}
\tilde{w}_y \theta_y^2 & \text{for a vertical waist shift } \tilde{w}_y \\
\eta_y \delta & \text{for vertical a dispersion } \eta_y \\
\tilde{d} \theta_z^2 & \text{for a skew coupling coeff. } \tilde{d}
\end{array} \right. \quad (1)$$

where the spot-size increase $\Delta \sigma_y$ is added in quadrature to the design rms spot size, which in the following is taken as $\sigma_y = 500 \text{ nm}$.

The relative luminosity degradation due to limited measurement precision ($\Delta \sigma_y/\sigma_{y0}$) for the $k$th aberration on a single beam is given by the formula

$$\frac{\Delta L}{L_0}\mid_{k,p} \approx \frac{1}{4} \left( \frac{\Delta \sigma_y}{\sigma_{y0}} \right)_k^2,$$  \quad (2)

where $L_0$ designates the ideal luminosity without any aberration, the subindex $p$ refers to the precision, and $k$ counts the different aberrations.

To estimate the luminosity loss which is implied by the rms incremental corrections, one has to make assumptions about the evolution of an aberration between two consecutive corrections. Assuming a random walk ($\sim \sqrt{t}$) between tunings, and considering a tuning interval which results in an incremental correction $\Delta \sigma_y/\sigma_{y0}\mid_{k,i}$ of the $k$th aberration, the average luminosity loss is $\Delta L/L_0\mid_{k,i} = 1 - 1/\sqrt{(\Delta \sigma_y/\sigma_{y0})_{k,i}^2/2 + 1}$, or, again expanding the square root,

$$\frac{\Delta L}{L}\mid_{k,i} \approx \frac{1}{8} \left[ \left( \frac{\Delta \sigma_y}{\sigma_{y0}} \right)_k^2 - \left( \frac{\Delta \sigma_y}{\sigma_{y0}} \right)_{k,p}^2 \right].$$  \quad (3)

where the subindex $i$ indicates that this luminosity loss is inferred from the 'incremental' correction. To avoid double counting, we have subtracted a contribution from the measurement precision. The total luminosity loss due to both precision and incremental changes of all vertical tuning corrections is finally obtained from

$$\frac{\Delta L}{L_0}\mid_{\text{tot}} \approx \frac{1}{8} \sum_k \left( \frac{\Delta \sigma_y}{\sigma_{y0}} \right)_{k,p}^2 + \frac{1}{8} \sum_k \left( \frac{\Delta \sigma_y}{\sigma_{y0}} \right)_{k,i}^2 \quad (4)$$

where in the SLC case, $k = 1, \ldots, 6$. Additional luminosity loss may arise from the horizontal tuning corrections.

Using the above formula, we can estimate the luminosity loss implied by the incremental corrections in Fig. 2 and by the quoted measurement precision. The results for the various aberrations are summarized in Table 1. A luminosity loss $\Delta L/L$ is equivalent to an increased vertical spot size of $\sigma_y/\sigma_{y0} \sim L_0/L \sim 1/(1 - \Delta L/L_0)$, where $\sigma_y \approx 500 \text{ nm}$ is the ideal single-beam spot size. A 38% luminosity reduction due to IP aberration tuning would thus correspond to a vertical spot size of 700 nm, which is remarkably close to the typically achieved good values!

<table>
<thead>
<tr>
<th>corr. knob</th>
<th>precision $\Delta L/L$</th>
<th>rms incr. $\Delta L/L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>waist shift</td>
<td>0.09 cm</td>
<td>6.5%</td>
</tr>
<tr>
<td>dispersion</td>
<td>0.11 mm</td>
<td>2.6%</td>
</tr>
<tr>
<td>skew</td>
<td>0.02 kG</td>
<td>0.2%</td>
</tr>
<tr>
<td>total</td>
<td>38%</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Quoted scan precision, rms knob increment and estimated luminosity loss from residual low-order vertical aberrations for the 1996 SLC run. The luminosity-loss numbers are relative to a 500-nm single-beam spot size.

### 3 Interpretation

If the applied corrections reflect real aberration drifts, due to, for example, orbit changes in the final-focus sextupoles, or rf phase changes in the linac etc., one might expect to see correlations in the corrections for different aberrations. In Fig. 3 we plot incremental changes to one knob versus those of another knob (i.e., for another aberration or the other beam) which were coincident within one hour. No correlation between any two knobs is evident, which suggests that the corrected aberration drifts are not real.

![Figure 3](https://via.placeholder.com/150)

Figure 3: Zero correlation between IP corrections for different aberrations and for the two beams.

To better understand the above findings, we performed hundreds of tuning simulations for waist, dispersion and coupling correction. In all of these simulations the aberration to be tuned was perfectly corrected initially. Then, for each beam-beam based tuning scan we added a random measurement error

$$\Delta \Sigma_y \approx \frac{0.12}{\Sigma_{y0} \mid_{\text{tot}}} \left( \sum_{k=1}^{6} \frac{\Sigma_y}{\Sigma_{y0}} \right)^{1/2},$$  \quad (5)
promising. Here, a knob is varied in some harmonic or
flection scans altogether with a feedback dither technique
range are no longer optimal.

scans!

sextupoles.

conjunction with fast orbit bumps across the final-focus
based on informations from a fast luminosity monitor, in
rough agreement with measurements, the error was scaled
for the waist position,

beam deflection scans. This could be achieved by a va-
ing the scan ranges

tors to correct for orbit variations, optimizing and adjust-
for the waist position,

and 0.09 kG for the skew coupling. These values are very
related to the convoluted IP spot size (inversely propor-

There are two possible approaches to alleviate this situa-
tion. First, one may improve the resolution of the beam-

An alternative approach is to replace the beam-beam de-
fection scans altogether with a feedback dither technique
based on informations from a fast luminosity monitor, in
conjuction with fast orbit bumps across the final-focus
sextupoles.

The second option is more innovative and also more
promising. Here, a knob is varied in some harmonic or
random pattern for thousands of pulses (roughly 10 s are
needed per 1000 pulses), and the corresponding luminosity
signal (radiated-Bhabha scattering events) is recorded.

Suppose the knob setting \( k \), taken as dimensionless, is
related to the convoluted IP spot size (inversely propor-
tional to the luminosity) as

\[
\sigma_y = \sigma_{y0} \sqrt{1 + S (k - k_0)^2}
\]  
(6)

where \( k_0 \) represents the residual aberration that we want to
correct, and the parameter \( S \) is a normalized 'sensitivity'.
If the aberration is completely corrected initially (\( k_0 = 0 \)),
a knob change by \( k = \pm 1 \) would reduce the luminosity by
a factor \( 1/\sqrt{1 + S} \).

In SLC operation the signal of the luminosity monitor
\( L_m \) is impaired by a large and fluctuating background
contribution, so that its distribution is fairly wide, with an rms
spread equal to about 30% of the average signal. If we ave-
rage over \( n \) pulses, the resolution of the luminosity signal
should improve as \( \Delta L_m / L_m \approx 0.3 / \sqrt{n} \). To be conser-
vative, in the following we assume that the spread of the
signal is 100%, i.e., we assume \( \Delta L_m / L_m \approx 1 / \sqrt{n} \).

We denote the average luminosity signal for the three
different knob settings \( k = -1, 0, +1 \) by \( L_{m-}, L_{m0} \) and
\( L_{m+} \). Fitting \( L_m(k) \) to a parabola and assuming \( S < 1 \)
and \( k < 1/\sqrt{2S} \), the approximate optimum knob value can be inferred:

\[
\Delta k_{opt} \approx \frac{L_{m+} - L_{m-}}{4L_{m0} - 2(L_{m+} + L_{m-})}.
\]  
(7)

If the luminosity is measured over \( n/3 \) pulses for each of
the three knob values, the statistical resolution in center-
ing the knob is \( \Delta k / k = \sqrt{3/(2n)} \Delta L_m / L_m \), and
the residual luminosity loss from the statistical error is
\( \Delta L / L \approx S (\Delta k)^2 / 2 \) or

\[
\frac{\Delta L}{L} \approx \frac{3}{4S} \left( \frac{\Delta L_m}{L_m} \right)^2 \approx \frac{3}{4Sn}
\]  
(8)

However, the systematic error made by the parabolic ap-
proximation in Eq. (7) is for most cases larger than the
statistical error, so that the tuning will have to be iterated.

For example, if \( S = 0.2 \) (5% luminosity loss during the
dithering) and using 10000 pulses of data, the statistical ac-
curacy is \( \Delta L / L \approx 0.04\% \) for a single knob, or 0.4% for
10 knobs! This is two orders of magnitude better than what
has been achieved by aberration tuning with beam-beam
deflection scans, but, recognizing additional systematic er-
ors, we aim for an overall improvement by a factor of 3–10.

5 CONCLUSIONS

There is strong evidence that inaccurate IP spot-size tuning
is responsible for about 20–40% average luminosity loss
over the last 2 SLC runs. For the next run, we will replace
the conventional tuning which is based on beam-beam de-
fection scans by a novel dithering feedback which we ex-
pect to be more effective and as much as ten times more
precise. This feedback correlates fast orbit bumps across
the final-focus sextupoles with the signal from a fast lumi-
nosity monitor.

Acknowledgements

The importance and luminosity impact of IP spot-size
tuning was first pointed out by John Irwin and Ghislain
Roy, for the Final-Focus Test Beam [3].

6 REFERENCES

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