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

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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 ($\sim 4 \times 10^{10}$ 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 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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A full set of beam-beam based corrections for a total of 10 aberrations (5 per beam: 3 vertical and 2 horizontal) requires about 1 hour of real time, during a large part of which the luminosity is then necessarily mistuned. In addition, often at least one tuning iteration is necessary, in order to achieve typical 'good' spot sizes. On average one correction is applied to each aberration about once per 8-hour shift. A qualititative illustration of the effect of tuning and the spot-size degradation between two tunings is shown in Fig. 1. In the figure, the degradation $\Delta\sigma/\sigma$ (which is added in quadrature to unity) is shown to grow linearly in time. In reality it may increase with the square root of time or, more likely, in some irregular fashion.

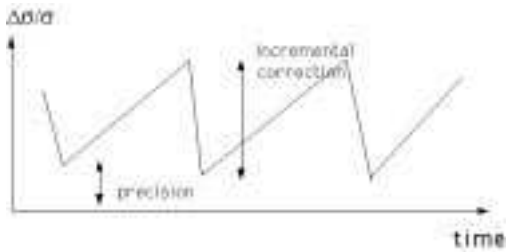

Figure 1: Schematic of tuning effect and spot-size increase between tunings.

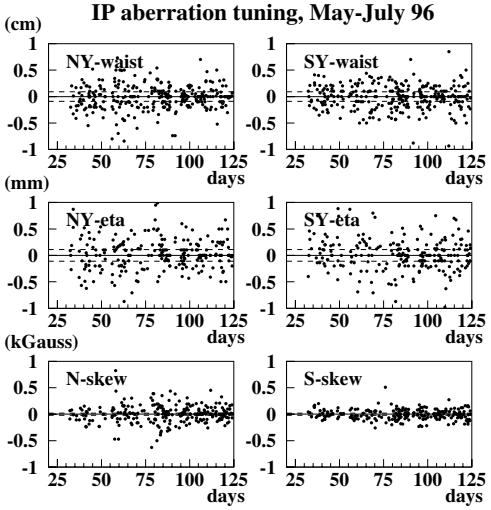

Figure 2: Incremental IP corrections of waist, dispersion and skew coupling during the 1996 SLC run. Shown dotted is the average resolution of an aberration scan as quoted by the SLC control system.

Figure 2 depicts all incremental corrections to the verti-

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 $\Delta\sigma$ due to imperfect correction is given by

$$\Delta\sigma_y = \begin{cases} w_y\theta_y^* & \text{for a vertical waist shift } w_y \\ \eta_y\delta & \text{for vertical a dispersion } \eta_y \\ d\,\theta_x^* & \text{for a skew coupling coeff. } d \end{cases} \quad (1)$$

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 $\sigma_{y0} = 500$ nm.

The relative luminosity degradation due to limited measurement precision $(\Delta\sigma_y/\sigma_{y0})$ for the kth aberration on a single beam is given by the formula $\Delta L/L_0|_{k,p} = 1 - 1/\sqrt{(\Delta\sigma_y/\sigma_{y0})^2_{k,p}/2+1}$, approximately equal to

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

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 $\Delta\sigma_y/\sigma_{y0}|_{k,i}$ of the kth aberration, the average luminosity loss is $\Delta L/L_0|_{k,i} = 1 - 1/\sqrt{(\Delta\sigma_y/\sigma_{y0})^2_{k,i}/2+1}$, or, again expanding the square root,

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

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

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

where in the SLC case, $k = 1, ..., 6$. 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 $\sigma_{y0} \approx 500$ 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!

corr. knob	precision	$\Delta L/L$	rms incr.	$\Delta L/L$
waist shift	0.09 cm	6.5%	0.23 cm	28.4%
dispersion	0.11 mm	2.6%	0.22 mm	9.4 %
skew	0.02 kG	0.2%	0.14 kG	10.0 %
total	38%			

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.

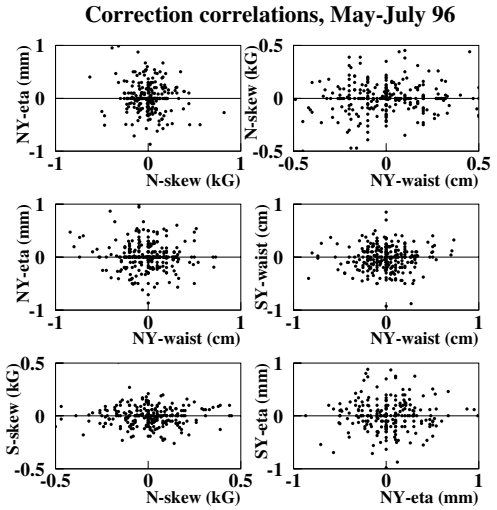

Figure 3: Zero correlation between IP corrections for different aberrations and for the two beams.

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

$$\Delta\Sigma_y \approx 0.12\,\Sigma_{y0}\left[\frac{\Sigma_y}{\Sigma_{y0}}\right]^{1/2}, \quad (5)$$

where $\Sigma_y \equiv \sqrt{\sigma^2_{y,e-} + \sigma^2_{y,e+}}$ denotes the convoluted spot size of the two beams at the IP, and the subindex 0 refers to the beam size at the minimum of the fitted parabola. In rough agreement with measurements, the error was scaled as the square of the spot size for each step of the scan. The error increases on the wings of the parabola, because, during a tuning scan, when, *e.g.*, the waist is off center, both the IP orbit-jitter correction [2] and the beam-beam scan range are no longer optimal.

The rms correction calculated in this way was 0.19 cm for the waist position, 0.24 mm for the vertical dispersion, and 0.09 kG for the skew coupling. These values are very close to the actual incremental corrections listed in Table 1. This strongly suggests that the quoted scan precicision widely underestimates the actual error, at least by a factor 3–4, and that the IP corrections were completely dominated by the limited resolution of the beam-beam deflection scans!

4 MITIGATIONS

There are two possible approaches to alleviate this situation. First, one may improve the resolution of the beam-beam deflection scans. This could be achieved by a variety of means, such as using better beam-position monitors to correct for orbit variations, optimizing and adjusting the scan ranges (*e.g.*, by expanding the scan range for larger beam sizes), or increasing the scan speed (*e.g.*, by using fewer BPMs or by shifting the waist with upstream quadrupoles and not with the superconducting final triplet).

An alternative approach is to replace the beam-beam deflection scans altogether with a feedback dither technique based on informations from a fast luminosity monitor, in conjunction 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 proportional to the luminosity) as

$$\Sigma_y = \Sigma_{y0}\sqrt{1 + S\,(k-k_0)^2} \qquad (6)$$

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 average over n pulses, the resolution of the luminosity signal should improve as $\Delta L_m/L_m \approx 0.3/\sqrt{n}$. To be conservative, 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:

$$k_{opt} \approx \frac{L_{m+} - L_{m-}}{4L_{m0} - 2(L_{m+} + L_{m-})}. \qquad (7)$$

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

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

However, the systematic error made by the parabolic approximation 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 accuracy 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 errors, 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 deflection scans by a novel dithering feedback which we expect 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 luminosity 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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