OPEN-99-243
27/09/99

Simulations of an Intra-Pulse Interaction Point Feedback for NLC

D. Schulte

September 27, 1999

Abstract

Position and angle jitter of the beams at the interaction point are important sources of luminosity degradation in future linear colliders. In order to reduce their effect, intra-pulse feedbacks can be used. Some simulations are presented to evaluate a position feedback at the interaction point. The influence of angle jitter onto this feedback are investigated and possible fixes are discussed. A feedback is proposed that allows to also reduce the effect of angle jitter.

1 Introduction

One of the most important sources of luminosity degradation in a future linear collider is expected to be due to relative position offsets of the two beams in the interaction point. To keep the loss of luminosity low, the offsets have to be small compared to the beam size. Figure 1 shows the relative luminosity as a function of the vertical offset for the NLC-B parameters from August 1999 [1] at a centre-of-mass energy $E_{cm} = 1\,\mathrm{TeV}$. If the beams collide at an angle, the luminosity will also be reduced by a comparable amount, see Fig. 2.

Two main source of beam jitter are expected. The beam entering the final focus system may have a position error in phase space. To lowest order the relative size of the error should be the same in vertical position and angle

$$\frac{\langle\Delta_y^2\rangle}{\sigma_y^2} = \frac{\langle\Delta_{y'}^2\rangle}{\sigma_{y'}^2}$$

The other main error source are the final focus magnets especially the final doublet. These will essentially only change the position of the beams in the interaction point not so much the angle.

$$\left(\frac{\langle\Delta_y^2\rangle}{\sigma_y^2}\right) = \left(\frac{\langle\Delta_{y'}^2\rangle}{\sigma_{y'}^2}\right) + \left(\frac{\langle\Delta_{y,ffs}^2\rangle}{\sigma_y^2}\right)$$

Depending on the relative size of the two contributions, the position offset may either be the dominant term or one of two comparable contributions. In the following, the situation with only position errors is considered first.

2 Simulation of the Beam-Beam Interaction

The dependence of kick angle and luminosity on the initial angle and offset of the two beams was determined using GUINEA-PIG [2]. As can be seen in Fig. 1, the luminosity drops less rapidly with vertical offset than predicted by the formula for a rigid beam. This is due to the high vertical disruption. For a three-sigma offset, the luminosity loss is less than a factor two instead of an order of magnitude expected from the low charge expression.

The sensitivity to angle errors is slightly larger than that to offsets. This is due to the fact that the vertical beta-function β_y is close to the bunch length σ_z.

The kick angle the beam experiences for a vertical offset is linear only over a small region, see Fig. 3. However it is close to linear over a much larger range. This should allow the use of a linear model in the feedback algorithm without compromising the speed of convergence significantly.

For errors that are not too large, one can approximate the luminosity with position and angle offsets as

$$\frac{\mathcal{L}(\Delta_{y1},\Delta_{y2},\Delta_{y'1},\Delta_{y'2})}{\mathcal{L}_0}\approx\frac{\mathcal{L}(\Delta_{y1}-\Delta_{y2})}{\mathcal{L}_0}\frac{\mathcal{L}(\Delta_{y'1}+\Delta_{y'2})}{\mathcal{L}_0}$$

Equivalently one can estimate the angle of the outgoing beam as

$$\theta_i(\Delta_{y1},\Delta_{y2},\Delta_{y'1},\Delta_{y'2})\approx\theta(\Delta_{y1}-\Delta_{y2})+\theta(\Delta_{y'1}+\Delta_{y'2})+\Delta_{y'i}$$

Around the zero point this can be rewritten as a linear expression

$$\theta_i(\Delta_{y1},\Delta_{y2},\Delta_{y'1},\Delta_{y'2})\approx A(\Delta_{y1}-\Delta_{y2})+A'(\Delta_{y'1}+\Delta_{y'2})+\Delta_{y'i}$$

Simulation shows that the coefficient A' is very small, see Fig. 4. Consequently the incoming angle is roughly preserved if no offset is present.

The simple model is correct to about 15 % in a region of $-3\sigma_y^*\leq\Delta_y\leq3\sigma_y^*$ and $-3\sigma_{y'}^*\leq\Delta_{y'}\leq3\sigma_{y'}^*$, see Fig 5. The simple approach overestimates the loss of luminosity.

In the following simulations, a truly two dimensional scan in angle and offset is used.

3 Feedback Model

In order to have fast correction feedback corrector and pickup need to be located close together. Thus the correction is not applied to the measured beam but the

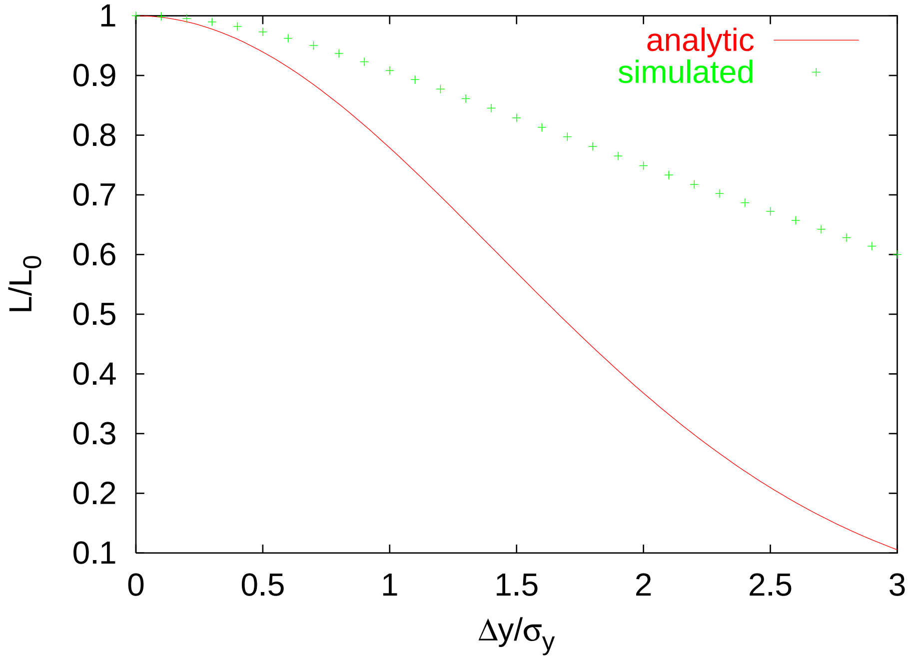

Figure 1: Dependence of the luminosity on the vertical relative offset of the two beams.

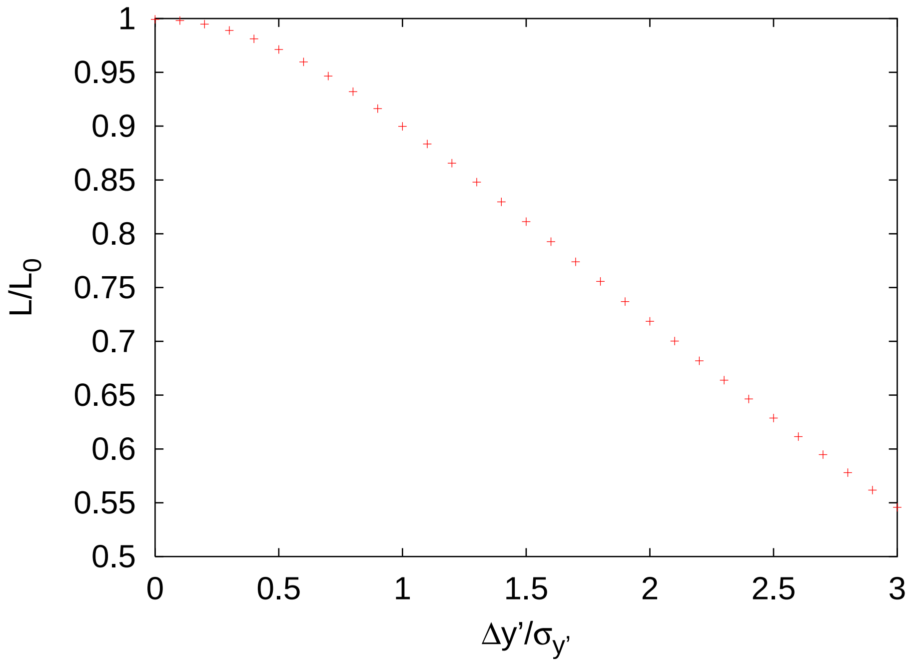

Figure 2: Dependence of the luminosity on the vertical collision angle.

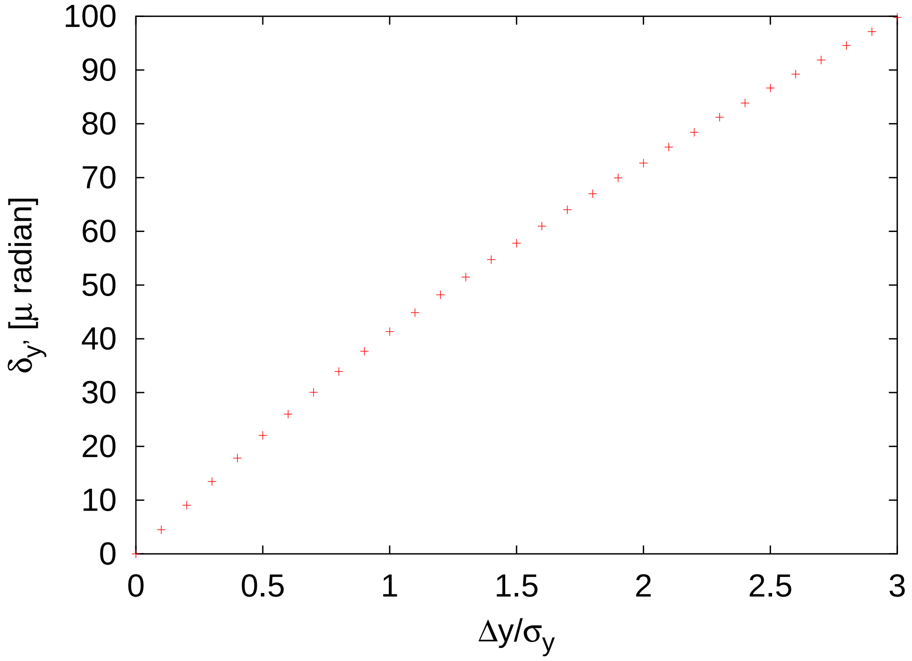

Figure 3: Dependence of the deflection angle on the vertical relative offset of the two beams.

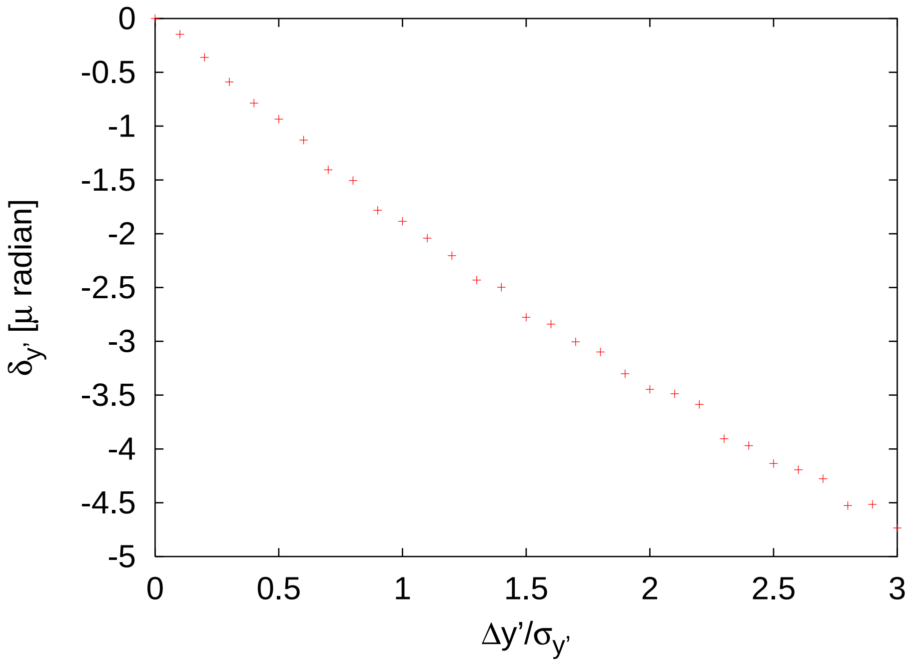

Figure 4: The additional deflection angle beams experience that are colliding at an angle.

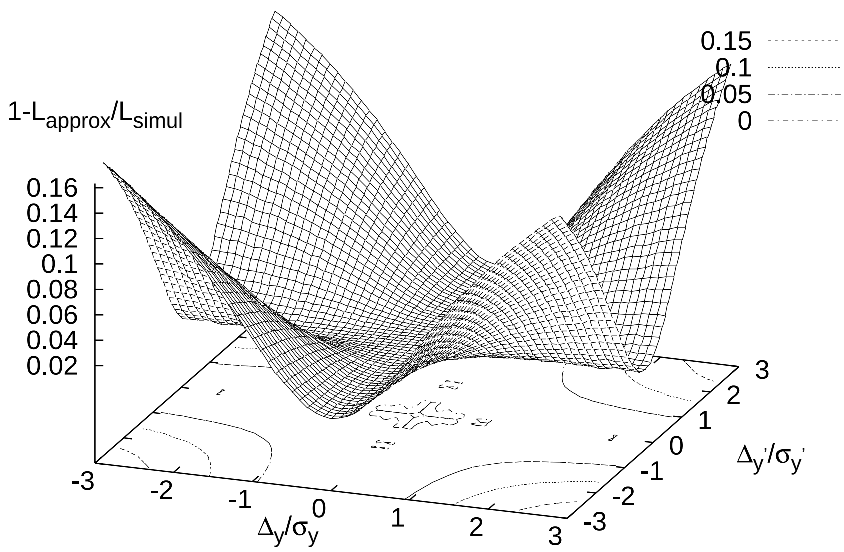

Figure 5: The relative error for the simple luminosity estimate.

other one. This significantly reduces the time necessary to transport the signal from the BPM to the kicker. The feedback latency τ_d is given by

$$\tau_d = \tau_p + \tau_k + \tau_{pf} + \tau_{kf} + \tau_s \tag{1}$$

Here, τ_p is the time the BPM electronics needs to measure the beam offsets and to process the data, τ_k is the response time of the kicker and τ_s is the transport time of the signal from BPM to kicker. τ_{pf} and τ_{kf} are the times of flight from the interaction point to the BPM and from the kicker to the interaction point, respectively. In the following, a total of $\tau_d = 20\,\mathrm{ns}$ is assumed, half of which is due to $\tau_{pf} + \tau_{kf}$.

The hardware of the feedback has not yet been design. It should consist of a BPM and a strip-line kicker. The kick angle that can be provided is given by[3]

$$v_\perp = 2Z \tanh \frac{\pi w}{4b} \frac{l}{b} \frac{\sin(\omega l/c)}{\omega l/Sc} I$$

Here, $Z = 50\,\Omega$ is the matched impedance, l the kicker length, b its half gap width, ω its frequency and w its width. I is the current provided by the amplifier. A current of $I = 1\,\mathrm{A}$ should be feasible using semiconductors [4]. Larger currents of up to about $10\,\mathrm{A}$ seem not to be excluded if one uses two stages of traveling wave tube amplification which adds an additional delay of the order of two nanoseconds [5]. In this case, one has to worry about the heat production, the order of tens of Watts, and about the limited tube lifetime. The feedback can not be easily accessed since it is implemented in the detector.

Assuming a distance between kicker and interaction point of 1.6 m, the beam can be corrected by $\Delta_y = 2\sigma_y^*$ with current of $I = 1$ A. With $I = 10$ A it is possible to extend this even up to $\Delta_y = 20\sigma_y^*$.

4 Correcting Offsets

The effect of the feedback on the relative beam positions is shown in Figure 6. An initial offset $\Delta_y = 2\sigma_y^*$ is corrected with three different gains. Here, the gain g is defined via the correction δ_y applied in between two bunches

$$\frac{\delta_y}{\sigma_y^*} = g\frac{\theta}{\sigma_{y'}^*}$$

As can be seen, the gain $g = 0.03$ achieves a smooth correction while $g = 0.06$ and $g = 0.09$ produce an overshoot. As is visible in the bottom part of the figure, the value of $g = 0.06$ is best (the total loss of luminosity is proportional to the area below the curves).

Figure 7 shows the dependence of the total luminosity loss on the feedback gain. Without feedback the luminosity loss would be $\Delta L/L \approx 0.18\,\%$ for $\Delta_y = 1/8\sigma_y^*$ and $\Delta L/L \approx 25\,\%$ for $\Delta_y = 2\sigma_y^*$. A wide range of gains gives good results. The luminosity loss can in both cases be reduced by about a factor 6.

If the incoming beam does not have a constant offset but rather bunch-to-bunch variations, the feedback will have the tendency to amplify this noise. As shown in Fig. 8 this effect is however very small in the region which yields the best preservation of luminosity. This is due to the fact that the gain had to be low in the first place because of the long latency.

For a very large offset of $\Delta_y = 12\sigma_y^*$ the luminosity is only 3.5 % of the nominal value. With the help of the feedback this can be improved to 73 % for a moderate gain $g = 0.06$, see Fig. 9. This certainly requires the range of the feedback to be adequate.

5 Feedforward

It is also possible to consider the feedback working as a feedforward. In this case, one measures a single bunch or a few bunches and corrects their offset for the rest of the train. In the case where only the first bunch is used, this can be faster than the feedback. The luminosity loss would be only $8/95 \approx 1/12$-times the one without correction, compared to a factor six gain in feedback mode. The feedforward would reduce the luminosity loss by another factor two compared to the feedback. However, this system has a number of difficulties. Transient effects

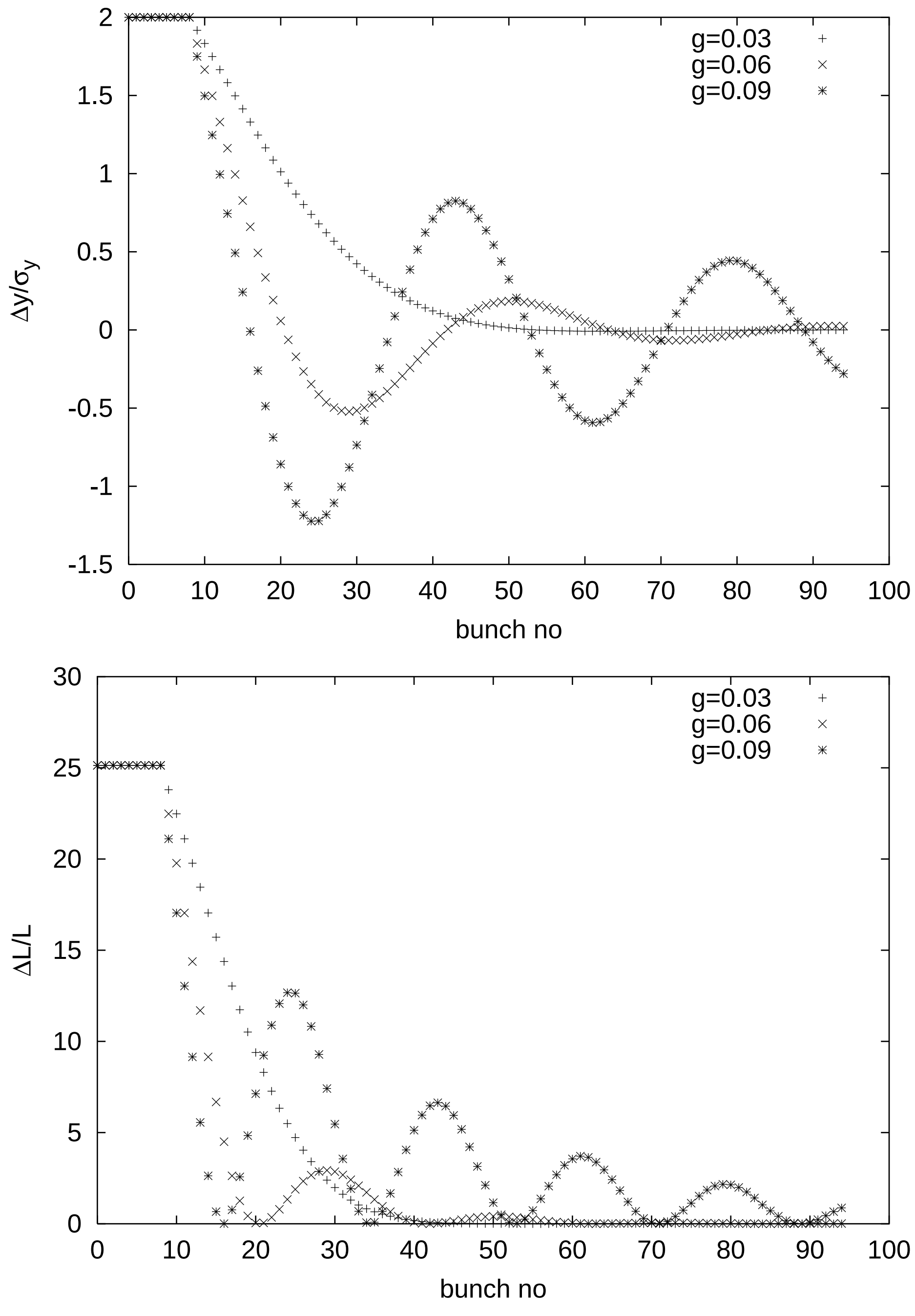

Figure 6: The effect of the feedback on the relative offsets of the two beams. Three different gain factors are shown.

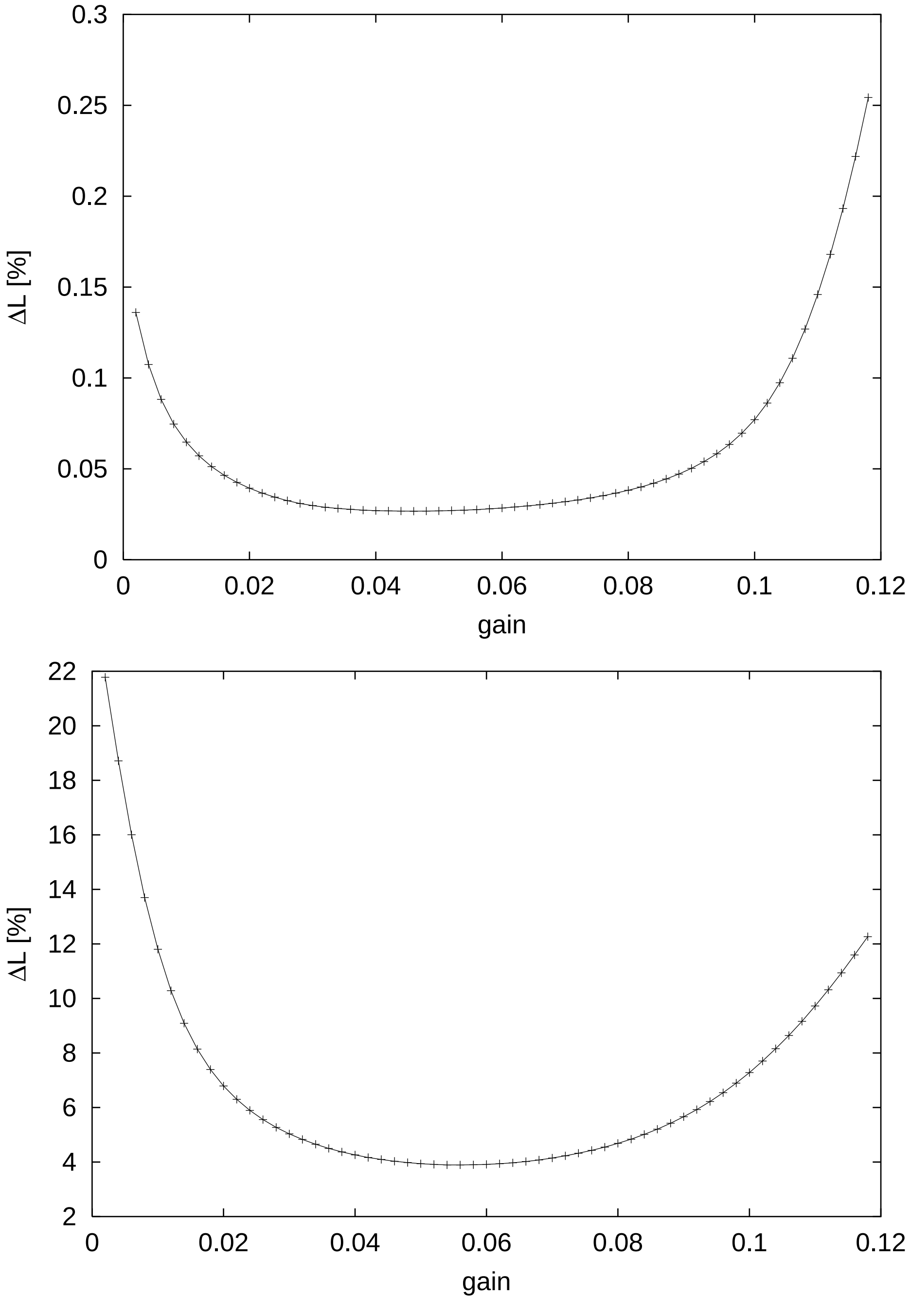

Figure 7: The remaining luminosity loss with the feedback as a function of the gain. The initial offsets where $\Delta_y = 1/8\sigma_y^*$ and $\Delta_y = 2\sigma_y^*$, respectively.

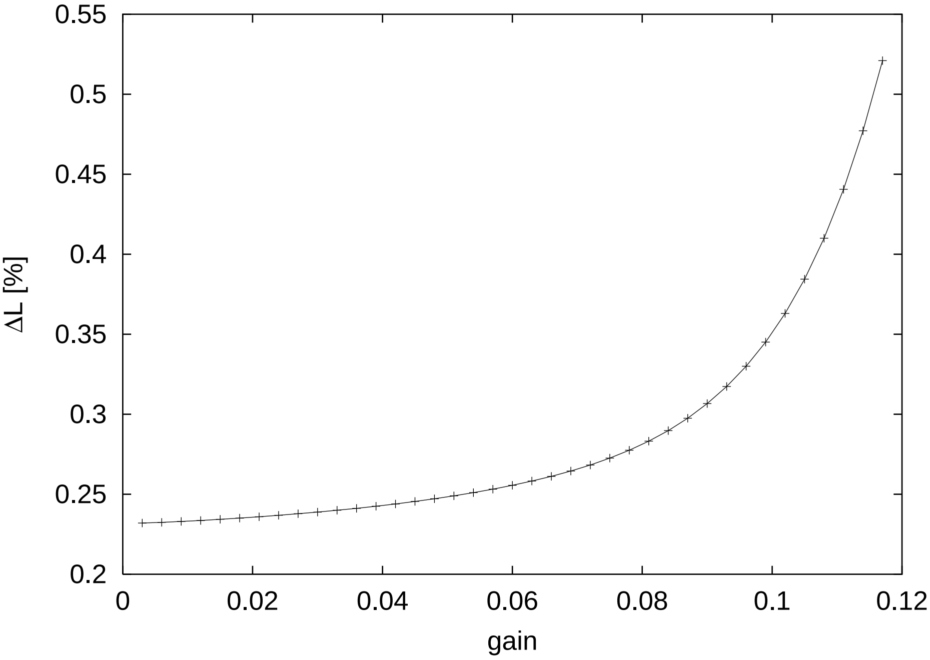

Figure 8: The luminosity loss due to bunch to bunch jitter with the feedback as a function of the gain. The RMS offset where $\langle \Delta_y \rangle = 0.1\sigma_y^*$.

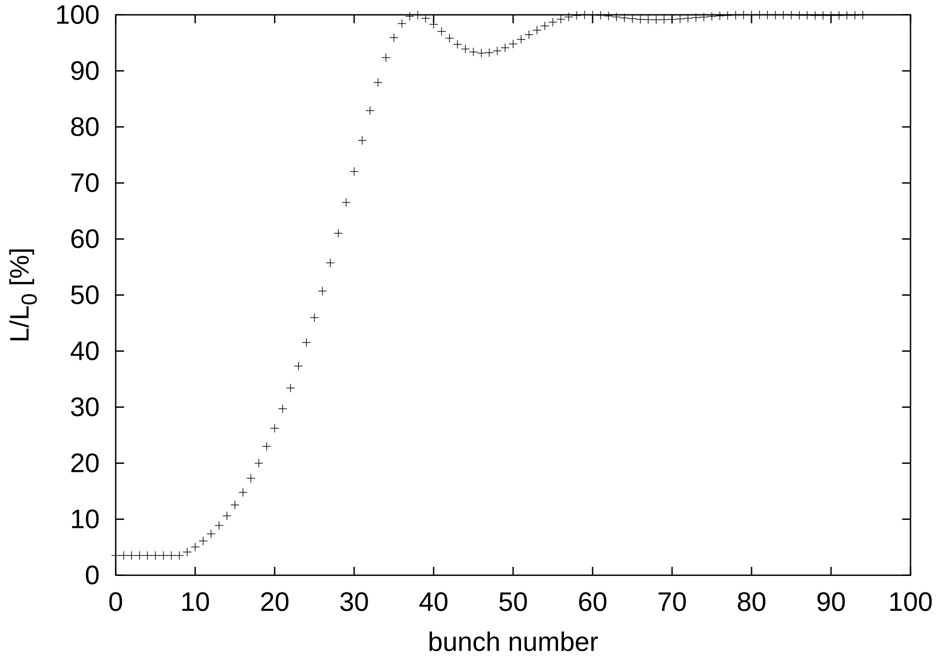

Figure 9: The relative luminosity as a function of the bunch crossing. Initially the beams were separated by $\Delta_y = 12\sigma_y^*$

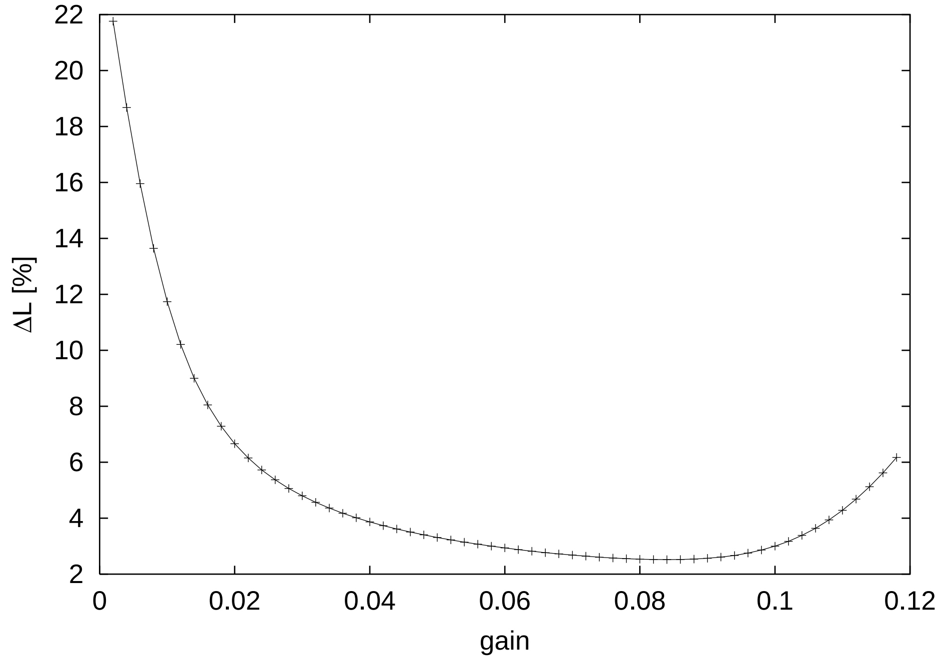

Figure 10: Luminosity loss as a function of the gain factor using the feedback as feedforward. The initial beam offset was $\Delta_y = 2\sigma_y^*$.

in the linac, for example resulting from multi-bunch wakefields, affect the first few bunches very differently from those of the main part of the pulse. While this could be solved by not using the first but some later bunch this would be very imprectical. Either all bunches before the pilot bunch have no counterpart in the other beam leading to a large loss of luminosity or one has to create a hole for the pilot bunch which is very difficult indeed. In addition, the feedforward needs to estimate the goal position of the beam accurately. It is therefore necessary to have the beam parameters stable from bunch train to bunch train. Also the nonlinear dependence of the kick angle on the beam offsets can become important. In the feedback mode this is of much less concern.

A feedback with a gain that varies from bunch to bunch can serve as a feed-forward as well as a feedback. If the dominant source of jitter is the final focus, it can be corrected using the first bunch only. If the main jitter source is the linac and the first bunches are very different from those on the flat top, they can be ignored to improve the feedback performance. It is also possible to use every eighths bunch only with a gain a factor eight higher.

In case the whole pulse is offset, the main drawback of the simple feedback scheme is that all of the eight bunches which pass the interaction point during one feedback latency are necessary to correct the measured offset. In priciple one could use the first bunch with a gain eight times larger and ignore the next seven bunches, the following bunch again would be used, the next seven ignored and so forth. This allows the correction to be faster but may not be simple to implement in the hardware and is more susceptible to noise. An even more sophisticated system could use the first bunch of each sample of eight to do a full correction and then take the difference of the second bunch to the first to aplly a further correction and so forth. This would combine the advantages of the fast response with the better stability of a feedback using all bunches but seems quite complicated.

In Fig. 10, a case is shown where the first bunch takes eight times the normal gain while the next seven bunches have no gain. The other bunches have all the same nominal gain. This corresponds to a feedforward followed by a feedback. The luminosity loss is reduced by a factor of more than ten rather than by a factor six as with feedback alone. The optimal setting for the gain distribution has to be determined empirically, once all error sizes are known.

6 Influence of Angles

An angle between the two colliding beams reduces the luminosity directly as shown before. If it is not taken into account in the feedback, it will also mimic an offset of the two beams in the interaction point, which the feedback tries to correct. This leads to an offset of the colliding beams. The transverse offset induced by the feedback in case of an initial angle can be calculated as

$$\Delta_y \approx \Delta_{y'} \frac{A'}{A} + \frac{1}{A} \Delta_{y'_i}$$

Since A' is small the main effect arises from the intital angle of the measured beam.

As seen before, the deflection for an offset $\Delta_y = \sigma_y^*$ gives a kick angle of $42\,\mu$radian $\approx 1.6\sigma_{y'}*$. Consequently an initial angle $\Delta_{y'} = 1.6\sigma_{y'}^*$ of the measured beam leads an offset of $\Delta_y = \sigma_y^*$ via the feedback. For large angles the situation becomes even worse since the kick angle grows less than linearly.

There are three ways to deal with the problem of the incoming angles. First, one can ignore this problem at the interaction point. This requires the angle errors to be much smaller than the position errors.

Second, one can use a pilot bunch. In this scheme, the first bunch of the measured train has no counterpart in the second train. It will therefore not be deflected by another bunch, preserving its initial angle. This value is then subtracted from the angles measured for the other bunches. The main drawback of this method is that it needs the transient effects during the passage of the train to be small. This may be difficult to achieve, since the first bunch is the one most likely to be different from the ones in the bulk of the train. Among the possible problems are transients in the extraction from the damping rings, long-range wakefields in the main linac, and other intra-pulse feedbacks. It may be possible to straighten the pulse with some slow feedbacks but the necessity to watch for the first bunch puts strong constraints on this, and it may not be practical at all if the beam jitter is significant. In addition, the required feedback hardware layout may be difficult.

In the third approach, one uses a BPM on each side of the interaction point to subtract the angle offset by adding the two signals. This can be easily achieved by sending the signal of the first BPM together with the beam to the second one. While the hardware layout would be very simple it may well interfere with the detector, because the signal has to be send through a region where low material density is extremely important.

In addition, the second and third solution do not reduce the direct loss of luminosity due to the collision angle. For these reasons, it seems advantageous to use the first method. In case the angle jitter is significant, one can use an additional angle feedback on each side to correct this.

7 Angle Feedback

The angle feedback consists of a BPM and a stripline kicker. The BPM has to be at a phase $(n + \frac{1}{2})\pi$ away from the interaction point and the kicker has to at $(n - k)\pi$. It is convenient to have large beta-functions at these points, in the first case to have a larger signal in the second to have a smaller divergence and thus correction angle. One possible position would be at the end of the horizontal chromatic correction section (CCS) just before the vertical CCS [6]; another possible location would be in the diagnostic section [7]. In the latter, the beta-function at the BPM and kick are about 50 m. The beam size thus is $\sigma_y = \sqrt{47.5/(0.15 \cdot 10^{-3})}\sigma_y^* \approx 2.2\,\mu\text{m}$, the divergence $\sigma_y' = \sqrt{0.15 \cdot 10^{-3}/47.5}\sigma_{y'}^* \approx 46$ nanoradian. To avoid introducing significant noise, the pickup resolution has thus to be a fraction of a micron. Using the same kicker as at the interaction point a current of $I \approx 20\,\text{A}$ is required to be able to kick the beam by $\Delta_{y'} = 2\sigma_{y'}$. At the location before the chromatic correction section the beta-functions are 2000 m at the pickup and 0.42 m at the kicker. The beam size thus is $\sigma_y \approx 14\,\mu\text{m}$, a resolution of a micron or so would be sufficient. The required kick angle for a two sigma deflection is about $1\,\mu$radian. This would require a current of $I \approx 200\,\text{A}$.

While the feedback at the diagnostics section seems feasible, the one before the chromatic correction section seems too difficult. The necessary current of $I = 20\,\text{A}$ can be reduced by using a longer kicker (or two in in series) or by reducing the gap (which may be difficult). Adding amplifier tubes after the semiconductor amplifier, should again allow a current of $I \approx 10\,\text{A}$[5]. The resulting problems for the interaction point feedback should be less severe in this case, since the feedback is much easier to access for maintenance.

8 Angle Feedback Model

This feedback is relatively simple using a constant gain for each bunch. The latency τ_d is given by

$$\tau_d = \tau_p + \tau_k + \tau_s + \tau_{kf} - \tau_{pf}$$

with the same meaning as in equation 1. If the signal transmission occurs at speed of light one would obtain $\tau_t = \tau_p + \tau_k$. In the following, a value of $\tau_t = 15\,\mathrm{ns}$ is assumed. It does not seem useful to employ a feedforward mode for this feedback. The most likely source of an angle offset is in or before the linac. Due to the multi-bunch wakefields, the first bunch is likely to be slightly different from the others. Thus it may be useful to be able to vary the gain for each bunch in order to avoid a strong influence of the first few bunches.

9 Simulation

In order to evaluate the performance of the angle feedback, simulations were performed with a one of the beams having an angle. The interaction point feedback was switched off. Figure 11 shows the luminosity loss as a function of the gain for two different constant offsets. The reduction factor for the luminosity loss is about ten in both cases. Figure 12 shows the luminosity loss for a bunch to bunch offset of $0.1\sigma_{y'}$. For a gain of $g = 0.1$ that works well for correcting an offset pulse, the increase of the luminosity loss due to noise is very small.

The dependence of the luminosity loss on the relative sizes of the position and angle offset are illustrated in Fig. 13. For the interaction point feedback a gain of $g_0 = 0.06$ is chosen, for the angle feedback $g_1 = 0.1$. While the interaction point feedback works at small angles, it gives little improvement for large ones, regardless whether or not the angle is corrected in the measurement. The additional angle feedback on the other hand works nicely together with the position feedback.

10 Conclusion

If the appropriate hardware can be build, the intra-pulse feedback at the interaction point seems to offer a reduction of the luminosity loss due to pulse-to-pulse jitter by a factor of about six. Even in a catastrophic offset of twelve times the beam size more than 70 % of the luminosity are recovered, increasing it for this case by a factor twenty.

If a source upstream of the final focus system causes significant angle jitter of the bunch trains, it is not sufficient to correct the measured kick angle accordingly. The luminosity loss due to this jitter is large enough to require an additional feedback for the angle. This angle feedback seems feasible.

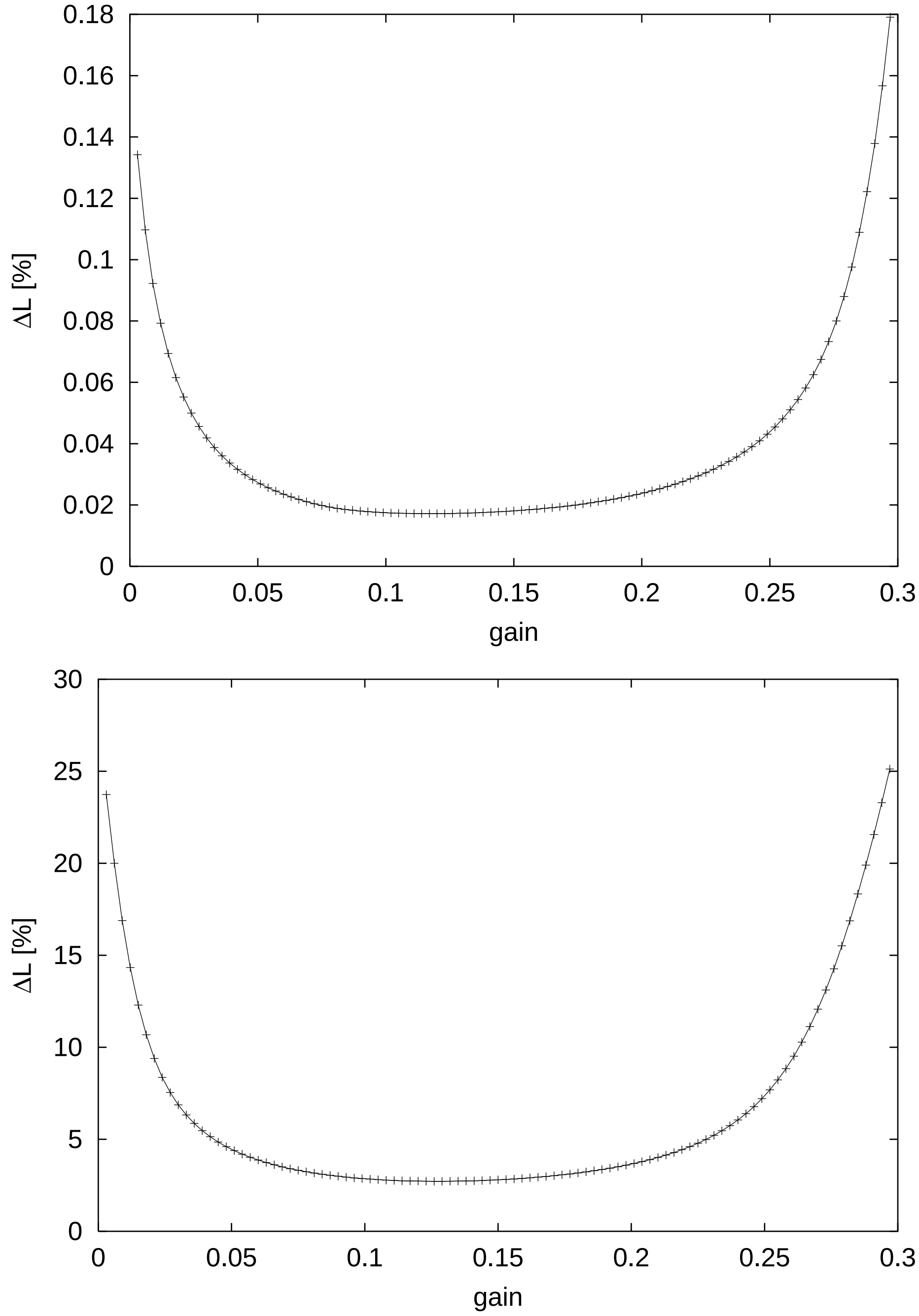

Figure 11: The luminosity loss as a function of the gain for the angle feedback. Angle offsets where $\Delta_{y'} = 1/8\sigma_{y'}$ and $\Delta_{y'} = 2\sigma_{y'}$. The luminosity loss without feedback would have been 0.17 % and 28 %, respectively.

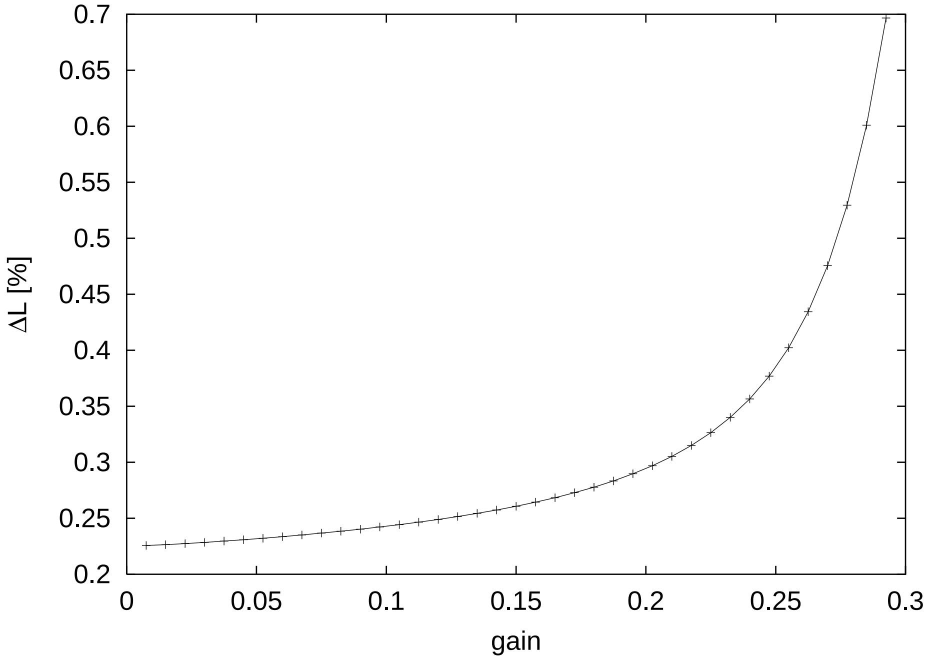

Figure 12: The luminosity loss as a function of the gain for beams with with bunch to bunch angle variations. $\langle \Delta_{y'} \rangle = 0.1\sigma_{y'}$ for both beams.

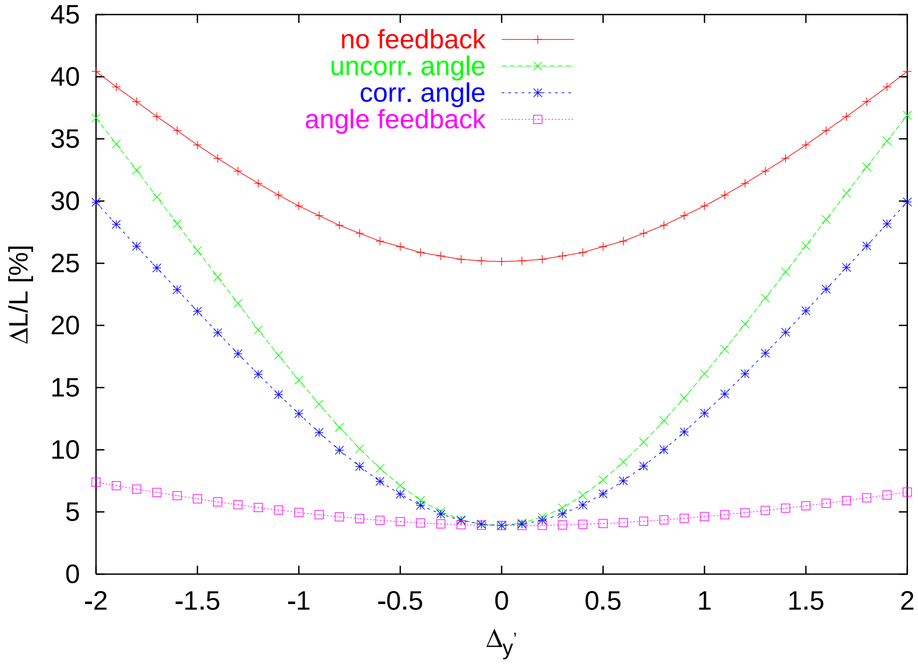

Figure 13: The total luminosity loss as a function of the initial angle of the measured beam. The beam-beam position separation in the interaction point is $\Delta_y = 2\sigma_y^*$.

11 Aknowledgements

I would like to thank T. Raubenheimer for inviting me to SLAC. I am grateful to M. Breidenbach, P. Emma, J. Frisch, G. Haller, T. Raubenheimer and P. Tennenbaum for very helpful dicussions.

References

[1] NLC parameter can be found under URL `http://www-project.slac.stanford.edu/lc/local/AccelPhysics/Accel_Physics_index.htm`.

[2] D. Schulte. Phd thesis. TESLA-97-08 (1996).

[3] J. T. Rogers. In: A. W. Chao and M. Tigner (ed). Handbook of Accelerator Physics and Engineering.

[4] G. Haller, M. Breidenbach. Private communication.

[5] J. Frisch. Private communication.

[6] P. Tennenbaum. Private communication.

[7] T. Raubenheimer and P. Tennenbaum. Private communication.