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Linear Collider Collaboration Tech Notes

Design of an NLC Intrapulse Feedback System

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INTRODUCTION

The small beam spot size at the interaction point of the Next Linear Collider (NLC) makes its luminosity sensitive to beam jitter. A mechanism for aligning the beams to each other which acts during the bunch-train crossing time (~265 ns) has been proposed to maintain luminosity in the presence of beam jitter[1,2]. Here I describe conceptual designs of several components of the system: a fast position monitor, a kicker, and a feedback regulator which properly compensates for the round-trip time-of-flight to the interaction point. Simulation shows that a simple system consisting of conventional components may be effective at reducing the loss of NLC luminosity in the presence of vertical beam jitter many times larger than the vertical beam size.

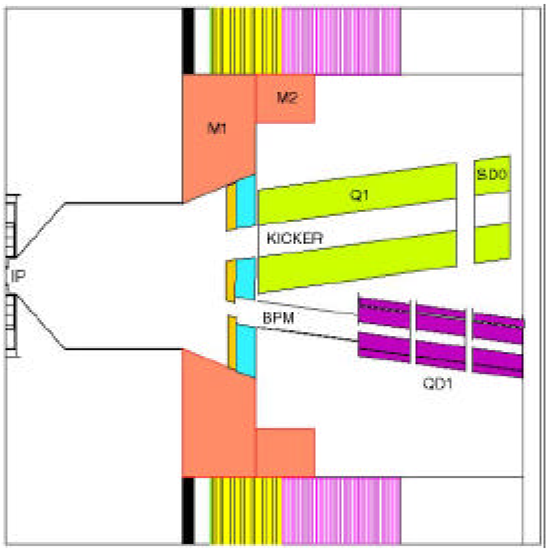

FIGURE 1. Cross section of one-half of the NLC Interaction Region showing beam position monitor and kicker locations.

BEAM PROPERTIES

Interaction point beam properties are taken from the "NLC500H" parameter set, which features a train of 190 bunches of $0.75\text{x}10^{10}$ particles at a spacing of 1.4 ns. Beam-beam deflection parameters are from Yokoya and Chen[3].

TABLE 1. Beam parameters at the Interaction Point.

Parameter	Value	Comments
CMS Energy	490 GeV	
Bunch Charge	$0.75 \text{ x } 10^{10}$ $e^{+/-}$	
Bunches/Pulse	190	
σ_x /σ_y at IP	245 nm / 2.7 nm	
σ_z at IP	110 μm	
D_y	14	Disruption parameter
Deflection slope	10 μradian/nm	At zero beam-beam offset
Displacement slope	40 μm/nm	At BPM

BEAM POSITION MONITOR CONCEPTUAL DESIGN

Transducer

We propose a conventional stripline-type beam position monitor pickup, located about 4 meters from the IP. The strips are assumed to be 10 cm long, so the round-trip time is 0.7 ns. This peaks the response near the 714 MHz bunch spacing frequency. A 20 mm diameter BPM diameter is modeled here, although it may be made considerably larger without impairing feedback performance significantly. The strips are 50 Ohm lines with a width of about 4 mm. Care must be taken to minimize radiation hitting the BPM, and to keep RF from propagating into the BPM duct.

TABLE 2. Beam Position Monitor Transducer Parameters.

Parameter	Value	Comments
Distance to IP	4 m	
Duct diameter	2 cm	
Stripline length	10 cm	
Stripline roundtrip time	0.7 ns	
Stripline Impedance	50 Ohms	
Stripline Width	4.4 mm	

Processor

The position monitor processor produces an analog output proportional to beam position. This signal must have a fast rise time to be useful in intra-pulse feedback. We propose to demodulate a 360 MHz-wide band around the 714 MHz center frequency of the BPM stripline. The processor consists of an RF hybrid, a bandpass filter, and a mixer driven by a 714 MHz reference from the timing system, all followed by a lowpass filter. See Figure 2. This produces a fast signal whose amplitude is proportional to the product of beam position and beam current.

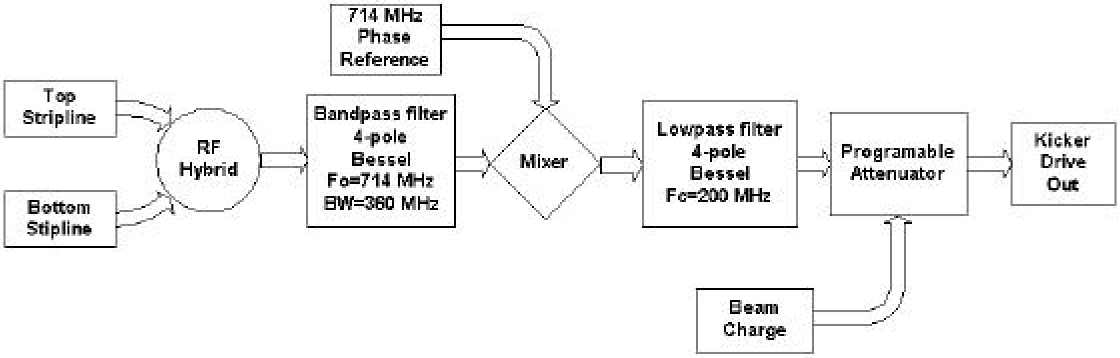

FIGURE 2. Beam Position Monitor Processor block diagram

TABLE 3. Beam Position Processor Parameters.

Parameter	Value	Comments
Type	RF hybrid, heterodyne, zero-IF	
Input Frequency	714 MHz	Center frequency
Bandwidth	360 MHz	
Input filter	4-pole bandpass	Bessel
LO (phase reference)	714 MHz	From timing system
Bandwidth at Baseband	200 MHz	
Baseband filter characteristic	4-pole lowpass	Bessel
Output amplitude	150 mV rms	peak
Output rise time	3 ns	0-60%

A variable attenuator is used to scale the output amplitude inversely proportional to the beam intensity of the current pulse in order to recover the position signal. This scaling must be set up before the pulse, either with information from the MPS system about the expected current, or from slow feedback based on the amplitude of recent pulses. Using standard RF components we can achieve an output rise time of less than 3 ns and position resolutions well below a micron. Figure 3 shows a simulation of the turn-on transient.

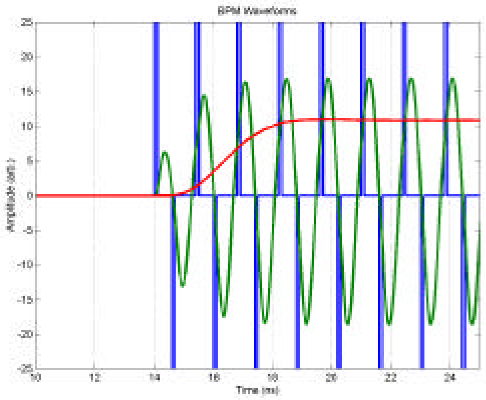

FIGURE 3. Beam Position Monitor response time simulation. The blue trace is the voltage on a stripline (the peaks are offscale), green is the response of the 714 MHz input bandpass filter, and red is the lowpass-filtered analog output, which rises to > 90% of its final value in less than three bunch periods.

Noise

Intrinsic (thermal) resolution of such a pickup/processor combination is less than 50 nm rms, without even using a low-noise amplifier before the mixer. This corresponds to a beam-beam offset resolution on the picometer scale, absent all other error terms. The feedback system requires position resolution of only a few microns, so this is an excellent start.

Absorption of charged particles and secondary emission from the striplines is another potential source of position noise. This design is sensitive at the level of about 3 pm per secondary electron knocked off the striplines, and somewhat less for those knocked off the walls of the beam duct inside the BPM. Therefore imbalances of intercepted spray on the order of 10^5 particles per bunch would be a problem for this BPM.

The near-IR region is likely to be a rich source of RF power. These fields propagating into the BPM give rise to position errors. The beam duct leading into the BPM from both directions must be well below the cutoff frequency for the highest frequencies at which the BPM electronics are sensitive (~1.5 GHz). Cutoff frequency in a circular waveguide is given by $F_{cutoff} = 0.766 \cdot \frac{c}{a} = 11 GHz$ for $a = 2$ cm. The proposed BPM diameter is way below the cutoff frequency so external RF fields are excluded as long as the 2 cm diameter duct is continued upstream and downstream from the BPM for some distance, *e.g.* 10 cm, to attenuate evanescent modes. Such a duct may also reduce the noise from spray on the electrodes as well.

KICKER

Our model for the kicker has curved striplines at a 6 mm radius (12 mm full gap), and a length of 75 cm. Each stripline subtends 120^{o} from the beamline. Such a kicker will have an impedance of 50 Ohms if its enclosed in a beam duct of radius about 10mm. The kicker is to be operated at baseband, so that several bunches may be propagating concurrently through it. The impulse response of the kicker is a rectangular pulse of width given by $t_r = \frac{2L}{c} \approx 5 ns$.

Hence the step response is a linear ramp with 0-100% rise time of 5 ns. In the present system model, this represents the slowest rise-time in the system. Faster response may be obtained by shortening the stripline, at the cost of quadratically increasing the power required for a given deflection.

TABLE 4. Kicker Parameters.

Parameter	Value	Comments
Distance to IP	4 m	
Duct diameter	2 cm	
Stripline length	75 cm	
Stripline roundtrip time	5 ns	
Stripline radius	6 mm	
Stripline Impedance	50 Ohms	
Stripline azimuthal coverage	120 degrees	
Chamber inner diameter	20 mm	
Drive voltage needed	250 mV / nm	Per stripline
Drive power	1.25 mW / nm^2	Each amplifier
Maximum drive power	12.5 Watts	For 100 nm correction at IP

FEEDBACK REGULATOR

The feedback regulator must converge rapidly to the optimal beam position. There are three major issues here. The lag in loop response due to the roundtrip time-of-flight to the IP must be compensated to get rapid, stable convergence. The beam-beam deflection response has a non-linear character which slows convergence for large initial beam-beam offsets. Finally, angle jitter in the incoming beam contributes to an error in estimation of the beam-beam deflection angle.

Compensating the Loop Response

The IP round-trip delay, about 27 ns for a BPM and a kicker each 4 meters from the IP amounts to 10% of the entire bunch train length, making a conventional PID regulator work poorly; the gain on the integral term must be kept small to avoid oscillation due to the round-trip lag. Low gain leads to slow convergence[1]. A higher-order regulator allows for improved convergence. In particular we assume a comb-filter-like integration of the response from one full loop propagation time earlier. The physical implementation is just a delay cable which transmits the output of the kicker driver back to the feedback summing node. See Figure 4. The delay length of this cable is adjusted to the full loop propagation delay, including the round-trip to the IP and propagation delays in the electronics and kicker driver. This lets the feedback compare what was the kicker amplitude back at the time when it was relevant to the beam deflection now being measured. Critical fine-tuning is not required for eventual convergence or stability. Optimum convergence speed requires setting the delay accurately to less than the kicker response time, ½-ns accuracy should be adequate. Compensation for the kicker fill time is warranted; we've modeled this as a simple RC, although in principle the kicker rise-time compensator should have a rectangular impulse response just like the kicker. In summary, the loop compensation is an electrical model of the response of the physical system, composed of cable delay, and an RC shaper with a rise time roughly that of the kicker.

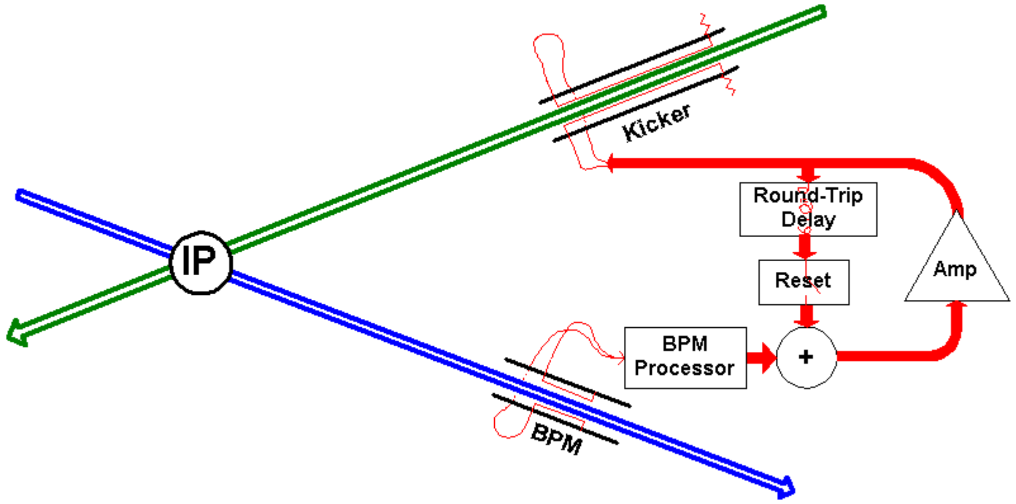

FIGURE 4. Block diagram of feedback system. The deflected beam (blue) leaving the IP goes through the BPM. Signal flow is in red. The incoming beam (green) is kicked into collision at the IP. The reset switch is *opened* to reset the loop integrator when beam is not present.

The system was modeled in Simulink, which shows very rapid correction of beam-beam offsets. A simulated capture transient for an initial beam offset of 8 nm (~3 σ_y) is shown in Figure 5. This offset is within the range where deflection is linear with beam offset, in which case convergence occurs in little more than the time of one round-trip to the IP.

Contributions to convergence time come in three flavors: propagation delays, rise times, and modeling errors. Propagation delays add algebraically, and are dominated by the round-trip time of flight to the IP (27 ns with the present parameters) and approximately 6 ns of cable delay between the striplines, the BPM processor, the kicker amplifier, and the kicker striplines. Rise times (like the BPM processor response, the kicker amplifier, and the kicker fill time) convolute rather than add. These are likely to be dominated by the kicker fill time, which is 5 ns full width for a 75 cm long kicker. The Simulink model properly combines the rise times and propagation delays. Modeling errors reduce convergence; in the presence of gain errors, a mis-scaled correction is made at each step, which is left to be fixed in subsequent cycles. The simulation here assumes certain parameters of the problem are known accurately; *e.g.* the slope of the beam-beam deflection curve. In the physical installation of this system, an external controller will adjust these parameters adaptively from pulse to pulse.

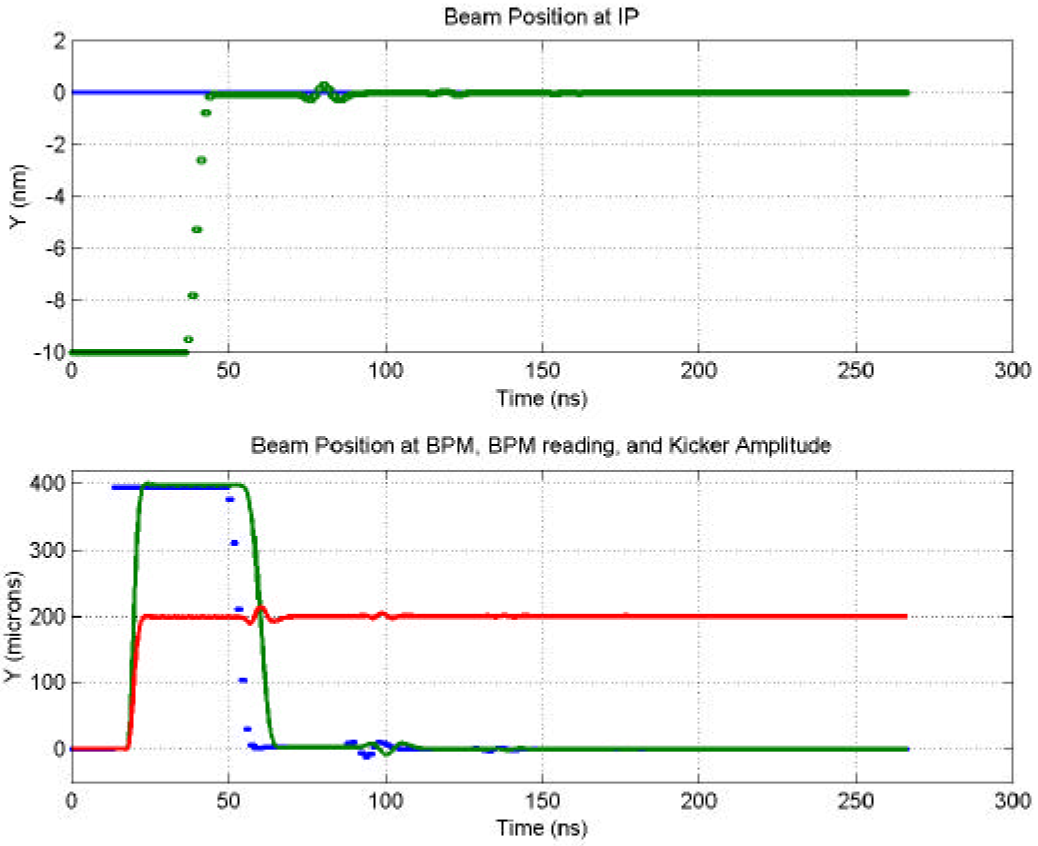

FIGURE 5. Capture transient from an initial beam-beam offset of 8nm (3 σ_y). The upper plot shows the position of the beams at the IP. The lower plot shows the position of the outgoing beam at the BPM (blue), the analog response of the BPM processor (green), and the kicker drive signal, in arbitrary units, is in red. Essentially full luminosity is restored in 42 ns.

Stability

Without beam the loop is unstable even at DC. A reset gate is needed to hold the loop integrator nulled until shortly before the beam arrives. The loop is stable while beam is present, but it amplifies some bunch-bunch noise frequencies. With the parameters show here, bunch-bunch displacements with periods shorter than the bunch train lengths are amplified. An incoming beam position oscillation with a period of 80 ns is amplified by a factor of two. The gain and the range of frequencies amplified depend on the details of the feedback regulator. A higher-order comb regulator can flatten this gain peak, but not remove it entirely. The open-loop Bode plot in Figure 6 shows the comb-filter characteristic of the feedback regulator.

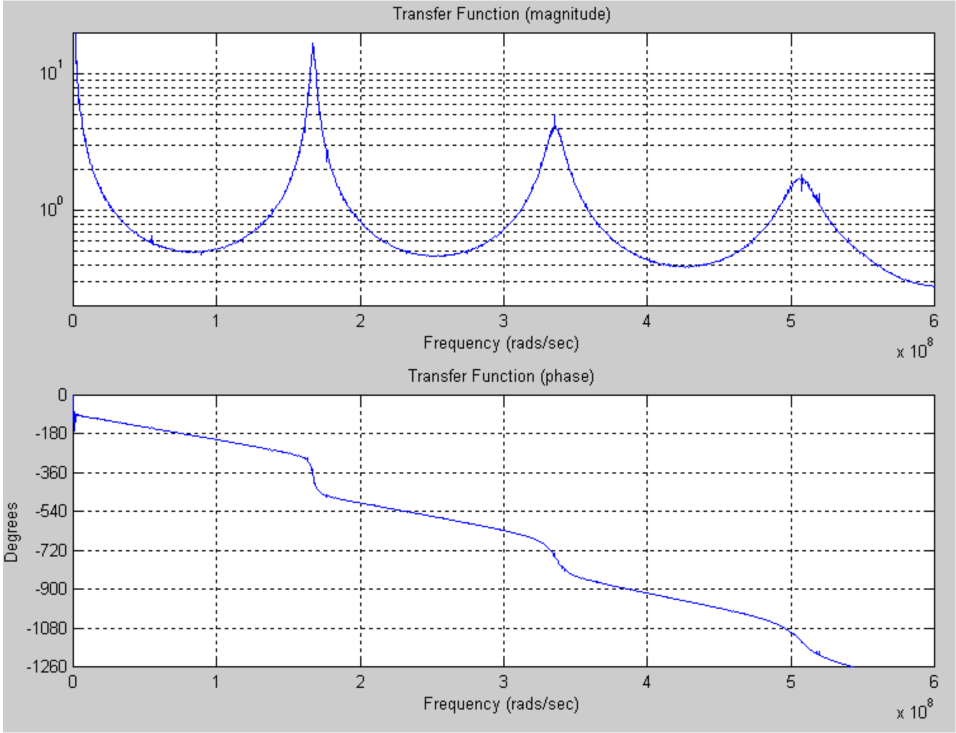

FIGURE 6. Open-loop Bode plot. The closed-loop response is stable since the open-loop phase crosses odd multiples of 180 degrees only when the open-loop gain is below unity. The recurring frequency response is characteristic of comb filters.

This feedback scheme doesn't help much for position jitter within the train; the train lasts for only 7 times the feedback loop delay, and the feedback only begins to act at the interaction point after one loop delay. However this feedback can fix step changes in offset where the incoming beams are stable after a discontinuity, or slow ramp-like displacements. In the later case, displacements linear with time, the feedback settles to a residual error amounting to the bunch displacement in the loop round-trip time, about 40ns. For example, if each bunch is displaced by 0.1nm with respect to the previous one, the end of the bunch train would be displaced 19 nm, but the feedback would correct the error to an accuracy of

$$\frac{0.1nm}{bunch}\cdot\frac{1bunch}{1.4ns}\cdot 40ns = 3nm\,.$$

Deflection Curve Non-Linearity

The deflection angle is linear in displacement for small vertical displacements, but the slope of the response flattens when the beam-beam offset is greater than about 10 σ of the vertical beam size. This means the overall gain of the feedback loop drops like 1/δ for large offsets. A linear regulator will then take many loop propagation delays to reach the linear part of the deflection curve. Then it converges rapidly in the linear region. At sufficiently large initial offsets, convergence is too slow to recover luminosity before the end of the bunch train. See Figure 7 for a simulated capture transient from an initial beam-beam offset of 100 nm. This shows restoration of full luminosity in 120 ns, meaning that a little more than 50% of nominal luminosity is recovered even when the beams start out missing each other by 37 σ!

Convergence speed from way out can be improved by increasing loop gain, at the cost of slowing convergence from small initial opffsets.[4] The optimal loop gain then depends on average jitter conditions. This speedup technique was not invoked in the present simulation.

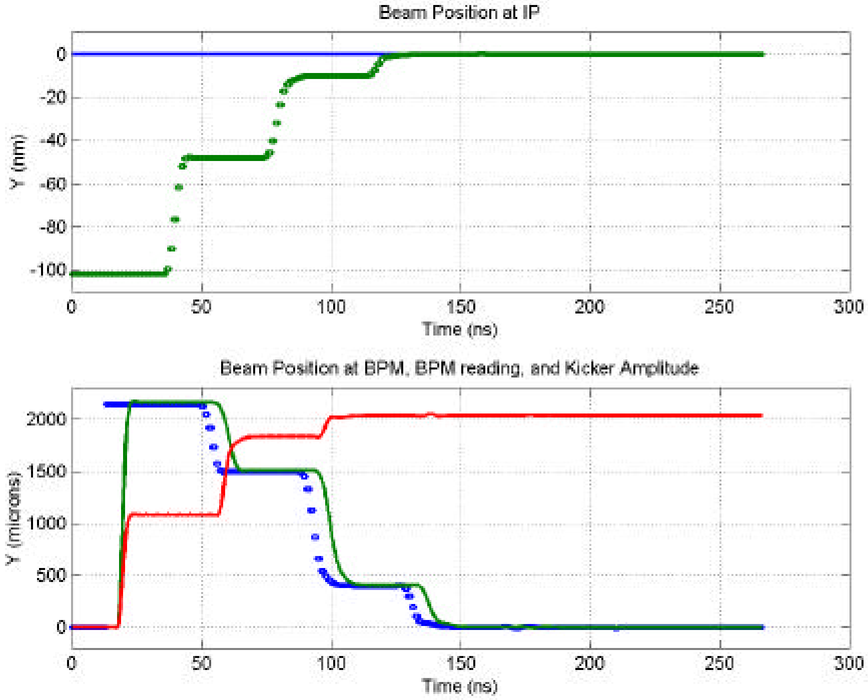

FIGURE 7. Capture transient from an initial beam-beam offset of 100nm $(37\sigma_y)$, way beyond the limits of deflection angle linearity. Essentially full luminosity is restored in 120 ns. The steps occur since it takes several round-trips to the IP to converge.

Incoming Angle Compensation

Jitter in the interaction-point angle of the incoming beams has two deleterious consequences. First, the high aspect ratio of the beam spots in the y-z plane means bunches must be aligned precisely to get luminosity. Therefore if the incoming angle jitter is of the order of $\Theta \approx \frac{s_y}{s_z} = \frac{2.7nm}{110mm} = 24 \cdot mradian$ then an incoming angle feedback, not considered here, must be implemented.

Second, the incoming angle of the beam heading to the feedback BPM contributes to the position signal at that BPM. If not compensated, this angle is interpreted as beam-beam deflection signal and is incorporated, in error, in the intra-pulse feedback. This may be compensated within the beam crossing time if another fast BPM is installed on the incoming beam, on the other side of the IP, and its analog output brought around or through the detector in some timely fashion. This additional term is readily added to the feedback summing node. However the need for this complication is not clear; if the bunches jitter enough to need compensation, one probably needs the steering feedback to get luminosity, in which case angle compensation is not required in this feedback.

CONCLUSIONS

We've presented a conceptual design of an intra-pulse beam-beam feedback for the Next Linear Collider interaction point. Principle components have been sketched in sufficient detail to model the system, including beam-beam effects, the BPM stripline and processor internals, the feedback regulator and the kicker. Simulink was used to perform the simulations; its output shows very rapid convergence from initial offsets of a few beam σ, and that convergence from large offsets is fast enough to recover 50% of the nominal luminosity. Conventional RF components may be used to implement the position monitor processor, the feedback regulator, and the kicker amplifier. Further optimization is warranted.

ACKNOWLEDGEMENTS

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