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SIMULATION STUDIES OF INTRA-TRAIN, BUNCH-BY-BUNCH FEEDBACK SYSTEMS AT THE INTERNATIONAL LINEAR COLLIDER

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Abstract

The International Linear Collider (ILC) is a proposed electron-positron collider targeting collision energies from 250 GeV to 1 TeV. With design luminosities of order 10^{34} cm^{-2}s^{-1}, a beam-based, intra-train feedback system would be required near the Interaction Point (IP) to provide nanometre-level stabilisation of the beam overlap in the collisions. Here we present results from beam-tracking simulations of the 500 GeV ILC, including the impact of beam-trajectory imperfections on the luminosity, and the capability of the IP feedback system to compensate for them. Effects investigated include the position jitter introduced by the damping ring extraction kicker, short-range and long-range wakefields, and ground motion. The feedback system was shown to be able to correct for beam-beam offsets of up to 200 nm and stabilise the collision overlap to the nanometre level, within a few bunch crossings.

INTRODUCTION

The International Linear Collider [1] (ILC) is a proposed, next-generation, electron-positron collider, with an initial collision energy of 250 GeV and options for upgrades including stages at 500 GeV and 1 TeV [2]. The ILC could be used for precision tests of the properties of the Higgs boson [2]. The 500 GeV-stage parameters are given in Table 1. The electrons would be produced with a DC photo-cathode gun, accelerated in a 5 GeV injector linac and injected into a 3.2-km-long damping ring (DR). The bunches would be individually extracted from the DR to the Ring To Main Linac (RTML) using a fast extraction kicker. The beam would then be transferred to the Main Linac (ML) for acceleration to full energy and transferred to the Beam Delivery System (BDS) which would bring the beam to a focal point at the interaction point (IP).

The luminosity, $\mathscr{L}$, of a linear collider is given by [3]

$$\mathscr{L} = H_D \frac{N^2}{4\pi\sigma_x^*\sigma_y^*} n_b f, \tag{1}$$

where H_D is the luminosity enhancement from the focussing between opposing bunches, and the remaining terms are defined in Table 1. The strong electromagnetic fields at collision produce ‘beamstrahlung’ [4], which increases the energy spread of the beam and is characterised by the parameter, Υ, with $\langle\Upsilon\rangle \propto 1/(\sigma_x + \sigma_y)$. Therefore, to both

Table 1: ILC Parameters for the 500 GeV Stage [2]

Parameter	Value
Repetition frequency (f)	5 Hz
Bunches per pulse (n_b)	1312
Particles per bunch (N)	2×10^{10}
Bunch separation	554 ns
Bunch length at IP	300 µm
Peak luminosity ($\mathscr{L}$)	1.8×10^{34} cm^{-2}s^{-1}
Horizontal beam size at IP (σ_x^*)	474 nm
Vertical beam size at IP (σ_y^*)	5.9 nm

maximise the luminosity and reduce beamstrahlung, the beam is designed to collide with $\sigma_x >> \sigma_y$.

An intra-train beam position feedback system [5] has been proposed for stabilising collisions at the IP; a schematic of the system is shown in Fig. 1. The deflection of an outgoing beam, caused by the misalignment of the two incoming beams at the IP, is measured with a stripline beam position monitor (BPM) [7] ~4 m downstream of the IP. A compensating angular deflection is applied via a kicker ~ 8 m upstream from the IP. If the offsets of the outgoing electron bunches are measured, the incoming positron bunches are corrected and vice versa, thus reducing the additional latency from signal propagation time. For bunch-by-bunch feedback, the system latency must be less than the 554 ns bunch separation. The design, construction and tests of a prototype bunch-by-bunch IP feedback system are presented in [8], demonstrating that the ILC IP feedback system latency, resolution and dynamic-range requirements were met.

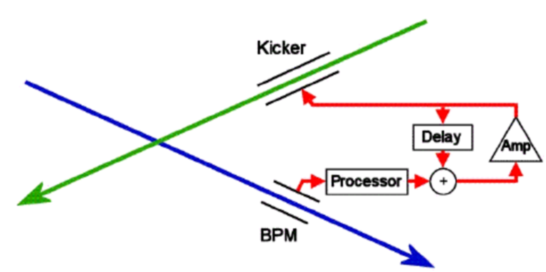

Figure 1: FONT IP feedback system layout [6].

As $\sigma_x >> \sigma_y$, here we focus on the more challenging vertical plane. The feedback system should operate over a $\pm$200 nm range of relative vertical bunch position offsets

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at the IP. For a 250 GeV beam, this corresponds to a BPM dynamic range of ±1400 μm and a kicker angular deflection range of ±60 nrad [8].

ILC SIMULATIONS

The beam transport in the ML and BDS were simulated with the tracking code PLACET (version 1.0.3) [9], the beam-beam interaction at the IP with GUINEA-PIG (version 1.2.0) [10], and the IP feedback system with Octave [11]. The 2016 ILC lattice (RC2016X) [12] was used with beam parameters as specified in [2]. Bunches tracked through an ideal lattice to the IP had r.m.s bunch sizes $\sigma_x = 472$ nm, $\sigma_y = 5.8$ nm and $\sigma_z = 295$ μm in the horizontal, vertical and longitudinal planes, respectively.

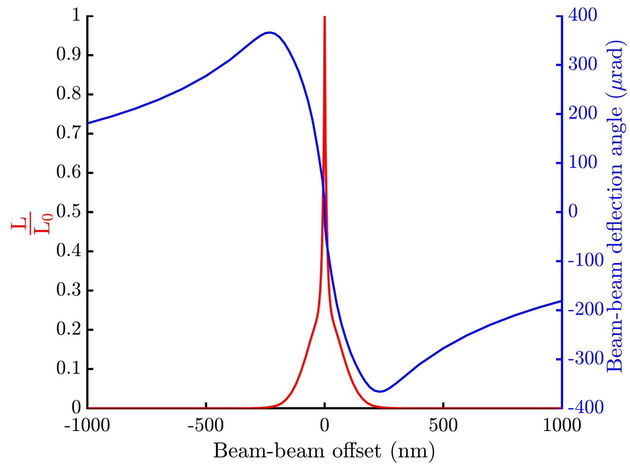
The individual bunch extraction from the DR means that shot-to-shot variation in the extraction kicker voltage would produce angular beam jitter at the entrance of the RTML [13]. Several feedback systems are proposed throughout the machine to manage beam jitter, including a feed-forward loop in the turnaround of the RTML to correct for DR extraction kicker jitter [14]. A 5 Hz cascaded feedback system comprising 5 feedback loops would stabilise pulse-by-pulse orbit variations in the ML. An IP angle feedback system would correct the beam orbit through the final focus [15], therefore stabilising the beam angle at the IP.

Four ground motion models were considered, each measured in a diferent location: model K (based on measurements from KEK, Japan) and model C (DESY) are noisier models, and models A (CERN) and B (Fermilab) are quieter [16, 17]. Ground motion can be characterised as 'slow' (<1 Hz) and 'fast' (>1 Hz). A feedback system acting between successive beam pulses could correct for ground motion at frequencies <5 Hz but fast ground motion would require intra-train feedback.

Wakefields induced, e.g. at bellows, flanges and transitions between beam pipes, together with the transverse beam jitter, increase the beam emittance. Intra-bunch ('short-range') wakefields generate E-z coupling within the bunch [18], whereas inter-bunch ('long-range') wakefields created by the first bunches in the train impart transverse kicks to subsequent bunches. These were modelled using wake potentials for the fourteen most destructive modes based on measurements at the ATF2 [19].

The angle of deflection and luminosity from collisions between misaligned bunches at the IP are given in Fig. 2. The peak luminosity was simulated to be 1.79×10^{34} cm^{-2}s^{-1}, dropping to 99% with an offset of 0.3 nm. The extrema of the deflection-angle curve are at ±230 nm, outside of which the IP intra-train feedback would erroneously estimate the bunch offset from the deflection angle.

The IP feedback system uses the deflection-angle curve as a mapping between the offset measured at the BPM and the offset at the IP, therefore, it is essential to understand the behaviour of this function. The deflection-angle curve depends on the charge of the bunches, N, this is shown in Fig. 3(a) for charges between 10% and 110% of the nominal



(a)

Figure 2: Normalised luminosity (red) and deflection angle (blue) vs. relative vertical IP offset.

value. For lower bunch charges, the maximum deflection angle is reduced and occurs at a smaller offset leading to a reduced resolution of the position measurement. The deflection angle also depends on σ_x and σ_y; this is shown in Figs. 3(b) and (c). As with reducing N, for larger σ_x the resolution of the measurement of the relative beam-beam offset is significantly reduced. For the scan of σ_y values, at larger offsets the curves converge because the change in the bunch distributions become negligible compared with the y-offset. Therefore, the system should be relatively robust to variations in σ_y.

IP FEEDBACK SYSTEM SIMULATION

Simulations of the ILC and the IP feedback system were used to study the beam stabilisation in the presence of wakefield effects, ground motion and bunch jitter. The IP feedback corrector was modelled with a 0.1% kick error and the BPM with a 1 μm resolution. Angular jitter was added to simulate the DR extraction kicker jitter, corresponding to a 10% beam-size increase at the IP, as suggested in [20]. A random seed of ground-motion model K, was applied for 0.2 seconds to the electron and positron beamlines; for studies of other ground motion models see [21]. The relative Final Doublet jitter was simulated to have a standard deviation of 100 nm at frequencies below 5 Hz.

For the IP feedback system, Proportional-Only feedback was simulated; the results are presented in Fig. 4. For further results with Proportional-Integral control and the application of filters see [21]. With a gain of 1, nearly all of the luminosity was recovered by the second bunch, as all of the bunch trains were within the capture range of the feedback system. The luminosity for the subsequent bunches is limited by the BPM resolution and bunch-to-bunch jitter.

To account for uncorrelated effects such as bunch-to-bunch jitter and BPM resolution, the gain of the feedback should be reduced correspondingly. The effect of the gain

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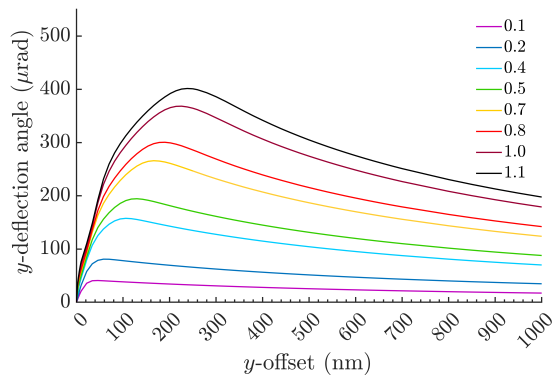
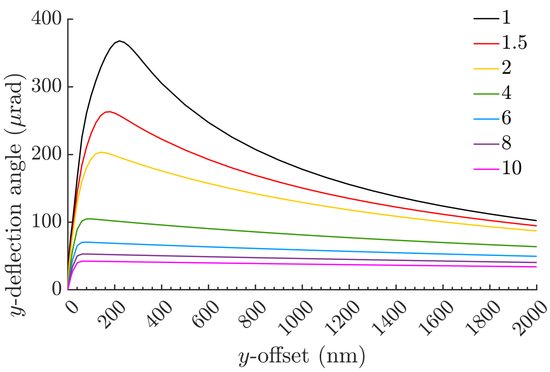
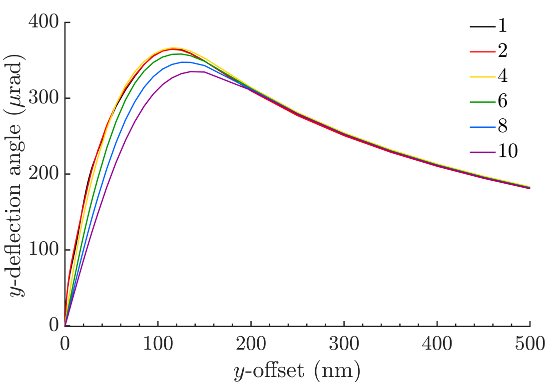


(a)



(b)

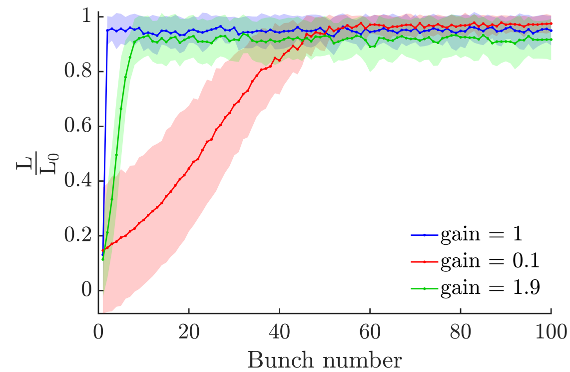


(c)

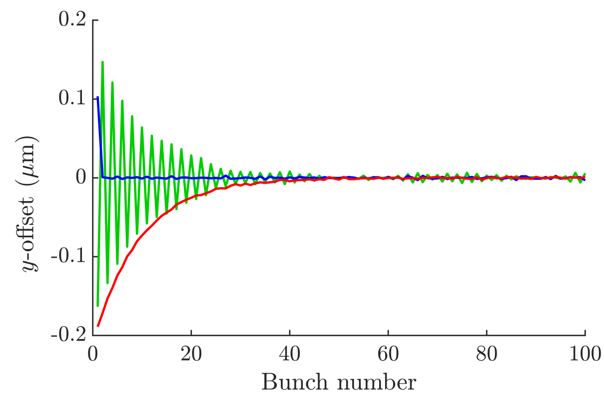
Figure 3: Deflection angle vs. vertical beam-beam offset at the IP, where the colour of the line denotes the (a) charge, (b) horizontal and (c) vertical bunch sizes at the IP, given as a multiple of the respective nominal value.

choice is illustrated in Fig. 4. For a lower gain, the beam takes longer to converge; however, even with a gain as low as 0.1 the luminosity is almost fully recovered by bunch 40. With a train of 1312 bunches this represents a luminosity loss of only a few percent. For a real system the feedback gain would be set slightly lower than unity in order to make the system more robust to noise and errors.

If the gain is set too high, e.g. for $g = 1.9$, the system takes longer to converge and a lower final luminosity is achieved, with the over-correction causing 'ringing' (see Fig. 4(b)).



(a)



(b)

Figure 4: (a) Normalised luminosity vs. bunch number for simulations of 100 error seeds with Proportional-Only IP feedback operating. Data points show the mean luminosity and the shaded region the standard deviation. (b) Vertical bunch-bunch offset at the IP for a single seed of each. The feedback gains are given in the legend of (a).

For $g = 0.1$, 1.0 and 1.9, the luminosity reaches 97%, 95% and 92% of the design value, respectively. The feedback gain could also be varied with bunch number along the train, with an initially higher gain to quickly reduce the offset and a reduced gain later to achieve the highest final luminosity.

CONCLUSION

We have presented the results from simulations of the proposed 500 GeV ILC IP feedback system. Sources of beam instability were modelled including wakefields, jitter sources and ground motion. The impact of these effects on the beam-beam offset and luminosity were studied together with the potential of recovering luminosity with an intra-train IP feedback system. The ideal luminosity was simulated to be $1.79 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ and the maximum deflection angle to be 360 µrad. Within its dynamic range, the IP feedback was shown to maintain the luminosity at 95% of the design value, where the remaining luminosity loss stemmed from the finite BPM resolution and the uncorrelated bunch-to-bunch jitter. More complex feedback algorithms should be explored, taking into account the fre-

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quencies and magnitudes of the various contributions to beam instability.

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