Optimising the Linear Collider Luminosity: Feedback on Nanosecond Timescales

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I summarise the R&D programme on a nanosecond-timescale fast-feedback system for luminosity optimisation at the linear collider.

1. Introduction

The luminosity achievable in a colliding-beam accelerator may be written:

$$L = \frac{f\ N\ N_1\ N_2\ H}{4\pi\ \sigma_x\ \sigma_y}$$

where f is the number of machine cycles per second, N is the number of bunches per machine cycle, N_1 and N_2 are the number of particles per bunch, and σ_x, σ_y are the transverse overlaps of the colliding bunches. For an e^+e^- collider H is the beam-beam self-focussing parameter or 'pinch enhancement'. The table shows the values of several of these parameters for the various designs of a next-generation e^+e^- linear collider currently under consideration. Δt is the time separation between the N bunches in the train.
The nanometre-level vertical beam overlap is a particularly challenging goal for all these designs, most notably CLIC. Any source of beam motion which results in relative vertical offsets of the two beams at the interaction point (IP) at the nm level will clearly reduce the luminosity from the nominal value. In all of the collider designs stabilisation below the 1σ level is required to keep the luminosity loss below 10%.

The many kinds of potential beam motion may be characterised in two classes: (i) slow drifts resulting from eg. thermal excursions or component settling, with characteristic timescales varying from seconds to months; (ii) jitter on a timescale comparable with the machine repetition time. Both kinds of motion were experienced in the decade-long experience at SLC, and were dealt with by employing slow- and fast-feedback systems, respectively.

We are addressing the design of an intra-bunch-train fast-feedback (FB) system for the next-generation linear collider (LC). The system comprises a fast beam position monitor (BPM) to detect the relative misalignment of the leading electron and positron bunches at the IP, a feedback loop, and a fast kicker for kicking the trailing bunches back into collision.

The system time-response requirements for J/NLC and CLIC are clearly very different from those for TESLA. We have therefore chosen the more challenging case of J/NLC and CLIC as the primary focus of our efforts to develop a working prototype hardware system. However, from the timing point-of-view, a system which works on the 10ns scale could clearly be applied to the less

Design	Technology	c.m. energy (GeV)	f (Hz)	N	Δt (ns)	σ_x (nm)	σ_y (nm)
TESLA	superconducting	500-800	5	2820	337	553	5
J/NLC	X-band	500-1000	120	190	1.4	234	4
CLIC	2-beam	3000	75	90	0.6	40	0.6

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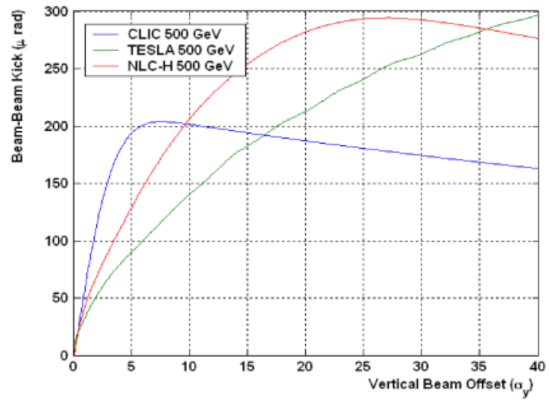

Figure 1: Simulation of the beam-beam kick that results from beam misalignments at the IP. This is illustrated for the NLC, TESLA and CLIC machine parameters.

demanding TESLA timescale of 300ns. With current technology it is clear that a system for J/NLC and CLIC must be based on fast analogue signal processing, rather than digital processing [1]. However, given the rapid advances in signal processing speeds over the past decade it is quite possible that digital technology will be fast enough by the time the real LC system is deployed c. 2010; if so, the FB electronics could look almost identical for any of J/NLC, CLIC or TESLA. We aim to monitor this situation and to take advantage of technological developments as they arise.

2. Simulation Studies

During the past 18 months we have created powerful software tools for the simulation of a nanosecond timescale feedback system for correcting the relative displacement of nanometre-sized beams.

- We have imported and installed the code GUINEAPIG [2]. This allows us to simulate the beam-beam interaction between colliding electron and positron beams of arbitrary size and bunch charge. When they do not collide head-on each bunch gives the other a strong transverse EM kick which can be detected in a downstream BPM. This forms the physical input to the FB system (Figure 1).
- We have installed MATLAB and SIMULINK to create a modular FB system simulation. The response times of the BPM, feedback loop and kicker magnet, as well as cable delays, can all be chosen arbitrarily. The feedback algorithm can similarly be programmed at will.
- We have set up a GEANT model of the NLC interaction region to allow us to incorporate the FB system components. The location of the BPM and kicker directly affect the system latency (due to signal propagation times). In addition, the material of these components can contribute to knock-on backgrounds in the detector resulting from the showering of beam-produced photons and e^+e^-. A corresponding model of the CLIC interaction region is currently being implemented.
- We have set up an equivalent FLUKA model to allow us to calculate background neutron production.

We have used these tools to simulate the luminosity loss due to beam misalignment for J/NLC, TESLA and CLIC (Figure 2). For the NLC and TESLA cases we have set up a feedback model which simulates the performance of the real hardware components: the BPM, the kicker, the FB logic/loop, with signal delay times corresponding to the actual locations of the components within the respective IR. In addition, for NLC we have evaluated the neutron and e^+e^- pair backgrounds in the IR that result from interactions with the material of the added components; the equivalent simulations will be done for CLIC.

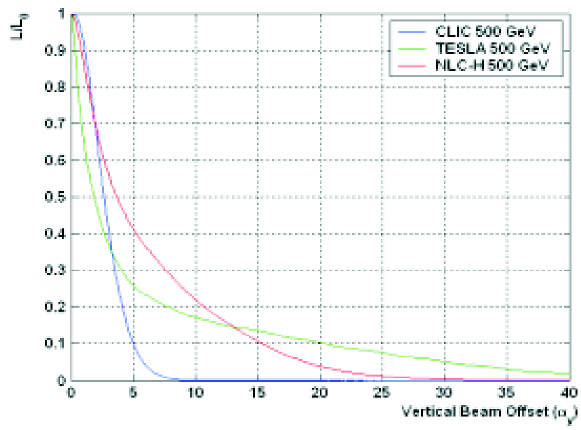

Figure 2: Fraction of nominal luminosity achieved vs. beam offsets for NLC, TESLA and CLIC, without feedback.

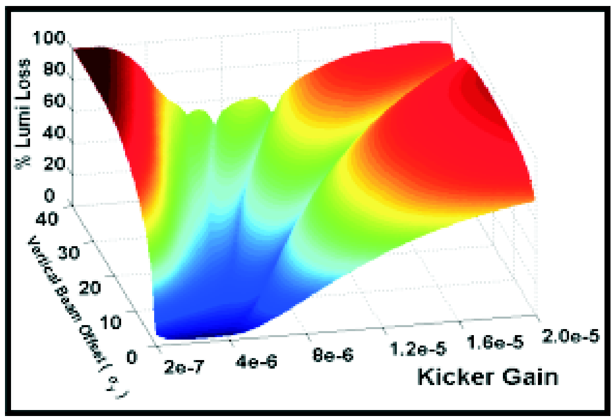

Figure 3: Simulated luminosity loss for NLC, with feedback. The 'valleys' are a feature of the latency of the system.

We have used this software infrastructure to optimise the design of the FB system for the NLC case in terms of the minimisation of the response time and the knock-on backgrounds, subject to the constraints imposed by the locations of the other components in the crowded IR, principally the final-focus quadrupole magnets and the vertex detector. Figure 3 [3] shows the performance for the optimal hardware layout in terms of the luminosity loss vs. beam offset and kicker gain. For offsets below 10σ there is a comfortable 'valley' in which the specific gain choice is not critical. However, for offsets significantly larger than 10σ the choice of gain is delicate; an unfortunate choice could lead to catastrophic luminosity loss. We are now in a position to perform similar design optimisation studies for CLIC and TESLA.

3. FONT1: First Beam Test at the NLC Test Accelerator

The importance of FB systems in accelerator stabilisation/control and luminosity optimisation was learned painfully at SLC. No future linear collider can be physically aligned for nm-size beam-beam collisions. The Feedback on Nanosecond Timescales (FONT) system is key to successful operation of the future linear collider; without it the luminosity may be 1–2 orders of magnitude below the nominal design. It is therefore highly desirable to test experimentally a prototype FB system under conditions as close as possible to those at the LC [4].

For J/NLC or CLIC one requires an experiment with *colliding* trains of O(100) bunches with an inter-bunch separation of O(1 ns); no such facility exists, or is likely to exist, until the collider turns on. However, *non-colliding* bunch trains with similar properties can be produced. We have decided to base our first-round test, FONT1, at the NLC Test Accelerator (NLCTA), located in the Research Yard at SLAC. NLCTA is currently used for the evaluation of RF components such as Cu structures, but the downstream section is relatively 'open' beamline. NLCTA can be operated in a 'long-pulse' mode, which provides a train of bunches filled at X-band frequency, 11.4 GHz, typically of 120 ns duration. This train length is within a factor of 2 of J/NLC and CLIC requirements, and the total train charge is comparable, although the bunch spacing, 0.1 ns, is about an order of magnitude shorter; the prototype experiment is in some sense therefore 'harder' than the real case. We intend to use a dipole magnet to perturb the whole train, a fast BPM to monitor the displacement at a given point, an analogue FB circuit, a fast kicker to attempt to correct the displacement as fast as possible, and two downstream BPMs to measure and monitor the correction.

The key components of the system, and their status, are listed below:

- **Dipole magnet:** A suitable magnet has been found, a 'type 4 linac corrector', amongst spares at SLAC. It will produce a dipole offset (i.e. angular deviation) that corresponds to up to 5 mm position offset at the measurement BPM. The peak current is 6A and it is planned to use an existing power supply. The dipole can be pre-triggered so as to be fully 'on' by the time the bunch train arrives.
- **Fast BPM:** A prototype X-band 'button' BPM has been fabricated. The response of the BPM at X-band has been measured using a network analyser, as well as using the BPM test facility at Lawrence Berkeley Laboratory. Its resolution has been characterised and appears to be of the order of 10 μm, which is more than adequate for our test.
- **Fast kicker:** Three suitable fast kickers have been found amongst spares at SLAC; only one is needed for a 1-dimensional test.
- **Kicker amplifier:** A preliminary design study for a multi-stage tube amplifier capable of delivering up to 5 kW peak power has been made. The design employs Y690 planar triode tubes.
- **Diagnostic BPMs:** Two downstream X-band BPMs (see above) will be used to monitor the beam position with the FB in off/on modes.

4. Schedule

We expect to take data on the FB system performance in spring and summer 2002. Initially a fixed offset will be applied, and we will attempt to 'zero' it as fast as possible within the bunch train passage time. The fixed offset will then be varied to simulate different beam offsets in the NLC, and we will characterise the performance vs. offset, investigating the effect of the choice of gain. The ultimate test will be to wire a random-number generator to the dipole and have the FB system operate 'blind'.

Without pre-empting the results of these tests, it is possible to envision an extended R&D programme for investigation of a number of issues germane to a real FB system:

- Testing of improved analogue processing algorithms.
- Handling of correlated 'jitter' within the bunch train, eg. sinusoidal or other regular transverse position oscillations.
- Dynamic gain choice, either from adaptive learning or using a priori information from upstream systems.
- Interplay between position-correction and angle-correction; here we have addressed only the former.
- Correction in both planes: dealing with transverse beam coupling.
- Dealing with bunch tails in highly non-Gaussian (i.e. realistic) bunches.
- Upgrade to digital technology as signal processing speed improves.

Some of these could be carried out at the NLCTA, and/or at other facilities such as the ATF at KEK, TTF at DESY, or CTF3 which is under construction at CERN.

References

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[3] G. White, Feedback on nanosecond timescales
[4] P.N. Burrows, 'Experimental test of feedback on nanosecond timescales'; http://accelerator.dl.ac.uk/ap/bdir2000/