Feedback On Nano-Second Timescales: Fast Feedback Simulations

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Abstract

The FONT group are responsible for the design of the IP fast intra-train feedback system to be implemented in the IR of the future linear collider. This system is intended to correct for luminosity loss due to high frequency ground motion. The work presented here was carried out to test the feasibility of such a feedback system and to investigate, through simulation, the optimum design and operating parameters.

1 INTRODUCTION

All of the proposals for the future linear collider require similarly challenging final beam spot sizes: TESLA [1] 5nm, NLC/JLC [2] 2.7nm and CLIC [3] 1nm, are the proposed vertical bunch spot sizes at the IP. This places very rigorous stability requirements on all three designs. The most severe tolerance is for the final focusing quadrupole magnets. To keep the luminosity loss to within a few percent, the beams need to be kept in collision to within 10% of the vertical beam spot size. This implies a tolerance on the final quadrupoles of 0.27nm, and 0.1nm for TESLA and NLC/JLC/CLIC respectively.

The limiting factor for stability along the beamline for the linear collider is that of ground motion. There has been a considerable effort undertaken into the study of the magnitudes and effects of ground motion at different possible sites for the linear collider which are covered in detail elsewhere[4]. If uncorrected, ground motion causes a total loss of luminosity at the linear collider within seconds through beam misalignment and emittance growth. To combat this, a program of passive and active support systems to stabilise the beamline elements, together with different levels of beam-based feedback systems, is being pursued.

Three levels of beam-based feedback system are being developed. A slow feedback will move quadrupoles and structures onto the beam trajectory about every 30 minutes to compensate for low frequency ground motion. An inter-pulse feedback acts in a few locations to correct accumulated errors that occur in between the action of the slow system, and also to provide the possibility of straightening the beam. Finally, a fast intra-train feedback system acting at the IP keeps the beam in alignment, correcting for high frequency cultural ground motion moving the final quadrupoles. For TESLA, a second intra-train system will be used further upstream to additionally remove any incoming angle jitter which also leads to a loss in luminosity.

2 BEAM SIMULATIONS INCORPORATING FAST-FEEDBACK SYSTEMS

The fast feedback systems are designed to remove beam jitter that occurs at frequencies comparable with the repetition rate of the machine by measuring the first few bunches in the train and correcting the following bunches within that train. The bunch structure thus dictates the operating requirements for the system. For NLC/CLIC designs there are 192/154 bunches per train separated by 1.4/0.7 ns. TESLA will have 2820 bunches separated by 337 ns. The NLC/CLIC case requires a much more aggressive design requiring, at present, a purely analogue electronic approach. The TESLA scheme allows for a more complex digital based algorithm to be employed. Simulations of the fast feedback systems are written in the Matlab/Simulink environment. The feedback system for NLC and CLIC is based on the system designed by S. Smith at SLAC [5]. The feedback system for TESLA is implemented as per the TESLA TDR [6], which includes an angle feedback system 850m upstream of the IP.

3 SIMULATION RESULTS

3.1 NLC

The effect of vertical beam offsets at the IP of the NLC-H 500GeV machine was studied with different variants of the feedback design implemented in the Simulink model, using the GUINEA-PIG [7] modelling package to calculate the beam-beam kick effects and luminosities. In the simulation, the BPM and kicker are assumed to be positioned at a distance of 4.3m from the IP at the same side of the IP, where the beam deflection is measured on one beam, and the other incoming beam is then kicked. This is possible at NLC (and CLIC) due to the non-zero crossing angle. Although, at the NLC, with mechanical stabilisation systems active, the IP offsets are expected to be small ($\Delta y < 5\sigma$)- the effect of offsets of up to 40 times the vertical IP beam spot size were investigated to see the full capabilities of the system. Fig. 1a shows the results of running the simulation over one full bunch train (192 bunches) with different initial offsets. Shown in the filled-in region is the case with no feedback, where the luminosity quickly drops off as the beams are offset, with 60% luminosity loss for a 5 σ_y offset. The top two curves show the effect of our standard feedback algorithm with a single gain stage set at 2 different levels (‘low’ and ‘high’). Low gain is better at low offset, high at larger offsets due to the non-linearity of the beam-beam kick vs. beam offset function. In an attempt to remove this effect, a linearisation step is included in the simulation where the gain is chosen based on the incoming BPM signal. The third curve shows the effect of a 3-stage linearisation to the predicted beam-beam kick curve. The last curve shows the effects of incorporating a further gain stage in the feedback loop to damp down the oscillatory effects arising from having a too high gain for the given offset.

Being closely integrated into the IR close to the IP, the feedback system is forced to operate in an environment of background particles generated at the IP during beam collsions. This could potentially mean a damaging effect to the system itself, and also, through secondary production and scattering of background particles to the sensitive particle detectors (principally the vertex and central tracking systems). To model the potential impact of the feedback system in the IR, GEANT3 [10] and FLUKA99 [11] models of the IR were taken and the material making up the feedback system was added. Fig. 2 shows the positioning of the BPM and kicker of the feedback system within the IR of the NLC as implemented in the models. The source of background modeled was that of the coherent e^+e^- pairs which were generated with the GUINEA-PIG model and then tracked through the GEANT and FLUKA models. Fig. 3 shows just a few e^+e^- pairs and the associated scattered secondaries tracked on one side of the IP. Fig. 4 shows the intercepted elecromagnetic background in the strips of the feedback BPM strips. According to S. Smith[5], the feedback system will be sensitive to intercepted EM radiation at the level of 3pm of Δy^* resolution per electron knocked off the BPM strips. The background radiation would thus present a significant source of noise in the feedback system if an intecepted spray of particles at the BPM at the level of 10^5 per bunch crossing existed. As can be seen in Fig. 4, the expected level is much less than this. Fig. 5 shows the rate of secondary EM particles hitting the layers of the vertex and central tracking detectors with and without the BPM and kicker of the feedback system incuded in the GEANT model. As can be seen, the inclusion of the system has very little impact on the background levels. This is due to the positioning of the system behind the masks and LCAL system which are designed to shield the IP from scattered secondaries. Modeling of the system forward of this mask where the system is clearly within the field of pairs confined by the solenoid field seen in fig. 3 shows a large increase in detector backgrounds. Fig. 6 shows the neutron flux in the vertex tracking layers, again- this positioning of the feedback system has little impact on the background levels. The integrated flux with the FB system included is $6.6 \pm 1.3 \times 10^9$ 1 MeV equivalent neutrons per cm^2 per year. The default value without the FB system in is $5.5 \pm 0.8 \times 10^9$.

3.2 CLIC

For the CLIC simulation, the same system is used as in NLC. The curves in fig. 1b show the effect of offset beams on luminosity for the cases of no feedback, and the system

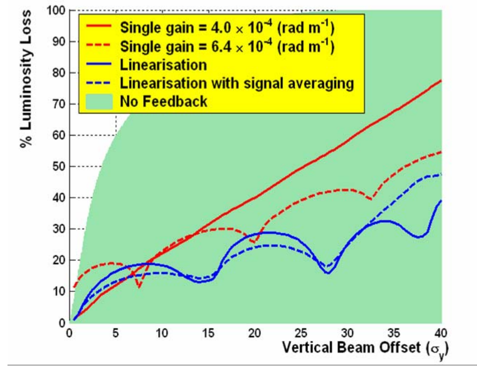

Figure 1: Simulation of luminosity loss at NLC-H (left) and CLIC (right) 500 GeV machines with varying initial beam offsets at the IP.

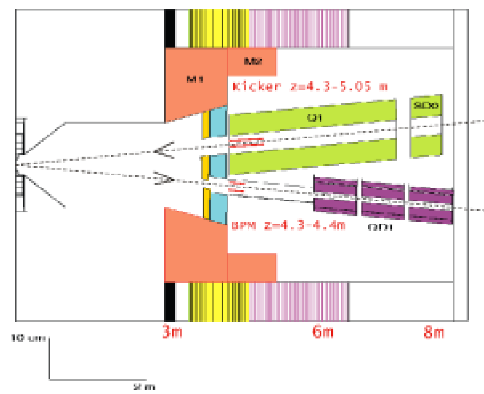

Figure 2: GEANT model of NLC IR showing the positioning of the IP feedback kicker and BPM components.

as described in the above section with the 3-stage linearisation, placed at a distance of 4.3m as in NLC and closer, 1.5m as maybe possible with the CLIC IR design. As can be seen, the CLIC luminosity is very dependent on highly aligned beams, the smaller train length and shorter bunch spacing gives the feedback system less tries at correcting the offsets. The latency of the system is dominated by the time of flight of the beams between IP and feedback components.

As described above for the NLC case, the impact of the feedback system in CLIC has also been started to be investigated by G. Myatt at Oxford. Fig. 8 shows the GEANT models used for CLIC- a 'far' and a 'close' model with different feedback-IP distances. Work is still ongoing, but it was found that relative to no feedback system present, the 'far' position gives about 2 $hits/mm^2/train$ extra in the inner vertex tracking layer. The 'close' configuration produces little extra radiation for the vertex tracker but produces considerable extra background in the end of the unprotected TPC. Plots of background rates in the ver-

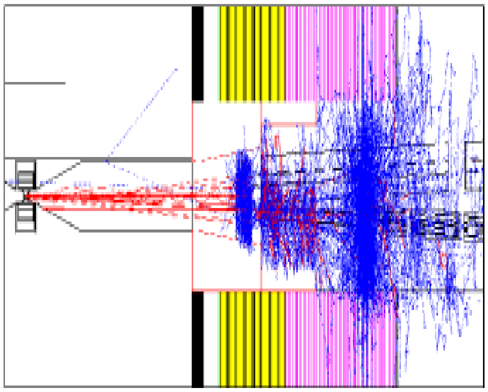

Figure 3: GEANT model of NLC IR with 20 tracked e^+e^- background pairs. The scattered and secondary charged particles are shown in red and neutral photons in blue.

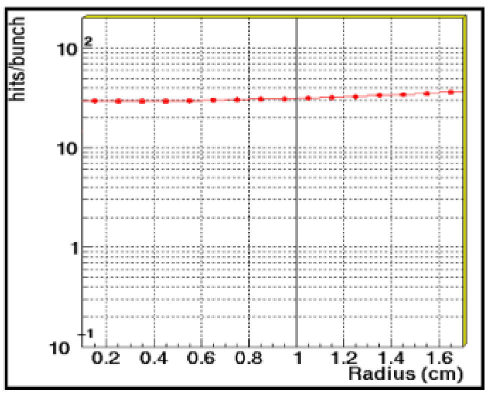

Figure 4: EM background flux at the z location of the feedback BPM. The stripline radius is shown as 1cm in the plot.

tex tracker and TPC for the 2 configurations are shown in figs. 9 and 10.

3.3 TESLA

For TESLA, a simulation has been put together under Matlab of the TESLA collider from the exit of the damping rings through to the IP including the beam-beam interaction and the fast feedback systems. This brings together the codes of PLACET [8], MERLIN [9] and GUINEA-PIG together with the purpose written feedback code. This allows the effect of banana-shape bunches caused by short-range wakefield effects in the accelerating structures to be accounted for. This has been found to be an important effect- the vertical emmitance growth of just 1-2% naively would give a luminosity loss of just a few perscent. However, due to the strong beam-beam effect, simulation with GUINEA-PIG have shown that the banana bunch effect can lead to a much larger degradation in luminosity, factors of 2-3 down on the nominal luminosity have been simulated [12]. In addition to a large drop in luminosity, the beam-beam dy-

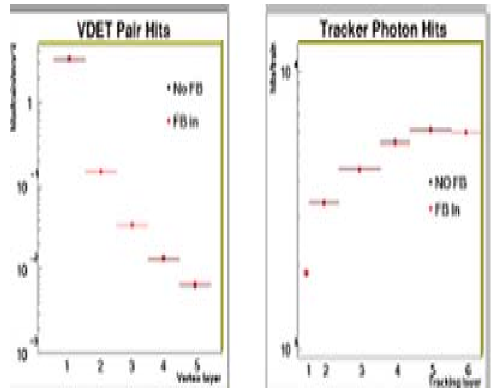

Figure 5: Background particle flux in the vertex (left) and central (right) trackers. The predominent backgrounds of charged particles in the vertex tracker and photons in the TPC are plotted for the IR with and without the feedback material included.

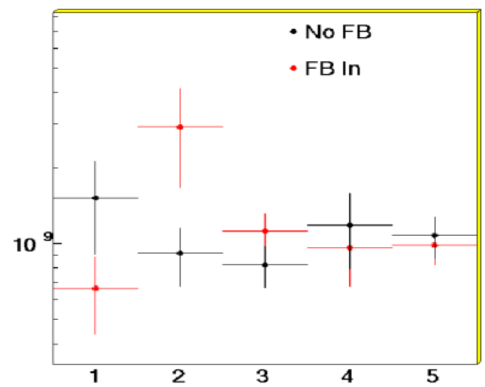

Figure 6: The neutron flux in the 5 layers of the vertex tracker with and without the feedback system included in the IR FLUKA99 model.

namics are also altered with the banana shaped bunches. Fig. 11 shows the expected luminosity of colliding 2 'banana' bunches with offsets in y and y' in the $[-2:2]\sigma_{y,y'}$ range. With gaussian beams, the optimal collision parameter is with a zero y, y' offset. With the banana bunches this changes, so that a non-zero offset is now optimal. The blue region shaded in fig. 11 shows where the feedback system will settle by default. The angle system still settles at zero, but the IP feedback system will settle with a small non-zero y offset which, desirably, is always slightly in the direction of optimal luminosity. To optimise the luminosity, it is required that the feedback system now have an additional luminosity feedback element which locates the optimal collision parameters in y and y'. Previous studies [6] have indicated that by using the inner layer of the LCAL system to count the coherent e^+e^- pairs created in the beam-beam interaction- a signal proportional to luminosity could be made available to the feedback system on a

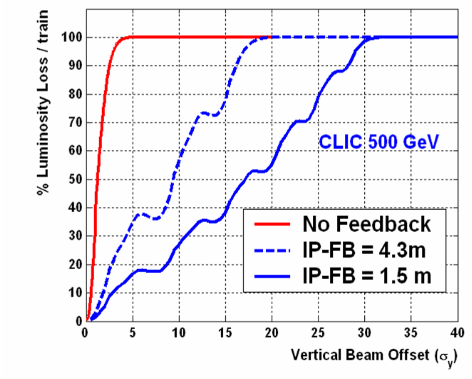

Figure 7: Simulation of luminosity loss at CLIC 500 GeV machine with varying initial beam offsets at the IP.

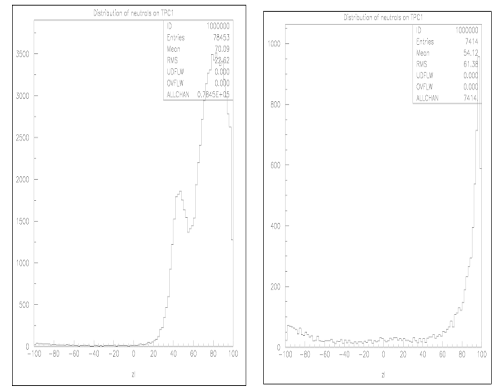

Figure 9: Distribution of background photon flux in the TPC for the 'near' and 'far' feedback configurations.

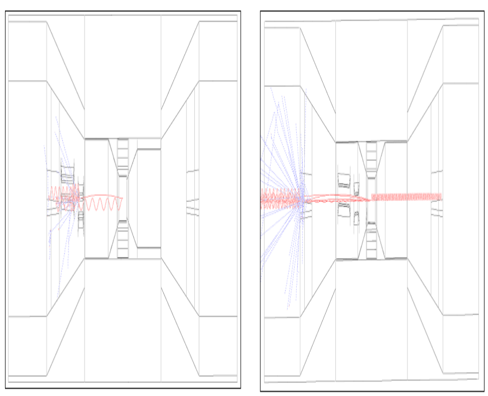

Figure 8: The CLIC IR geometry with 2 feedback configurations: 'near' (right) and 'far' (left).

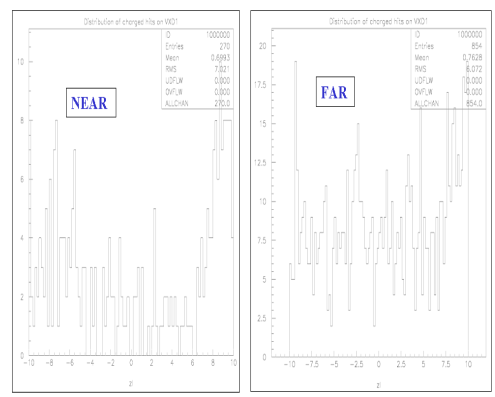

Figure 10: The charged background particle distribution in the vertex tracker for the 2 feedback configurations.

bunch by bunch basis.

A test run of 400 bunches was performed to show the operation of the feedback system in the presence of banana bunches. The parameters of this test run are:

PLACET: 400 bunches generated with a flat injection error of $+1\sigma_y$ in the vertical axis and a perfectly aligned lattice.

MERLIN: Random jitter on quads of 70nm RMS which represents an anticipated worse case scenario, also a 0.14% RMS energy jitter was added to the electron bunches to simulate their passage through the positron source undulator. There were 80,000 macro particles per bunch tracked through MERLIN and passed on to GUINEA-PIG.

Feedback: BPM resolutions of $2\mu m$ for the angle feedback and $5\mu m$ for the IP feedback system were assumed, and kicker errors of 0.1% RMS bunch-bunch were also assumed. An algorithm simulating the PI control system was tuned on 2 test bunches to provide stable rejection of noise at the $0.1\sigma_{y,y'}$ level.

Fig. 12 shows the feedback system bringing the beams into alignment over the first 100 bunches. Note the 10 bunch latency of the angle feedback system due to the kicker-BPM separation. The system is assumed to then settle down to it's 'zero' position after the first 100 bunches. The simulation then uses a lumi monitor signal as described above to optimise the collision parameters. This system was modeled by tracking the e^+e^- pairs generated by GUINEA-PIG through 3m of a 4T solenoid field and counting how many hit an annulus of radius between 1.2cm and 6.2cm. It was found to be optimal to integrate the lumi signal over 10 bunches to avoid statistical luminosity fluctuations. Fig. 13 shows the operation of the lumi feedback system in conjunction with the IP feedback system. One beam is ramped past the other in $0.1\sigma_y$ steps and the corresponding LCAL signal is found, the BPM input signal corresponding to this maximum signal is then passed to the PI feedback controller as a set-point allowing this optimal collsion parameter to be held.

The same procedure is applied to the angle system at the 200 bunch point. The luminosity as a function of bunch number in the test 400 bunch train is shown in fig. 14. The integrated luminosity for bunches 50-100 ($3.4120 \times$

$10^{34}cm^{-2}s^{-1}$) and 350-450 ($3.4502 \times 10^{34}cm^{-2}s^{-1}$) serves as a comparison of the performance of the system before and after the lumi feedback steps. A small improvement is shown for this example case. A program of producing greater statistics of simulation runs with realistic ground motion parameters is now underway to investigate the expected luminosity performance of the real TESLA accelerator.

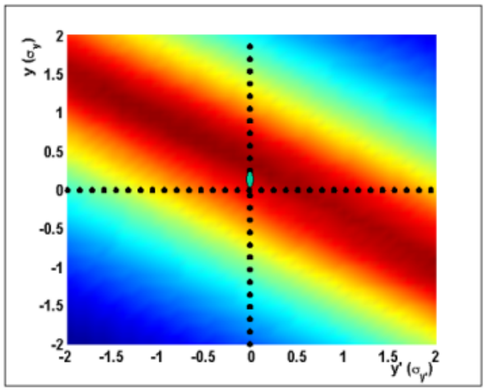

Figure 11: Luminosity of test 2 bunch banana bunch collision with varying Δ_y, y' offsets.

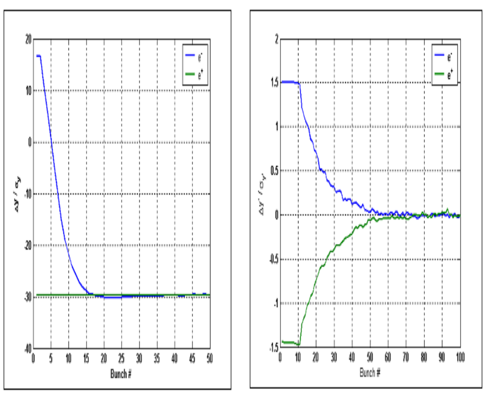

Figure 12: IP y and y' bunch positions at the IP for the first 100 bunches in the train with the fast feedback system operational.

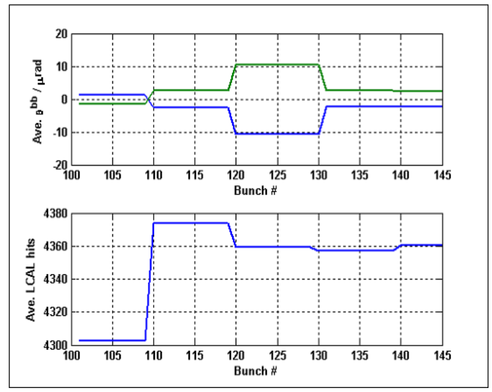

Figure 13: The beam-beam kick (proportional to IP FB BPM reading) for bunches 100-150 demonstrating the luminosity feedback system in operation. The bottom plot shows the luminosity monitor signal (e^+e^- pairs hitting LCAL). Note the integration over 10 bunches per signal.

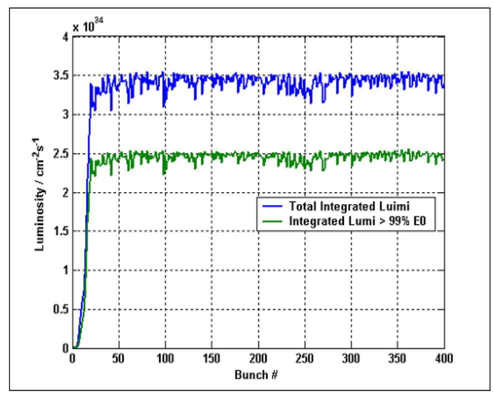

Figure 14: Luminosity (total integrated and integrated $> 99\%$ of E_0) along test 400 bunch train.

4 REFERENCES

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