DESIGN AND SIMULATION OF THE ILC INTRA-TRAIN ORBIT AND LUMINOSITY FEEDBACK SYSTEMS* **

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Abstract

To maintain luminosity to within a few percent of the design at the International Linear Collider (ILC), beam stability at the IP needs to be maintained at the sub-nanometre level. To achieve the beam stability required in the presence of ground motion, multiple feedback systems are required. The baseline design calls for a 5-Hz system to control the orbit in the Linac and Beam Delivery System (BDS) and an intra-train system to address high-frequency ground motion and mechanical disturbances which cause orbit distortions at the IP between pulses enough to completely destroy the luminosity. Details of the slower feedback systems have been addressed elsewhere [1]. The detailed design and simulation of the intra-train feedback systems are described here. This system controls the vertical position and angle at the IP such that luminosity is maximised. The system brings the beams into collision based on BPM-derived information from the initial bunches of the train. It then tunes the IP collision parameters (both position and angle) based on a fast (bunch-by-bunch) luminosity signal from the BeamCal. The system is implemented in fast digital FPGA logic, designed using Matlab's Simulink.

BUNCH-BUNCH FEEDBACK SYSTEMS LAYOUT AND DESCRIPTION

There are 4 independent bunch-bunch feedback/feedforward systems under study for the ILC which work in conjunction with a luminosity-signal based feedback system to optimise the collision parameters. The IP fast-feedback system is near to (~3m upstream of) the IP to correct for vertical and horizontal position offsets at the collision point itself. The IP-ANGLE fast-feedback system is non-local to the IP and is positioned at the entrance to the Final Focus System (FFS) about 1800m upstream of the IP, this corrects and optimises the orbit at the IP phase and thus the IP angular offset. There is one other possible fast-feedback system in the BDS at the exit of the LINAC section. There are no bunch-bunch feedback systems required in the LINAC itself, the system at the LINAC exit has multiple purposes. It is used as a train-straightener to remove any static component to the bunch train (such as introduced through long-range wakefield effects in the accelerating cavities). It also performs bunch-bunch scale feedback which removes any dynamic component to the static train-shape. As a consequence of feeding-back on the bunch-bunch timescale it also performs the task of allowing the independent running of the BDS and LINAC 5-Hz feedback systems without mutual interference. Finally, a bunch-bunch feed*forward* system is possible at the turn-around section coming out of the DR in the RTML section. This allows for some of the effect of bunch-bunch jitter imparted by the DR extraction kicker to be mitigated, potentially reducing the extremely tight tolerances on the kicker. This final system still needs to be studied in detail. Details of the other fast-feedback subsystems are laid out below. In addition to these beam-position based systems, a luminosity-based signal is required as an input to the fast-feedback algorithms. This has as its input an integrated signal of the number of electron-positron pairs hitting the first layer of the BeamCal which is maximal at maximum luminosity. This allows the optimal position and angle of the colliding beams to be found. This is non-zero due to the non-gaussian shape of the bunches which arises as a consequence of the short-range wakefield interactions in the accelerating cavities [4].

IP Fast-Feedback System

The IP fast-feedback system relies on the strong beam-beam interaction dynamics for its operation. For nm-scale offsets at the IP, beam-beam deflections of 10's to 100's of urad's are produced. The ideal dynamic operating range of the IP fast-feedback is given by the monotonically-increasing portion of these curves where the convergence rate of the feedback is highest. It is possible to extend well beyond this point where there is still signal, but the degenerate signal implies a penalty on the rate of feedback, which translates into luminosity performance degradation. The ideal operating range for the parameter sets; TESLA, USSC, Nominal, Low Q, Large Y, Low P, High Lum. (as defined in [3]) respectively then are approximately: 100, 120, 70, 30, 170, 80, 70 nm. These also represent the capture requirements of the 5-Hz feedback. Results [2] indicate that with ground motion alone, all these tolerances (apart from the Low Q case) can be met, but not with expected additional jitter from magnetic components. To rectify this, a much lower gain than that modelled could be used, however the effect on emittance growth needs to be studied.

The hardware for this system consists of a stripline or button BPM which is installed immediately downstream of the BeamCal and a stripline electrostatic kicker installed just upstream of FFS sextupole SD0. The design of the BPM requires a modest O(10um) resolution to control the IP beam position to the ~0.1σ level which roughly represents controlling the luminosity to better than the 2% level. One concern regarding the BPM under study is what derogatory effects, if any, are expected given the high-radiation background from the beam-beam interaction. Simulations [5] suggest that, even with the harshest of the parameter sets, the background levels

intercepted by the BPM are below an order-of-magnitude beneath what would expected to be a problem. These estimates are being checked by further simulation studies and with beam tests at ESA, SLAC.

For the kicker, the radiation environment behind SD0 is very much reduced compared to the BPM and isn't expected to pose a problem. The requirement of this location does place limitations on the maximum possible kick due to the beam having to pass through SD0 however. Studies have shown [6] that to keep the beam size growth due to the non-linear sextupole fields to a desirable level (beamsize growth < 2%), the maximum kick which can be delivered in the vertical plane is up to 70σ. This extends considerably beyond the desired dynamic range of this system as specified above. Using 70σ as the upper limit on the desired kick, the strips of the kicker can be up to 1m in length and need to deliver a kick of up to 150 nrad, requiring a maximum output from the driving amplifier of up to 600V/m for the 20 mrad crossing scheme and up to 3KV/m for the 2 mrad crossing scheme (where beam pipe aperture is much larger ~9cm) for a 250 GeV beam. The pulse width needs to cover the bunch train length of ~1ms.

IP-ANGLE Fast-Feedback System

This system consists of one or more consecutive stripline kickers at an $n\pi$ phase-advance from the IP and a BPM of the same type as the IP feedback BPM at a phase $\pi/2$ downstream from the kicker(s). The angle at the IP is corrected by zeroing the signal in the BPM using the kicker(s). As all the magnets forward of this location are at the same IP phase, no further angle jitter is introduced after the correction point. The latency of the feedback system due to the distance between the kicker and BPM is 4 bunches at the nominal bunch spacing.

The maximum conceivable expected kick requirement equating to about 5 $\sigma_{y'}$ (max ~ 500nrad deflection at kicker) can be achieved by three 1m length kickers with similar drive requirements as that for the IP feedback kicker. If the kicker is not placed precisely at the right phase, the feedback correction cross-couples slightly into position ruining the orthogonality between the two systems. If this happens due to poor placement, or through lattice errors, the effect can be reduced by either reducing the gain of the feedback or mitigated entirely by running the angle feedback on every-other pulse to the IP feedback. Each of these has a luminosity-penalty though, and such effects need to be considered as part of the global luminosity optimisation procedure. The required BPM resolution to control the IP angle at the 0.1σ level is about 2um, which has been shown to be achievable with stripline technology in the past, but requires careful design and operation.

LINAC-Exit Bunch-Bunch Feedback System

This system consists of a pair of kicker-BPM systems similar to that described above for the IP-ANGLE feedback case. Each pair operates at a different phase to null the orbit in both vertical degrees of freedom. The system is placed at the beginning of the BDS. The BPM has a higher resolution requirement compared with the systems described above to have sensitivity at the $0.1\sigma_{y,y'}$ level. With the current BDS optics, 100nm resolution is needed which requires the use of a cavity-BPM. It still needs to be satisfactorily demonstrated that a cavity-BPM can be used in multi-bunch mode for this purpose. The alternative is to redesign the optics at this place to give higher value beta-functions at the BPM and kicker locations such that a stripline BPM can be used. The required delivered voltage to the kicker to provide the same IP y and y' dynamic range as the other feedbacks is 100 times greater than that for the IP and IP-ANGLE feedback kickers for the current beta-functions.

Feedback Electronics

The feedback electronics itself is implemented in FPGA logic, based on a classical digital PI control feedback algorithm. Within the context of the FONT hardware tests at ATF, KEK [7], a commercially produced signal processing board purchased from Lyrtech Signal Processing was used to test the feedback algorithms needed for the ILC fast-feedback systems. Using an onboard Virtex-II Xilinx FPGA chip, the full algorithm was programmed using the System Generator blockset toolbox for Simulink. This allowed the actual feedback model used in the simulations of the system to be directly programmed and tested in hardware. The hardware performed as modelled, with a total throughput latency of ~190 ns proving to be useable for bunch-bunch feedback at the ILC.

SIMULATION TO ASSESS FAST-FEEDBACK PERFORMANCE

A more detailed description of the simulation environment and a more thorough description of the effects simulated to understand the fast-feedback system are shown in [8].

In order to fully understand the operation of the fast feedback system, the beam dynamics are simulated through from the start of the LINAC to the IP, including the beam-beam interaction. The LINAC is simulated using PLACET [10] with short- and long-range wakefield effects included in the simulation of the accelerating cavities. Up to 600 bunches are tracked with a beamline tuned with expected cavity, BPM and magnet offsets and tilts. A seed with the nominal design emittance is then chosen for further simulation. Ground motion model K [9] is used with an additional 100nm RMS noise added to LINAC magnets (effective component jitter on an inter-train timescale). The beam is tracked through the BDS (assumed to be initially perfectly tuned plus 0.2s of ground motion) using MatMERLIN [11] and GUINEA-PIG [12] which simulates the beam-beam interaction. The feedback systems themselves are modelled using Matlab and Simulink.

The simulation allows the feedback systems to cancel out the initial y, y' offsets, and then after 150 bunches (by which time effects due to the damping time of the HOMs in the accelerating cavities have died out) a 2-D scan in y-y' space is performed. Using the pairs signal from the
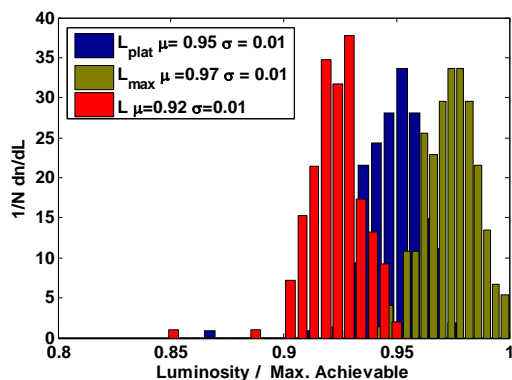

Figure 1: Results from 200-seed simulation run.

BeamCal, the optimum collision parameters are determined by first scanning the 8 points in y-y' space around the starting location. Then the search algorithm samples the 3 points beyond the point of highest luminosity found in the previous search step. This last procedure is then iterated until a peak is found. The y and y' co-ordinates corresponding to this luminosity peak are then programmed as set-points into the feedback controllers which maintain these collision parameters for the remaining duration of the bunch train. The final results depend upon the bunch shape which is distorted through short-range wakefield effects in the accelerating cavities, modelled in PLACET. It was found with previous multi-seed simulations that it is not sufficient to perform two 1-D scans (y then y') as that method did not always find the maximum Luminosity peak. There is typically ~20% improvement in luminosity after the 2D scan. Figure 1 shows the result of a 200 seed run. There are 3 histograms in this figure, the red histogram shows the luminosity as calculated by the sum of the ~600 bunches in the simulation corresponding to the first ~600 bunches in the train, with the last 50 bunches weighted to represent the remaining bunches in the train. This shows the overall performance of the system as modelled, and shows a mean luminosity loss, over the maximum achievable given a head-on collision between 2 gaussian beams, of 8 +/- 1 %. As a way of demonstrating where this loss comes from, the other two histograms shown are of the luminosities calculated as coming from the plateaux of the last 50 bunches (Lplat) and Lmax shows the luminosity derived from the top of the envelope of this region. Lplat then effectively shows the luminosity achieved if the initial feedback and optimisation were not necessary, Lmax further removes the bunch-bunch noise from the simulated component imperfections, magnified by the operation of the fast-feedback. The results show that, on average, 3% loss is irreducible- coming from luminosity losses due to lack of ability to completely compensate for the bunch shape plus emittance growth

due to component jitter. A further 2 % is lost due to high-frequency jitter sources which are magnified by the fast-feedback. This can be mitigated by reducing the gain of the feedback, perhaps even dynamically after the initial correction and optimisation period. This however depends on the straightness of the rest of the train, if there are still considerable dynamic components to remove it may be better leaving the gain high- this is an operational optimisation concern. The final 3 % effect is due to the time taken to initially correct and optimise collisions. This can be reduced in 3 main ways; by reducing the number of bunches to average each luminosity measurement over (5 in this simulation), by reducing the 'pixel' resolution of the 2-D scan, or by increasing the gain of the feedback. The limitation on all of these is the magnitude and characteristics of the bunch-bunch jitter, making this also an operational optimisation concern.

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