Chapter 9

Summary and Conclusions

9.1 Summary

The development of a feedback system for y position offset correction at the ILC interaction point has been successful both in test beams demonstrating the position correction and in electromagnetic background tests. In order to test the robustness of the system in backgrounds, ILC backgrounds were studied and reproduced using different methods at the ESA facility at SLAC. The response of a stripline to the backgrounds was analysed.

9.1.1 Feedback tests of the full FONT system

The feedback system for position correction at the IP has been tested at NLCTA and ATF and the ability to correct offsets on the required timescales has been demonstrated. The development of a digital component to the feedback system is ongoing. The tests performed to date and their results are summarised in table 9.1.

The initial FONT experiments (FONT1, section 2.1, and FONT2, section 2.2) were at NLCTA used a bunch train of 2000 bunches, lasting 177 ns. To demonstrate the full feedback system of not only correcting beam offsets but also retaining that correction after a latency period, the latency needed to be under 80 ns. This was achieved (FONT1 feedback latency was 70 ns and FONT2 feedback latency was 57 ns). A correction for position offsets given to the beam was observed when feedback was on and it was retained over the full bunchtrain with the delay loop on (figure 2.2 and figure 2.3) The addition of beam flattening using an AWG plus charge normalisation on the same pulse made FONT2 a remarkable success with a 14:1 correction of the beam.

FONT3 moved the experiment to ATF and used a much shorted bunch train of 20 bunches lasting 56 ns. This required a much lower latency, ∼20 ns, to demonstrate the full feedback system. It was, however, a beam with low position jitter and a flat profile in both charge and position (when well-tuned) making it possible to achieve better corrections. Plus, the beam energy of ∼1 GeV meant that demonstrating micron-level correction at ATF corresponded to nanometre-level correction at ∼1 TeV with the same feedback system.

	FONT1	FONT2	FONT3	FONT4
Components	• 1 button BPM • Analogue Processor • Charge normalisation with one pulse delay using AWG • Valve Amplifier	• 3 button BPMs (one feedback and two witness BPMs) • Analogue Processor • Charge normalisation using logarithmic amplifiers • AWG used as a beam flattener • Solid-state amplifier	• 3 stripline BPMs (one feedback and two witness BPMs) • Analogue Processor • No charge normalisation • Solid-state amplifier	• 3 stripline BPMs (one feedback and two witness BPMs) • Analogue Processor • Digital processor (able to implement charge normalisation) • Solid-state amplifier
Test Beam	NLCTA	NLCTA	ATF	ATF
Beam Energy (GeV)	0.065	0.065	1.28	1.28
Latency (ns)	70	57	24	140
Resolution (μm)	-	10.9	12.2 single bunch, 2.3 multibunch	7.9
Correction Ratio	10:1	14:1	23:1	7:1

Table 9.1: A summary of FONT test beam results from NLCTA and ATF.

Feedback was successfully demonstrated (as shown in figure 2.9) though it appeared from subsequent simulations that the amplifier was non-linear and the delay loop length was too short. However, with a 23:1 correction of the beam, 2.3 μm resolution and a latency of 24 ns, it was undoubtedly a great achievement.

FONT4 continued at ATF with a train of three bunches separated by between 140 and 154 ns. To demonstrate the full feedback system, the latency of the system had to be $\sim$140 ns. As the bunch spacing at the ILC is, at the smallest, 153.8 ns, this also met the ideal conditions for being able to do bunch-to-bunch feedback at the ILC. With the comparatively long time available between bunches, the feedback system was made more powerful by introducing digital processing. The analogue processor provided difference and sum signals that could be sampled by an ADC. The digital processor, an FPGA, was used with two methods: one was to apply a gain and the other to charge normalise. In both cases, correction of the second and third bunch was demonstrated within a latency of $\sim$140 ns.

The future of FONT4 development is two-fold. There is a drive to improve the front-end analogue processor to micron resolution. The dependence on an external reference (the 714 MHz local oscillator) is a potential source of resolution degradation as the phase of the signal drifts with time. A correlation with temperature has been found and there are plans to improve its stability. However, a processing scheme that is independent of an external reference could be necessary.

The main development however is with the FPGA logic as FONT exploits its power. Algorithms in the future can be produced to remove static bunch train profiles, apply variable gains and involve other inputs.

9.1.2 Background tests of a stripline BPM

A module was built that could be inserted into the beamline at ESA, replicating the important materials, lengths and inner radii of the ILC IR (as described in chapter 4). This meant that no matter how different the beam at ESA from the pair backgrounds at ILC, the background distributions at the FONT module striplines were close to the background distributions at the ILC IP BPM striplines (figures 5.2, 6.10 and 7.6 show the energy distribution of particle hits on the striplines and tables 5.2 and 6.6 show the percentages of hits that are electrons, positrons and photons).

Method A (chapter 5) was developed and then put into effect during July 2006 and March 2007. It used a low charge electron beam at ESA to scan the front face of the FONT module (the low-Z mask), recording the signals from the striplines at different locations. The positions at the front face of the module illuminated by the beam were summed together using weightings from simulations of the 14 mrad crossing angle ILC case (with worst case pair backgrounds from Scheme 14) such that it approximated the pairs number density at the low-Z mask (z = 285 cm). The stripline signals associated with these positions in Method A were likewise summed together producing likely stripline signals for the IP feedback BPM as shown in figure 5.16. The prediction for ILC indicated that the effect on the striplines of the beam-beam pair backgrounds and the secondary backgrounds produced an error in

position measurement of less than 60 nm.

Method B (chapter 6) was developed and then put into effect in March 2007. It used a thin radiator (up to 5% X_0 aluminium) to create a halo of scattered electrons (plus some photons and positrons) around the main beam. The halo interacted with the material of the module (the low-Z and the BeamCal) to produce secondary backgrounds at the location of the stripline BPM. No difference was seen in the stripline signals with these secondary backgrounds present. The experimental errors allow an upper limit to be placed on the size of the effect on the striplines from secondary backgrounds. Using a scaling factor based on the particle hits on the striplines weighted by the cross-section of the particle interaction, the upper limit for the effect of the secondary backgrounds at the ILC was found to be 8.6 nm (95% confidence level). The processed position signals were also investigated but the results were dominated by drift possibly from the reference signal used in the processor to downmix the stripline signal. The processed results were, however, able to confirm that any effect will be below a micron.

Method C (chapter 7) was developed but not put into effect due to the results of the previous two methods, which were easier to implement and produced worse backgrounds. It would have been able to produce, at ESA, a secondary beam of electrons that matched the number density and energy density of the ILC pairs at the location of the low-Z mask. It could exceed the density at the ILC by a factor of forty. A thick radiator (42.7% X_0 beryllium) located in the beam switchyard would have produced primary backgrounds in a broad range of energies. The A-line could be tuned to transport one particular momenta (with a 2% momentum spread) to ESA with the spatial distribution of the transported spray beam set by the collimators in the A-line (mainly the entrance to the D10 dump). The results are expected to be similar to those of Method A but for an entirely illuminated low-Z mask (removing the need to sum the results of illuminated spots).

The observation of shapes such as those shown in the results for Method A (figures 5.11 and 5.12) that could be qualitatively explained through signals caused by charge particle hits and emissions along the length of the stripline, spurred on the development of tools based on GEANT3 simulations that could predict stripline signals in any background environment. The method created for constructing the expected stripline signals (as described in section 8.1) was tested and calibrated against the Method A signals. It was found to be able to recreate the stripline signal shapes that were observed with only minor tweaks being necessary. It was applied to the results of a GEANT3 ILC simulation (for 14 mrad crossing angle, scheme 14 accelerator parameter set and an untuned anti-DID). It predicted a position error below 13 nm.

These methods and results are summarised in table 9.2.

9.2 Outlook

The FONT prototype R&D is ongoing with successful demonstrations of feedback correcting position offsets at NLCTA (FONT1 and FONT2) and ATF (FONT3 and the continuing

	Method A	Method B	Method C	Simulation
Method	Target low charge beam at low-Z mask to create secondary backgrounds.	Use a thin radiator to create a halo around the beam that interacts with the module to create secondary backgrounds.	Use a thick radiator to create a wide spray beam that can be transported to ESA. This interacts with the module to create secondary backgrounds.	Simulations only.
Components	FONT Module. Low beam charge instrumentation.	FONT module. Aluminium foils.	FONT module. Beryllium target. Very low beam charge instrumentation.	GUINEA-PIG and GEANT3 simulations.
Times worse than ILC	~ 800	990 (striplines) 28 (processors)	40	-
Analysis	Matching number density of charged particles hitting the plane at the low-Z position in Method A to the ILC 14 mrad crossing angle IR (according to simulation).	Comparing the number of particle hits on the striplines in Method B to the ILC 14 mrad crossing angle IR (according to simulation) weighted by cross-section of the particle interaction.	By matching number density and energy density, a direct result is achieved such that Method C stripline signals are good approximations already to ILC stripline signals.	Analytical consideration of what signals are caused and how using time of flight and position data from GEANT3 simulations.
Prediction for position error on ILC IP BPM	< 60 nm	< 8.6 nm	-	< 13 nm

Table 9.2: A summary of EM background methods and results for stripline tests.

development of FONT4). The main concerns currently are to improve the resolution of the analogue front-end to the processor and to demonstrate the power of the FPGA in producing good corrections even with bunch trains with irregular charge or position profiles.

The placement of the IP feedback BPM in the proposed location of the IR, downstream of the BeamCal, is in an environment with high secondary backgrounds but the results for estimating the errors such backgrounds would create indicate that this is unlikely to be a concern. The primary and secondary backgrounds from the beam-beam interaction and the subsequent interactions of electron-positron pairs with IR material, will not decrease the sensitivity of the micron resolution IP feedback BPM in measuring position. Indeed, even for the worse case with a 1 TeV centre of mass energy and high luminosity accelerator parameter set plus an untuned anti-DID, the effect appears to be below 8.6 nm.

Although these studies into the stripline signals due to backgrounds are complete, further investigation into them could be achieved using a stripline with the downstream end terminated through 50 Ω (the characteristic impedance of the stripline) instead of being shorted (as shown in figure 1.15). Here, the only signal off the downstream end of the stripline would be the signal from impacting and emitted charges since the "normal" stripline response is mainly cancelled from the signal as the image charge hops from the stripline to the beampipe wall (as described in section 1.5.2). Some "normal" stripline response would appear on the downstream end of the stripline as termination is rarely perfect, the velocities of the beam and signal in the striplines are not an exact match and there are often discontinuities in the stripline [39]. However, this could help confirm and perfect the understanding of the emission and impaction signals as described in chapter 8 if better understanding is required. In these studies, the small predicted effect on the striplines due to ILC pair backgrounds does not motivate further investigation.

The simulations in chapter 8 could also be improved with a full electromagnetic simulation of the striplines in charged particle backgrounds. There does not appear to be any existing electromagnetic simulation software that models both fields and the addition and subtraction of charges [81], so such a simulation would require more work than the method used in this thesis. Again, there is no reason to suspect this will change the result of the predictions in this thesis by much, if at all, and since the effect on the striplines is predicted to be so small, there is no motivation to investigate it further.

The performance of the stripline BPM over time was not investigated. The difference between the mechanical and the electrical centres of a stripline BPM can change by the order of microns over a time period of up to one week [115]. Frequent calibration is therefore necessary. The background studies could be performed over long periods of time in case these have an effect on the frequency of calibration. They may also be some other drift of position reading with time in the processor that needs to be investigated, possibly with temperature.

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