



Detector development for Polarimetry

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Abstract

The precisions of the polarimeters planned to be implemented at the International Linear Collider are currently limited by the stability Photo-Multiplier tubes. Current calibration methods (used to correct for PMT non-linearity) rely heavily on UV LED scans - devices also prone to instability - thus it would be advantageous to have a secondary side detection method, which is not necessarily limited to small amounts of light, to monitor this LED stability. PIN diodes can offer such a tool. We explore the possibility of using PIN diodes as photodetectors both directly at the ILC, or as a side calibration tool for PMTs. It is found that such stability can be measured to within a fluctuation of 10% (after extensive repeats), and this is currently only limited by the precision of the charge integrators available, and as such, will only be reduced.

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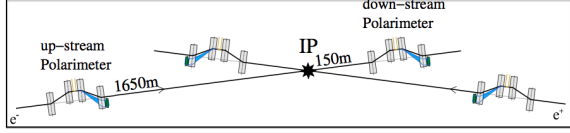


Figure 1. *Planned positions of the four polarimeters for use at the ILC. Note the separate devices for both lepton streams, either side of the IP. All follow a similar design involving a magnetic chicane (figure 2), and an array of Cerenkov detectors and PMTs.*

1 Introduction.

The International Linear Collider (ILC) is planned to be built at the start of the next decade. The nature of linear colliders having much cleaner events (due to reduced colour noise) has normally meant linear colliders are used for precision measurements, often of discoveries made by older hadron colliders at higher energies (due to the heavier colliding particles). Such measurements might include the spin of the latest boson resonance at 126GeV, recently discovered at the LHC. The ILC is no exception to this pattern, and again, precision is the highest priority.

Specifically, the ILC will have the capability to set (to within 10% precision) the polarisation (spin) of the colliding leptons. The success of this feature could be reconstructed computationally weeks or months after an event, or alternatively, the polarisation could be measured in real time with the use of polarimeters on each beam, and either side of the interaction point (IP). Such a set up is shown in figure 1. The design of each polarimeter is similar, and figure 2 shows an example of the magnetic chicane planned for use upstream. Here, dipoles 1 and 2 displace the lepton beam from the beam axis, which is then passed through a laser. A small fraction of particles ($\mathcal{O}(10^3)$) will interact with the laser via Compton scattering, and as such, will have an angular distribution that is dependant on the energy (hence polarisation) of the lepton beam. On passing through dipoles 3 and 4, this (small) angular distribution is converted to a spatial distribution, and directed onto an array of Cerenkov detectors to measure the position of the scattered particles. Particles that did not interact with the laser are displaced back to the beam axis, undisturbed. The Cerenkov light emitted from the Cerenkov material is so small that PMTs offer the only realistic sensitivity.

The desired precision of these polarisation measurements (as not to hinder other calculations) is 0.25%

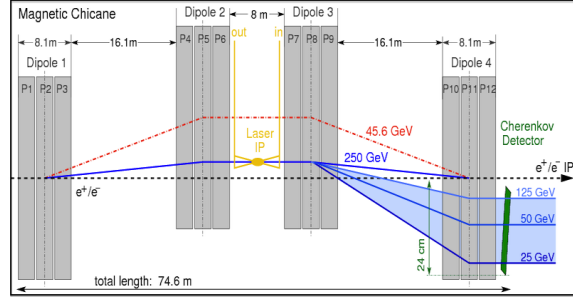


Figure 2. *Schematic design of the upstream chicane. A small part of the displaced beam interacts with the laser via Compton scattering, and is spread out via dipole 3 and 4 into a spatial distribution, onto an array of Cerenkov detectors with PMTs. The 2 contours of beam lines show the range of expected beam energies.*

(25 per mil), and the limitation from such precision is currently dominated by the stability of the PMTs. Ongoing calibration methods involve scans of a UV LED pulses at varying intensities, and this is to correct for the PMTs small non linearity. One source of instability in this calibration might involve that of the UV LED itself - thus there is motivation to develop a secondary independent measurement of this LED along side the current calibration setup. This has the advantage of not necessarily being limited to small amounts of light (unlike that required for a PMT). Such a setup might be that imagined in figure 3. Here, a secondary circuit is placed alongside the already existing LED to PMT setup, which involves a PIN diode. This diode would be required to receive the majority of the light emitted from the UV LED, which is indeed possible, as filters are already being used during the calibration. Wavelength lengthening fibre optics may also be used as PIN diodes have limited quantum efficiency in the UV band (see below).

This report considers the possibility of a secondary stability measurement involving PIN diodes. Further sections include the functionality of PIN diodes, an extended results section, and an outlook for further developments of the PMT calibration techniques. It also covers the work conducted over the summer 2012, and as such, sometimes suffers a chronological story telling style. Unless otherwise stated, errors bars are 1σ . Approximately 1/3 of this project was computationally based, modifying the existing classes for logging capability, which is not covered in this report.

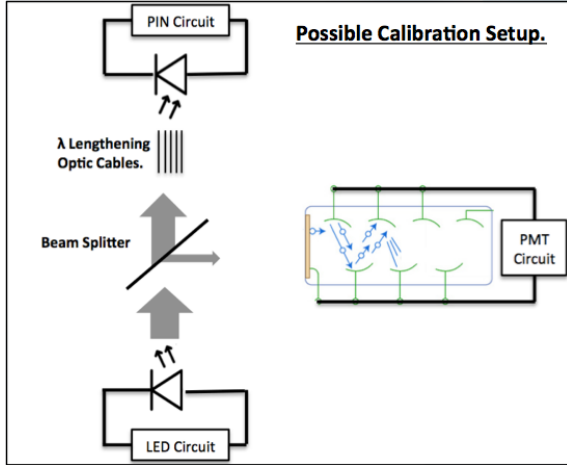


Figure 3. Possible experimental setup to verify LED stability. The bulk of the light passes through the beam-splitter to the PIN, as this is far less sensitive compared to a PMT.

2 Functionality of PIN Diodes.

2.1 Physics of PINs.

A PIN diode is effectively a p-n junction, with a middle lightly doped (almost) intrinsic semiconductor middle layer (p-intrinsic-n, thus PIN) [1]. This is shown in figure 4. This setup has the useful feature of having a wider space charge zone, thus increasing the amount of flux incident on the diode, when compared to a conventional photodiode.

In an analogous way to a p-n junction, there exists a band gap in the diode, and thus an incident photon (with sufficient energy) can create an electron hole pair. Due to the electric field between the p and n side (caused by concentration differences), charges accumulate at either side of the diode. The PIN is now effectively a capacitor, and as such, has a set recovery time for the electron-hole pair to recombine. This has the useful property of any induced current being proportional to the incident flux (as the number of generated charge pairs is certainly far below Avagadro's number, and no saturation effects are seen). The user also has the option of applying a reverse bias, and this has the advantage of lowering this recovery time of the diode [1].

2.2 PIN Diode criteria for polarimetry.

PINs come in many designs for specific roles. In polarimetry, we seek three specific criteria:

- UV sensitivity - PIN diodes are typically not sensitive in the UV range, and behave more efficiently in the visible band. This is shown in

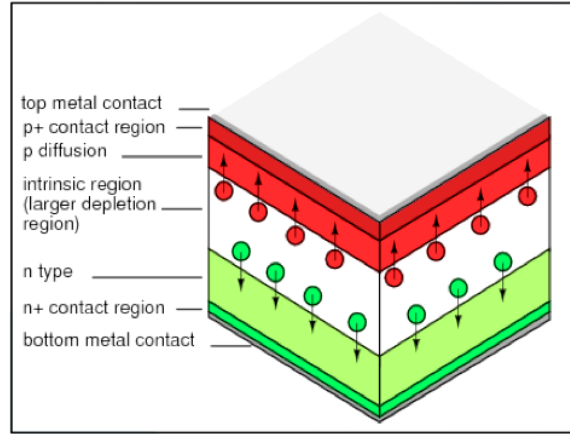


Figure 4. Diagram of a typical PIN diode. Here exists an electric E field from p to n (top to bottom), and hence a current flows in this direction (opposite direction to the charge carriers themselves).

figure 5, which shows a typical efficiency plot vs wavelength λ . This inefficiency is due to many reasons, one including the glass window of the diode filtering some of the UV light (which can be modified).

- Speed - PMTs can contently operate at MHz rates, unlike PINs, which typically work at kHz rates; thus to be a useful tool, the rates must be somewhat comparable.
- Effective Area - This is useful to maximise the signal generated by the PIN, but can be detrimental to the speed of the diode (similar to a capacitor) - hence this is secondary concern.

After contacting the company Hamamatsu - and upon learning the plans for the ILC - two appropriate diodes readily became available for testing. These include:

- S1074 "Fish-eye diode" - named due to an extra lens on its surface, increasing the effective area of the diode without the expense of increased recovery time. This diode operates at $\mathcal{O}(100MHz)$ rates, as well as having relatively decent efficiency in the UV band.
- S9055 "SPIN diode" - named "Speedy PIN", then "Surviving PIN", then "Suddenly-dead PIN". This PIN operates (/operated) at GHz rates, and coincidentally was also the best performing in the UV. The SPIN diode also has relatively decent area.

It is also useful to introduce a third diode here, used as an emergency replacement, the "Conrad BPW34", which has a very large area at severe expense to speed (operating at kHz rates).

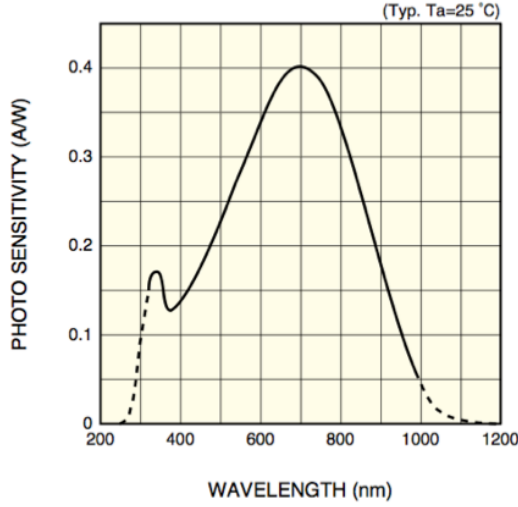


Figure 5. Plot of actual weight A/W (equivalent to efficiency) vs wavelength λ for a typical PIN diode.

2.3 Possible circuit setups.

From data sheets, and considerations of photon energies with bang gaps, we can deduce that the signal to noise ratio when using a charge integrator is $\mathcal{O}(10)$. As such, filtering and amplification are likely to be required. Several companies all recommend similar circuit setups, and the two most popular are shown in figure 6. The top circuit involves a reverse bias voltage across the PIN with an RC filter to remove noise below a set frequency (tuned by the values of R and C - the cutoff frequency being $f_{cutoff} = 1/RC$ [2]). The bottom circuit involves a deadaly operational amplifier, whose amplification factor is set by the value of the feedback resistor. The signal from this circuit (unlike the former) is converted from a current to a voltage. In both cases of course, the act of adding more components automatically adds further noise.

2.4 Preliminary work on Normal Diodes.

As the functionality of a PIN diode is analogous to that of a conventional pn diode, some work was conducted for familiarity with diode behaviour [3]. Specifically, as an aim of this project is to find a set up maximising signal involving a choice of reverse bias, it is useful to know how the current through a diode varies with bias voltage. This is also useful for testing experimental setups, as this $I(V_{Bias})$ is already well known. The results are shown for two standard diodes in figure 7. When reversed biased (AKA Photoconductive mode) we see a steep increase in the absolute value of the current, and

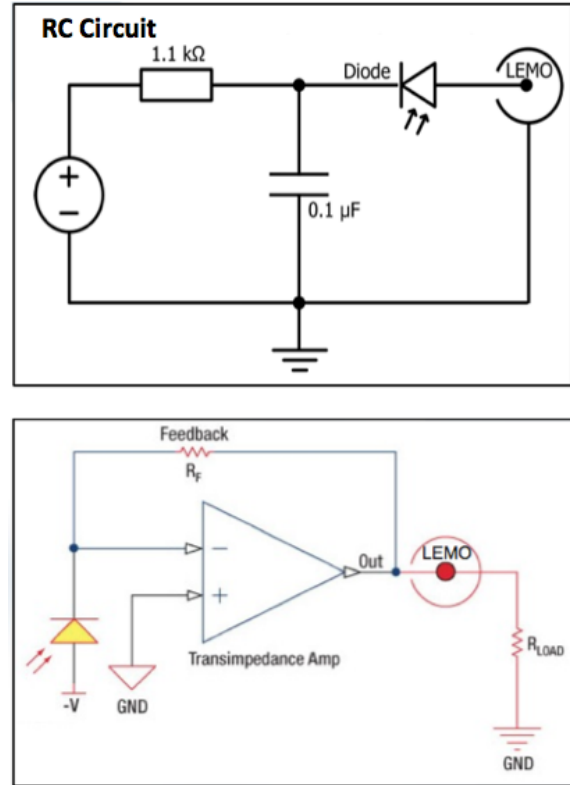


Figure 6. Circuit diagrams of the two suggested setups from numerous companies. The RC circuit involves an RC filter to remove unwanted frequencies below a certain f_{cutoff} , where as the transimpedance amplifier circuit amplifies the signal (as well as converting a current to a voltage) at the expense of further noise.

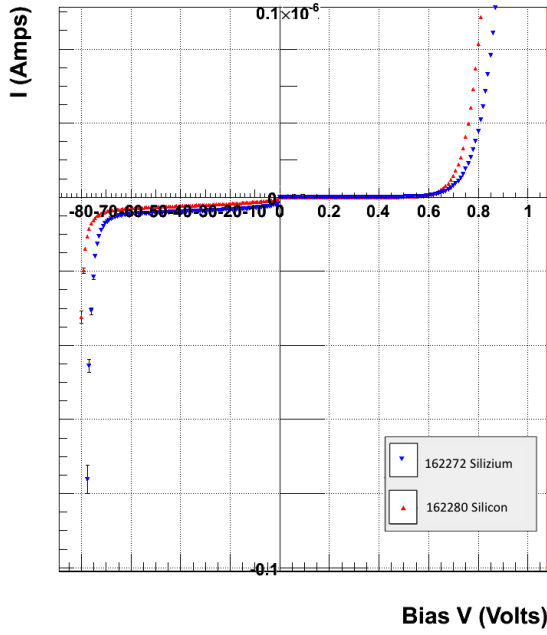


Figure 7. The famous $I(V_{Bias})$ curves for two standard diodes, used as a test of circuitry, and to gain familiarity of typical diode behaviour. Note that each axis is scaled differently, and the turn about the origin is actually smooth.

this can lead to a break down of the diode. The induced current does add to the photocurrent, and this can increase noise, however in most cases this extra current is much smaller than noise from other circuit components (such as a load resistor required for voltage measurements, or an RC filter). When forward biased (AKA Photovoltaic mode), the diode begins to allow current to pass, and this is a disadvantage for photodetection as this leads to difficulties in disentangling signal current from induced current.

3 Results.

Many separate results are presented, including:

- LED Time Dependence.
- Verification of PIN linearity.
- SNR vs Bias Voltage.
- Modification to pulses.
- Measuring LED stabilities.

All are presented as each was important in gaining experience with PIN diodes, and might be useful for other unfamiliar parties.

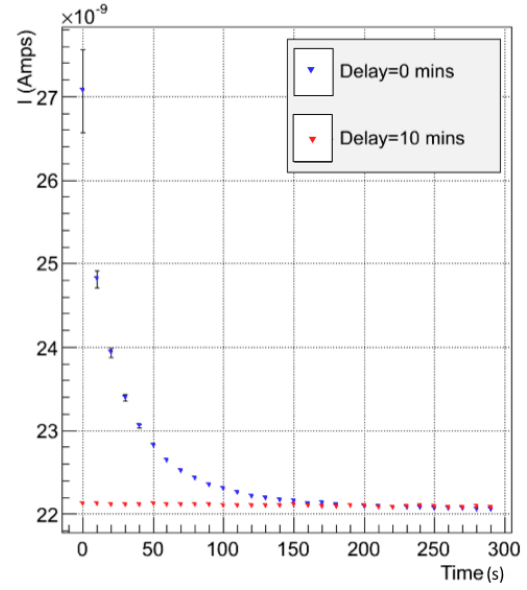


Figure 8. Plot to show the time dependance of the red LED. As such, all investigations are delayed by at least ten mins.

3.1 LED Time Dependence.

Upon connecting a simple circuit to measure induced current (in the absence of other components), a decreasing time dependance was noticed when using a red LED as a source, and not seen when using a lamp. To quantify this effect, the induced current was measured over a period of 5 mins, and repeated after a further 10 mins. The results are shown in figure 8. An "exponential-like" decay can be seen, and can be fitted with the following exponential:

$$I(t) = (-1.965 \pm 0.002) \exp(-2.71 \pm 0.02) \text{ Amps} \quad (1)$$

Solving for a time (from $t=0$, when the LED begins to emit light) such that any variation in $I(t)$ over the length of an experiment is an order of magnitude below the random noise, we find all investigations to be delayed by at least ten mins.

3.2 Verification of PIN linearity.

To test the linearity of the PIN diodes, the distance between the source and PIN was varied, and one would expect the signal to drop via the inverse square law. Assuming the induced photocurrent $I \propto F$, and given the known relation of the distance r square law $F \propto 1/r^2$, one would of course expect $I \propto 1/r^2$. The results of this investigation are shown in figure 9.

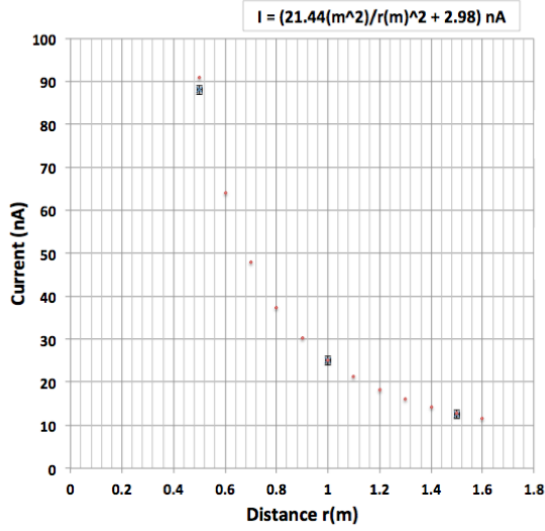


Figure 9. Plot to show the current dependence on distance from one source of light. Note that the small data points show the fitted function (hence without error). The constant is added to account for background reflections and other luminous devices present in the experiment setup.

It transpires a much better fit is found when accounting for some constant due to background light from other devices and reflections. Note that there is no justified reason to add the constant in the first axiom by conservation of current.

3.3 SNR vs Bias Voltage.

A point of interest is the effect of Bias Voltage on the signal and noise ratios, as the Bias Voltage will be varied further later to quicken the PINs, and as such, we want to the best balance. Using a constant source (in time), we expect the only source of noise to be from thermal random noise, and a smaller dark current I_d from the PIN (data sheets suggest this to be well below thermal noise). Using the SPIN diode, which is designed to be self thermal regulating (not to heat up), the bias voltage was varied, and the SNR ratios measured. The results are shown in figure 10. The noise was taken to be the standard deviation of a large number of repeats, as defined by [4].

Note that initially further stability issues were noticed in the signals, which was not accounted for by the random sigma, but upon randomising the time delay between measurements, these vanished. It is expected that some time dependent noise, whose time period is of order the time taken to record

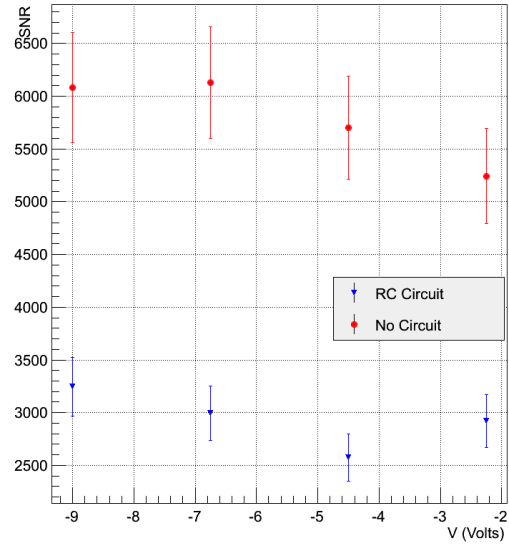


Figure 10. Signal to Noise vs Reverse Bias across the SPIN diode. No obvious trend seen, as expected.

several measurements for a fixed voltage (such as the 50Hz power source) are responsible for this instability - indeed a peak is present in the Fourier Transform when the PIN is measured with a scope.

It can be seen that there is no significant variation in SNR with bias voltage. It should be also be noted that the dark current was measured to $\mathcal{O}(pA)$ compared to signal noise of $\mathcal{O}(nA)$, and so the extra current from the reverse bias has not had a significant effect. To multimeter precision was also $\mathcal{O}(pA)$, and so errors seen are dominated by randoms and not systematics.

3.4 Modification to Pulses.

To quantify the effect of reverse bias on speed, the PIN is now connected to a scope, and the red LED pulsed via an signal generator. This also allows for LED stability measurements to be made - effectively an aim of this project. Figure 11 shows the recorded waveforms for various reverse bias voltages. As expected, the pulses are slow in comparison to a PMT, with a recovery time of 0.001s, giving a frequency of 1kHz (3 orders of magnitude less than a typical PMT). The waveforms are visibly shorter, and this effect is quantified below.

One method of quantifying the effect of varying reverse bias V_B would be to define some piece (or gate) of time t_{gate} , which is less than the recovery

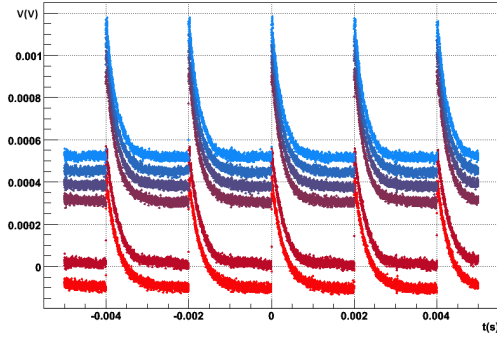


Figure 11. Waveform of the Conrad PIN diode, viewed via a scope (hence signal is now a voltage measured across a load resistor, which add's further noise).

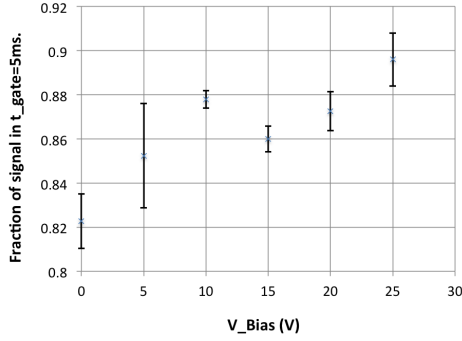


Figure 12. Fractional area of signal pulse inside a gate of 5ms, vs bBias Voltage. Given the thinning of the pulses with V_B , one would expect for this fraction to increase with V_B , as observed.

time of the diode, and begins at start of the decay. Here, we consider the fractional integral, i.e. $Area_{Gate}/Area_{Pulse}$. If the diode is increasing in speed, this value would be expected to increase with V_B . This method is useful as similar calculations involving gates and fractions of signals are needed later. This is shown in figure 12, and the expected increase is seen - the effect of reverse bias of up to 30V brings an extra 10% of the signal into the gate

Alternatively, the pulse could be fitted with an exponential (as expected by probability of recombination considerations), and one could consider the e-folding time (time for the signal to drop by a factor of e). For a signal $I(t) = Ae^{-Bt}$, it can easily be shown $t_{e,fold} = 1/B$ (effectively an inverse measure of steepness). These values are shown in figure 13. By considering both plots, it can be seen that beyond a reverse bias of $\approx 20V$ there is no large

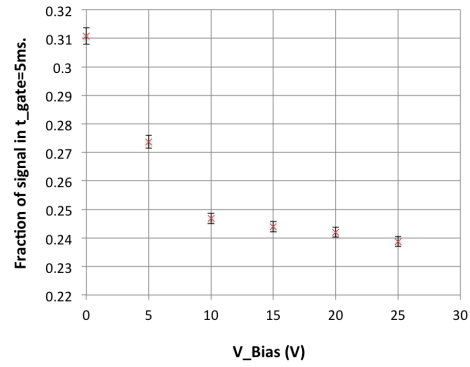


Figure 13. E folding time of the contours shown above. For increasing speed, we expect decreasing $t_{e,fold}$, as observed.

change in the speed of the diode, and so to avoid risk, from here the reverse bias is fixed at $V_B = 20V$.

3.5 Measuring LED Stability.

Stability measurements of an LED can be with some modifications to the experimental setup. A charge integrator can be used to calculate the total charge in some t_{gate} , which can be defined. Since the size of the waveform is not necessarily constant for all measurements, it is useful to set t_{gate} such that it always contains the whole signal (at least until the tail becomes indistinguishable from noise). One disadvantage of this setup is the need for a pedestal current I_{per} for safety of the QDC, and I_{ped} introduces further (albeit small) instability, increasing the error measured signals. This effect is shown quantitatively in figure 14, where for increasing LED intensity (equivalent to voltage from the signal generator), the signal to noise ratio is now $\mathcal{O}(10)$ compared to the $\mathcal{O}(10^3)$ previously). Note that the noise is taken to be the standard deviation of several repeats of many measurements, and seen to be constant, implying a thin distribution of signal charge compared to the pedestal charge. This also explains the trend seen in this figure, where the increase is due to increased intensity of the LED, and this is not expected to be linear due to varying the voltage (note that linearity of the PIN diode has already been verified).

The distributions of measured charges for these various LED intensities (set by the voltage from the signal generator) are shown in figure 15. Note that a linear relationship between voltage and charge is not expected. An instability would be noticed as a perturbation of the pedestal distribution shape;

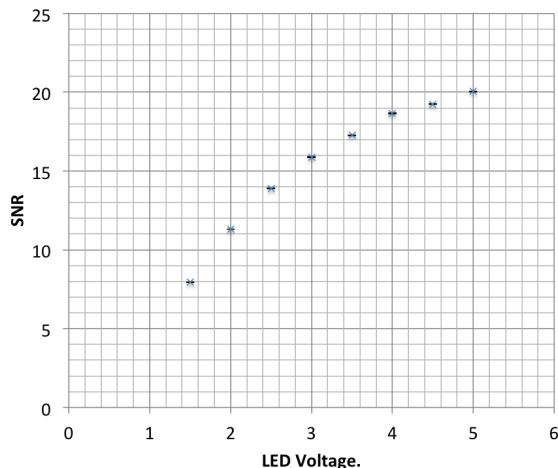


Figure 14. *SNR vs LED voltage. Note the drop in SNR by factor 100 due to using the pulsing QDC setup.*

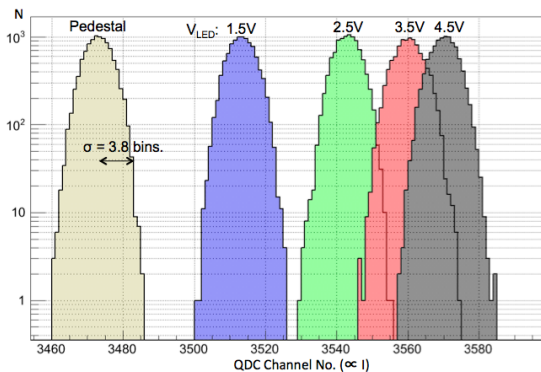


Figure 15. *Charge distributions recorded by the QDC for varying LED intensities (set by the voltage from the signal generator). Linear spacing is not expected.*

however this is severely limited by the precision of the charge measurement from the QDC (an instability would need to be at least the width of the QDC bin - $\mathcal{O}(10\% \text{Signal})$). A further requirement would also be extensive repeats, so to reduce the gaussian \sqrt{N} random error, as to notice a significant perturbation to the distribution.

4 Outlook.

The current instabilities seen in the calibration of the PMT's (planned for ILC polarimetry) are significantly greater than $\mathcal{O}(10\% \text{Signal})$, and as such, this system is a viable monitor. However, smaller instabilities are currently undetectable. One modification to increase the precision of the current setup might involve the addition of a stable "shifting cur-

rent", such that all measurements are shifted by half a bin. This effectively increases the precision of the measurements by a factor of 2, and can be varied via the size of the shift for further increases in precision (depending on the stability and provision of the shifting current source). The LED signal itself can be easily increased via the use of Fibre-optic cables for wavelength lengthening (gaining an extra factor of 2), and with the use of filters and amplifiers. These increases in signal will be required when using a faster PIN (such as the SPIN diode) due to the drop in SNR. Alternatively, a more precise integrator is required.

5 Conclusions.

A stability detection method involving PIN diodes was developed to monitor the current calibration system of the PMTs planned for use at the ILC. Instabilities which are currently seen in calibrations would be noticed if the instability came solely from the LED. Modifications are required (but still possible) to increase the precision of the stability measurements for smaller variations, and might involve the use of some variable shifting current, or a more precise current integrator. The current signal to noise ratio for the detection method is $\mathcal{O}(10)$ for the slower CONRAD diode, and expected to decrease when using a faster diode. However, this drop can be salvaged with the introduction of amplifiers and filters. Other conclusions involve the understand that DESY is a fab place, and there is hope to return to continue this work in Germany, and (most likely) Japan. DESY SummerSchool rocks! Many thanks to my supervisors Benedikt Vormwald, and Annika Vauth for their awesome supervision, unlike the stereotypical comic of the week cliché.

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