ILC Cherenkov Detector: Photodetector Studies

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Albuquerque – Sep.29 - Oct.03, 2009
Theory & Practice

- Non-linearity definitions: DNL & INL
- Test facility setup

Linearity Measurements

- Readout electronics: QDC
- Photodetector spectra & QDC correction
- PDs: INL methods
- PDs: DNL methods

Long-term Stability

- Measurements & corrections
- Applicable at the ILC?

Summary & Outlook
ILC Polarimetry Concept

Two Compton polarimeters per beam are foreseen in the BDS system. One upstream & one downstream of the collider $e^+e^-$ IP.

Reminder: We want to do precision physics
Thus, we need precise measurements of the beam polarisation.

Hoping to achieve: $\frac{dP}{P} = 0.25\%$ per polarimeter

SLD polarimeter: achieving this goal is limited by systematics effects
→ detector linearity is a crucial factor!

Need Cherenkov detector with exceptional linearity!
⇒ Study photodetectors (PD) & electronics (QDC) in test setup!
Cherenkov Detector for ILC Polarimetry

- **Overview**
- **Theory & Practice**
- **Linearity Measurements**
- **Long-term Stability**
- **Summary & Outlook**

**Photodetector Studies**

- **LEDs**
- **Cherenkov photons**
- **photodetectors**
- **gas-filled aluminum channel**
- **aluminum tubes**

**Cherenkov photons**

- **e⁻-beam**

**Beam**

**Daniela Käfer**

ALCPG'09 Sep.29-Oct.3 2009
Theory & Practice
Definitions of DNL and INL

**Differential non-linearity: DNL**

Response $R$ to fixed change $\Delta S$ in signals $S_i$ and $S_i + \Delta S$ dep. on $S_i$

**Integral non-linearity: INL**

Maximal deviation (add $\pm$ dev.) between data & straight line fit

Ideal: $R_{S_i+\Delta S} = R_{S_i} + R_{\Delta S}$ indep. of $S_i$

Real: $R_{\Delta S}$ depends on $S_i$

\[
\begin{align*}
\left\{ R_{\Delta S} \right\} \Rightarrow DNL(S_i) &= \frac{R_{\Delta S}(S_i)}{R_{\Delta S}^{ideal}} - 1
\end{align*}
\]

$R_{\Delta S}^{ideal}$ needed: okay for QDC, where $R_{\Delta S}^{ideal} = 1$ LSB (least significant bit), use mean of all recorded $R_{\Delta S}(S_i)$
mountings for several PDs available: conv. PM, MAPM, SiPM

function generator controlled blue LED ($\lambda_{peak} = 470$ nm, FWHM = 35 nm) + optical fibers + choice of different optical filters (attenuation)

readout: 8-channel, 12-bit QDC with dual ranges (high, low)

high: $0..800$ pC $\leftrightarrow$ $200$ fC LSB

and

low: $0..100$ pC $\leftrightarrow$ $25$ fC LSB
What is the Objective?

Want to...

- measure PD (non-)linearities with sub-percent accuracy
- establish measurement methods sensitive to this level for both DNL & INL measurements
- develop procedures to correct possible non-linearities (mostly DNL)
- apply correction procedures to repeated a/o long-term measurements to test & refine both (meas. methods and correction procedure)

Although several PDs could be tested, concentrate on one type only.

⇒ **Study type R5900U-00-M4 (Hamamatsu, 2×2 MAPM) thoroughly!**
Linearity Measurements
QDC non-linearities

- long, slow (10 Hz) ramp waveform as input signal → test channel (covers high range up to 1500 QDC-cts)
  - short, fast (∼20 kHz) random gate triggered by white noise (function gen.)
    ▷ short → high sampling rate
    ▷ fast & random → avoid phase effects
  - on average: 2000 samples per ramp

- actual/ideal bin width → DNLs
  - DNLs ≈ 0.01 LSB in high range
    (low/high bins generally narrower/wider)

- sum DNLs up to \( n^{th} \) bin → INL
  - INL ≈ 3 LSBs ≈ 1% in high range
QDC non-linearities

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Sum DNLs up to $n^{th}$ bin → INL

INL ≈ 3 LSBs in high range

Inspired by:
Maxim, Application Note 2085, 2003
QDC non-linearities

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PD spectrum in QDC high range
no sharp peak, but **Gaussian shape**
from fluctuations in $N_\gamma$ (LED)
and PD gain variations

- apply DNL correction to spectrum
  weigh contents of each QDC bin by $1/DNL$
  $\rightarrow$ reduces contents of wider bins, vice-versa

Typical PD spectrum as recorded in QDC high range (200 fC LSB)

- account for warm-up phases of:
  - PD: 5h, LED: 2h prior to measuring
- always use same anode of $2\times2$ MAPM
- minimize stat. errors $\rightarrow$ 10 million ev.
PD spectrum & QDC correction

- PD spectrum in QDC high range
  - no sharp peak, but Gaussian shape
    - from fluctuations in $N\gamma$ (LED)
    - and PD gain variations

- apply DNL correction to spectrum
  - weigh contents of each QDC bin by $1/DNL$
  - → reduces contents of wider bins, vice-versa

- check a series of 25 PD spectra
  - ⇒ effects are minute!

- $\chi^2/\text{ndf}$ of gaussian fit

![Graph showing the effect of DNL correction on $\chi^2/\text{ndf}$](image)
PD spectrum & QDC correction

- PD spectrum in QDC high range, no sharp peak, but Gaussian shape from fluctuations in $N^\gamma$ (LED) and PD gain variations
- Apply DNL correction to spectrum
  - Weigh contents of each QDC bin by $1/DNL$
  - Reduces contents of wider bins, vice-versa
- Check a series of 25 PD spectra
  - $\Rightarrow$ Effects are minute!
  - $\chi^2$/ndf of Gaussian fit
  - Relative change of peak position:
    $$\Delta S = \frac{S^* - S}{S} \lesssim 0.02\%$$ (mostly)
  - Corr. causes 0.05% effect only close to the large dip in the DNL distr. (600-700 QDC cts.)
**PD: Signal Modelling**

- **Multi-Poisson fit model:**
  - **pros:** determines $N^{p.e.}$ and gain, but PD linearity vs. output charge suffices
  - **cons:** time consuming; very susceptible to slight changes in initial conditions

- **Gaussian fit model:**
  - **pros:** robust method; determines $N^{p.e.}$
  - **cons:** uses only a narrow region of the signal peak ($\pm 1$ rms)

- **Goodness of fit:**

  \[ \Lambda = \frac{\sigma_{\text{gauss}}}{\sqrt{Q_{QDC} - DC}} \]

  with dark current (prev. measured):
  
  $\text{DC} = 62.5$ QDC counts
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$\chi^2/\text{ndof} = 116/51$
$\Lambda = 1.502$

\[ \chi^2 / \text{ndf} = 115.8 / 51 \]
Constant $1.465 \times 10^5 \pm 81$
Mean $391.5 \pm 0.0$
Sigma $27.25 \pm 0.04$
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  \]

  with dark current (prev. measured):
  \[
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  \]

\[
\chi^2/\text{ndof} = 124/65
\]
\[
\Lambda = 1.503
\]
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- **Goodness of fit:**
  $$\Lambda = \frac{\sigma_{\text{gauss}}}{\sqrt{Q_{\text{QDC}} - DC}}$$

  with dark current (prev. measured):
  - $DC = 62.5$ QDC counts

  $\chi^2/\text{ndof} = 164/77$
  $$\Lambda = 1.501$$

  ![Graph](image)
PD: Signal Modelling

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  \[ \Lambda = \frac{\sigma_{\text{gauss}}}{\sqrt{Q_{\text{QDC}} - \text{DC}}} \]

  with dark current (prev. measured):
  
  DC = 62.5 QDC counts

  \[ \chi^2/\text{ndof} = 144/87 \]
  \[ \Lambda = 1.499 \]
‘Optical Filters’:
- used to attenuate light from the LED by a fixed/known(? ) amount
- filter calibration not precise enough
- method discarded for now (→ backup)
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‘Pulse-Length’ method:
- want to ensure a linear variation of light on PD cathode
- need to vary LED light output linearly → how?
- operate LED with a function generator, using rectangular pulses
- vary pulse lengths linearly: 30...150 ns, in 5 ns steps
  - minimal pulse length must be longer than LED rise & fall times of ≈ 5 ns
  - keep pulse length variations below a factor 5 → avoid shielding PD dynode structure
    (potential differences) by the traversing $e^-$—shower (ultimately affects PD linearity)
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- operate LED with a function generator, using rectangular pulses
- vary pulse lengths linearly: 30...150 ns, in 5 ns steps
  ▶ minimal pulse length must be longer than LED rise & fall times of \( \approx 5 \text{ ns} \)
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    (potential differences) by the traversing \( e^- \)—shower (ultimately affects PD linearity)
‘Pulse-Length’ method → INL

- vary LED light output via rectangular pulses: 30..150 ns (5 ns steps)
  
  LED: \( f = 10 \text{ kHz}, U = -5 \text{ V} \);  
  QDC: gate width 200 ns;  
  PD: bias voltage \( U_{HV} = -800 \text{ V} \)

- single measurement: \( 10^7 \) LED pulses → minimise statistical errors

- systematic uncertainties → study two sources
  > pulse length accuracy \( \Delta t/t \)
  > fitting procedure \( (\chi^2) \)

- straight-line fit to central part
  \( \chi^2 \)-test to find correct order
  of magnitude for syst. errors

(\( \chi^2 \approx 1 \), if errors okay & assuming
the pulse inaccuracy is the only source)

- initial inaccuracy: \( 10^{-3} \)
  syst. error: \( \Delta t/t = 10^{-4} \)
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---

First iteration of $\chi^2$-test

$\chi^2/\text{ndof} = 0.22$
Fit PD spectrum with either the Multi-Poisson, or the Gauss fit model → study systematic influence of the fit model on the derived INL

Prominent dip at a pulse length of 80..100 ns → corresponds to the zero-crossing of the INL ⇒ equally well reproduced by both methods
Influence of Fit Methods on INL

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Find estimate of the uncertainty of one fit model → average results?
Fit PD spectrum with either the Multi-Poisson, or the Gauss fit model → study systematic influence of the fit model on the derived INL

Difference averaged over 7 measurement series and both fit methods. ⇒ **systematic uncertainty due to fitting procedure: $5 \cdot 10^{-4}$**
Fit PD spectrum with either the Multi-Poisson, or the Gauss fit model → study systematic influence of the fit model on the derived INL

RMS of 7 series of measurements: Multi-Poisson vs. Gauss fit model
Difference between both fit models is an order of magnitude smaller than differences within each method ⇒ negligible!
INL from ‘Pulse-Length’ measurement + all systematic uncertainties of pulse length inaccuracy \((10^{-4})\) and fitting procedures \((5 \cdot 10^{-4})\).

\(\text{'Pulse-Length'}\) measurement with statistical errors only !

from measurement derived INL with statistical errors only
INL from ‘Pulse-Length’ measurement + all systematic uncertainties of pulse length inaccuracy ($10^{-4}$) and fitting procedures ($5 \cdot 10^{-4}$).

‘Pulse-Length’ measurement with statistical errors only !

from measurement derived INL + PD systematics
INL from 'Pulse-Length' measurement + all systematic uncertainties of pulse length inaccuracy ($10^{-4}$) and fitting procedures ($5 \cdot 10^{-4}$).

'Pulse-Length' measurement with statistical errors only!

INL is measured & controlled with accuracy: $\text{INL} = (0.5 \pm 0.05)\%$
PD: Measuring DNL (2 methods)

‘Double-Pulse’ method:
- use two LEDs: LED1 as in ‘Pulse-Length’ method
  LED2 operated with a fixed, very short pulse
- compare signals pulsing: both LEDs simultaneously ↔ only LED1
  (simultaneity achieved using synchronised output channels (function gen.): f = 10 kHz)
  LED1: U = -5 V, pulse length: \( t_1 = 30\ldots150 \text{ ns} \) (5 ns steps)
  LED2: U = -2 V, pulse length: \( t_2 = 25 \text{ ns} \), fix

‘E158’ method: (inspired by: E158 collaboration, Technical Note No.67, 2005)
- use two LEDs (f = 10 kHz, U = -5 V), both operated with fixed pulses
- compare signals pulsing: both LEDs simult. ↔ LED1+LED2 sep.
  LED1: pulse length: \( t_1 = 50 \text{ ns} \) results in QDC signals with
  LED2: pulse length: \( t_1 = 150 \text{ ns} \) a ratio of \( Q_1/Q_2 \approx 1/4 \)
  (charge ratio \( \neq 1/3 \) due to different LED performance a/o coupling to optical fibers)
- attenuate LED light intensity with optical filters → measure DNLs
  (actual attenuation is not relevant → no filter transmission coefficients are needed)
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- attenuate LED light intensity with optical filters → measure DNLs
  (actual attenuation is not relevant → no filter transmission coefficients are needed)
‘Double-Pulse’ method → DNL

- vary signals using two LEDs: variable pulse + fixed pulse
  - LED1: $U = -5\, \text{V}$, pulse length: $t_1 = 30\text{..}150\, \text{ns}$ (5 ns steps) → $Q(t_1)$
  - LED2: $U = -2\, \text{V}$, pulse length: $t_2 = 25\, \text{ns}$, fix → $q(t_2)$

- single measurement: $10^7$ LED pulses → minimise statistical errors

- use parametrised function of a perfectly linear PD to fit the data

- insufficient accuracy!
  - DNLs up to 10% → bias(?) or faulty measurement?
    (several causes investigated → excluded)

- method discarded…

### Diagram

- anode charge vs. pulse $t_1$ (LED1)
  - pairs $(Q, Q + q)$

<table>
<thead>
<tr>
<th>Pulse Width (ns)</th>
<th>Anode Charge (pC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>60</td>
<td>60</td>
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<tr>
<td>80</td>
<td>80</td>
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<tr>
<td>100</td>
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<td>120</td>
<td>120</td>
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<td>140</td>
<td>140</td>
</tr>
<tr>
<td>160</td>
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'Double-Pulse' method → DNL

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\[
\frac{(Q+q) - Q}{Q} = \frac{q}{Q}
\]
‘Double-Pulse’ method $\rightarrow$ DNL

- vary signals using two LEDs: variable pulse + fixed pulse
  - LED1: $U = -5$ V, pulse length: $t_1 = 30..150$ ns (5 ns steps) $\rightarrow Q(t_1)$
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- single measurement: $10^7$ LED pulses $\rightarrow$ minimise statistical errors

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'E158-method' → DNL

- vary signals using 3 LED config’s (fixed pulses) + 8 filters (for attenuation)
  - LED1: fixed pulse length: $t_1 = 50$ ns $\rightarrow Q_1$
  - LED2: fixed pulse length: $t_2 = 150$ ns $\rightarrow Q_2$
  - LED1+LED2: $\rightarrow Q_{1+2}$

- single measurement: $10^7$ LED pulses
  $\rightarrow$ minimise statistical errors

- calculate $DNL = \frac{Q_1 + Q_2}{Q_{1+2}}$

- good accuracy: mostly DNLs $\leq 0.5\%$
'E158-method' $\rightarrow$ DNL

- vary signals using 3 LED config’s (fixed pulses) + 8 filters (for attenuation)
  - LED1: fixed pulse length: $t_1 = 50$ ns $\rightarrow Q_1$
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  - LED1+LED2: $\rightarrow Q_{1+2}$

- single measurement: $10^7$ LED pulses $\rightarrow$ minimise statistical errors

- calculate DNL $= \frac{Q_1 + Q_2}{Q_{1+2}}$

- good accuracy: mostly DNLs $\leq 0.5\%$

\[\text{DNL} = \frac{Q_1 + Q_2}{Q_{1+2}}\]
‘Pulse-Length’ → DNL Interpretation

- ‘Double-Pulse’ DNL interpretation of ‘Pulse-Length’ measurement
  - only one LED1: varied pulse length: \( t_1 = 30..150 \text{ ns} \); equal 5 ns steps (fix)
  - → assume signals for consecutive pulse lengths as pairs \((Q_t, Q_{t+5 \text{ ns}})\)

- single measurement: \(10^7\) LED pulses
  - → minimise statistical errors

- use parametrised function of a perfectly linear PD to fit the data:

\[
\frac{Q_{5 \text{ ns}}}{Q} = \frac{(Q_t + Q_{t+5 \text{ ns}}) - Q_t}{Q_t}
\]

- calculate for pairs:

\[
\begin{align*}
\frac{Q_{5 \text{ ns}}}{Q} &= \frac{(Q_t + Q_{t+5 \text{ ns}}) - Q_t}{Q_t} \\
&= \frac{(Q_t + Q_{t+5 \text{ ns}}) - Q_t}{Q_t} \\
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- single measurement: $10^7$ LED pulses
  - → minimise statistical errors

- use parametrised function of a perfectly linear PD to fit the data:

$$\frac{Q_{5 \text{ ns}}}{Q} = \frac{(Q_t + Q_{t+5 \text{ ns}}) - Q_t}{Q_t}$$

- 'Double-Pulse' interpretation
  - fit: perfectly linear PD
  - data: good agreement
DNL Comparison: ’E158’ vs. ‘Pulse-Length’

‘Double-Pulse’ DNL interpretation of ‘Pulse-Length’ measurement

- only one LED1: varied pulse length: \( t_1 = 30\text{..}150 \text{ ns; equal } 5 \text{ ns steps (fix)} \)
- \( \rightarrow \) assume signals for consecutive pulse lengths as pairs (\( Q_{t}, Q_{t+5 \text{ ns}} \))

• single measurement: \( 10^7 \) LED pulses
  \( \rightarrow \) minimise statistical errors

’E158’ method measures

DNLs at \( \lesssim 0.5\% \) level

’Double-Pulse’ Interpretation of ’Pulse-Length’ signals yields similar accuracy!

\( \Rightarrow \) mostly DNL \( \lesssim 0.5\% \)
DNL Comparison: 'E158' vs. ‘Pulse-Length’

- ‘Double-Pulse’ DNL interpretation of ‘Pulse-Length’ measurement
  only one LED1: varied pulse length: \( t_1 = 30..150 \text{ ns} \); equal 5 ns steps (fix)
  → assume signals for consecutive pulse lengths as pairs \((Q_t, Q_{t+5 \text{ ns}})\)

- single measurement: \(10^7\) LED pulses
  → minimise statistical errors

- 'E158' method measures DNLs at \(\leq 0.5\%\) level

- 'Double-Pulse' Interpretation of 'Pulse-Length' signals yields similar accuracy!
  ⇒ mostly DNL \(\leq 0.5\%\)
Long-term Stability & Corrections
Using a single reference measurement for the correction:

(e) reference measurement: 0 h
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(a) -74 h (-3 days)
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(b) -60 h (-2.5 days)
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(c) -46 h (-2 days)
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(d) -31 h (-1 days)
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(f) +24 h (+1 days)
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(g) +92 h (+4 days)

Successful INL correction for data recorded up to 7 days apart!
⇒ measured & controlled to an accuracy of INL \( \leq 0.1\% \)
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(h) +168 h (+7 days)

Successful INL correction for data recorded up to 7 days apart!

⇒ measured & controlled to an accuracy of INL ≤ 0.1%
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(i) +672 h (28 days)

Data recorded much later than the reference measurement cannot be corrected successfully anymore → reference measurements need to be taken regularly & not more than a week apart!
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(j) +696 h (29 days)

Data recorded much later than the reference measurement cannot be corrected successfully anymore → reference measurements need to be taken regularly & not more than a week apart!
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(k) +718 h (30 days)

Data recorded much later than the reference measurement cannot be corrected successfully anymore → reference measurements need to be taken regularly & not more than a week apart!
Using a single reference measurement for the correction:

(e) reference measurement: 0 h

(l) $+839\ h$ (35 days)

Data recorded much later than the reference measurement cannot be corrected successfully anymore $\rightarrow$ reference measurements need to be taken regularly & not more than a week apart!
PD (non-)linearity is intrinsic quality → should not change over time
Not only PD is studied, but entire setup for calibration measurements!

The data recorded more than seven days after the previously used reference measurement could be successfully corrected using a more recent measurement as reference!

Could this be used in an ILC environment?

- **YES.** Presented calibration/correction procedure is also applicable to data from an ILC Cherenkov detector

  - Could take reference measurements (LED calibration runs) between ILC runs, or even in between consecutive trains ($\Delta t_{\text{trains}} \approx 200 \text{ ms}$)
    - Readout frequency $\approx 20 \text{ kHz} \rightarrow \approx 4000$ LED pulses during $\Delta t_{\text{trains}}$

  - Cumulate sufficient statistics for to be used as reference
  - Use sliding average over most recent couple of measurements

  $\Rightarrow$ An up-to-date calibration at all times can be guaranteed!
Conclusions & Outlook
Polarisation measurements at the ILC will be limited by systematic effects, not by statistics.

One crucial factor is the linearity of the Cherenkov detector, especially the linearities, both DNL & INL, of the utilised PDs.

Several methods to measure QDC & PD linearities were developed:

- QDC linearity: DNLs & INL can be controlled at 0.1% level.
- PD linearity: two methods were successfully established:
  - ‘Pulse-Length’ method measuring INL = (0.5 ± 0.05)%
  - ‘E158’ method: measuring DNLs also at a level of 0.1%.

Long-term stability & reproducibility were studied (‘Pulse-Length’ method)
(Although a definite time dep. was observed, the PD non-linearities could still be successfully corrected for measurements taken a week apart.)
Variations of the pulse length might still influence the linearity of the device under study, i.e. LED → PD → QDC.

Limited dynamic range of the 'Pulse-Length' method can be expanded by gradually increasing the LED amplitude voltage.

Both methods & the presented correction procedures can also be applied to an ILC polarimeter Cherenkov detector (between, or even during physics runs, using the foreseen LEDs for calibration).