ILC Cherenkov Detector:
Photodetector Studies

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1. Theory & Practice
   - Non-linearity definitions: DNL & INL
   - Test facility setup
2. Linearity Measurements
   - Readout electronics: QDC
   - Photodetector spectra & QDC correction
   - PDs: INL methods
   - PDs: DNL methods
3. Long-term Stability
   - Measurements & corrections
   - Applicable at the ILC?
4. Summary & Outlook

ILC Polarimetry Concept

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

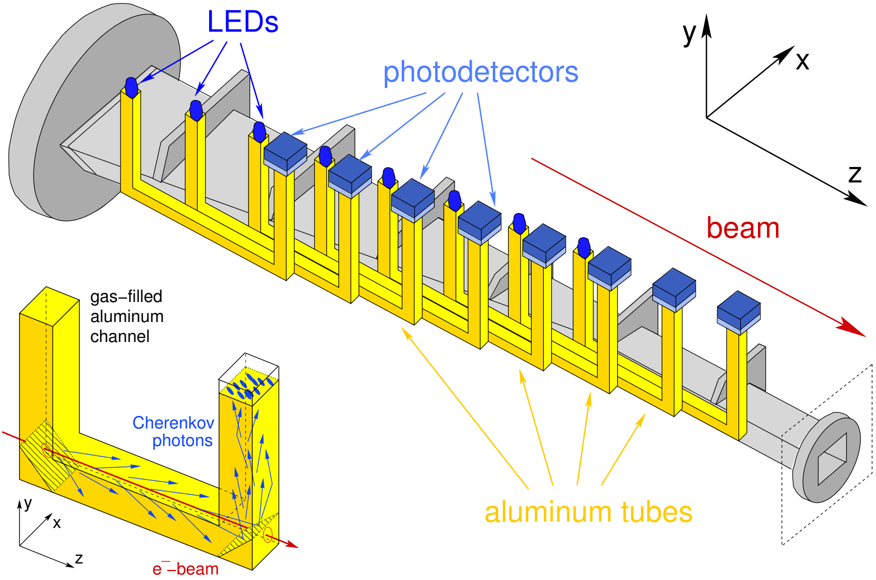
Reminder: We want to do precision physics
Thus, we **need** precise measurements of the beam polarisation.

Hoping to achieve: $\frac{d\mathcal{P}}{\mathcal{P}} = 0.25\%$ **per polarimeter**

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

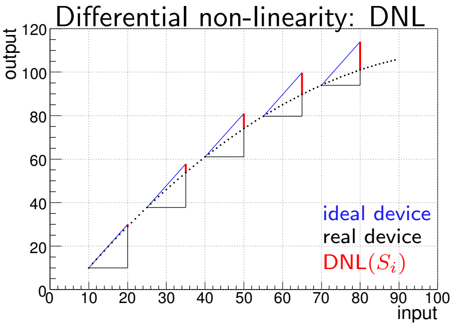
Need Cherenkov detector with exceptional linearity !
$\Rightarrow$ **Study photodetectors (PD) & electronics (QDC) in test setup!**

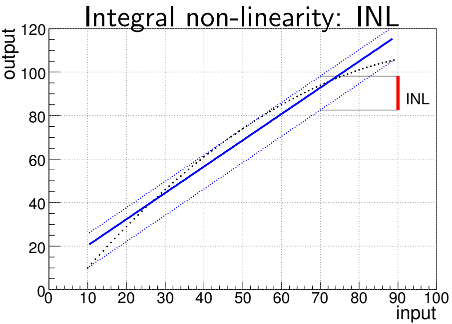
Cherenkov Detector for ILC Polarimetry



Theory & Practice

Definitions of DNL and INL





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

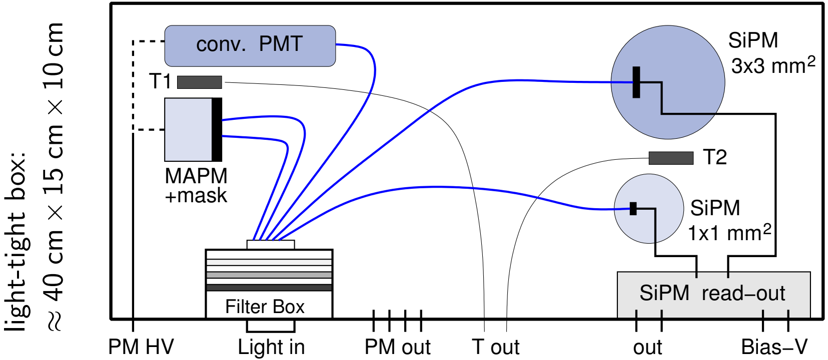
maximal deviation (add $\pm$dev.) between data & straight line fit

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

$$\Rightarrow \text{DNL}(S_i) = \frac{R_{\Delta S}(S_i)}{R^{ideal}_{\Delta S}} - 1$$

$R^{ideal}_{\Delta S}$ needed: okay for QDC, where $R^{ideal}_{\Delta S} = 1$ LSB (least significant bit), but it's usually unknown for PDs $\rightarrow$ use mean of all recorded $R_{\Delta S}(S_i)$

Test Facility

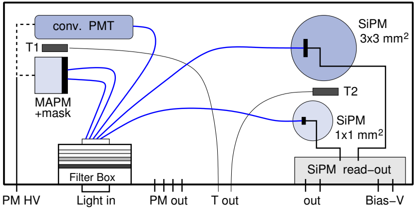


- mountings for several PDs available: conv. PM, MAPM, SiPM
- function generator controlled blue LED ($\lambda_{peak} = 470$ nm, FWHM $= 35$ nm) + optical fibers + choice of different optical filters (attenuation)
- readout: 8-channel, 12-bit QDC with dual ranges (high, low)
  high: 0..800 pC ↔ 200 fC LSB and *low:* 0..100 pC ↔ 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!**

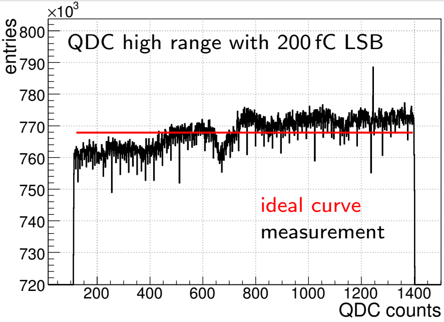
Linearity Measurements

QDC non-linearities

inspired by:
Maxim, Application Note 2085, 2003

- 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

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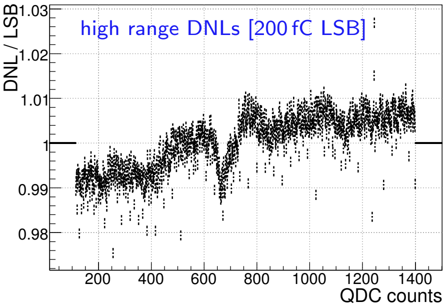

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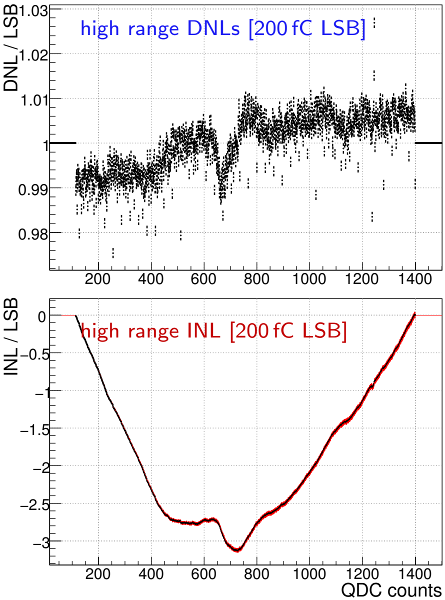

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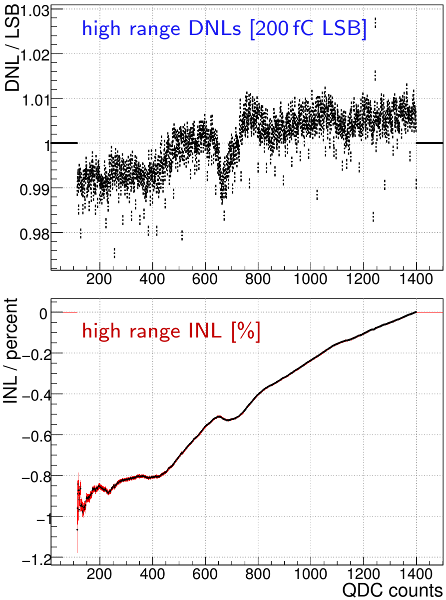
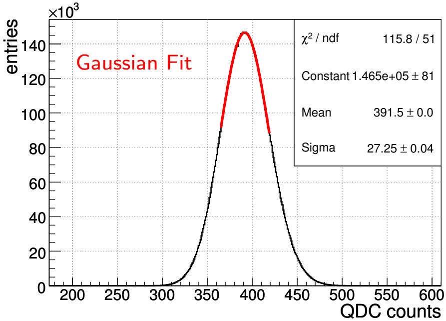


PD spectrum & QDC correction

- PD spectrum in QDC high range
  no sharp peak, but Gaussian shape
  from fluctuations in N^γ (LED)
  and PD gain variations
- apply DNL correction to spectrum
  weigh contents of each QDC bin by 1/DNL
  $\longrightarrow$ 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 2×2 MAPM

▷ minimize stat. errors $\longrightarrow$ 10 million ev.

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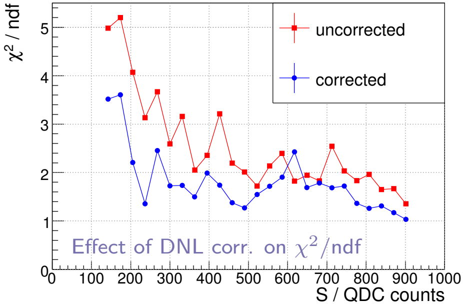
- check a series of 25 PD spectra
  $\Rightarrow$ effects are minute!

  ▷ χ^2/ndf of gaussian fit



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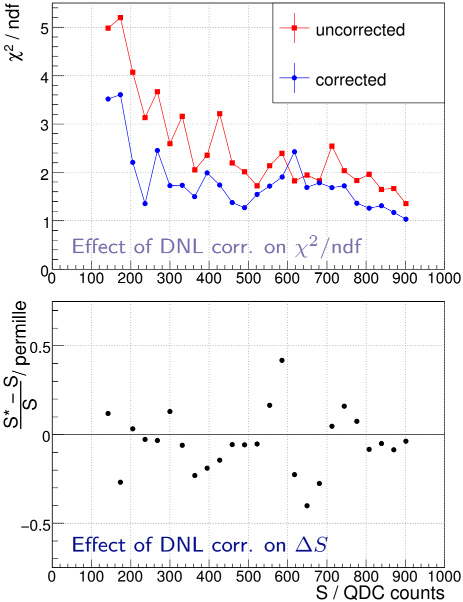
- check a series of 25 PD spectra
  ⇒ effects are minute!
  - ▷ χ^2/ndf of gaussian fit
  - ▷ relative change of peak position:

$$\Delta S = \frac{S^* - S}{S} \lesssim 0.02\% \text{ (mostly)}$$

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 (± 1 rms)

- Goodness of fit:

$$\Lambda = \frac{\sigma^{\text{gauss}}}{\sqrt{Q_{\text{QDC}} - \text{DC}}}$$

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

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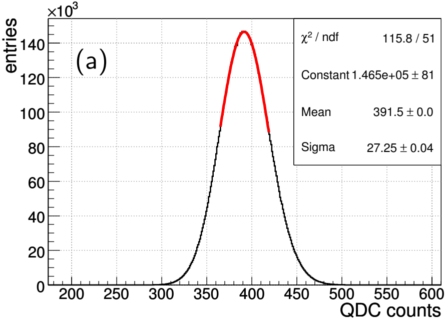
χ^2/ndof = 116/51

Λ = 1.502



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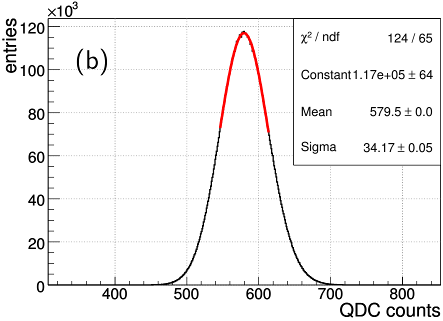
$\chi^2/\text{ndof} = 124/65$

$\Lambda = 1.503$



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χ^2/ndof = 164/77
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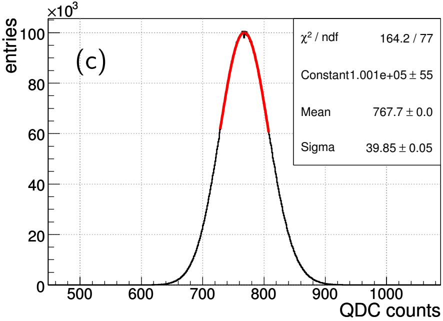

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with dark current (prev. measured):
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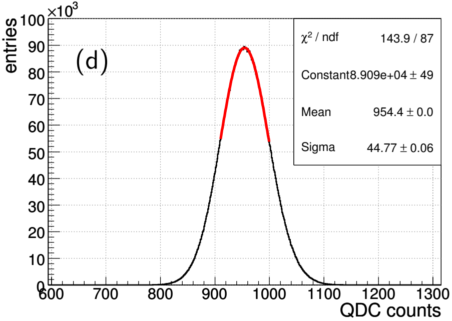
$\chi^2/\text{ndof} = 144/87$

$\Lambda = 1.499$



PD: Measuring INL (2 methods)

'Optical Filters':

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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
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'Pulse-Length' method → INL

- vary LED light output via rectangular pulses: 30..150 ns (5 ns steps)

  LED: f = 10 kHz, U = -5 V; QDC: gate width 200 ns; PD: bias voltage U_{HV} = -800 V
- single measurement: 10^7 LED pulses → minimise statistical errors

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

- straight-line fit to central part

  χ^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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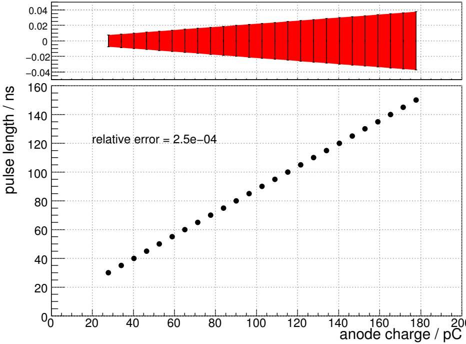
first iteration of χ^2-test

relative error $= 2.5 \cdot 10^{-4}$



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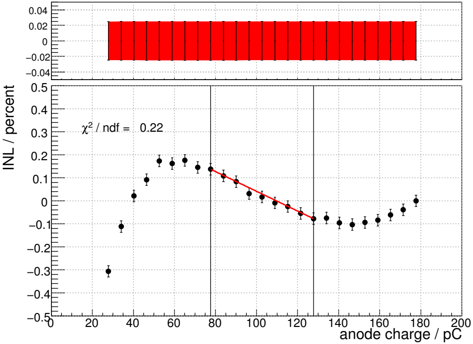
first iteration of χ^2-test
χ^2/ndof = 0.22



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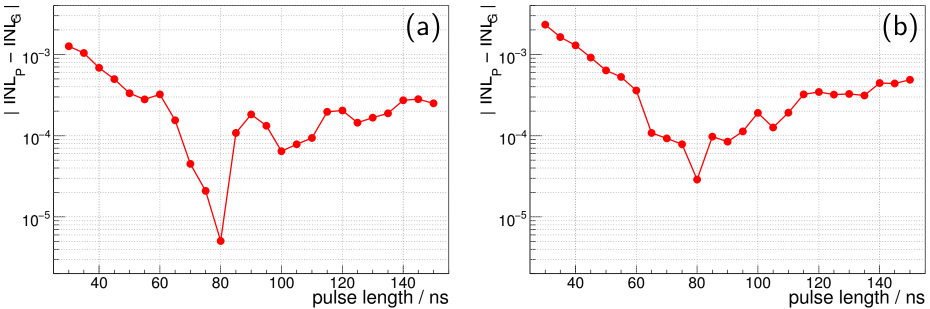
Influence of Fit Methods on INL

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

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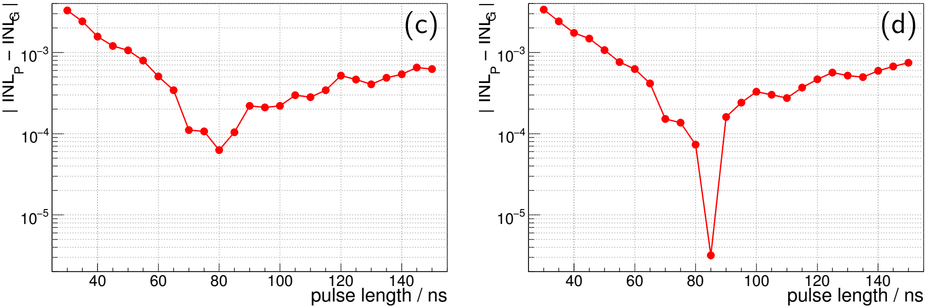

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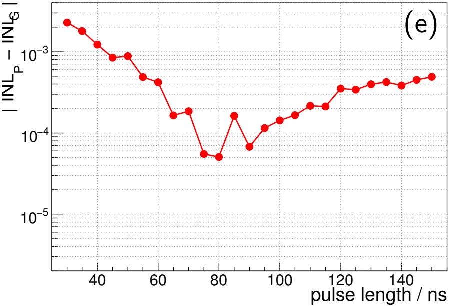

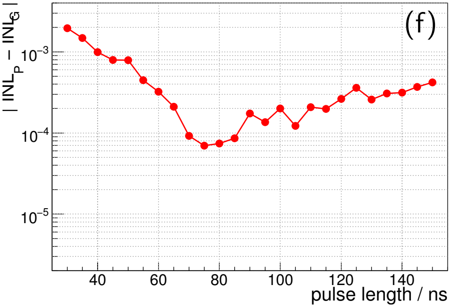

Prominent dip at a pulse length of 80..100 ns → corresponds to the zero-crossing of the INL ⇒ equally well reproduced by both methods
Find estimate of the uncertainty of one fit model → average results?

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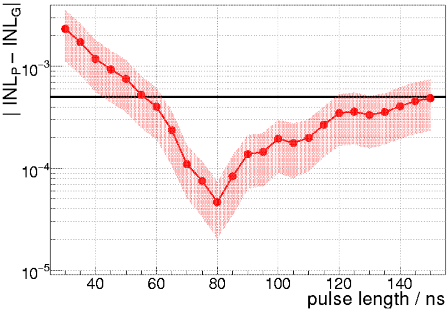

Difference averaged over 7 measurement series and both fit methods.
⇒ **systematic uncertainty due to fitting procedure: $5 \cdot 10^{-4}$**

Influence of Fit Methods on INL (cont'd)

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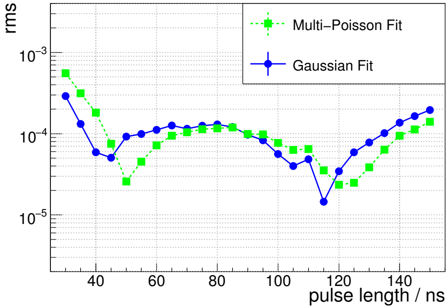
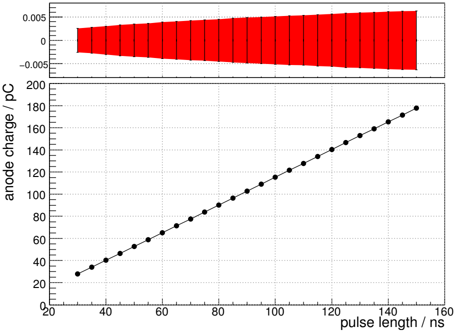


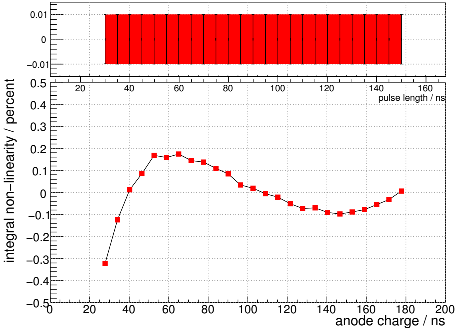
RMS of 7 series of measurements: Multi-Poisson vs. Gauss fit model
Difference between both fit models is an order of magnitude smaller than differences within each method $\Rightarrow$ **negligible !**

'Pulse-Length' + Systematics ⟶ INL

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 with statistical errors only

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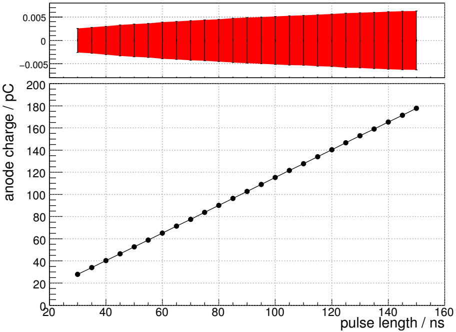

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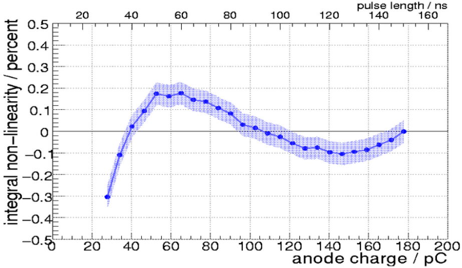

from measurement derived INL + PD systematics

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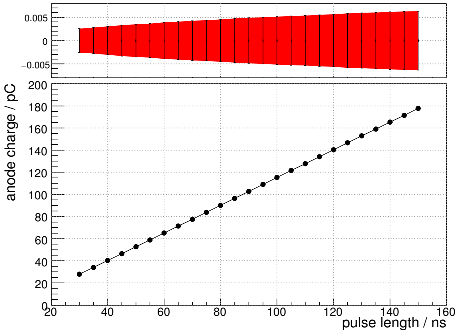

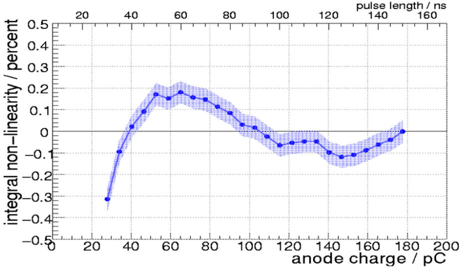

'Pulse-Length' measurement with statistical errors only !

from measurement derived INL + PD systematics + DNL(QDC)

INL is measured & controled with accuracy: INL = (0.5 ± 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: $t_1 = 30..150\,\text{ns}$ (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: $t_1 = 50\,\text{ns}$
  LED2: pulse length: $t_1 = 150\,\text{ns}$
  } results in QDC signals with 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!)

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..150 ns (5 ns steps)
  LED2: U = -2 V, pulse length: t_2 = 25 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 ns
  LED2: pulse length: t_1 = 150 ns
  } results in QDC signals with a ratio of $Q_1/Q_2 \approx 1/4$

  (charge ratio ≠ 1/3 due to different LED performance a/o coupling to optical fibers)
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'Double-Pulse' method ⟶ DNL

- vary signals using two LEDs: variable pulse + fixed pulse

  LED1: U = -5 V, pulse length: t_1 = 30..150 ns (5 ns steps) → Q (t_1)

  LED2: U = -2 V, pulse length: t_2 = 25 ns, fix → q (t_2)

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

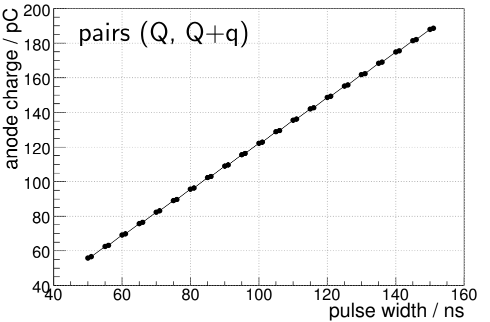
- use parametrised function of a perfectly linear PD to fit the data

- **insufficient accuracy!** DNLs up to 10% → bias(?) or faulty measurement?

  (several causes investigated → excluded)

- method discarded . . .

anode charge vs. pulse t_1 (LED1)



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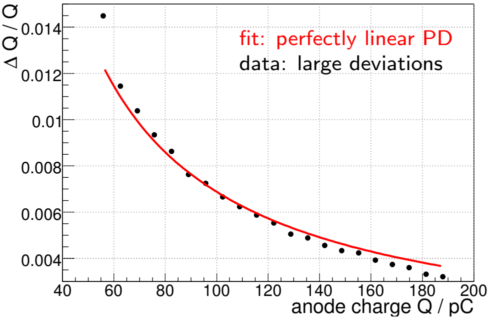
fix pulse effect: $\frac{(Q+q) - Q}{Q} = \frac{q}{Q}$



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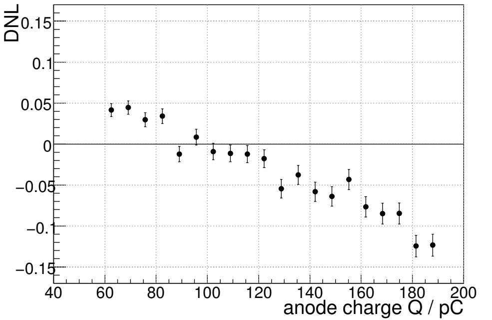
DNLs up to 10%



'E158-method' ⟶ DNL

- vary signals using 3 LED config's (fixed pulses) + 8 filters (for attenuation)

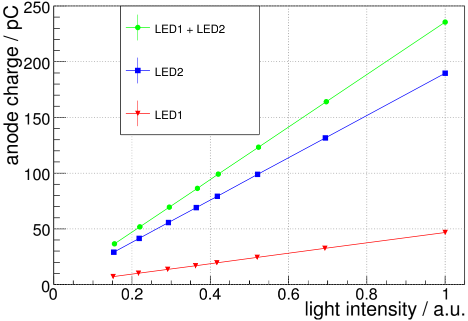
  LED1: fixed pulse length: $t_1 = 50$ ns ⟶ Q_1
  LED2: fixed pulse length: $t_2 = 150$ ns ⟶ Q_2
  LED1+LED2: ⟶ Q_{1+2}

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

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

- **good accuracy: mostly DNLs $\lesssim 0.5\%$**

'E158' anode charge
3 LEDs config's + 8 filters



'E158-method' $\longrightarrow$ DNL

- vary signals using 3 LED config's (fixed pulses) + 8 filters (for attenuation)

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  LED1+LED2: $\longrightarrow$ Q_{1+2}

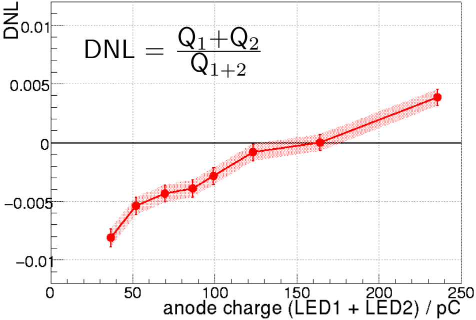
- single measurement: 10^7 LED pulses

  $\longrightarrow$ minimise statistical errors

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

- **good accuracy: mostly DNLs $\lesssim$ 0.5%**

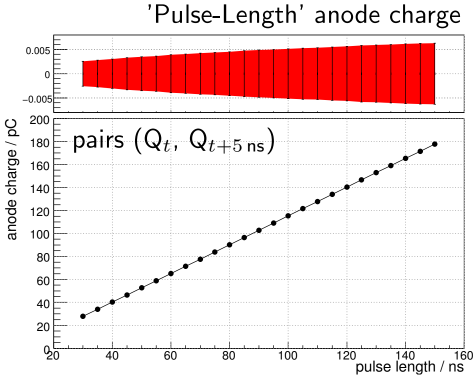
'E158': DNLs $\lesssim$ 0.5%



‘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:

- calculate for pairs:
  $$\frac{Q_{5\,\text{ns}}}{Q} = \frac{(Q_t + Q_{t+5\,\text{ns}}) - Q_t}{Q_t}$$

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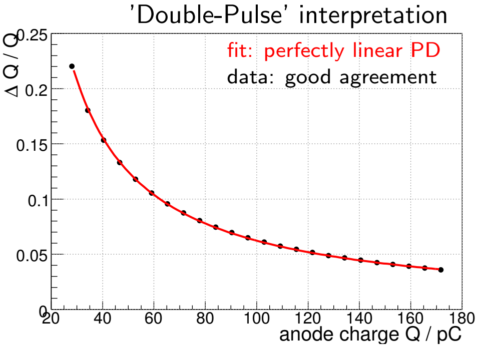
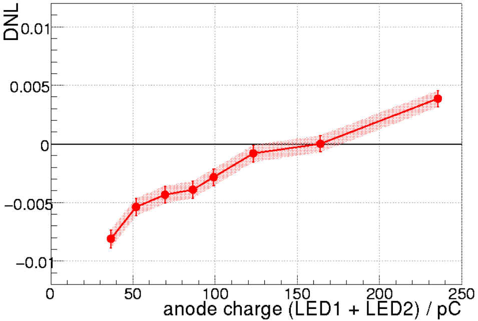


DNL Comparison: 'E158' vs. 'Pulse-Length'

- 'Double-Pulse' DNL interpretation of 'Pulse-Length' measurement
  only one LED1: varied pulse length: $t_1 = 30..150$ ns; equal 5 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%**

'E158' method: DNL



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  only one LED1: varied pulse length: $t_1 = 30..150$ ns; equal 5 ns steps (fix)
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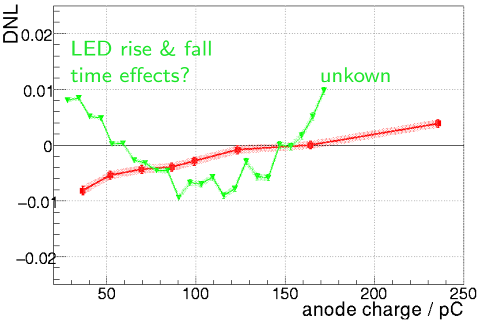
⇒ **mostly DNL $\lesssim$ 0.5%**

'E158' & 'Double-Pulse': DNL

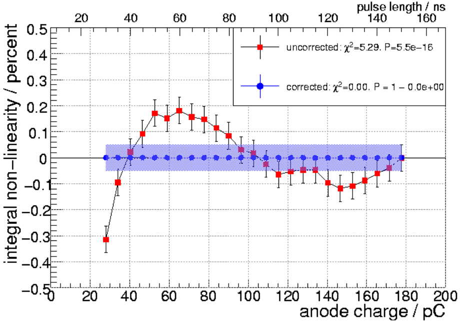


Long-term Stability & Corrections

Long-term Stability I

Using a single reference measurement for the correction:

(e) reference measurement: 0 h



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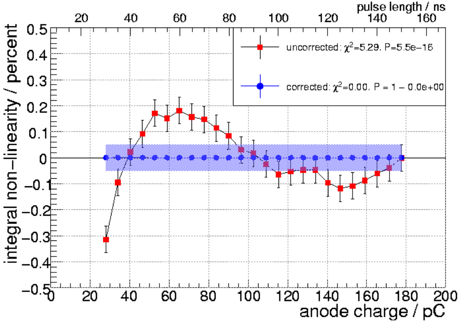
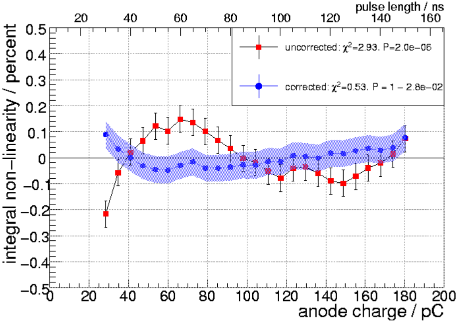


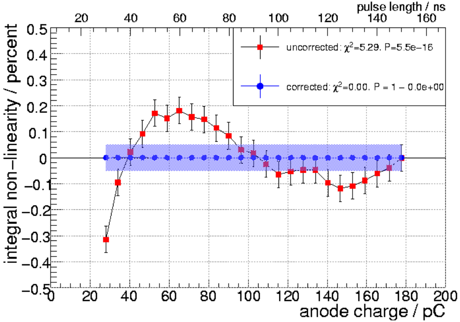
(a) -74 h (-3 days)



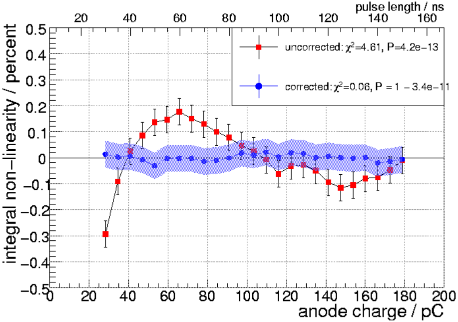
Long-term Stability I

Using a single reference measurement for the correction:

(e) reference measurement: 0 h



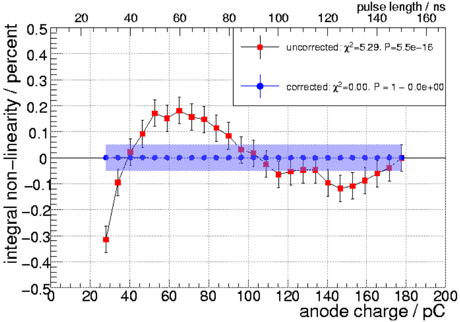
(b) -60 h (-2.5 days)



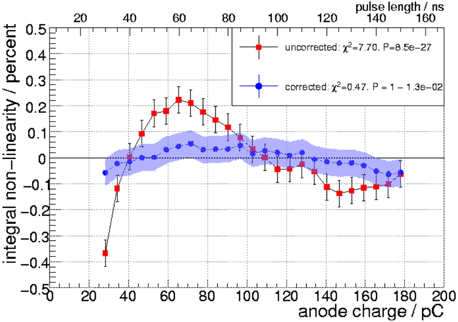
Long-term Stability I

Using a single reference measurement for the correction:

(e) reference measurement: 0 h



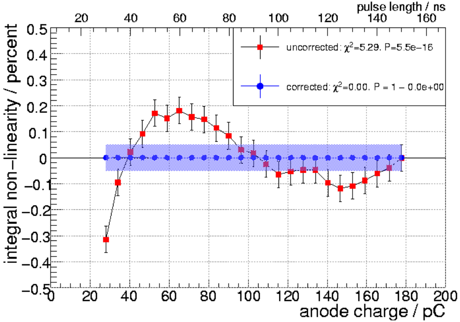
(c) -46 h (-2 days)



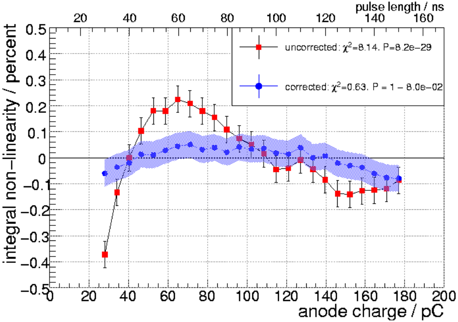
Long-term Stability I

Using a single reference measurement for the correction:

(e) reference measurement: 0 h



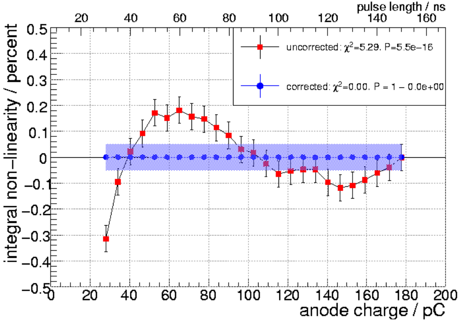
(d) -31 h (-1 days)



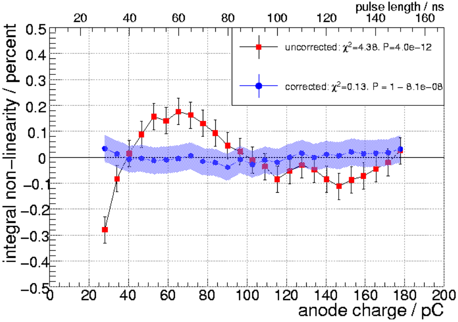
Long-term Stability I

Using a single reference measurement for the correction:

(e) reference measurement: 0 h



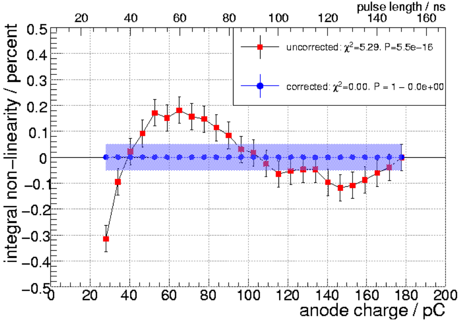
(f) +24 h (+1 days)



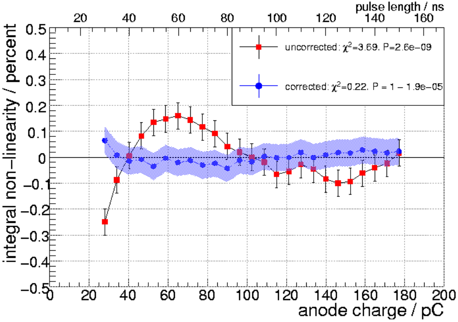
Long-term Stability I

Using a single reference measurement for the correction:

(e) reference measurement: 0 h



(g) +92 h (+4 days)



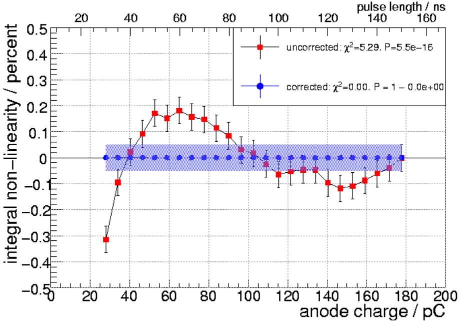
Successful INL correction for data recorded up to 7 days apart!

$\Rightarrow$ **measured & controlled to an accuracy of INL $\lesssim$ 0.1%**

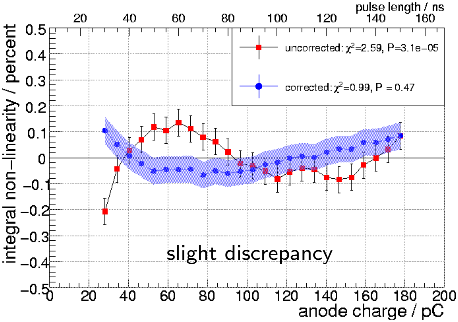
Long-term Stability I

Using a single reference measurement for the correction:

(e) reference measurement: 0 h



(h) +168 h (+7 days)



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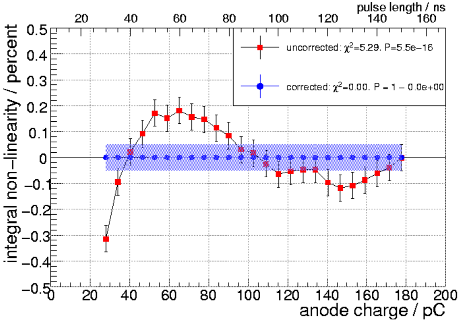
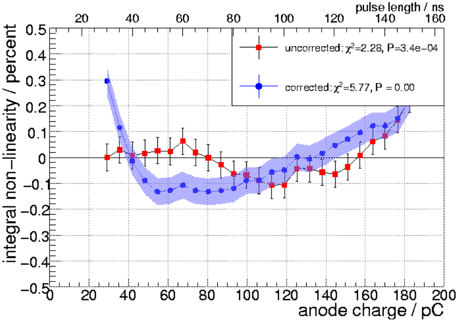


(i) +672 h (28 days)

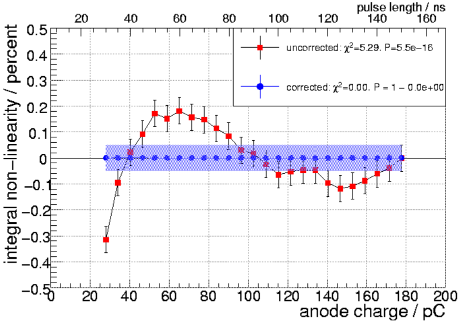


Data recorded much later than the reference measurement cannot be corrected successfully anymore → reference measurements need to be taken regularly & not more than a week apart!

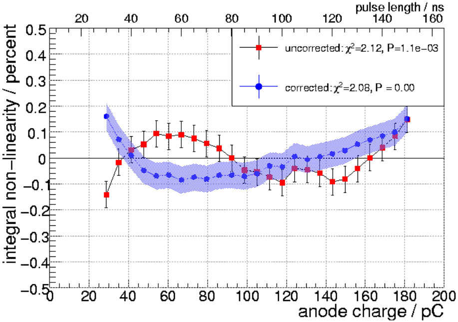
Long-term Stability I

Using a single reference measurement for the correction:

(e) reference measurement: 0 h



(j) +696 h (29 days)



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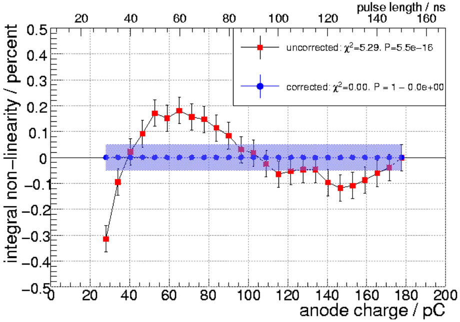
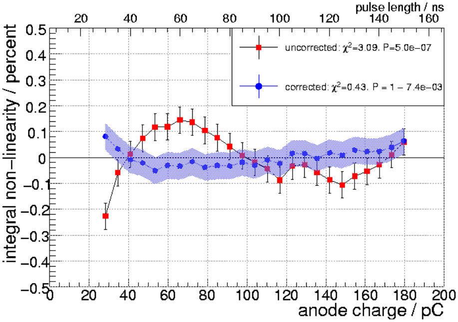
Using a single reference measurement for the correction:

(e) reference measurement: 0 h



(k) +718 h (30 days)



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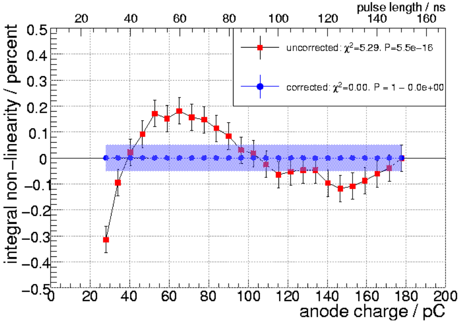
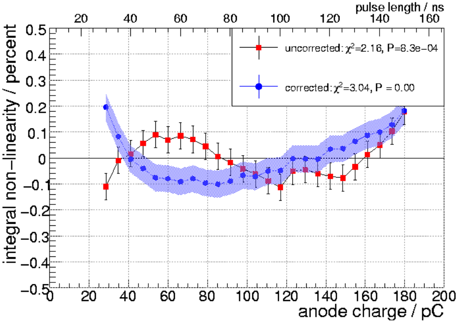
Using a single reference measurement for the correction:

(e) reference measurement: 0 h



(l) +839 h (35 days)



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

Long-term Stability II

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 ($\Delta t_{\text{trains}} \approx 200$ ms)
  - ▷ readout frequency ≈ 20 kHz → ≈ 4000 LED pulses during Δt_{trains}
- cumulate sufficient statistics for to be used as refrence
- use sliding average over most recent couple of measurements

⇒ **An up-to-date calibration at all times can be guaranteered!**

Conclusions & Outlook

Conclusions

- 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 $= (0.5 \pm 0.05)\%$
  - ▷ *'E158'* method: measureing 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.)

Outlook

- Variations of the pulse length might still influence the linearity of the device under study, i.e. LED $\rightarrow$ PD $\rightarrow$ 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)