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sense and simplicity

The Status of the Digital Silicon Photomultiplier Development

Thomas Frach, Andreas Thon, Ben Zwaans, Carsten Degenhardt, Rik de Gruyter, Oliver Mülhens

Philips Digital Photon Counting

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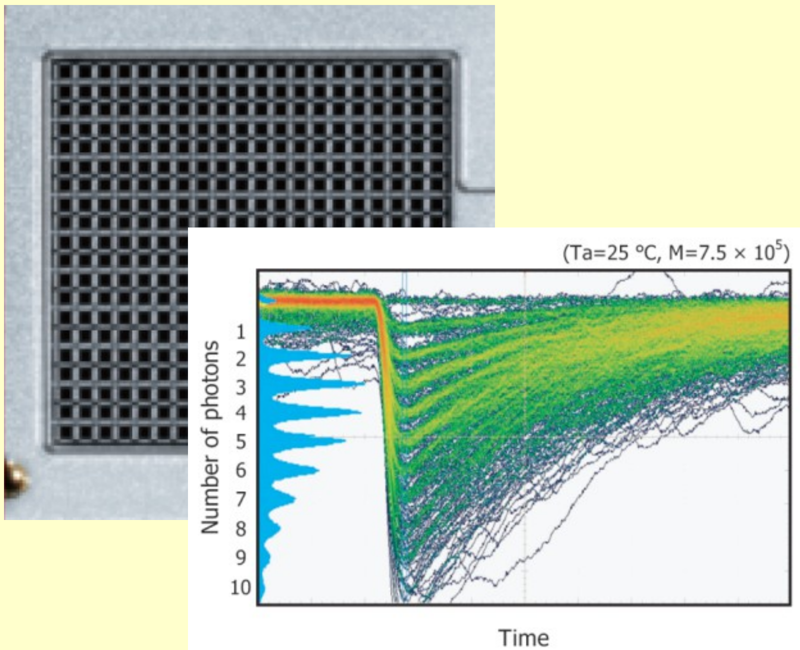
Digital SiPM – New Type of Silicon Photomultiplier

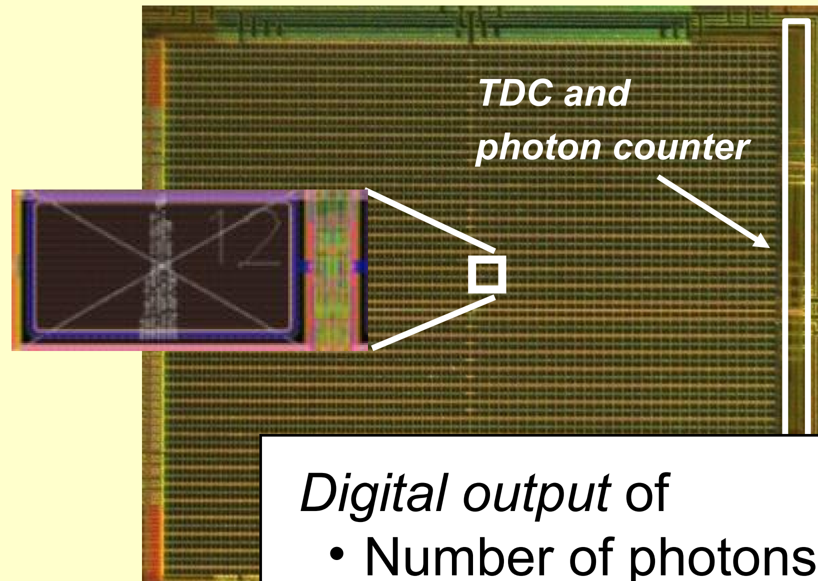
Analog SiPM



www.hamamatsu.com

- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

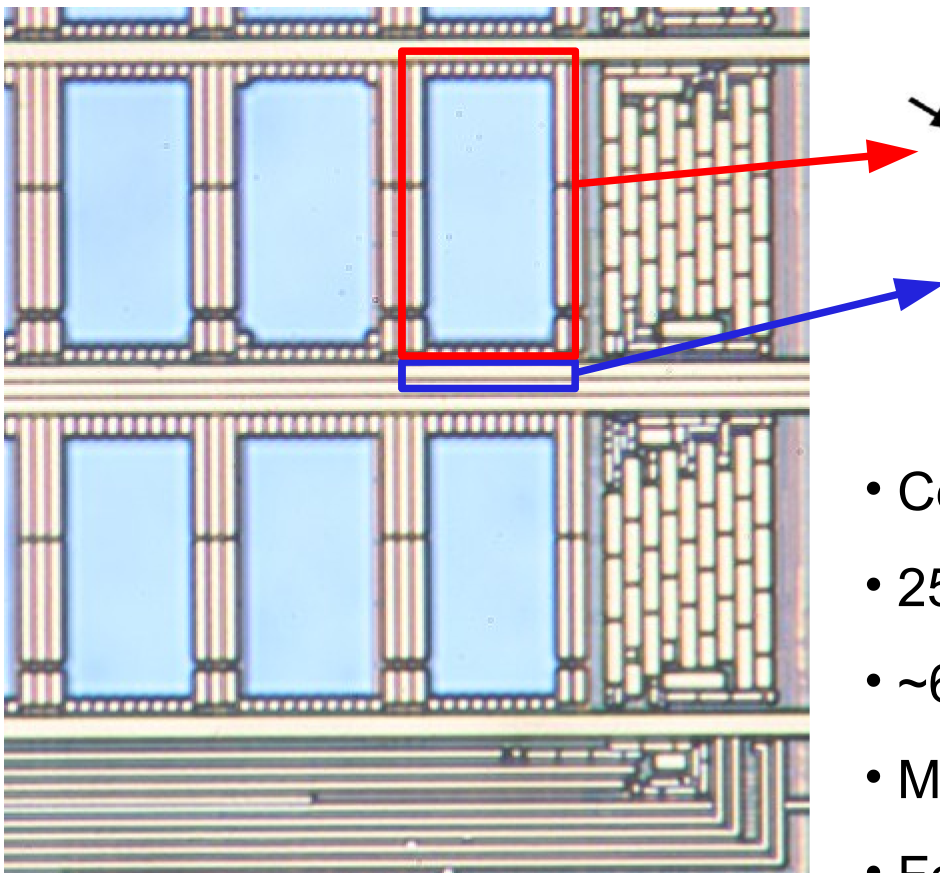
Digital SiPM

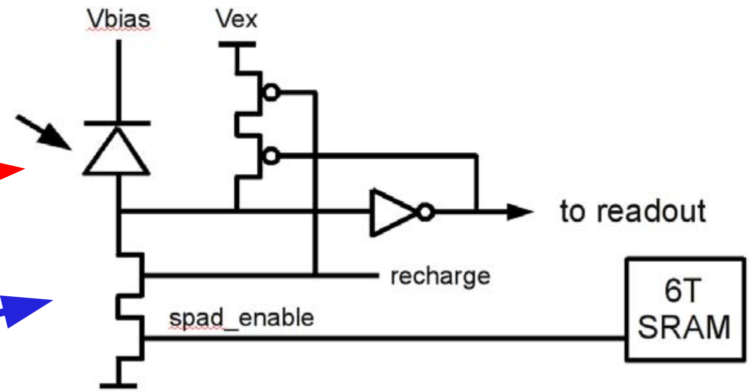


Digital output of
- Number of photons
- Time-stamp

- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output

Digital SiPM – Cell Electronics





- Cell electronics area: 120µm²
- 25 transistors including 6T SRAM
- ~6% of total cell area
- Modified 0.18µm 5M CMOS
- Foundry: NXP Nijmegen

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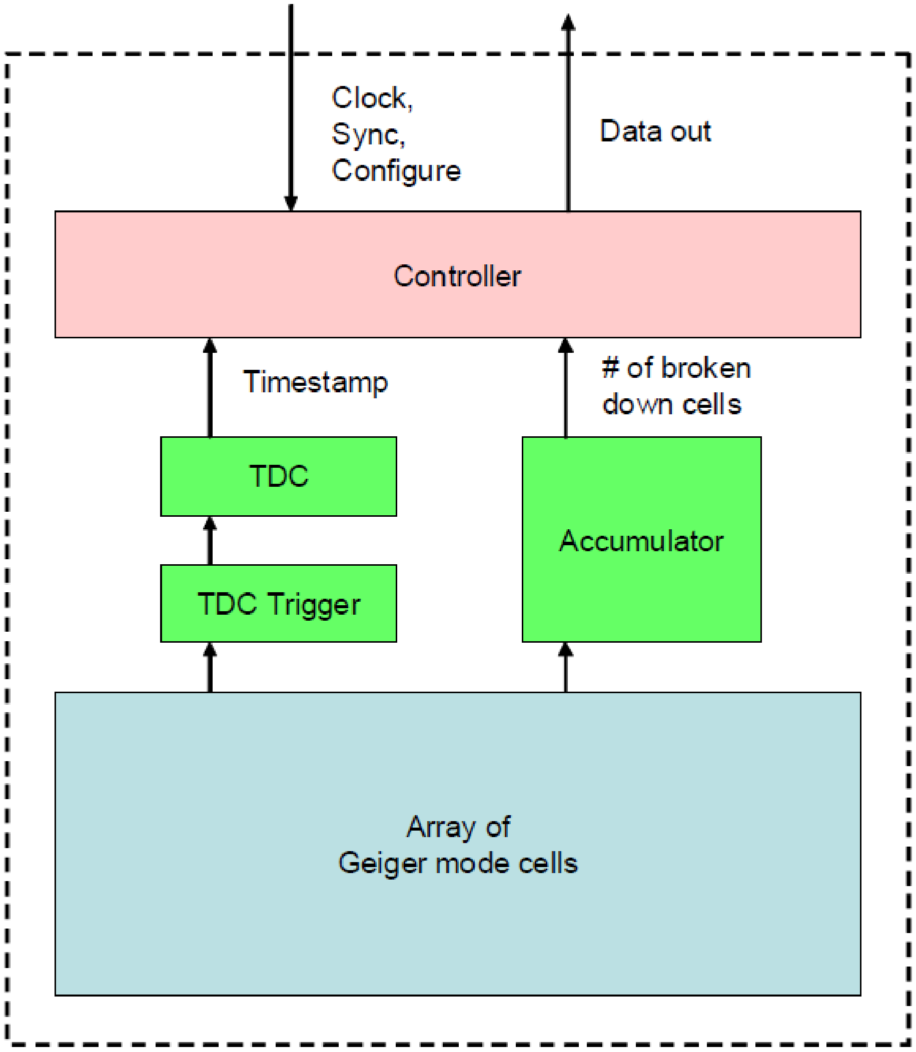
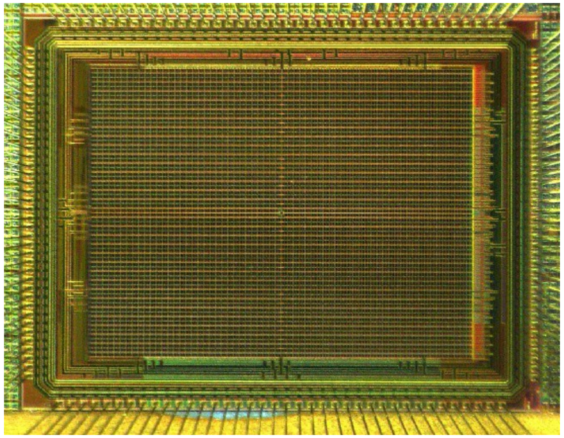
Digital SiPM – Sensor Architecture

- Operating frequency: 200MHz
- 9bit TDC (23ps bin width)
- Configurable trigger network
- Validation logic to reduce sensor dead time due to dark counts
- JTAG interface
- Electrical trigger input for test and TDC calibration



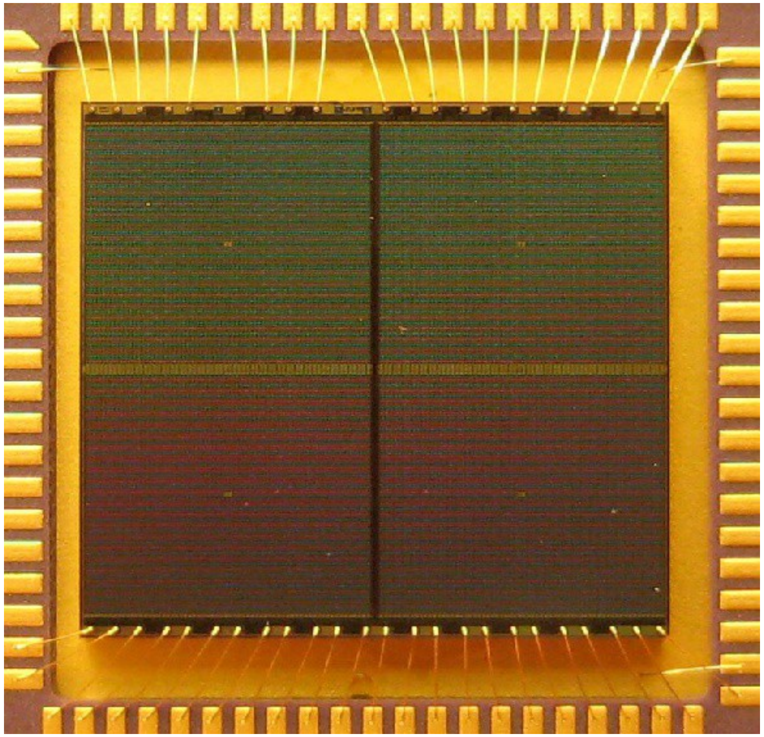
Digital SiPM – Sensor Family

DLD8K Demonstrator (2009):



- 8192 cells
- Integrated TDC
- On-chip inhibit memory controller
- External FPGA controller
- 160 bond wires

DLS 6400-22 digital SiPM (2010):



- 25600 cells
- TDCs, controller, data buffers
- JTAG for configuration & test
- 48 bond wires

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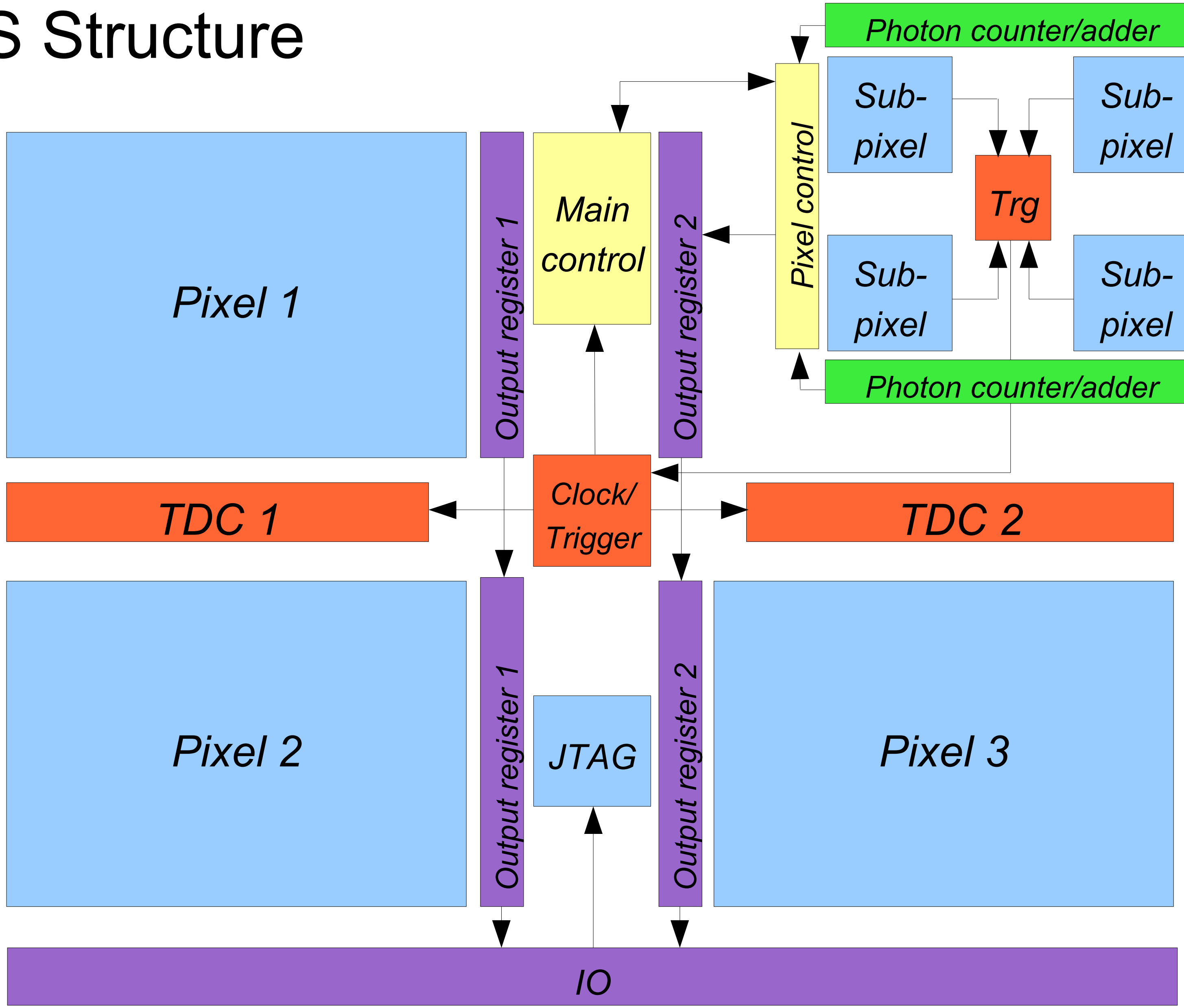
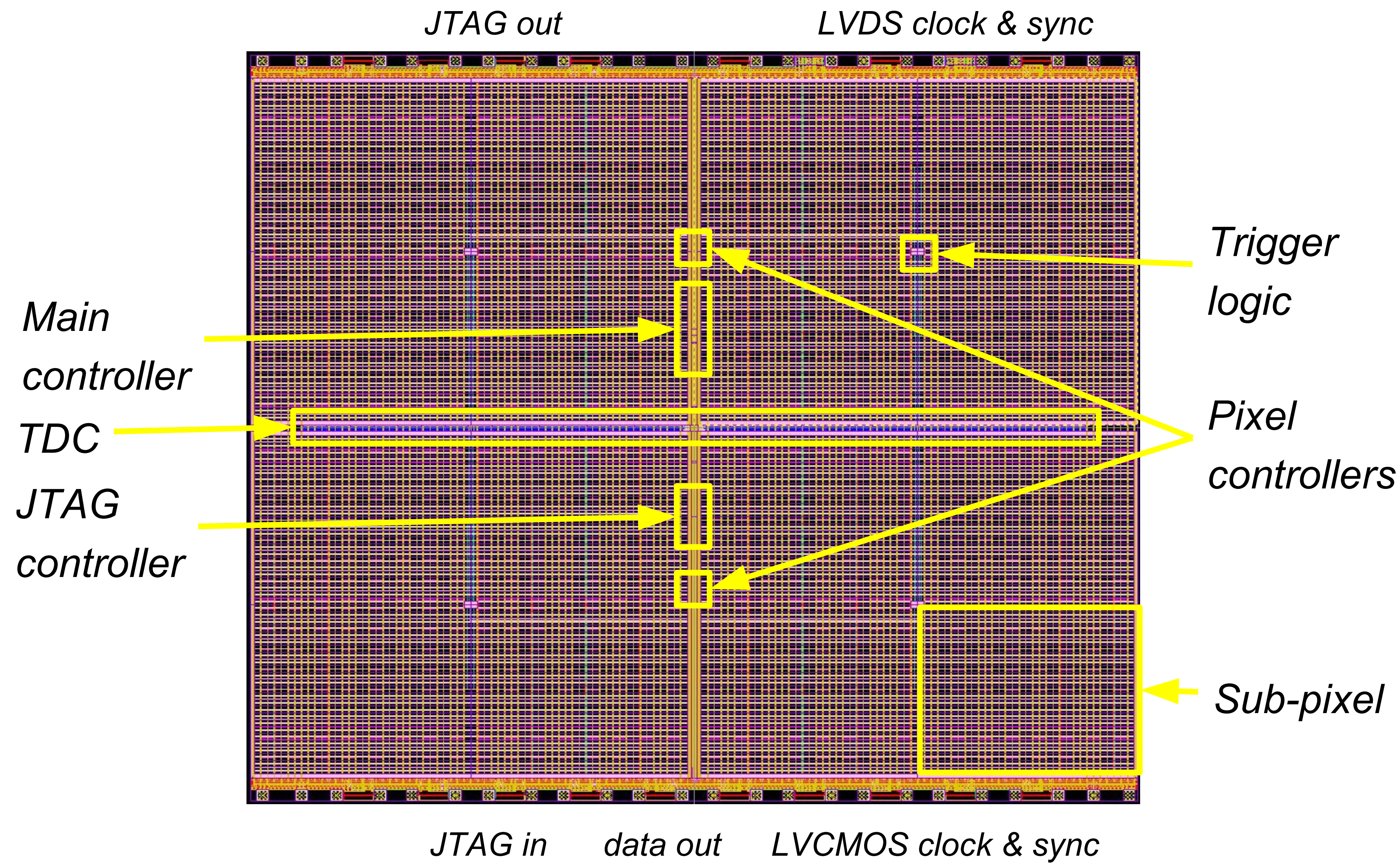
DLS Structure



DLS – Sensor Architecture



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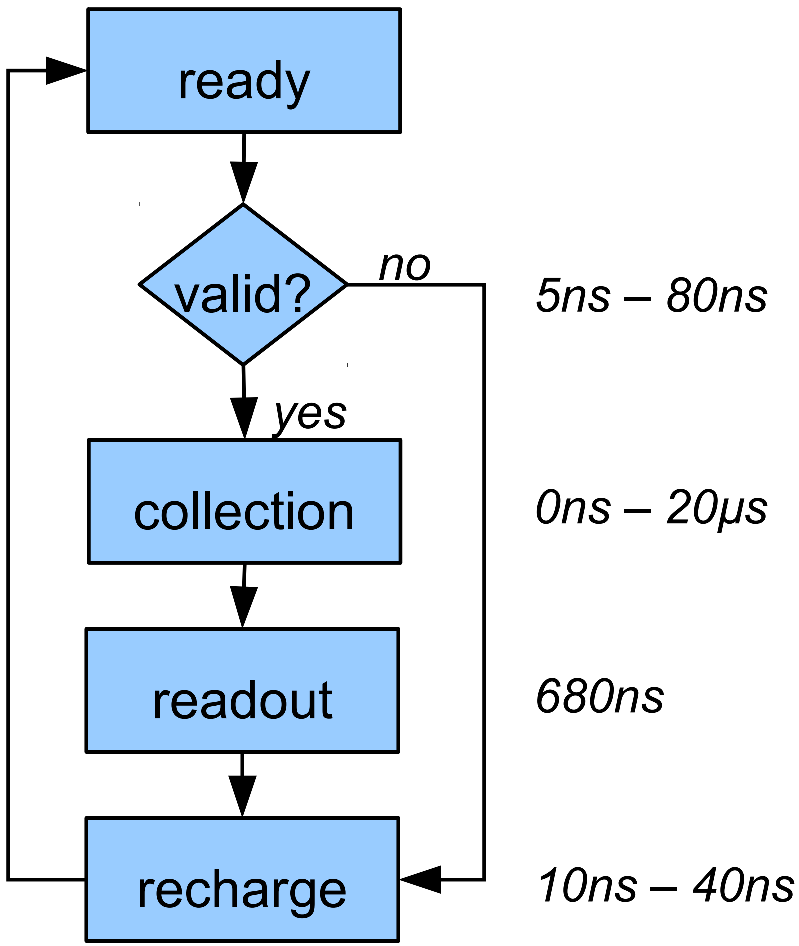
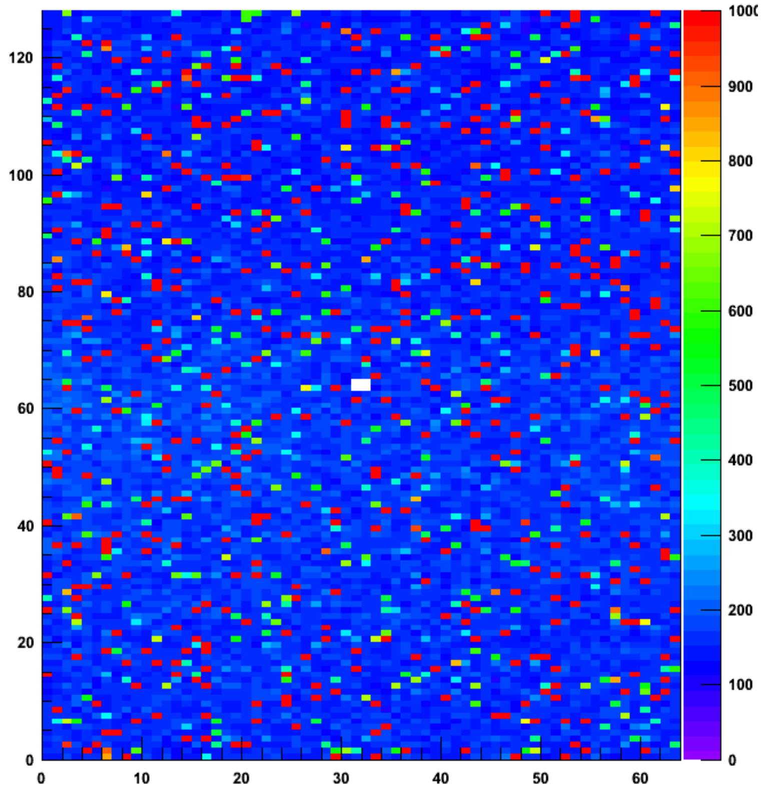
DLS – State Machine

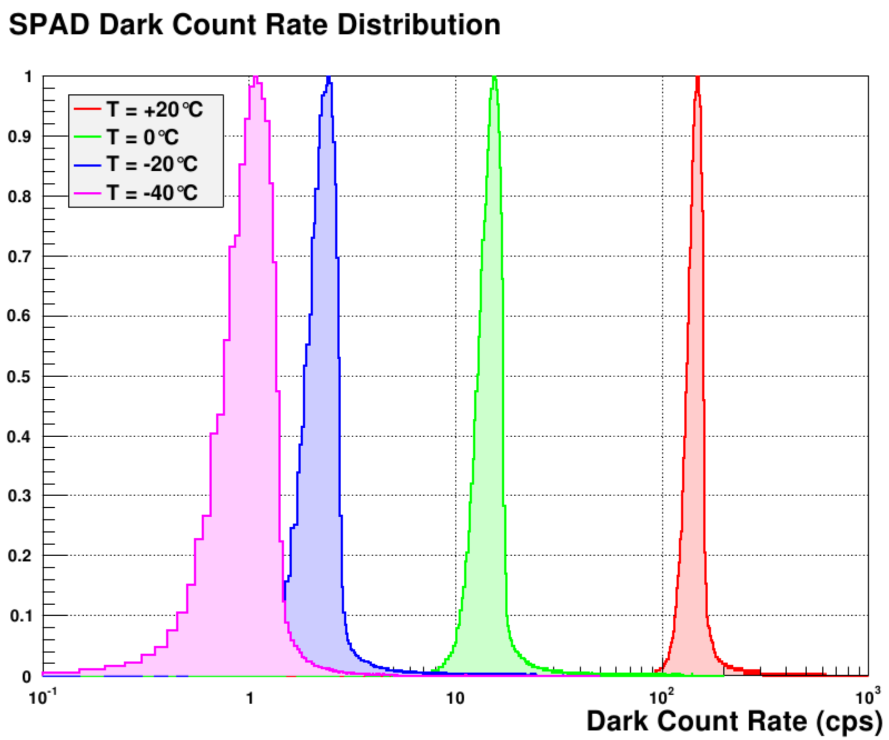


- *200MHz (5ns) system clock*
- *Variable light collection time 0 - 20µs*
- *20ns min. dark count recovery*
- *dark counts => sensor dead-time*
- *data output parallel to the acquisition of the next event (no dead time)*
- *Trigger at 1, ≥2, ≥3 and ≥4 photons*
- *Validate at ≥4 ... ≥64 photons (possible to bypass event validation)*

DLD8K – Dark Counts

Control over individual SPADs enables detailed device characterization





- Over 90% good diodes (dark count rate close to average)
- Typical dark count rate at 20°C and 3.3V excess voltage: ~150cps / diode
- Low dark counts (~1-2cps) per diode at -40°C

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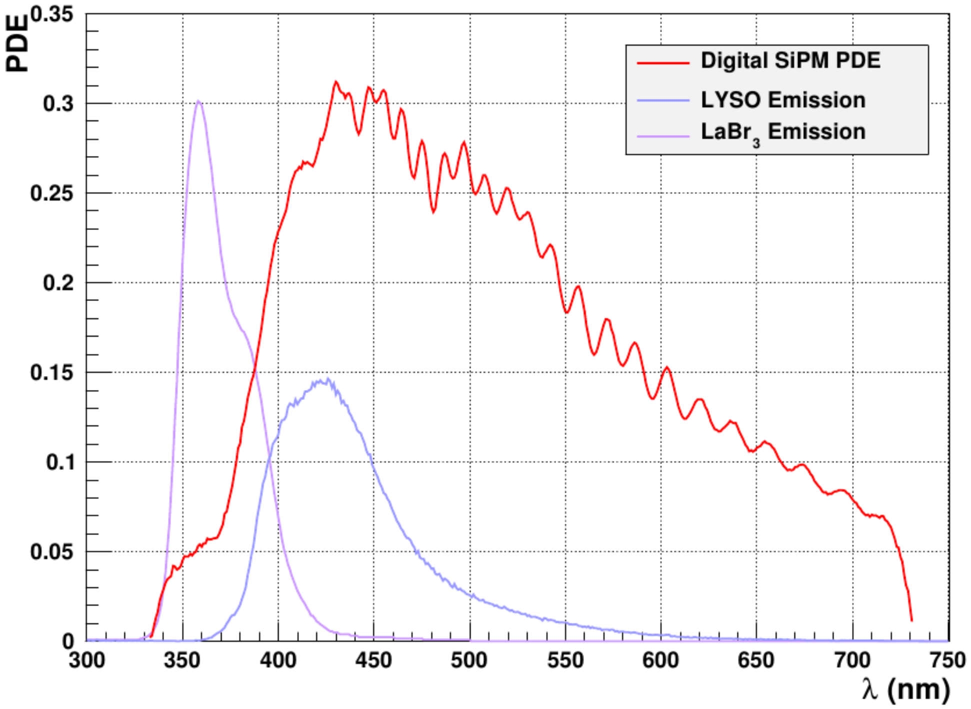
DLD8K – Photon Detection Efficiency



Effective PDE:

LYSO(Ce)	25.9%
CsI(Na)	23.7%
CsI(Tl)	20.5%
NaI(Tl)	24.2%
BGO	24.2%
$LaBr_3$(Ce)	9.6%

- Peak PDE >30% at 430nm and 3.3V excess voltage
- No anti-reflective coating used, optical coupling not optimized
- Needs independent verification

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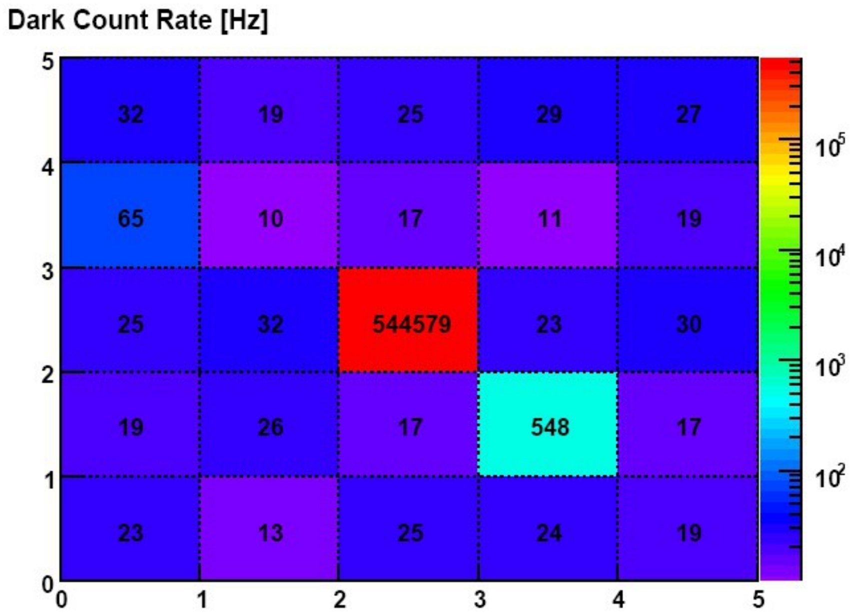
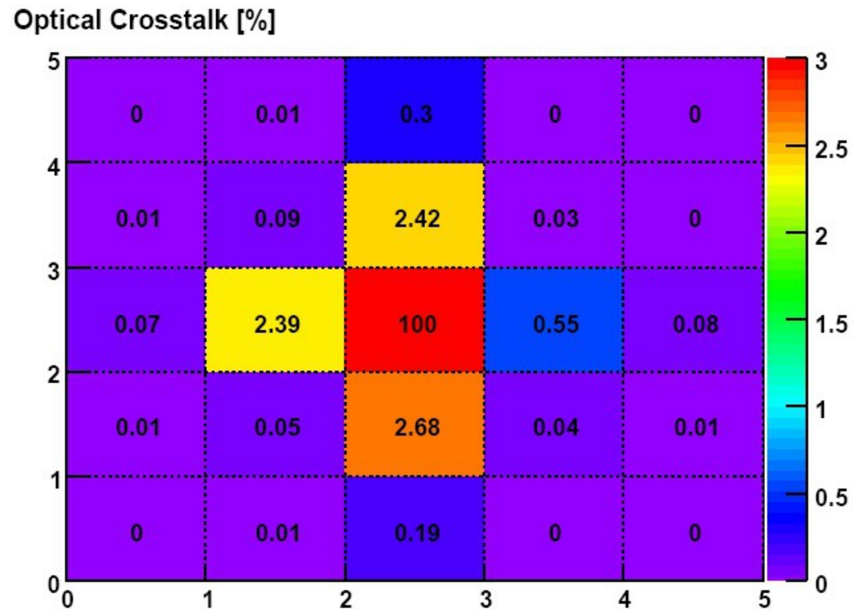
DLD8K – Optical Crosstalk





Direct measurement using one ‚bad' diode as light generator:

- Acquire dark count map around the light source for corrections
- Activate light source **and** test diode simultaneously:
  - Events with 1 photon are dark counts
  - Events with 2 photons are either randoms or optical crosstalk
- Use the dark count map to correct for randoms

Typical total optical crosstalk in a 5x5 neighborhood: 7% - 9%

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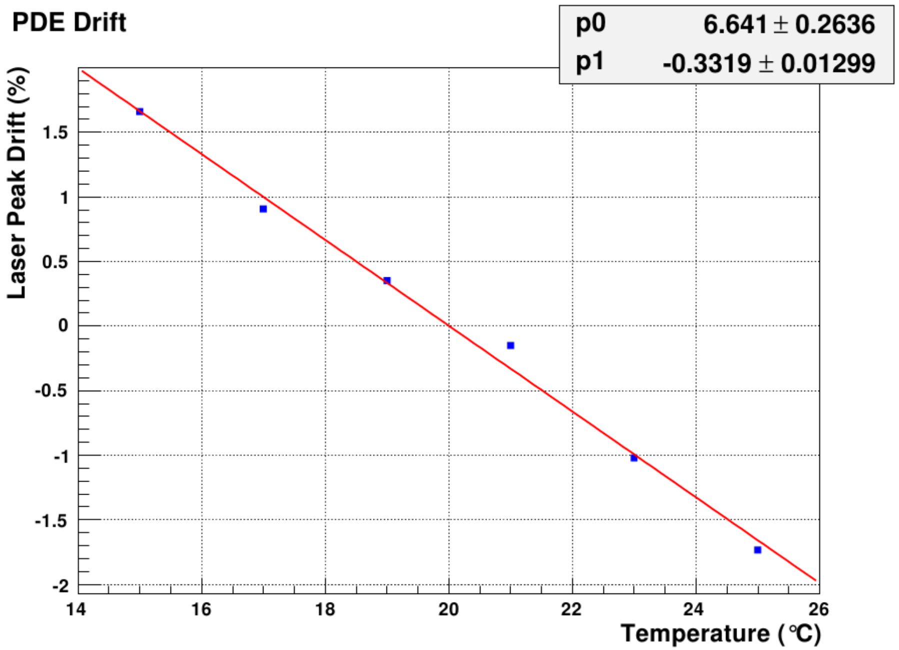
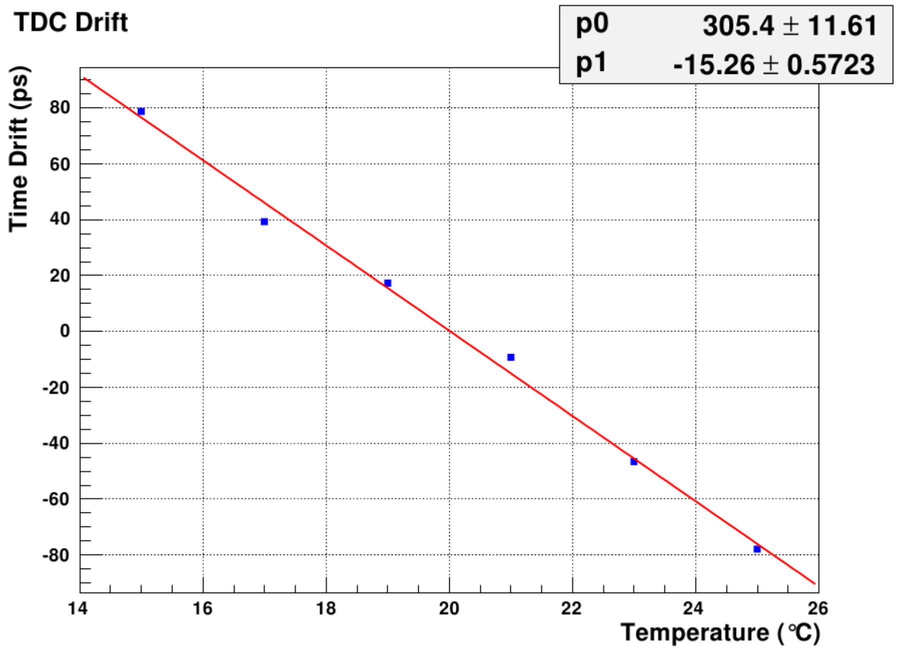
DLD8K – Temperature Sensitivity





ps-laser trigger, 2100 photons/pulse, 24ps FWHM timing resolution

- PDE drift: 0.33% K^{-1}
- TDC drift: 15.3ps K^{-1}
- PDE drift compensation by adapting the bias voltage
- TDC re-calibration using electrical trigger

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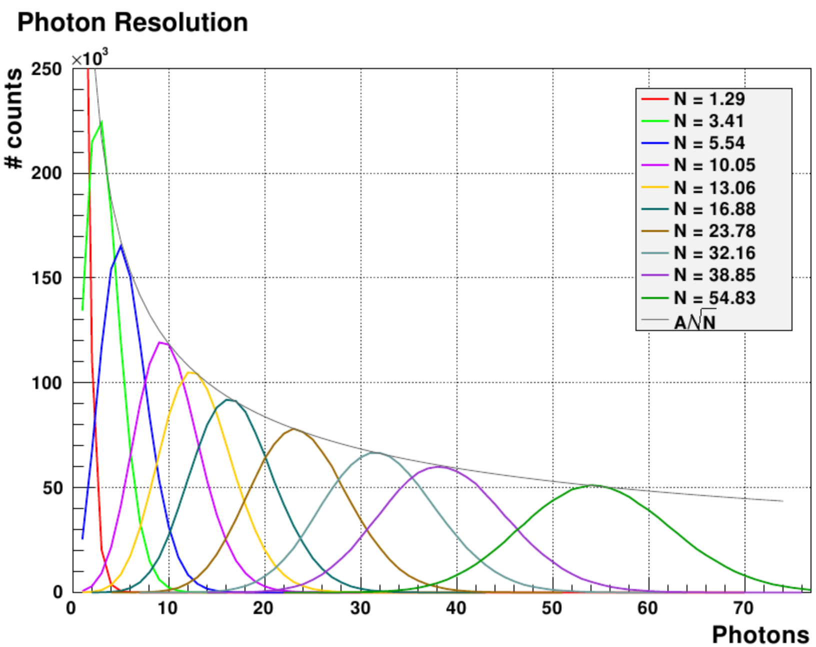
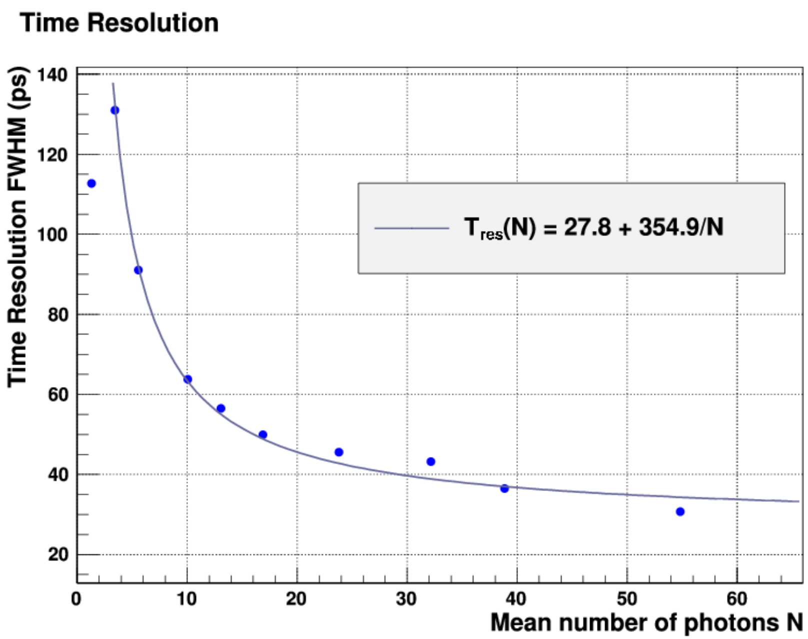
DLD8K – Photon And Time Resolution



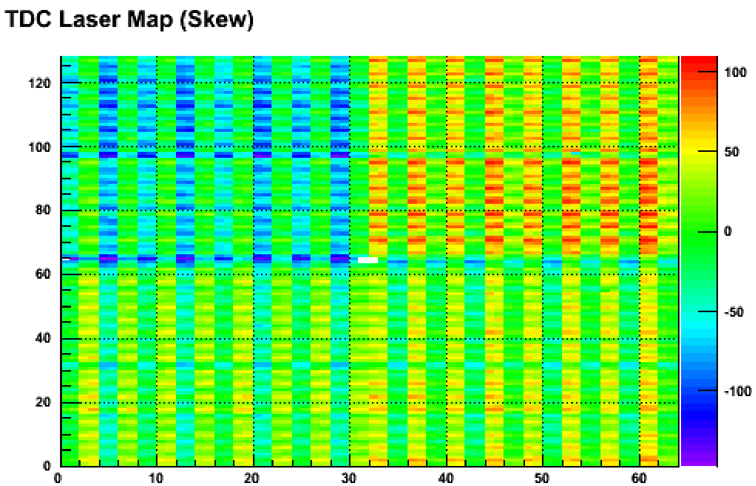


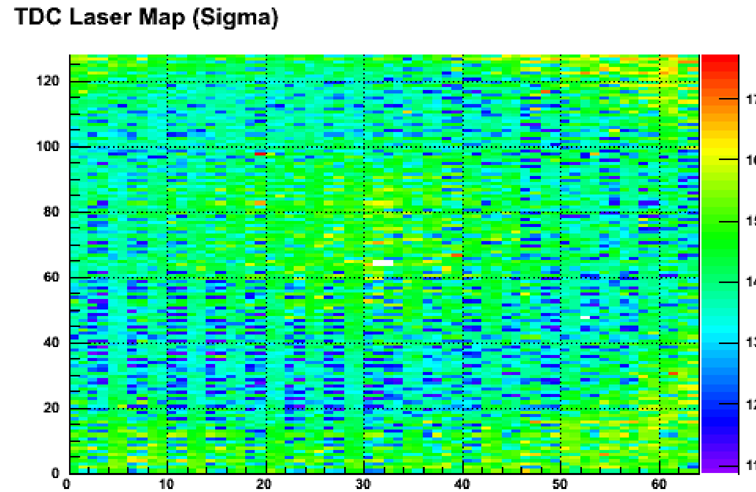
- Sensor triggered by attenuated laser pulses at first photon level
- Laser pulse width: 36ps FWHM, λ = 410nm
- Contribution to time resolution (FWHM):

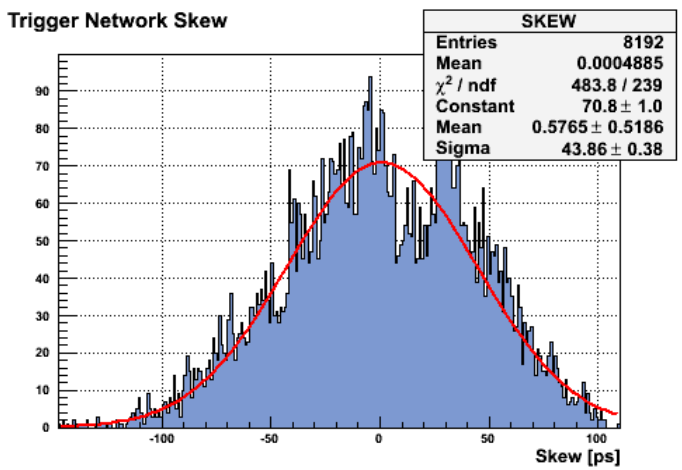
  SPAD: 54ps, trigger network: 110ps, TDC: 20ps

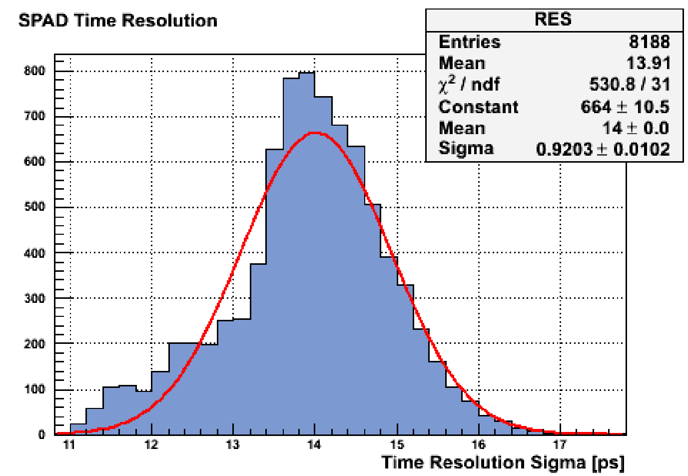
- Trigger network skew currently limits the timing resolution

DLD8K – Trigger Network Skew



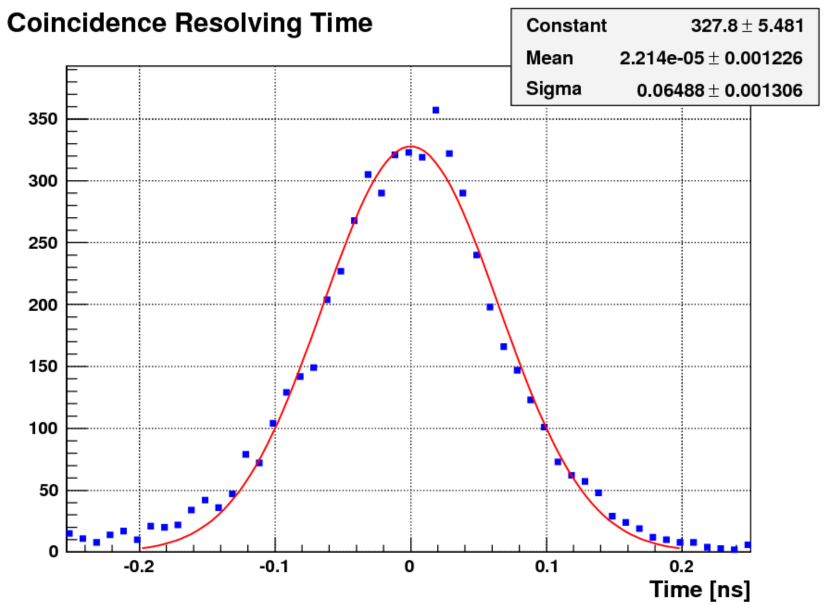


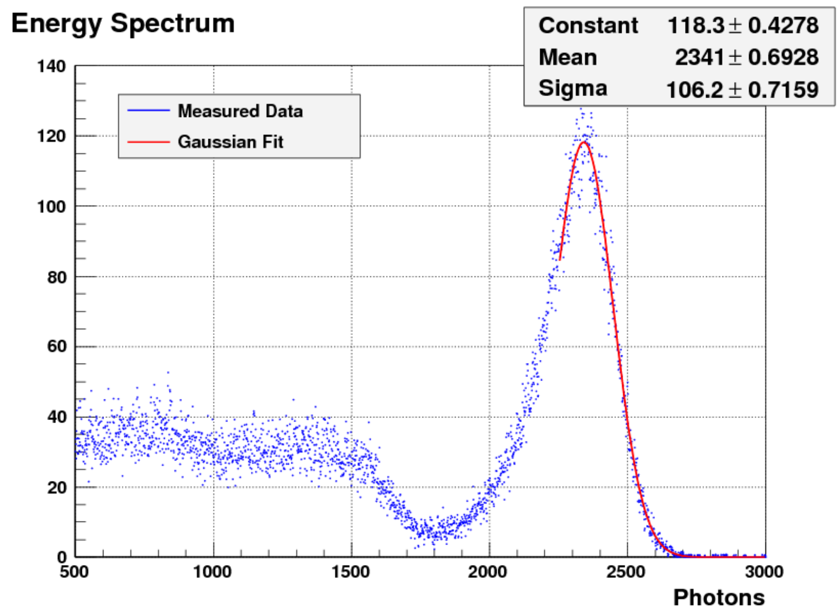




- Diodes activated one-by-one and triggered by a divergent ps-laser pulse.
- Many photons per diode&pulse → negligible avalanche spread uncertainty.
- Laser trigger&pulse spread and TDC resolutions are included in the final σ.

DLD8K – Scintillator Measurements





- 3 x 3 x 5 mm³ LYSO in coincidence, Na-22 source
- Time resolution in coincidence: **153ps** FWHM
- Energy resolution (excluding escape peak): **10.7%**
- Excess voltage 3.3V, 98.5% active cells
- Room temperature (31°C board temperature, not stabilized)

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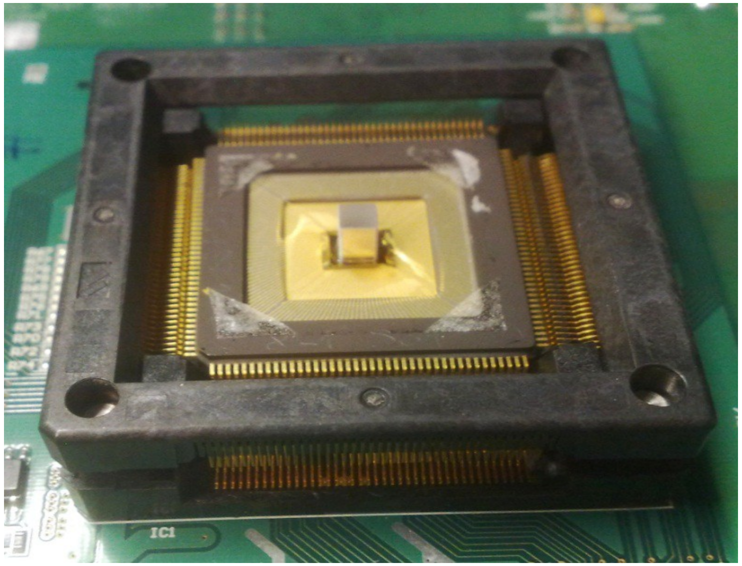
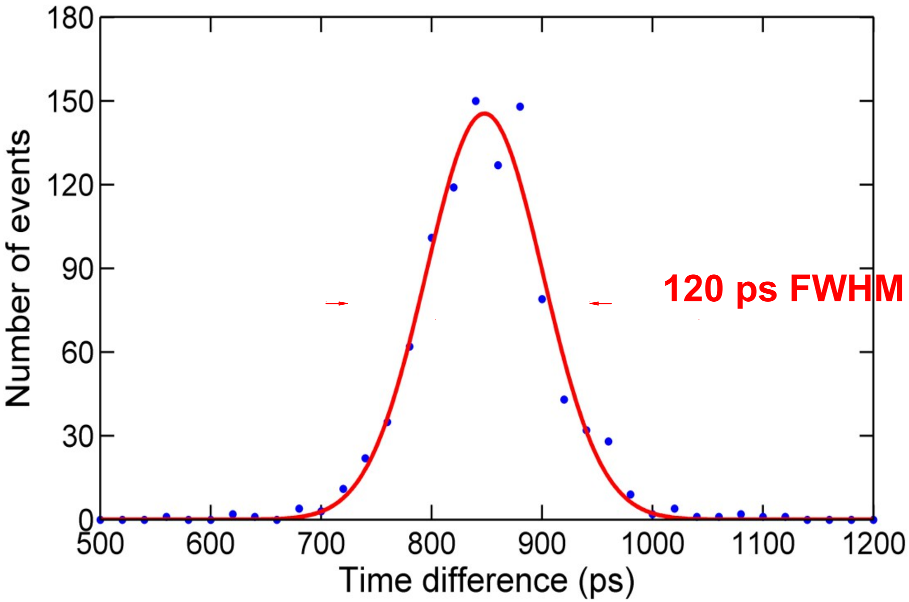
DLD8K – Scintillator Measurements (II)





- 3 x 3 x 5 mm³ Ca co-doped LSO:Ce in coincidence, Na-22 source
- Time resolution in coincidence: **120ps** FWHM
- Energy resolution: **10%**
- Room temperature

D. R. Schaart, H. T. van Dam, G. J. van der Lei, S. Seifert,
"The Digital SiPM: Initial Evaluation of a New Photosensor for Time-of-Flight PET,"
2011 IEEE Nuclear Science Symposium and Medical Imaging Conference,
Valencia, Spain, October 23-29, 201

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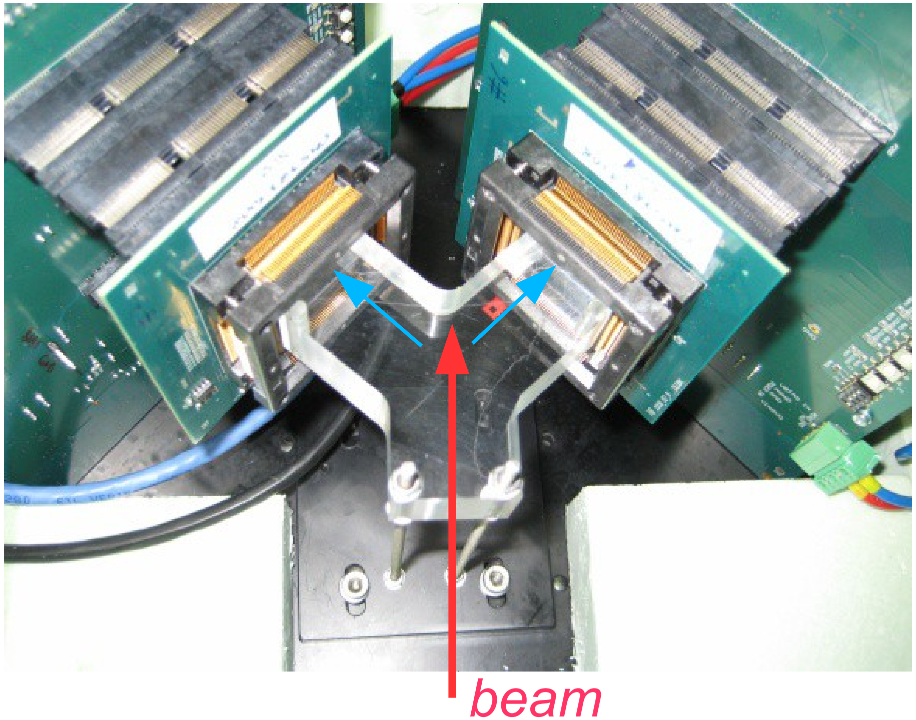
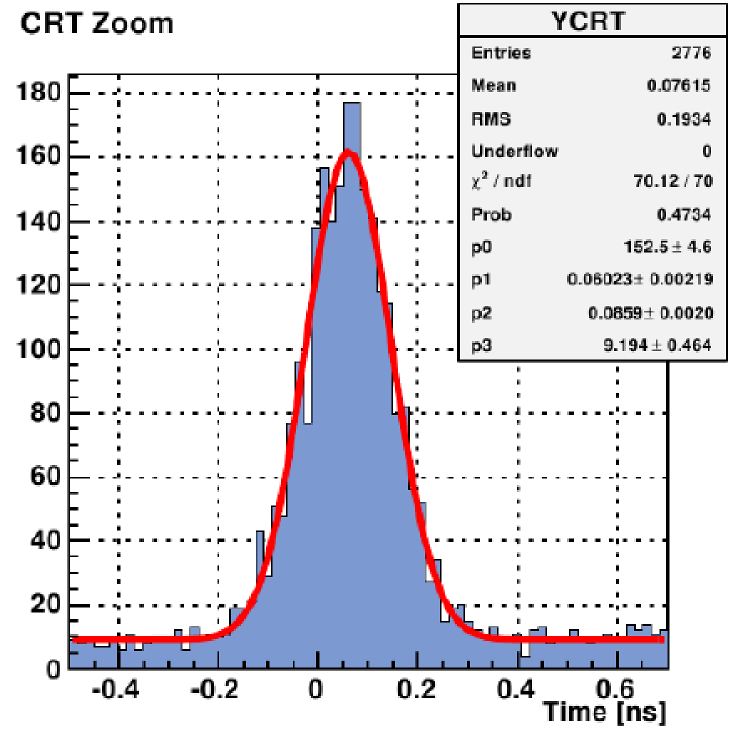
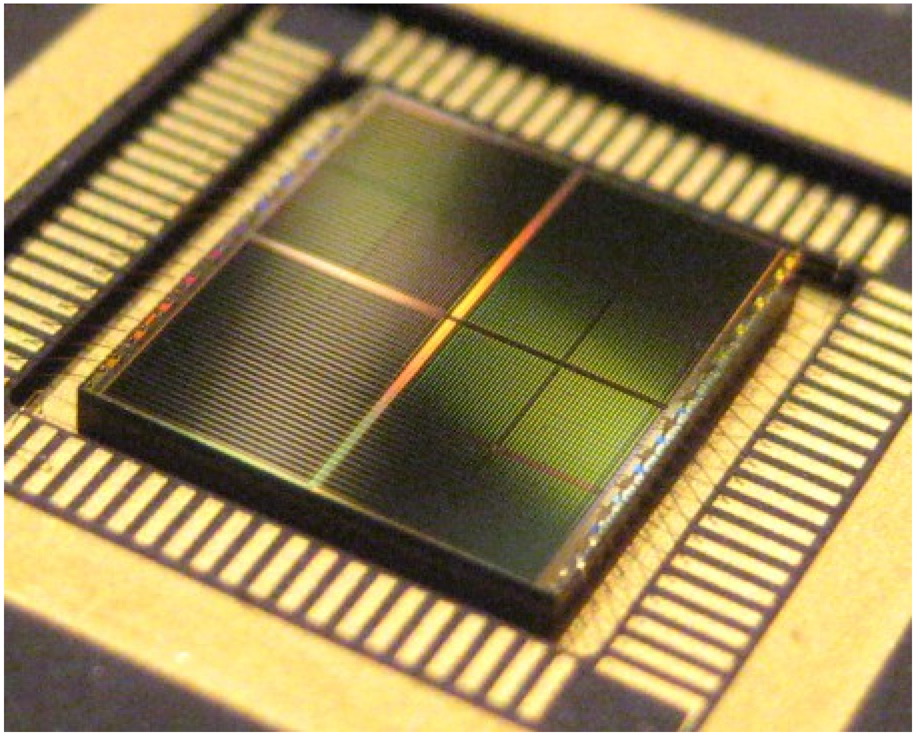
DLD8K – Čerenkov Light Detection





- PMMA radiator coupled via air gap to two dSiPMs (DLD8K) in coincidence
- Box isolated and temperature-controlled with a TEC to 2 – 3°C
- Cooperation between Giessen University (Prof. Düren) and Philips DPC
- First measurements at CERN SPS: **σ = 60.7ps**

DLS 3200-22 (2011)



- Based on DLS 6400-22
- Fully compatible interface
- Two diode cells merged vertically resulting in 59.4µm x 64µm cell
- 3200 micro-cells per pixel
- Max. fill factor 84%
- Currently 78% (wide guard rings)
- Improved trigger network
- New trigger level scheme
- Modified validation scheme
- Improved event processing

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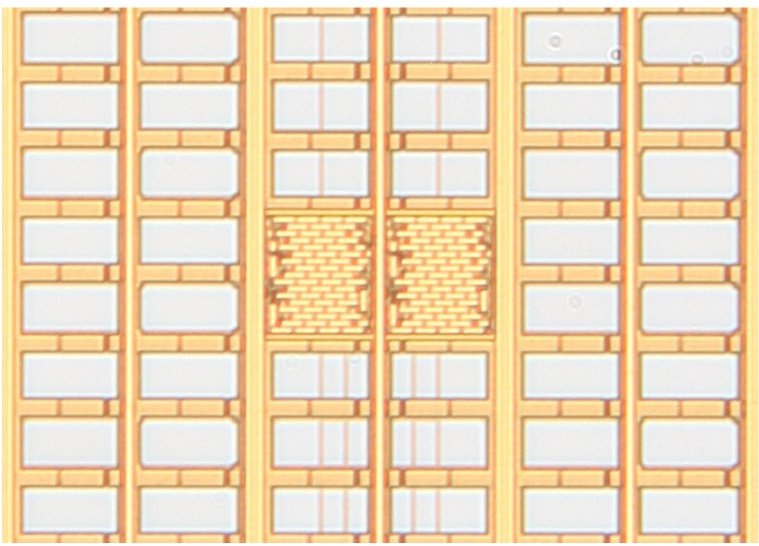
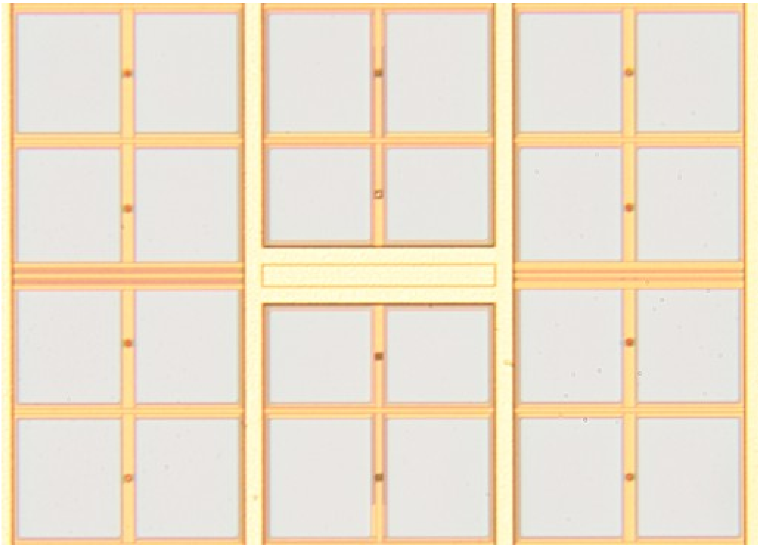
DLS 3200-22 – Comparision

New Experimental Design DLS 3200-22:

- 3200 cells per pixel, 12800 cells per sensor
- 59.4µm x 64µm cell size, 78% area efficiency (incl. electronics)
- Based on (and compatible to) DLS 6400-22 sensor

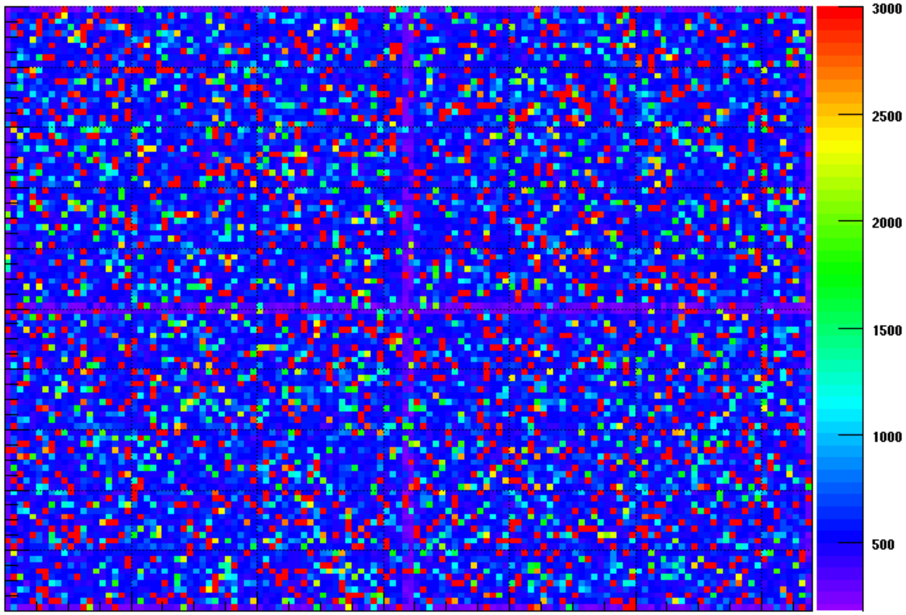


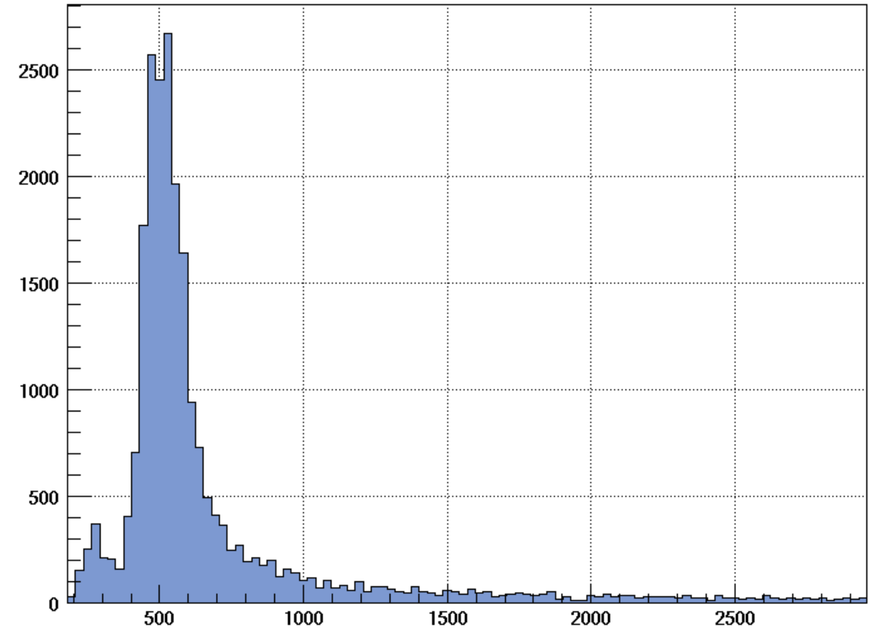
DLS 6400-22



DLS 3200-22

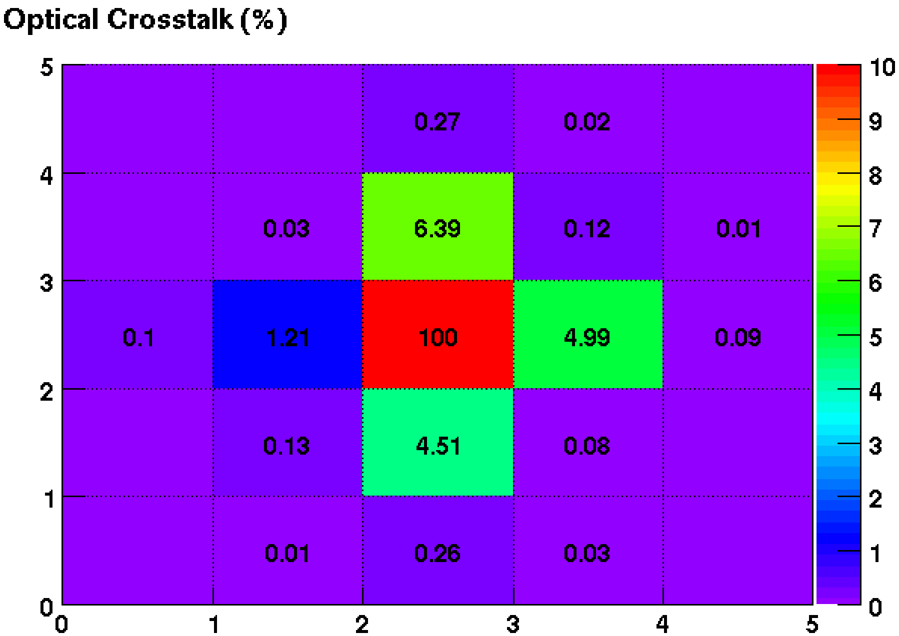
DLS 3200-22 – Dark Count Rate

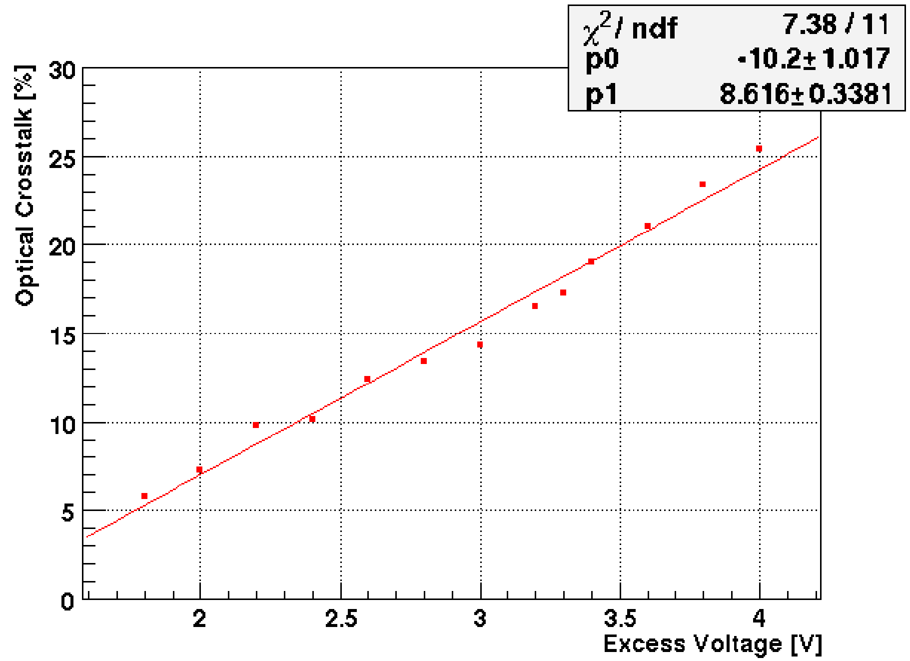




- Dark count rate at 20°C, 3.3V excess voltage
- Average dark count rate ~ 550cps per SPAD
- Scales with SPAD sensitive area (2954μm² vs. 783μm² in DLD8K)

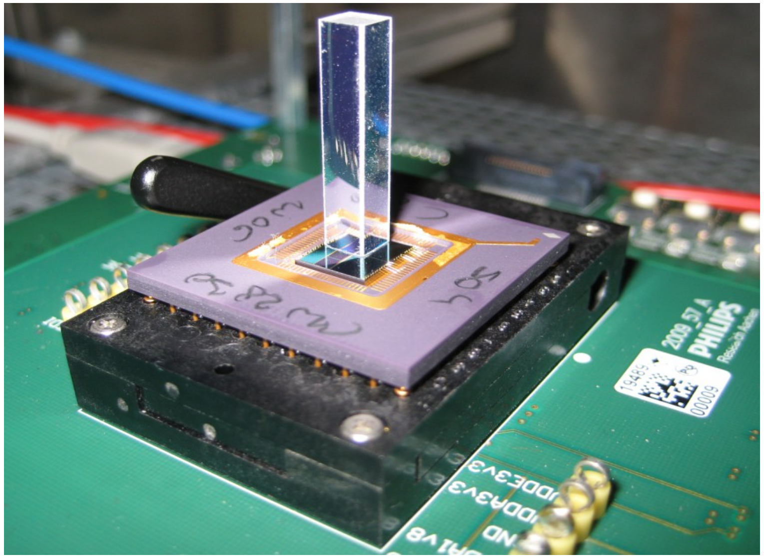
DLS 3200-22 – Optical Crosstalk



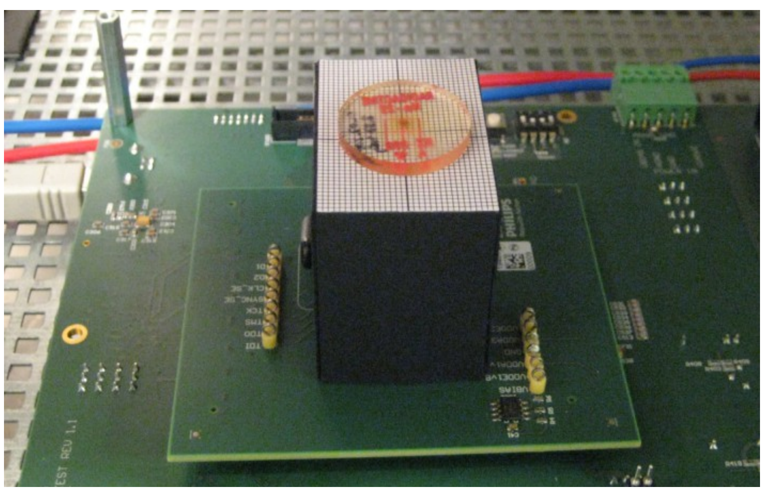


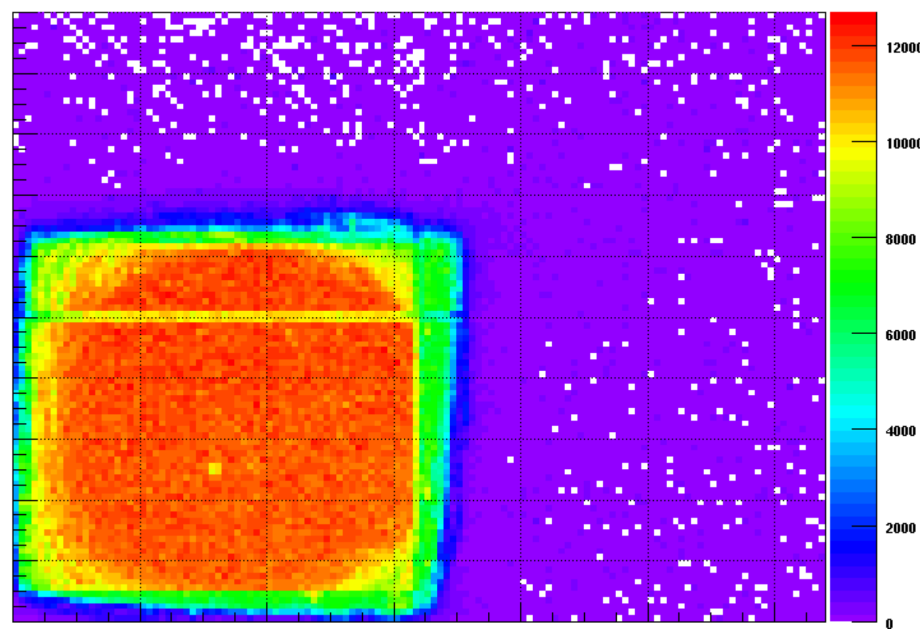
- Optical crosstalk ~18% due to higher diode capacitance (factor ~2.8)
- Linear dependence on excess voltage (as expected)
- Has to be taken into account in saturation correction

DLS 3200-22 – Energy Resolution

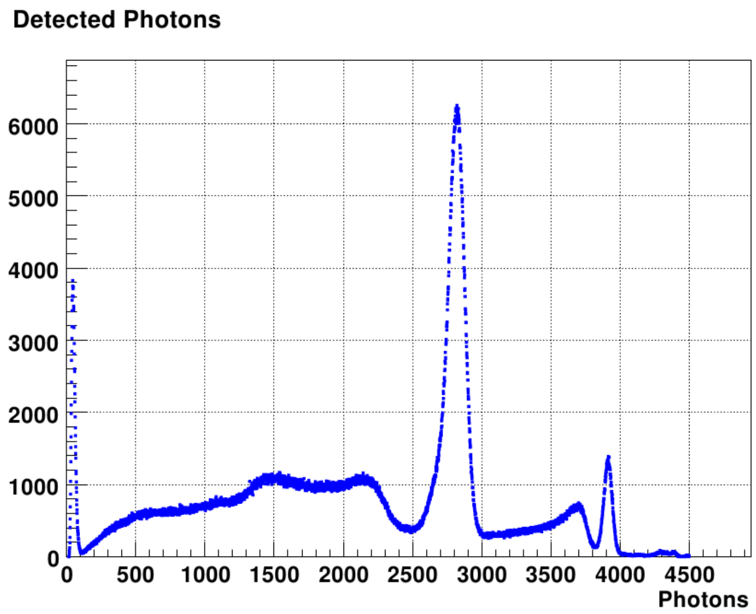


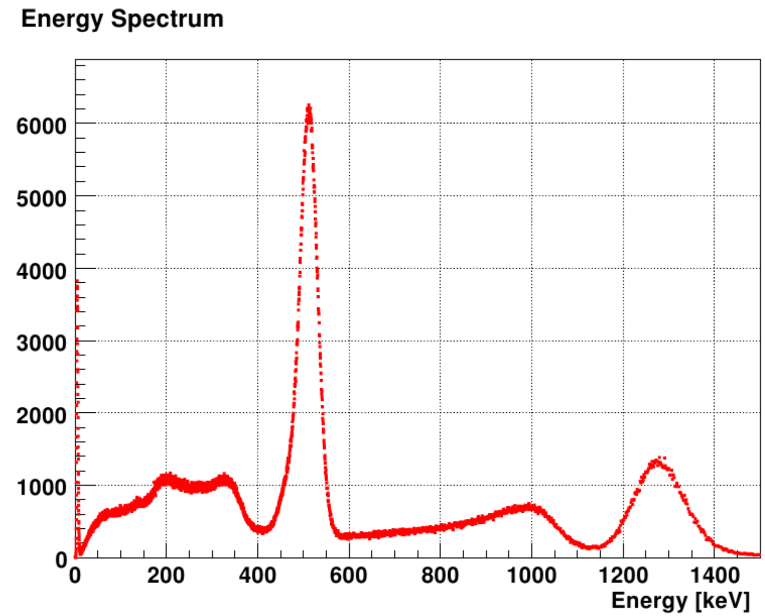
- 4 x 4 x 22 mm³ LYSO crystal
- Vikuiti reflector
- Attached with Meltmount
- Na-22 source

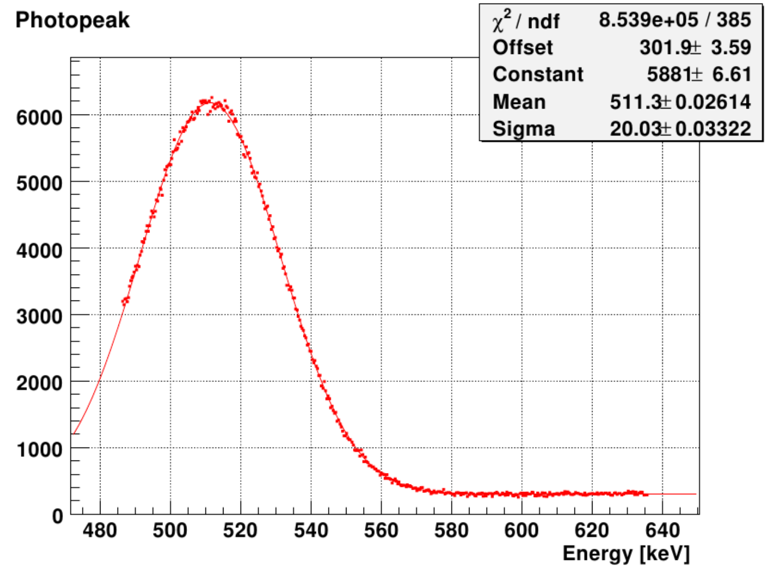




DLS 3200-22 – Energy Resolution







- 3.3V excess voltage, 20°C
- 99% active cells
- Non-linearity correction
- Optical crosstalk included [Burr et al.]
- dE/E = 9.2%

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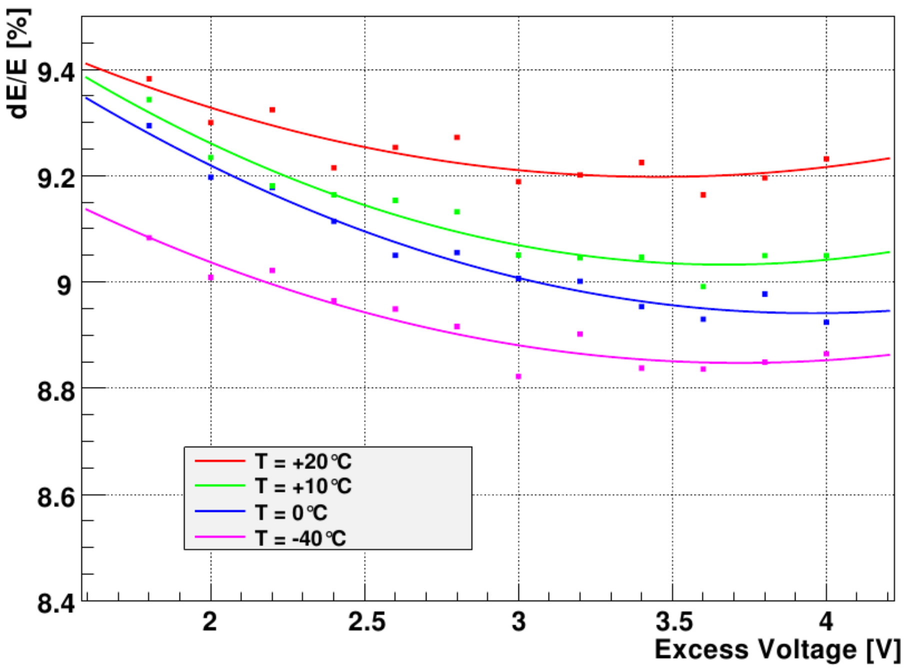
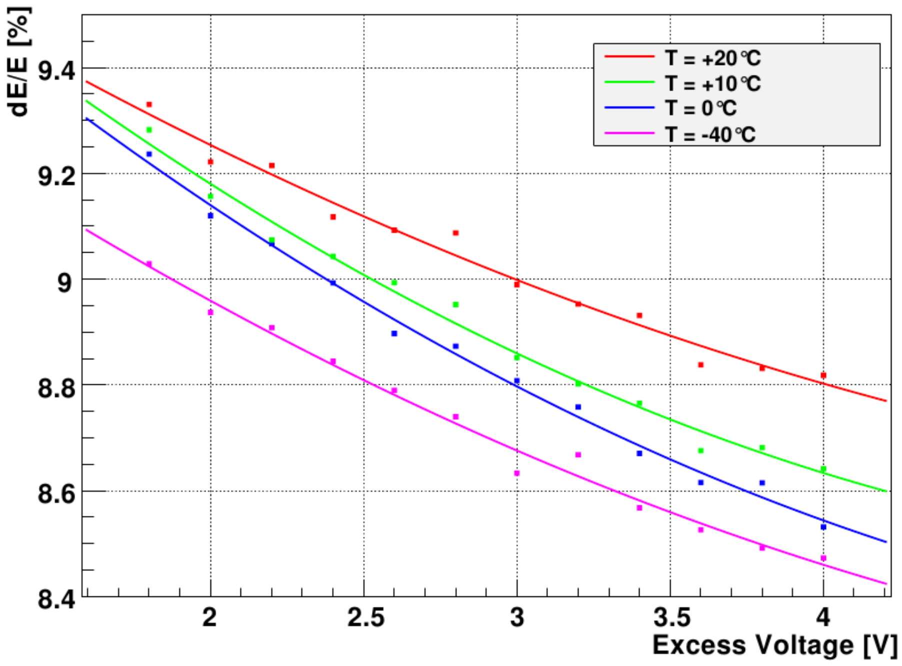
DLS 3200-22 – Saturation Correction

Saturation correction including optical crosstalk model [Burr et al.,2007]:

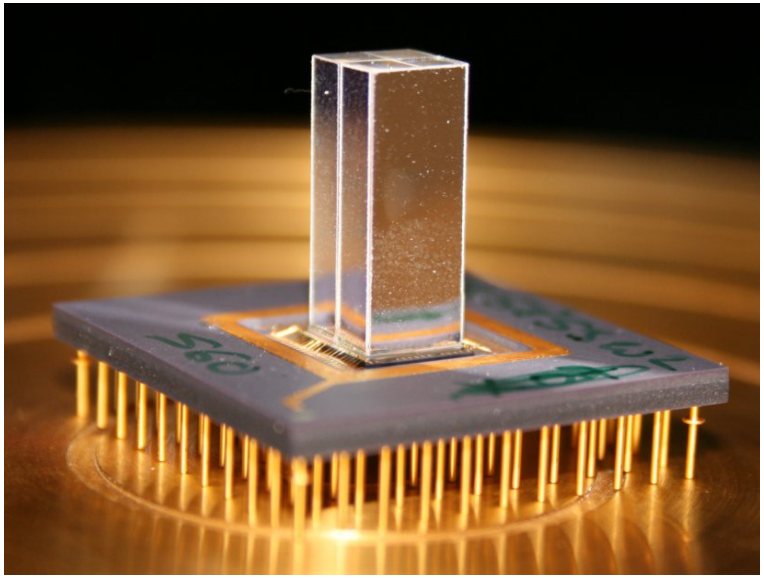


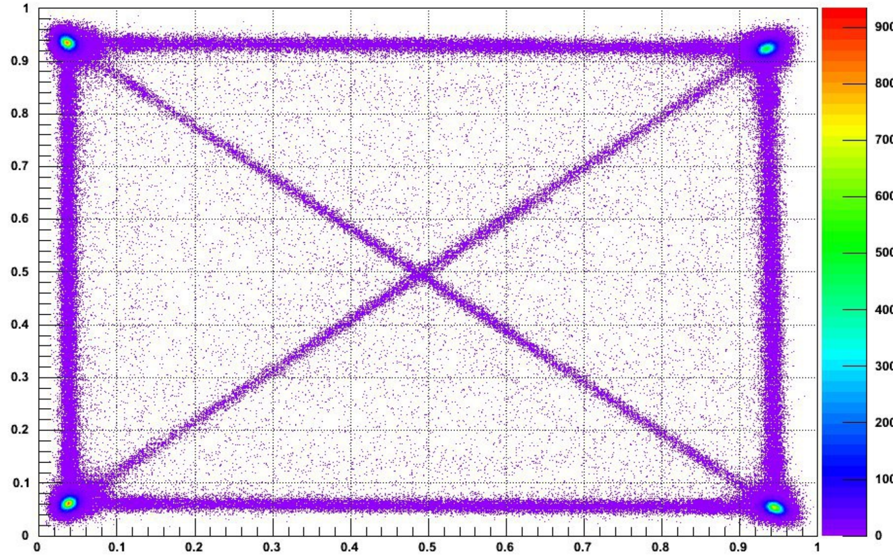
Simple saturation correction neglecting optical crosstalk:

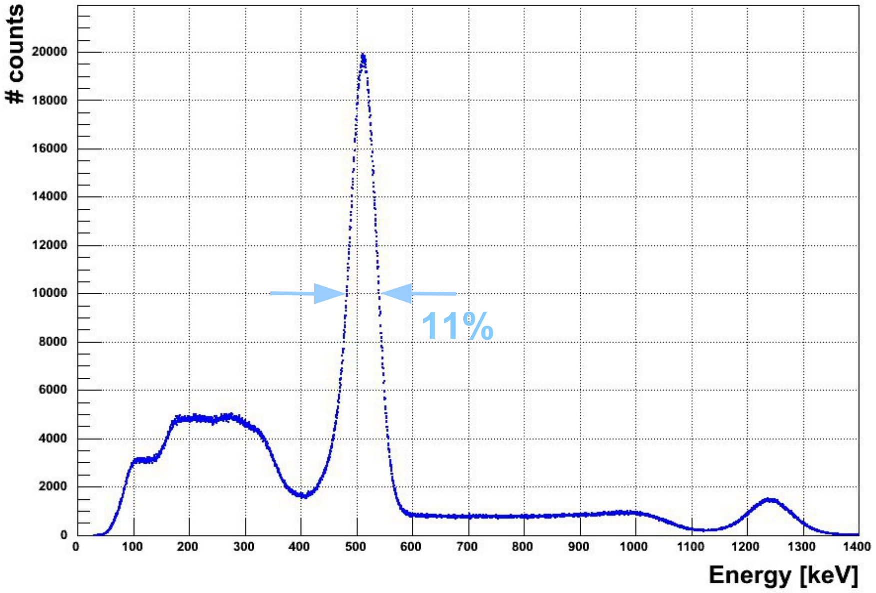


- Optical crosstalk seems to limit the energy resolution

DLS 6400-22 – Crystal Identification







- 2x2 Array of 3x3x15mm³ LYSO
- 1:1 coupling using MeltMount
- Illuminated by ^{22}Na source
- Corrected only for saturation
- dE/E = 11% (combined)

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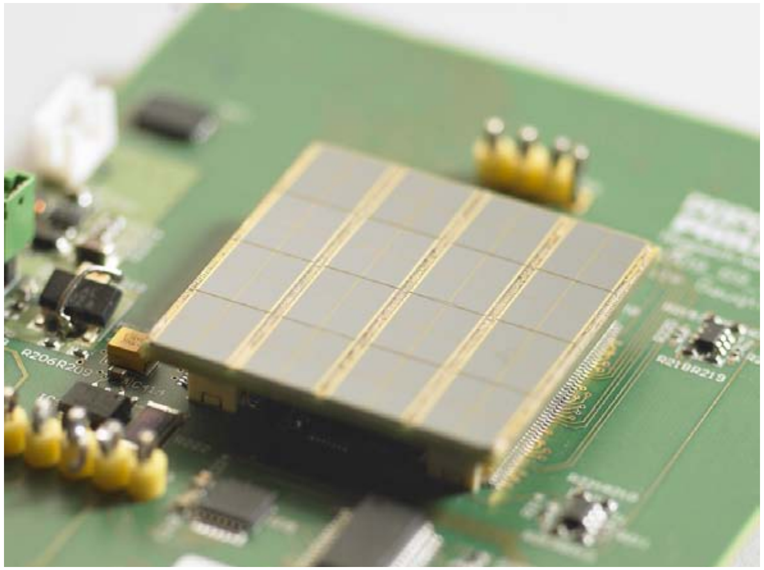
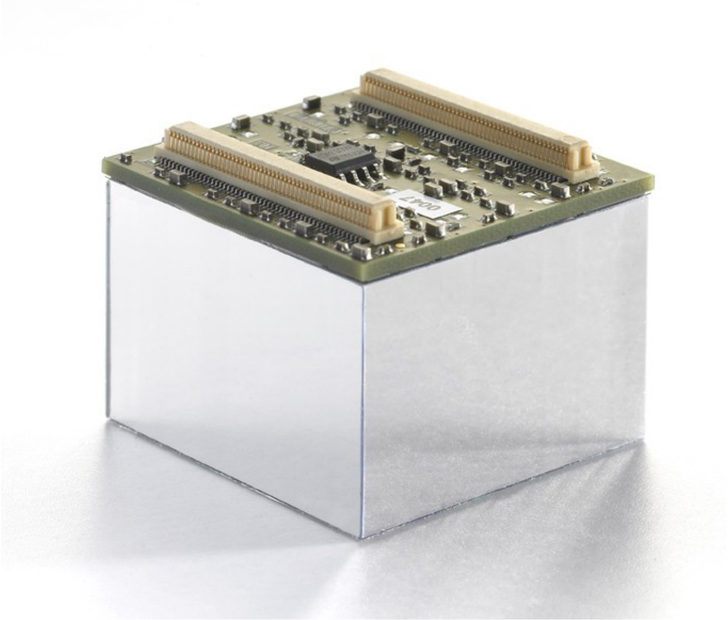
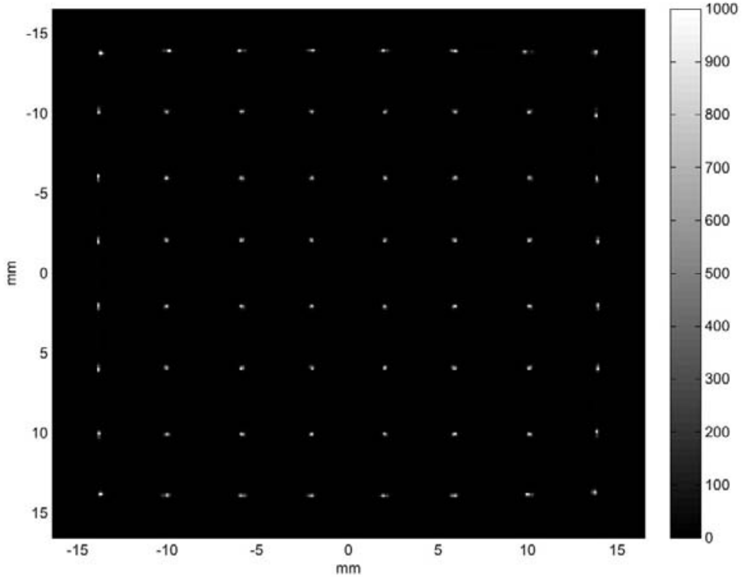
Digital SiPM – Tiles



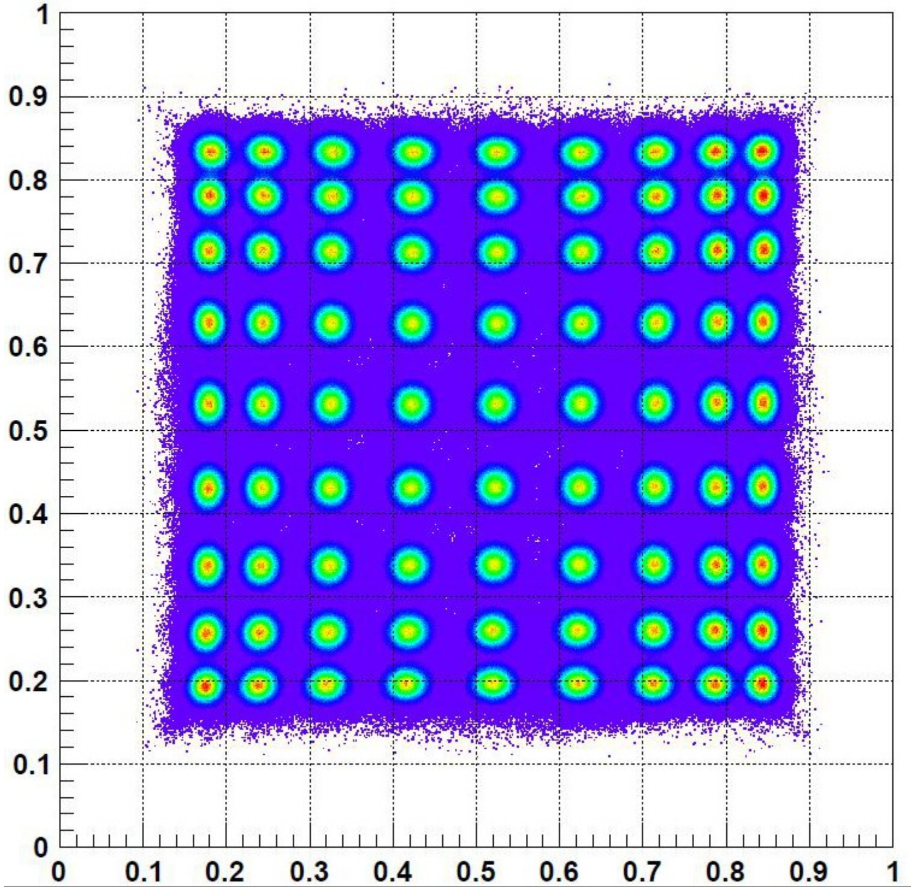


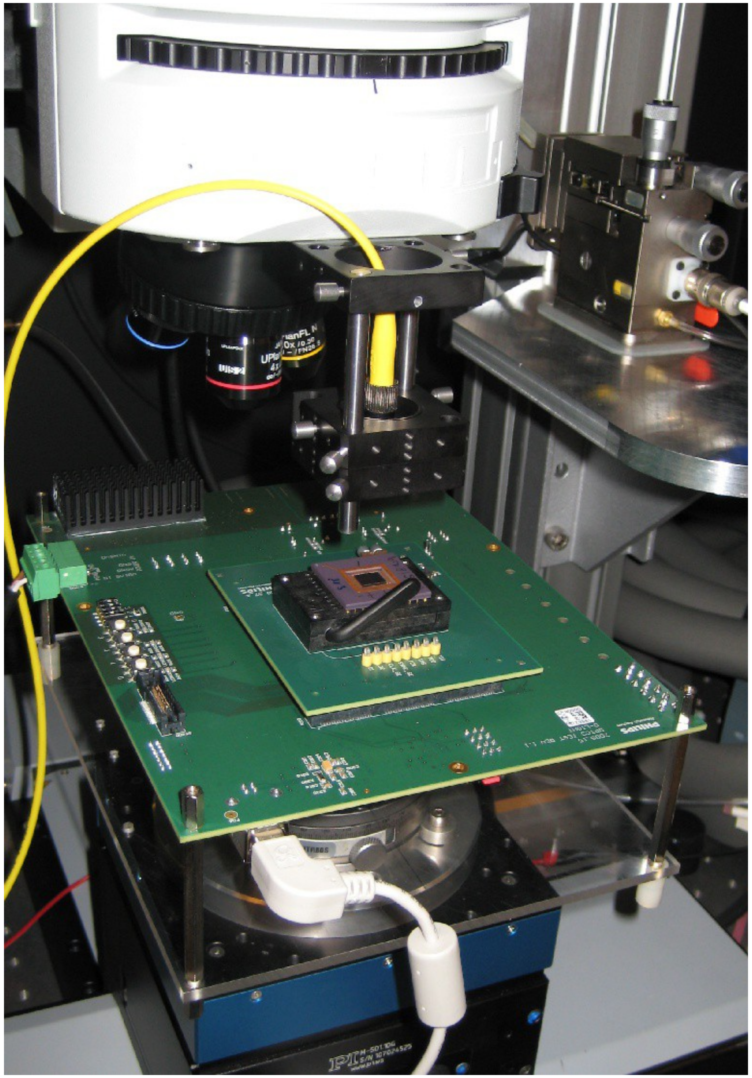
- 4 x 4 sensor array
- 8 x 8 pixels
- 4-sides tileable



Digital SiPM – Small Crystal Identification

- Laser measurements on a 0.5mm grid
- Best case (no scatter, no light guide)
- ~1600 photons per laser pulse





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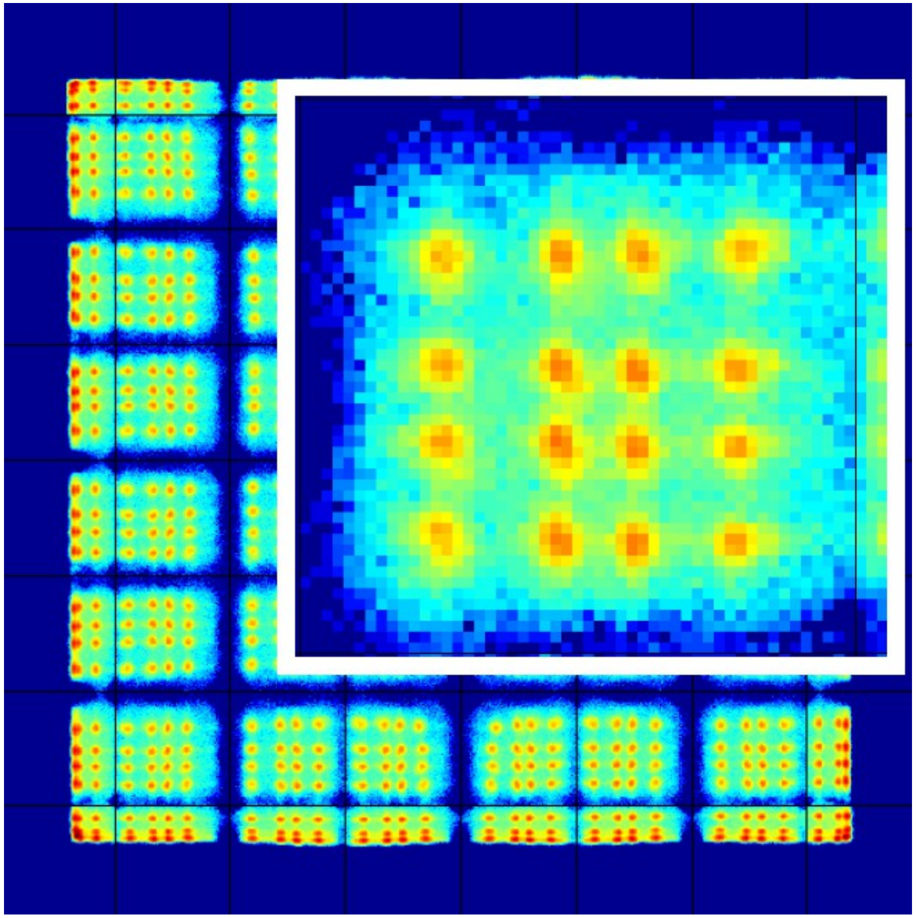
Digital SiPM – Small Crystal Identification

- Array of 30 x 30 LYSO crystals
- Crystal size: 1 x 1 x 10mm³
- Coupled via light guide to one digital SiPM tile (4 x 4 dies)
- Data plotted in log scale
- Strong floodmap compression close to tile edge due to missing neighbor tiles



P. Düppenbecker, Philips Research

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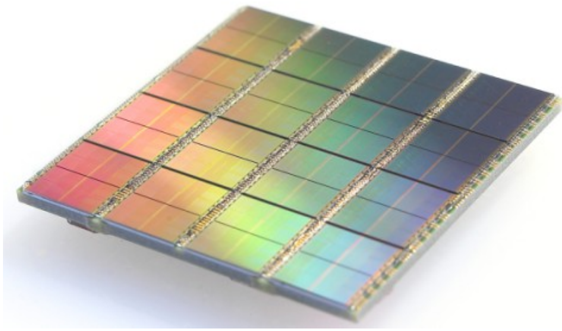
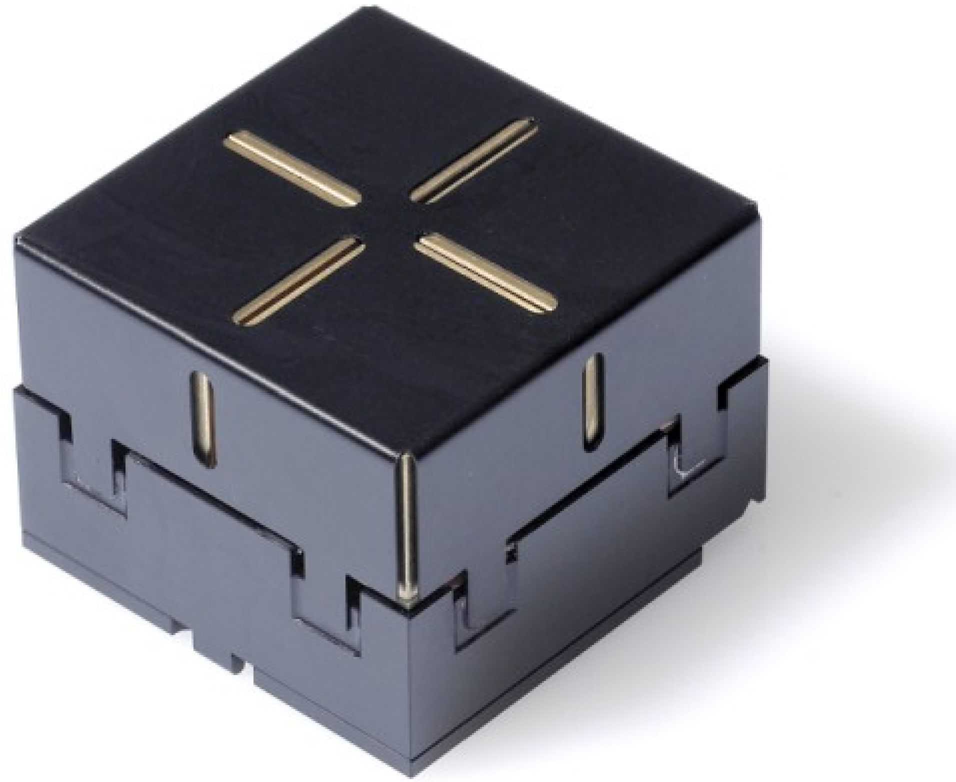
DLS Tiles an Modules





- Enables the construction of scalable detectors with large number of channels
- Power / thermal management included in design

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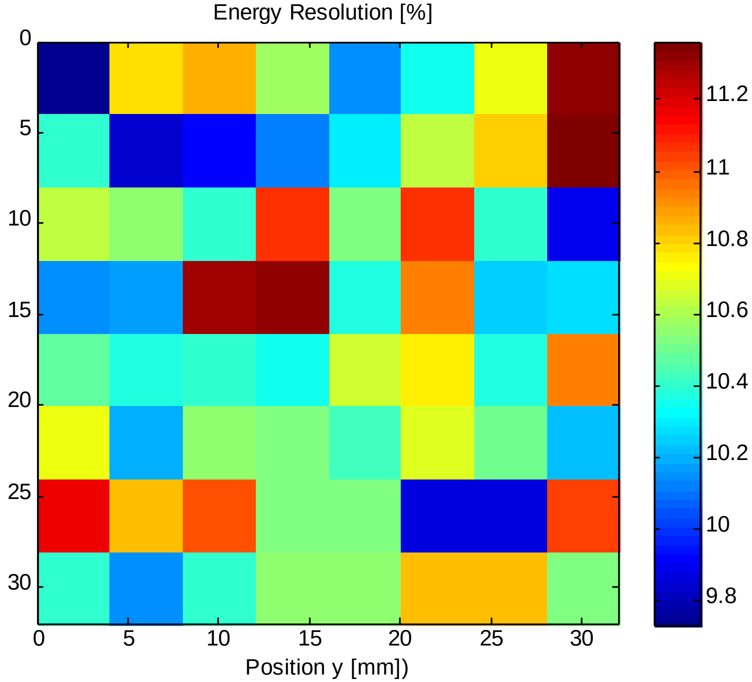
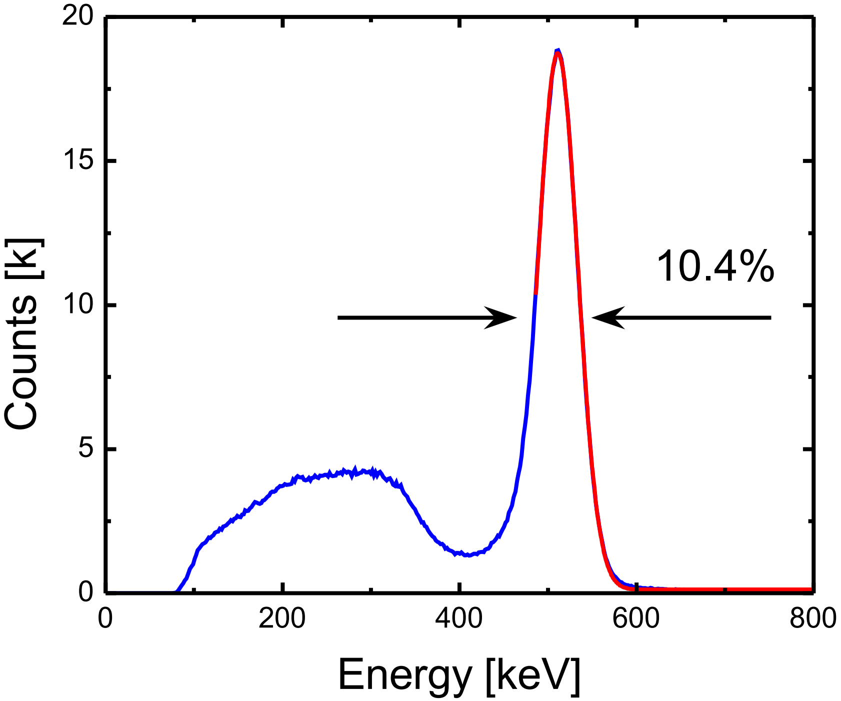
DLS Tile – Scintillator Readout

- *LYSO array, 8 x 8 crystals, 4 mm x 4 mm pitch, 22 mm length*
- *DLS-3200-22-44, measurement at +10°C*

Energy resolution per pixel



Summed histogram over all 64 pixels

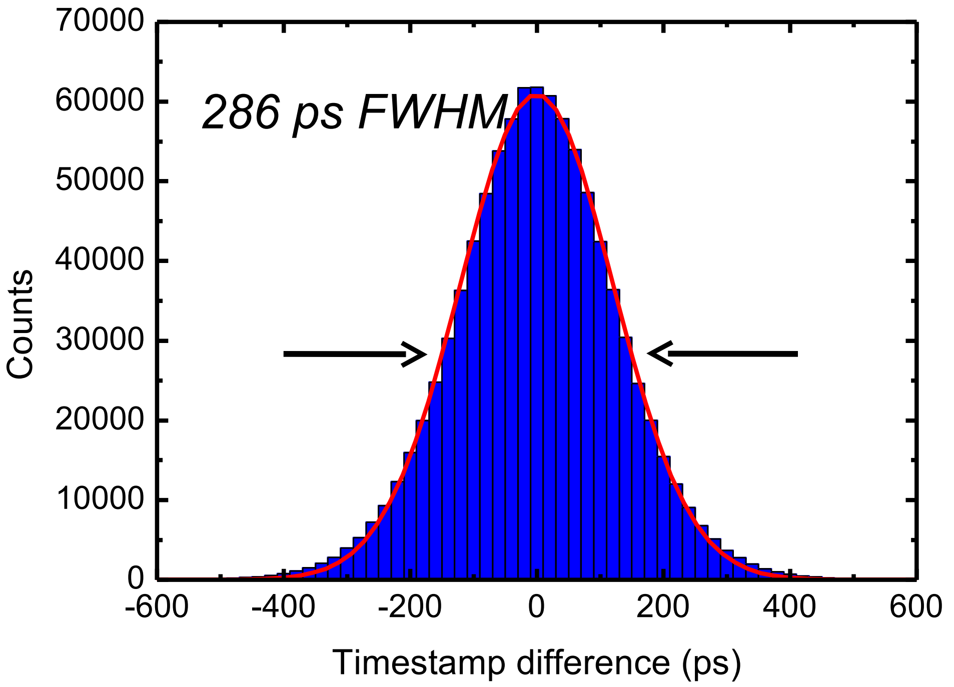


DLS Tile – Scintillator Readout

- LYSO array, 8 x 8 crystals, 4 mm x 4 mm pitch, 22 mm length
- DLS-3200-22-44, measurement at +10°C

Timing resolution per pixel [ps]

Summed histogram over all 64 pixels



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Sensors For New Applications

- Cutting-edge experiments need high-performance sensors
  - Current sensor architecture may not fulfill all requirements
  - Ideally, the existing sensor can be extended to match the requirements but this is not always possible (different requirements on cell/chip size)
  - Dedicated designs needed but require large NRE investment per design

- Dedicated SiPMs, different cell and die sizes, analog or digital data processing
  - Vanishing boundary between photon detection and data processing
  - Early user feedback and application knowledge crucial for development

    → allow the users to develop their own dedicated digital SiPMs

→ **Philips/NXP plan to offer multi-project wafer runs to the HEP community**

  - Many experienced designers already working on mixed-signal ROCs
  - Develop your own digital SiPM sensors tailored to your experiment
  - Share the experience and mask cost with other users
  - Is there sufficient demand for multi-project wafer service in this technology?

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Summary

- Digital SiPM implemented in a high-volume CMOS process
- Configurable architecture, individual control of each SPAD
- Tiles of 4 x 4 sensors and modules with 2 x 2 tiles developed
- New design with improved fill factor of 78% currently being tested

- Multi-project wafer runs planned to allow users to develop application specific sensors. Please contact us if you are interested.

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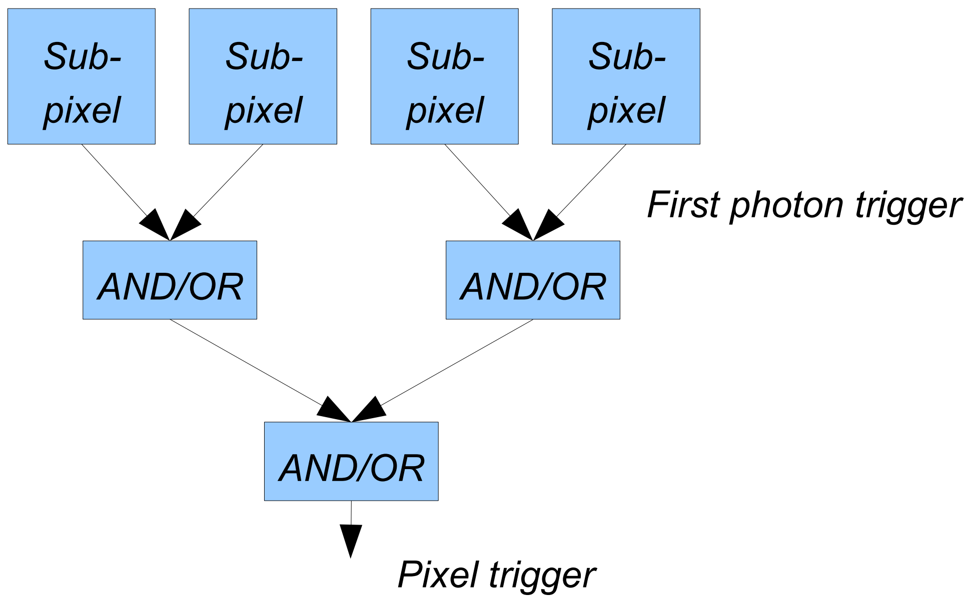
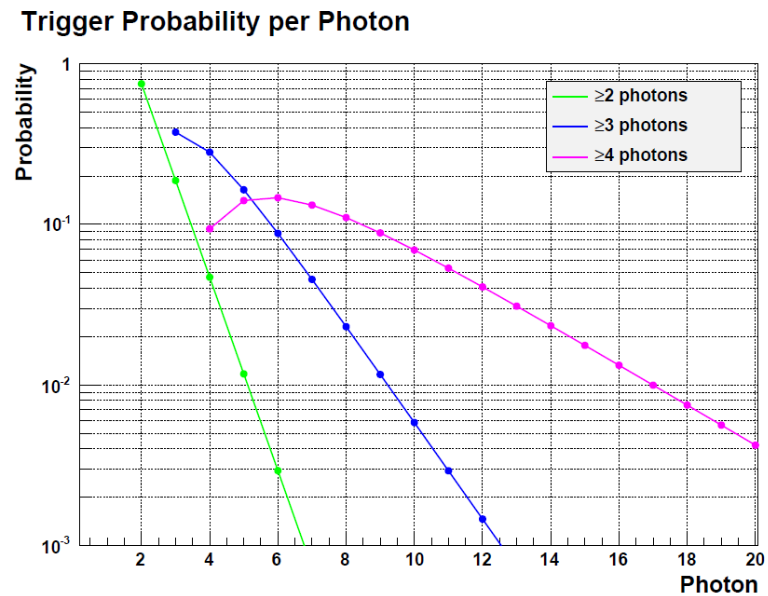
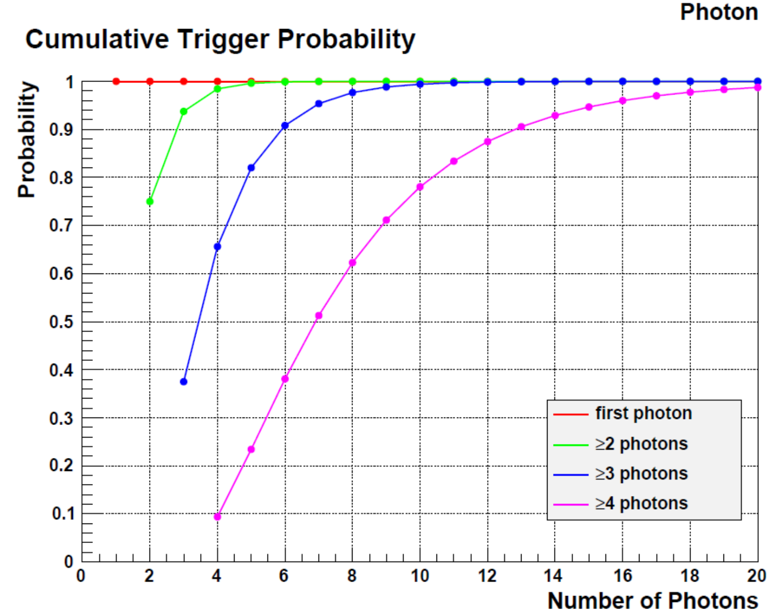
Digital SiPM – Trigger Logic

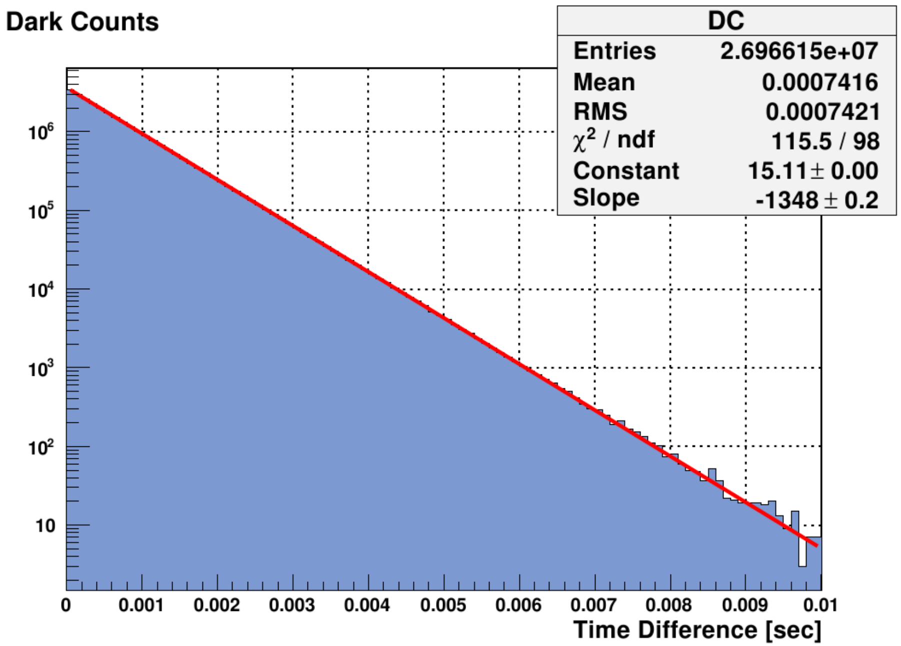


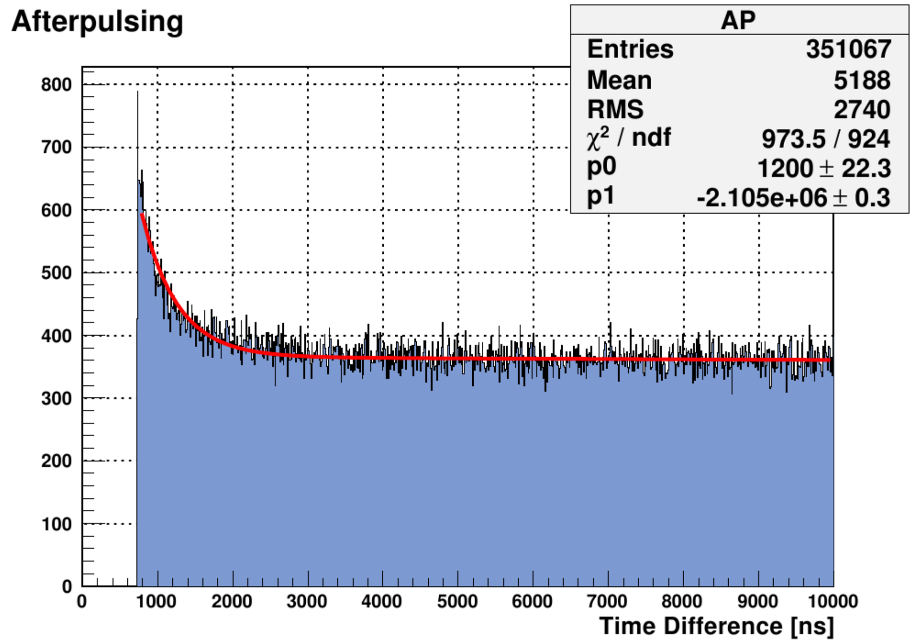
- Each sub-pixel triggers at first photon
- Sub-pixel trigger can be OR-ed or AND-ed to generate probabilistic trigger thresholds
- Higher trigger threshold decreases system dead-time at high dark count rates at the cost of time resolution





Digital SiPM – Afterpulsing Probability





Time differences of two consecutive dark counts in a single diode.

Afterpulsing: deviation from the Poisson distribution in the first few µs.

Many diodes show afterpulsing probabilities of less than 0.1%, few are in the 2-3% range.

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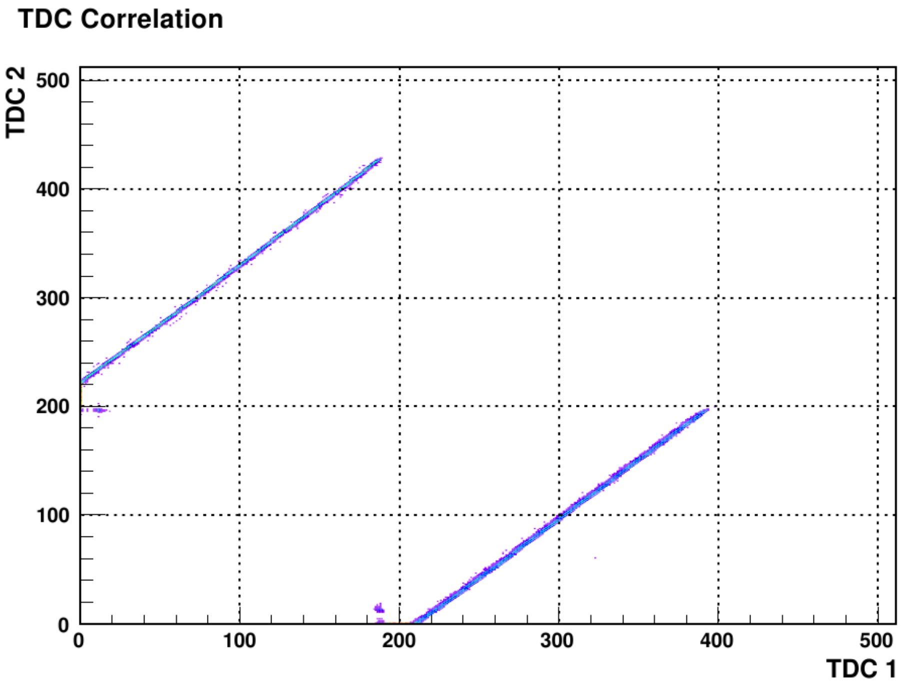
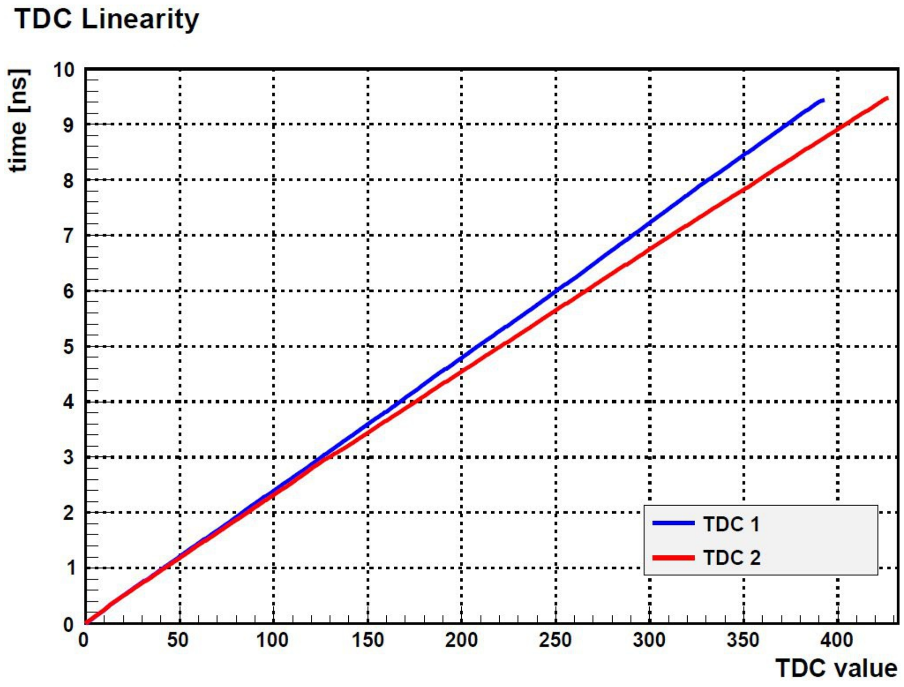
Digital SiPM – Time-to-Digital Converter





- Two identical 9 bit TDCs running with 180° phase-shifted clocks
- 100MHz reference clock generated from 200MHz system clock
- Each TDC has ~0.5ns wide 'blind spot' close to clock edge → bin 0
- Two-phase clock guarantees at least one valid TDC value for any event
- For ~90% of the events, both TDC values can be used to increase accuracy
- TDC calibration using dark counts or randomly distributed events

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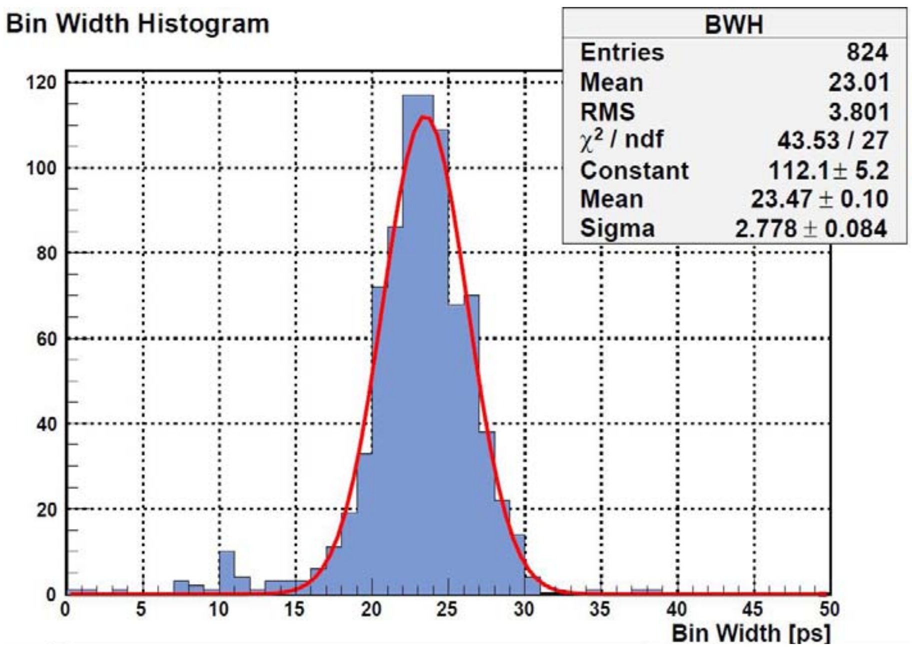
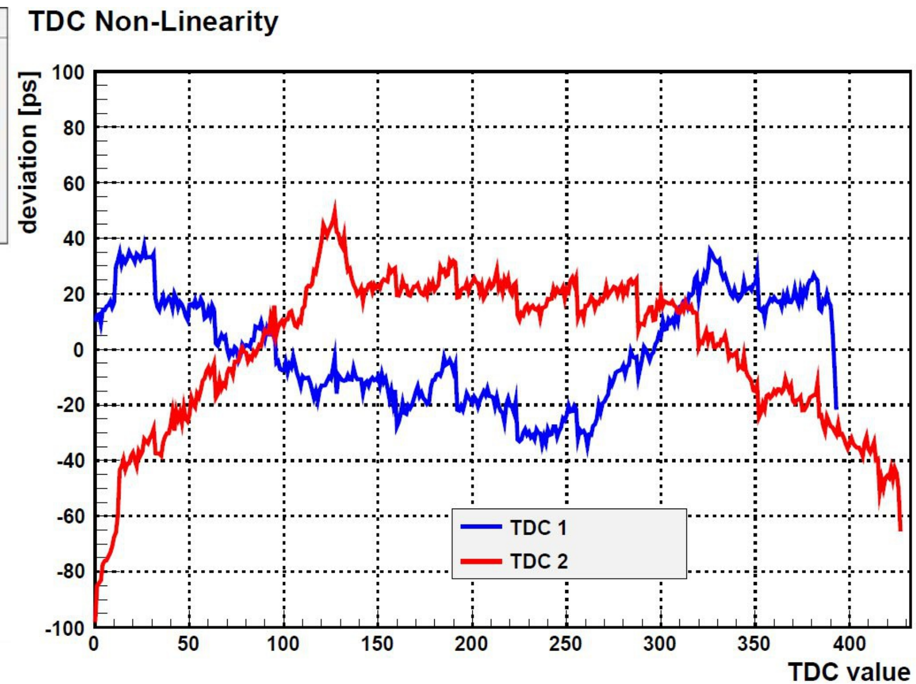
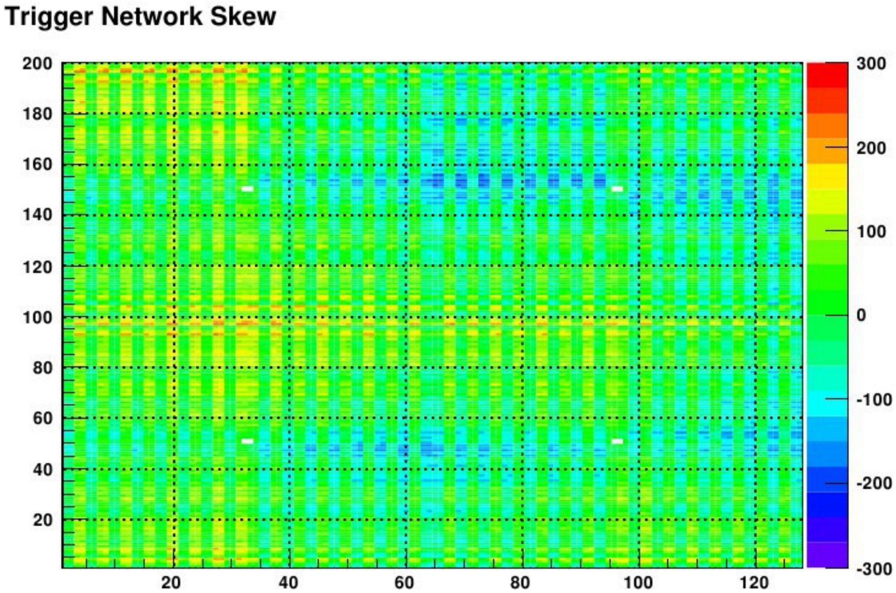
Digital SiPM – Time-to-Digital Converter

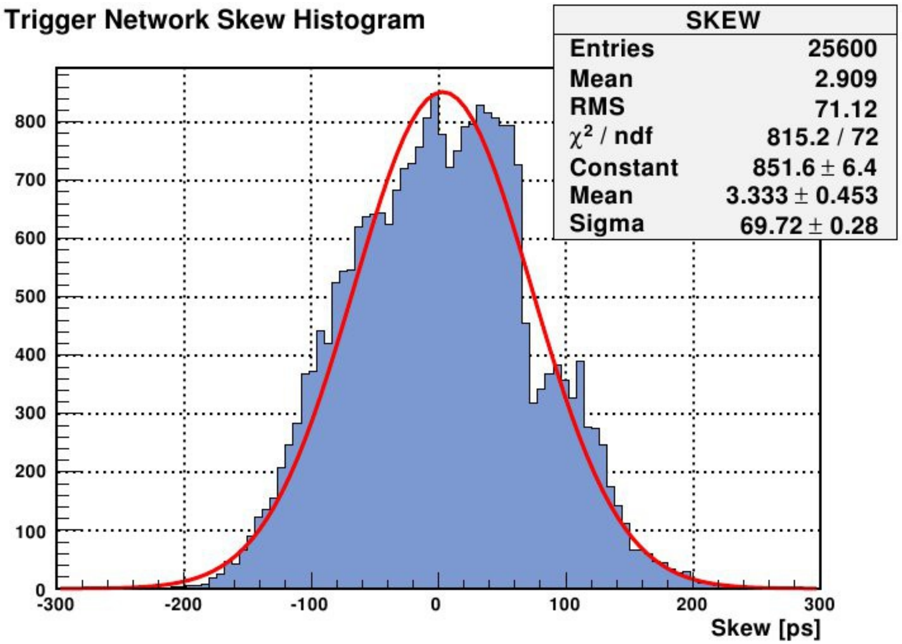




- Average TDC bin width 23 ± 2.8ps
- Non-linearity corrected by look-up tables inside the readout FPGA
- Online correction for TDC drift due to temperature and voltage variation
- Periodic TDC calibration test using external (SYNC) signal

Digital SiPM – Trigger Network Skew





- Chip illuminated by divergent picosecond laser beam
- Laser trigger synchronized to the reference clock
- All diodes measured sequentially
- 10000 events captured and time stamp histogram fitted with a Gaussian
- Gaussian mean → delay of the selected trigger path
- Average trigger network delay subtracted from the data