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Digital Photon Counter Development at Philips

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Philips Digital Photon Counting

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Outline

- Geiger-mode APD basics
- G-APD development in Philips/NXP
- Digital SiPM architecture
- Many measurement results, scintillators & laser
- Potential extensions and some new ideas
- Conclusion

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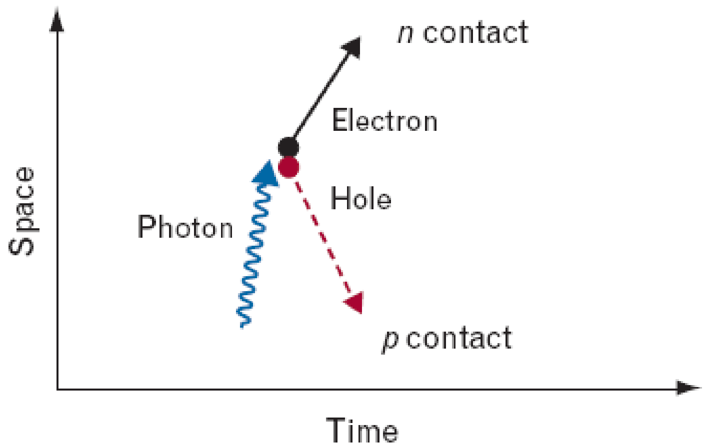
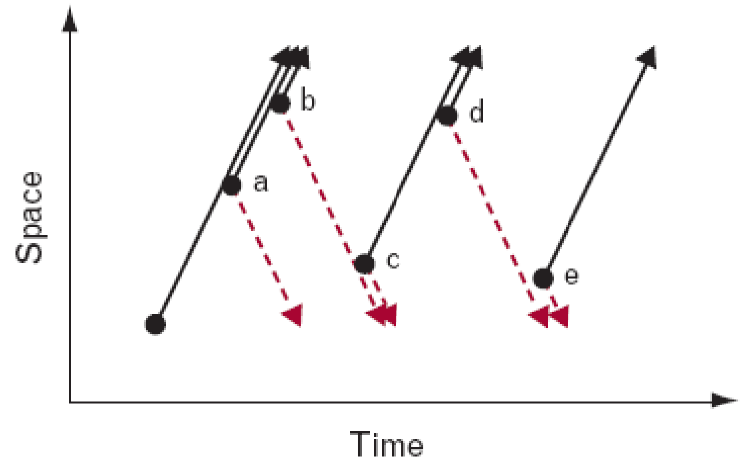
G-APD: Avalanche Multiplication





(Aull et al.)

- Incident photon is absorbed in Silicon, generates one electron-hole pair
- Both carriers are separated and accelerated by the strong electric field
- Gaining enough energy, both can impact-ionize and generate new carriers
- Below breakdown: charge is approximately proportional to number of photons
- Above breakdown: e-h pair can generate full breakdown of the diode
- Thermal generation of carriers acts as a noise component (dark counts)

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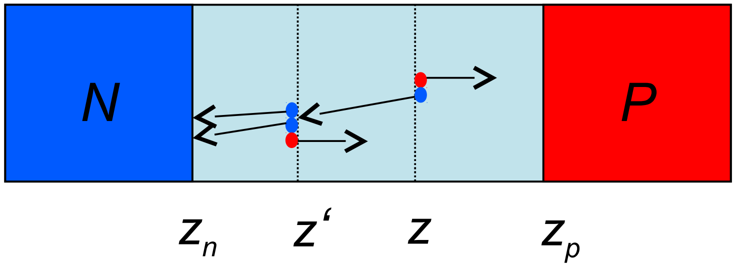
G-APD: Avalanche Breakdown



Avalanche multiplication equation:

$$M(z) = 1 + \int_{z_n}^{z} \alpha_n M(z')\,dz' + \int_{z}^{z_p} \alpha_p M(z')\,dz'$$

Solving for M leads to:

$$M_n = \frac{1}{1 - \int_{z_n}^{z_p} \alpha_n \exp\left(-\int_{z'}^{z_p} (\alpha_n - \alpha_p)\,dz''\right) dz'}$$

Breakdown condition:

$$\int_{z_n}^{z_p} \alpha_n \exp\left(-\int_{z'}^{z_p} (\alpha_n - \alpha_p)\,dz''\right) dz' = 1 \qquad \text{(McIntyre, 1966)}$$

where α_n and α_p denote the position-dependent ionization rates in silicon

G-APD: Ionization Rates α_n and α_p

- Number of new carriers created per cm of travel
- Ionization rate of holes approximately ½ that of electrons
- Mostly based on measured data, theoretical prediction still difficult

Chynoweths law: $$\alpha_i = \alpha_{i,\infty} \exp\left(-\frac{b_i}{E}\right), \quad i = n, p$$

E = local electric field strength

Coefficients by Overstraeten and de Man (1970):

<table>
<tr><th>$\alpha_{n,\infty}$ [cm^{-1}]</th><th>b_n</th><th colspan="2">Field range (kV/cm)</th><th>$\alpha_{p,\infty}$ [cm^{-1}]</th><th>b_p</th><th colspan="2">Field range (kV/cm)</th></tr>
<tr><td rowspan="2">703E3</td><td rowspan="2">1231E3</td><td rowspan="2">175</td><td rowspan="2">600</td><td>1582E3</td><td>2036E3</td><td></td><td>400</td></tr>
<tr><td>671E3</td><td>1693E3</td><td>400</td><td>600</td></tr>
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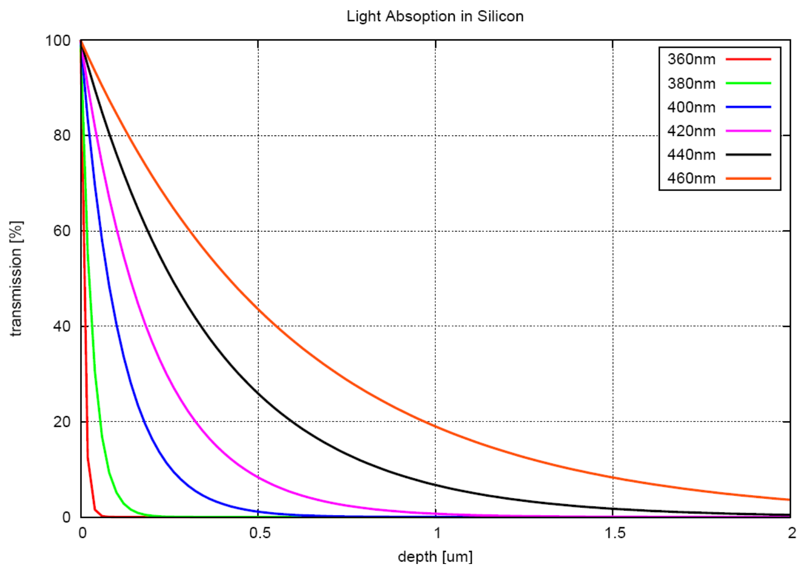
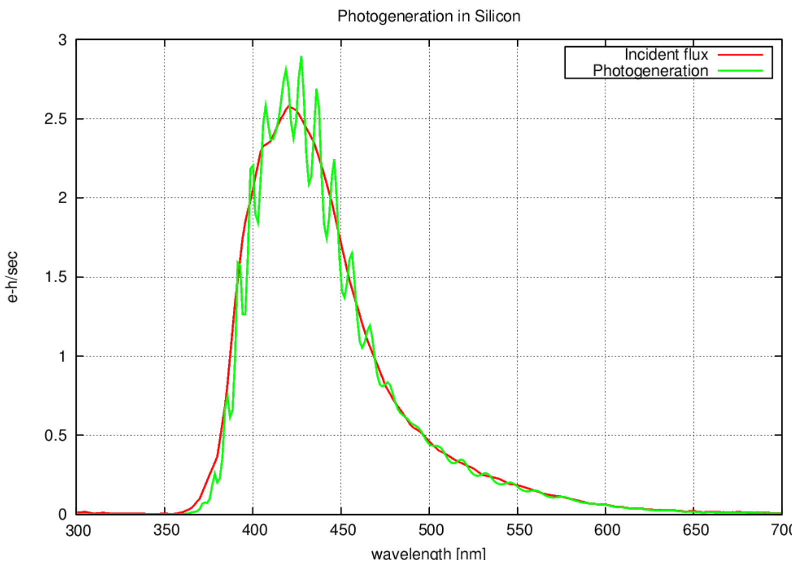
For a detailed discussion of CMOS-based G-APDs see the thesis of W. Kindt.

G-APD: Quantum Efficiency





1µm junction incl. 5-metal stack and passivation

- Wavelength-dependent absorption in Silicon
- Charge collection area (drift, diffusion)
- Minority carrier lifetimes (doping level, defect density)
- Interferences in the back-end stack (metal/insulator layers and passivation)

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G-APD: Avalanche Probability

Probability depends on the position of the e-h generation:

$$P_p(z) = P_{pe}(z) + P_{ph}(z) - P_{pe}(z)P_{ph}(z)$$

For electrons (similar for holes):

$$P_{pe}(z+dz) = P_{pe}(z) + \alpha_n dz \cdot P_p(z) - P_{pe}(z) \cdot \alpha_n dz \cdot P_p(z)$$

Leads to:

$$\frac{dP_{pe}}{dz} = +(1 - P_{pe})\alpha_n(P_{pe} + P_{ph} - P_{pe}P_{ph})$$

Function of bias and position

$$\frac{dP_{ph}}{dz} = -(1 - P_{ph})\alpha_p(P_{pe} + P_{ph} - P_{pe}P_{ph})$$

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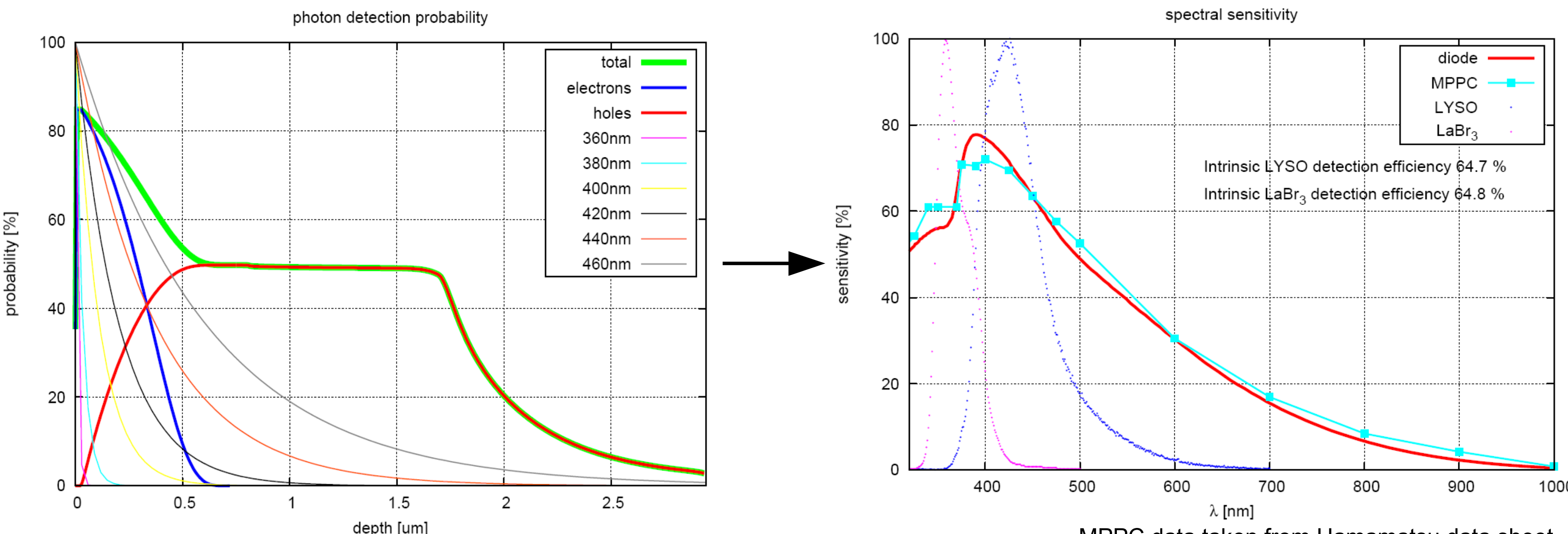
G-APD: Photon Detection Probability

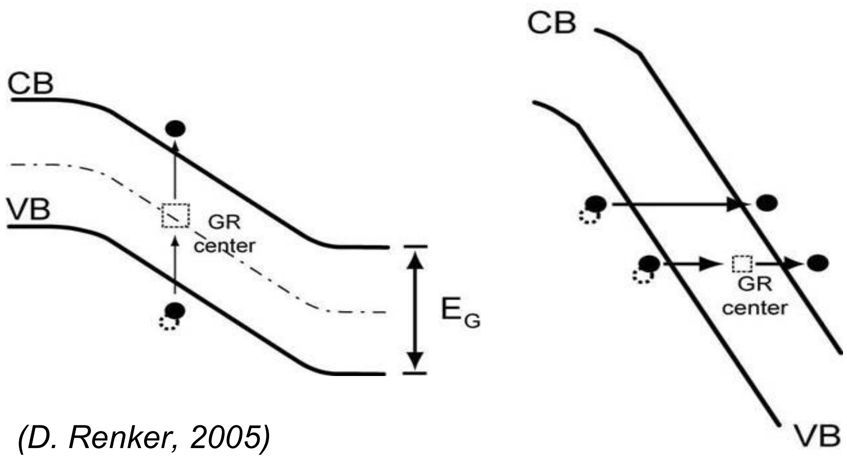


MPPC data taken from Hamamatsu data sheet
scaled with the fill factor of the MPPC

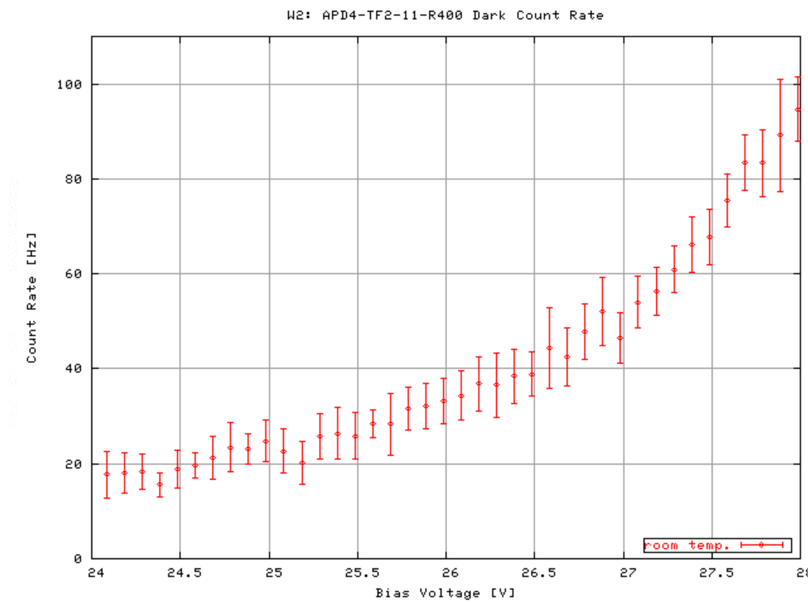
- Electrons lead to higher PDE → let electrons start the avalanche
- In P-on-N diodes, electrons travel from top (anode) into the bulk

→ P-on-N G-APDs with shallow junction exhibit higher sensitivity in blue/UV
→ N-on-P G-APDs with larger depletion depth have higher sensitivity in the NIR

G-APD: Dark Counts



(D. Renker, 2005)



- Thermal generation of carriers (diode leakage) and trap-assisted tunneling
- Direct band-to-band tunneling at low breakdown voltages (< 25V)
- 100kHz up to several MHz per mm² at room temperature
- Reduction of the DCR by factor of 2 every 8°K
- Exponential dependence on excess voltage

  → Reduce the number of generation centers in the diode (gettering)

  → Reduce excess voltage (but also sensitivity!)

  → Reduce the temperature

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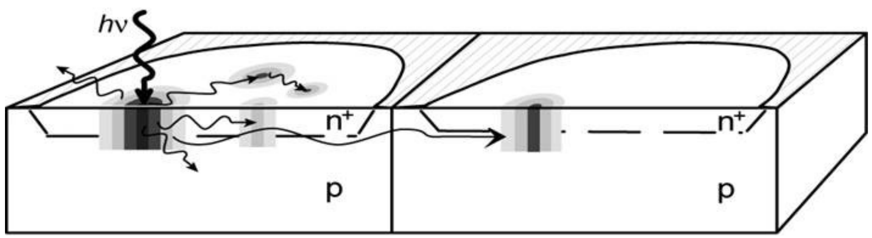
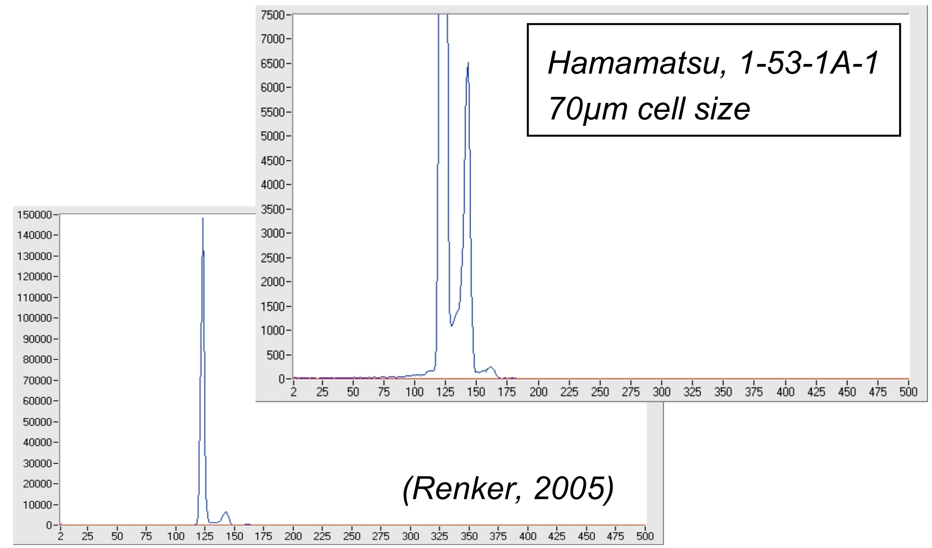
G-APD: Optical Crosstalk



(Lacaita, 1993)



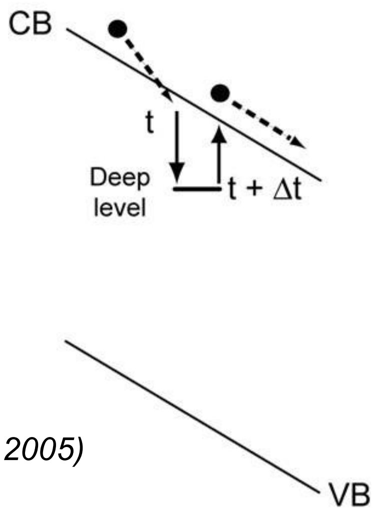
(Renker, 2005)

- Hot carrier luminescence
- 100k carriers generate on average 3 photons with energy higher than 1.14eV (Lacaita,1993)
- Several physical processes combined, full band structure due to high carrier energies
- Isotropic emission process; photons can trigger neighboring cells
- Emission allows simple characterization of the device (photoemission microscopy)

  → Reduce current through the device during discharge (active quenching)

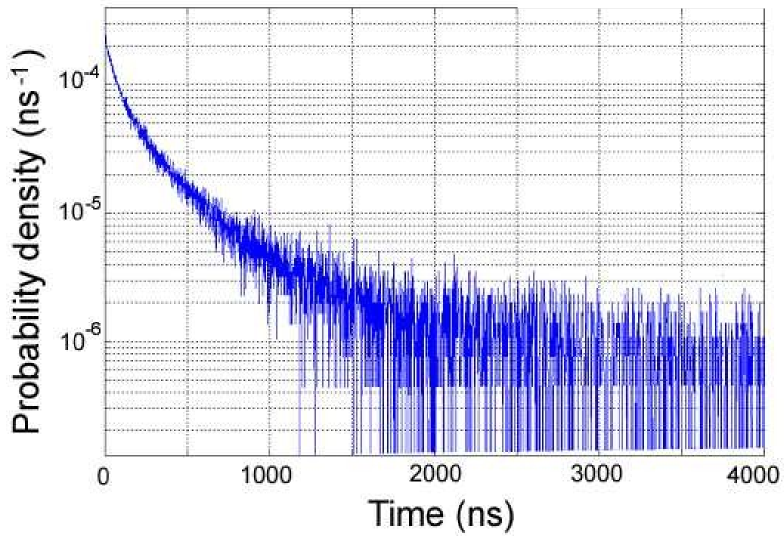
  → Optical isolation trenches filled with metal effective to suppress crosstalk

G-APD: Afterpulsing



(D. Renker, 2005)

(S. Cova, 2003)

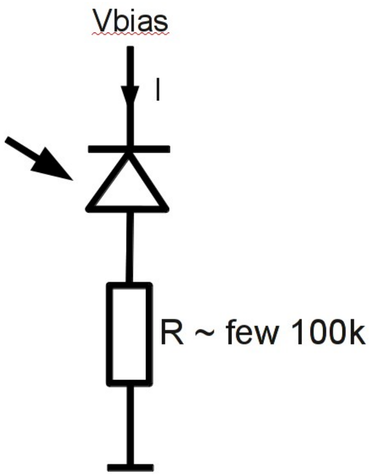


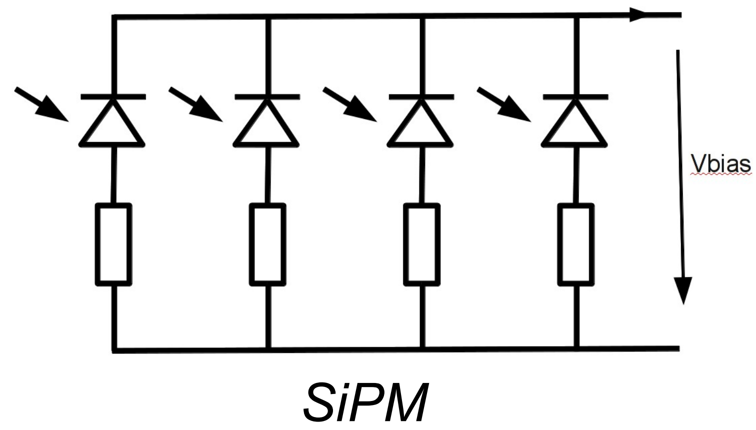
- Pulses correlated to a previous pulse
- Impurities (Iron, Gold) and defects (point, dislocation) create deep levels in the band gap
- These can trap a carrier during a discharge and release it later on to create new pulse
- Time constant depends on the energy of the deep level (impurity type → process control)
- Time constants in the order of nanoseconds to microseconds
- Time constants increase at low temperatures (factor 3 every 25°K)
- Most of the carriers are released early after the initial pulse

  → Reduce current through the device during discharge (active quenching)

  → Increase hold-off time before recharge if possible (active recharge)

G-APD: Passive Quenching/Recharge





- Limit the recharge current to < 20µA (R ~ V_{ov} / 20µA)
- Output is charge pulse: Gain G = C_{diode} x V_{ov}
- Recovery time: ~ R x C_{diode}
- Simple concept but tricky to implement (high-ohmic resistors needed)
- Used in most SiPMs as the summation can be easily implemented
- Output signal compatible with that of PMTs (re-use of readout infrastructure)

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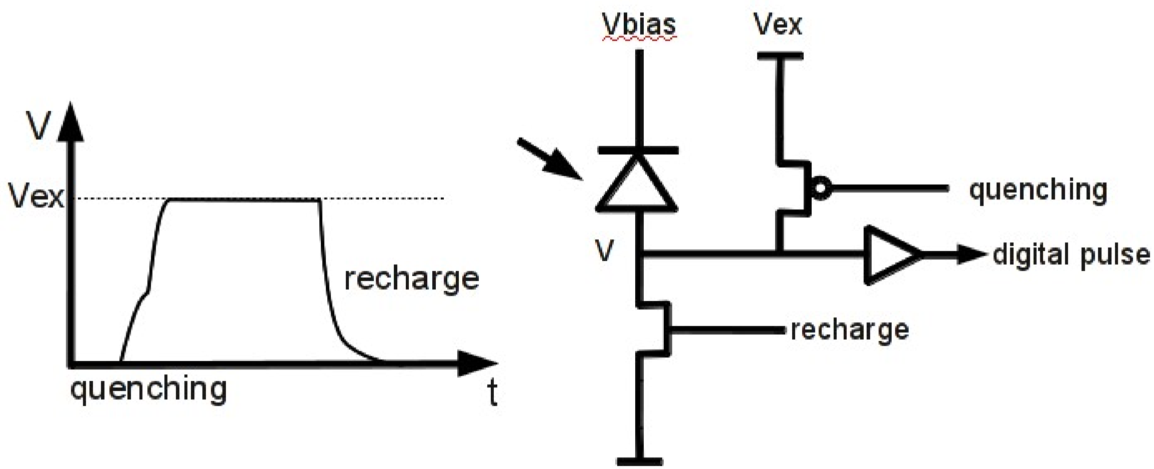
G-APD: Active Quenching/Recharge



- Sense the voltage at the diode terminal
- Use transistors to actively discharge/recharge the diode
- Flexibility: programmable timing possible, disabling of faulty cells
- But: requires SPAD/CMOS or 3D integration (cost)
- In case of SPAD/CMOS integration, electronics area affects fill factor
- Fast digital signals (gate delays of ~30ps, rise/fall times ~90ps), low parasitics

Separation of photon number, time of arrival and position information right at the detection element could potentially enable new detector concepts

Digital Silicon Photomultiplier

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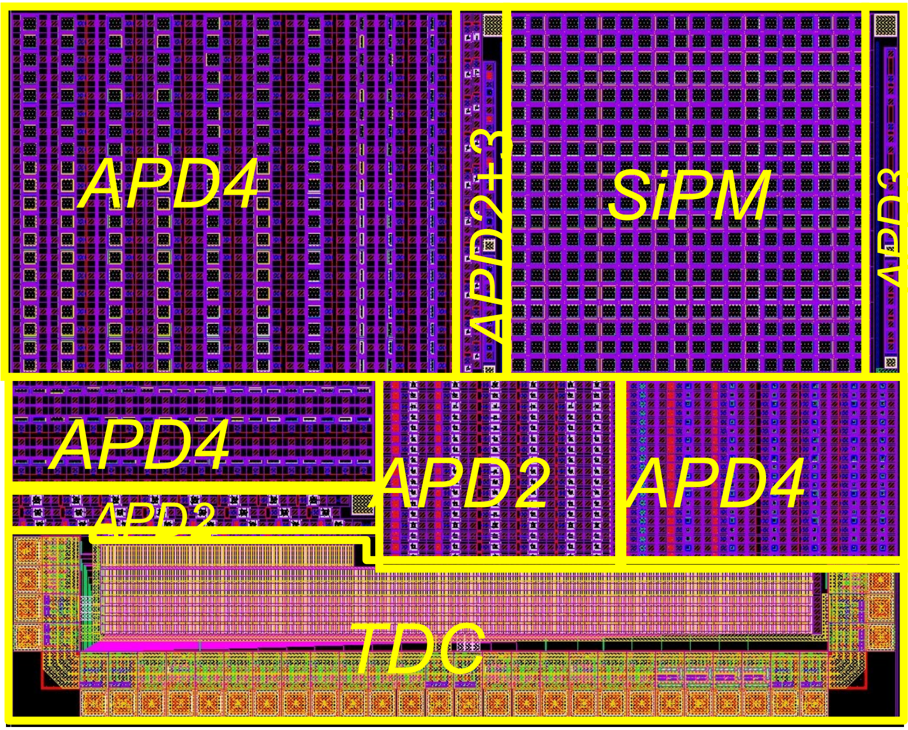
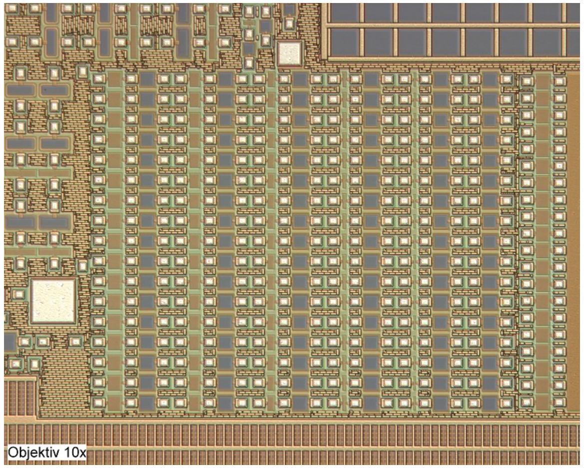
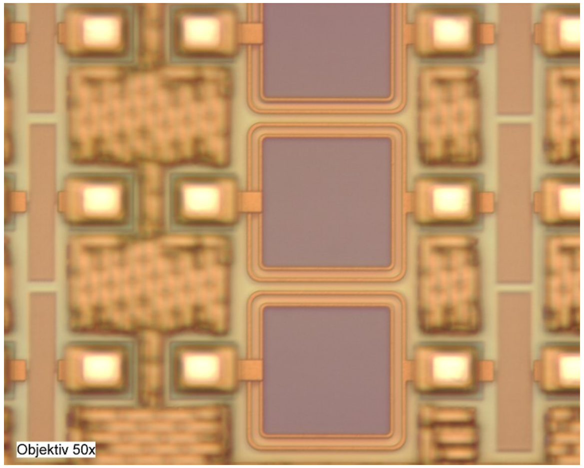
Early Designs: DPTC1 (2005/6)

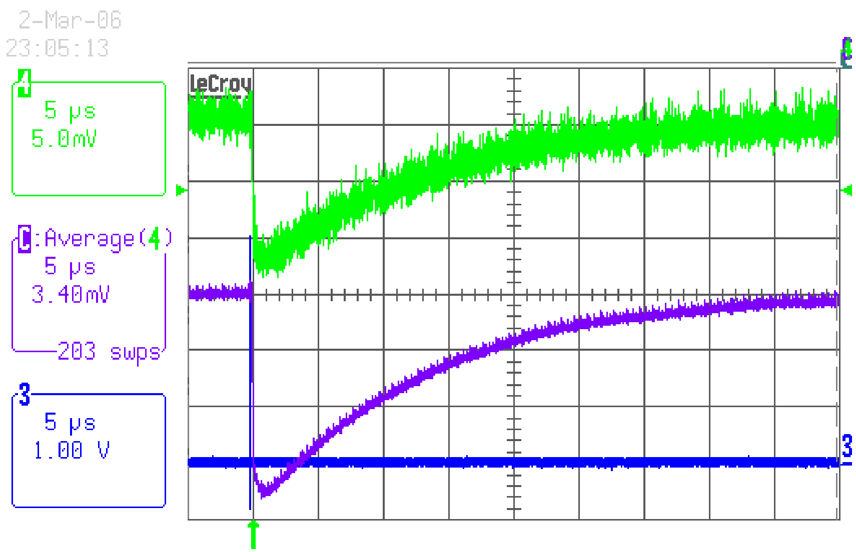


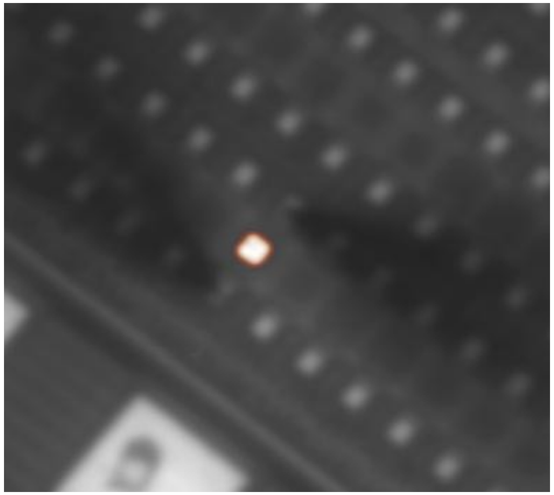


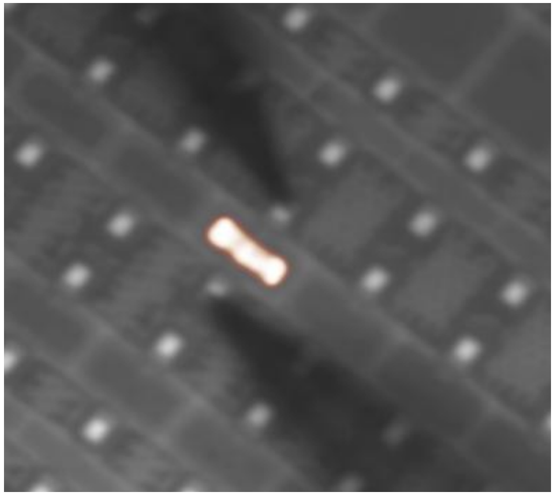


- First test chip submitted in standard HV CMOS 0.18μm multi-project wafer
- 5mm², ~400 diodes, 8 TDCs, < 20ps bin width
- Proof of concept, but sub-optimal performance found

Early Designs: DPTC1 (2005/6)







- First Geiger-mode pulses and photoemission confirm working diodes
- Long pulse due to large parasitic capacitance of the probe and large quenching resistor

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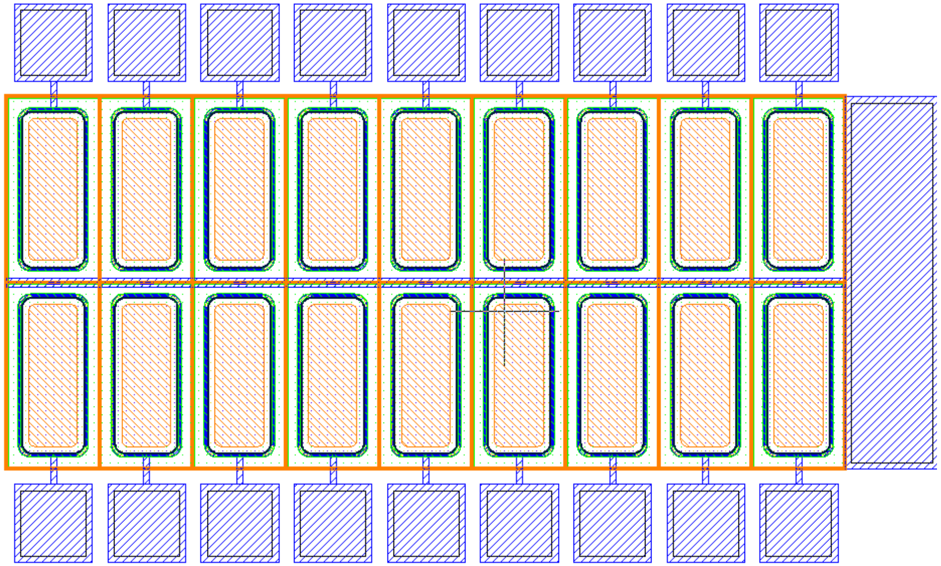
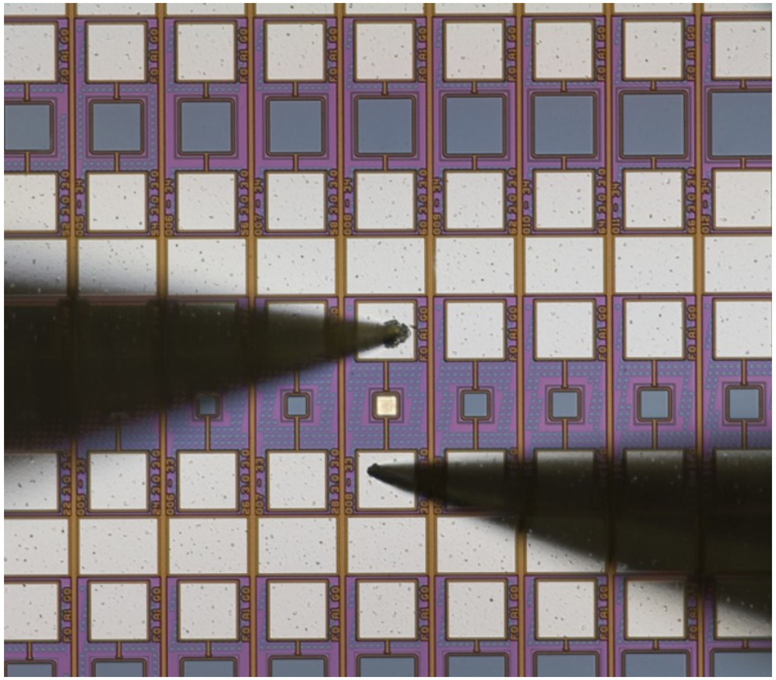
Process Development (2007/2008)

- Goal: integrate the SPAD monolithically into the 0.18µm CMOS process
- Challenge: do not change the CMOS process (re-qualification needed)
- Extensive TCAD simulations to optimize the diode performance
- Test vehicle: multi-layer reticle mask set with > 4000 diodes
- Semi-automated wafer level test equipment needed





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CMOS Integration

Not all attempts were successful ...

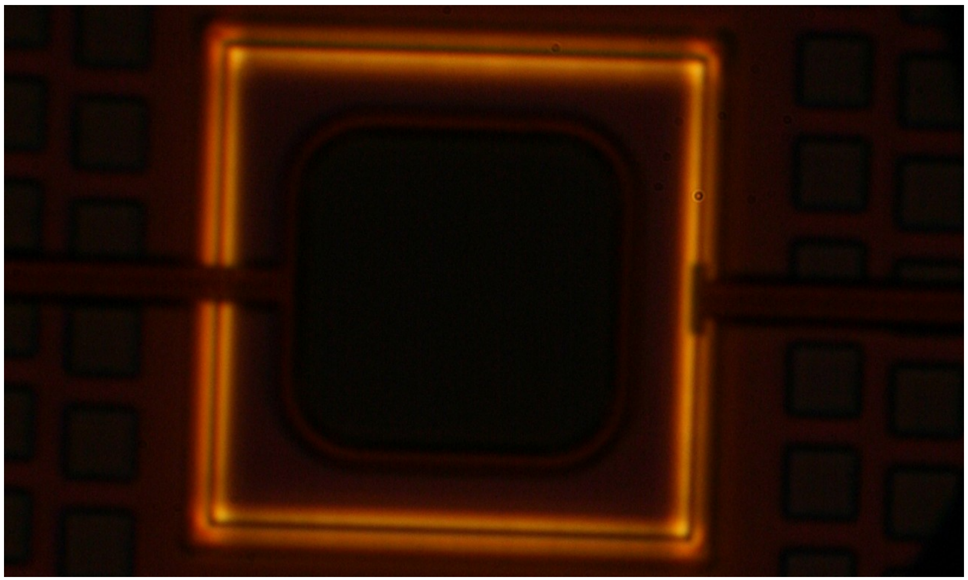
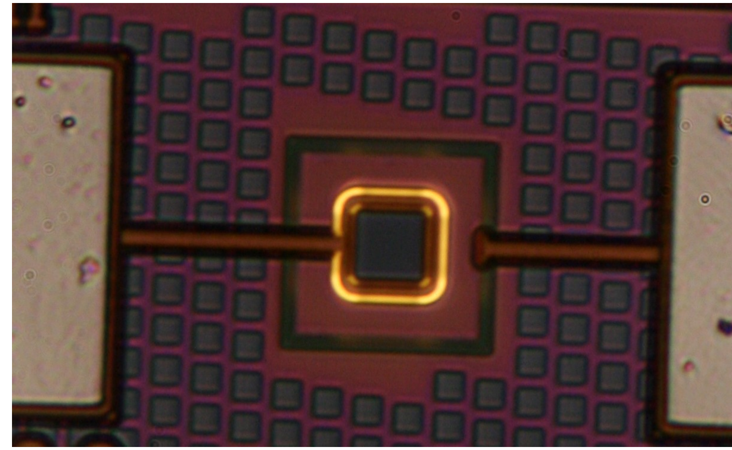
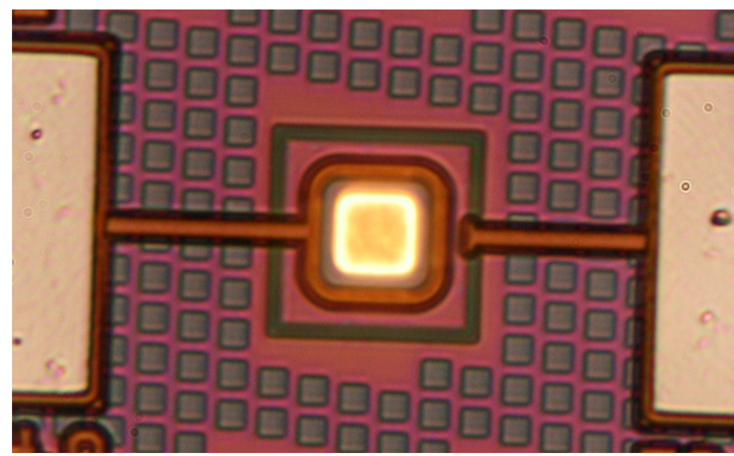


Photo-emission with DC current.



… but finally …



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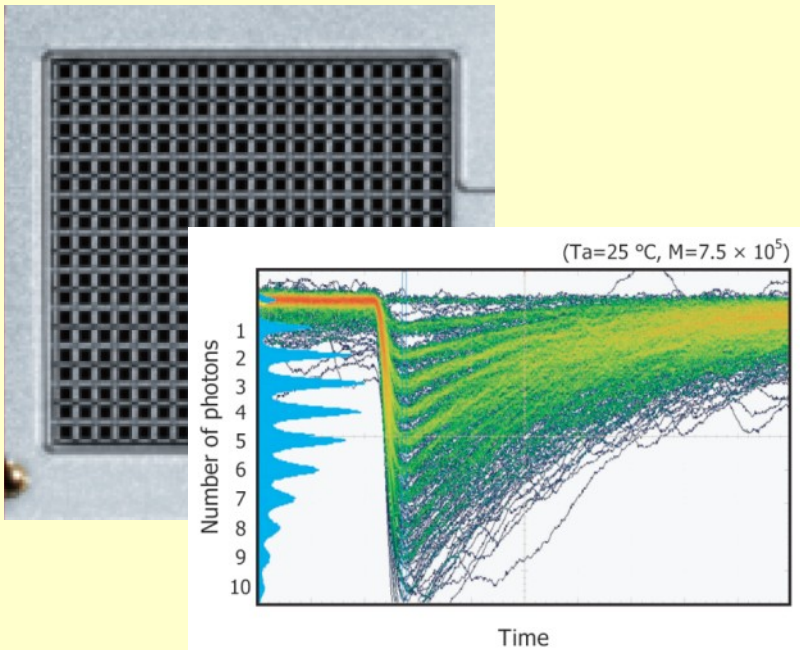
Digital SiPM – New Type of Silicon Photomultiplier

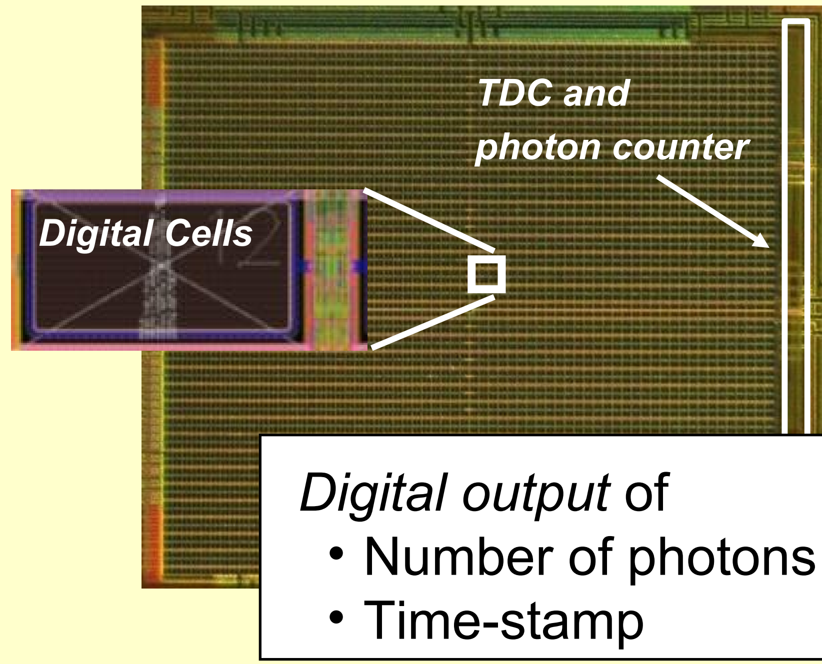
Analog SiPM



www.hamamatsu.com

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

Digital SiPM



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

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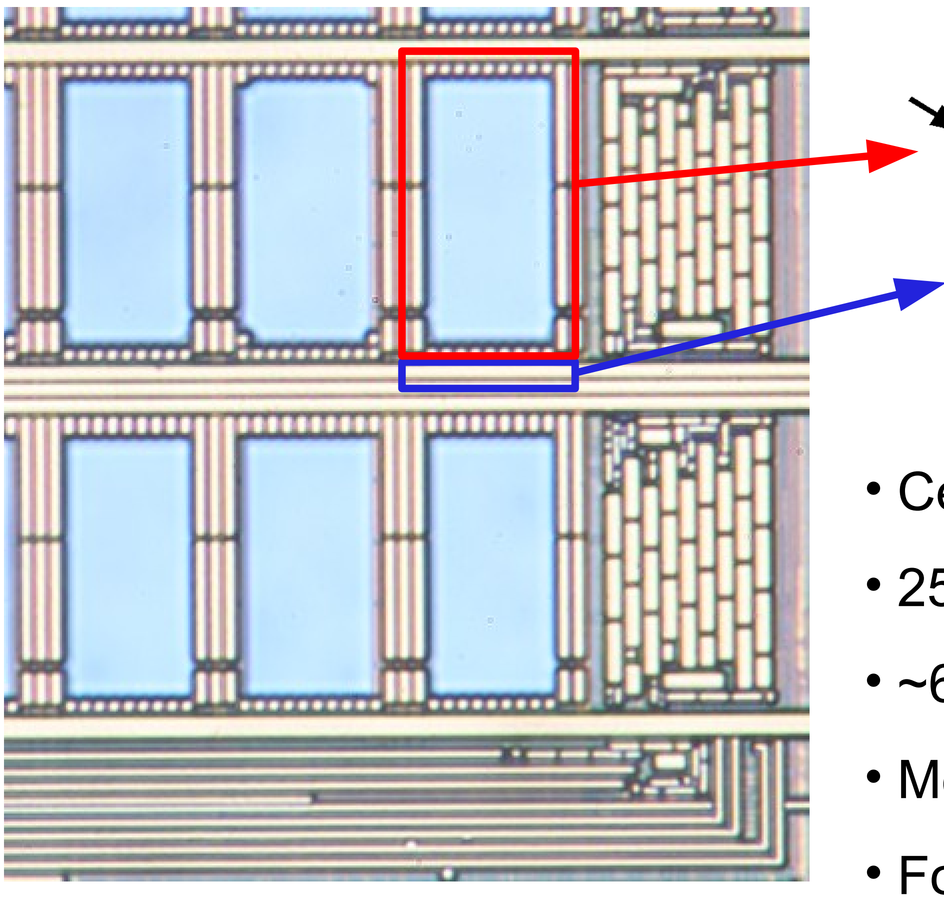
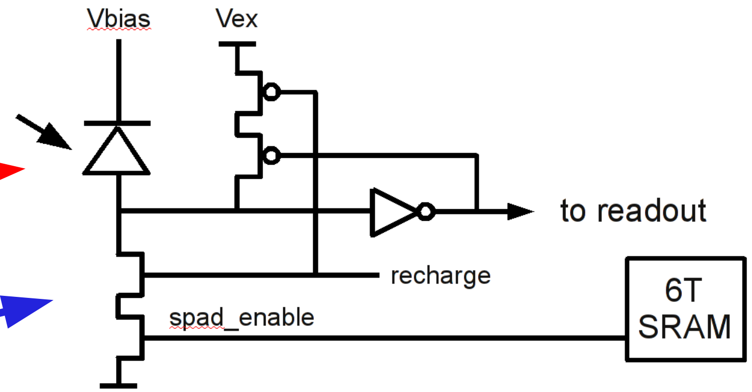
Digital SiPM – Cell Electronics





- 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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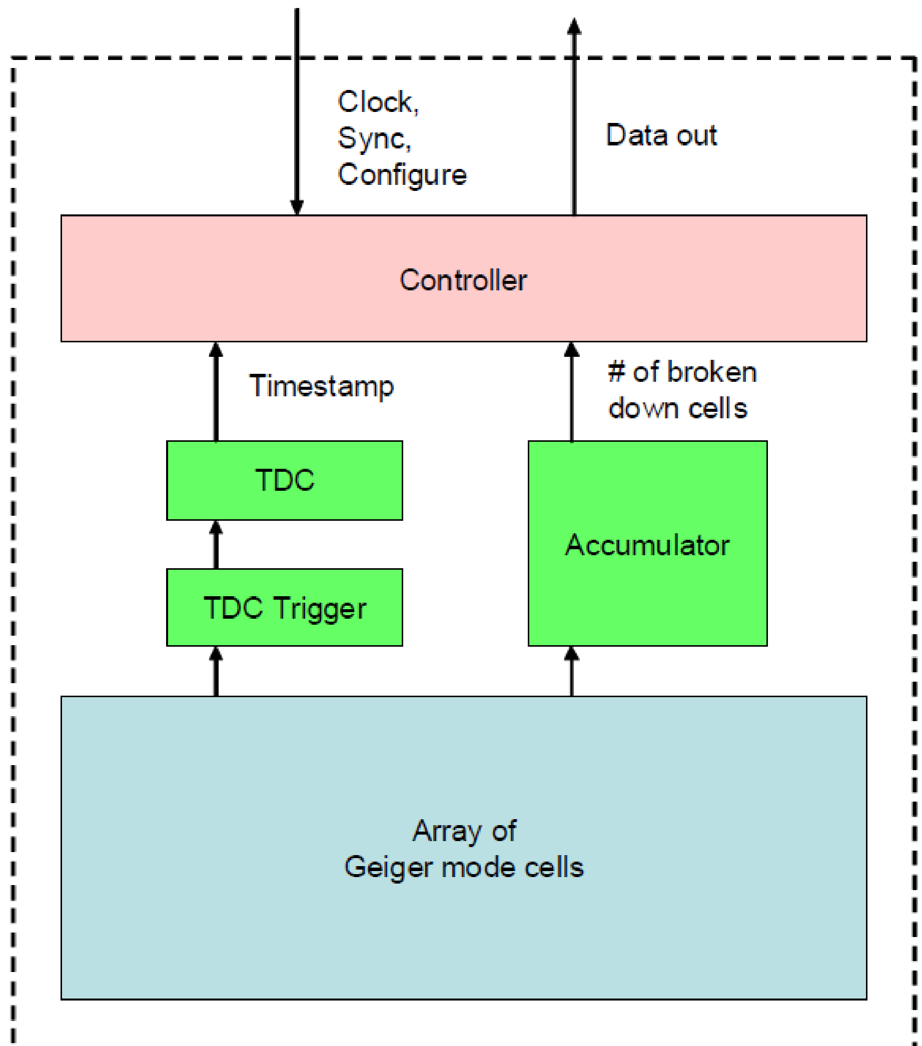
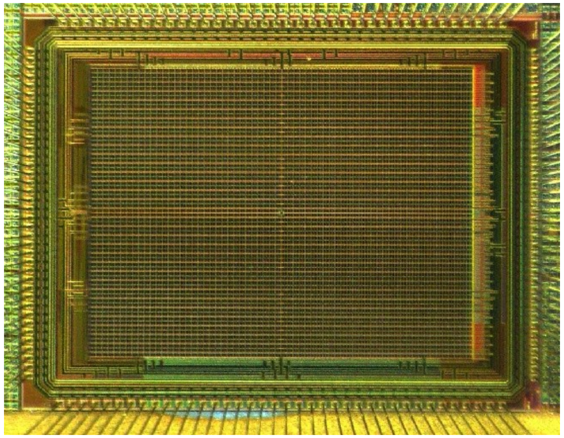
Digital SiPM – Sensor Architecture

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



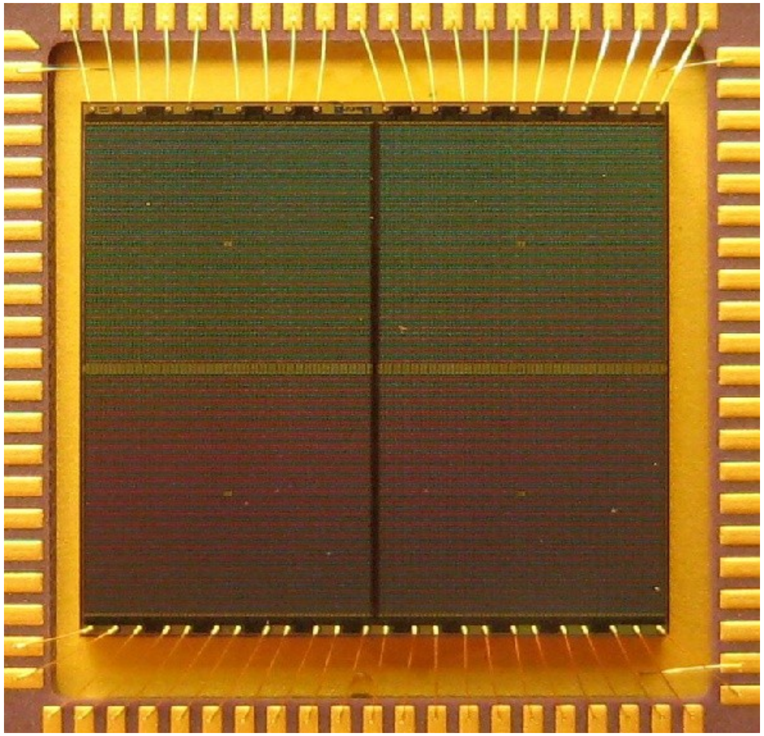
Digital SiPM – Sensor Family

DLD8K Demonstrator (2009):



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

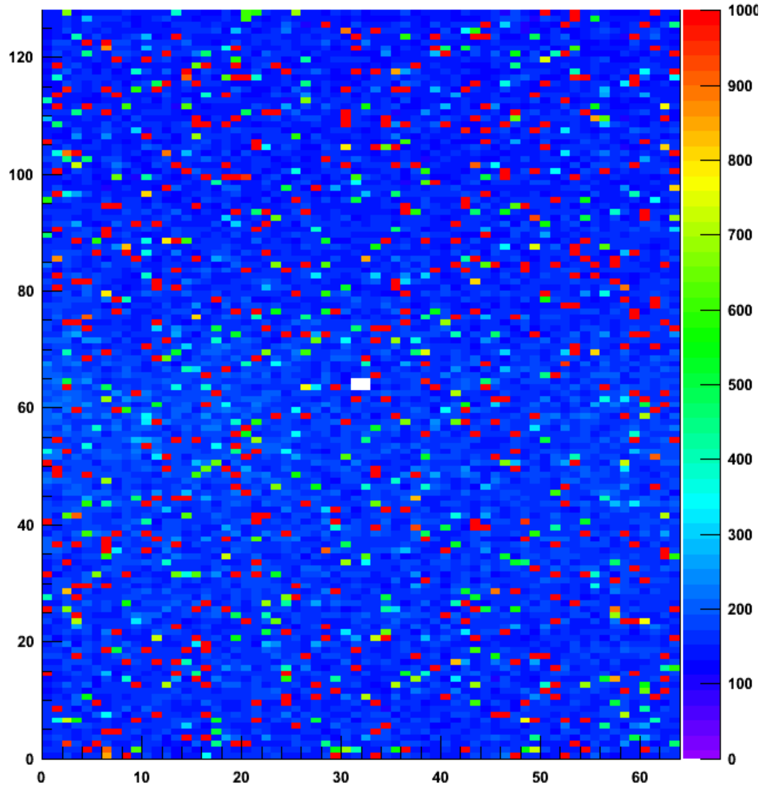
DLS 6400-22 digital SiPM (2010):

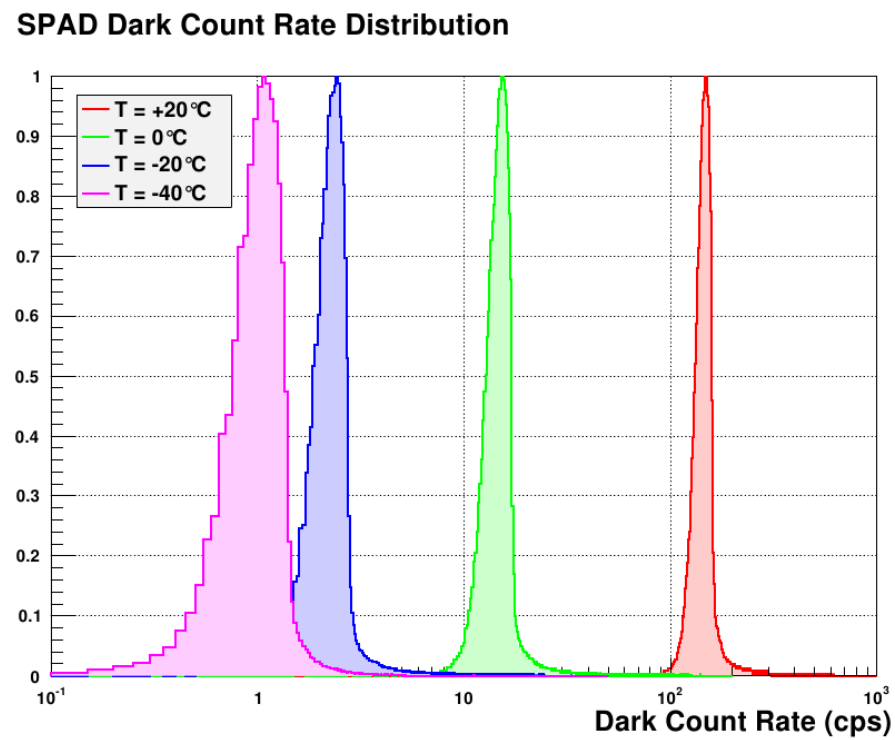


- 25600 cells
- 2 TDCs, controller, data buffers
- JTAG for configuration & test
- 48 bond wires

Digital SiPM – 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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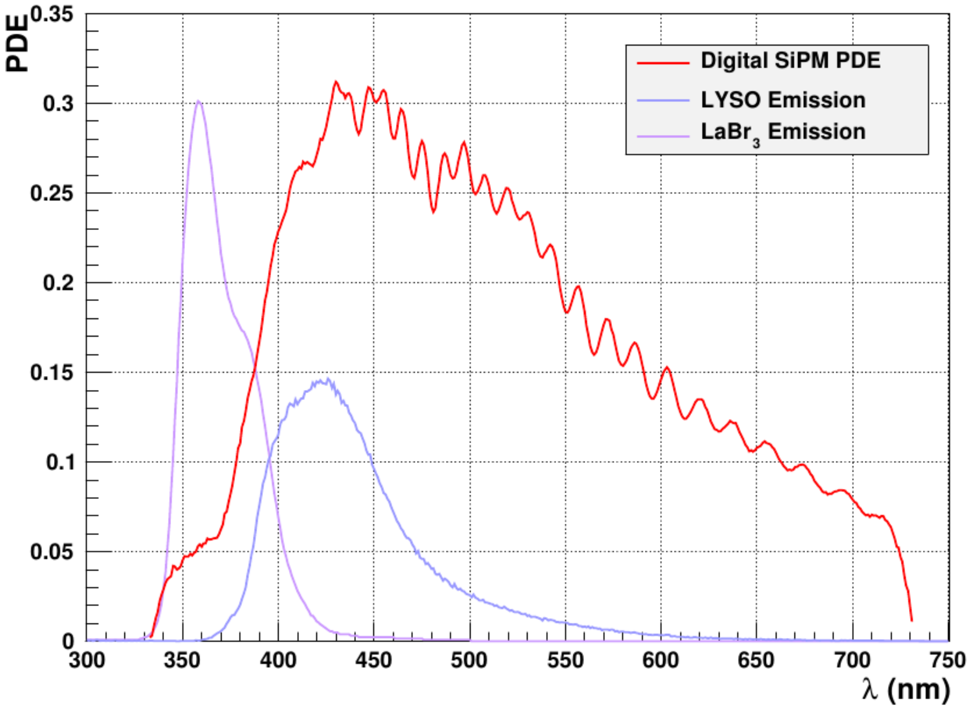
Digital SiPM – Photon Detection Efficiency

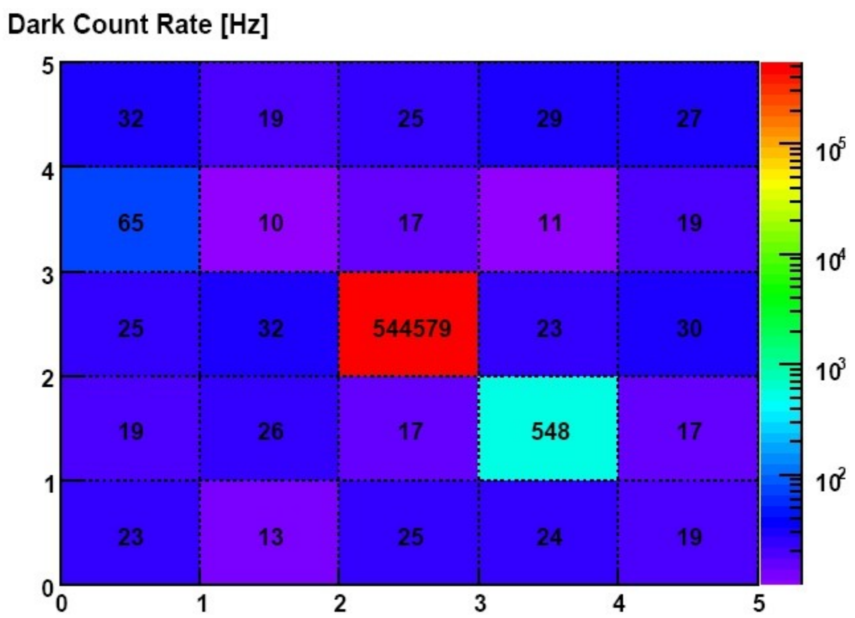


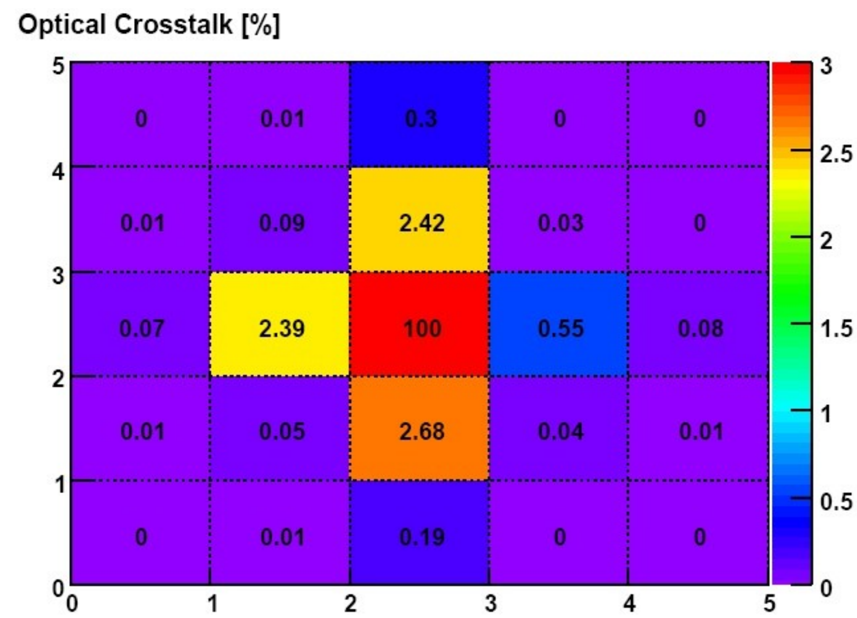
Effective PDE:

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

Digital SiPM – 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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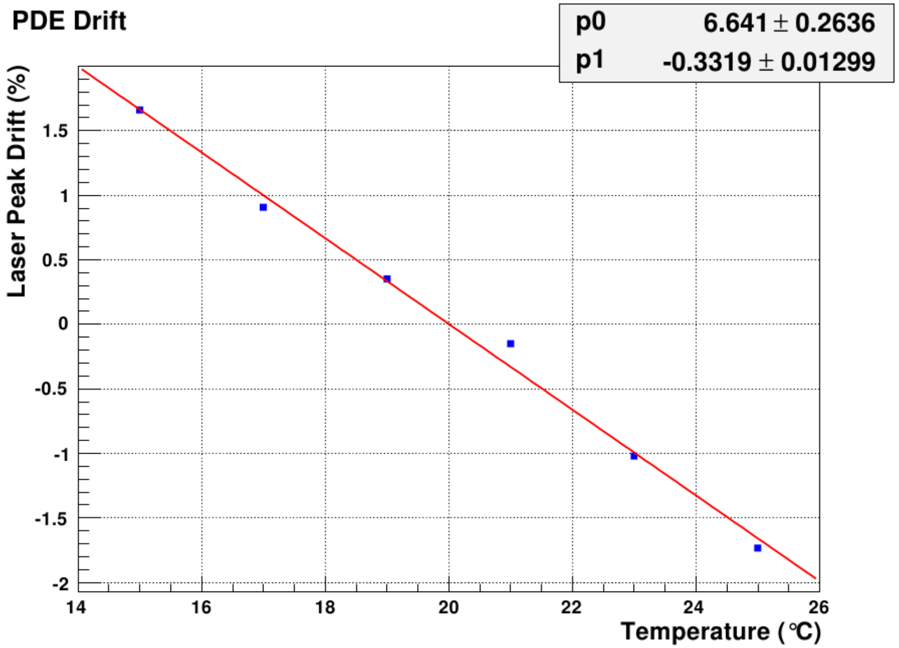
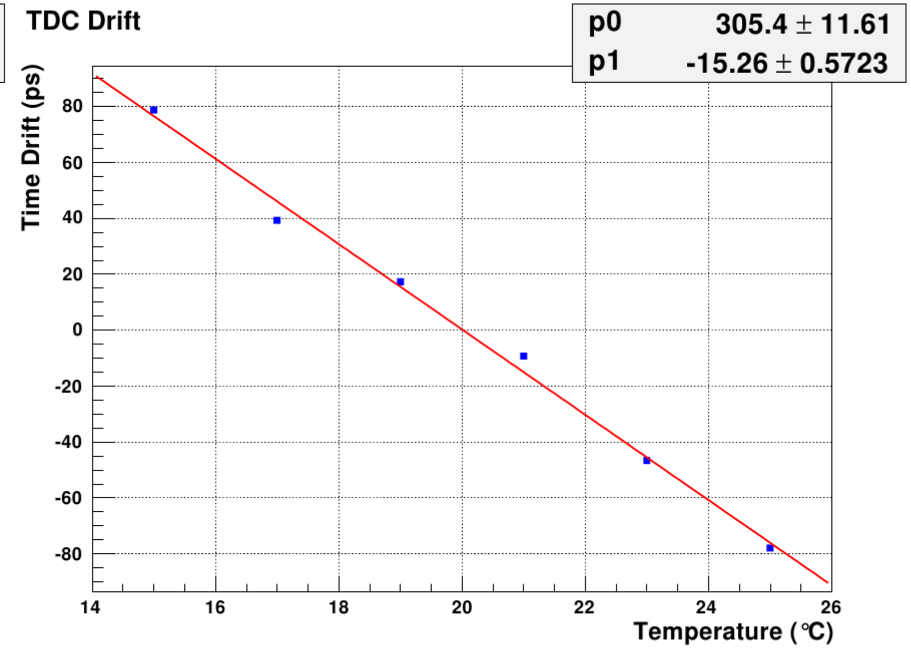
Digital SiPM – Temperature Sensitivity

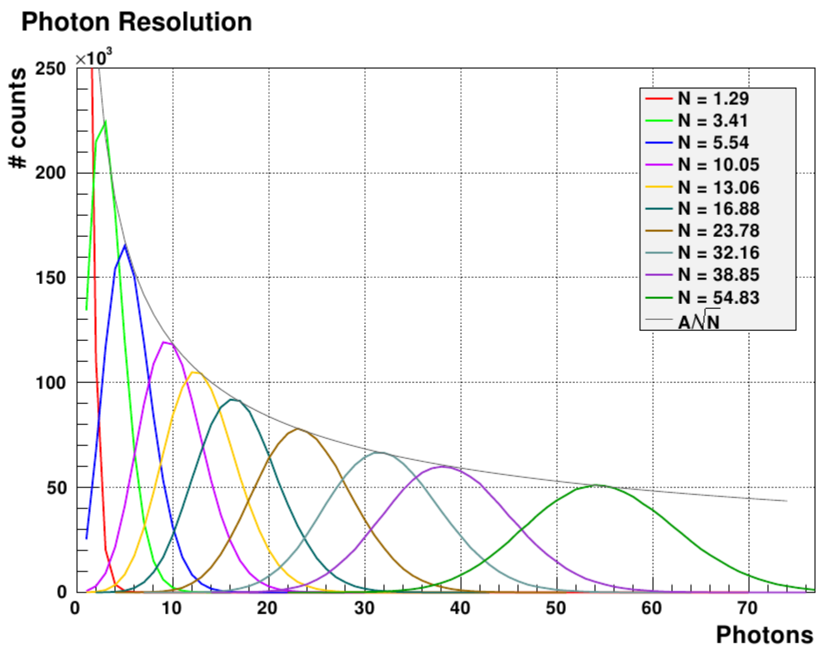


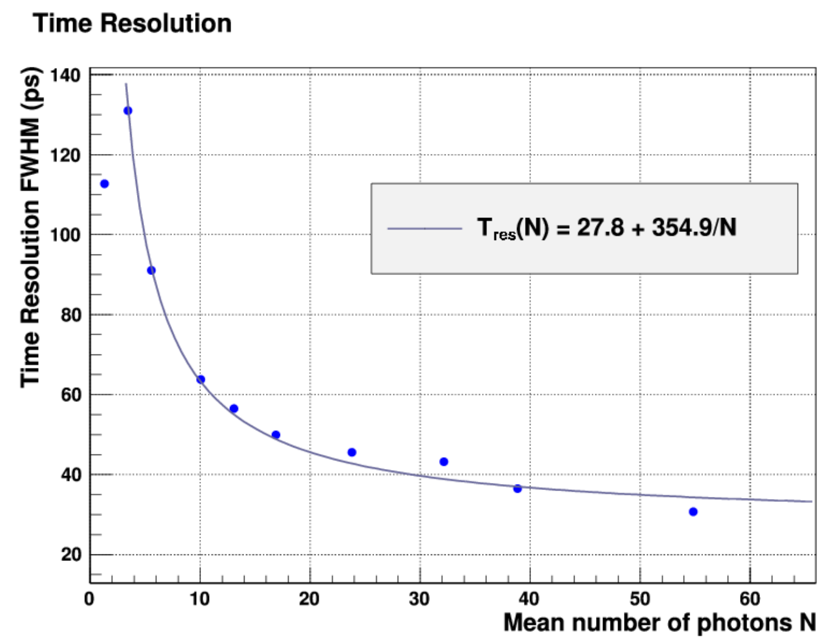


ps-laser trigger, 2100 photons/pulse, 24ps FWHM timing resolution

- 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

Digital SiPM – 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

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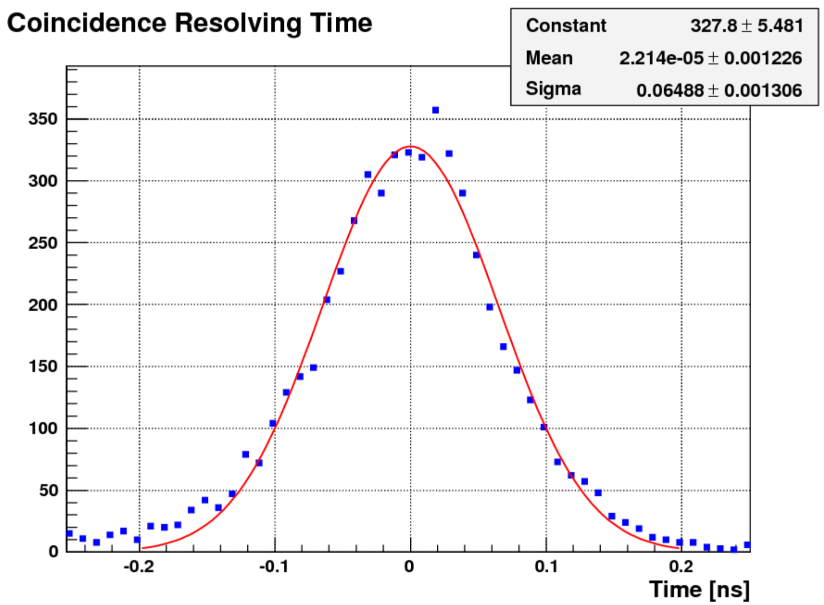
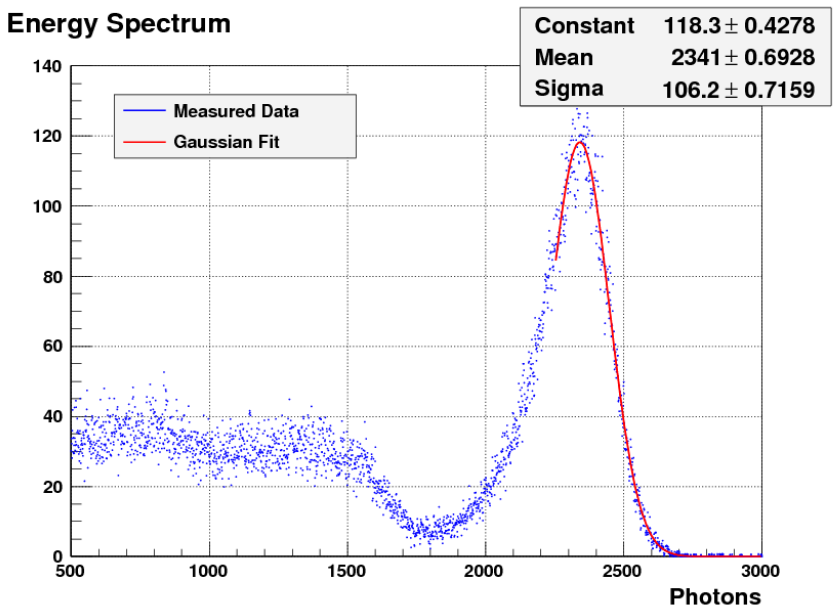
Digital SiPM – Scintillator Measurements



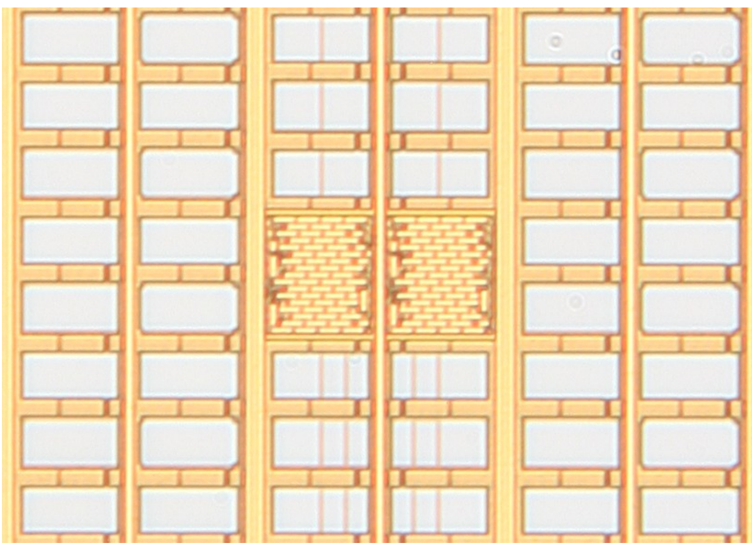


- 3 x 3 x 5 mm³ LYSO in coincidence, Na-22 source
- Time resolution in coincidence: **153ps** FWHM
- Energy resolution (excluding escape peak): **10.7%**
- Excess voltage 3.3V, 98.5% active cells
- Room temperature (31°C board temperature, not stabilized)

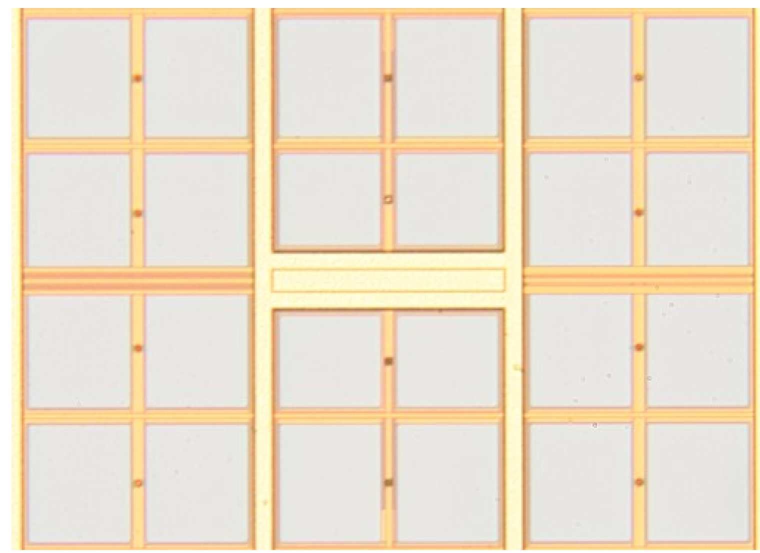
New Digital SiPM – DPC 3200-22 (2011)

New Sensor Design (DPC 3200-22):

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

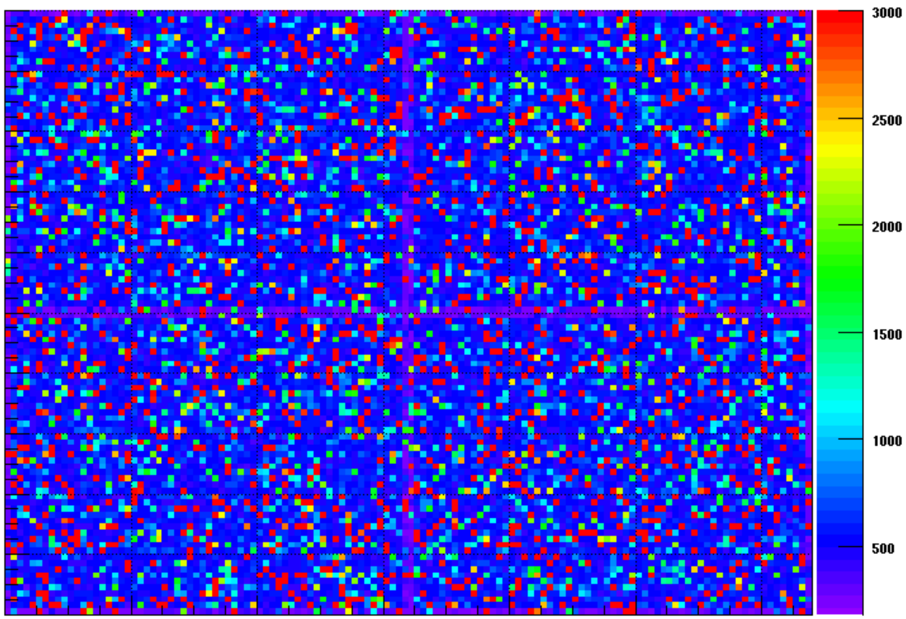


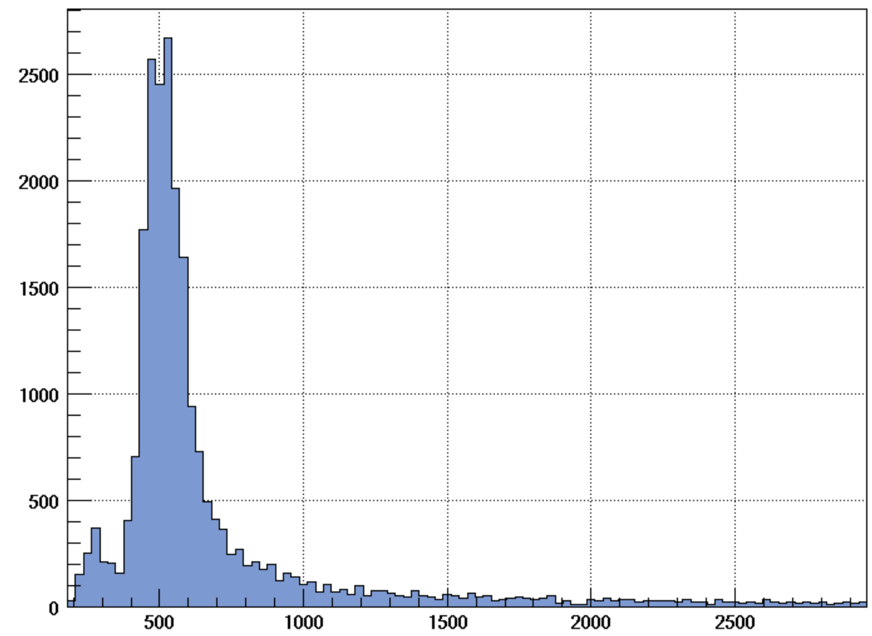
DLS 6400-22



DPC 3200-22

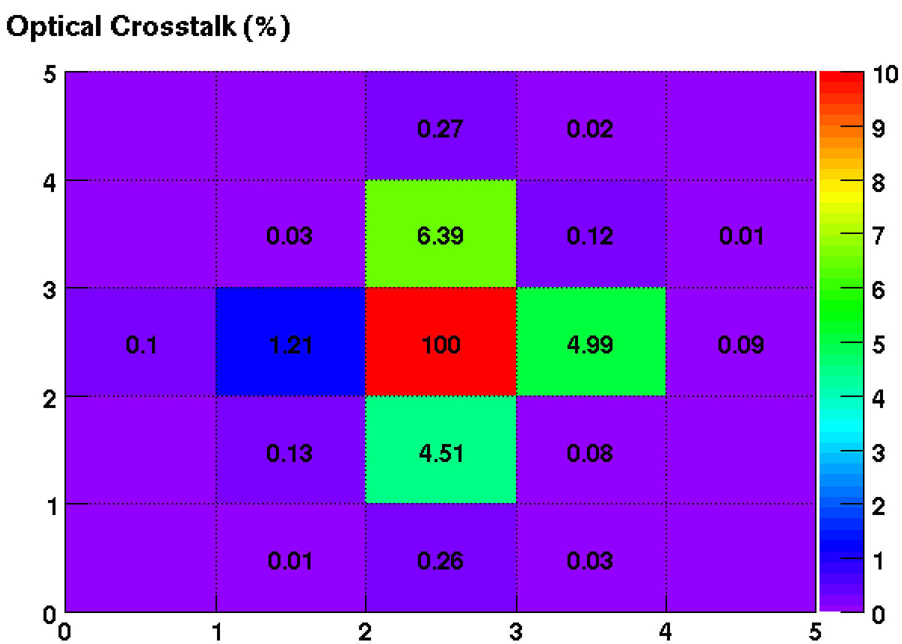
Digital SiPM – DLS 3200-22 Dark Count Rate

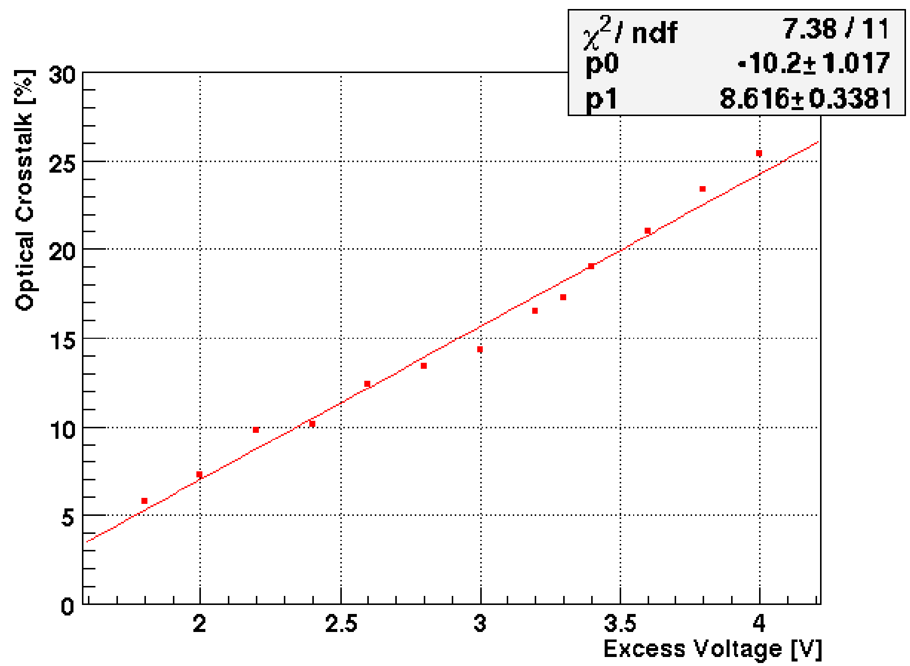




- Dark count rate at 20°C, 3.3V excess voltage
- Average dark count rate ~ 550cps per SPAD
- Scales with SPAD sensitive area (2954µm² vs. 783µm² in DLD8K)

Digital SiPM – 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

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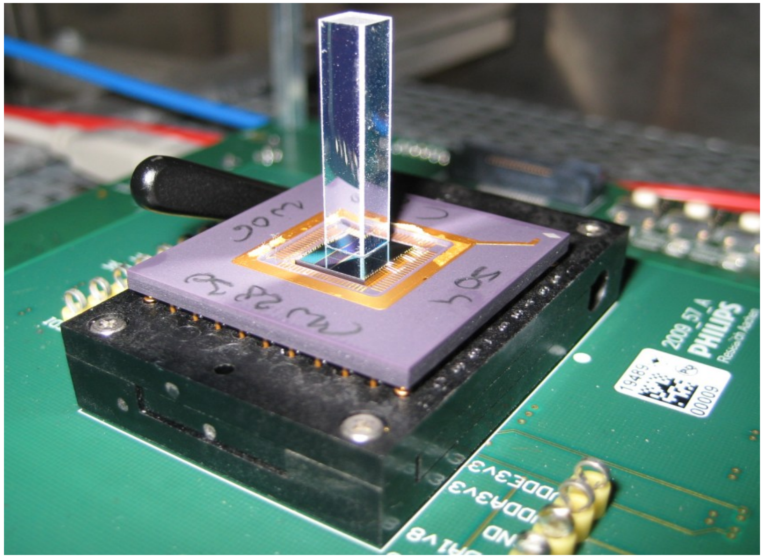
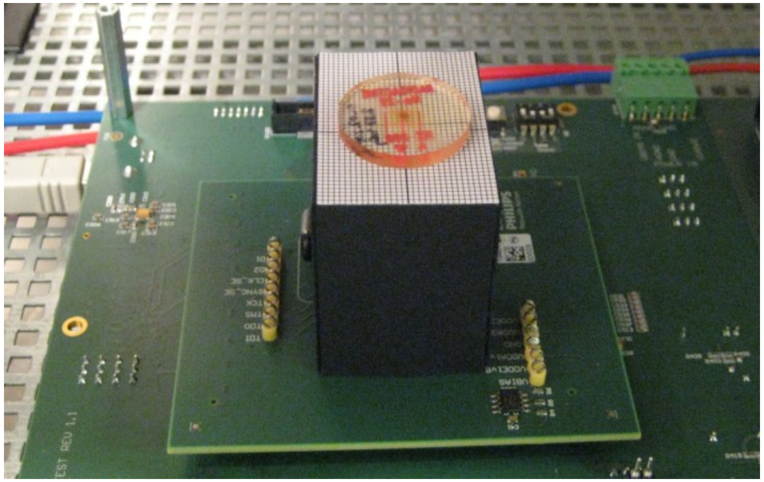
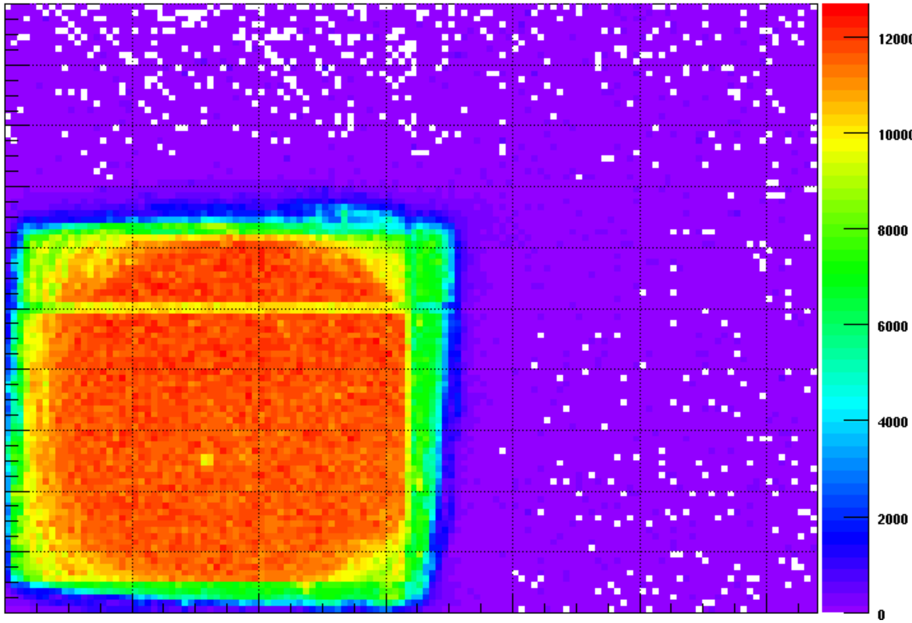
Digital SiPM – DLS 3200-22 Energy Resolution

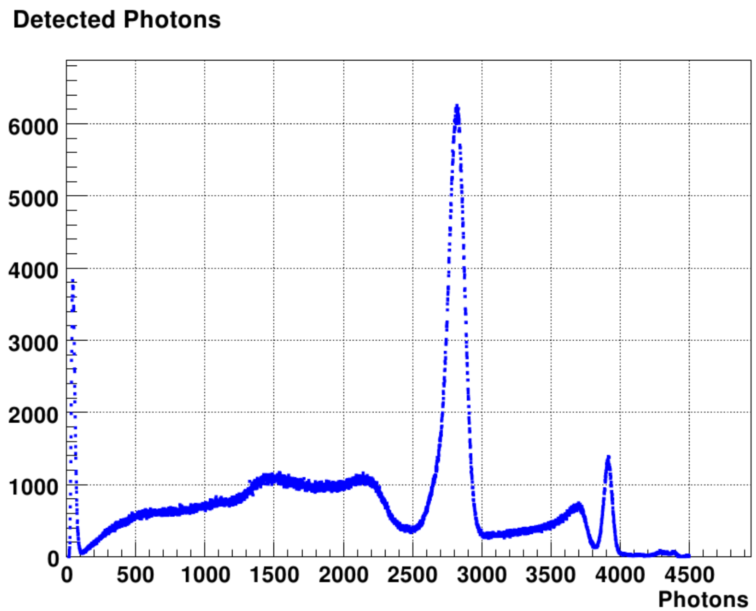


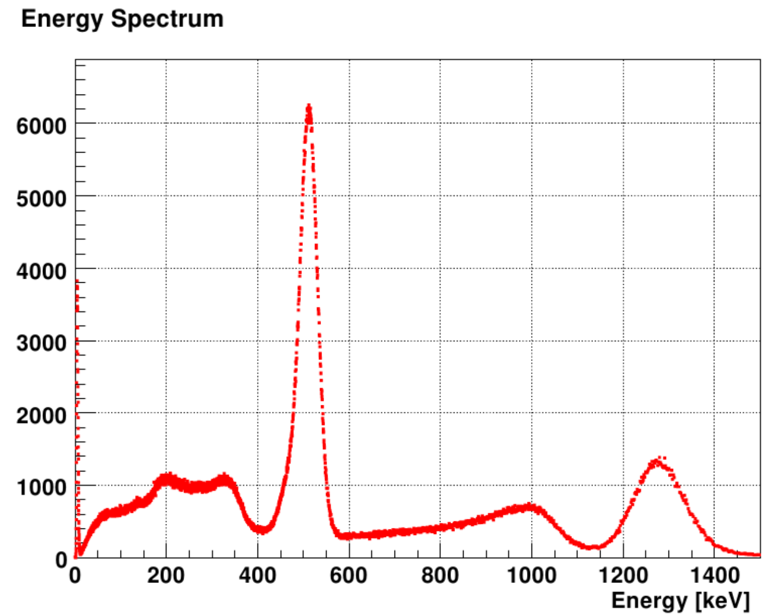


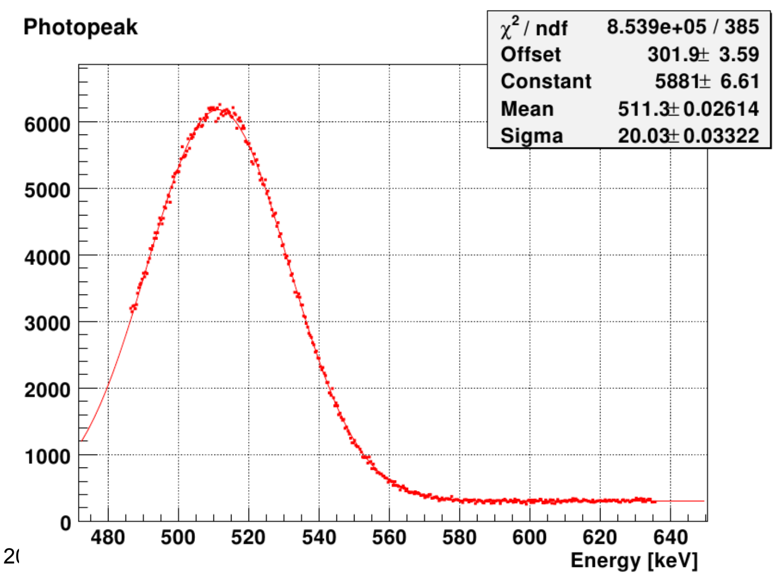
- 4 x 4 x 22 mm^3 LYSO crystal
- Vikuiti reflector
- Attached with Meltmount
- Na-22 source



Digital SiPM – 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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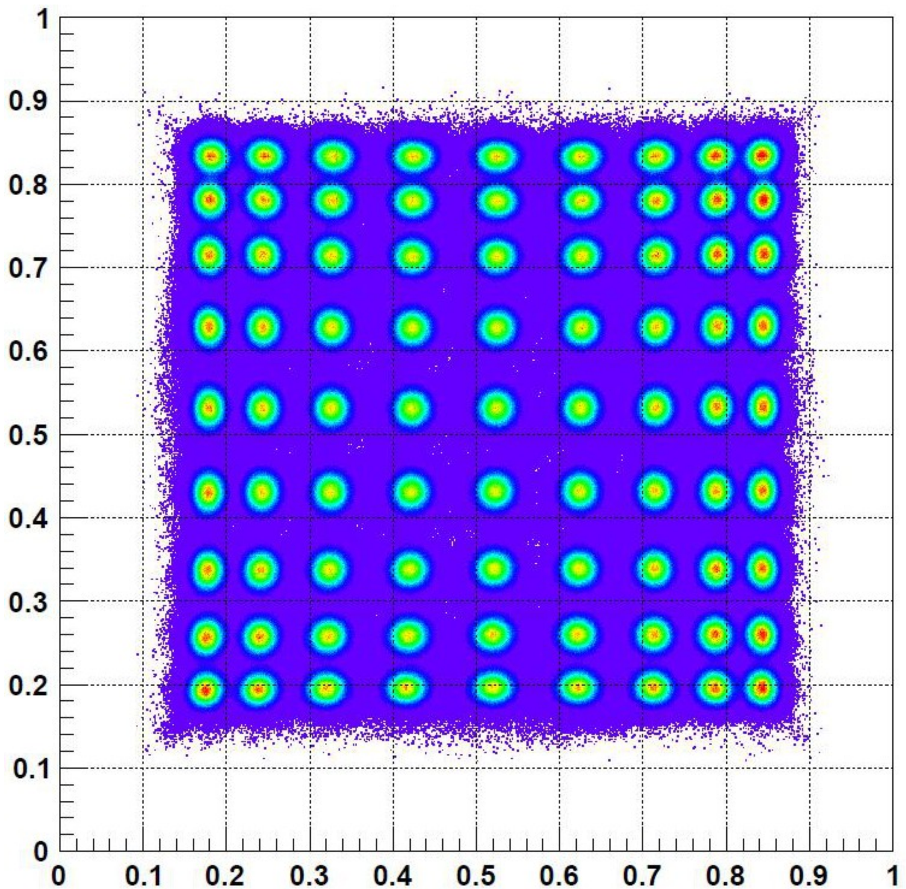
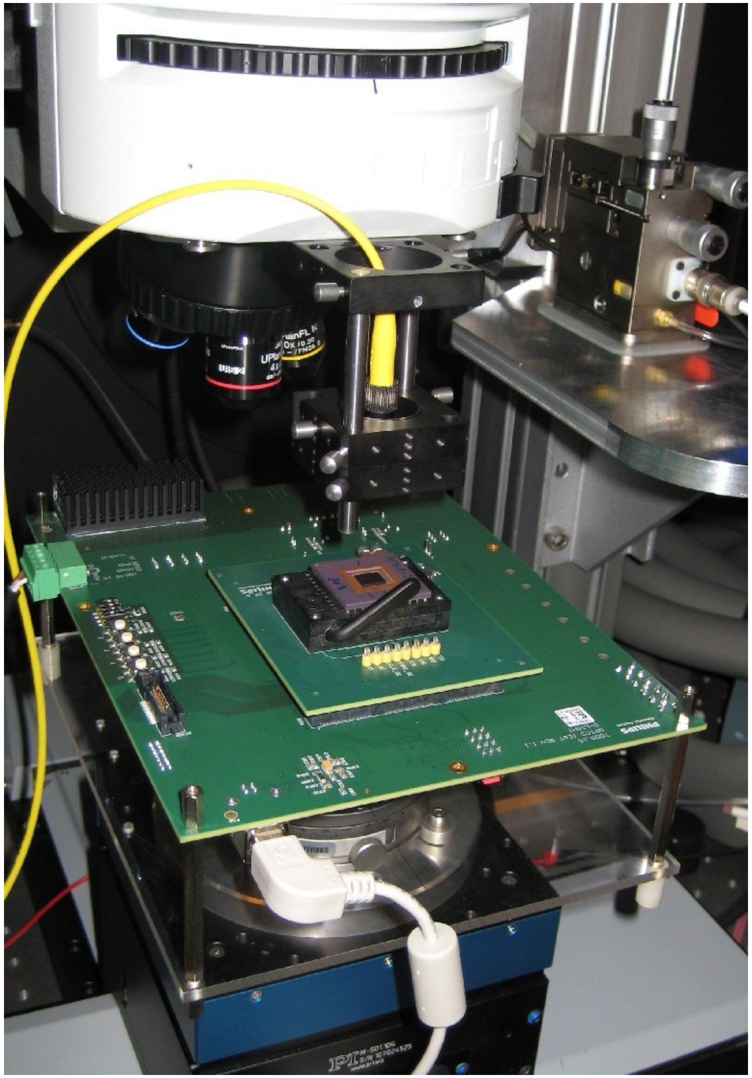
Digital SiPM – Small Crystal Identification

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





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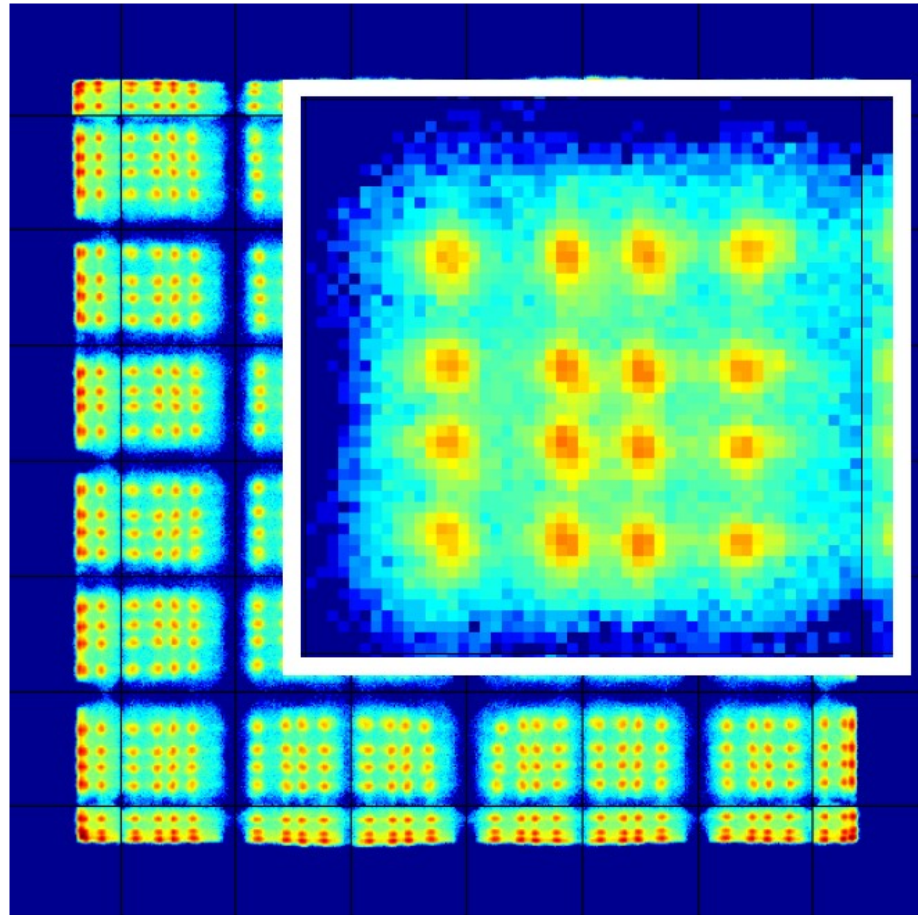
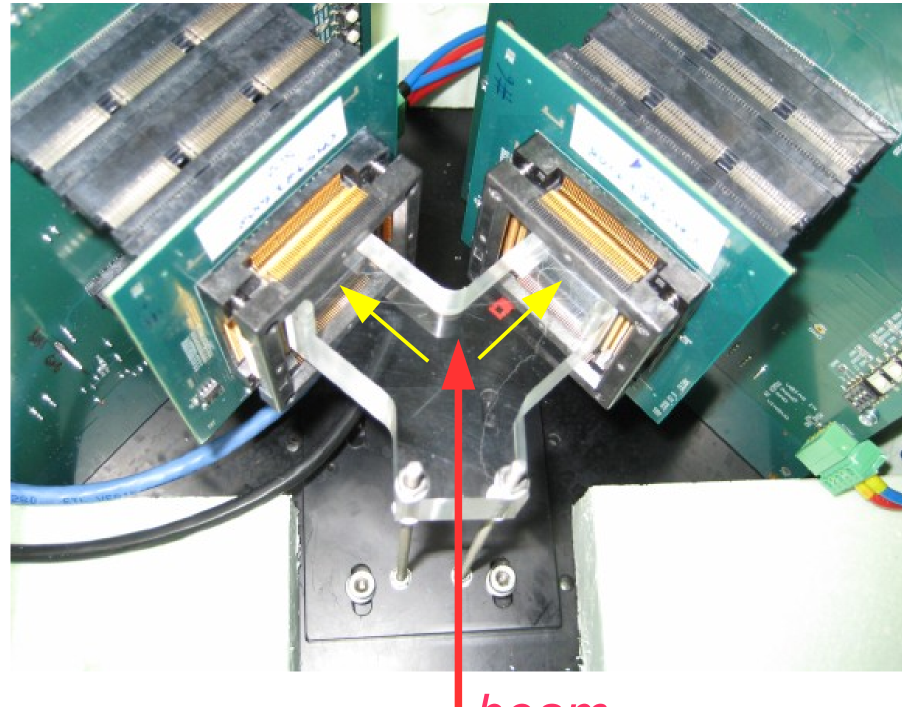
Digital SiPM – Small Crystal Identification

- Array of 30 x 30 LYSO crystals
- Crystal size: 1 x 1 x $10mm^3$
- 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

DLD8K – Čerenkov Light Detection



- PMMA radiator coupled via air gap to two DLD8K dSiPMs in coincidence
- Box isolated and temperature-controlled with a TEC to 2 – 3°C
- External beam gate signal to minimize randoms due to low beam duty-cycle
- Cooperation between Giessen University (Prof. Düren) and Philips DPC
- Test beam at the CERN SPS in Summer 2010

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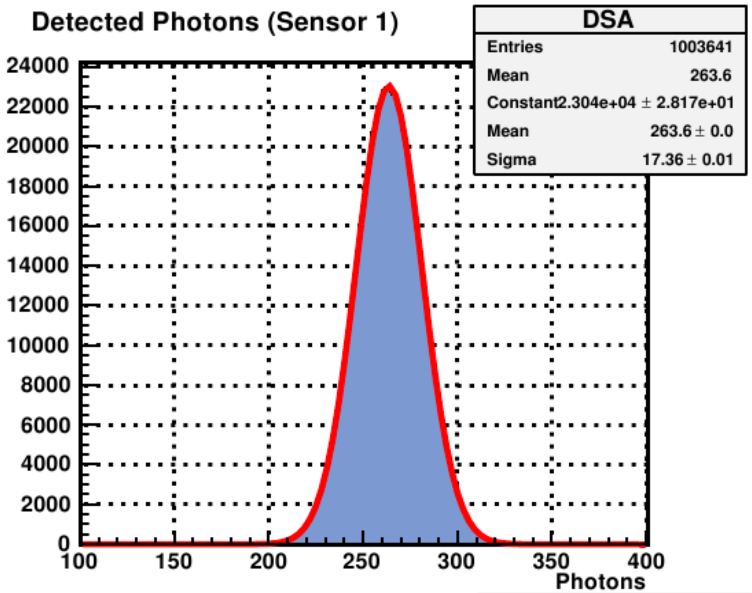
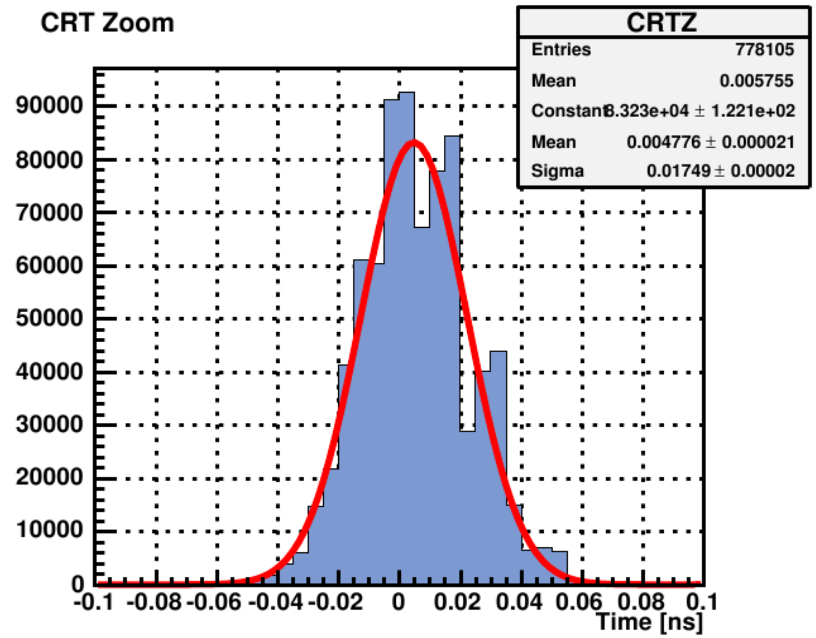
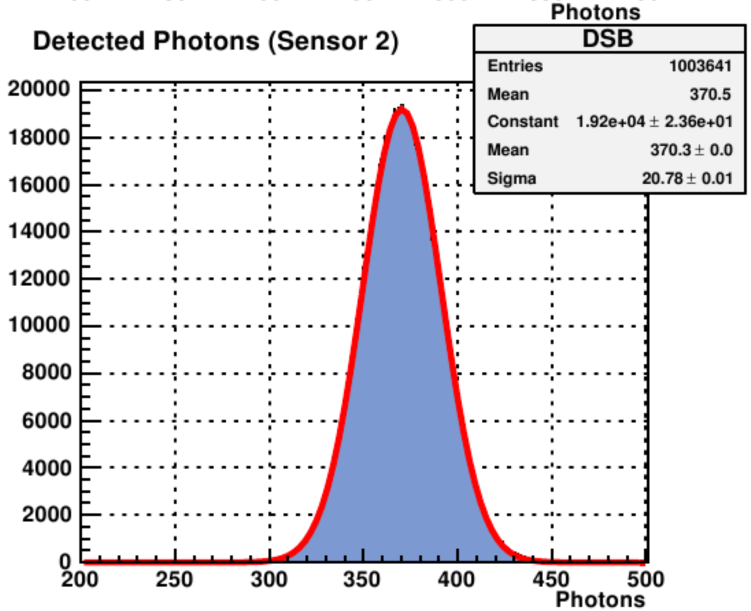
Laser Tests







- *Pico-second laser pulses*
- *Wide beam (no beam splitter used)*
- *95% diodes active*
- *3.3V excess voltage*
- *T=10°C*
- *CRT σ = 17.49ps*
- *Sensor resolution = 12.4ps*

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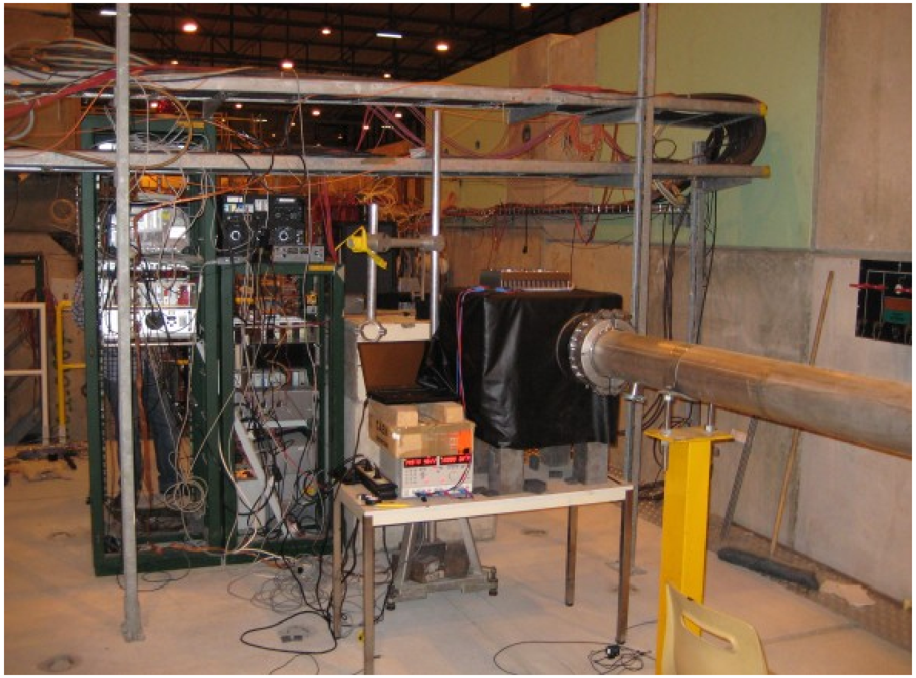
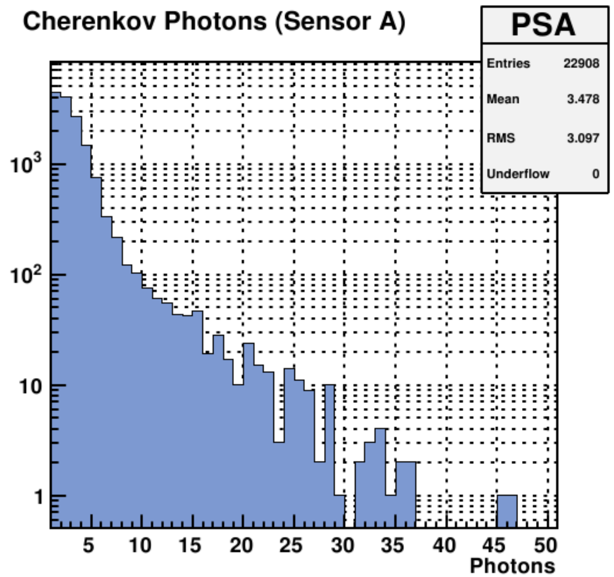
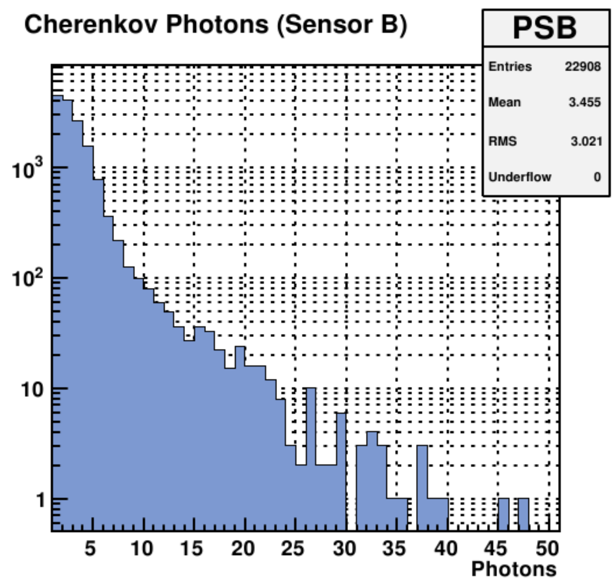
Setup at CERN SPS Test Beam

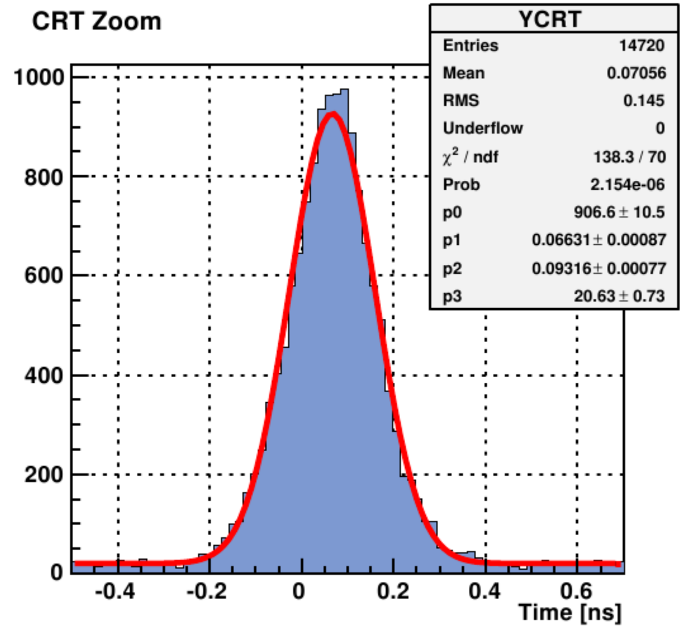


- Beam: protons at 120GeV, intensity ~5000/sec, beam diameter ~ 6mm RMS
- Difficult alignment (no alignment marks available), CERN survey not available
- USB extender cable failed to work, fortunately the cable was a CAT5 ethernet
- Beam duty cycle ~ 17%, significant randoms background
    - External beam gate signal provided by the Gießen Team

Digital SiPM – Čerenkov Light Detection







- 95% diodes active
- 3.3V excess voltage
- T=3°C, DCR = 250/177kHz
- First photon trigger
- All events validated
- CRT σ = 93.16ps
- Sensor resolution = 65.9ps

Future Extensions & New Applications

- Current dSiPM is best suited for scintillator readout:
  - Relatively large dead time when used for single photon detection
  - Loss of useful information (i.e. photon position, pulse shape)
  - Suboptimal use of real-estate when used for other applications
- Extension/modification of the digital SiPM architecture:
  - Cost-effective way of adding new features
  - But: any change in the present design means NRE (new mask set, test wafers)
  - Typically, any change means large design effort (full custom design)
  - Physical dimensions (chip size, diode size, bond pads) must not change
- There is much more:
  - Focal plane computing
  - Integration of data processing/reduction, image processing, etc.
  - But: is there enough volume to justify the NRE?
- Philips/NXP could offer access to Multi-Project Wafer runs to test new ideas
  - contact us if you are interested

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Summary

- Digital SiPM implemented in a high-volume CMOS process
- Configurable architecture, individual control of each SPAD
- Two-sides tile-able sensor design
- Tiles of 4 x 4 sensors developed to enable large-scale system integration

The author would like to thank Dr. Hein Valk of NXP Semiconductors
for his support and excellent cooperation during the process development

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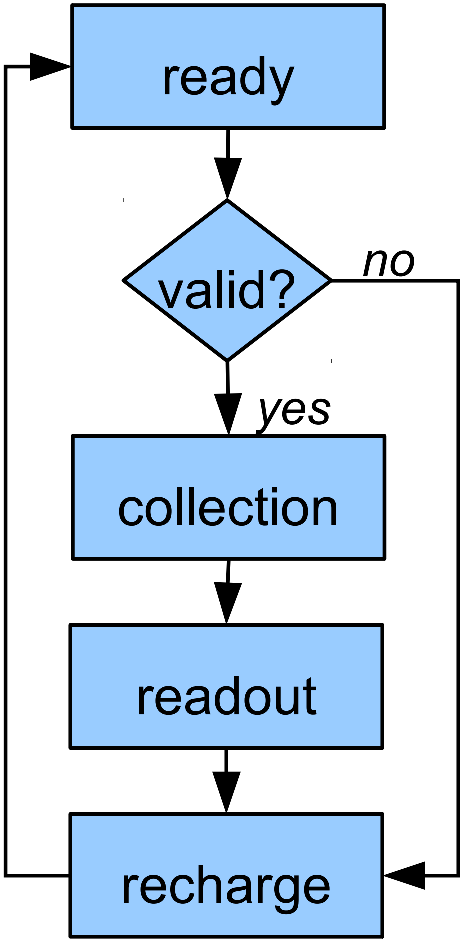
Digital SiPM – State Machine



5ns – 80ns

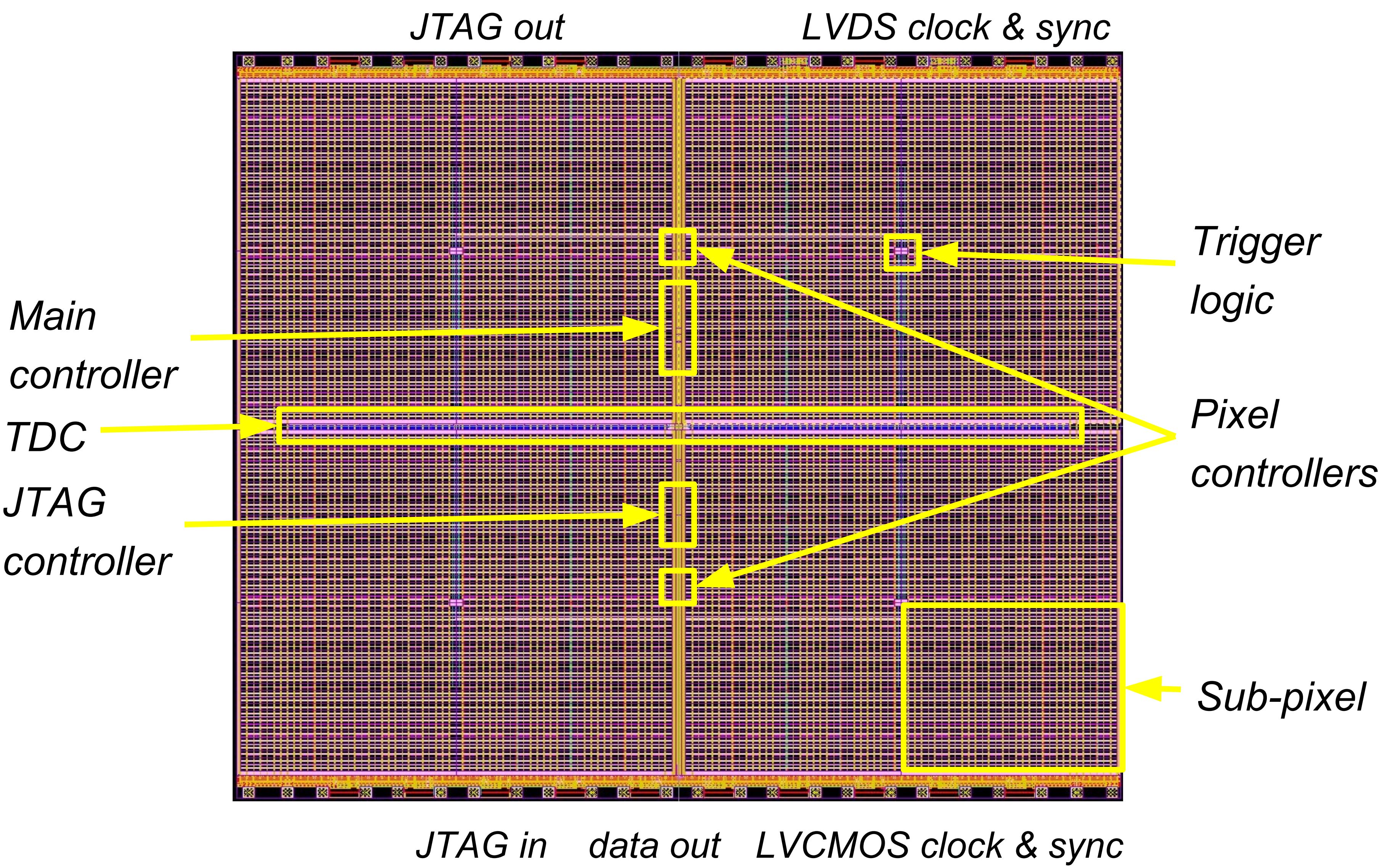
0ns – 20µs

680ns

10ns – 40ns

- *200MHz (5ns) system clock*
- *Variable light collection time up to 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 completely)*

Digital SiPM – Sensor Architecture



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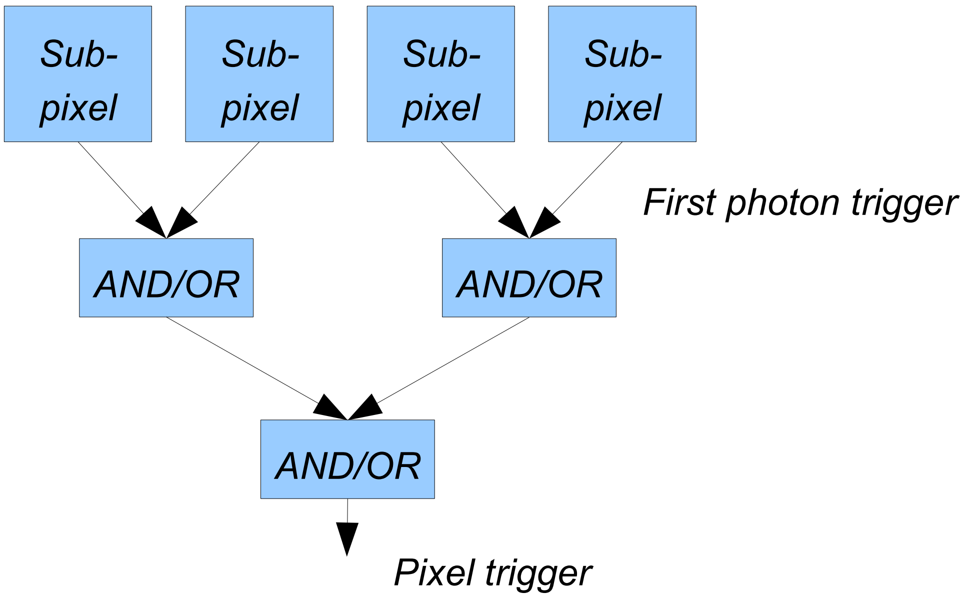
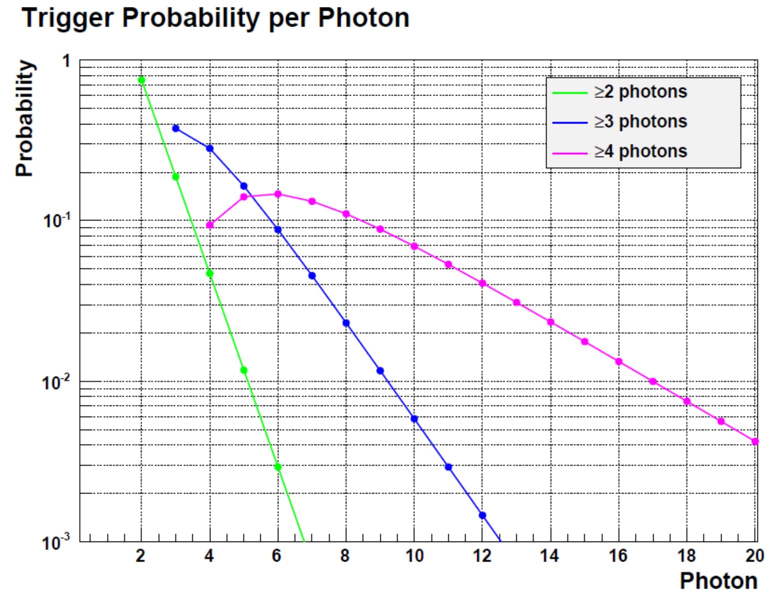
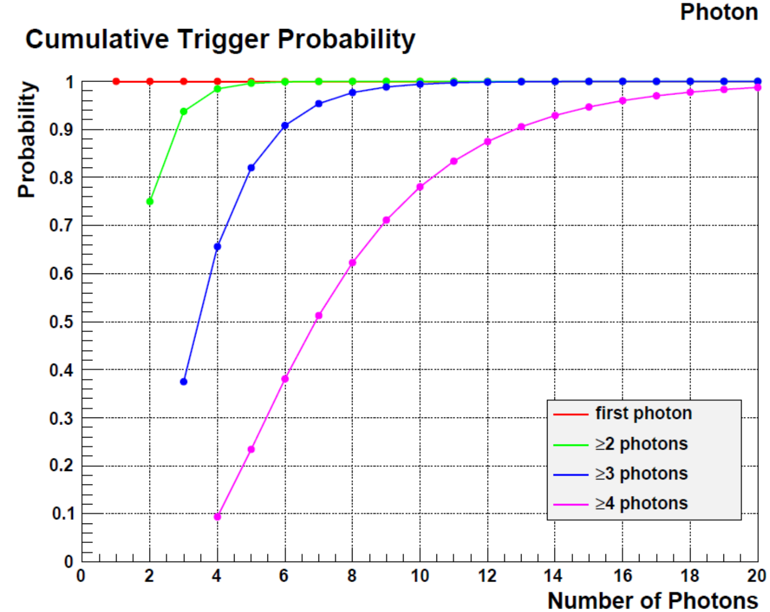
Digital SiPM – Trigger Logic

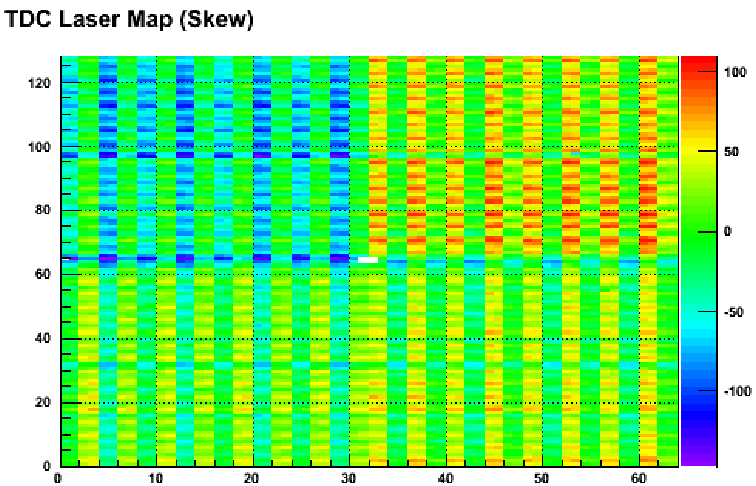


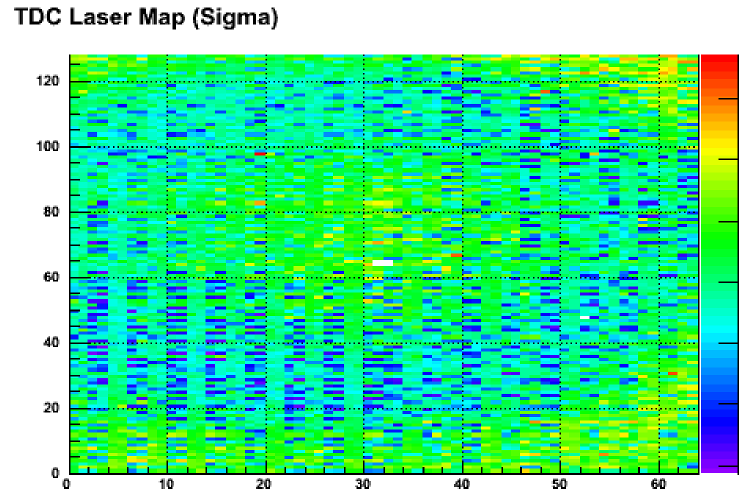


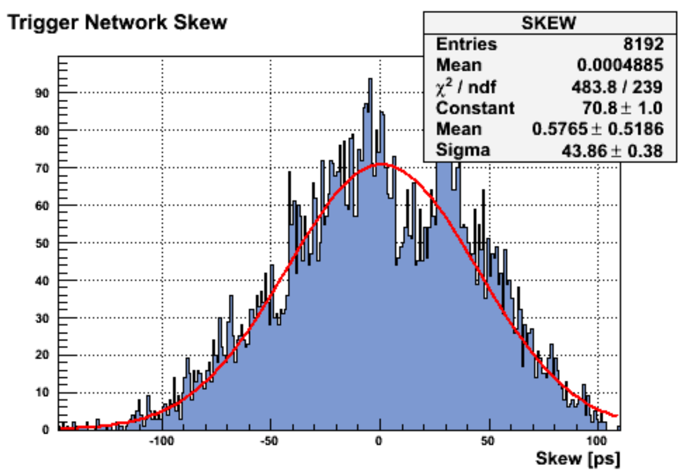


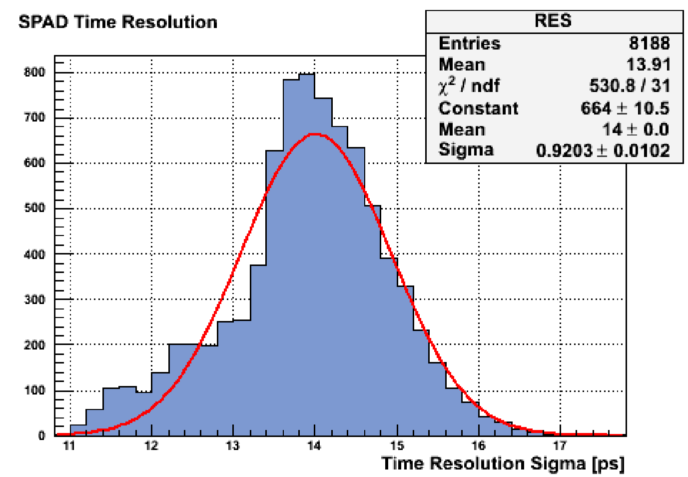
- *Each sub-pixel triggers at first photon*
- *Sub-pixel trigger can be OR-ed or AND-ed to generate probabilistic trigger thresholds*
- *Higher trigger threshold decreases system dead-time at high dark count rates at the cost of time resolution*

Digital SiPM – 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.

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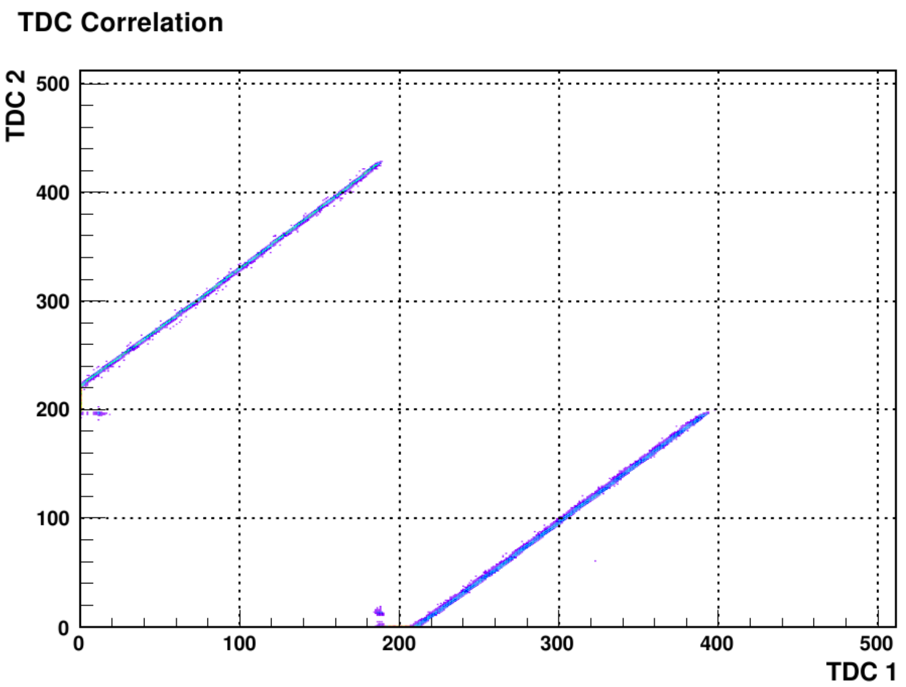
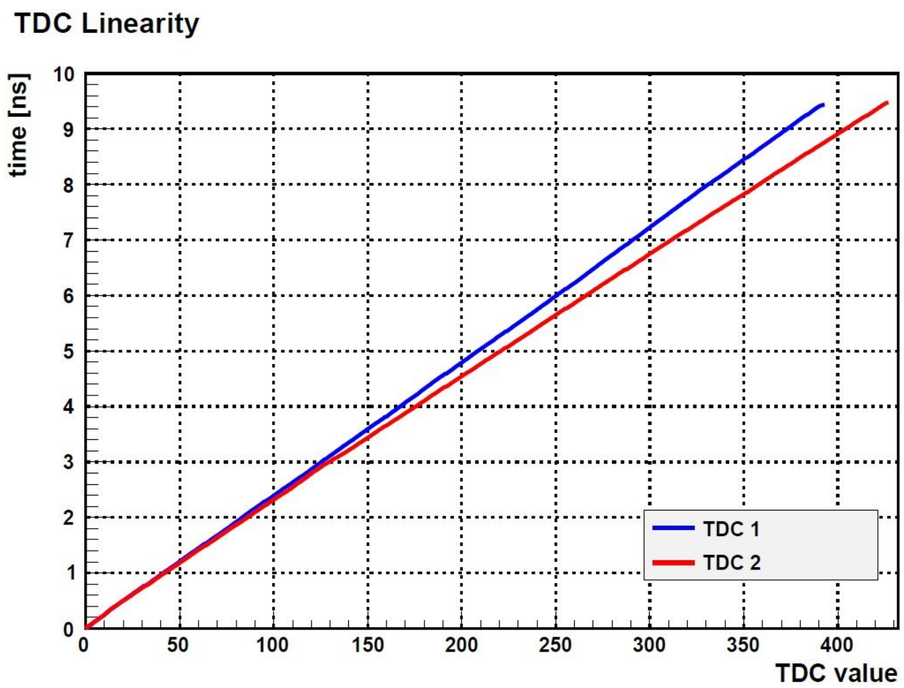
Digital SiPM – Time-to-Digital Converter





- 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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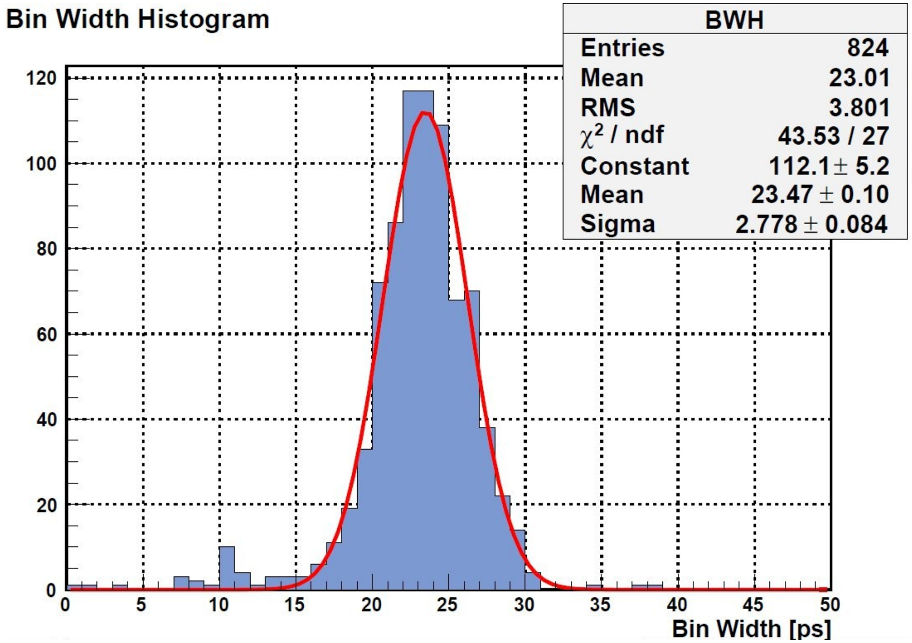
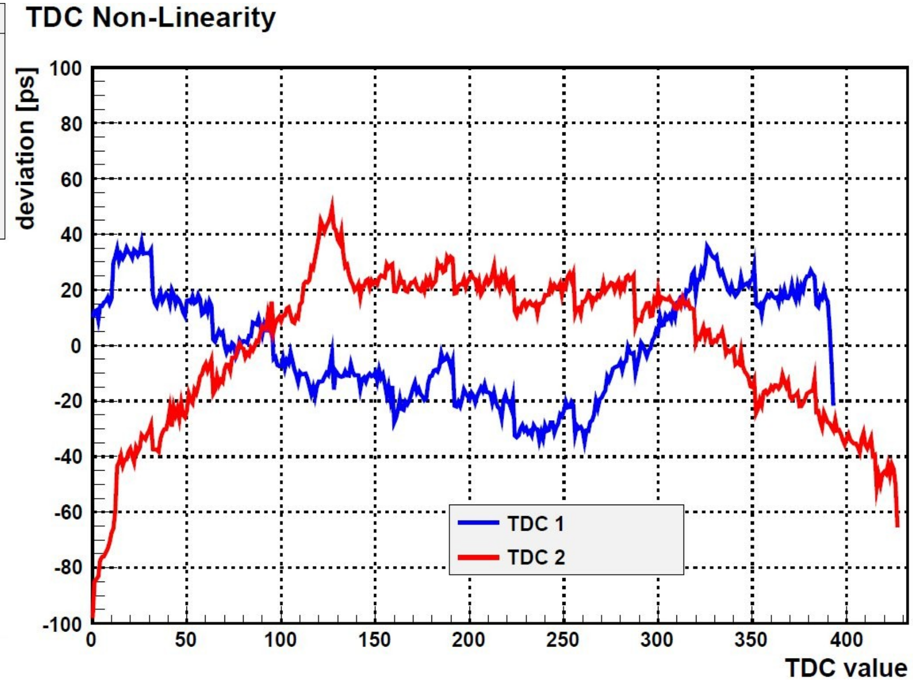
Digital SiPM – Time-to-Digital Converter





- 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

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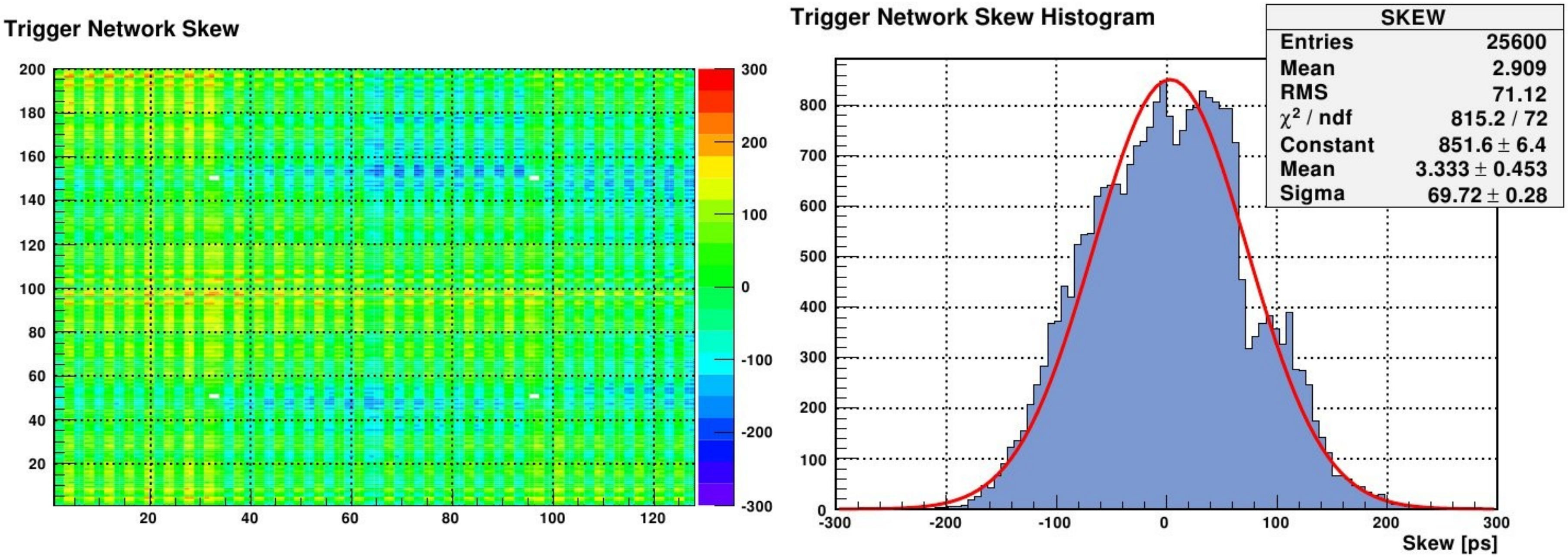
Digital SiPM – Trigger Network Skew



- 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