Beam Loss Monitoring – Detectors

Photon Detection and Silicon Photomultiplier Technology in accelerator and particle physics

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- 1. Introduction: the best photodetectors
- 2. Silicon Photomultipliers (SiPM) as new photon number resolving detectors
- 3. Benefits, drawbacks, and typical applications of SiPM
- 4. Evaluation studies of SiPMs for Beam Loss Monitoring
- 5. Modelling and analysis of comparative performance: SiPM vs PMT and APD
- 6. Trends and prospects of SiPM technology for BLM and accelerator applications

Introduction

- **1. Introduction: the best photodetectors**
  - **your choice?**
- **2. Silicon Photomultipliers (SiPM) as new photon number resolving detectors**
- **3. Benefits, drawbacks, and typical applications of SiPM**
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Photodetector #1 *

Adaptive focusing & trichromatic / monochromatic vision
High sensitivity due to 100 million rod cells (10-40 photons)
High resolution & double dynamic range due to 5 million cone cells
High readout rate of 30 frame/s
Internal signal processing (100M cells to 1M nerves @30fps)
540 million years old design

(*) Yu. Musienko, NDIP 2011

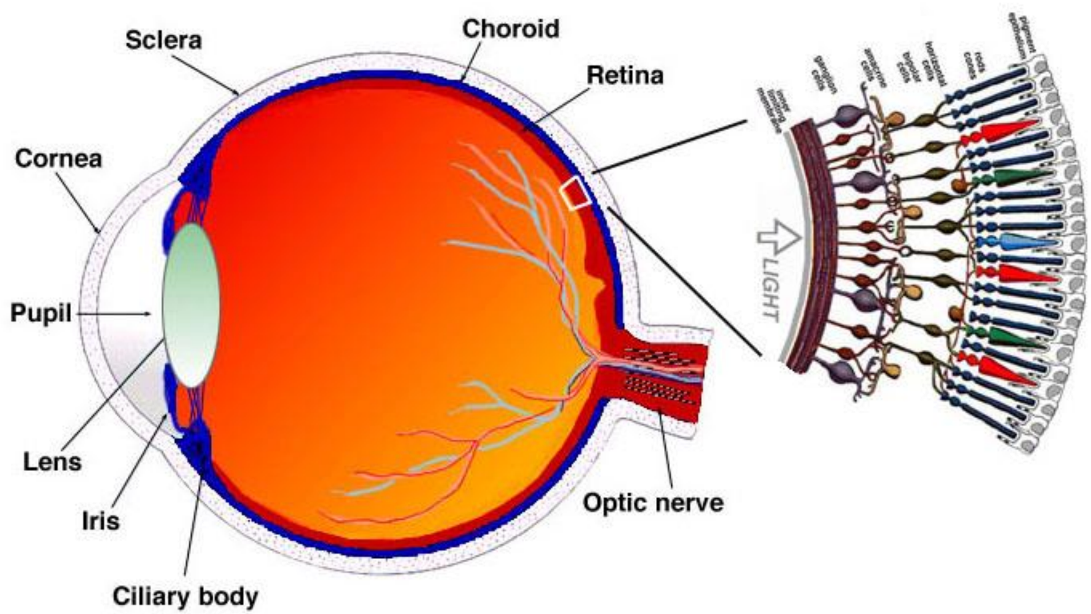
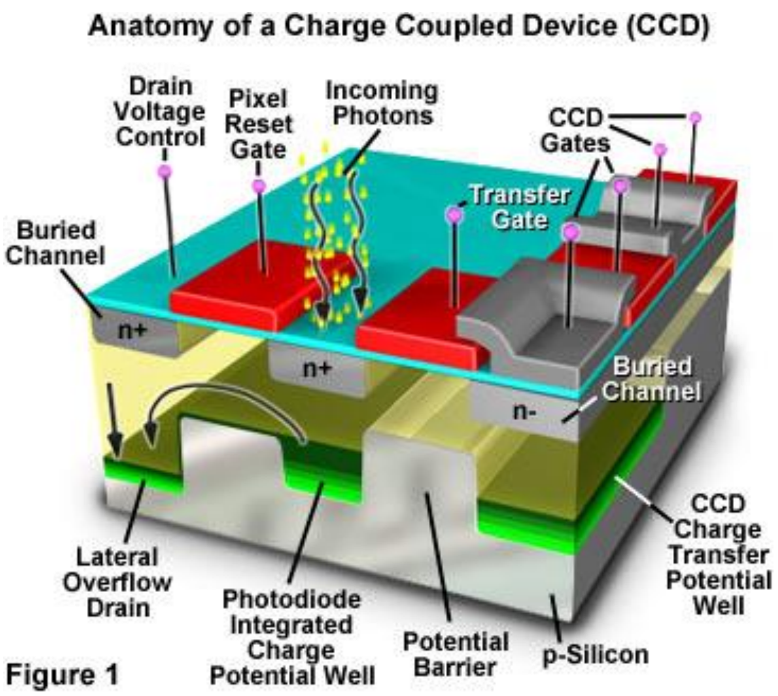
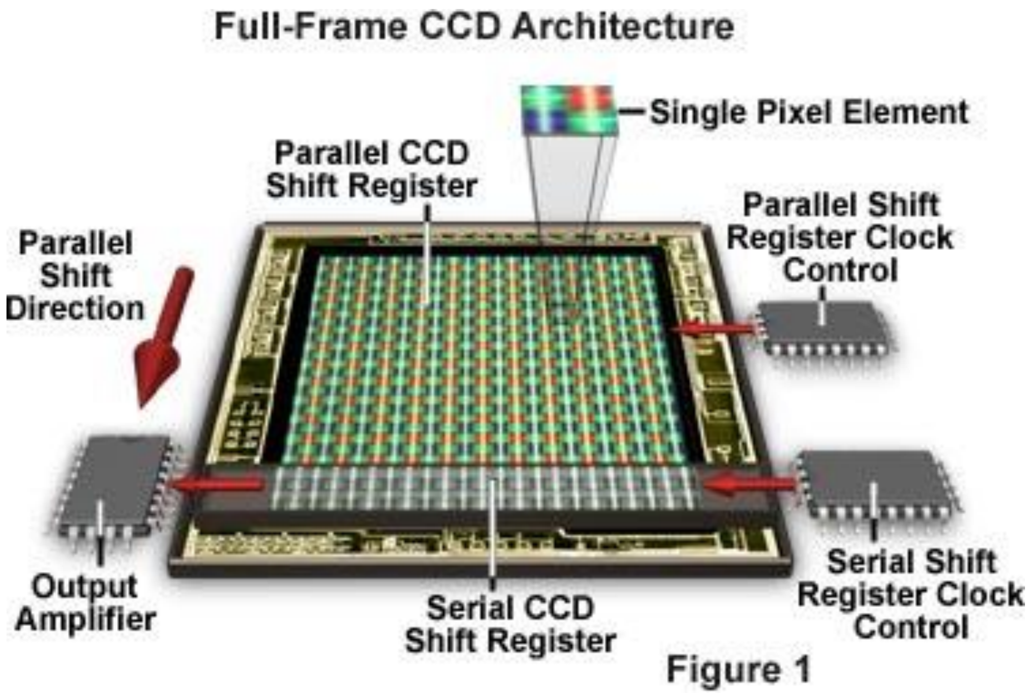


Fig. 1.1. A drawing of a section through the human eye with a schematic enlargement of the retina.

CCD/CMOS approach – toward to #1

Trichromatic / monochromatic vision
Number of pixels up to ~ 50 M
Sensitivity from ~ 10 -100 photons
Dynamic range up to ~ 50K
Readout up to ~ 1000 frame/s
<u>40 years old design</u>

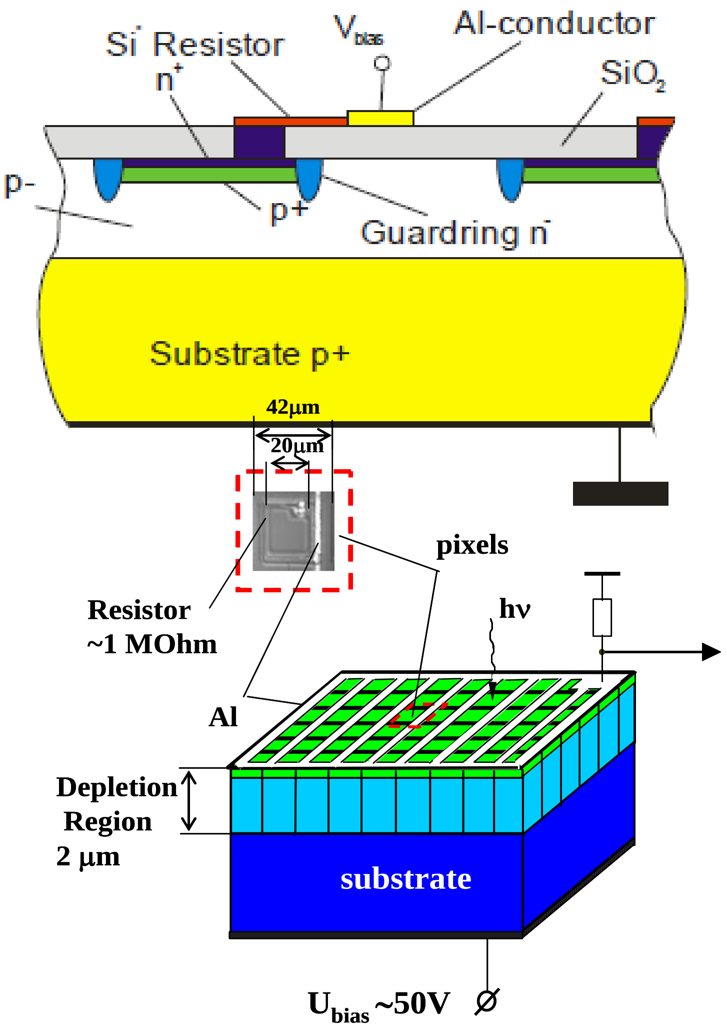




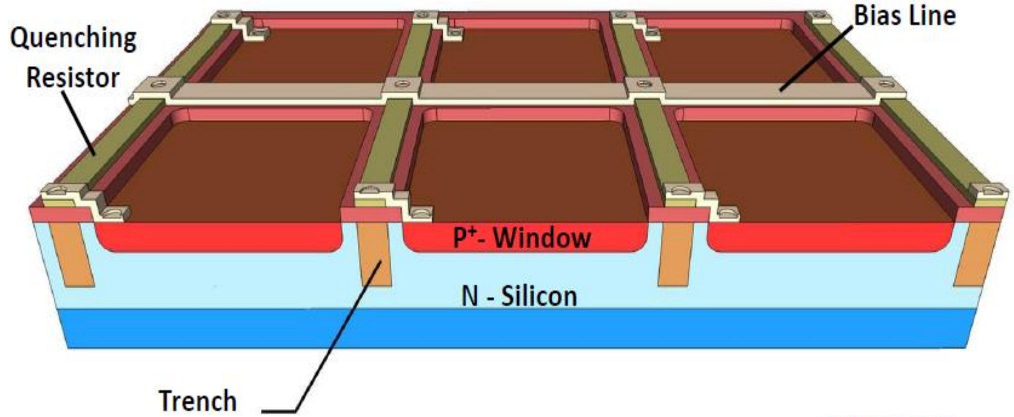
SiPM approach – toward to ideal low photon detection

QUASAR GROUP · UNIVERSITY OF LIVERPOOL · SiPM · The Cockcroft Institute of Accelerator Science and Technology · P.N.Lebedev Physical Institute of the Russian Academy of Science

20th Anniversary ~ now!



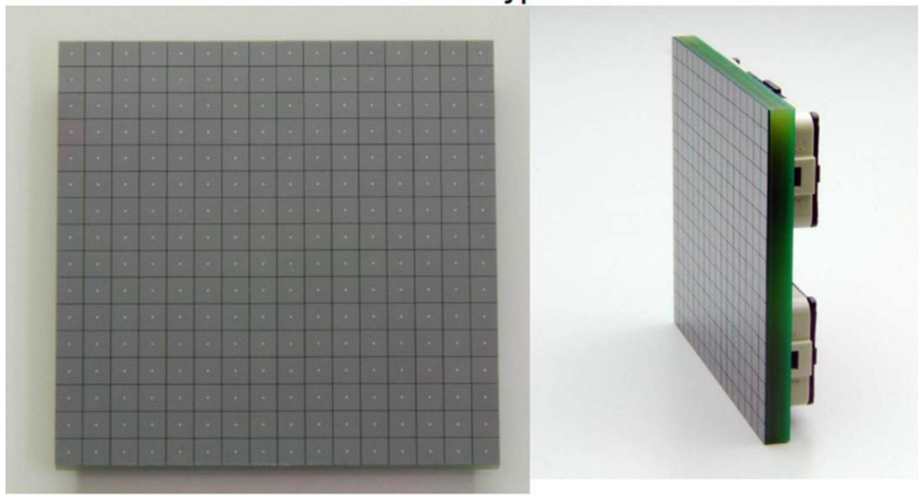
Section of KETEK SiPM Microcell



HAMAMATSU

2D MPPC Array with TSV

50µm pitch, 3x3mm chip,
16x16 channels with Connector type



Silicon Photomultipliers (SiPM) as new photon number resolving detectors

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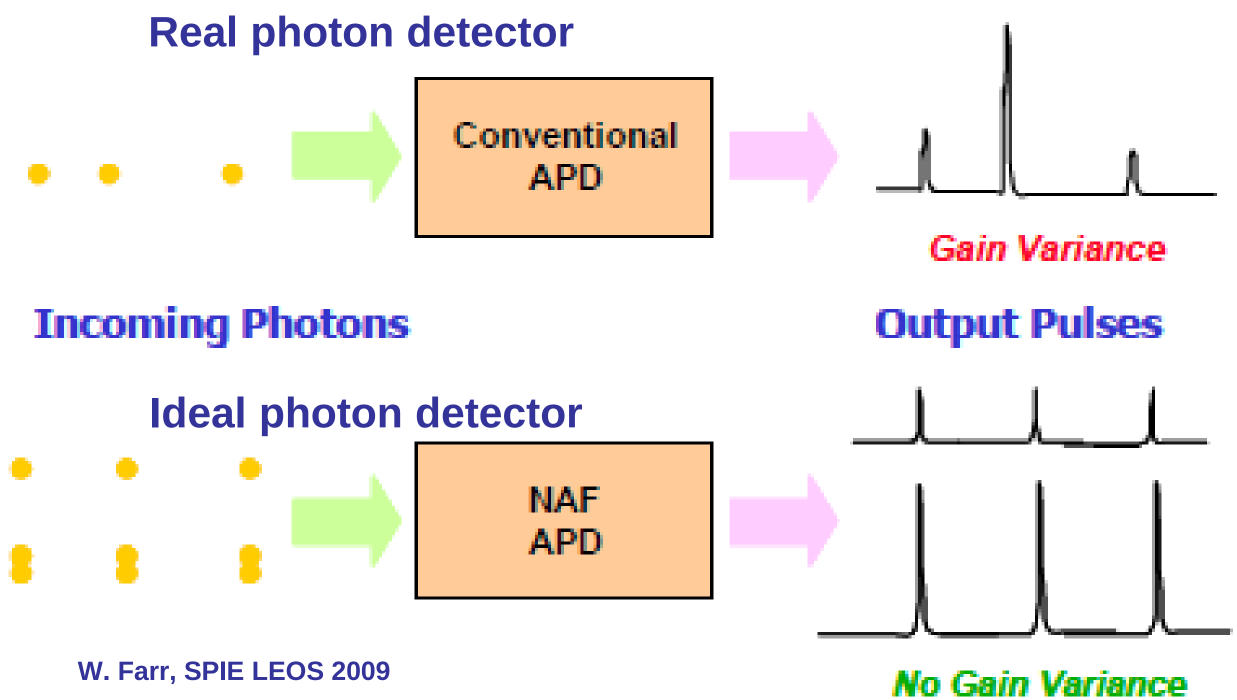
Concept of ideal detector: first step to SiPM

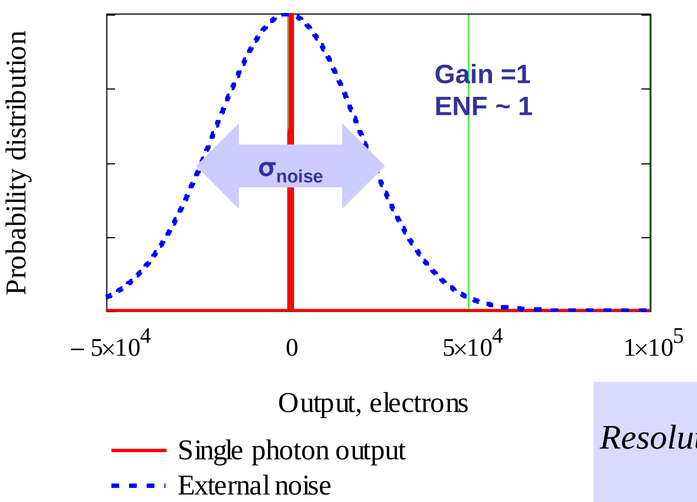
- Ideal detector: <u>conversion</u> of <u>any input</u> signal starting from single photon to <u>recognizable output</u> without <u>noise</u> and <u>distortion</u> in <u>amplitude</u> and <u>timing</u> of the signal



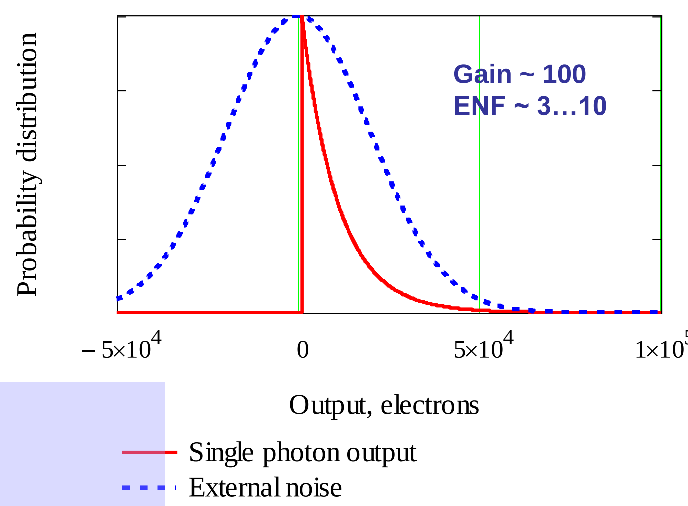
W. Farr, SPIE LEOS 2009

Single photon detection in 1 GHz BW with electronic noise 10^4 e

Photodiode



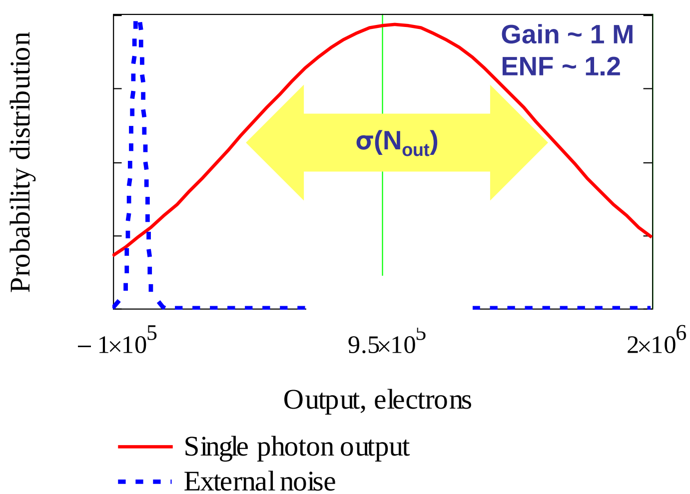
APD



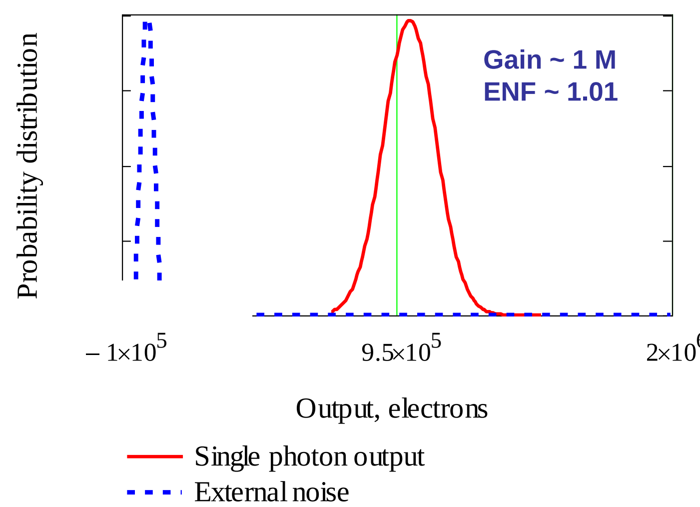
$$Resolution = \sqrt{\frac{\sigma^2(N_{out}) + \sigma^2{}_{noise}}{\langle N_{out}\rangle^2}}$$

$$ENF = 1 + \frac{\sigma^2(N_{out})}{\langle N_{out}\rangle^2} \quad - Excess\ \ Noise\ \ Factor$$

PMT

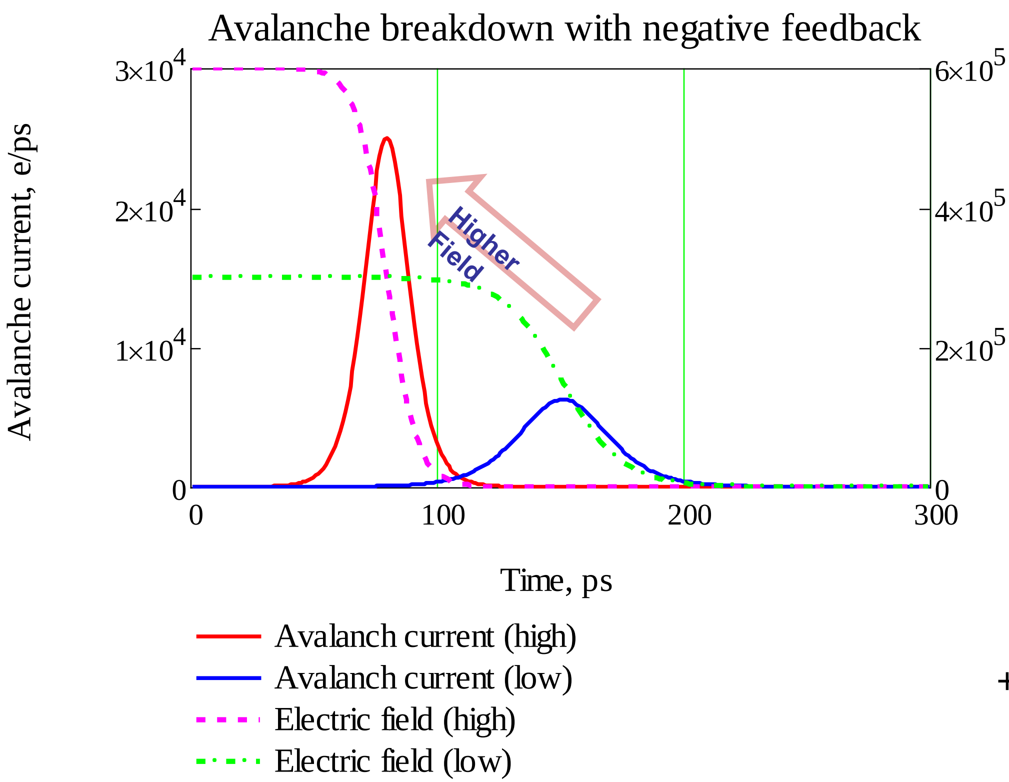


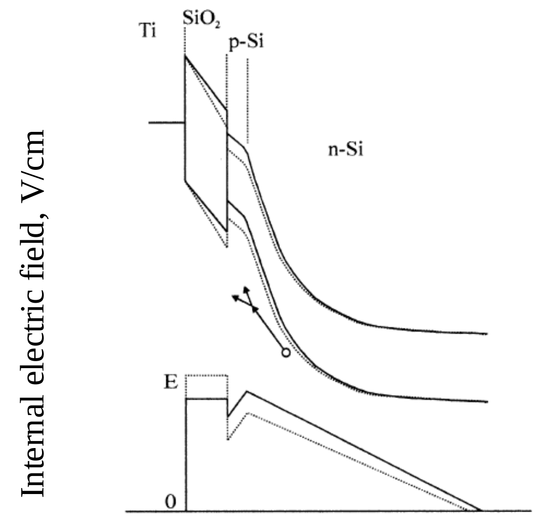
SiPM

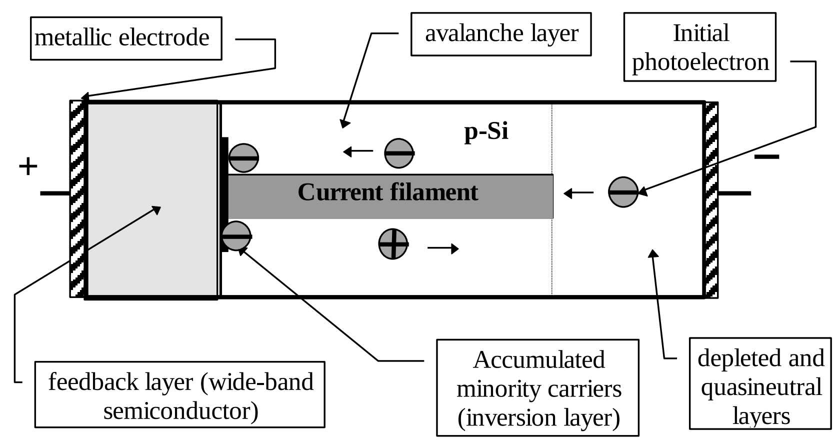


Avalanche with negative feedback: main step to SiPM

<u>Strong</u> negative feedback = <u>fast</u> quenching & <u>small</u> charge fluctuations







V. Shubin, D. Shushakov, Avalanche Photodetectors, 2003

Multi-pixel design & feedback resistor: final step to SiPM

MRS APD – 1990s

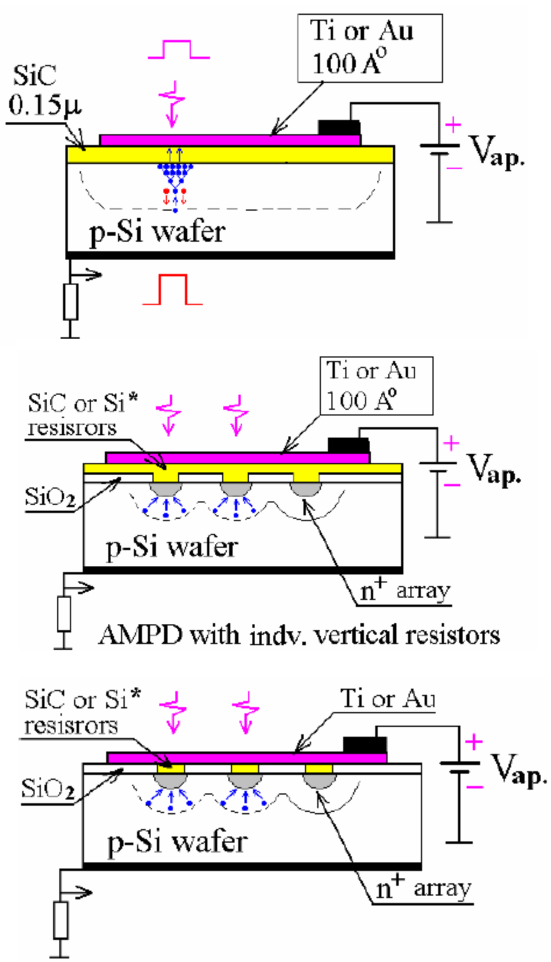


Fig. 1-4: Sadygov, NDIP 2005

SiPM – 1996 / 2000s

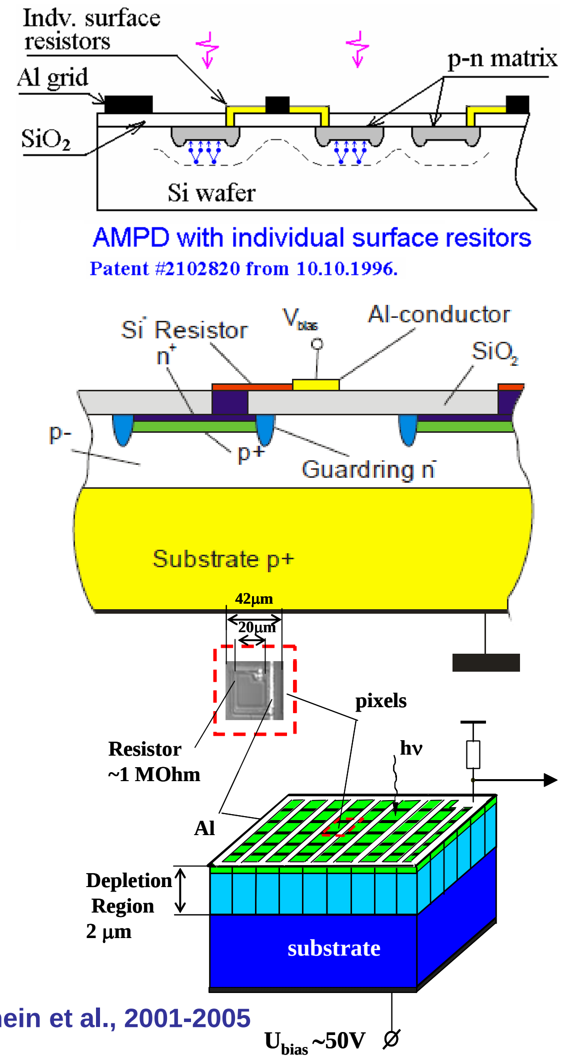
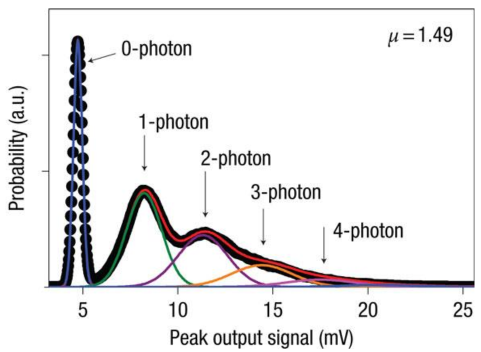


Fig. 5-7: B. Dolgoshein et al., 2001-2005

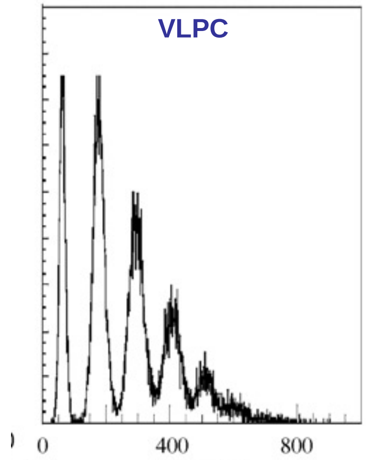
SiPM: photon number resolution

APD (self-differencing mode)

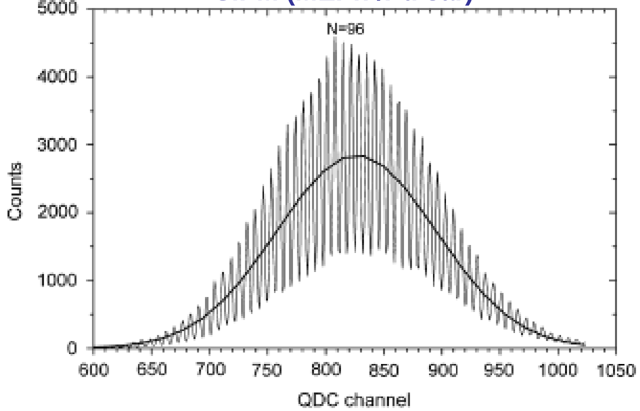


B. Kardinal et al., Nat. Photonics, 2008

VLPC

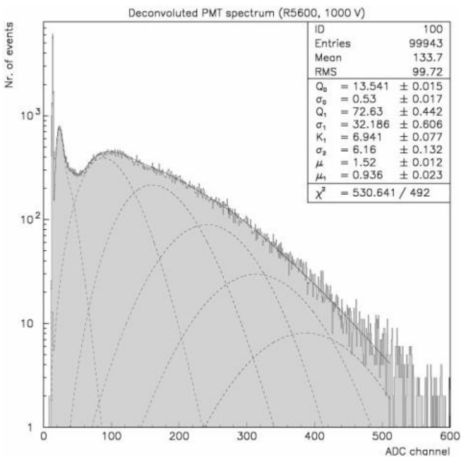


SiPM (MEPhI/Pulsar)



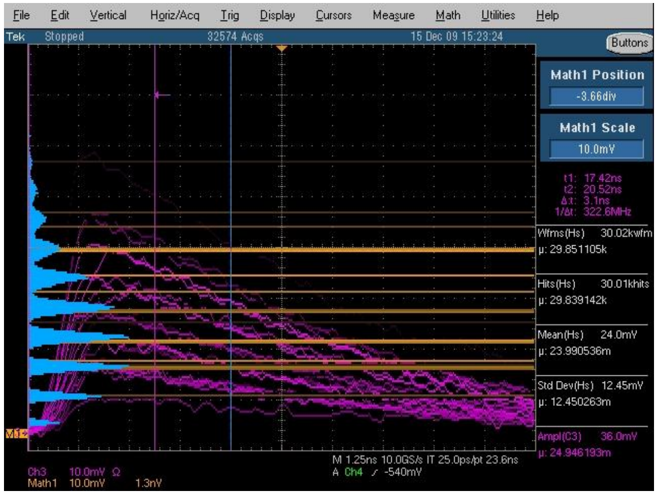
R. Mirzoyan et al., NDIP, 2008

PMT (Hamamatsu R5600)



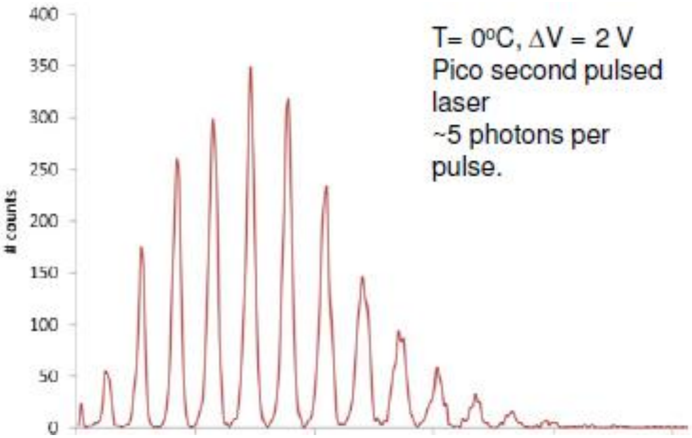
I. Chirikov-Zorin et al, NIMA 2001

MPPC (Hamamatsu)



S. Vinogradov, SPIE 2011

SiPM (Excelitas)

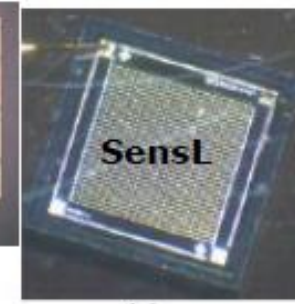


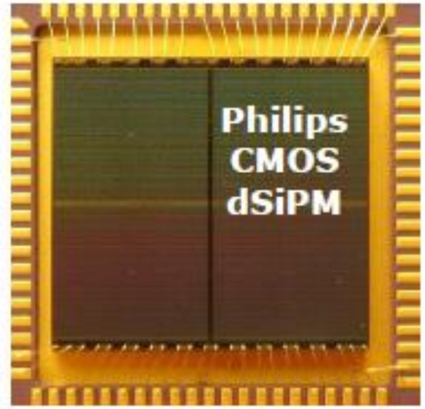
A. Barlow and J. Schilz, SiPM matching event, CERN, 2011

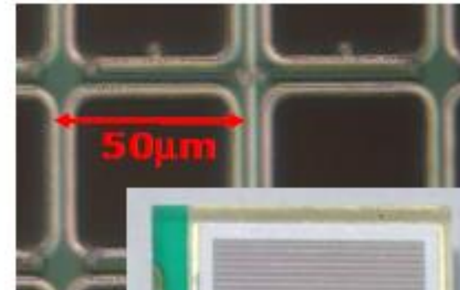
Today

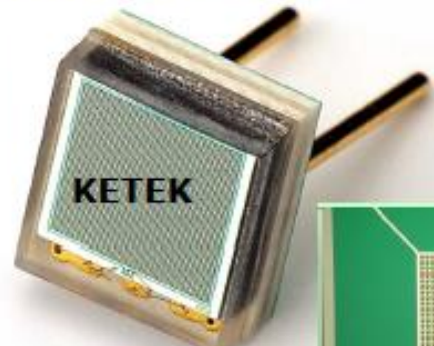
Many institutes/companies are involved in SiPM development/production:

- **CPTA**, Moscow, Russia
- **MePhi/Pulsar** Enterprise, Moscow, Russia
- **Zecotek,** Vancouver, Canada
- **Hamamatsu HPK**, Hamamatsu, Japan
- **FBK-AdvanSiD**, Trento, Italy
- **ST Microelectronics**, Catania, Italy
- **Amplification Technologies** Orlando, USA
- **SensL**, Cork, Ireland
- **MPI-HLL**, Munich, Germany
- **RMD**, Boston, USA
- **Philips**, Aachen, Germany
- **Excelitas** tech. (formerly Perkin-Elmer)
- **KETEK**, Munich, Germany
- **National Nano Fab Center**, Korea
- **Novel Device Laboratory** (**NDL**), Bejing, China
- **E2V**
- **CSEM**

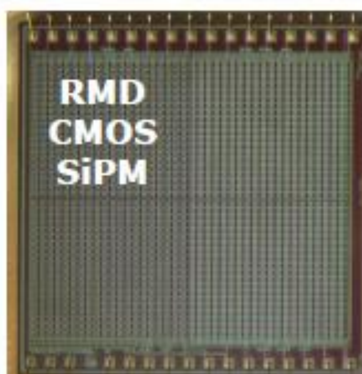


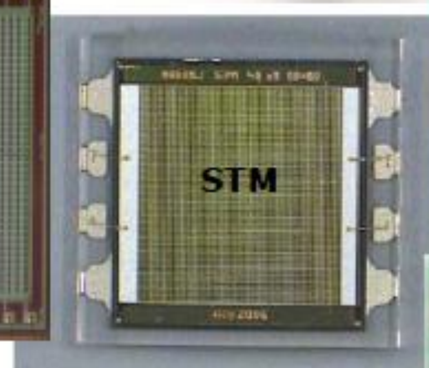






Amplification Technologies (DAPD)





Benefits, drawbacks, and typical applications of SiPM

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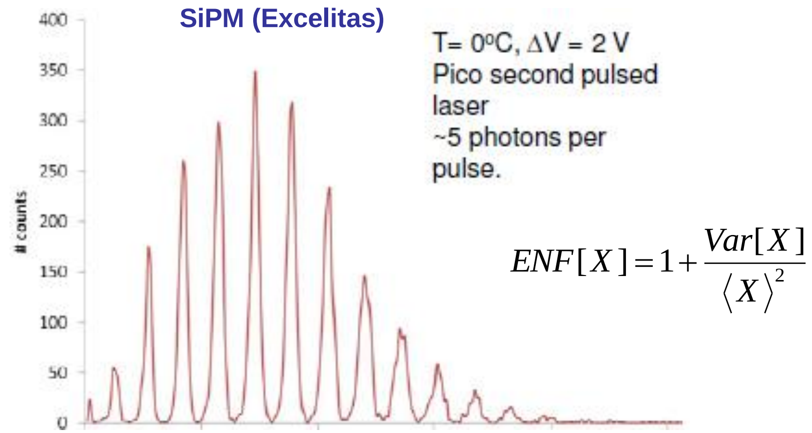
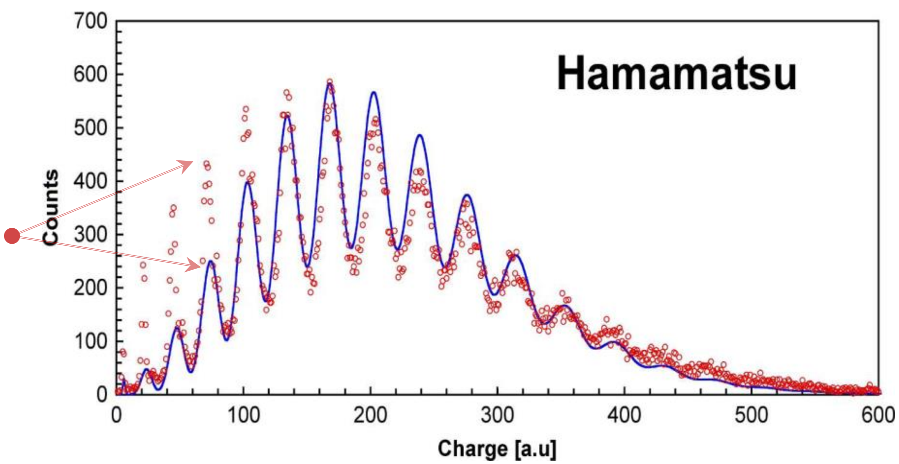
SiPM: photon number resolution

- **SiPM looks like ~ ideal detector**
  - **Near-ideal amplification:**
    - **— Gain > 10^5, ENF < 1.01**
  - **Room temperature**
  - **Low bias (<100 V)**
  - **Large area (6x6 mm^2)**
  - **Good timing (jitter < 200 ps)**
  - **Fast response (rise <1 ns, fall~20 ns)**



A. Barlow and J. Schilz, SiPM matching event, CERN, 2011

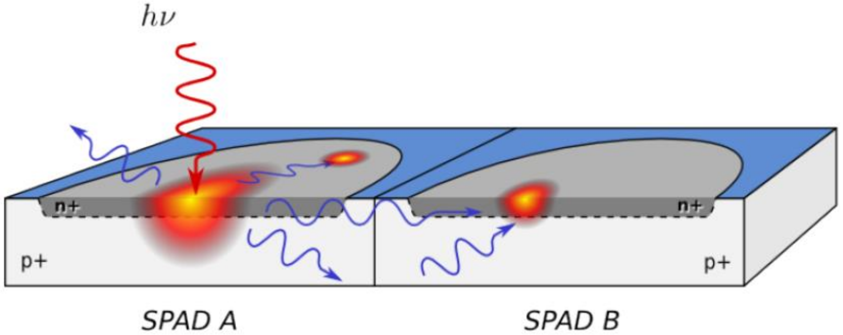
- **In fact, not a photon spectrum**
  - **Photoelectrons**
  - **Dark electrons**
  - **Crosstalk & Afterpulses**
- **In fact, non-Poissonian distribution**
  - **Why?**
  - **How much?**
  - **Distribution?**
  - **Resolution?**



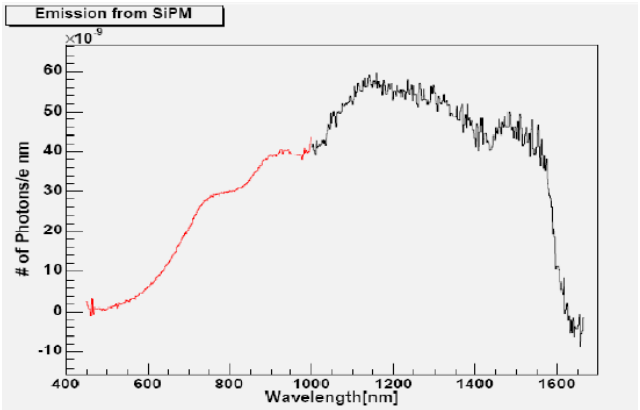
P. Finocchiaro et al., IEEE TNS, 2009

SiPM drawbacks: crosstalk

- **Crosstalk: hot carrier photon emission + detection = false event**

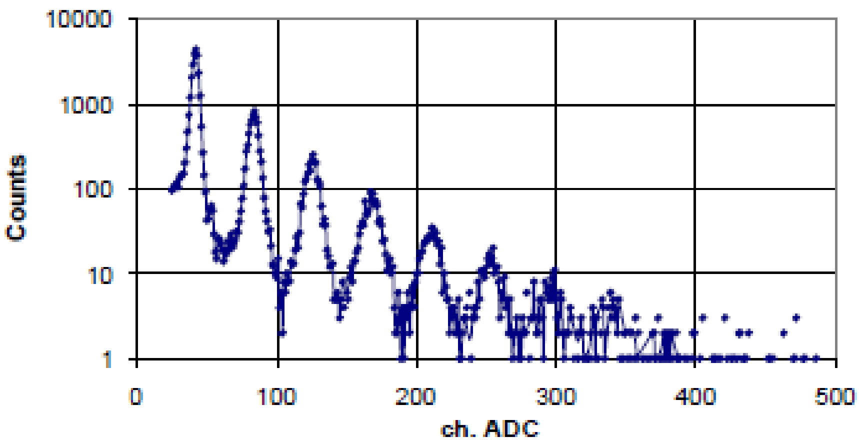


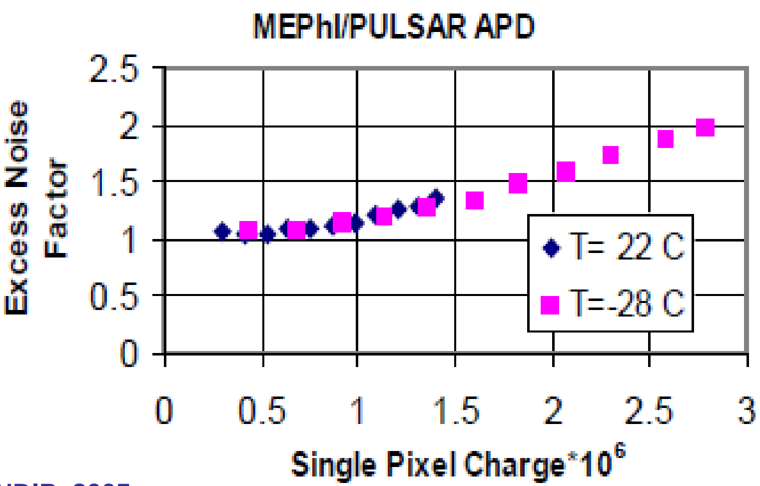
A. Lacaita et al., IEEE TED, 1993



R. Mirzoyan, NDIP, 2008

SES MEPhI/PULSAR APD, U=57.5V, T=-28 C

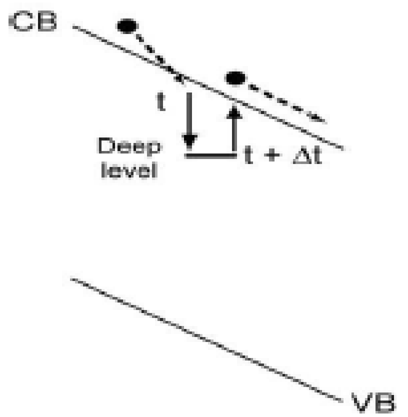


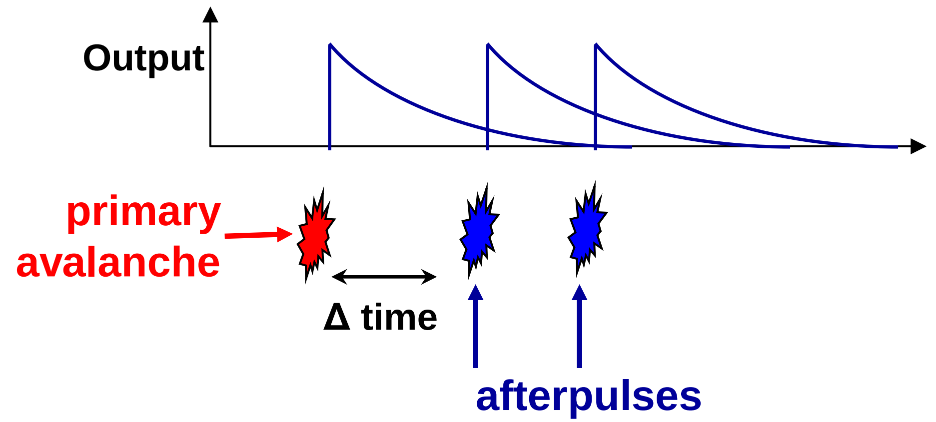


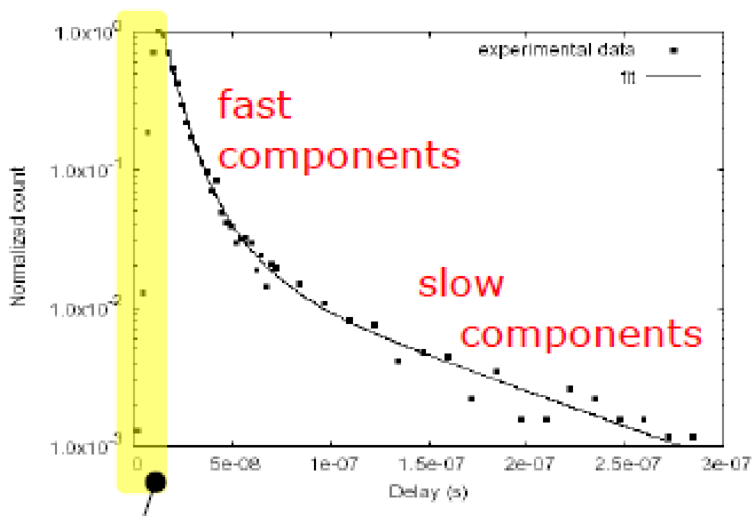
Yu. Musienko, NDIP, 2005

SiPM drawbacks: afterpulsing

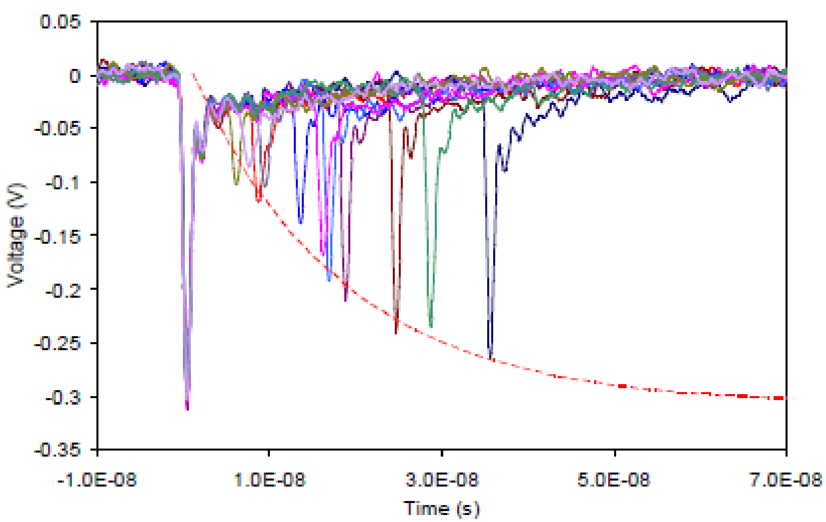
- **Afterpulsing: trapping + detrapping + detection = false event**







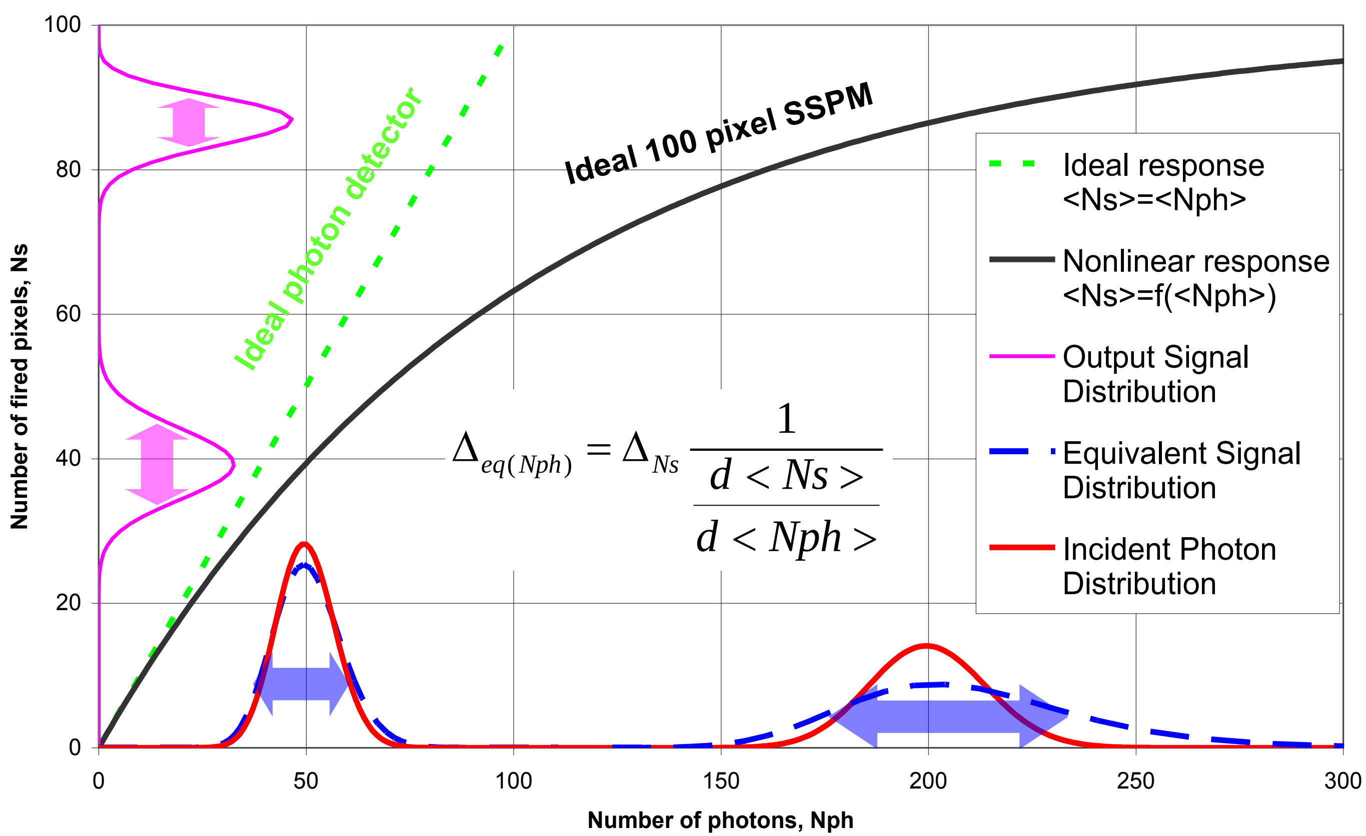
G. Collazuol, PhotoDet, 2012



C. Piemonte et al., *Perugia,* 2007

SiPM drawbacks: nonlinearity

- Limited number of pixels = losses of photons
- Dead time of pixels during recovery = losses of photons



Plot details:

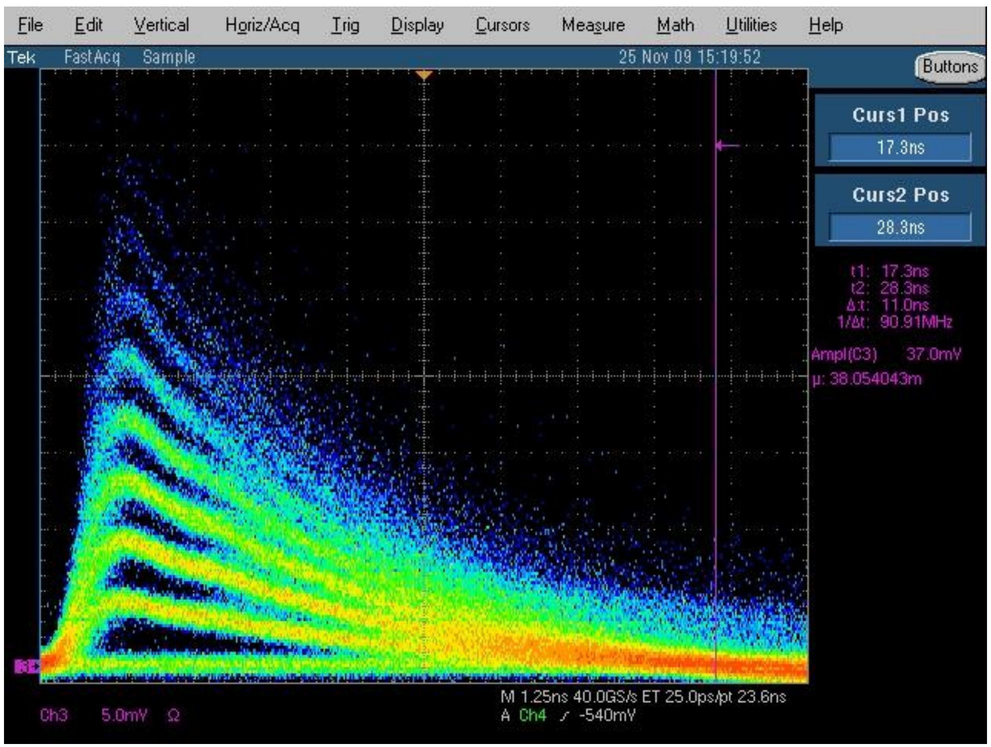
Npixel=100

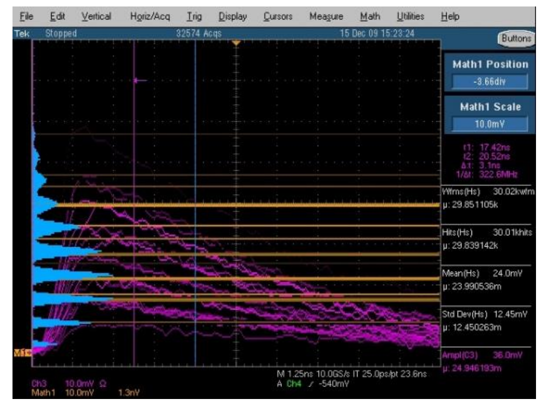
PDE=100%

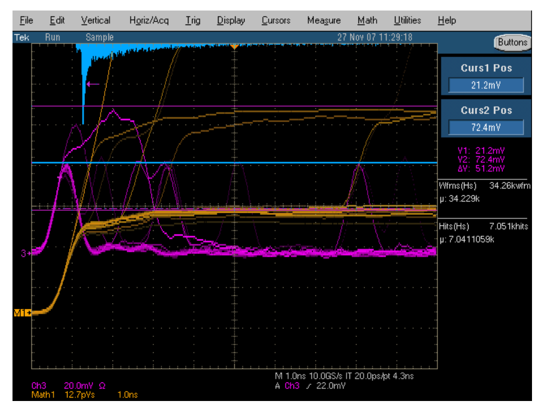
No Noise (DCR, CT, AP)

Application types

- Binary detection of light pulses – “events” (bit error rate) - NA
- Photon number resolution (noise-to-signal ratio, σ_n/μ_n) - Calorimetry
- Time-of-flight detection (transit time spread, σ_t) – TOF PET
- Detection of arbitrary signals starting from photon counting - $I_{ph}(t)$
  - Beam Loss Monitoring

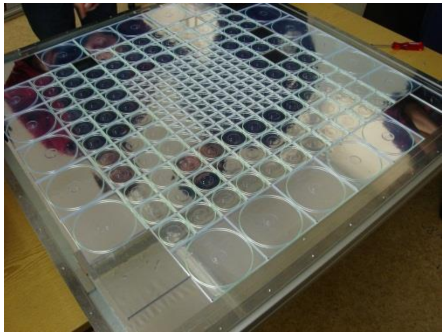




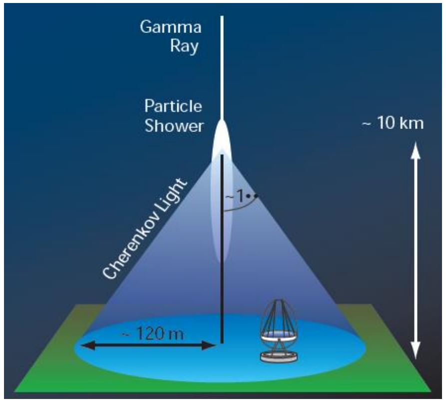


SiPM application examples

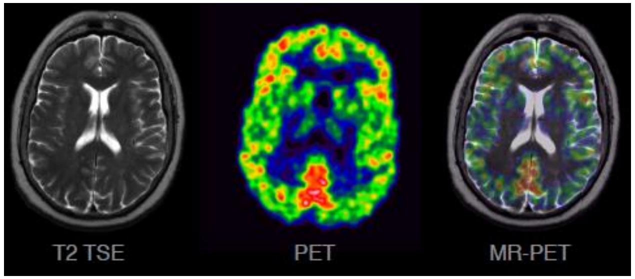
- **Calorimetry**
  - SiPM (MEPhI) small HCAL (MINICAL), DESY, 2003
  - MPPC (Hamamatsu), T2K, 2005-2009
  - MPPC at LHC CMS HCAL
  - RICH for ALICE (LHC)
  - FermiLab, Jefferson Lab calorimeter upgrade projects



- **Astrophysics**
  - SiPM cosmic ray detection in space (MEPhI, 2005)
  - Cherenkov light detection of air showers (CTA, 2013)



- **Medical imaging**
  - Positron Emission Tomography:
    - —TOF-PET
    - — PET / MRI



- **Telecommunication**
  - Quantum cryptography
  - Deep space laser link (Mars exploring program)

Evaluation studies of SiPMs for Beam Loss Monitoring

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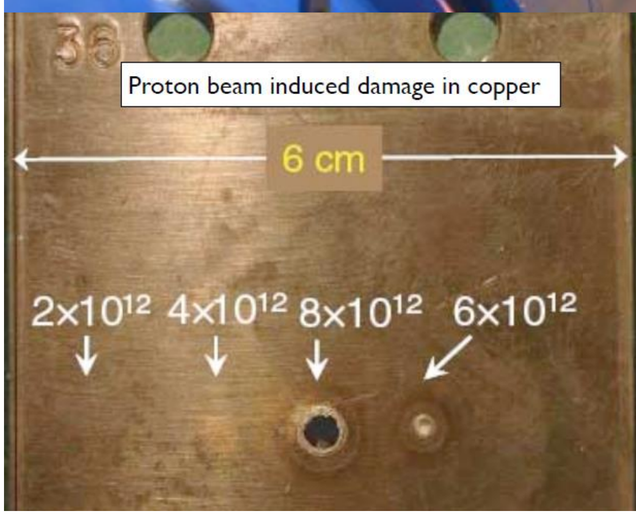
Beam Loss Monitoring
(ref. E. Nebot talk 08-07-14)

Objectives:

Protect
Monitor
Adjust



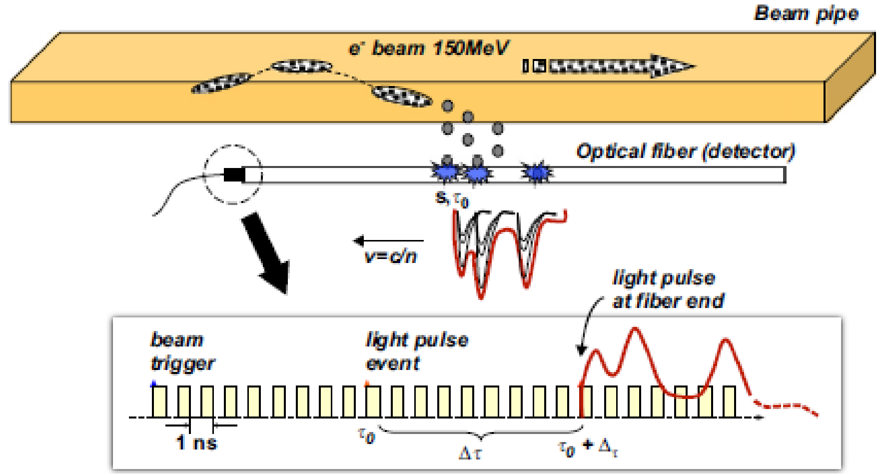
BLM: first evaluation of SiPM

QUASAR
UNIVERSITY OF LIVERPOOL
SiPM
The Cockcroft Institute of Accelerator Science and Technology
P.N.Lebedev Physical Institute of the Russian Academy of Science

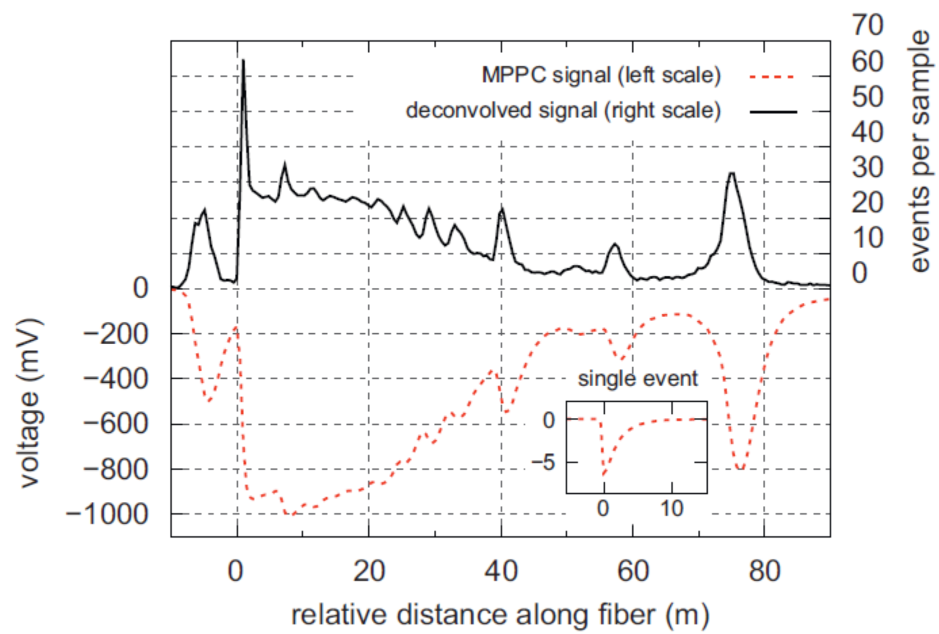
D. Di Giovenale et al., NIMA, 2011

SPARC accelerator, Frascati, INFN

FERMI@Elettra, Synchrotrone Trieste



- MPPC, 1mm^2, 400 pixels
- Quartz fiber 300 µm, 100 m
- Dark count noise: negligible
- Electronic noise: negligible
- Spectral dispersion in fiber: $n(\lambda) \rightarrow \Delta t(\lambda)$ ~ 3 ns @100 m
- τ_{fall} ~ 10 ns → *deconvolution*

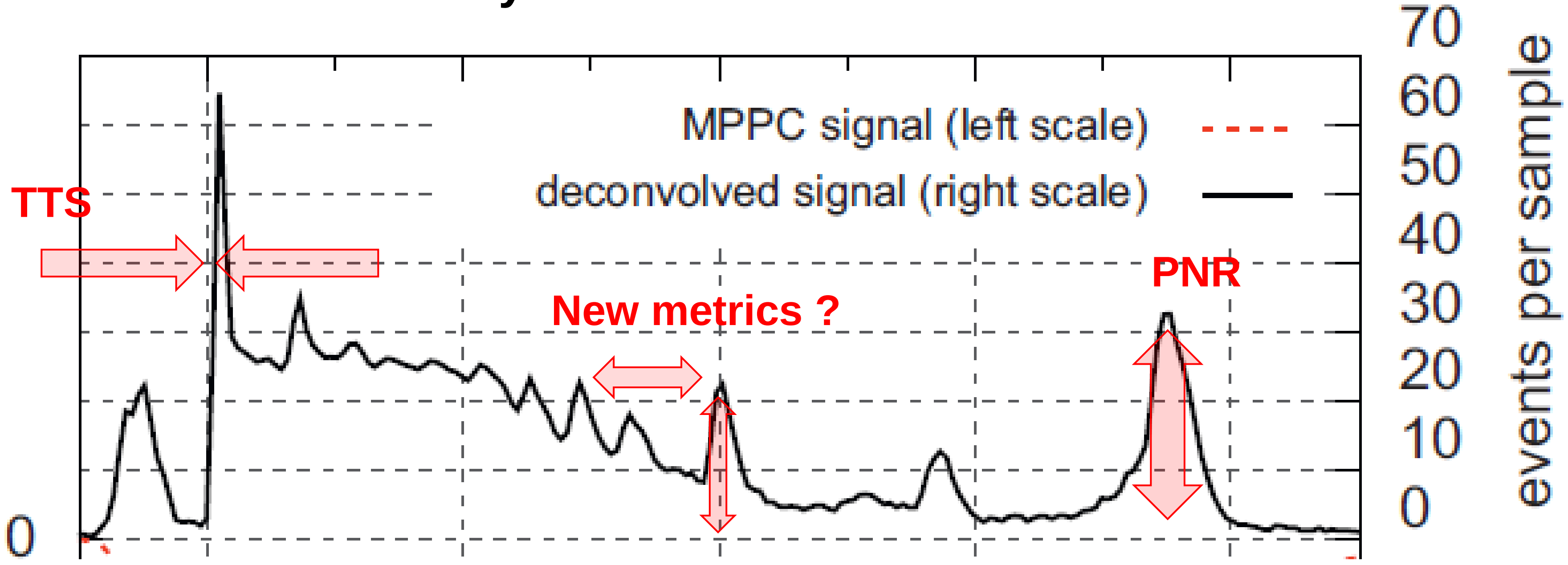


◙Compact low cost BLM

- 1m-scale resolution @100 m

SiPM performance metrics for BLM

- **Loss scenarios reconstruction**
  - **Amplitude → # photons → # particles per location (PNR)**
  - **Transit time to rising edge → single loss location (Time Res.)**
  - **Resolution of multiple loss locations & # particles**
    - **— Modulation transfer function (MTF) ?**
    - **— Nonlinearity has to be accounted !**



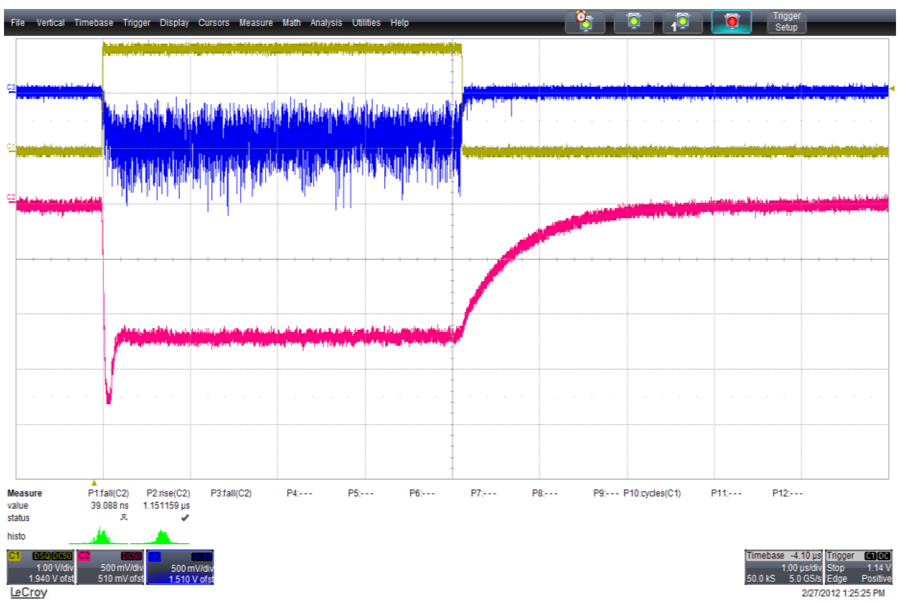
Challenges for SiPM in BLM: saturation, recovering, duplications

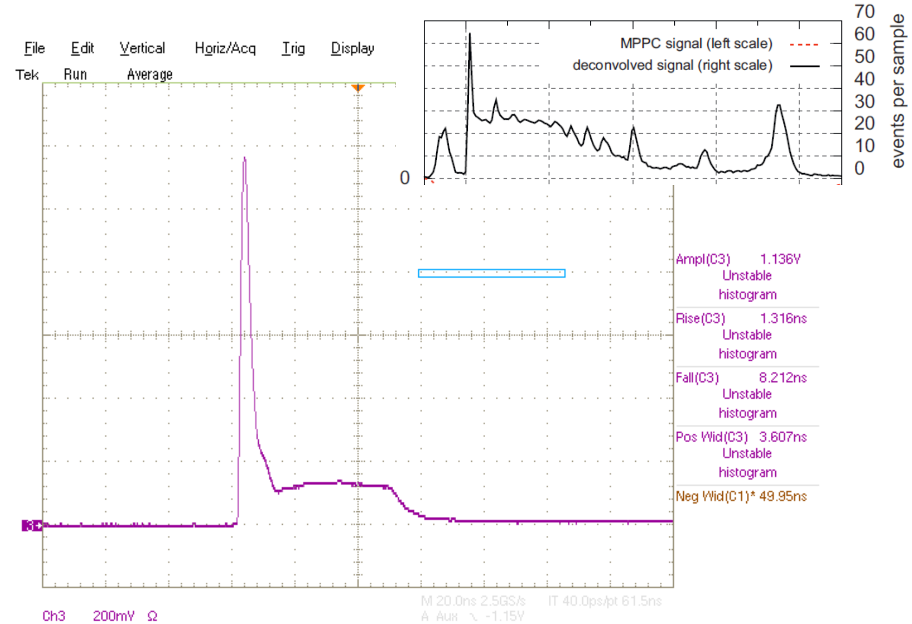
- **Transient nonlinearity of SiPM response**

  Large rectangular light pulse: Nph > Npix; Tpulse > Trec

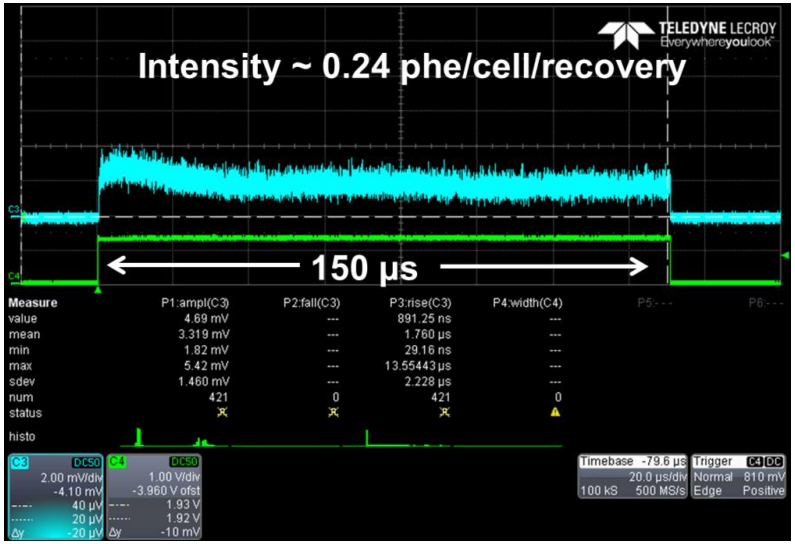
  - **Peak – initial avalanche events in ready-to-triggering pixels**
  - **Plateau – repetitive recovering and re-triggering of pixels**
  - **Fall – final recovering (without photons, but with afterpulses!)**

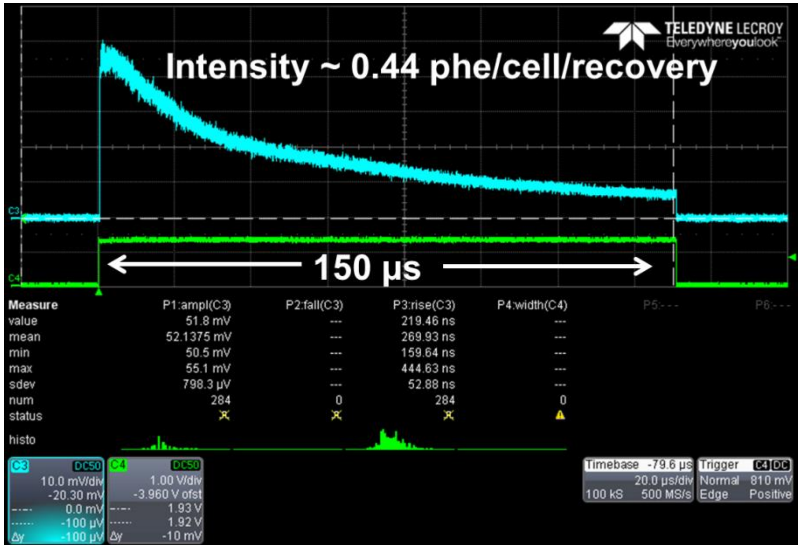
4 us pulse | **50 ns pulse**

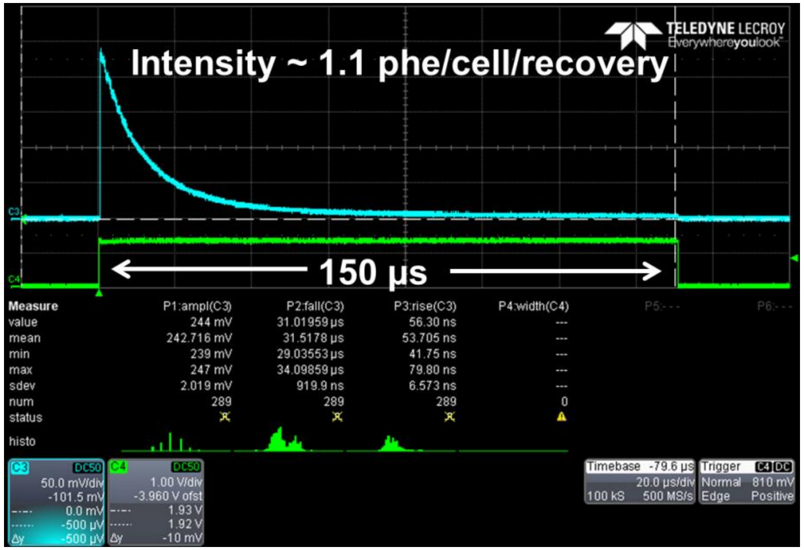


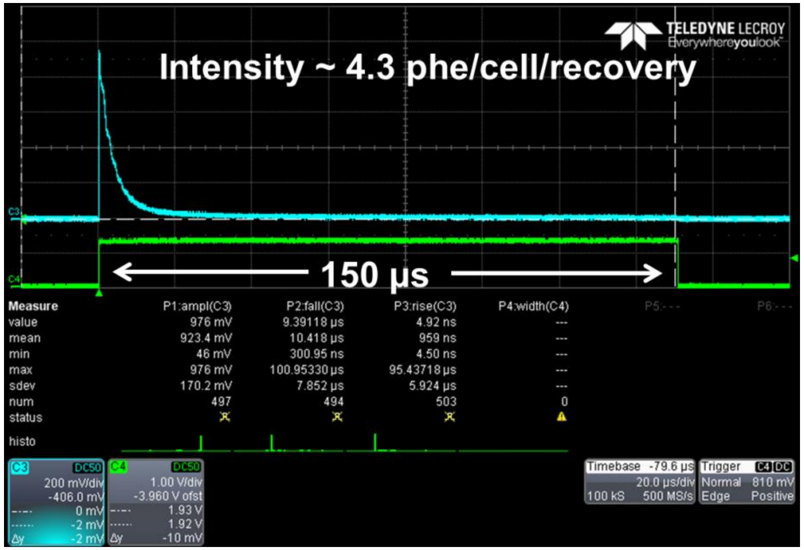


MPPC response on rectangular pulse









Modelling and analysis of comparative performance: SiPM vs PMT and APD

- 1. Introduction: the best photodetectors
- 2. Silicon Photomultipliers (SiPM) as new photon number resolving detectors
- 3. Benefits, drawbacks, and typical applications of SiPM
- 4. Evaluation studies of SiPMs for Beam Loss Monitoring
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- 6. Trends and prospects of SiPM technology for BLM and accelerator applications

Photon Number Resolution

Photon Number Resolution & Excess Noise Factor

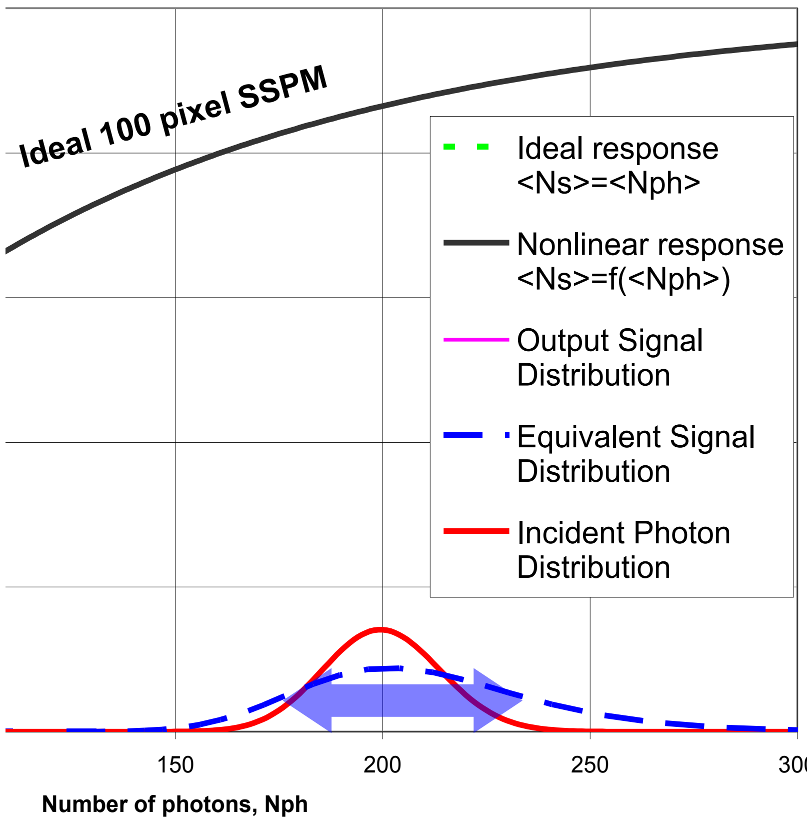
- **Burgess variance theorem**

$$ENF_1 = 1 + \frac{\sigma(N_{out})^2}{\langle N_{out}\rangle^2} \qquad if \quad N_{in} \equiv 1$$

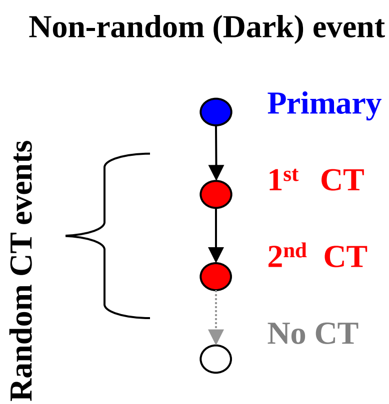
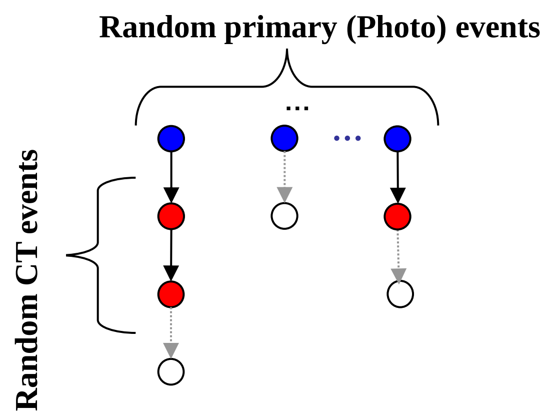
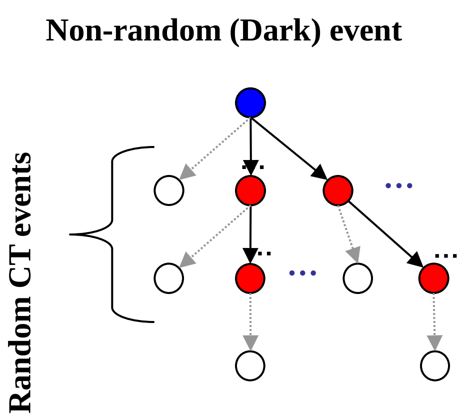
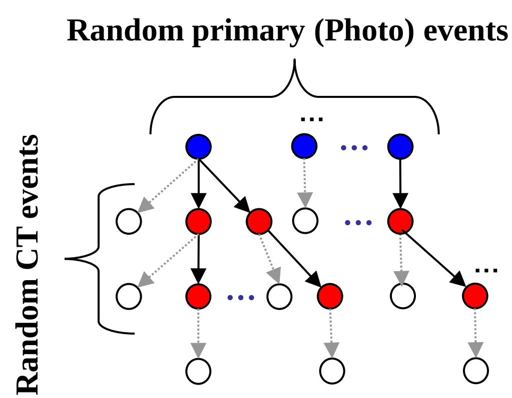
$$ENF_N = \frac{\sigma(N_{out})^2}{\langle N_{out}\rangle^2} \Big/ \frac{\sigma(N_{in})^2}{\langle N_{in}\rangle^2} \qquad if \quad N_{in} - random$$

$$PNR_{out} = \frac{\sigma(N_{out})}{\langle N_{out}\rangle} = \frac{\sigma(N_{in})}{\langle N_{in}\rangle} \cdot \sqrt{ENF_N}$$

$$if \quad N_{in} - Poissonian \quad \Rightarrow \quad ENF_N = ENF_1$$



Schematics of AP & CT stochastic processes

Duplication Models	Single primary event N≡1 e.g. SSPM Dark Spectrum	Poisson number of primaries <N>=μ e.g. SSPM Photon Spectrum
Geometric Chain Afterpulsing Process		
Branching Poisson Crosstalk Process		

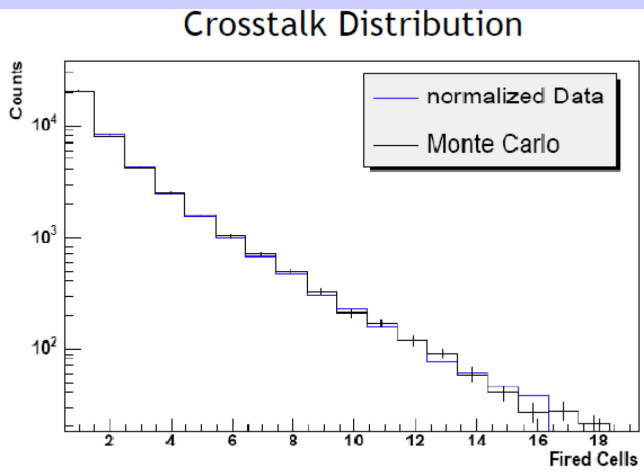
CT & AP model results

Results	**Geometric chain process**		**Branching Poisson process**	
Primary event distribution	Non-random single (N≡1)	Poisson (μ)	Non-random single (N≡1)	Poisson (μ)
Total event distribution	Geometric (p)	Compound Poisson (μ, p)	Borel (λ)	Generalized Poisson (μ, λ)
$P(X=k)$	$p^{k-1}\cdot(1-p)$	Ref. [1]	$\dfrac{(\lambda\cdot k)^{k-1}\cdot\exp(-k\cdot\lambda)}{k!}$	$\dfrac{\mu\cdot(\mu+\lambda\cdot k)^{k-1}\cdot\exp(-\mu-k\cdot\lambda)}{k!}$
$E[X]$	$\dfrac{1}{1-p}$	$\dfrac{\mu}{1-p}$	$\dfrac{1}{1-\lambda}$	$\dfrac{\mu}{1-\lambda}$
$Var[X]$	$\dfrac{p}{(1-p)^2}$	$\dfrac{\mu\cdot(1+p)}{(1-p)^2}$	$\dfrac{\lambda}{(1-\lambda)^3}$	$\dfrac{\mu}{(1-\lambda)^3}$
ENF	$1+p$		$\dfrac{1}{1-\lambda}\approx 1+p+\dfrac{3}{2}p^2+o(p^3)...$	

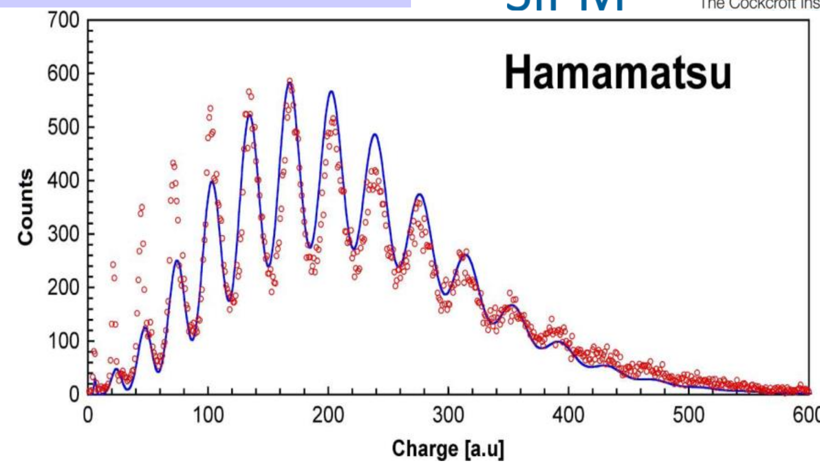
[1] S. Vinogradov et al., NSS/MIC 2009

λ is a mean number of successors in one branch generation

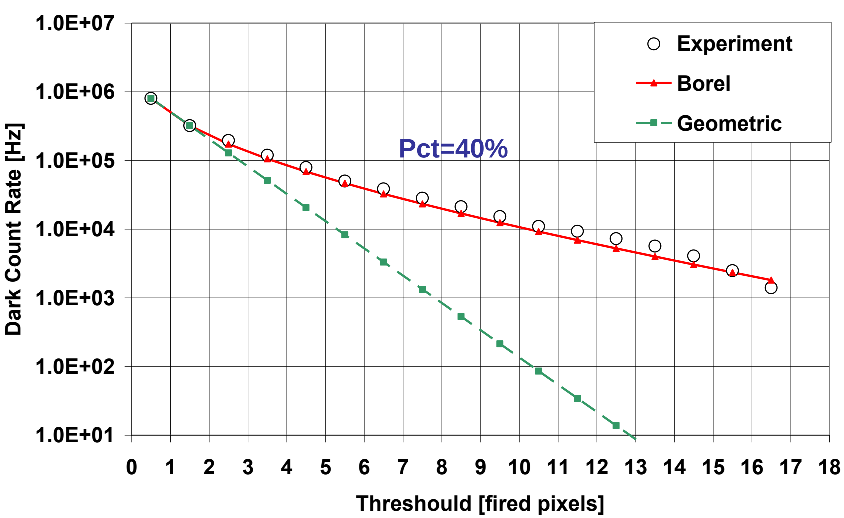
Crosstalk models and experiments



A.N. Otte, JINST 2007

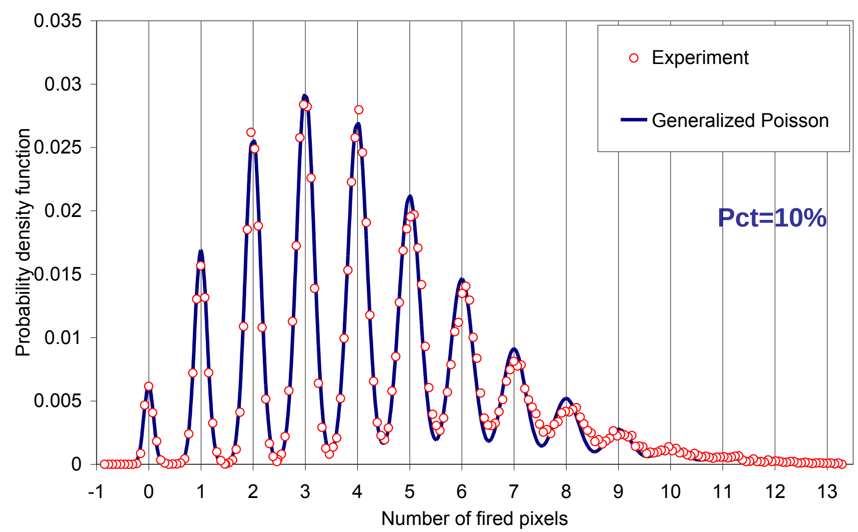


P. Finocchiaro et al., IEEE TNS, 2009



Dark event complimentary cumulative distribution – DCR vs. threshold

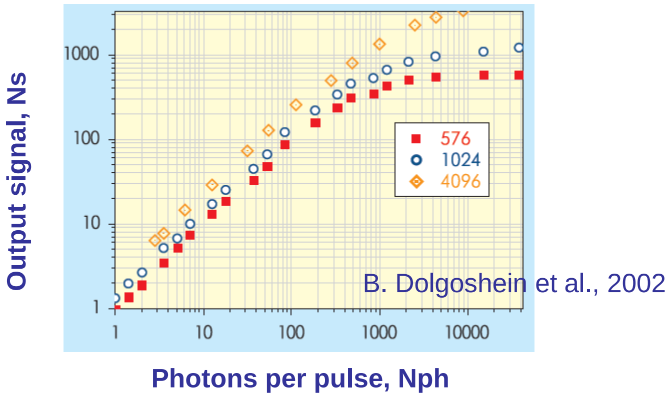
(S. Vinogradov, NDIP 2011; experiment B. Dolgoshein et al., NDIP 2008)

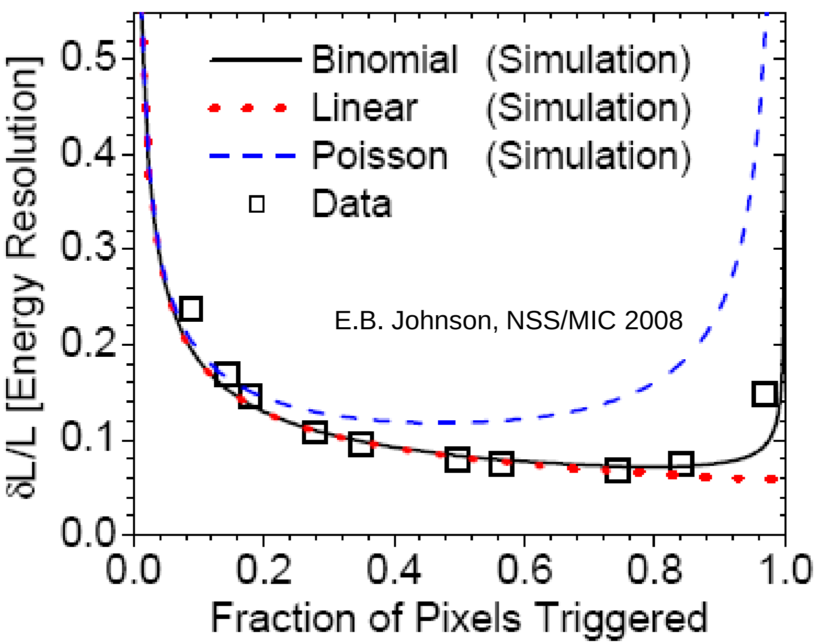


A few photon detection spectrum of Hamamatsu MPPC

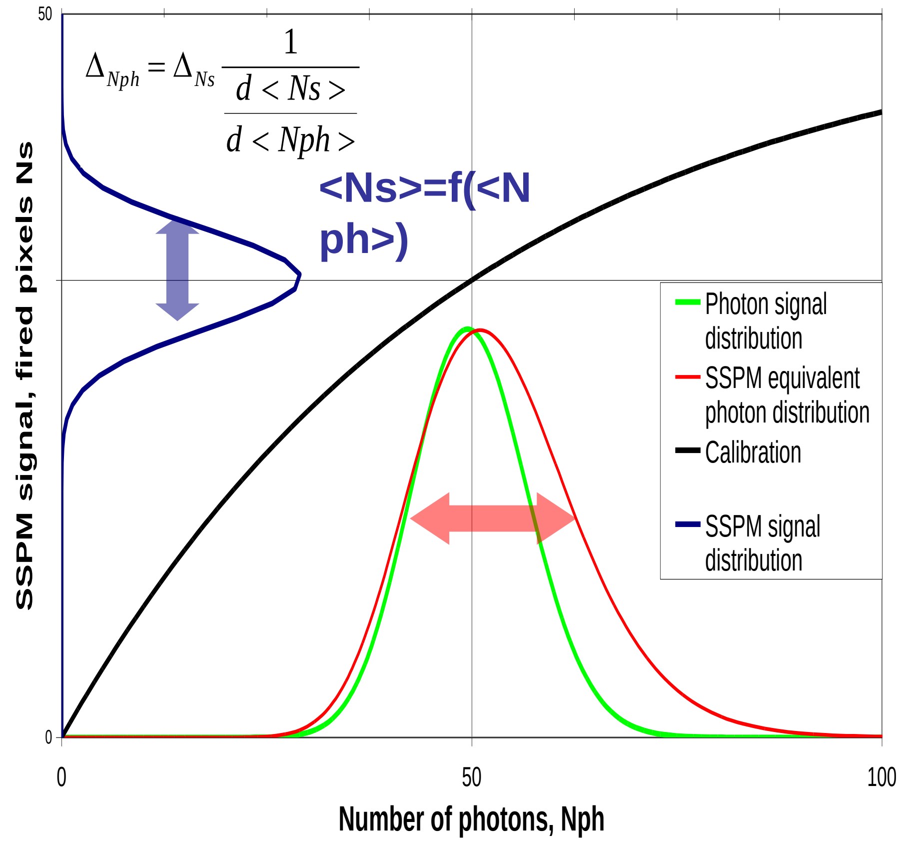
(S. Vinogradov, SPIE 2012)

SiPM binomial nonlinearity





Intrinsic Resolution in σ units; Npix=506



$$\overline{N_{fired}} = N_{cell} \cdot \left(1 - e^{-\frac{N_{ph} \cdot PDE}{N_{cell}}}\right) \qquad \sigma^2_{N_{fired}} = N_{cell} \cdot \left(1 - e^{-\frac{N_{ph} \cdot PDE}{N_{cell}}}\right) \cdot e^{-\frac{N_{ph} \cdot PDE}{N_{cell}}}$$

$$ENF = \frac{e^{+\frac{N_{ph} \cdot PDE}{N_{cell}}} - 1}{\frac{N_{ph} \cdot PDE}{N_{cell}}}$$

SiPM recovery nonlinearity

$$T_{pulse} >> T_{rec}$$

Nonparalizible dead time model
Probability distribution (~ Gaussian)

W. Feller, *An Introduction to Probability Theory and Its Applications*, Vol. 2, Ch. XI, John Willey & Sons, Inc., 1968

$$\mu_{Ns} = \frac{\lambda \cdot t}{1 + \lambda \cdot \tau_{dead}}$$

$$\sigma^2{}_{Ns} = \frac{\lambda \cdot t}{(1 + \lambda \cdot \tau_{dead})^3}$$

Recovery non-linearity → ENF

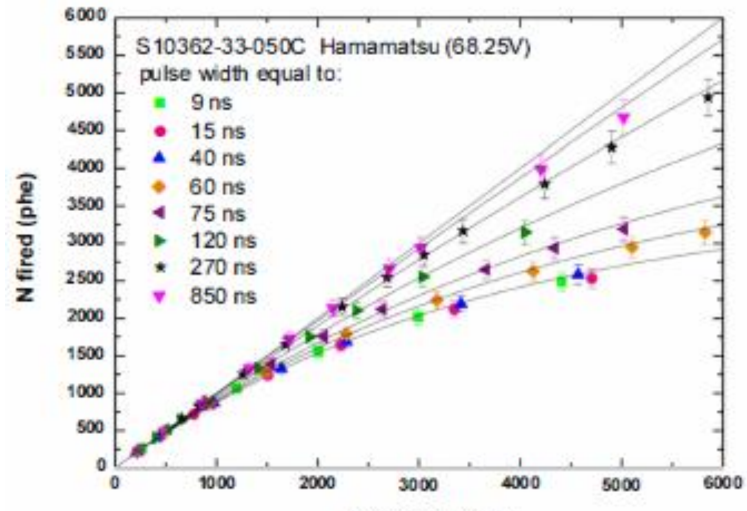
S. Vinogradov et al., IEEE NSS/MIC 2009

$$ENF_{eq(Nph)}(\lambda) = 1 + \lambda \cdot \tau_{dead}$$

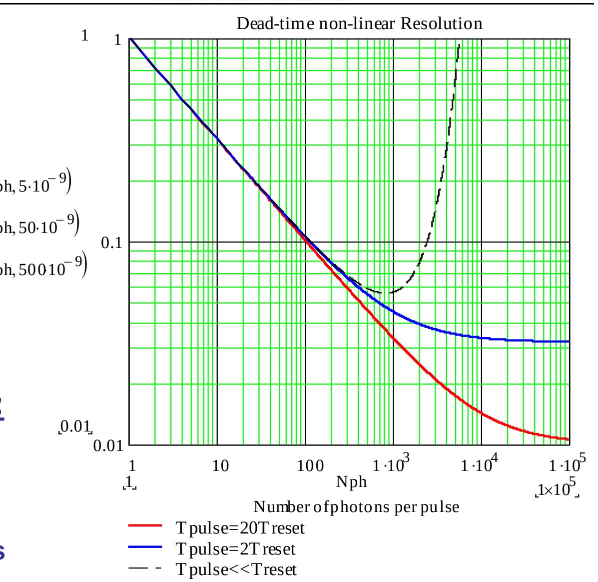
2) Exponential recovery of Gain m(t) accounting for Pdet(m)

S. Vinogradov, SPIE DSS, 2012

$$ENF_{eq(Nph)}(\lambda) = \frac{(1 + \lambda \cdot \tau_{rec})^3}{1 + \frac{\lambda \cdot \tau_{rec}}{2}} \quad \{if \quad P_{det}(m) = const\}$$



M.Grodzicka, NSS 2011



Plot details:

PDE=100%

Npixel=500

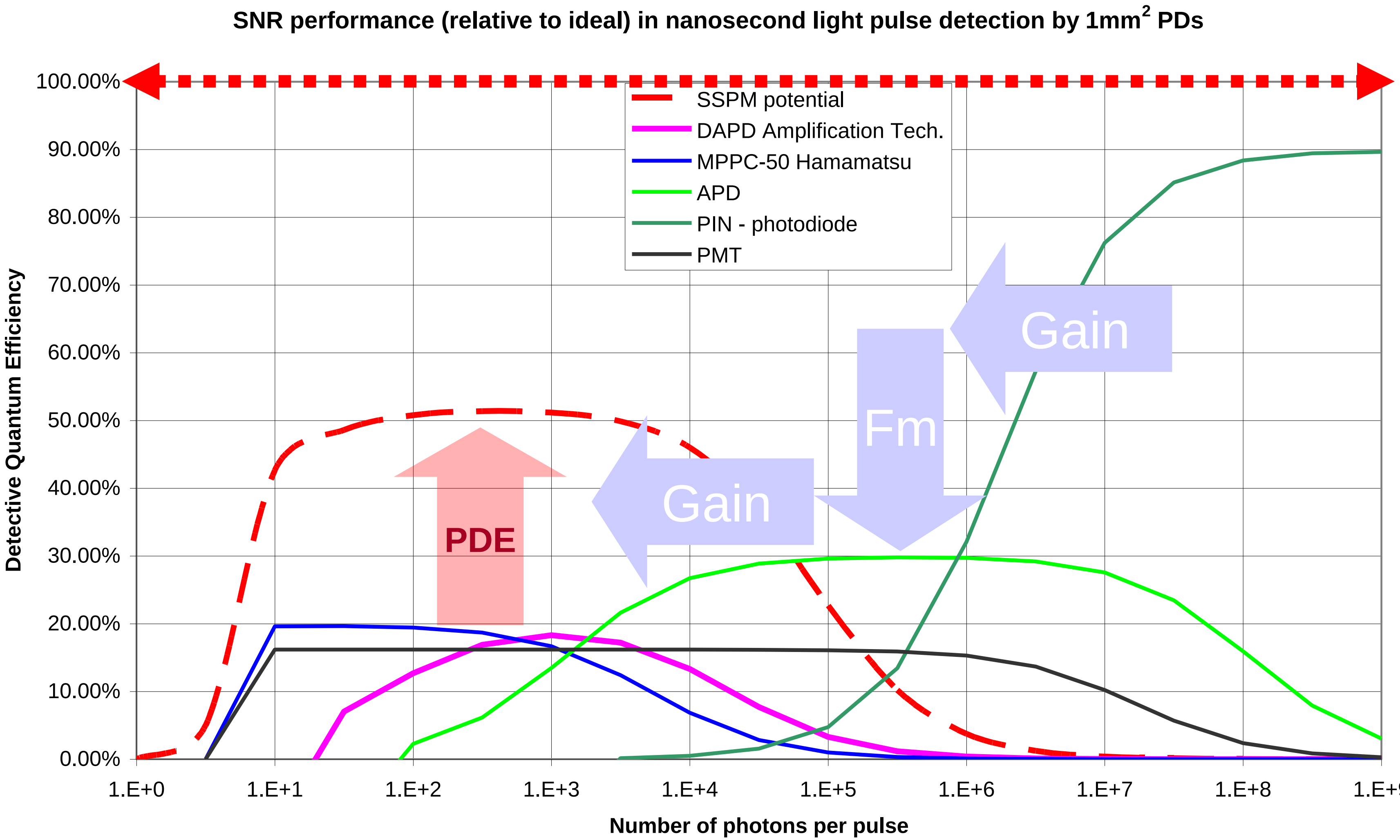
Tpulse=100 ns

Performance metrics: ENF and DQE

$$PNR_{out} = \frac{\sigma(N_{out*})}{\mu(N_{out*})} = PNR_{in}(Nph) \cdot \sqrt{ENF_{total}(Nph)} \qquad ENF_{total} = F_m \cdot F_{pde} \cdot F_{dcr} \cdot F_{ct} \cdot F_{ap} \cdot F_{nl} \qquad DQE = \frac{1}{ENF_{total}}$$

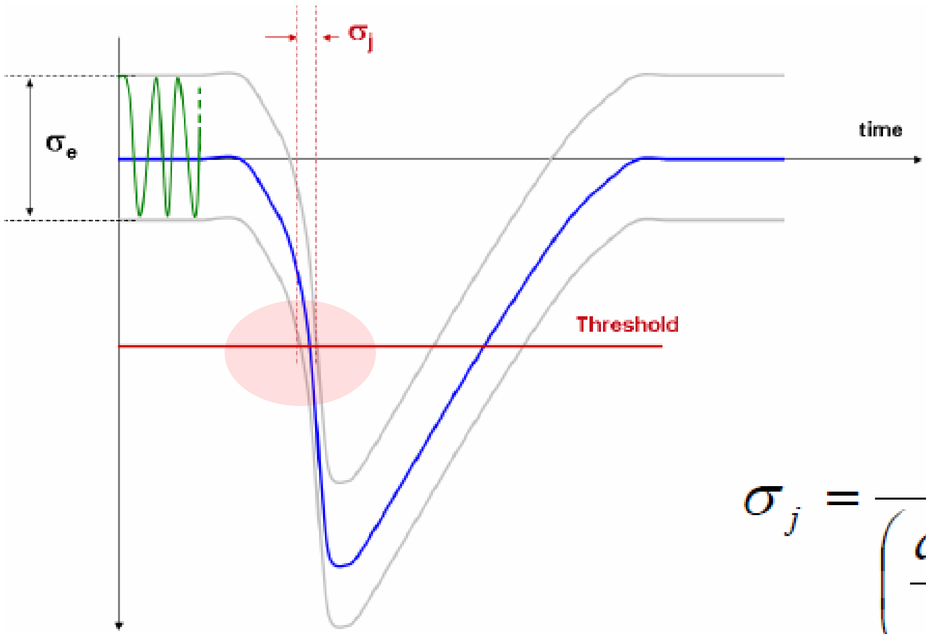
Noise source	Key parameter	Typical values for SiPM	ENF expression	SiPM ENF	PMT ENF
Fluctuation of multiplication	Mean *gain* and standard deviation of *gain*	μ(gain) ~ 10^6 σ(gain) ~ 10^5	$Fm = 1 + \frac{\sigma^2(gain)}{\mu^2(gain)}$	1.01	1.2
Crosstalk	Probability of crosstalk event *Pct*	5% – 40%	$Fct = \frac{1}{1+\ln(1-Pct)}$	1.05 – 2	1
Afterpulsing	Probability of afterpulse *Pap*	5% – 20%	$Fap = 1 + Pap$	1.05 – 1.2	1.01
Shot noise of dark counts	Dark count rate *DCR* Signal events in *Tpulse*	$10^5 - 10^7$ cps	$Fdcr = 1 + \frac{DCR \cdot Tpulse}{Nph \cdot PDE}$	1.01	1
Noise / losses of photon detections	Photon detection efficiency *PDE*	15% – 40%	$Fpde = \frac{1}{PDE}$	2.5 – 6.6	5
Total noise in linear dynamic range	Total *ENF_linear*	$ENF\_linear = Fm \cdot Fct \cdot Fap \cdot Fdcr \cdot Fpde$		2.8 – 16	6
Pixel number nonlinearity	Mean number of possible single pixel firings *n*	$n = \frac{Nph \cdot PDE}{Npix}$; $ENFpix = \frac{\exp(n)-1}{n}$; binomial distribution			
Recovery time nonlinearity	Mean rate of possible single pixel firings *λ*	$\lambda = \frac{n}{Tpulse}$; $ENFrec = 1 + \lambda \cdot Trec$; nonparalizible model			

Performance in DQE – various detectors



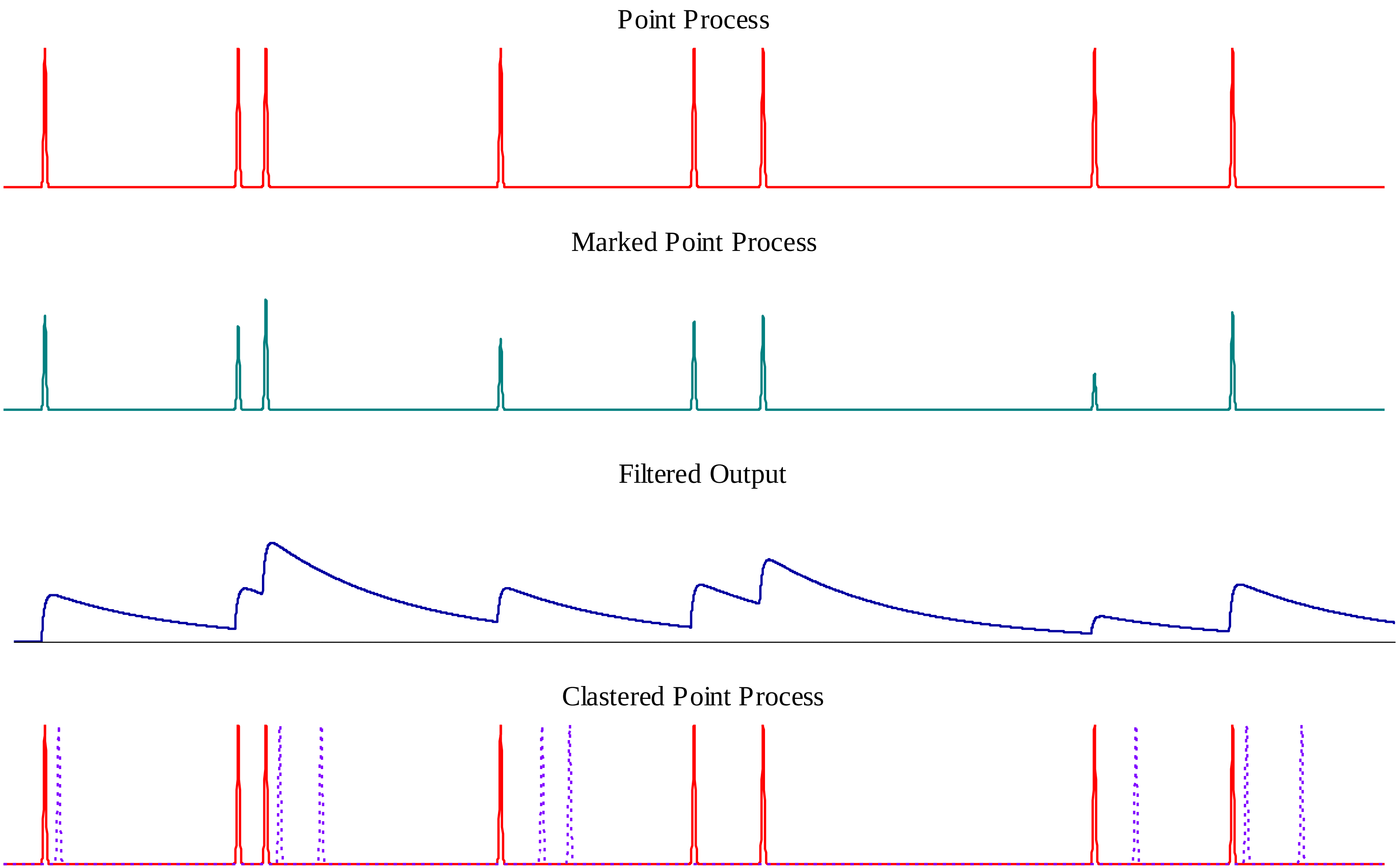
Time resolution

- Time resolution is combined as a sum of contributions
  - Transit time spread of photon arrival, avalanche triggering, avalanche development, and single electron response times
  - Jitter of signal amplitude fluctuations in a time scale



$$\sigma_j = \frac{\sigma_e}{\left(\frac{dV}{dt}\right)_{threshold}}$$

Filtered point process approach to amplitude fluctuations & time resolution



Clastered filtered point process model

- **Time resolution includes all essential factors and combines performance in time response and PNR (ENF)**

$$\sigma_t = \frac{\sqrt{\overline{N}_{pe} \cdot ENF_{gain} \cdot ENF_{\sec} \cdot \left\{ \left[\rho_{ph} * \rho_{sptr} * \rho_{\sec} * h_{ser}^2\right](t) + \delta_{sci}^2 \cdot \overline{N}_{pe}^2 \cdot \left[\rho_{ph} * \rho_{sptr} * \rho_{\sec} * h_{ser}\right]^2(t) \right\} + \frac{V_{n}}{\overline{V}_{ser}^2}}}{\overline{N}_{pe} \cdot \frac{d\left[\rho_{ph} * \rho_{sptr} * \rho_{\sec} * h_{ser}\right](t)}{dt}}$$

$$= \frac{\left[\rho_{ph} * \rho_{sptr} * \rho_{\sec} * h_{ser}\right](t)}{\frac{d\left[\rho_{ph} * \rho_{sptr} * \rho_{\sec} * h_{ser}\right](t)}{dt}} \cdot \sqrt{\frac{1}{\overline{N}_{pe}} \cdot ENF_{gain} \cdot ENF_{\sec} \cdot \left\{ \frac{\left[\rho_{ph} * \rho_{sptr} * \rho_{\sec} * h_{ser}^2\right](t)}{\left[\rho_{ph} * \rho_{sptr} * \rho_{\sec} * h_{ser}\right]^2(t)} + \delta_{sci}^2 \right\} + \frac{V_{noise}^2}{\overline{V_{out}(t)}^2}}$$

$$If \quad light\ pulse\ is\ fast\ and\ SER\ is\ slow: \quad \left[\rho_{ph} * \rho_{sptr} * \rho_{\sec} * h_{ser}\right](t) \approx h_{ser}(t) \quad \Rightarrow$$

$$\sigma_t \approx \tau_{rise} \cdot \sqrt{\frac{1}{\overline{N}_{ph}} \cdot ENF_{total} + \frac{V_{noise}^2}{V_{Thresh}^2}}$$

Time resolution: scintillation model & experiment

Most popular & demanded case study: LYSO+MPPC

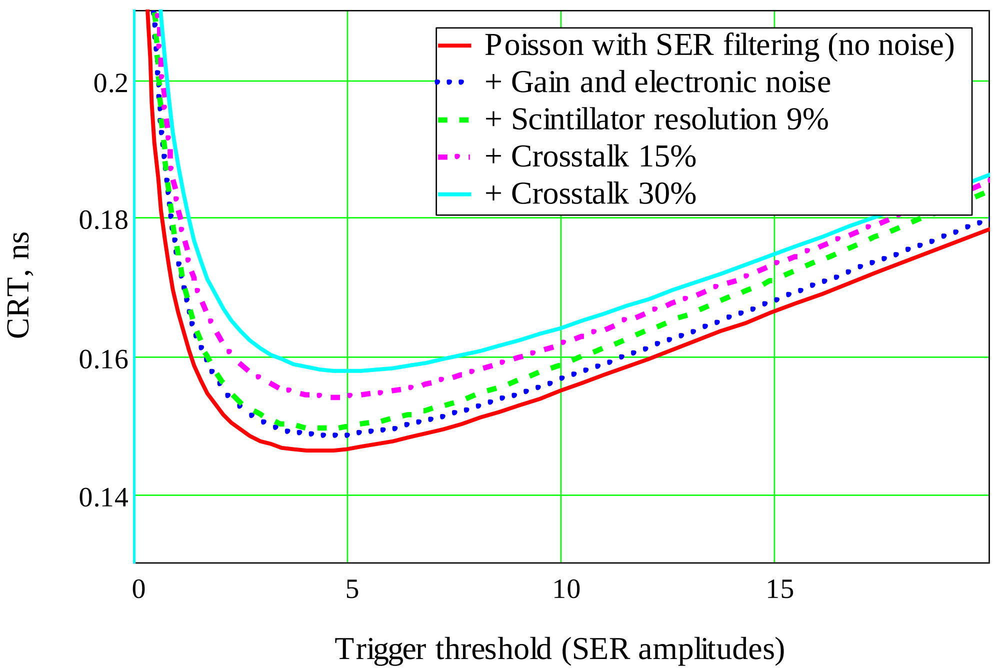
LYSO: 0.09 ns rise, 44 ns decay; 9% resolution

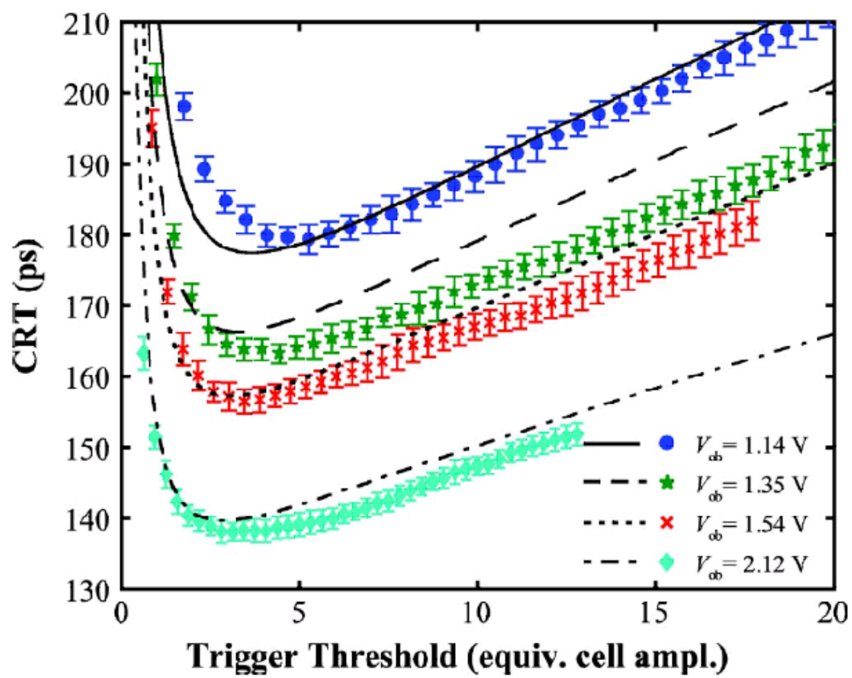
MPPC: Npe=3900, ENFgain=1.015, Pct=0.14; SPTR=0.124 ns, Vnoise=0.32 mV

S. Seifert et al, “A Comprehensive Mode to Predict the Timing Resolution ”, TNS, 2012.

MPPC SER pulse shape – analytical expression (~ 1 ns rise, ~ 25 ns decay)

D. Marano et al, “Silicon Photomultipliers Electrical Model: Extensive Analytical Analysis” TNS 2014





Arbitrary signal detection: rectangular pulse response model

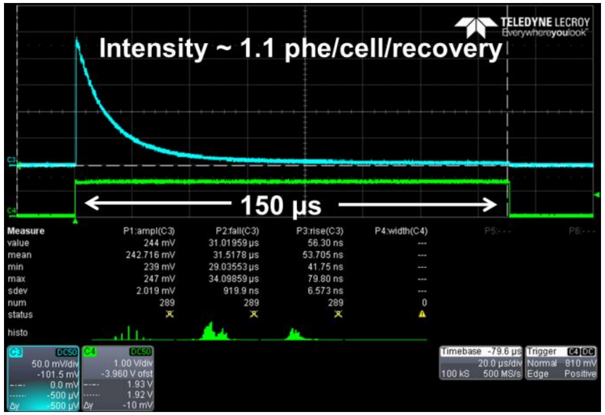
$$Nfired(t) = Ncell \cdot \exp\left(-\frac{Nph(t) \cdot PDE}{Ncell}\right) \quad Tpulse < Trec \quad binomial \quad distribution$$

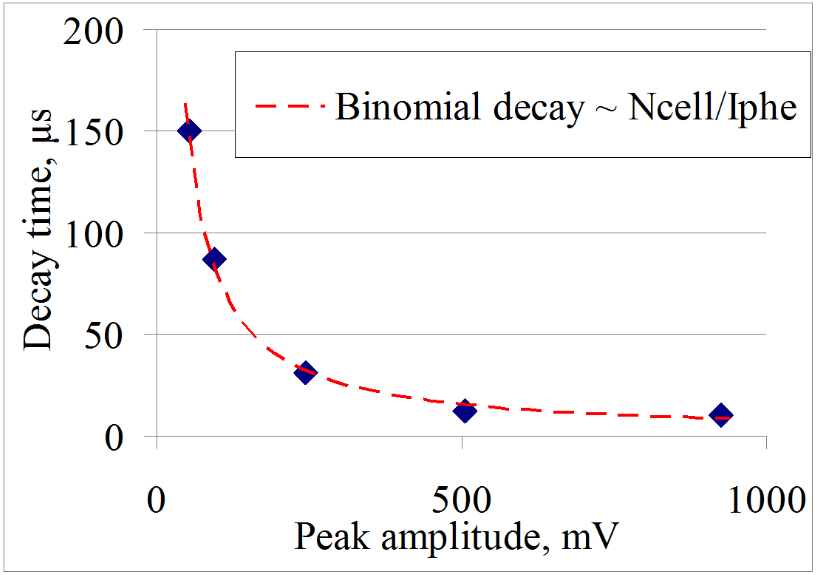
$$Nfired(t) = \frac{Nph(t) \cdot PDE}{1 + \frac{Nph(t) \cdot PDE \cdot Trec}{Ncell \cdot Tpulse}} \quad Tpulse > Trec \quad non-paralizible \quad dead \quad time$$

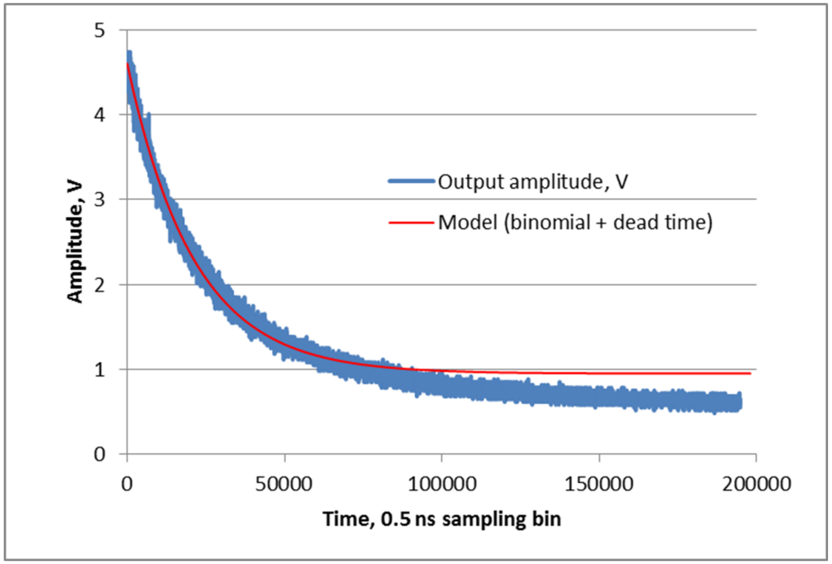
$$Ifired(t) = Ibinomial(t) + Idead\_time \quad @ \; Nph(t) = Iph \cdot t \qquad (1)$$

$$Ibinomial(t) = Iph \cdot PDE \cdot \exp\left(-\frac{Iph \cdot PDE \cdot t}{Ncell}\right) \qquad Ifired(t=0) = Iph \cdot PDE = Iphe$$

$$Idead\_time = \frac{Iph \cdot PDE}{1 + \frac{Iph \cdot PDE \cdot Trec}{Ncell}} = const \qquad Tdecay = \frac{Ncell}{Iph \cdot PDE} = \frac{Ncell}{Iphe} \qquad (2)$$







Trends and prospects of SiPMs for BLM and accelerator applications

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SiPM trends and advances

- Market leaders
  - Hamamatsu
  - KETEK
  - SensL
  - FBK / AdvanSiD
  - Excelitas / Perkin Elmer
  - Philips (digital SiPM)

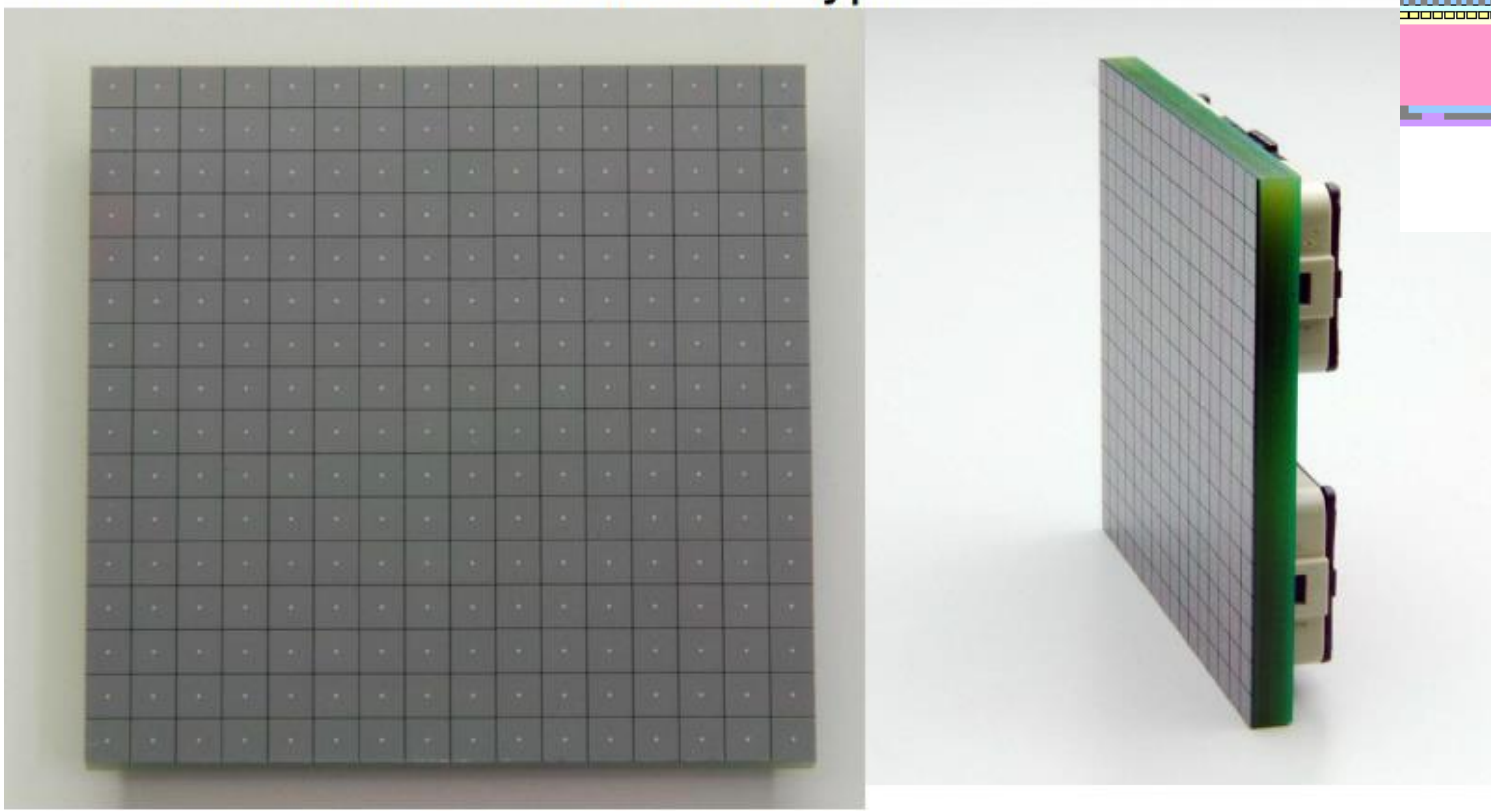
- Design improvements (~ in a few year time scale)
  - Higher Photon Detection Efficiency (30% → 70%)
  - Lower crosstalk, lower afterpulsing (30% → 3%)
  - Lower dark count rate (1000 → 40 Kcps/mm^2)
  - Faster SER, smaller pixel size (25 → 10 um)
  - Larger area, larger arrays (3x3→10x10mm^2, 4x4 → 16x16 channels)

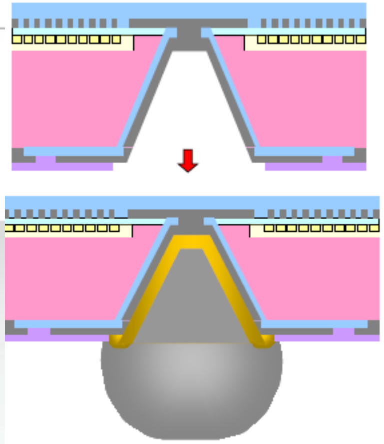
Latest news from 2nd SiPM Advanced Workshop and Conf . on New Development s in Photodetection, 2014

Hamamatsu: Through Silicon Vias

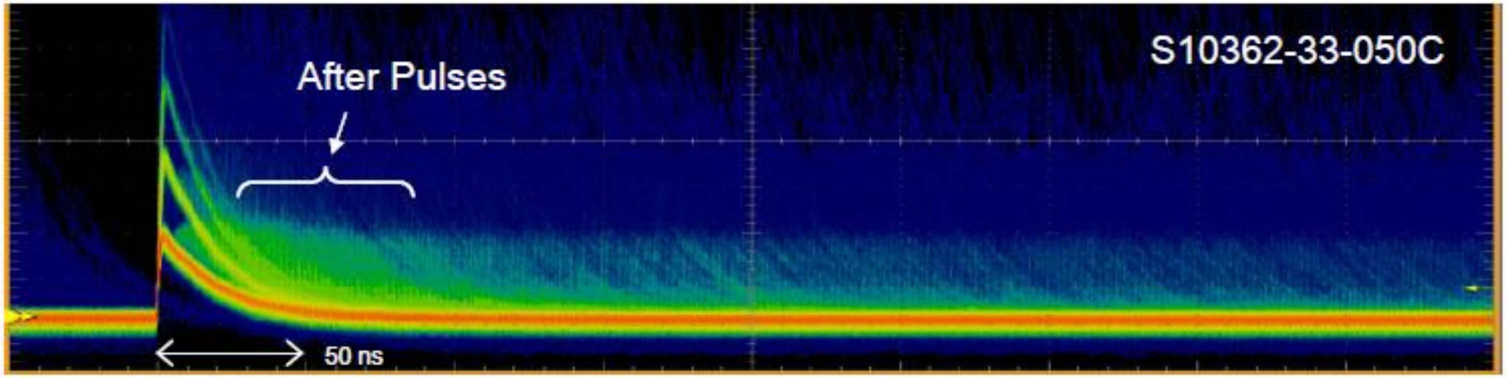
2D MPPC Array with TSV

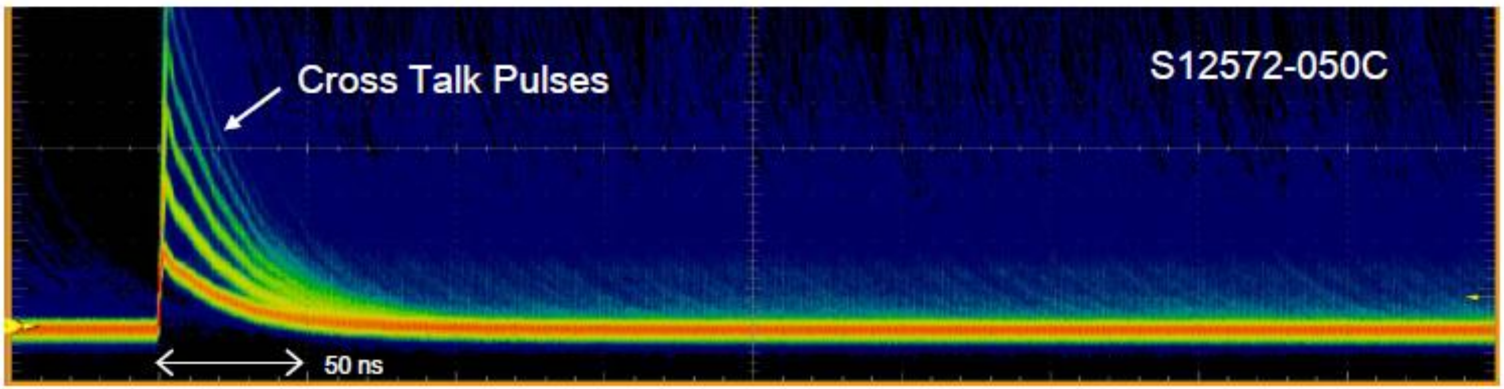
50μm pitch, 3x3mm chip,
16x16 channels with Connector type

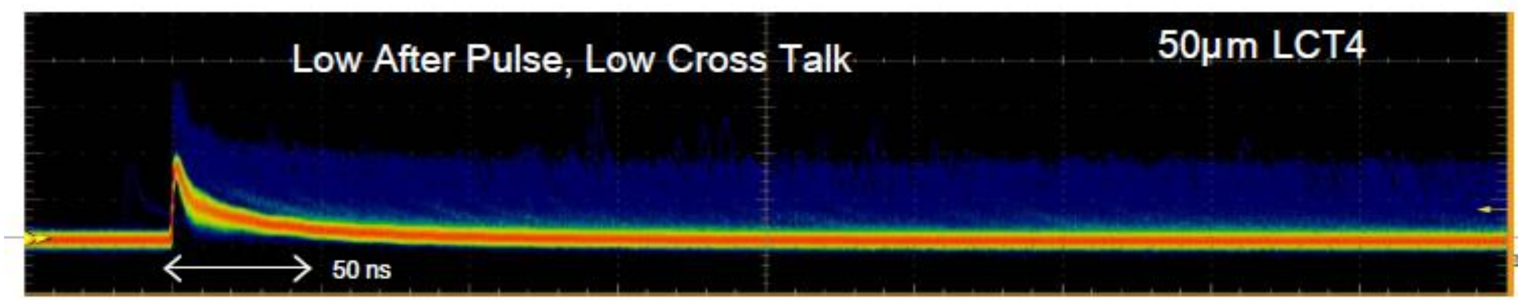




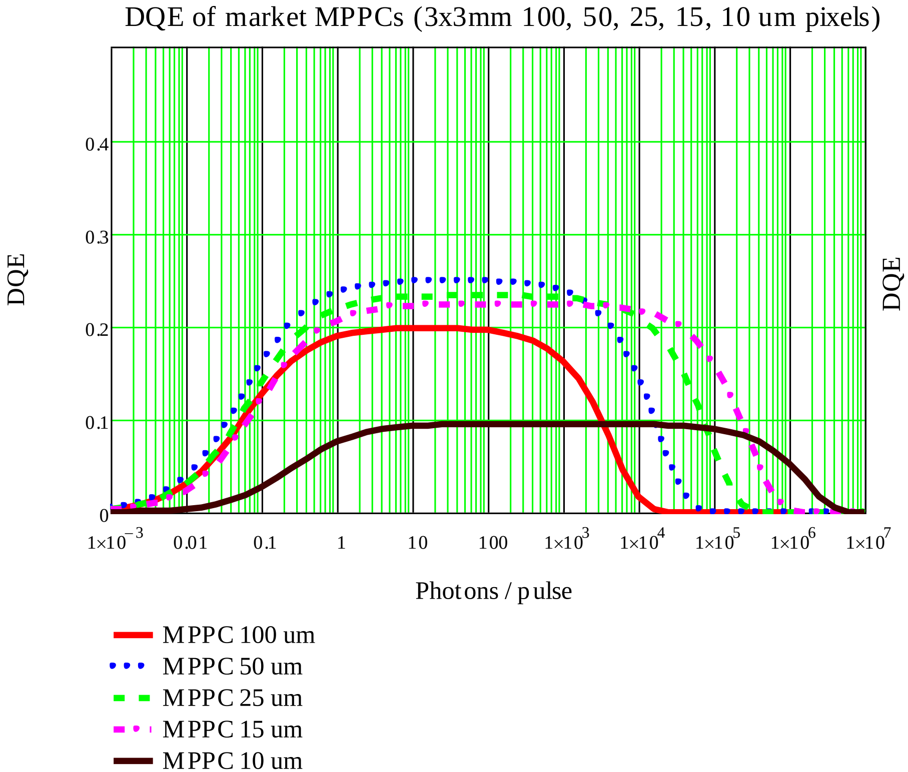
Hamamatsu: Low Crosstalk & Afterpulsing

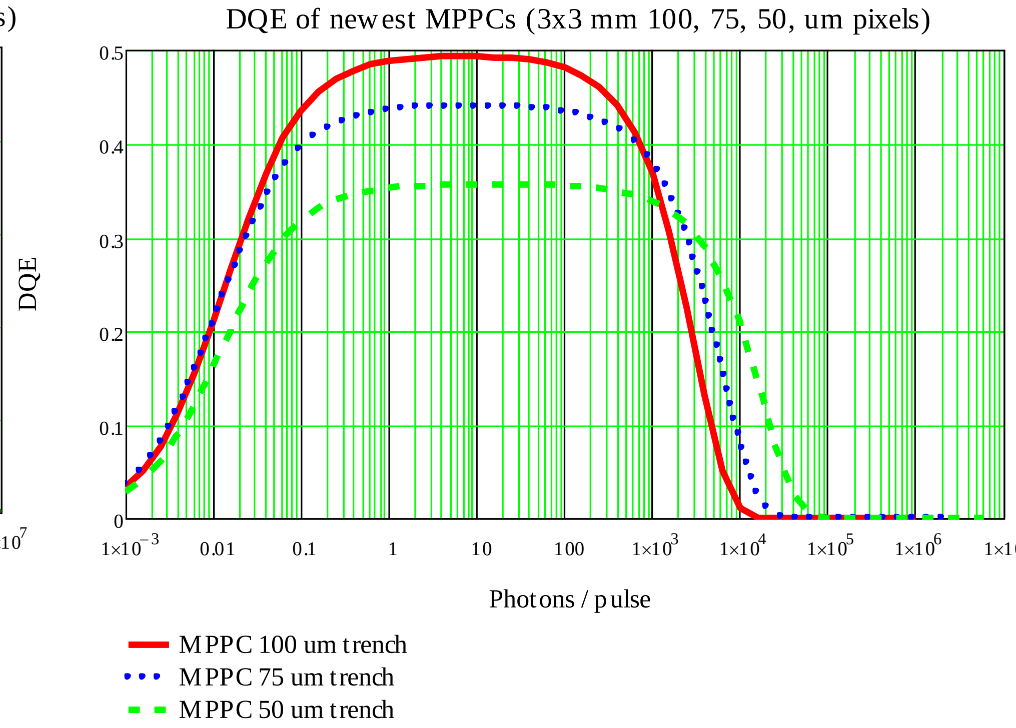






Performance in DQE - MPPC series



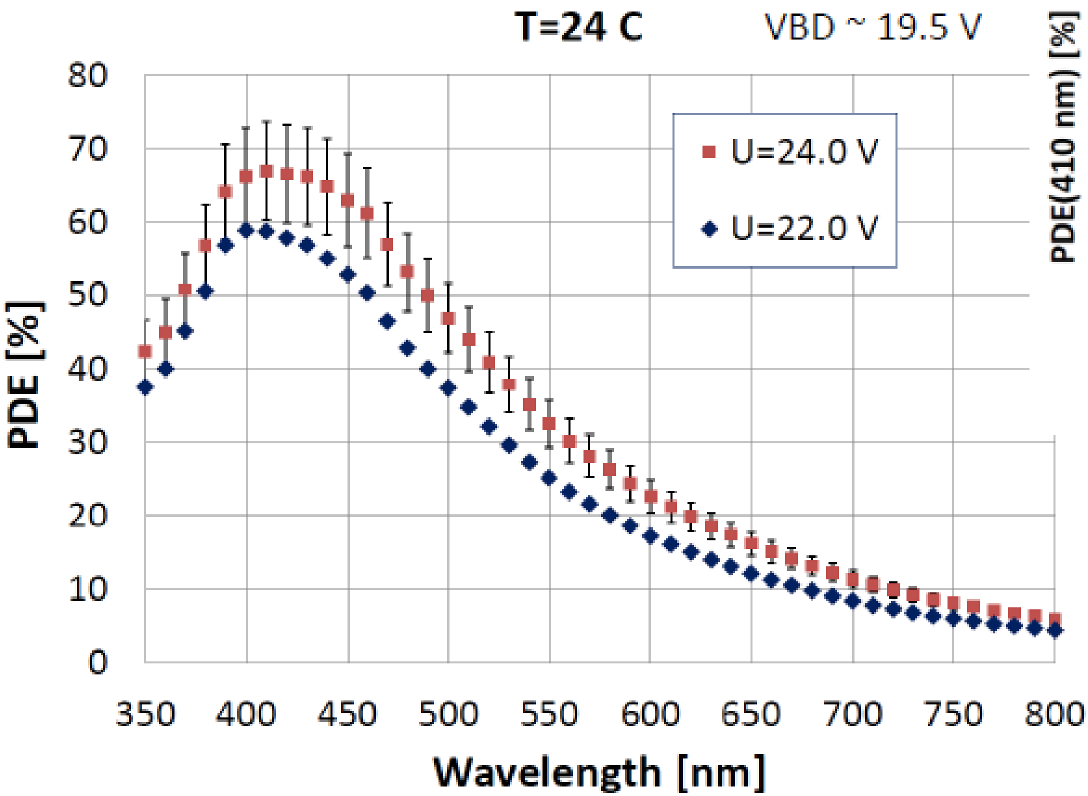


Pulse duration & detection time = 10 ns

KETEK

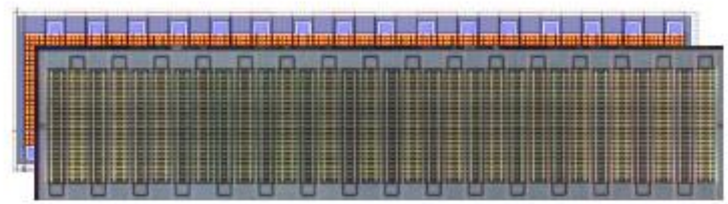
- Highest PDE @50 um pixels
- Various geometries
- 15 … 100 um pixels

PM1150-Prototype: *Measurements performed by CERN / Iouri Musienko*
(1.2 mm² active area, 50 µm cell pitch, 70% GE, no trench)

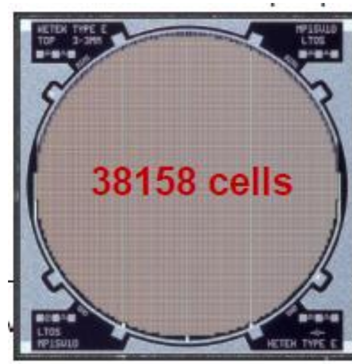


Type I (2013): 32 SiPM channels

Microcell Pitch:	**60 µm x 57.5 µm**
Quantity of cells:	**88 per channel**



45% PDE(410 nm) at 5% crosstalk!



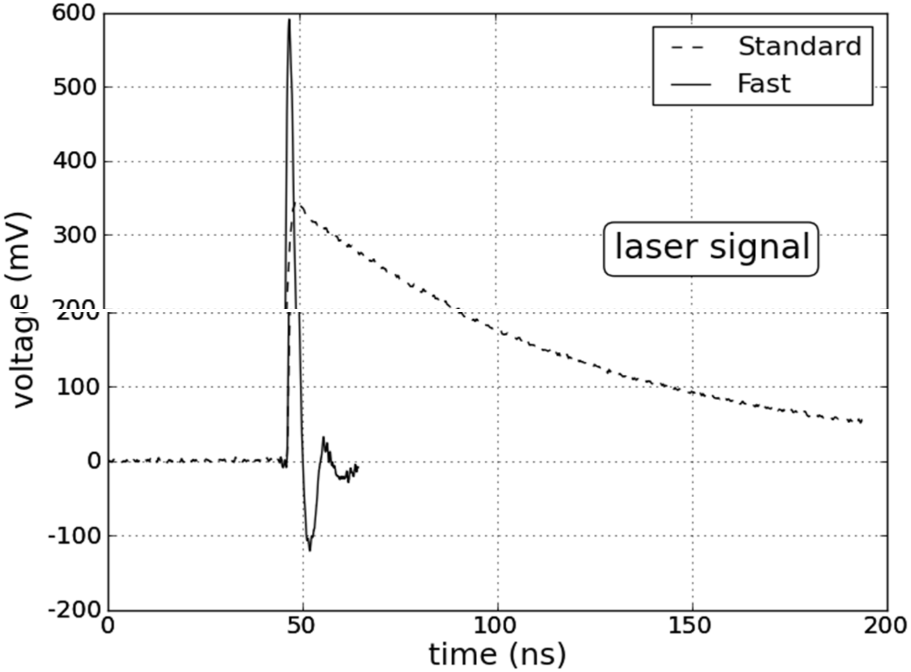
Chip Type E:

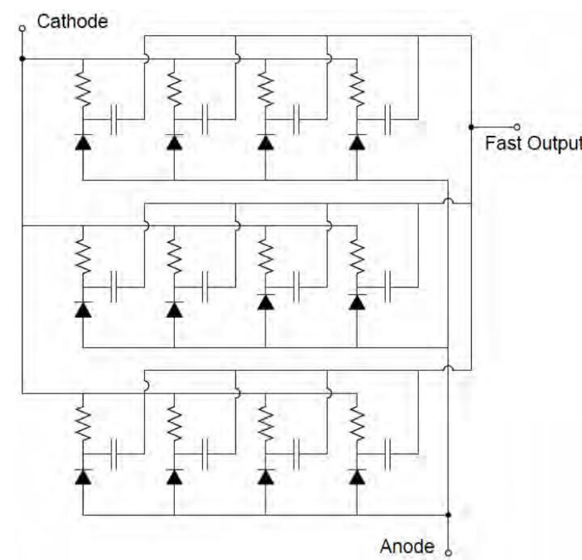
- Active area: 8.6 mm²
- 38158 cells - 15 µm pitch

EK GmbH 10

SensL

- Fast capacitive output
  - FWHM < 3.2 ns @ 6x6 mm^2
- Large arrays / modules
- Low cost



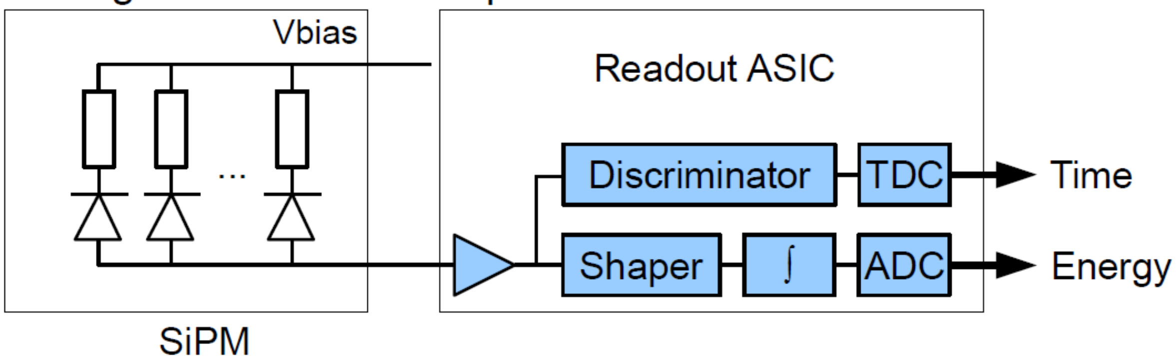


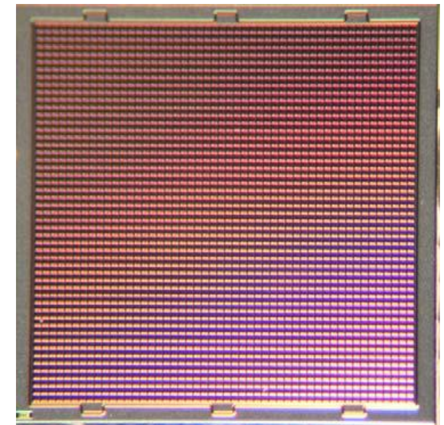
Philips: Digital SiPM
(Modern active quenching SPAD array)

PHILIPS

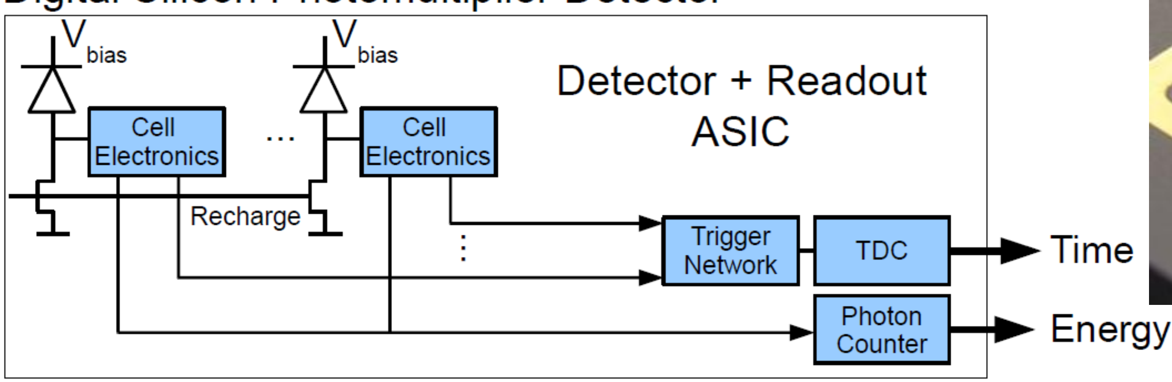
Digital SiPM – The Concept

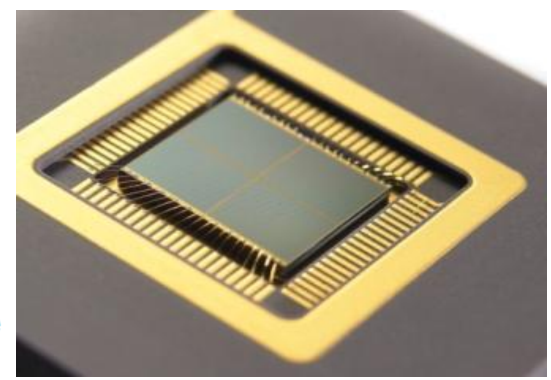
Analog Silicon Photomultiplier Detector





Digital Silicon Photomultiplier Detector





IEEE Nuclear Science Symposium / Medical Imaging Conference, Orlando, FL October 28, 2009

Summary on BLM with SiPM

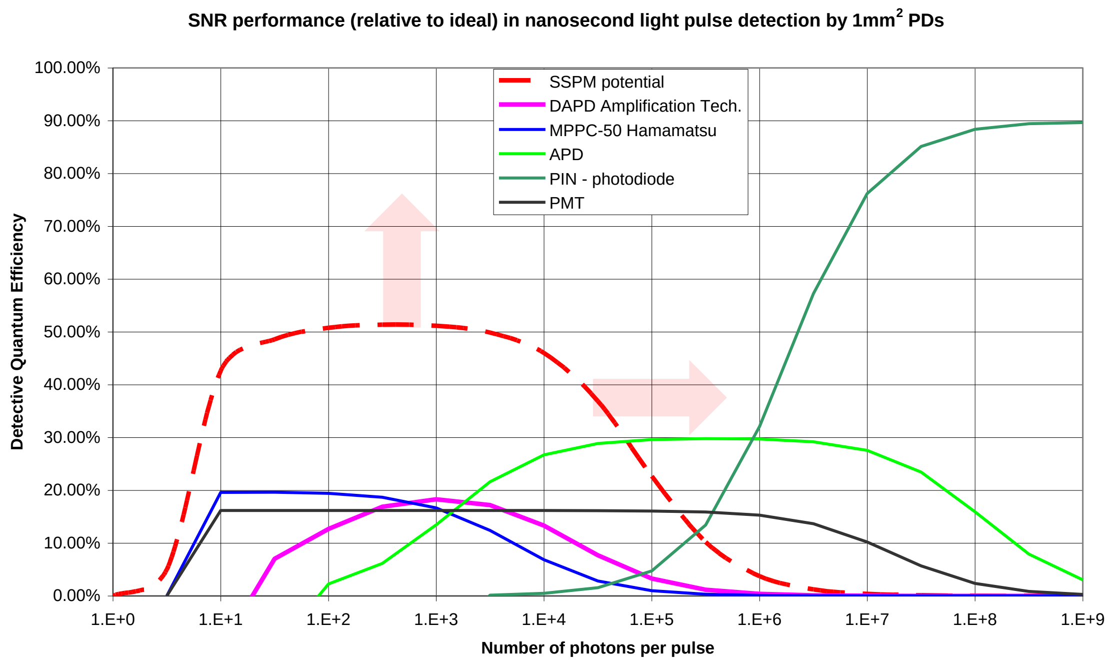
- BLM is one of the most challenging application for SiPM
  - Benefits
    - —Practical & efficient (cost, compactness, Si reliability…)
    - —Perfect Transit Time Resolution (as is for now)
    - —Acceptable DQE within dynamic range (may be better)
  - Drawbacks
    - —Upper margin of dynamic range is low (design improvement)
      - – Number / density of pixels (↑ 10 times)
      - – Pixel recovery time (↓ 10 times)
    - —Time response (bandwidth) (external measures)
      - – Analog / digital SiPM output signal processing

- BLM with SiPM: big problem with a chance to win
  - And with a lot of space for new ideas, designs, and fun

Summary on SiPM

- **SiPM technology: breakthrough in photon detection**
  - Photon number resolution at room temperature
  - Silicon technology / mass production / reliability / price
  - Highly competitive in short (< μs) pulse detection
  - Fast progress in improvements: DQE, Dynamic range, Timing

- **Welcome to SiPM applications**
  - Scintillation
  - Cherenkov
  - Laser pulse
  - And much more…



The end

- Thank you for your attention

- Questions?

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