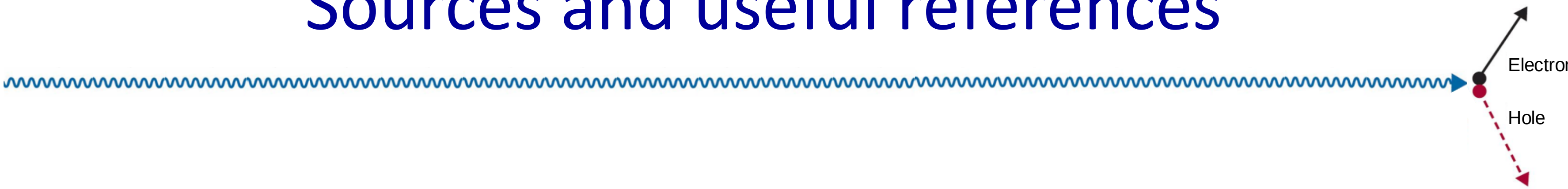
SiPM for HEP detectors

Erika Garutti (DESY)

Outline

- Review of commercially available SiPM
  - Comparison of properties
- A HEP detector with SiPM
  - Stability / spread of SiPM parameters
  - Readout electronics
  - Monitoring system
- Conclusions

Sources and useful references



- Alliance detector school on SiPM:

https://indico.desy.de/conferenceOtherViews.py?view=standard&confId=3279

Overview of available SiPMs, pros/cons (Jelena Ninković, MPI)

- Industry-academia matching event on SiPM and related technologies

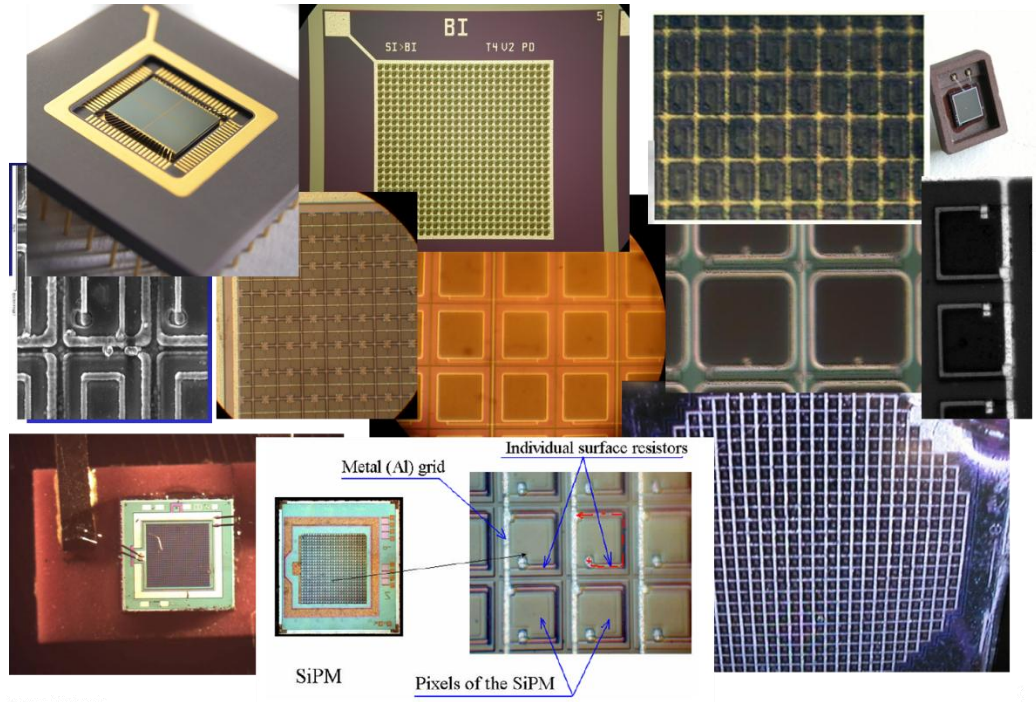
https://indico.cern.ch/conferenceTimeTable.py?confId=117424#20110216

State of the art in SiPM's (Iouri Musienko)

Review of ASIC developments for SiPM signal readout (Wojtek Kucewicz)

What is available

MEPhI/Pulsar (Moscow) - Dolgoshein
CPTA (Moscow) - Golovin
Zecotek(Singapore) - Sadygov
Amplification Technologies (Orlando, USA)
Hamamatsu Photonics (Hamamatsu, Japan)
SensL(Cork, Ireland)
AdvanSiD (former FBK-irst Trento, Italy)
STMicroelectronics (Italy)
KETEK (Munich)
RMD (Boston, USA)
ExcelitasTechnologies (former PerkinElmer)
MPI Semiconductor Laboratory (Munich)
Novel Device Laboratory (Beijing, China)
Philips (Netherlands)
….

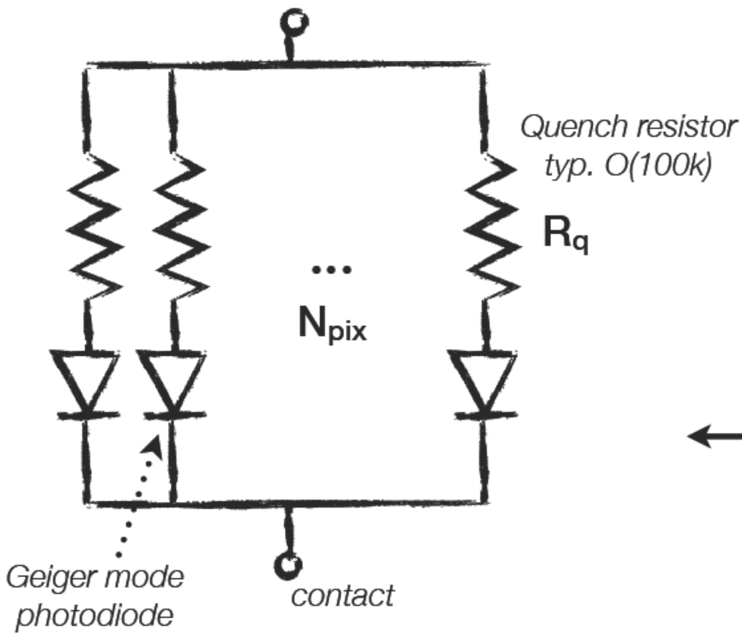


Every producer uses its own name for this type of device: MRS APD, MAPD, SiPM, SSPM, MPPC, SPM, DAPD, PPD, SiMPl , dSiPM…

SiPM basics

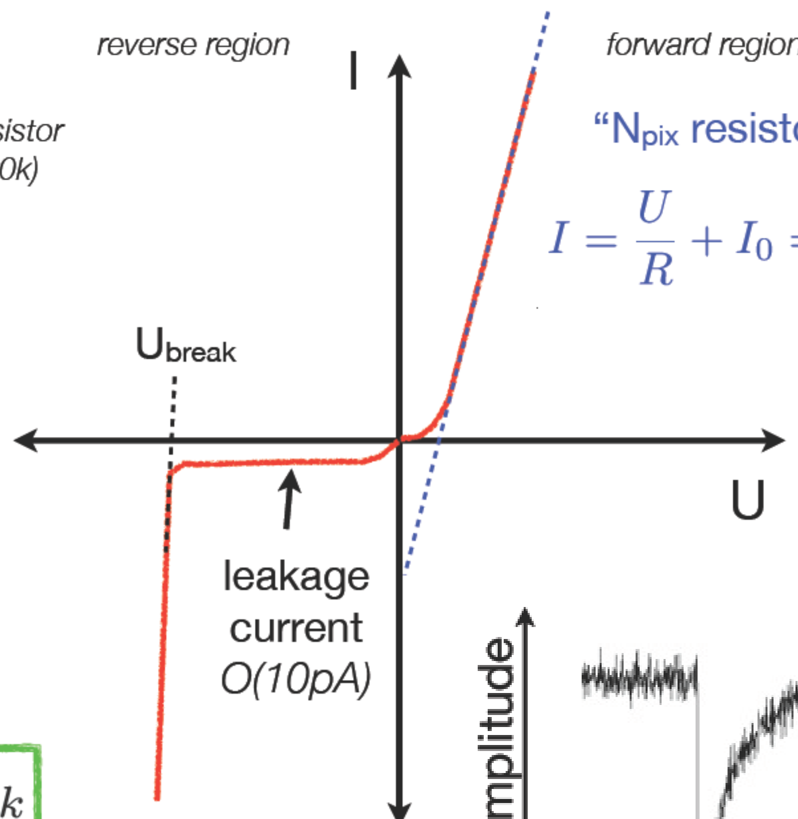
A. Tadday (UniHei)

SiPM equivalent diagram



$$U_{over} = U_{bias} - U_{break}$$

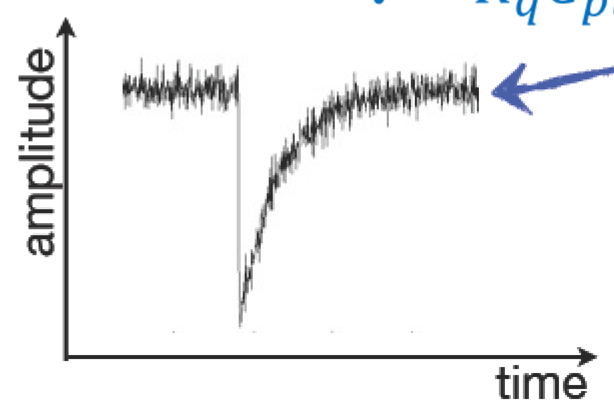
qualitative IV diagram (currents are not in scale)



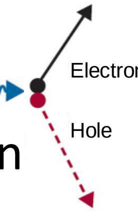
"N_{pix} resistors in parallel"

$$I = \frac{U}{R} + I_0 = \frac{U}{R_q / N_{pix}} + I_0$$

$$\tau = R_q C_{pix}$$



Pixel recovery time

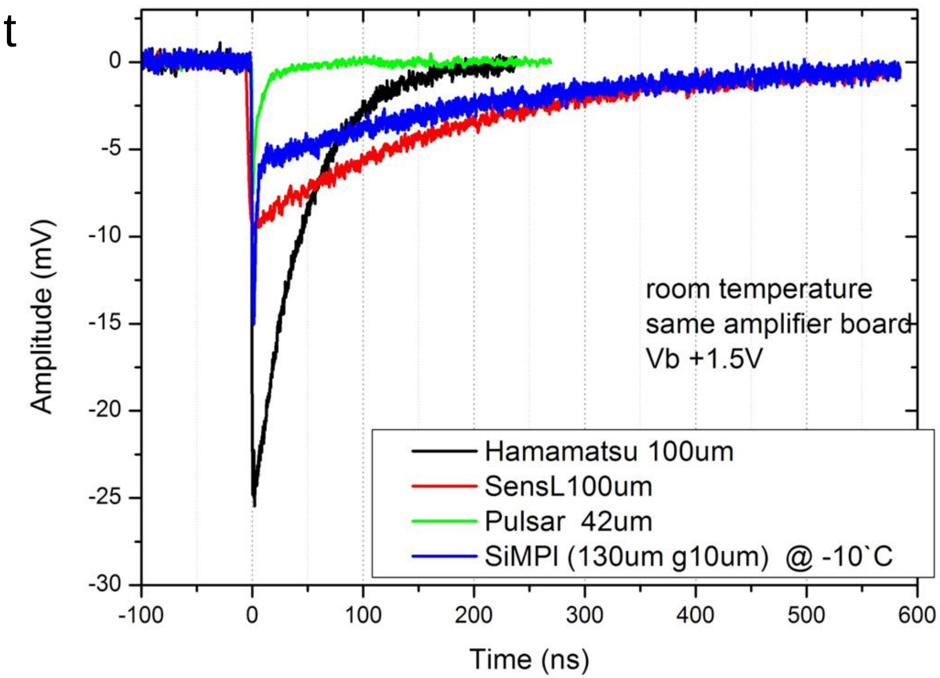


- The time needed to recharge a cell after a breakdown depends mostly on the cell size (C_{pix}) and the quenching resistor (R_q).
  Recovery time of SINGLE pixel:
  $\tau = R_q C_{pix}$ typical values: R_q ~ 0.5-20M□, C_{pix} ~ 20-150fF
  □ ~ 20ns - few μs

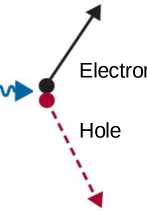
! Polysilicon resistors are T dependent
➔ favor high resistivity metal alloy

.

Important for design of readout electronics: Integration or shaping time has to match SiPM signal length, otherwise loss of gain



Gain

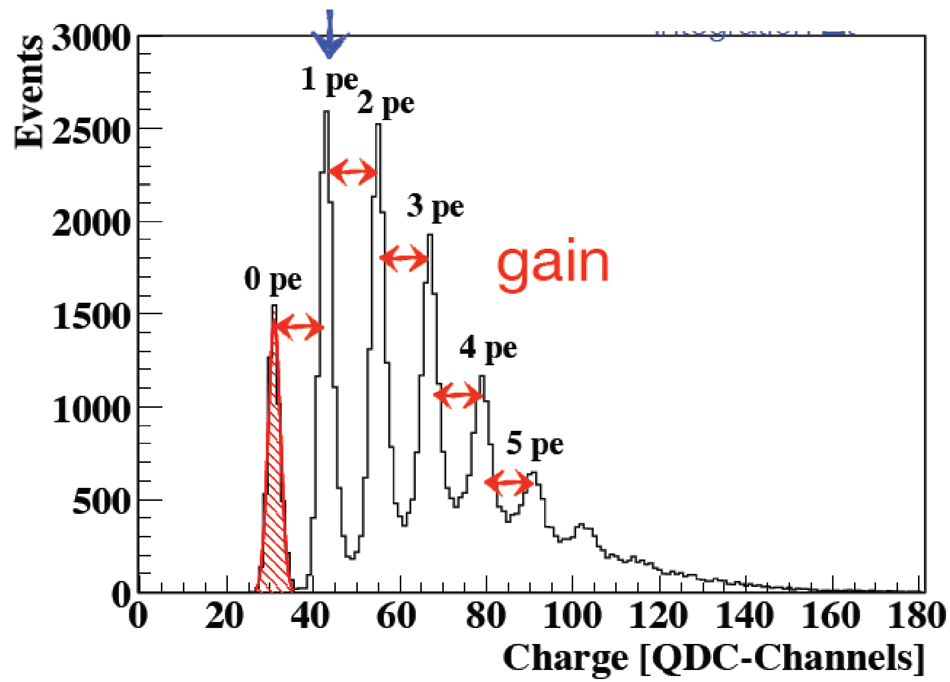


Each pixel is a binary device – several photons hitting the same cell at the same time produce the same charge (Q)

$$Q = C_{pix}(U_{bias} - U_{bd}) \qquad G \propto \frac{Q}{q_e}$$

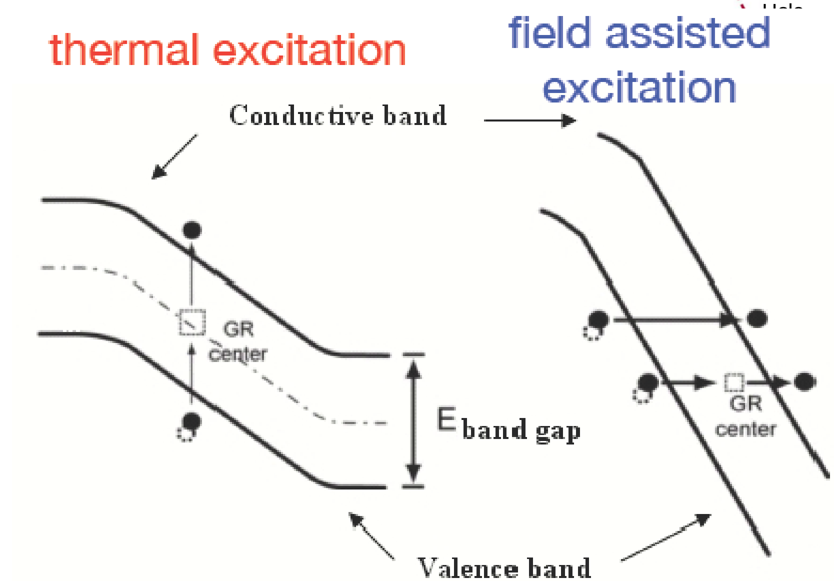
- As the SiPM is operated in Geiger mode the $G \sim 10^5 - 10^7$
- Single photoelectrons produce a signal of several mV on a 50 Ω load

If full charge is integrated pre-amplification x1-5 is adequate
Normally not the case with decoupling circuits or short shaping times (x10-50 needed)



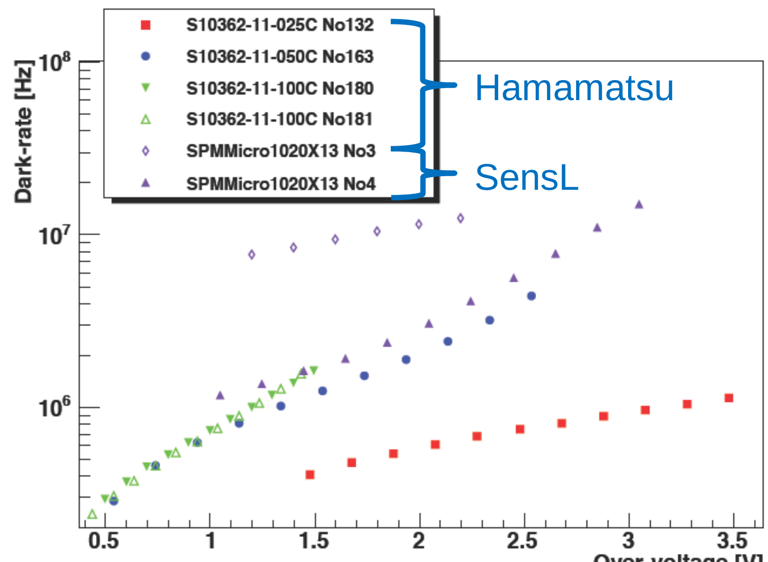
Dark Rate

- Electron hole pairs generated without the involvement of photons give rise to unwanted noise
- Two processes
  - Thermal excitation
  - Field assisted excitation (tunneling)
- Electron (hole) drifts into the high field region and causes avalanche breakdown
- Resulting signal is indistinguishable from a photon induced signal



Rule of thumb:
The thermal generated dark rate doubles for each temperature increase of 8 °C

Dark-rate rises exponentially with the applied over-voltage (this will lower the gain and the PDE!)



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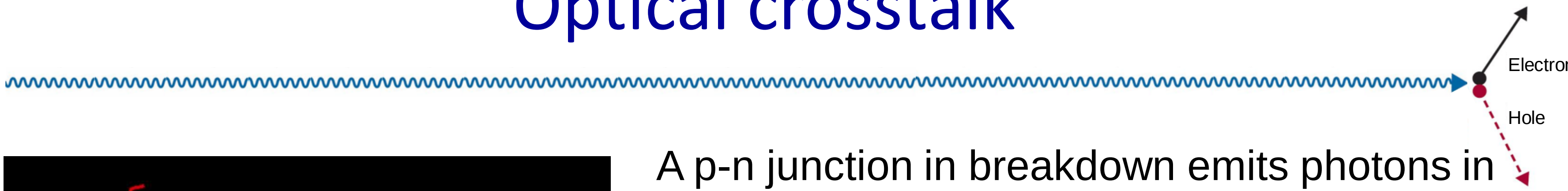
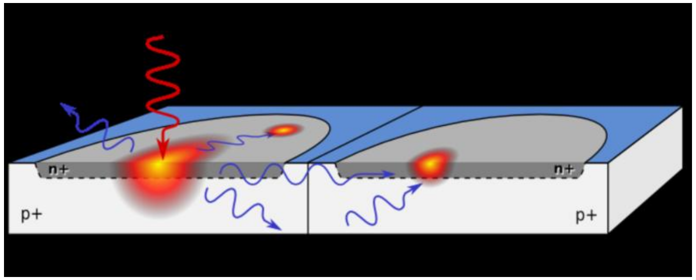
Optical crosstalk

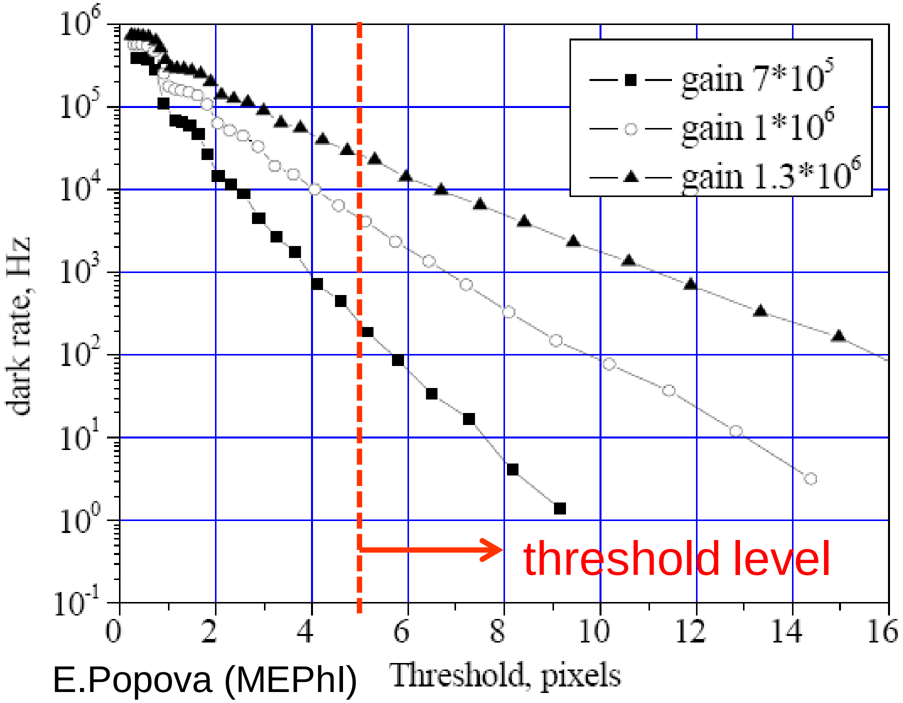




A p-n junction in breakdown emits photons in the visible range (~ 3 x 10^{-5} per charge carrier with a wavelength less than 1 μm*)

If they reach a neighboring pixel additional breakdown can be caused

* A. Lacaita, et al., IEEE Trans. Electron Devices ED-40 (1993) 577



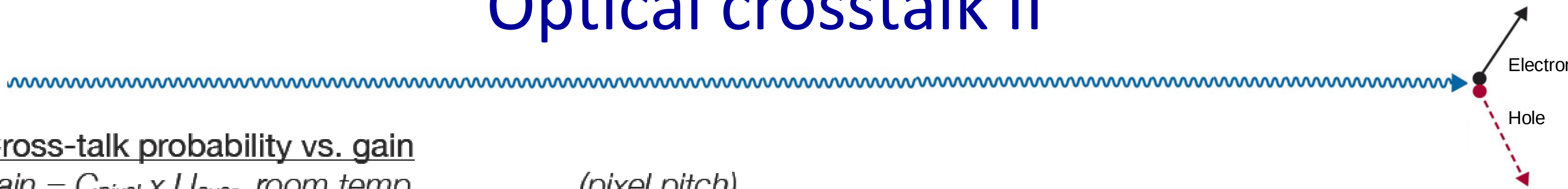
E.Popova (MEPhI)

Optical crosstalk

- responsible for the high rate at thresholds >1.5 p.e.
- Increases with overvoltage (or gain)

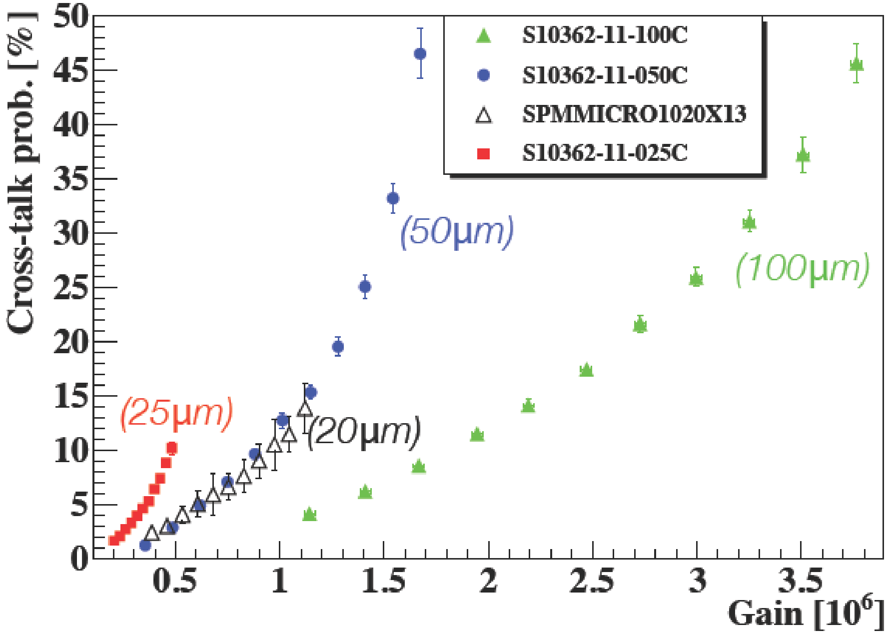
Limit to the SiPM sensitivity
Influence on acquisition rate & electronics design

Optical crosstalk II



Cross-talk probability vs. gain

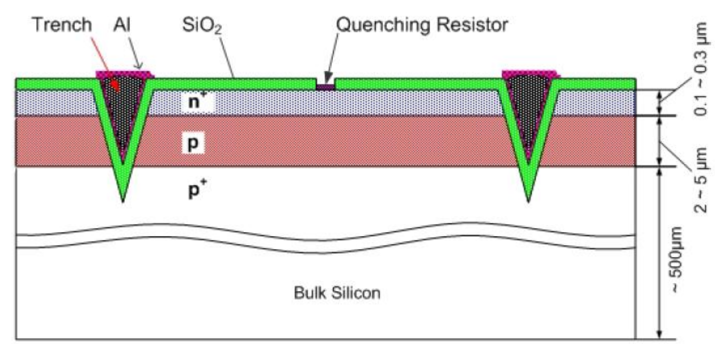
gain = C_{pixel} x U_{over}, room temp. *(pixel pitch)*



MPPC: At fixed gain values, small pixel devices have a higher crosstalk probability (average photon travel distance shorter)

SensL: small cross-talk due to trenches between pixels

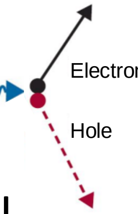
Solution: optically separate cells trenches



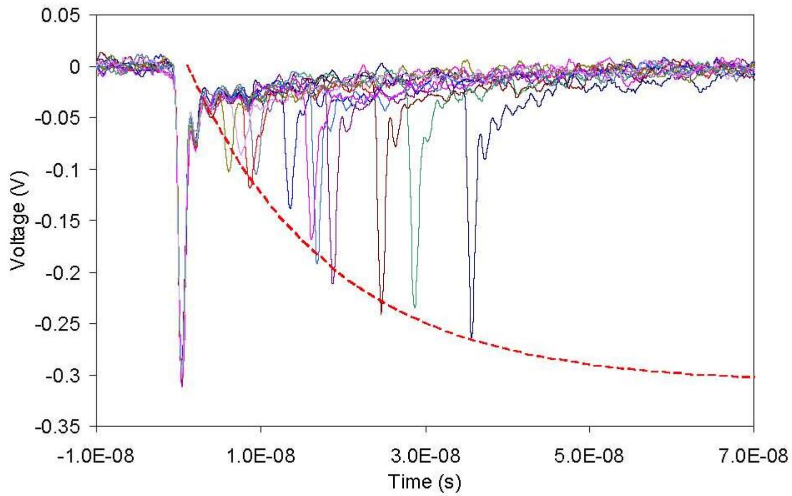
Trenches separating neighboring pixels
Introduced by CPTA /Photonique

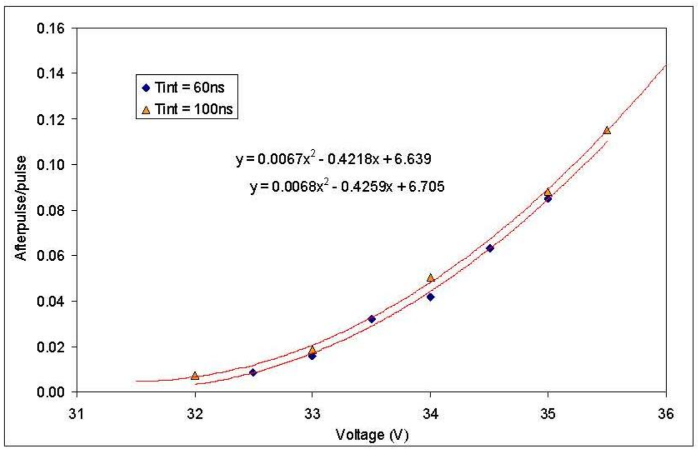
(D. McNally, G-APD workshop, GSI, Feb. 2009)

After-pulse



carriers can be trapped during the avalanche discharge and then released
→ trigger a new avalanche during a period of several 100 ns after the initial breakdown





Events with after-pulse measured on a single micropixel.

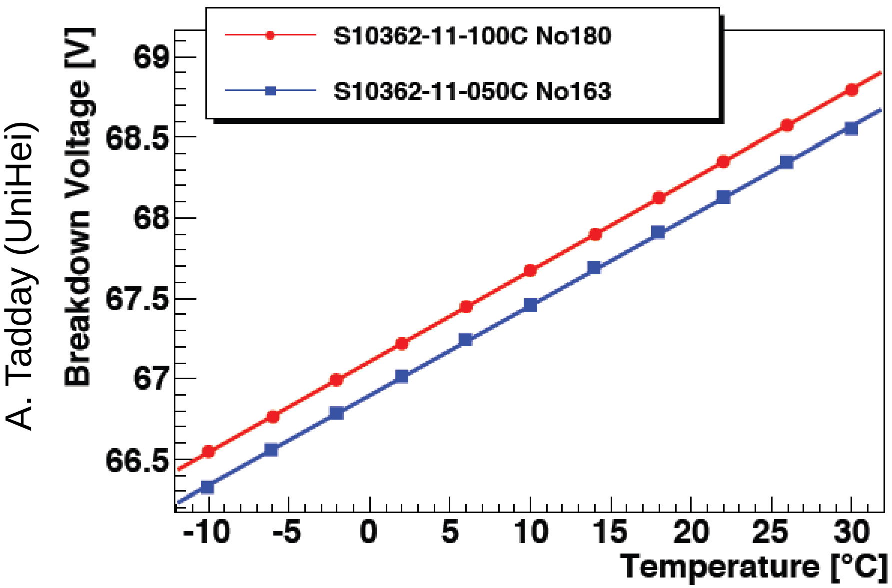
After-pulse probability increases with the bias

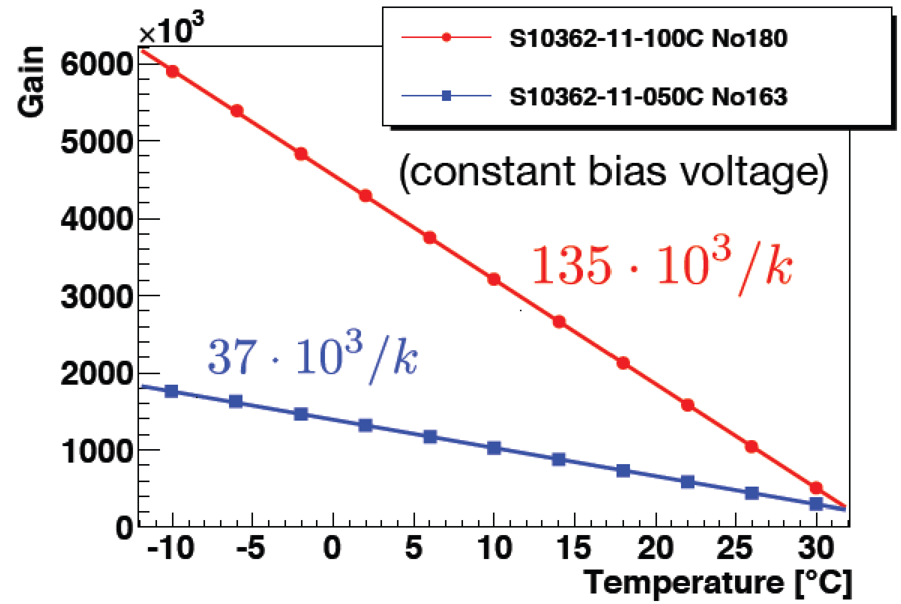
(C. Piemonte: June 13th, 2007, Perugia)

Solution:

- Cleaner/better technology
- Longer recovery time (large quenching resistor)
- Lower gain

Temperature dependence





Temperature coefficient

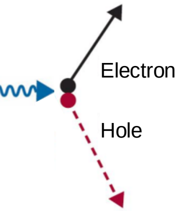
$$dU_{break}/dT = 56\,mV/K$$

Interaction with phonons (vibrations) slows down the charge carriers -> Higher field needed for breakdown

Large pixel capacitance causes large temperature dependence

$$\frac{dG}{dT} = -\frac{C_{pixel}}{qe} \cdot \frac{dU_{break}}{dT}$$

Photo-detection efficiency



- Definition:

$$PDE = \frac{Number\ of\ detected\ photons}{Number\ incident\ photons}$$

- In case of a SiPM:

$$\boxed{PDE = \epsilon_{geo} \cdot QE \cdot \epsilon_{trigger}}$$

$$\epsilon_{geo} = \frac{A_{sensitive}}{A_{total}}$$ (fill factor)

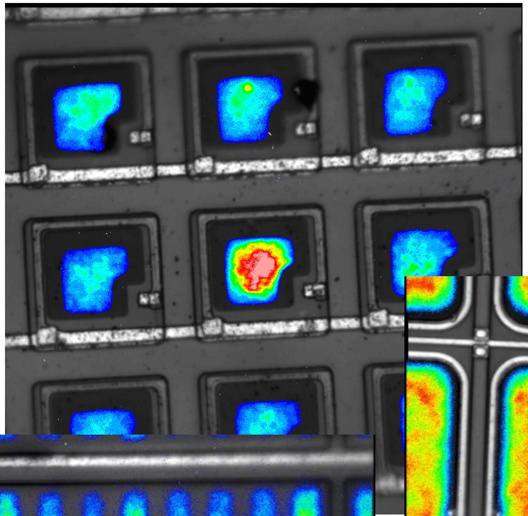
$$QE = Quantum\ efficiency$$

$$\epsilon_{trigger} = \text{avalanche trigger probability}$$

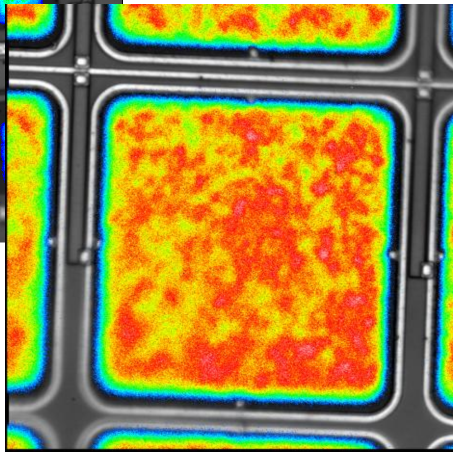
depends on U_{over} and position (λ)

Fill factor

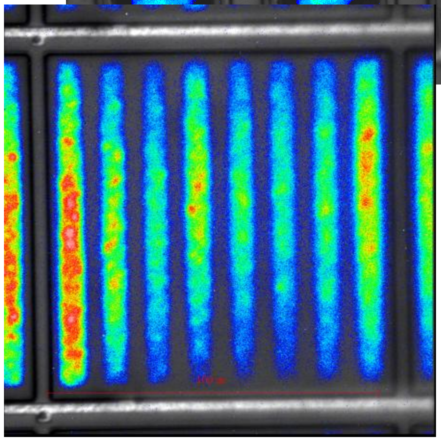
Photoemission image



Pulsar SiPM
42µm pitch size



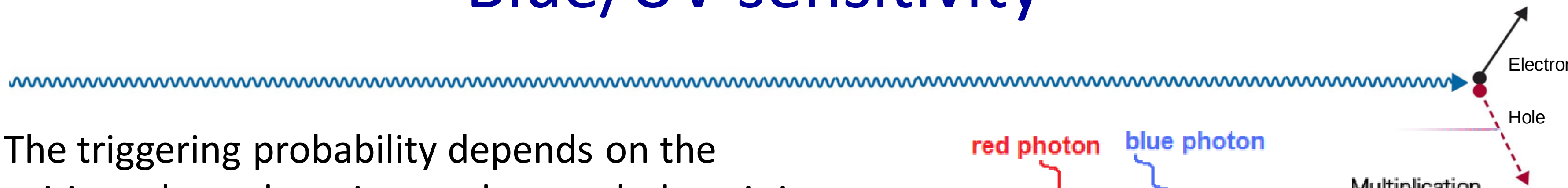
Hamamatsu MPPC,
100µm pixels



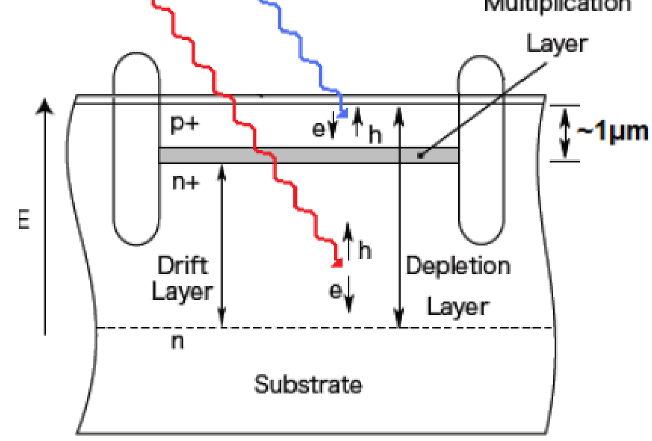
SensL, 35µm pixels

J.Ninkovic (MPI)

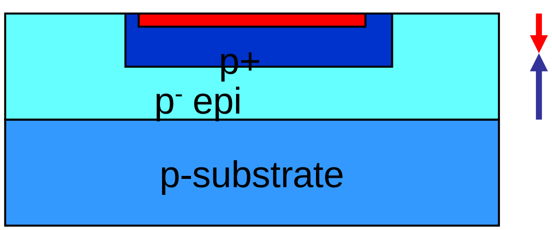
Blue/UV sensitivity



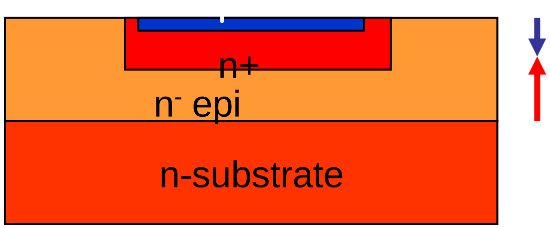
- The triggering probability depends on the position where the primary electron-hole pair is generated and it depends on the overvoltage.
- Electrons have in silicon a better chance to trigger a breakdown than holes (larger ionization coefficient). A conversion in the p+ layer has the highest probability to start a breakdown.



Standard SiPM structure (n-on-p), most of producers



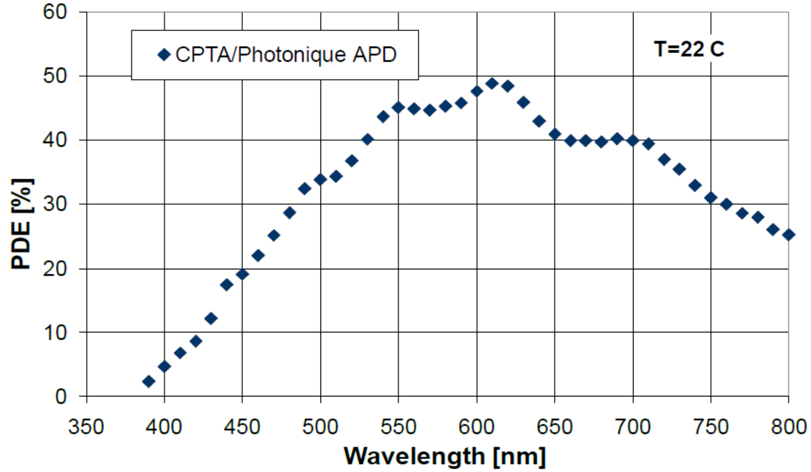
Inverted structure produced by MEPhI/Pulsar & Hamamatsu

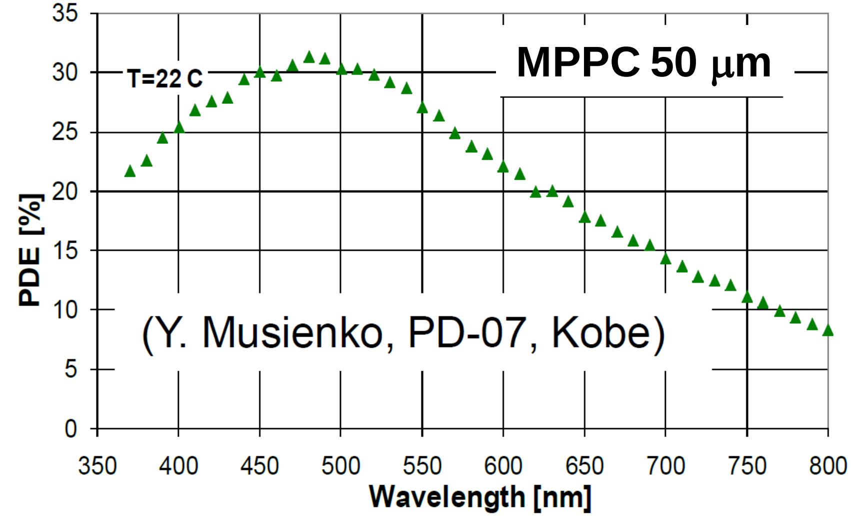


Wavelength dependence of PDE linked to depth of penetration of photon

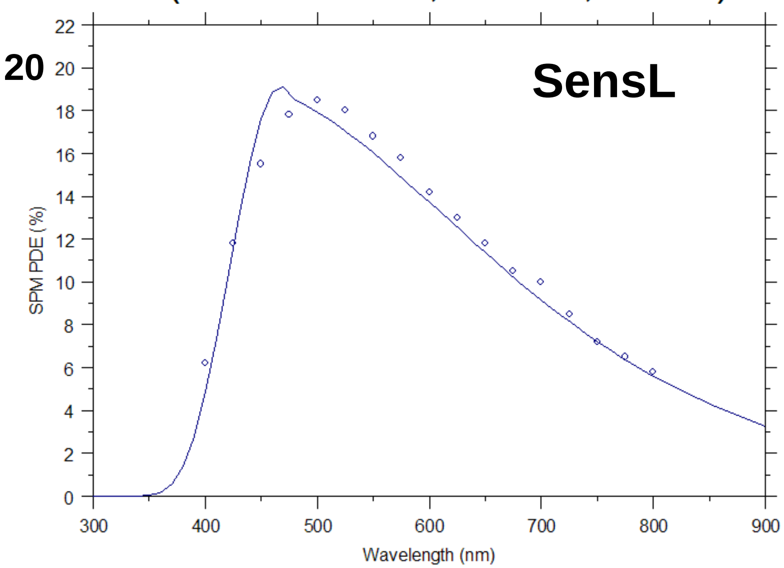
Blue (470nm)	0.6 µm
Green (525nm)	1.2 µm
Yellow (590nm)	2.2 µm
Red (625nm)	2.9 µm

Photo-detection efficiency II

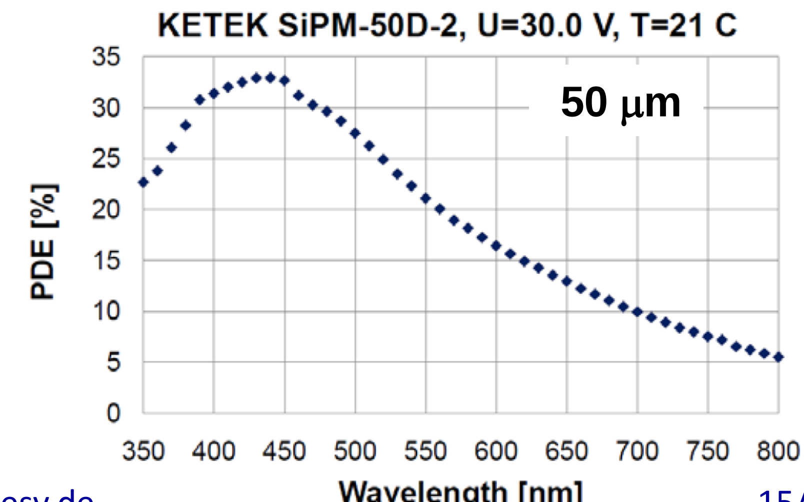




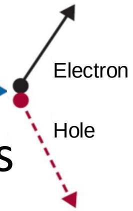
(Y. Musienko, PD-07, Kobe)



PDE absolute values sometimes includes cross-talk and after-pulsing



Non-linear response function



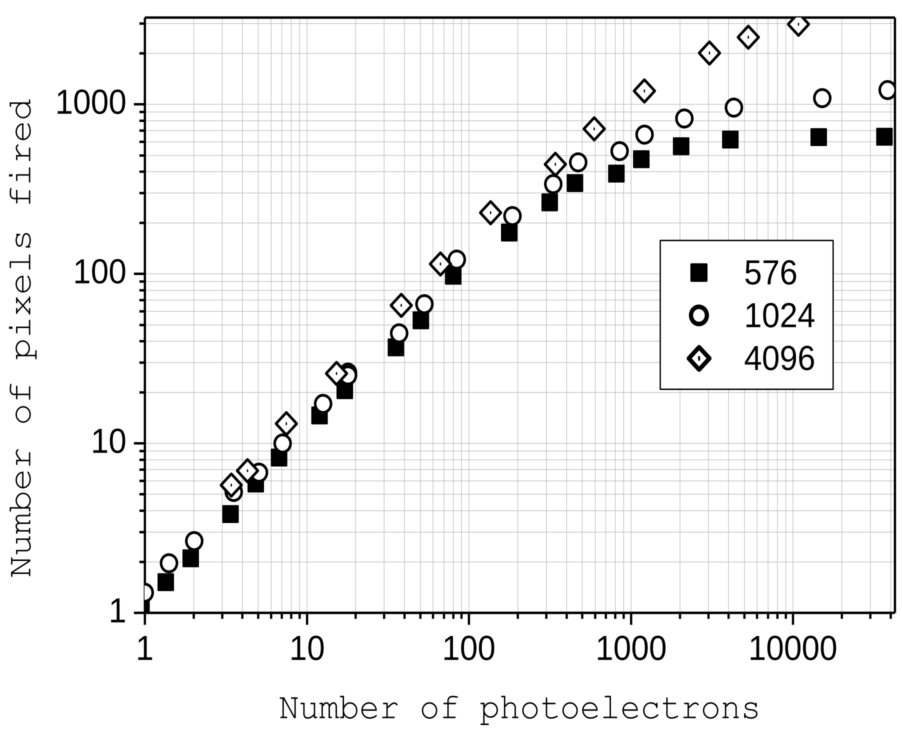
Linear response only when the number of detected photons (N_{photon} x PDE) is significantly smaller than the number of cells N_{total}.

$$A \approx N_{firedcells} = N_{total} \cdot (1 - e^{-\frac{N_{photon} \cdot PDE}{N_{total}}})$$

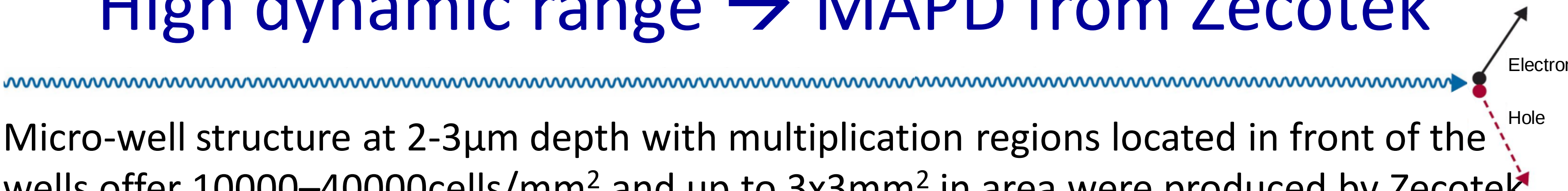
correct for an "ideal" SiPM (no cross-talk and no after-pulsing) as long as light pulses are shorter than pixel recovery time

Limit to the system dynamic range
Requires correction of non-linear response (individual/global curve)
Reduces acceptable spread in light yield of a system

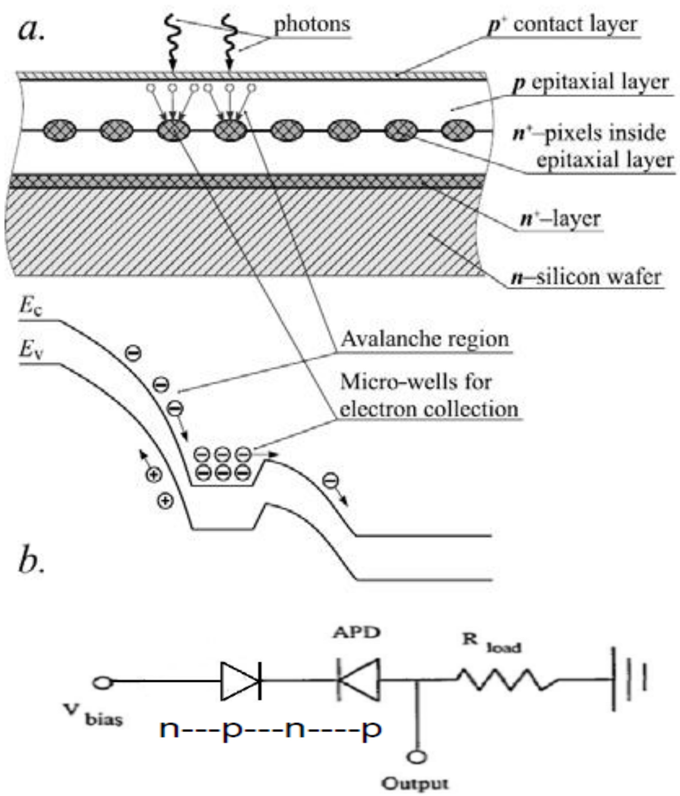
MEPhI/Pulsar



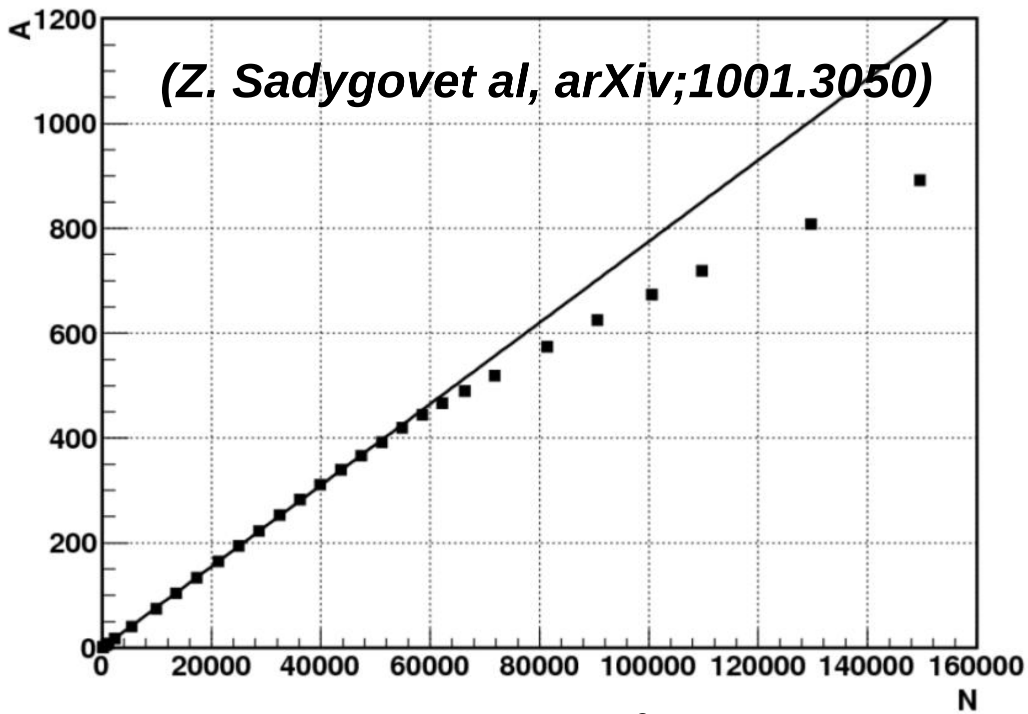
High dynamic range → MAPD from Zecotek



Micro-well structure at 2-3µm depth with multiplication regions located in front of the wells offer 10000–40000cells/mm^2 and up to 3x3mm^2 in area were produced by Zecotek

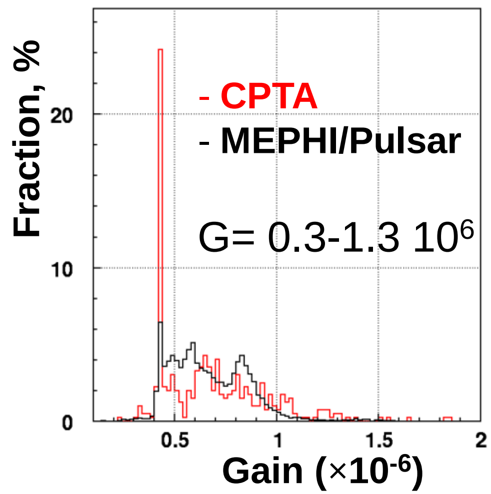


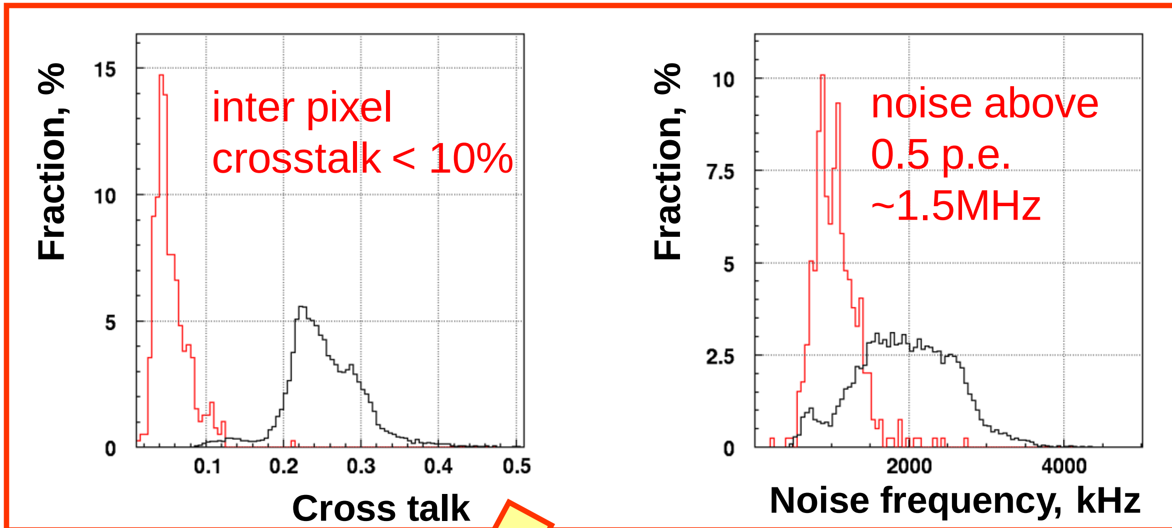
No quench resistors instead specially designed potential barriers are used to quench the avalanches.

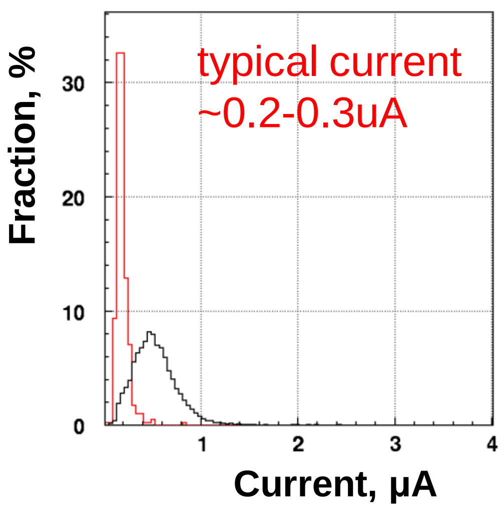


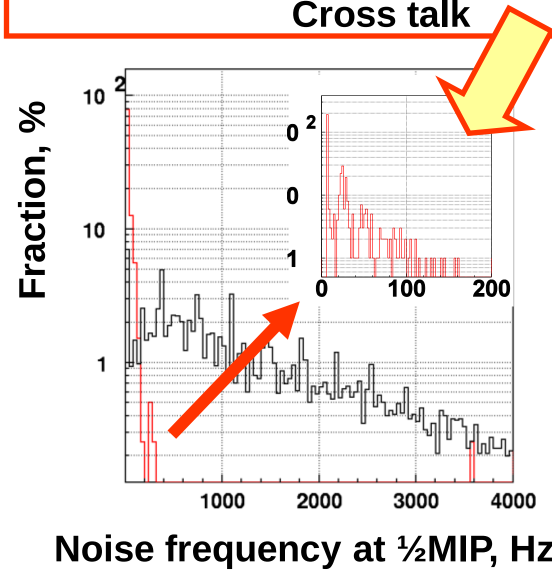
MAPD (135000cells,3x3mm^{2}area) signal amplitude A(in relative units) as function of a number of incident photons N

Spread in parameters





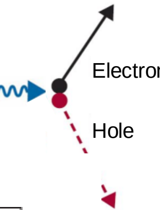




Very large spread on V_{bd} (30-75V)

Individual adjustment of bias
Individual preamp gain or
threshold adjustment

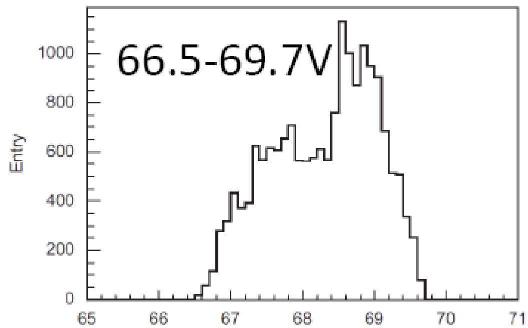
Spread in parameters II



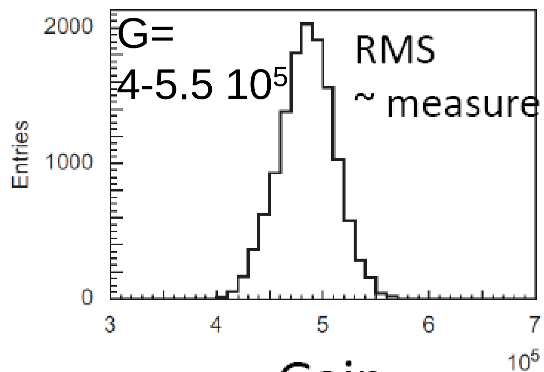
Hamamatsu MPPC 50μm

Mean=4.8 × 10^5

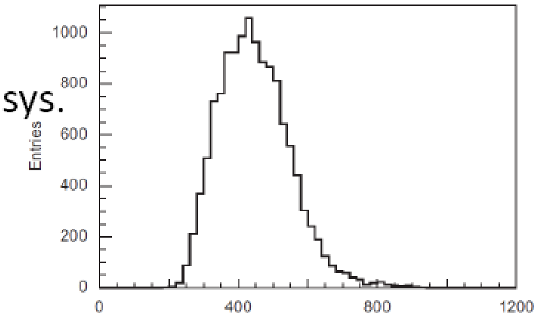
Mean=450 kHz



V_{bd} at 20˚C



Gain

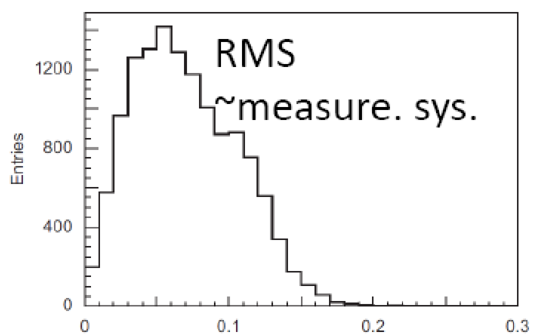


Dark rate (kHz)

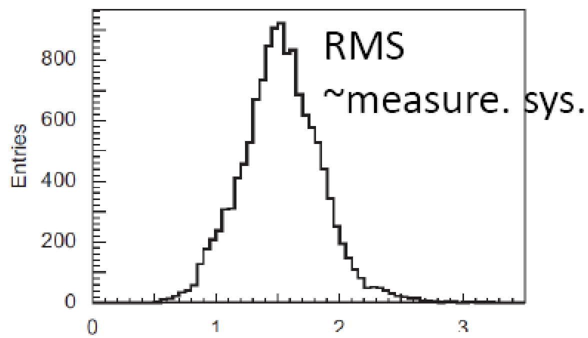
Test of 17000 MPPC for T2K

Mean=0.07

Mean=1.53



AP + CT prob.



PDE (xPMT)

<u>**ΔV = 1.0V and 20˚C**</u>

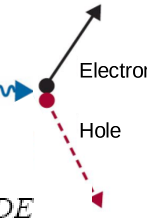
Failure rate < 0.05 %

M. Yokoyama et al.,
NIM A 622 (2010) 567-573

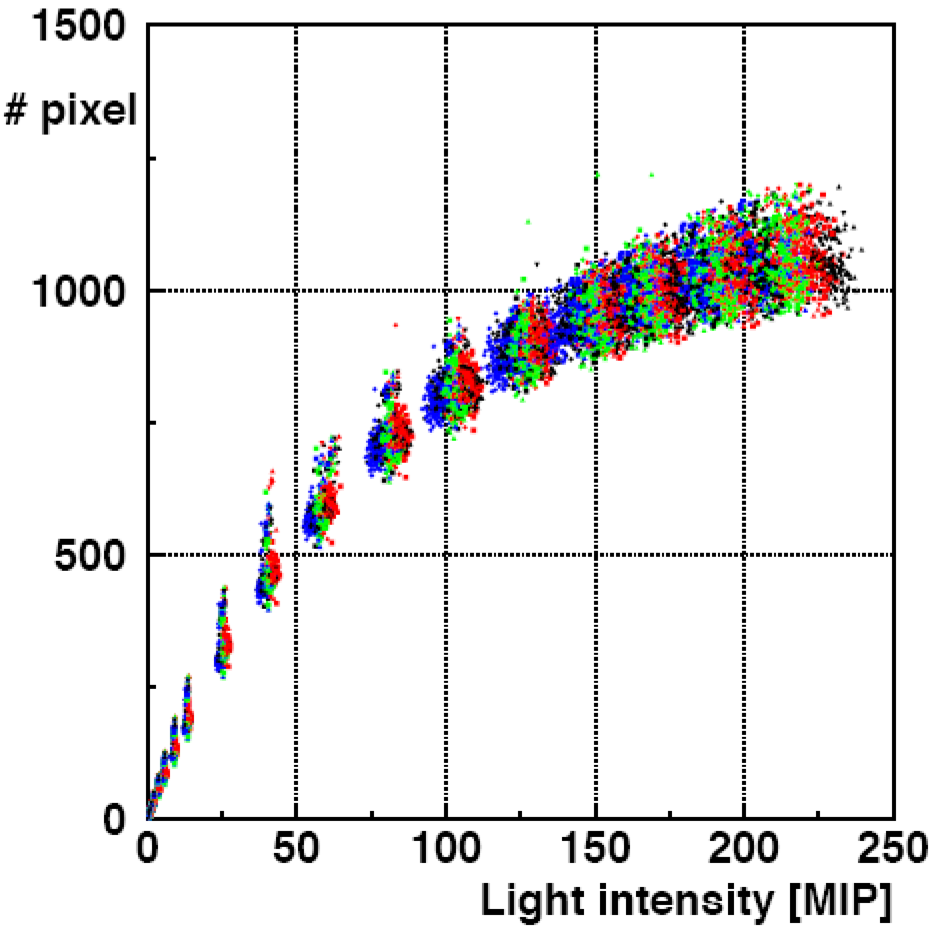
<u>Device uniformity itself is considered to be much better.</u>

20

Spread in parameters III



SiPM response curve (MEPhI/Pulsar)



$$A \approx N_{firedcells} = N_{total} \cdot (1 - e^{-\frac{N_{photon} \cdot PDE}{N_{total}}})$$

~ 20% spread in N_{total}

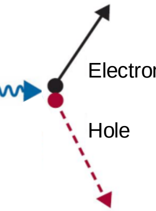
➔ Requires precise measurement of single response function

Typical LY (specific application) 10-20 pix

➔ Change in dynamic range ch.-to-ch.

SiPM applications in HEP experiments

SiPM pioneering experience



R&D for Calorimeters for the ILC

<u>The history:</u>

- After the LHC detectors (radiation hard / dense particle environment)
- The next generation HEP experiments ➔ precision experiments
- New paradigm for precision measurements in a jet environment

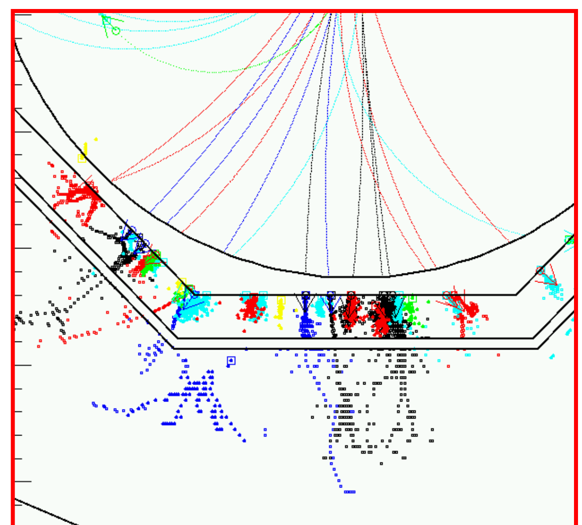
➔ Particle Flow

a concept to improve the jet energy resolution of a HEP detector based on:
proper detector design (high granular calorimeter!!!)
+ sophisticated reconstruction software

PFlow techniques have been shown to improve jet E resolution in existing detectors, but the full benefit can only be seen on the future generation of PFlow designed detectors

Requires the design of

- a highly granular calorimeter, O(1cm^2) cells
- dedicated electronics, O(20M channels)
- high level of integration



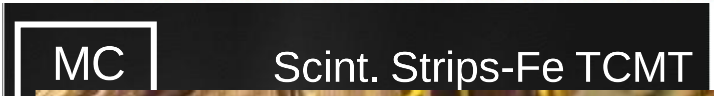
The prototype calorimeter system for ILC

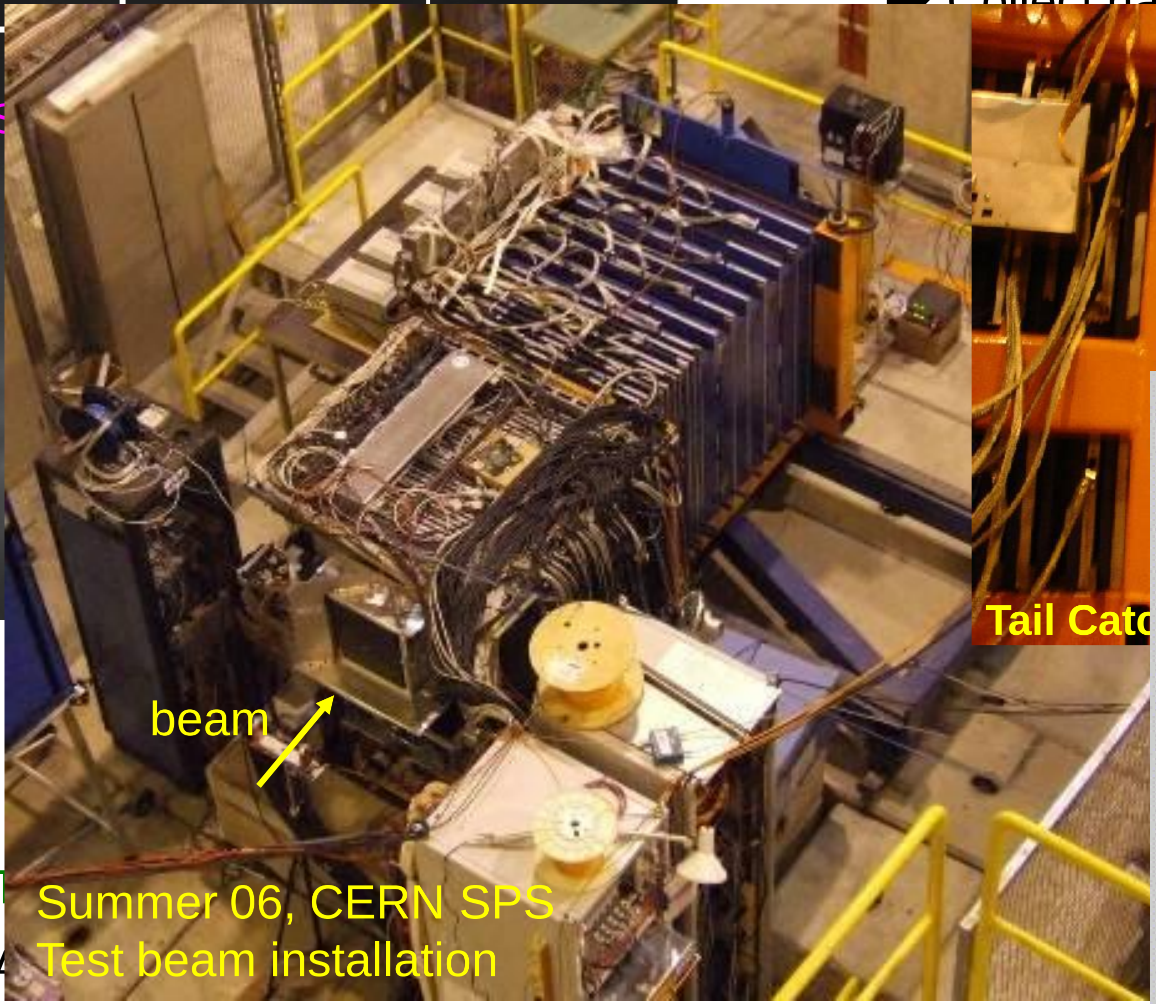
Electron

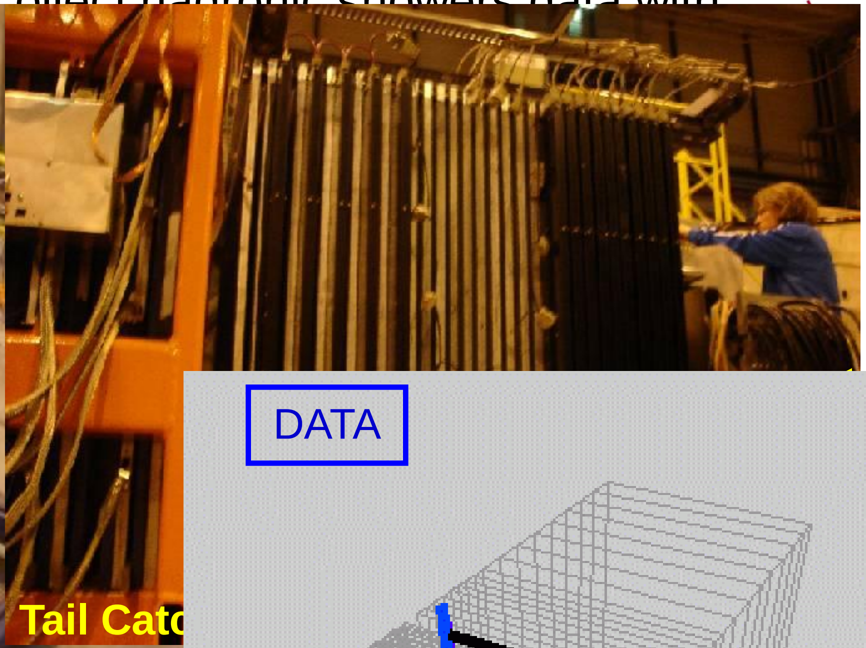
Hole

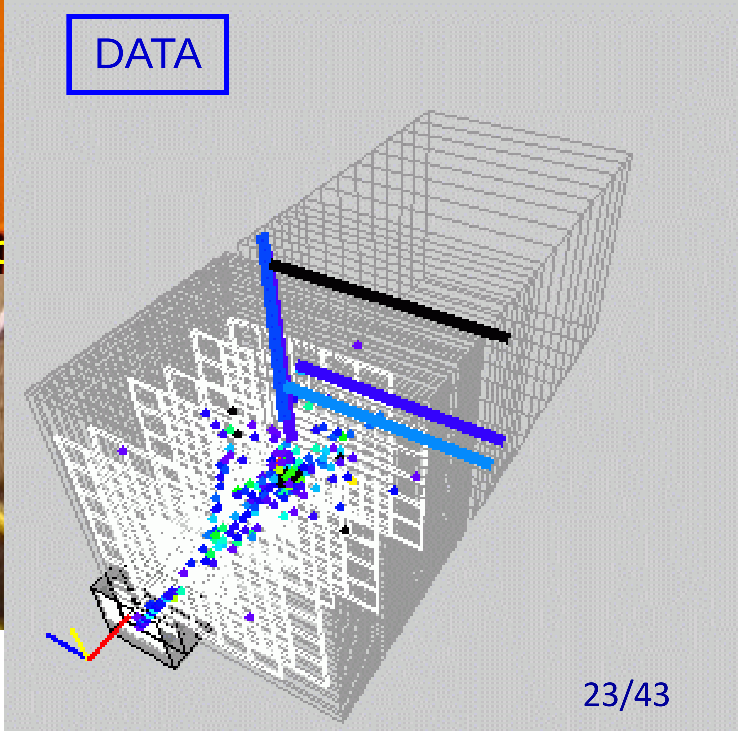
➔ Establish the technology

➔ Collect hadronic showers data with









A

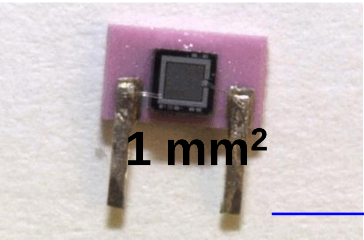
the Particle Flow measurement of multi-jets final state at the International Linear Collider

SiPM pioneering experience

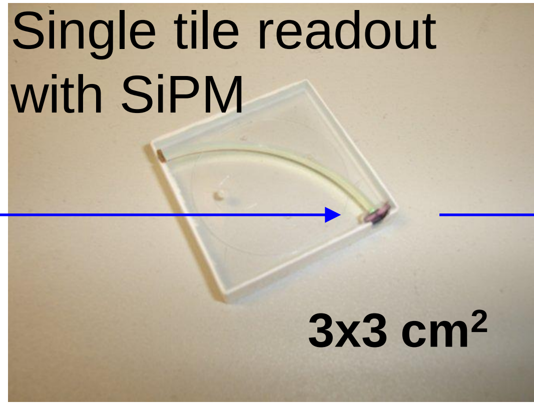
A crucial technology improvement to calorimetry

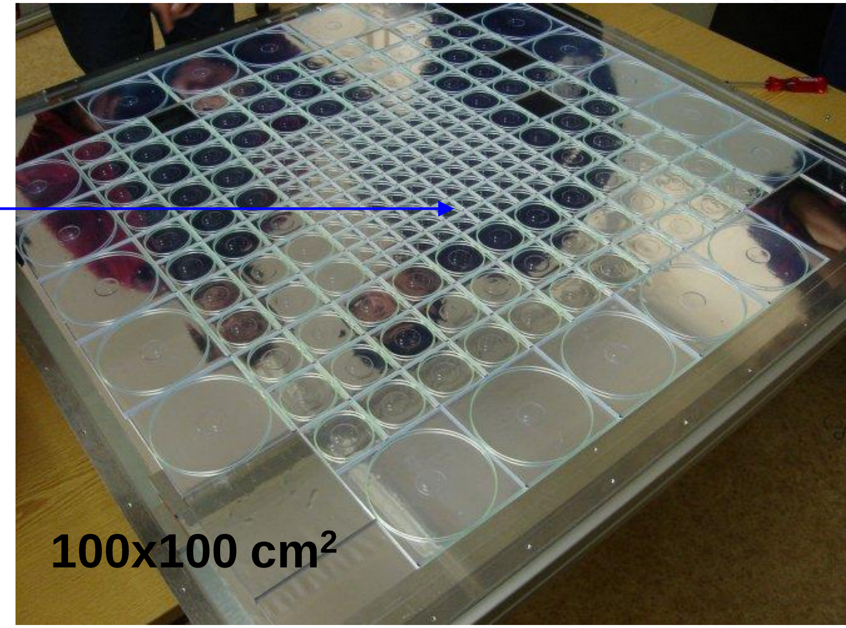
Electron

Hole

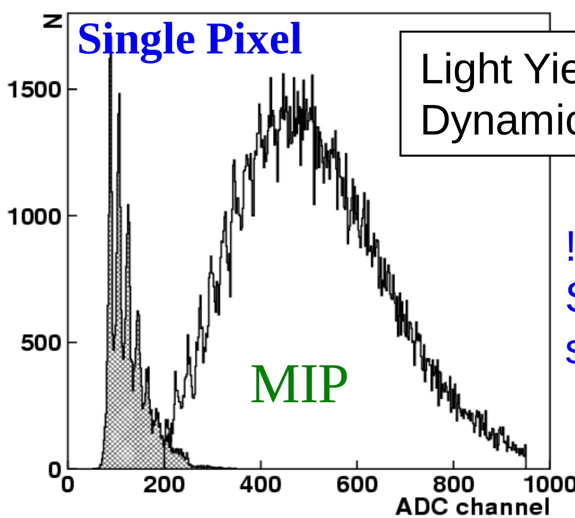


Si-based = insensitive to magnetic field!





1x1m² prototype calorimeter with 8000 channels readout with SiPM (MePHI/Pulsar)



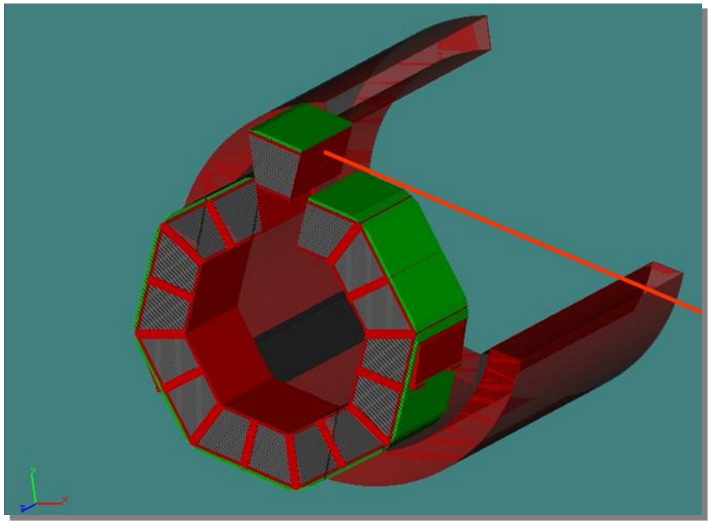
Light Yield = 15 pixels / MIP
Dynamic range ~ 100 MIPs

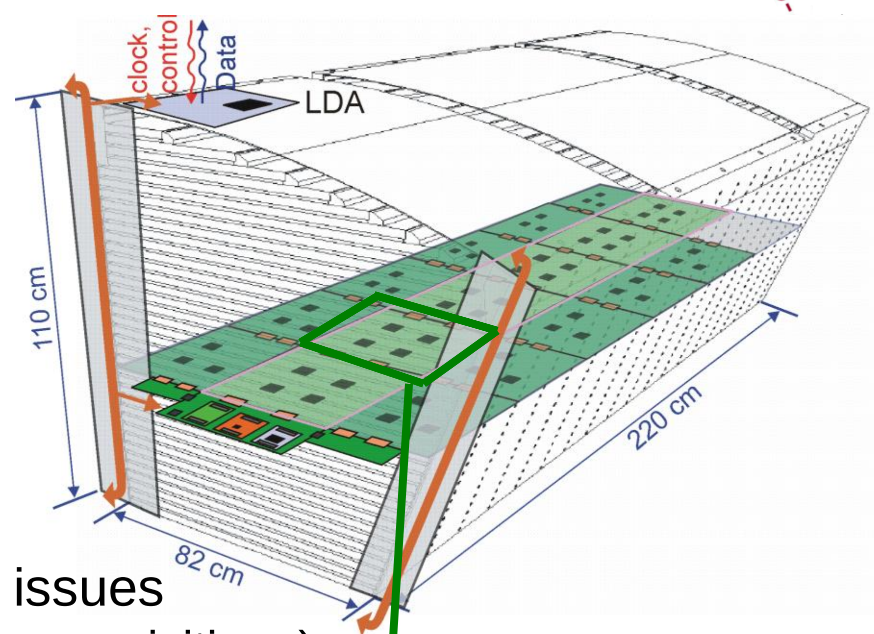
!! auto-calibration of SiPM gain from single-pixel spectra

Allows unprecedented high granularity

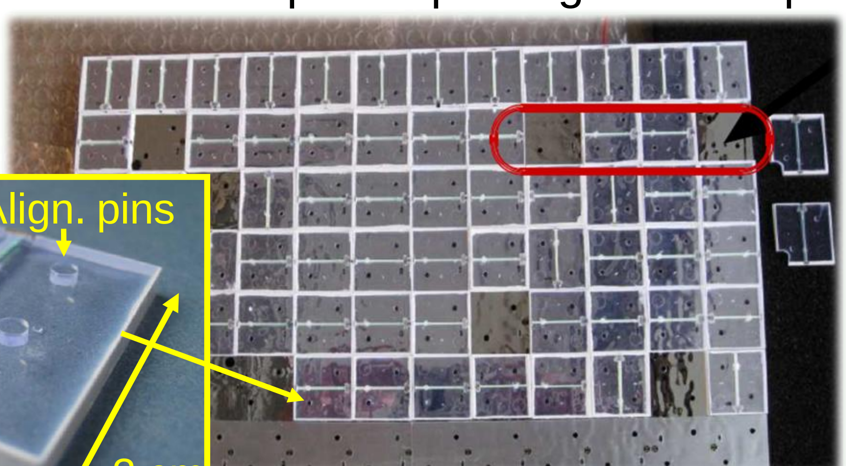
38 layers (~4.5 λ)
Scintillator – Steel sandwich structure (0.5:2cm)

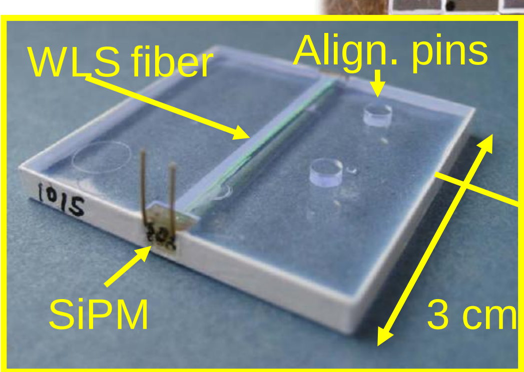
Next step towards a ILC detector

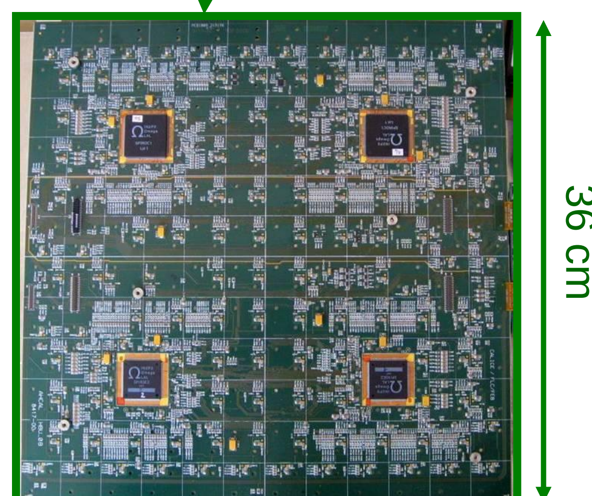




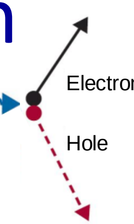
➔ Work on integration and scalability issues
(integrated electronics/ power pulsing/ data acquisition..)



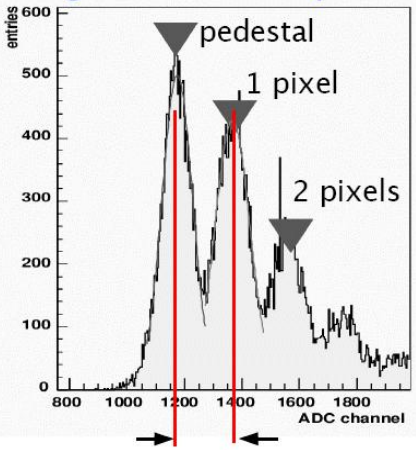




Redundant monitoring and calibration system



Single Photon Response



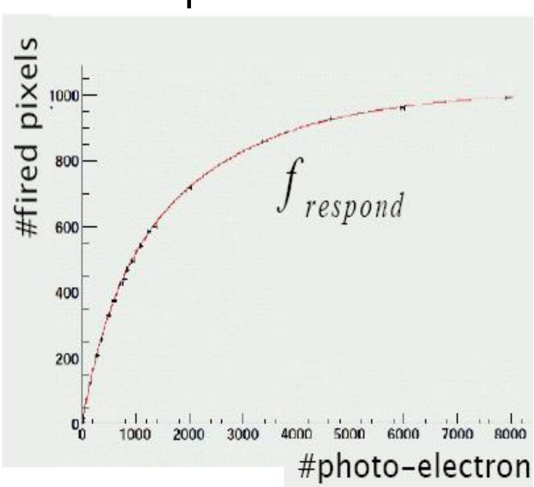
gain

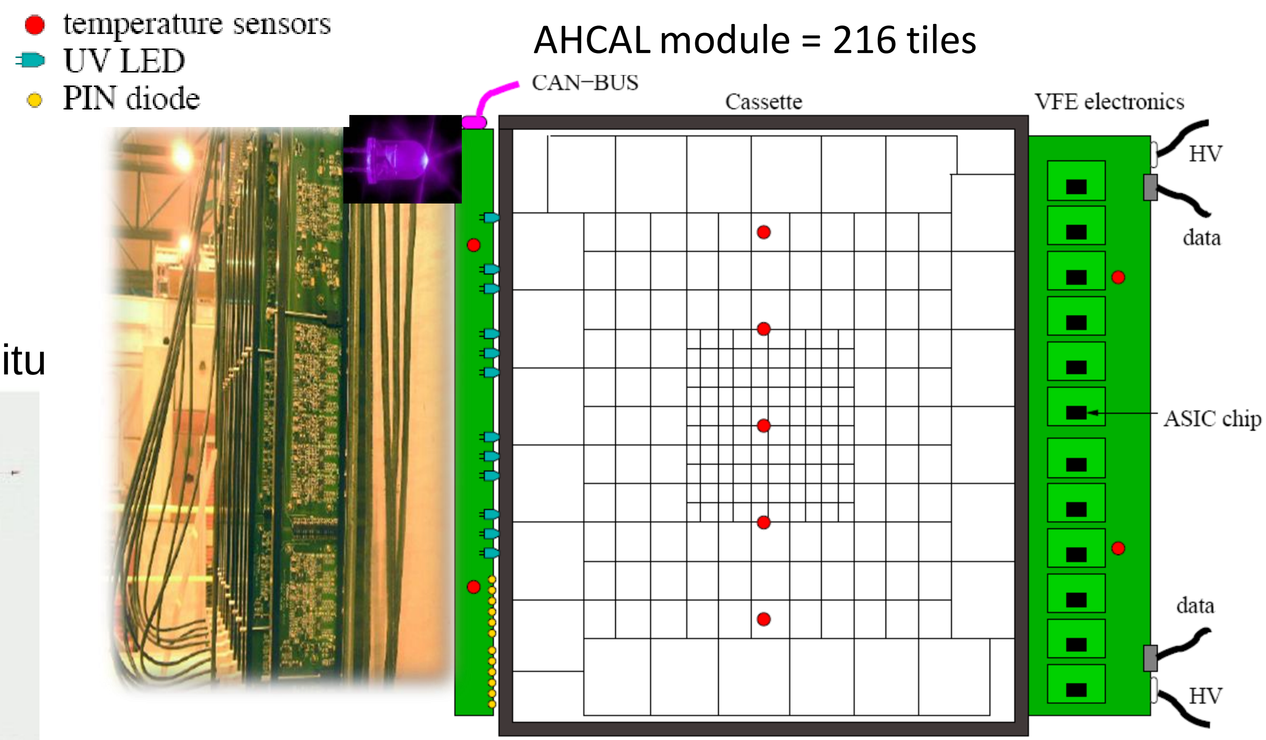
Conversion ADC ch.→pixels

Calibration/monitoring system based on UV LED delivers:

- Low intensity light for SiPM Gain calibration
- High intensity of light for saturation monitoring
- Medium intensity light for electronics calibration & monitoring
- Temperature measurement for monitoring

SiPM response curve in situ





Light distributed via clear fibers to each calo cell

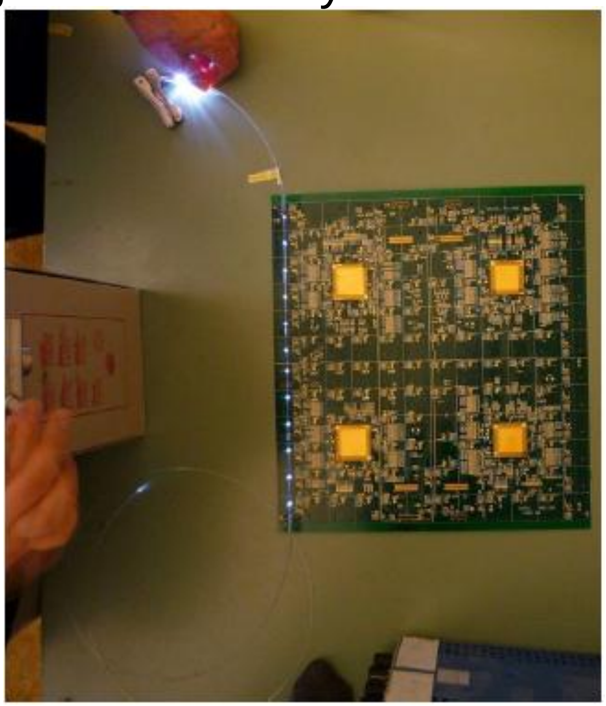
Intensity for 8000 ch. within factor 2 (>94% calibration eff.)

Next generation monitoring system

System task: SiPM gain calibration via single photoelectron peak spectra (~1-2 p.e.)
long term stability via response @ medium light (~20-100 p.e.)
measure SiPM saturation level (~2000 p.e.)

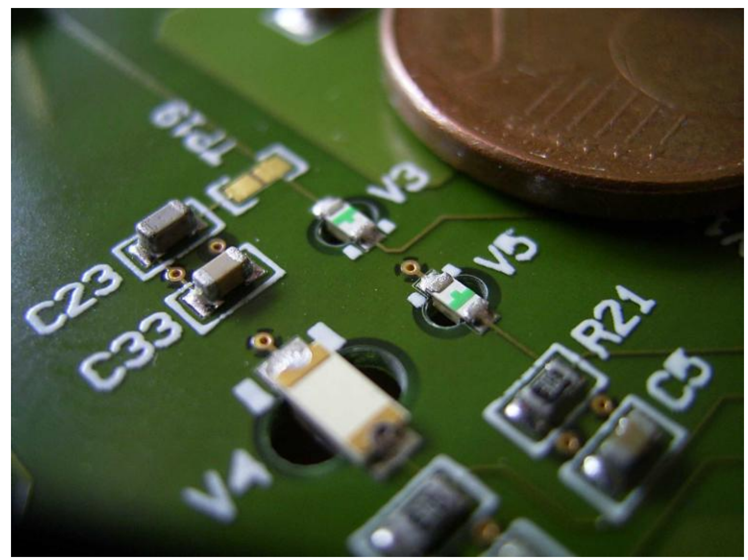
Two technological solutions:

Light distributed by notched fibres



I. Polak (Uni. Prague)

Light directly on tile by SMD-LED
- distributed LED



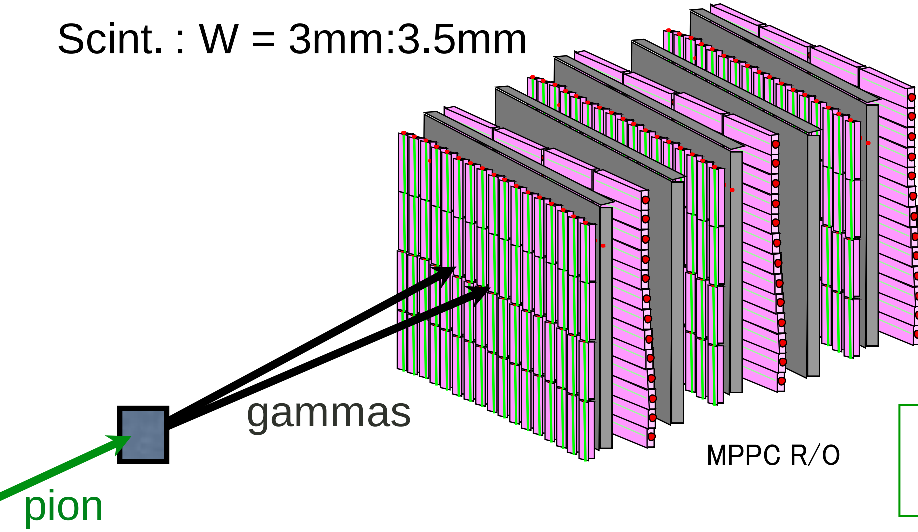
M. Reineke (DESY)

High granularity EM Calorimeter for ILC

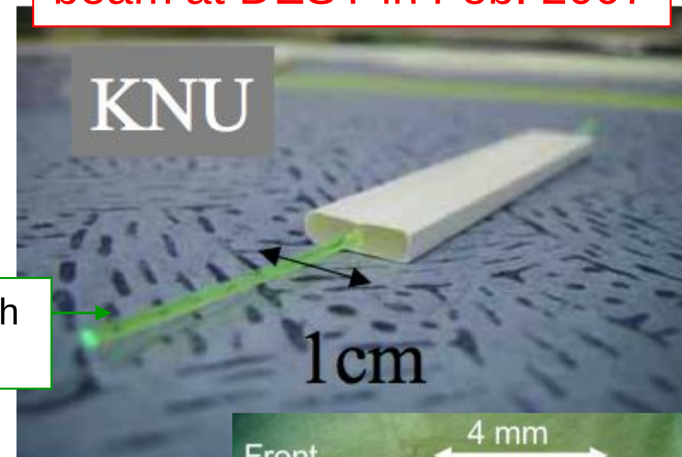
Scintillator – Tungsten sandwich structure

from T. Takeshita, Shinshu Uni., Japan

Scint. : W = 3mm:3.5mm



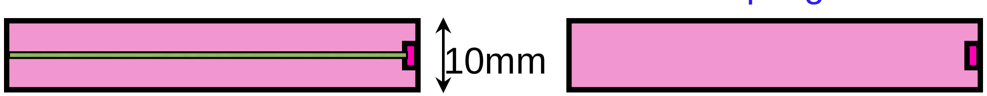
Fist prototype ready for test beam at DESY in Feb. 2007



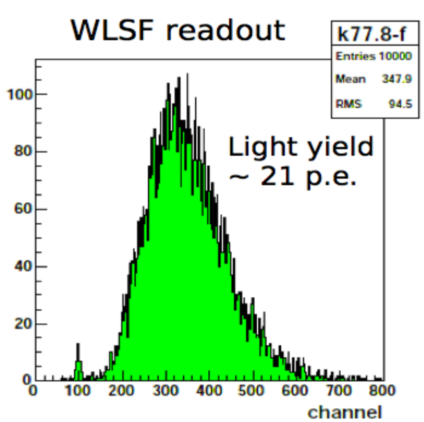
Wave-Length Shifter Fibre

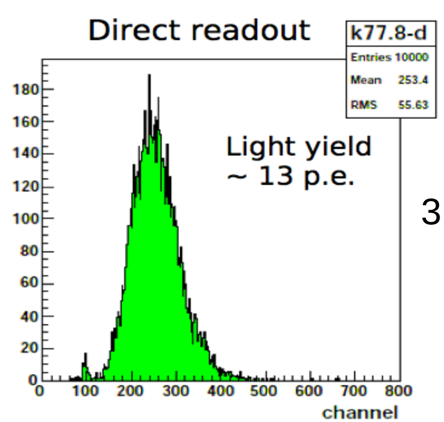
WLSF 4.5cm

Direct coupling 4.5cm

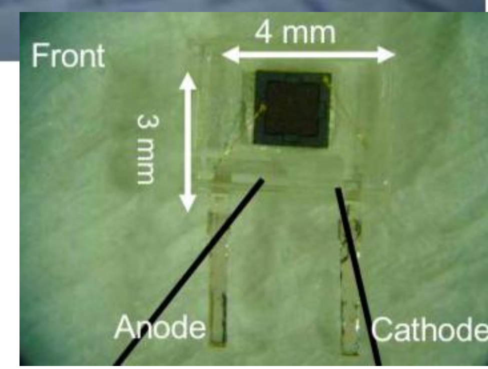


3mm thick



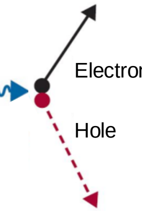


3M R.M.F.

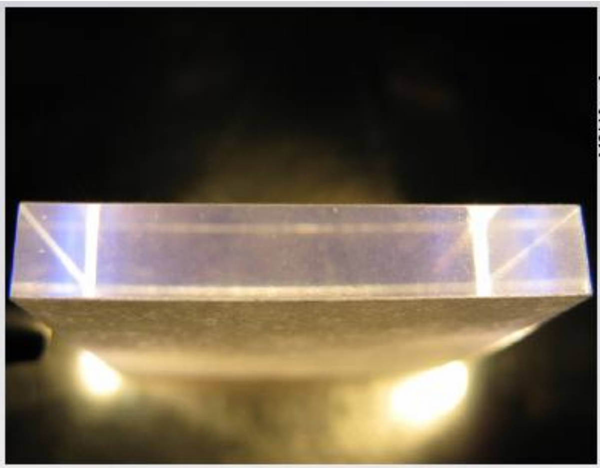


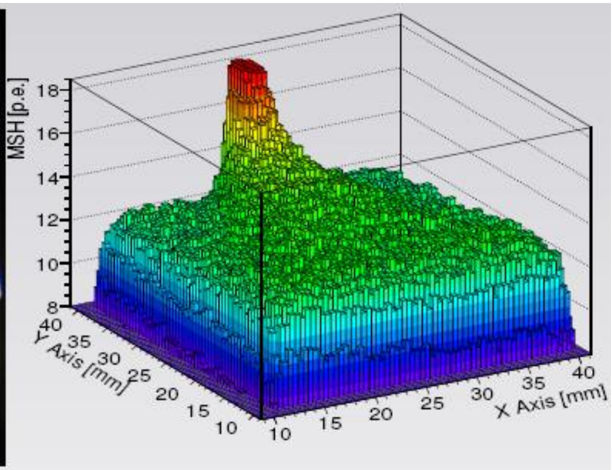
Multi-Pixel Photon Counter from Hamamatsu

Direct coupling of SiPM to scintillator



Coupling via WLS fiber has the advantage of higher uniformity:
- light from the whole tile is collected and guided to the SiPM

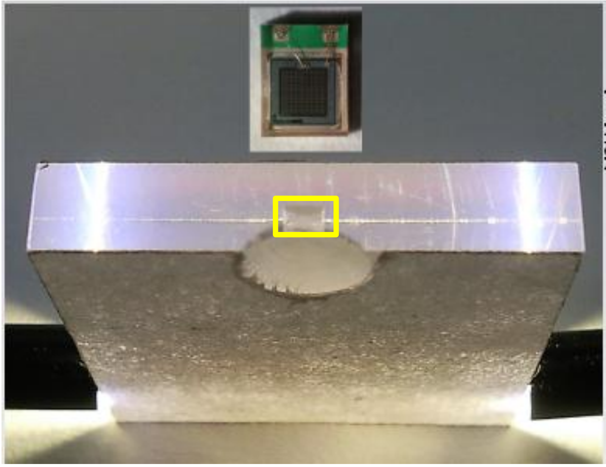


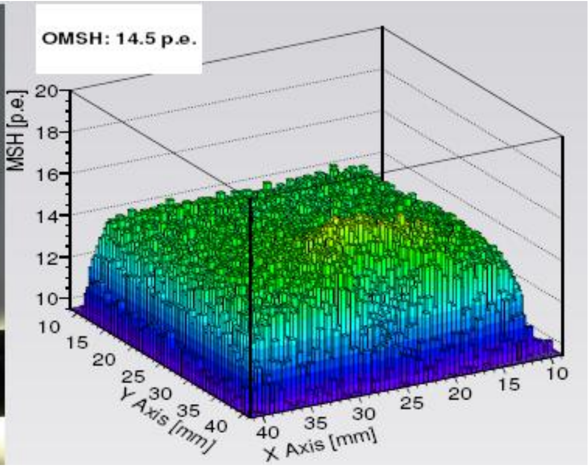


Direct coupling
➔ non-uniformity of light collection

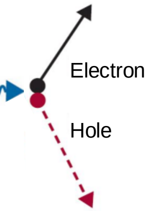
Special optimization of SiPM coupling through a dimple in the scintillator allows to recover good uniformity

(study: MPI Munich)

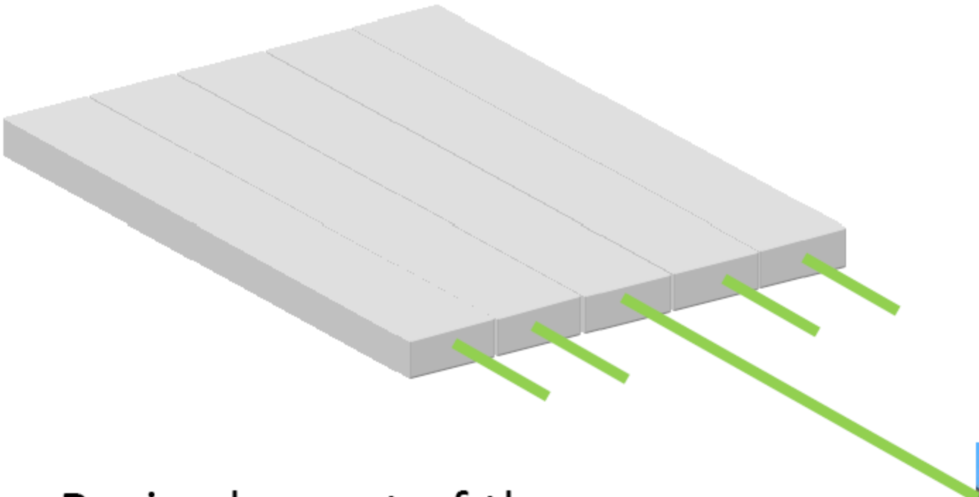


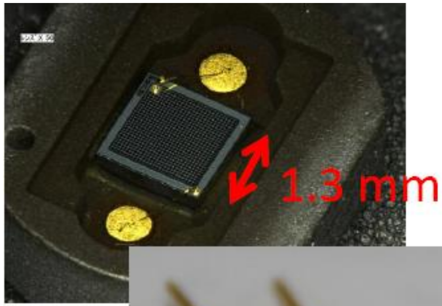


The design solution

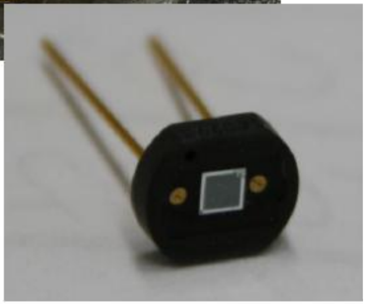


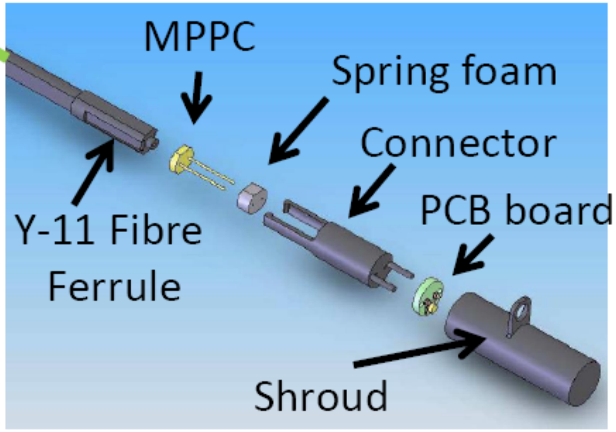
T2K experiment





MPPC

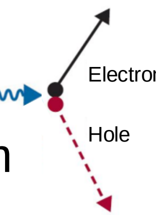


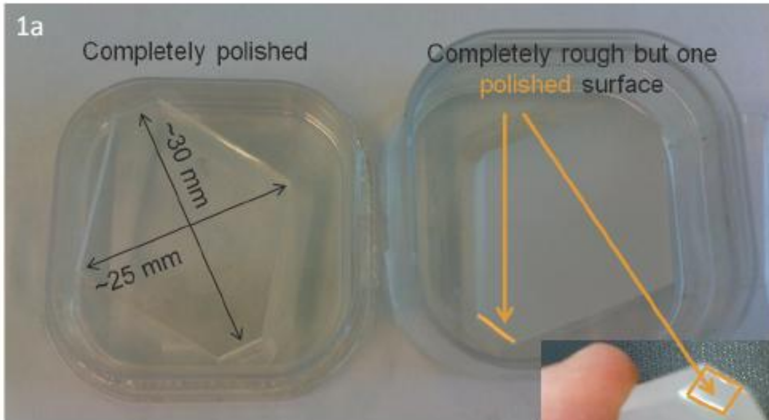


Connectors for P0D/ECAL/SMRD

- Basic element of the near detector scintillator subsystem (INGRID, P0D, FGD, ECAL, SMRD)
  - Extruded scintillator bar with embedded Y-11 fibre read out by individual MPPC in coupler
  - 56000 channels in total

Cherenkov light r/o

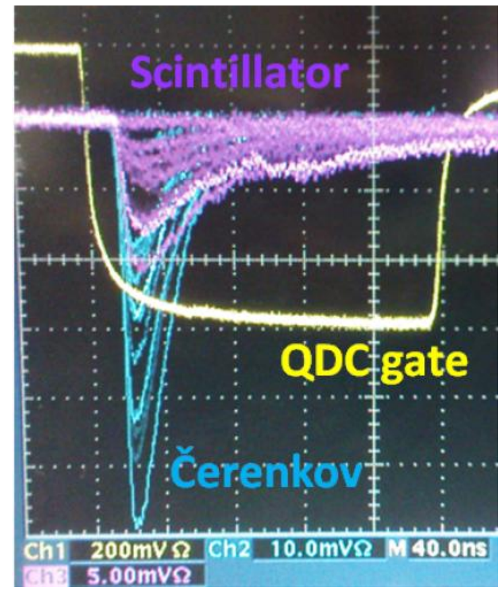


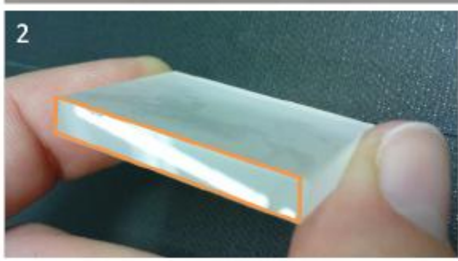


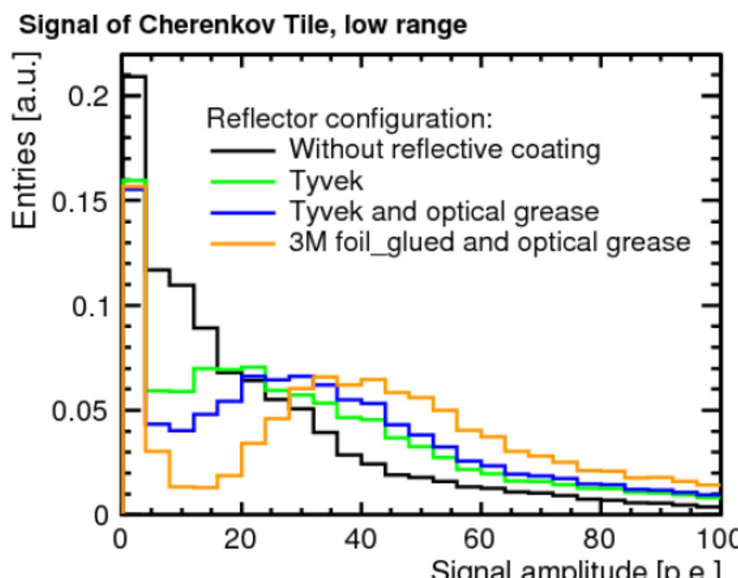
First test of Cherenkov light detection from Sapphire and lead glass tiles

S. Jungmann,
diploma thesis, Heidelberg

Tested at DESY TB with 3 GeV electrons







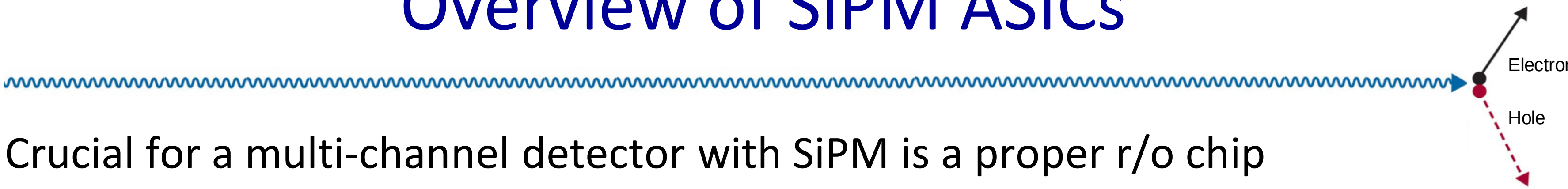
Coupled to 3x3 mm^2 MPPC, 50um pixel

Possible application in Dual readout calorimetry (CLIC?)

After optimization of coating and coupling
LY sufficient for calorimeter application
LY uniformity under study

Readout electronics for SiPM

Overview of SiPM ASICs



Crucial for a multi-channel detector with SiPM is a proper r/o chip

Tested in multi-channel applications:

1. FLC_SiPM– Orsay
2. MAROC – Orsay
3. SPIROC – Orsay
4. NINO – CERN
5. PETA – Heidelberg
6. BASIC – Bari/Pisa
7. SPIDER – Siena/Pisa
8. RAPSODI – Krakow

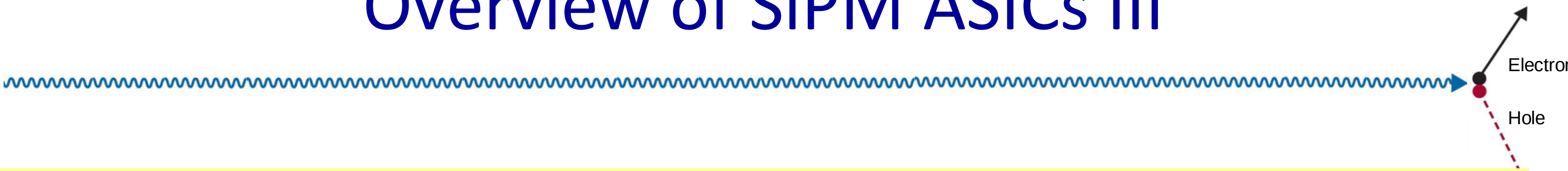
Review of ASIC developments for SiPM signal readout (Wojtek Kucewicz)

Overview of SiPM ASICs II

Chip Name	Measured quantity	Application	Input configuration	Technology
FLC_SiPM	Pulse charge	ILC Analog HCAL	Current input	CMOS 0,8 µm
MAROC	Pulse charge, trigger	ATLAS luminometer	Current input	SiGe 0,35 µm
SPIROC	Pulse charge, trigger, time	ILC HCAL	Current input	SiGe 0,35 µm
NINO	Trigger, pulse width	ALICE TOF	Differential input	CMOS 0,25 µm
PETA	Pulse charge, trigger,time	PET	Differential input	CMOS 0,18 µm
BASIC	Pulse height, trigger	PET	Current input	CMOS 0,35 µm
SPIDER (VATA64-HDR16)	Pulse height, trigger, time	SPIDER RICH	Current input	
RAPSODI	Pulse height, trigger	SNOOPER	Current input	CMOS 0,35 µm

Review of ASIC developments for SiPM signal readout (Wojtek Kucewicz)

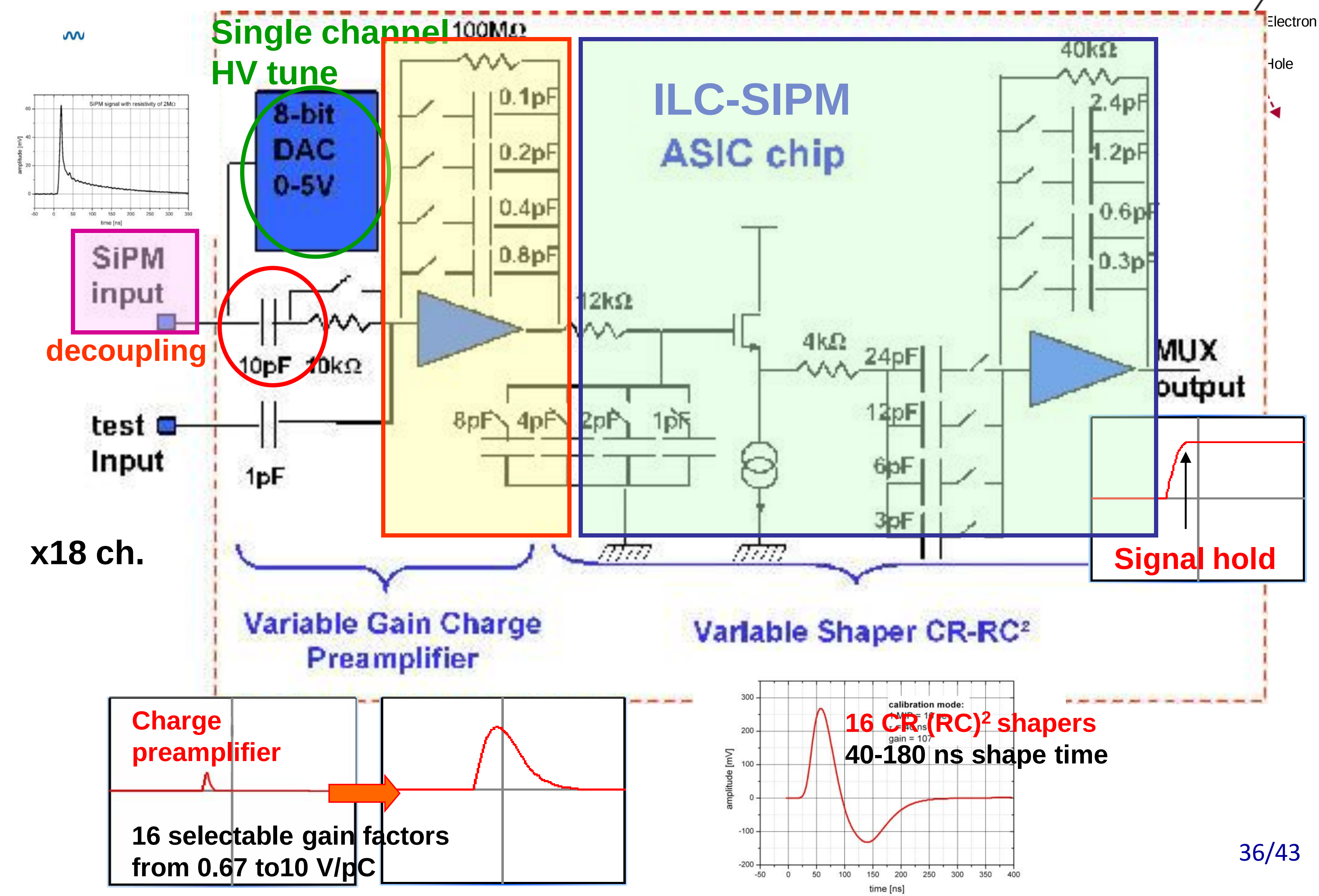
Overview of SiPM ASICs III



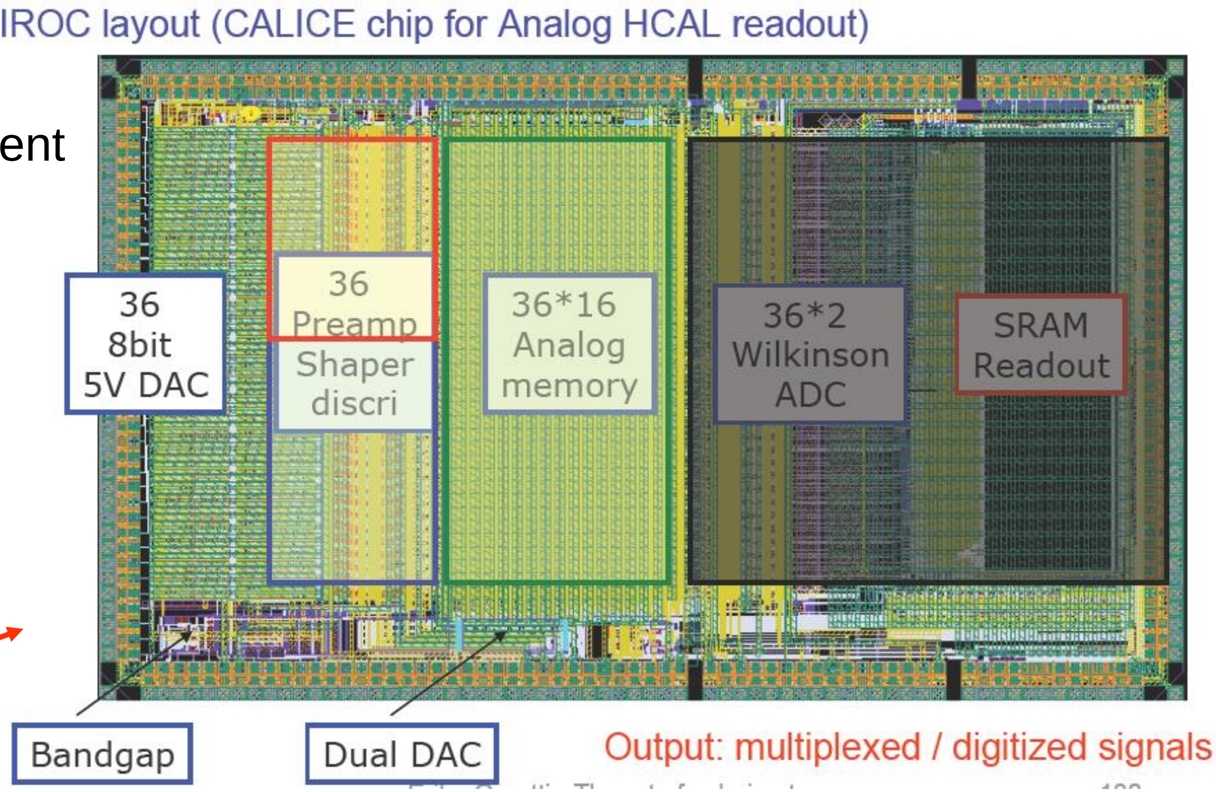
Chip Name	# of channels	Digital output	Power supply	Area [sqr mm]	Dynamic range	Input resistance	Timing jitter	Year
FLC_SiPM	18	n	5V (0,2W)	10			-	2004
MAROC2	64	y	5 V	16	80 pC	50 Ω		2006
SPIROC	36	y	5 V	32				2007
NINO	8	n	(0,24W)	8	2000 pe	20 Ω	260 ps	2004
PETA	40	y	(1,2W)	25	8 bit		50 ps	2008
BASIC	32	y	3,3 V	7	70 pC	17 Ω	~120 ps	2009
SPIDER (VATA64-HDR16)	64	n		15	12 pC			2009
RAPSODI	2	y	3,3 V (0,2W)	9	100 pC	20 Ω	-	2008

Review of ASIC developments for SiPM signal readout (Wojtek Kucewicz)

The FLC-SiPM chip (one channel scheme)



The SPIROC chip

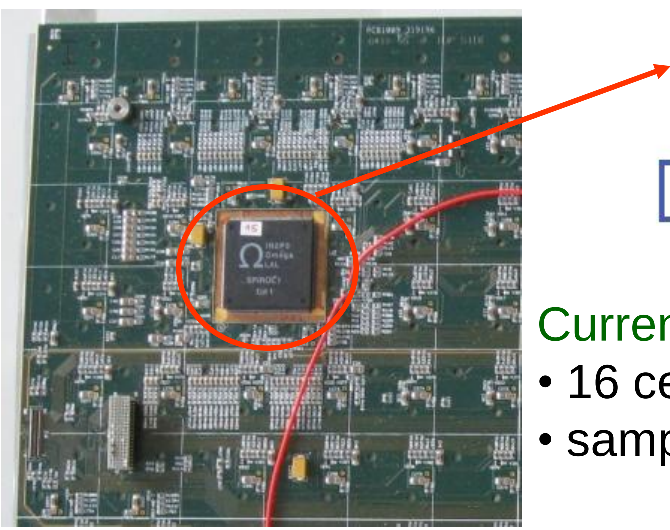


Specific chip for SiPM:

- input DAC for bias adjustment

Designed to work at ILC:

- power pulsing mode
- 25 μW /ch
- internal ADC
- auto-trigger mode
- time stamp (~1ns)

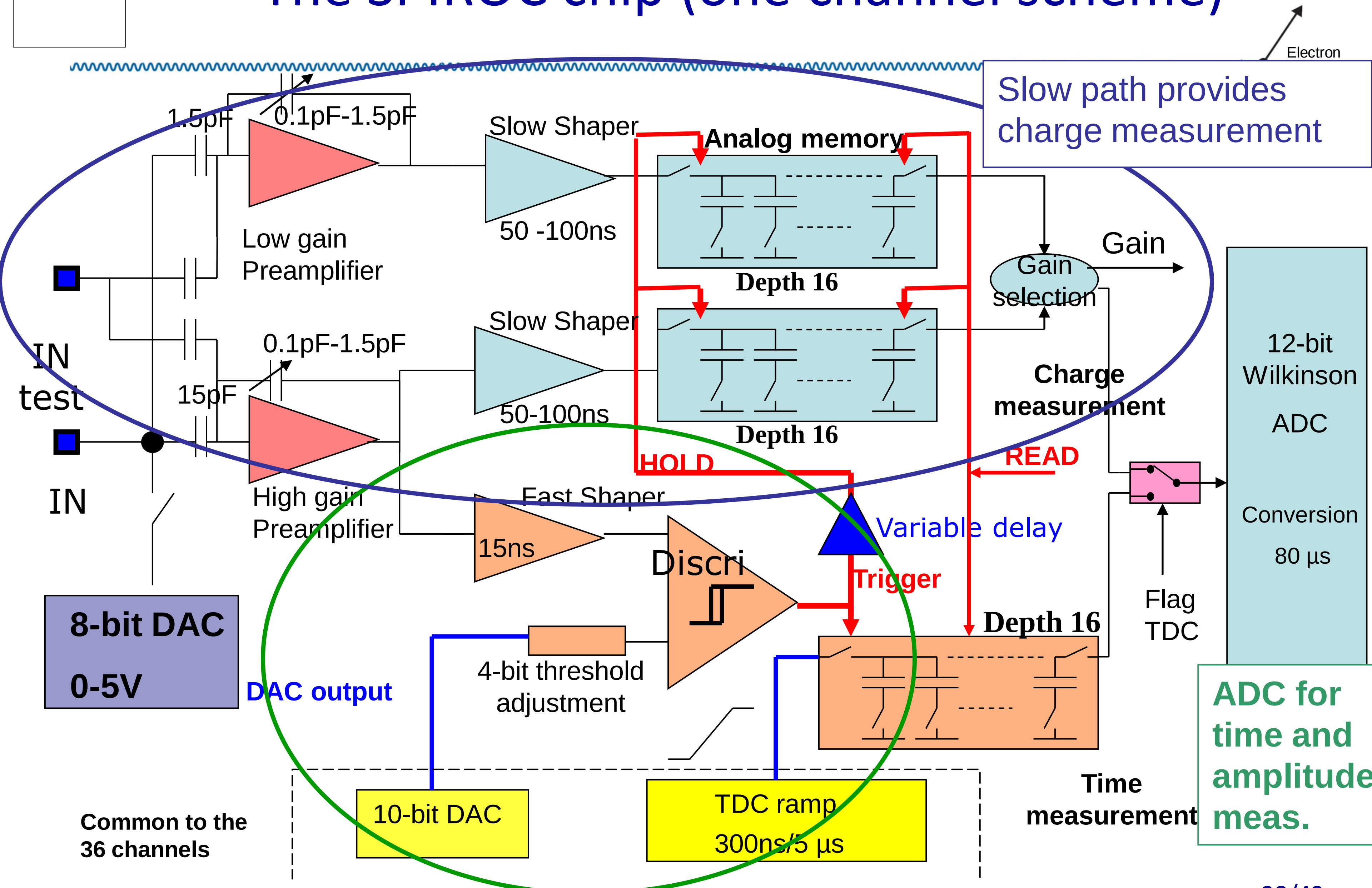


designed by Omega group LAL (Orsay)

Current challenges in chip understanding:

- 16 cell analog buffer memory ➔ characterize properties
- sample and hold method ➔ determine spread

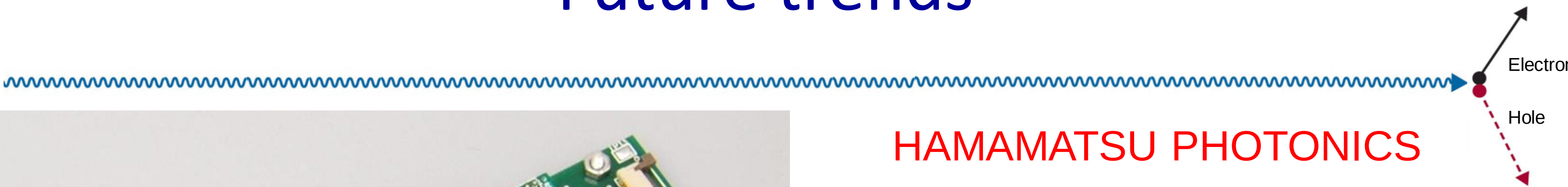
The SPIROC chip (one channel scheme)



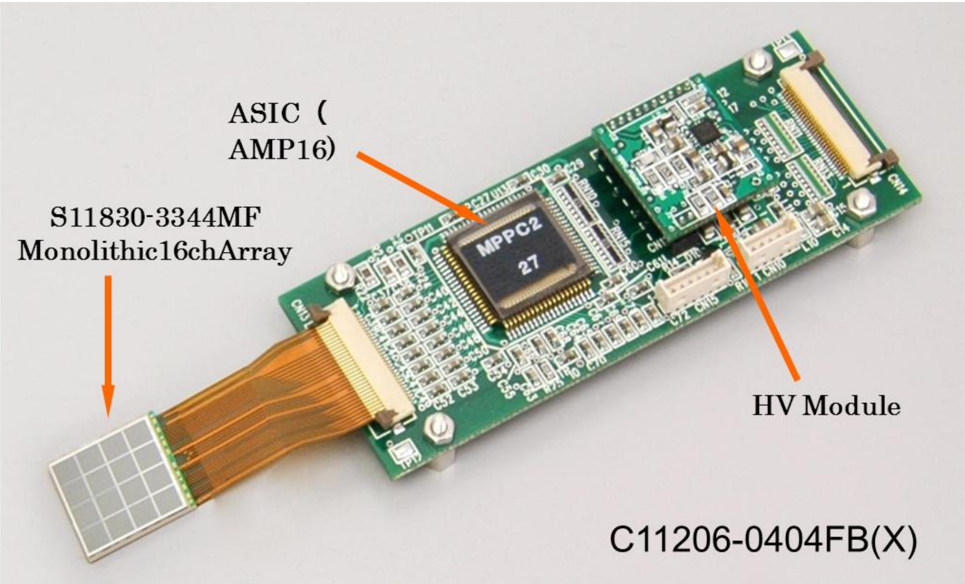
Fast path provides auto-trigger and time measurement

A look into the future

Future trends

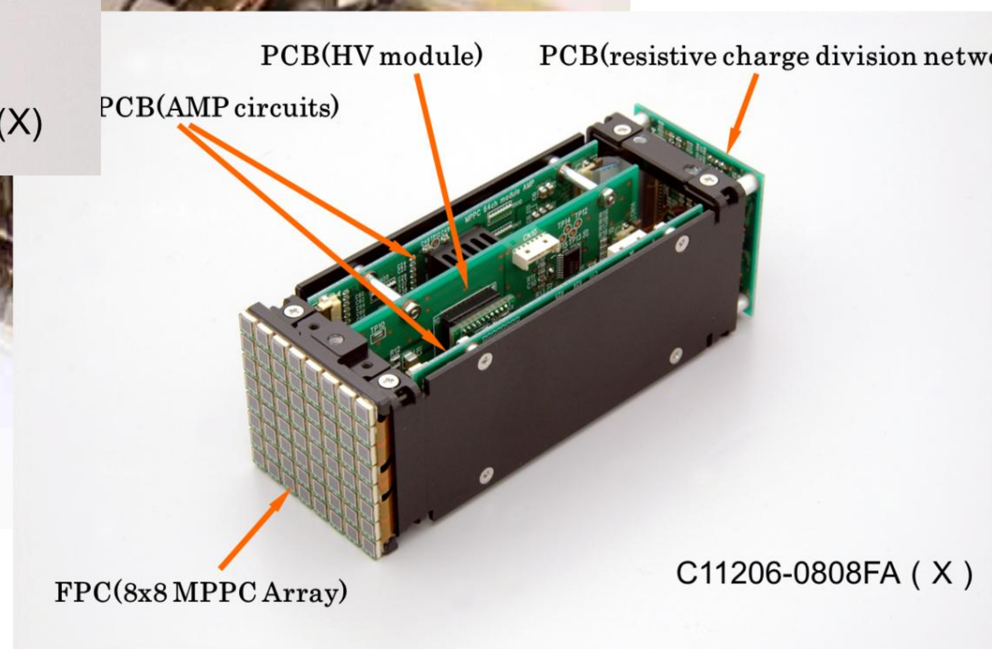


HAMAMATSU PHOTONICS



MPPC module 4x4

MPPC module 8x8 (prototype)



Including preamp and bias circuit for MPPC

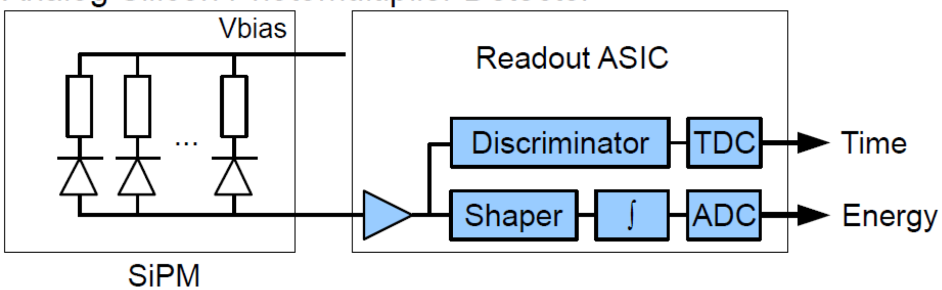
Replace vacuum phototube with silicon-based photo-detectors for "any size and need"

Future trends

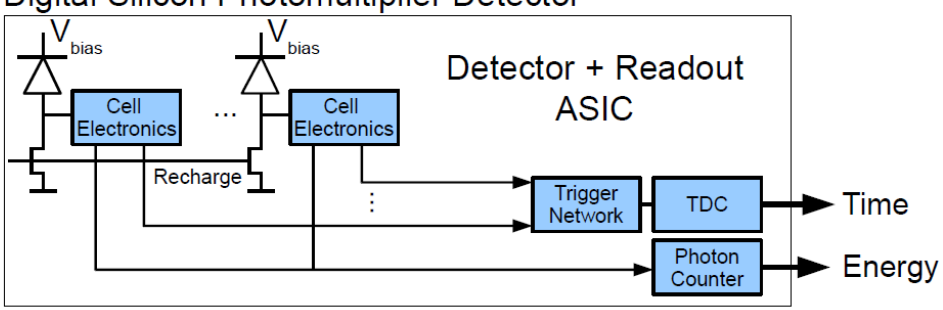
PHILIPS

Digital SiPM – The Concept

Analog Silicon Photomultiplier Detector



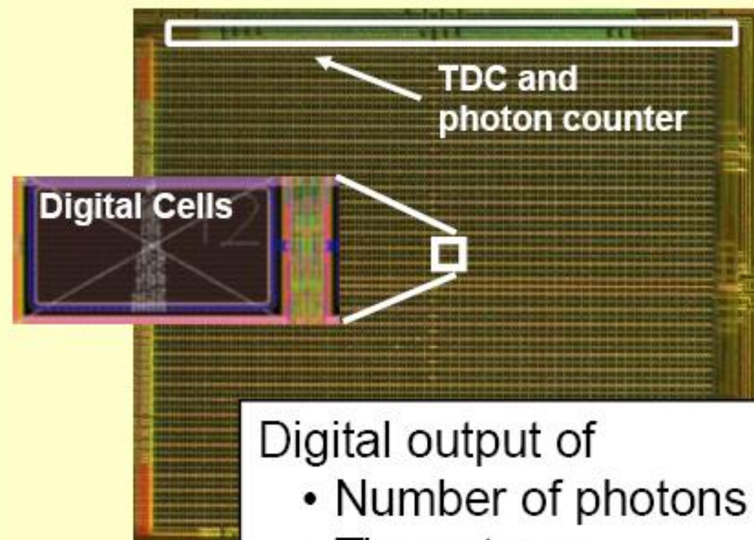
Digital Silicon Photomultiplier Detector



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

Industry-academia matching event on SiPM and related technologies:
http://indico.cern.ch/internalPage.py?pageId=0&confId=117424

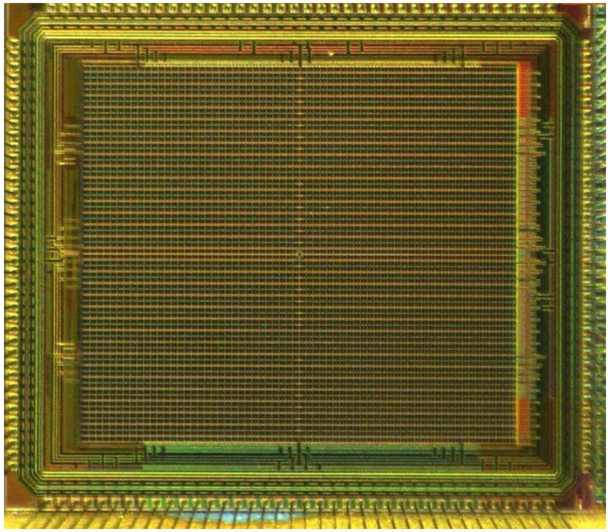
digital SiPM (dSiPM)



Digital output of
- Number of photons
- Time-stamp

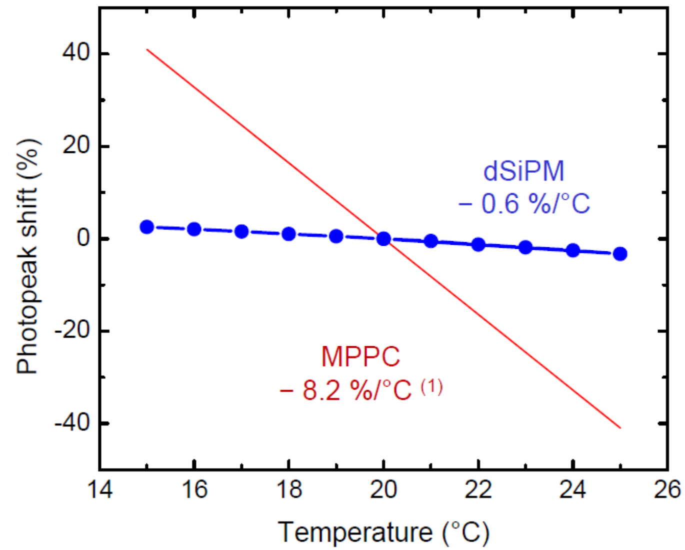
Integrated readout electronics is the key element to superior detector performance

Digital SiPM



PHILIPS

Temperature Dependence



Temperature dependent light output of LYSO:

− 0.2 %/°C [2]
− 0.45 %/°C [3]

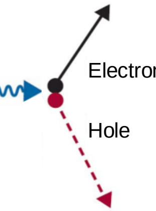
4 identical sub-pixels with 2047 microcells each
Microcell size 30μmx52μm, 50% fill factor including electronics

[1] K. Burr et al, Nuclear Science Symposium Conference Record, N18-2, 2007
[2] R. Mao et al, IEEE Transactions of Nuclear Science, vol. 55, 2008
[3] C. Kim, Nuclear Science Symposium Conference Record, M07-113, 2005

www.philips.com/digitalphotoncounting Philips Digital Photon Counting, October 27th, 2009

- 1 bit inhibit memory in each microcell to enable/disable faulty diodes
- Active quench & recharge, on-chip memory and array controllers
- Integrated time-to-digital converter with σ = 8ps time resolution
- Variable trigger (1-4 photons) and energy (1-64 photons) thresholds
- Acquisition controller implemented in FPGA for flexibility and testing

Concluding considerations



- SiPM is an innovative technology for photo-detection
- which opens revolutionary possibilities in detector development

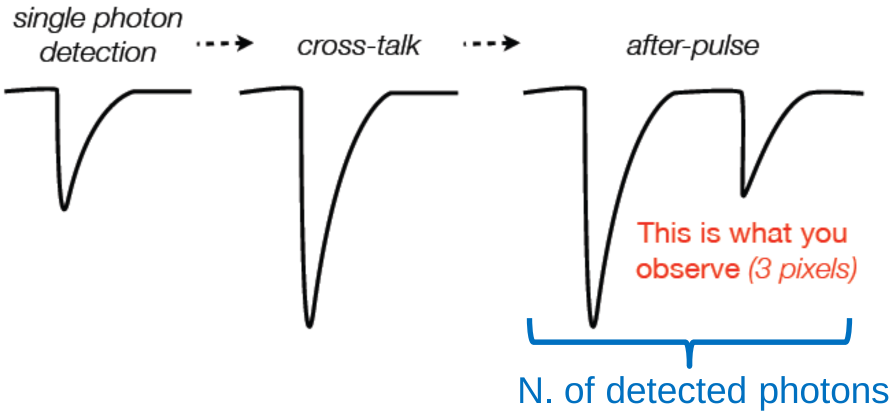
- HEP has been the driving field for SiPM developments
- Crucial for the operation of a multi-channel detector with SiPM
  - as small as possible spread of SiPM parameters OR precise characterization measurements of single photo-sensor
  - adequate readout chip
  - adequate monitoring system

- SiPMs may become the replacement of PMTs
- SiPM with digital readout is a further step in system simplifications

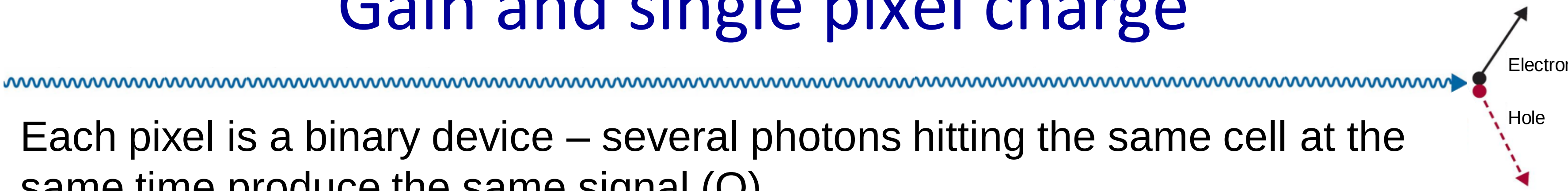
  ➔ electronics, integration, low cost

BACKUP

If this effect is not properly considered result in too large values of PDE (values larger than one are possible)

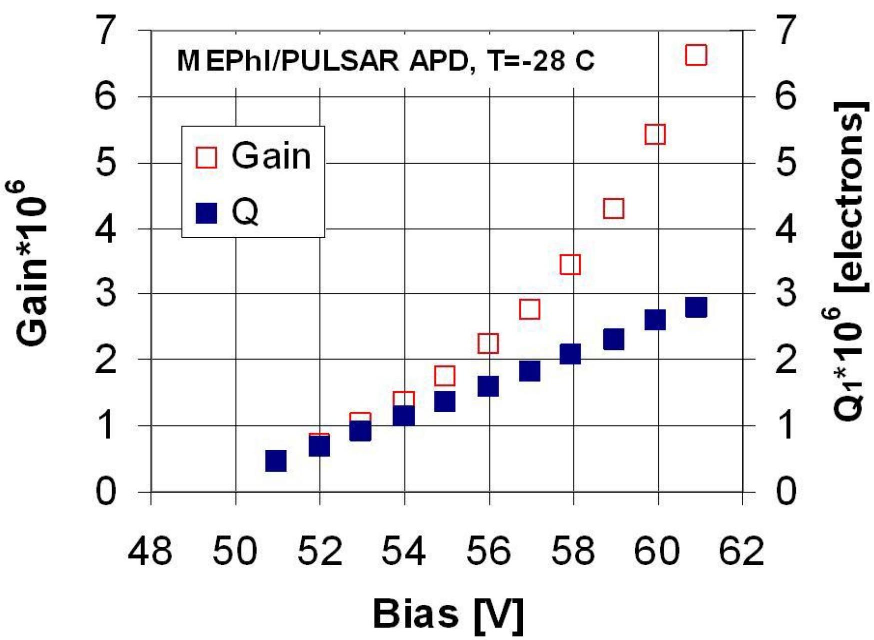


Gain and single pixel charge



Each pixel is a binary device – several photons hitting the same cell at the same time produce the same signal (Q)

$$Q = C_{pix}(U_{bias} - U_{bd})$$



(Y. Musienko, NDIP-05, Beaune)

For linear device a measured charge:

$$Q = N_{pe}\, G\, q_e$$

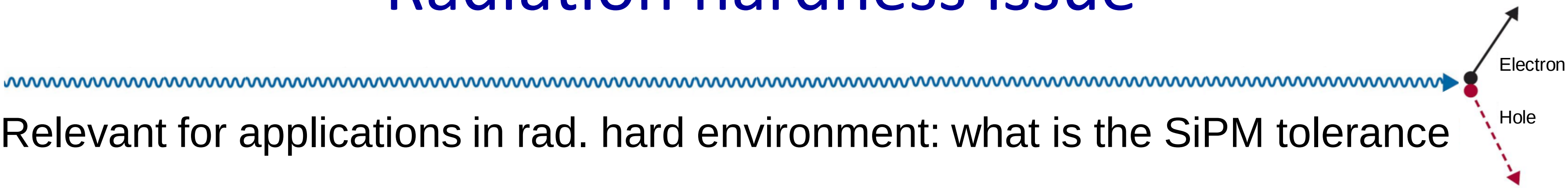
For SiPM this holds only at small ΔU as more than 1 pixel is fired by 1 primary photoelectron

$$G = n_p \frac{Q}{q_e}$$

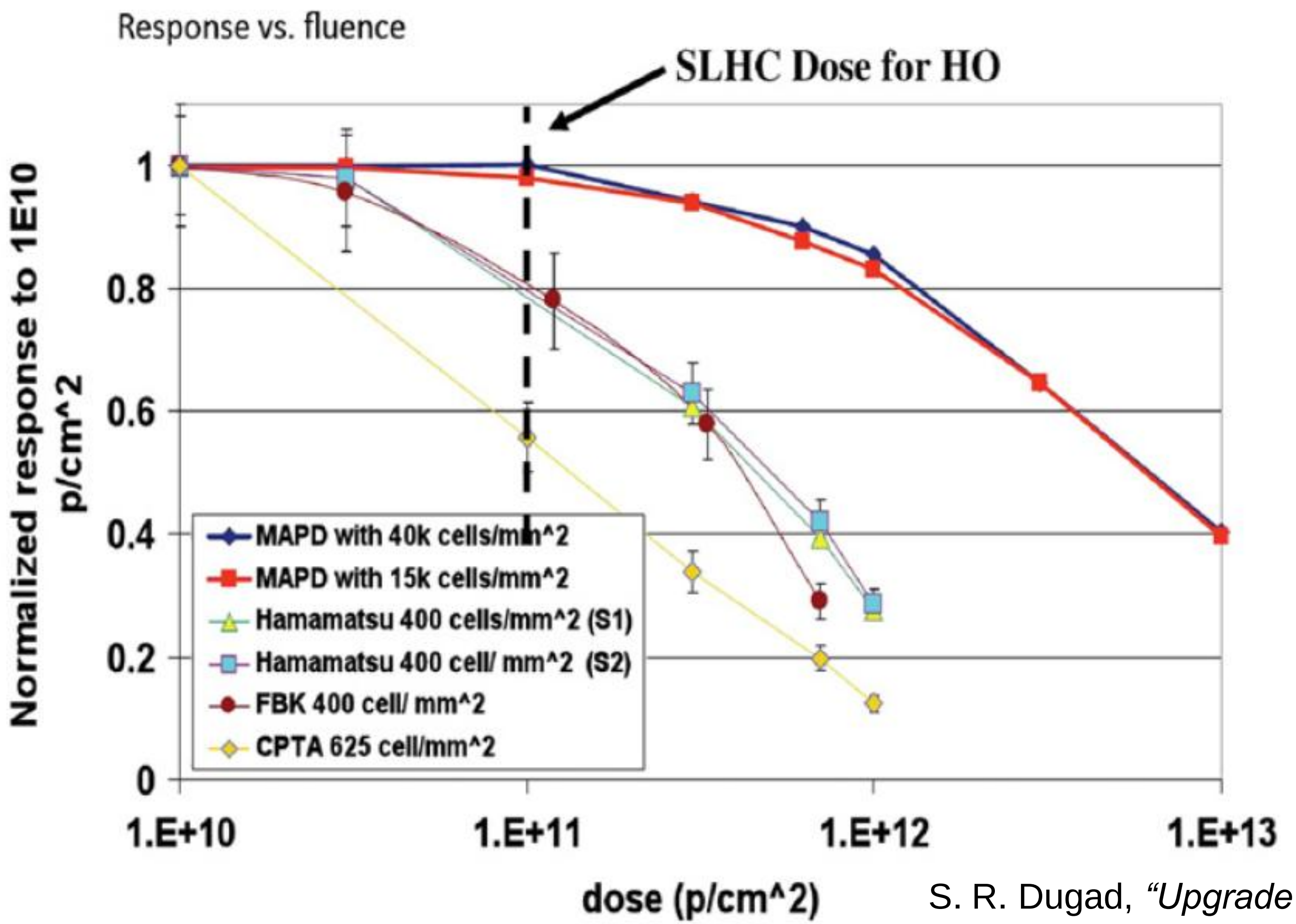
where n_p is average number of pixels fired by one primary photoelectron (>1) due to:

- optical cross-talk between pixels
- after-pulsing

Radiation hardness issue

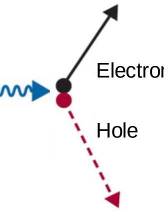


Relevant for applications in rad. hard environment: what is the SiPM tolerance

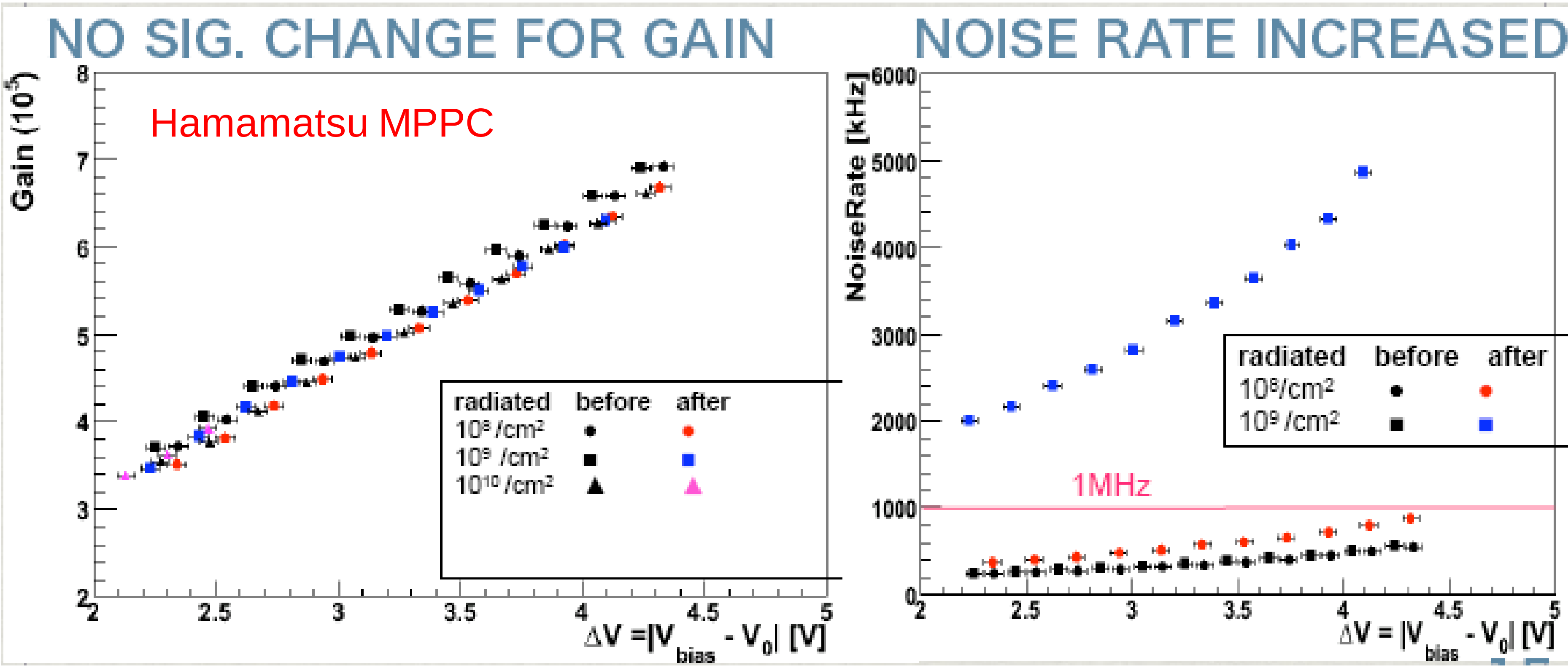


S. R. Dugad, *"Upgrade plans for hadron calorimeter in the CMS detector", Nucl. Inst. Meth. A (2010),* doi:10.1016/j.nima.2010.02.216

SiPM radiation hardness



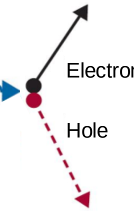
Neutron irradiation by reactor (E_n 0.8-1.2 MeV)



Only thermal noise increase after 10^9 n/cm², no other significant effects on Gain and response function

Gamma irradiation with ^{60}Co ➔ noise below MHz till 60Gy

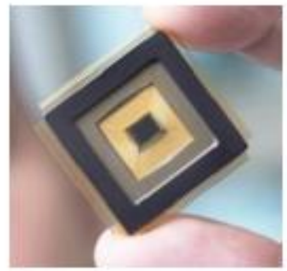
Future trends



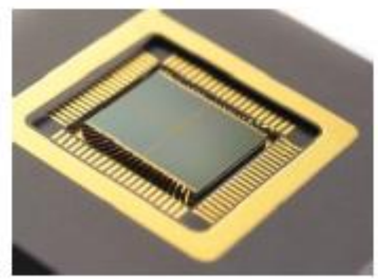
PHILIPS

How to replace old-fashioned PMT's?

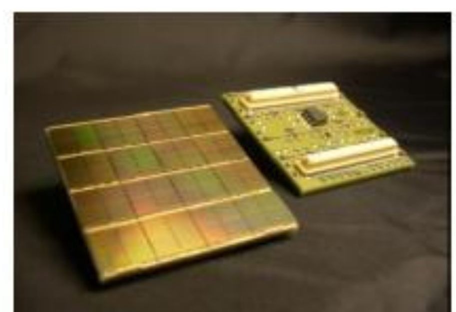
- Make the SiPM digital
  - 1 pixel



- Increase integration
  - 2 x 2 pixel on one chip (die)



- Assemble arrays
  - 8 x 8 pixels on one PCB (tile)



Industry-academia matching event on SiPM and related technologies:
http://indico.cern.ch/internalPage.py?pageId=0&confId=117424