Détecteurs SiPM

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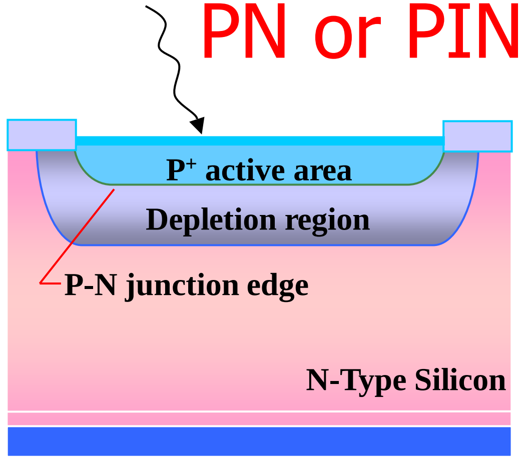
Outline:

- Introduction on solid-state photon detectors
- SiPM physics and characteristics
- SiPM applications

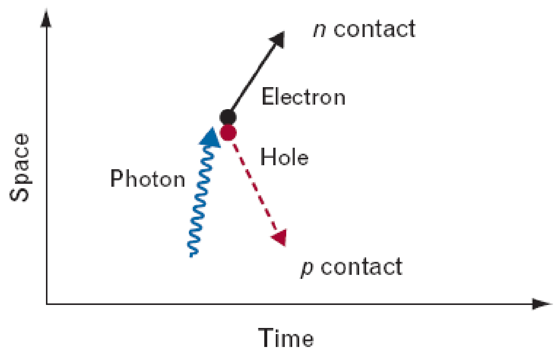
Review of solid-state photon detectors

Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013

PN or PIN

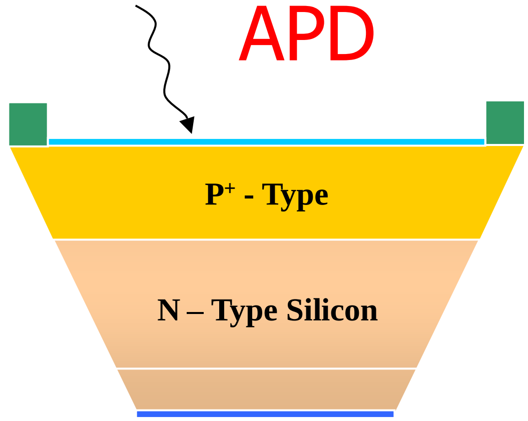


p-n junction,
reversed V_{bias} – 0-3 V

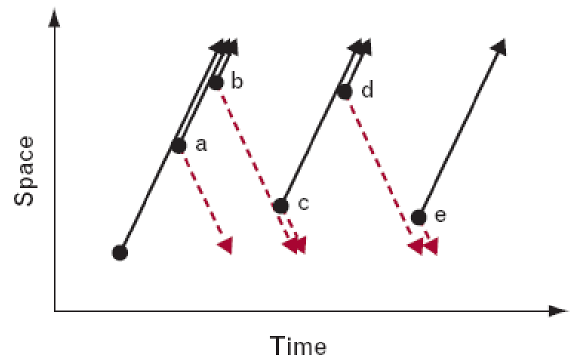


Gain = 1

APD



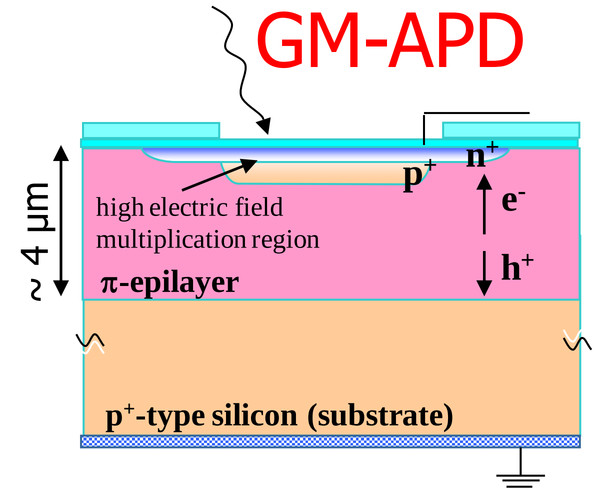
p-n junction,
reversed $V_{bias} < V_{BD}$



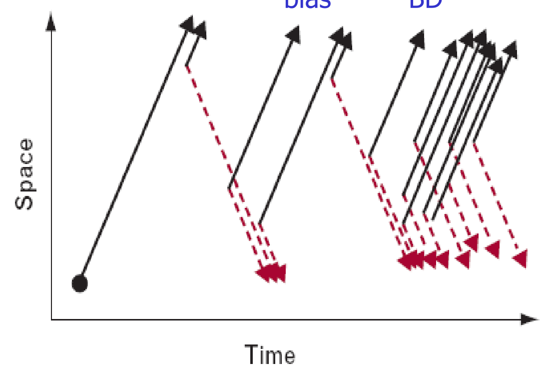
Gain = M (~ 50-500)

- linear mode operation-

GM-APD



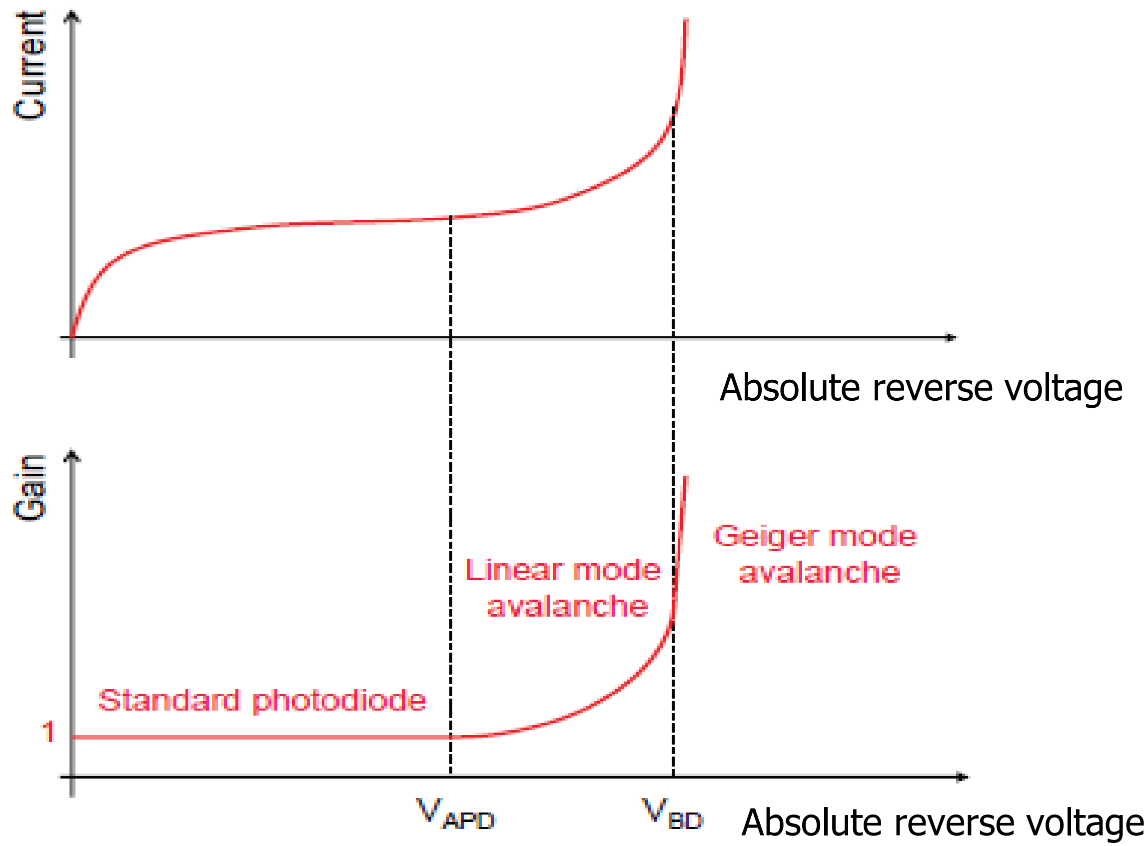
p-n junction,
reversed $V_{bias} > V_{BD}$



Gain → infinite

-Geiger-mode operation-

Working regimes of reversed biased diodes



Photodiode

- $0 < V_{bias} < V_{APD}$ (few volts)
- G = 1
- Operate at high light level (few hundreds of photons)

APD

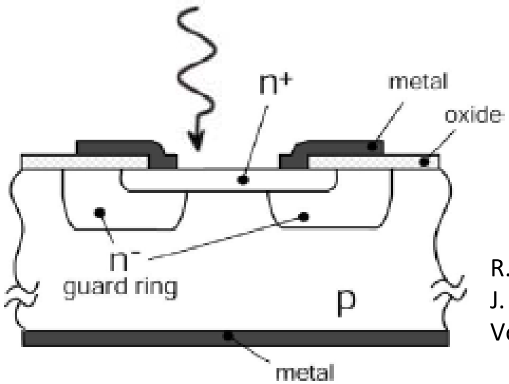
- $V_{APD} < V_{bias} < V_{BD}$
- G = M (50 - 500)
- Linear-mode operation

GM-APD or SPAD

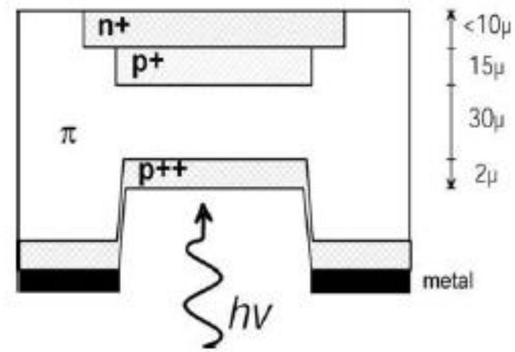
- $V_{bias} > V_{BD}$ (V_{bias}-V_{BD} ~ few volts)
- G ⇨ ∞
- Geiger-mode operation
- Can operate at single photon level

Geiger-Mode Avalanche Photodiode

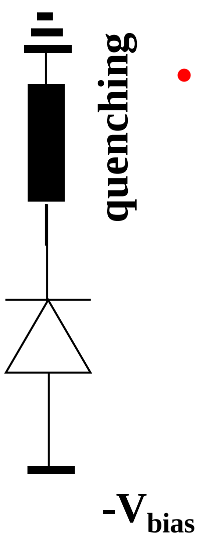
The first single photon detectors operated in Geiger-mode



R.H. Haitz
J. Appl. Phys.,
Vol. 36, No. 10 (1965) 3123



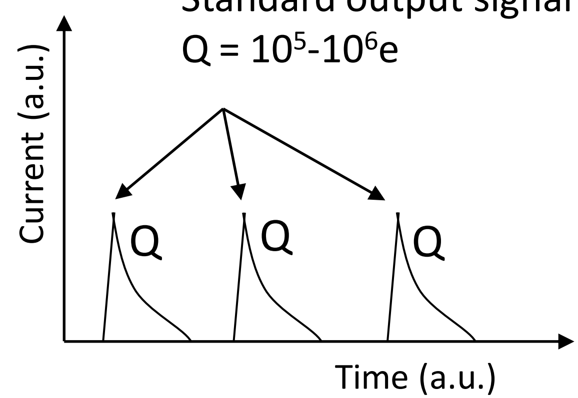
J.R. McIntire
IEEE Trans. Elec. Dev.
ED-13 (1966) 164



- Quenching mechanisms
  - Passive quenching: large resistance
  - Active quenching: analog circuits

S. Cova & al., App. Opt. 35 (1996) 1956-1976

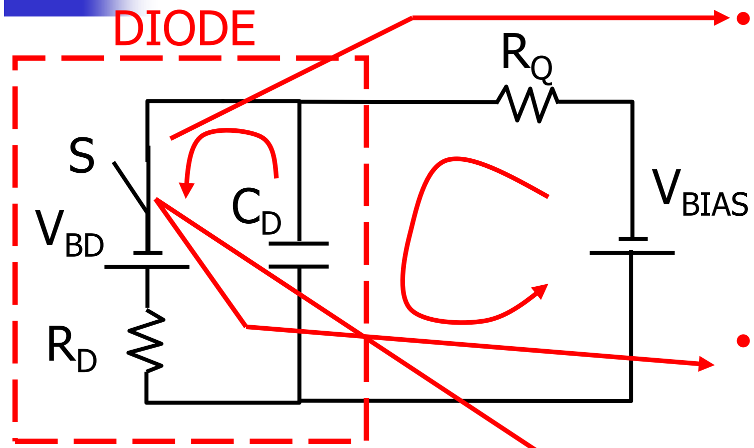
Standard output signal
$Q = 10^5\text{-}10^6 e$

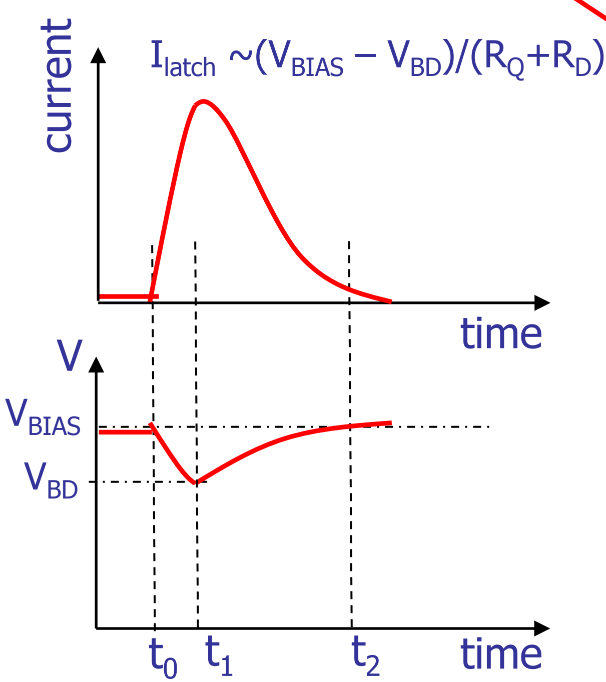


Binary device

- If one or more simultaneous photons fire the GM-APD, the output is anytime a standard signal: $Q \sim C(V_{bias} - V_{BD})$
- GM-APD does not give information on the light intensity

Model of GM – APD & passive quenching



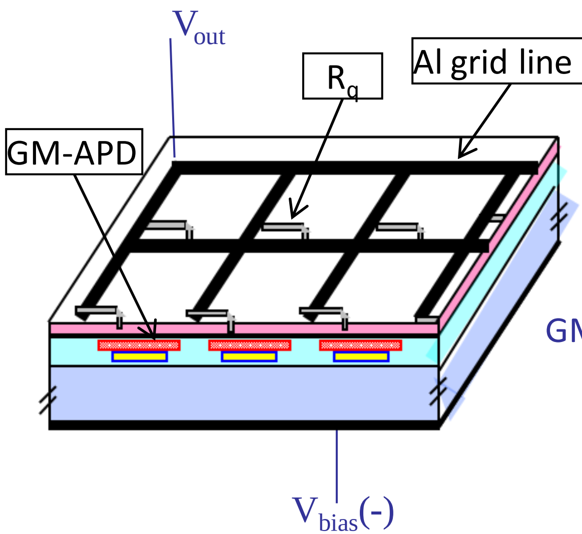


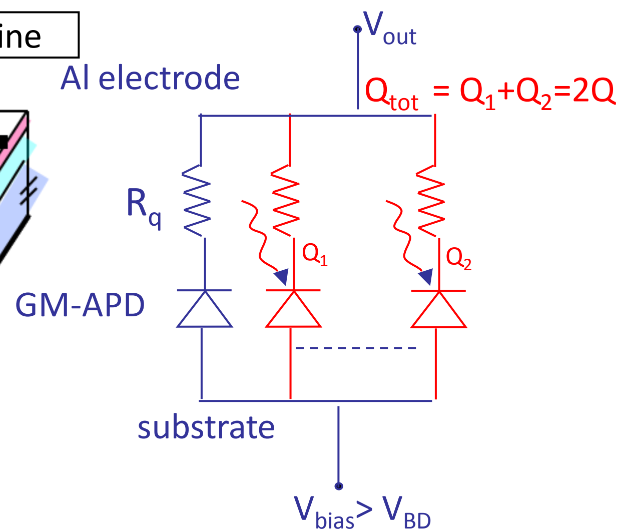
- OFF condition
  - No charge traversing the breakdown region
  - S – open
  - C_D – charged to $V_{BIAS} > V_{BD}$
  - i ~ 0 through the circuit
- ON condition
  - Avalanche discharge triggered by a carrier generated in the breakdown region (e.g. photon or thermal carrier)
  - S – closed
  - C_D discharge to V_{BD} with a time constant $\tau_{discharge} = \mathbf{R_D * C_D}$
  - Current through circuit increases asymptotically to $I_{latch} \sim (V_{BIAS} - V_{BD})/(R_Q + R_D)$
  - Diode voltage decreases from V_{BIAS} to V_{BD}
- OFF condition
  - S – open
  - C_D – recharge again to V_{BIAS} with a time constant $\mathbf{R_Q * C_D}$ (much longer than $R_D * C_D$)
- ready for a new detection

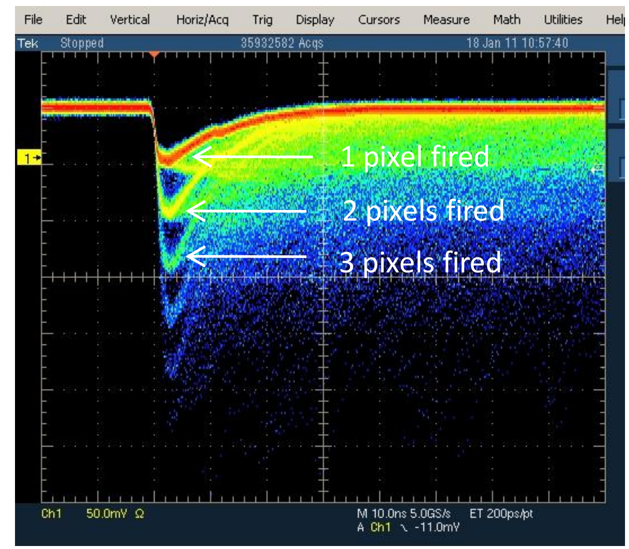
Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013

What is a Silicon Photomultiplier (SiPM)?

- matrix of n cells connected in parallel (e.g. few hundreds /mm^2) on a common Si substrate
- each cell = GM-APD in series with R_{quench}







Key personalities in this development:
V. Golovin, Z. Sadygov

Quasi-analog device:

- If simultaneously photons fires different cells, the output is the sum of the standard signals: $Q \sim \Sigma Q_i$
- SiPM gives information on light intensity

•Different producers give different names: SiPM, MRS-APD, SPM, MPPC…

Silicon Photomultiplier (SiPM)

Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013

Advantages

☺ high gain (10^5-10^6) with low voltage (<80V)

☺ low power consumption (<75μW/mm^2)

☺ fast (timing resolution ~ 50 ps RMS for single photons)

☺ insensitive to magnetic field (tested up to 7 T)

☺ high photon detection efficiency (30-40% blue-green)

☺ mechanically robust and compact

Possible drawbacks

☹ high dark count rate (DCR)

- early productions: ~100kHz – 1MHz/mm^2 at T~25°C; th=0.5pe
- today productions: ~20kHz at T~25°C; th=0.5pe
- thermal carriers, cross-talk, after-pulses

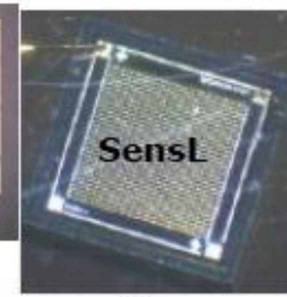
☹ temperature dependence

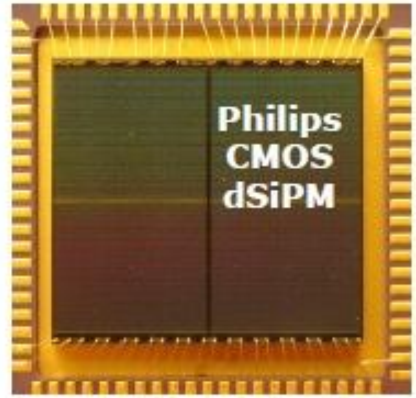
- V_{BD}, signal shape, R_q, DCR , PDE

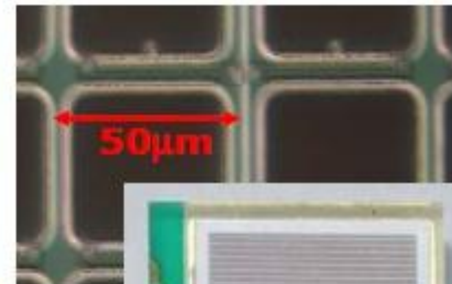
Today

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

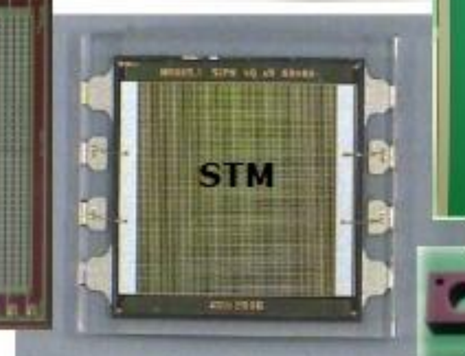
- **CPTA**, Moscow, Russia
- **MePhi/Pulsar** Enterprise, Moscow, Russia
- **Zecotek,** Vancouver, Canada
- **Hamamatsu HPK**, Hamamatsu, Japan
- **FBK-AdvanSiD**, Trento, Italy
- **ST Microelectronics**, Catania, Italy
- **Amplification Technologies** Orlando, USA
- **SensL**, Cork, Ireland
- **MPI-HLL**, 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**







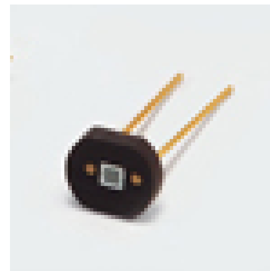
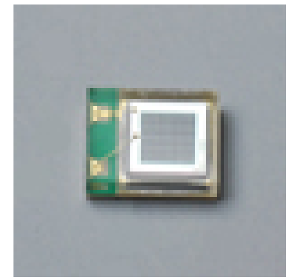
Amplification Technologies (DAPD)



Zecotek

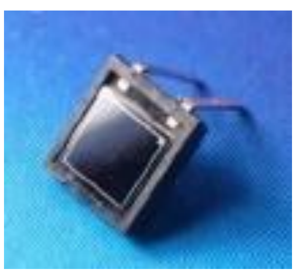
SiPM today (just few examples)

SiPM's of small area

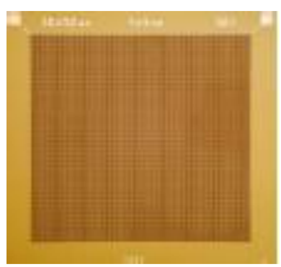




Hamamatsu HPK
S10362-11-025,050,100
1 X 1 mm^2

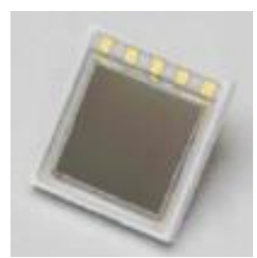
SiPM's of large area



ZEKOTEK
MAPD-3N
3 X 3 mm^2

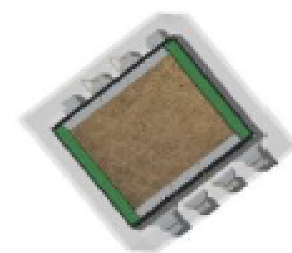


FBK - AdvanSiD
ASD-SiPM4s
4 X 4 mm^2



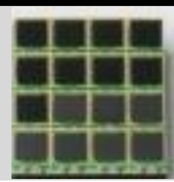
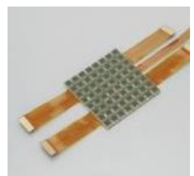
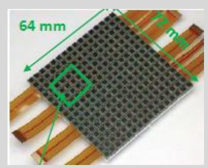
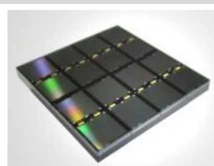
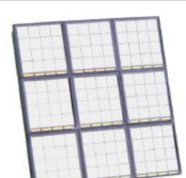
Hamamatsu HPK
S10985-50C
4 X 4 mm^2

KETEK
PM3350
3 X 3 mm^2

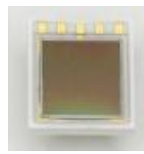
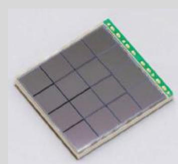
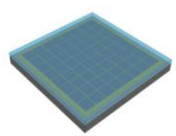
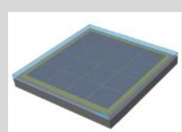


STMicroelectronics
SPM35AN
3,5 X 3,5 mm^2

Discrete SiPM arrays

Producer	Device ID	Picture	Total area (mm²)	SiPM area (mm²/channel)	Nr. channels	µcell size
Hamamatsu	S11064-025P S11064-050P		18 x 16.2	3x3	16(4x4) ch	25x25 µm 50x50 µm
Hamamatsu	C11206-0404DF			3x3	64(8x8) ch	
Hamamatsu	S11834-3388DF		72x64.8	3x3	256(16x16)ch	
FBK AdvanSiD	ASD-SiPM4s-P-4x4T-50 ASD-SiPM4s-P-4x4T-69		8.2 x 8.2	4x4	16(4x4) ch	50x50 µm 69x69 µm
FBK AdvanSiD	SiPM tile		32.7x32.7	4x4	64(8x8) ch	
SensL	ArraySM-4P9 ArraySB-4P9 (blue sensitive)		46.3 x 47.8	3x3	144(12x12) ch (based on monolithic Array SM4)	35x35 µm

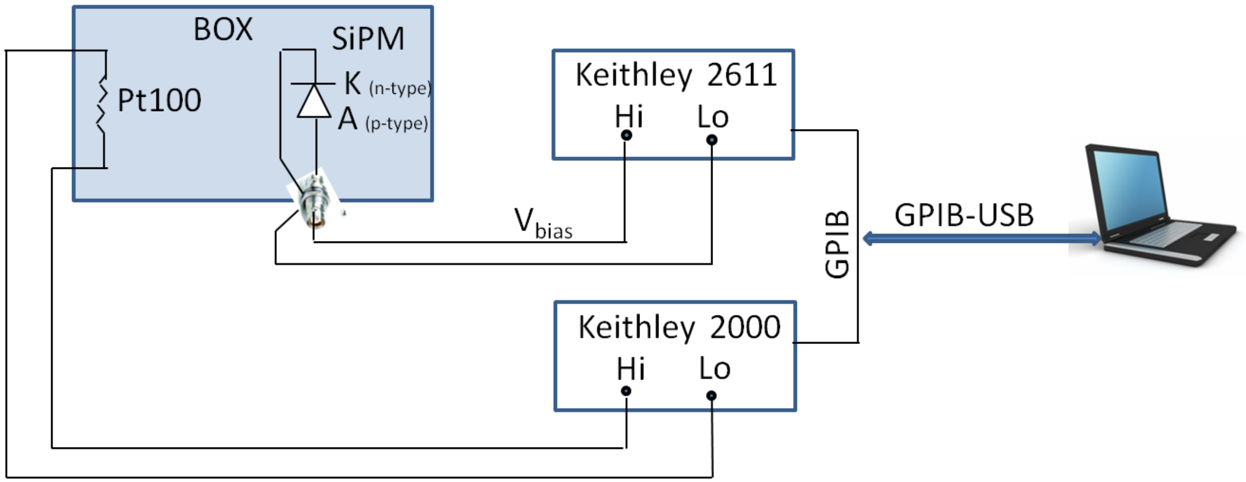
Monolithic SiPM arrays

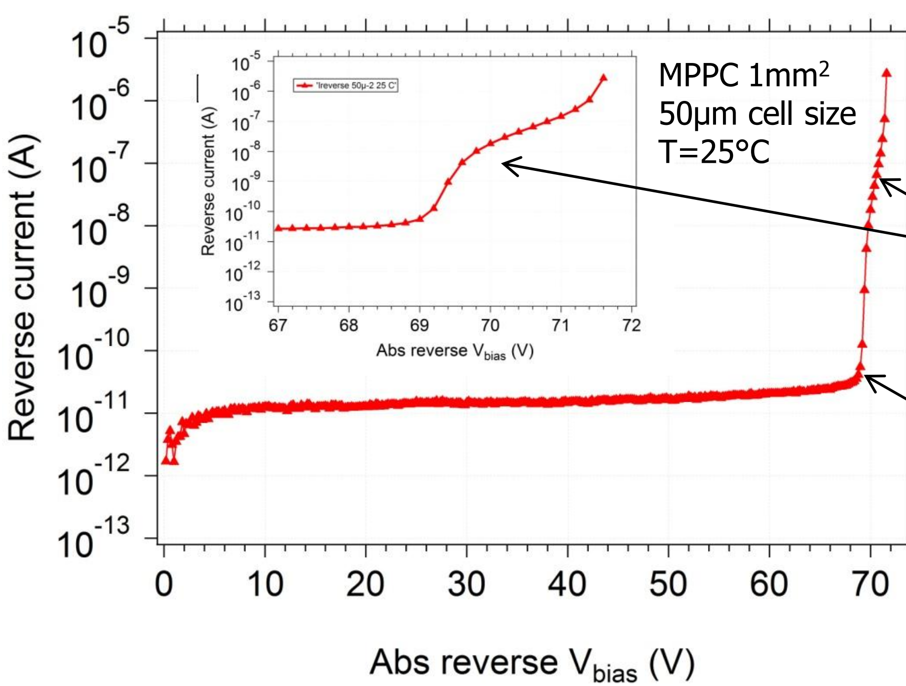
Producer	Device ID	Picture	Effective area (mm^2)	SiPM area/channel (mm^2)	Nr. channels	µcell size
Hamamatsu	S10984-025P S10984-050P S10984-100P		1 x 4	1x1	4(1x4) ch	25x25 µm 50x50 µm 100 x 100 µm
Hamamatsu	S10985-025C S10985-050C S10985-100C		6 x 6	3x3	4(2x2) ch	25x25 µm 50x50 µm 100 x 100 µm
Hamamatsu	S11828-3344M		12 x 12	3x3	16(4x4) ch	50x50 µm
FBK AdvanSiD	ASD-SiPM1.5s-P-8X8A		11.6 x 11.6	1.45x1.45	64(8x8) ch	50x50 µm
FBK AdvanSiD	ASD-SiPM3S-P-4X4A		11.8 x 11.8	2.95x2.95	16(4x4) ch	50x50 µm
SensL	Array SM-4 Array SB-4 (blue sensitive)		12 x 12	3x3	16(4x4) ch	35x35 µm

SiPM characteristics @ room temperature - dark conditions -

SiPM DC characteristics

First test to verify the functionality of the device: breakdown voltage & overvoltage range





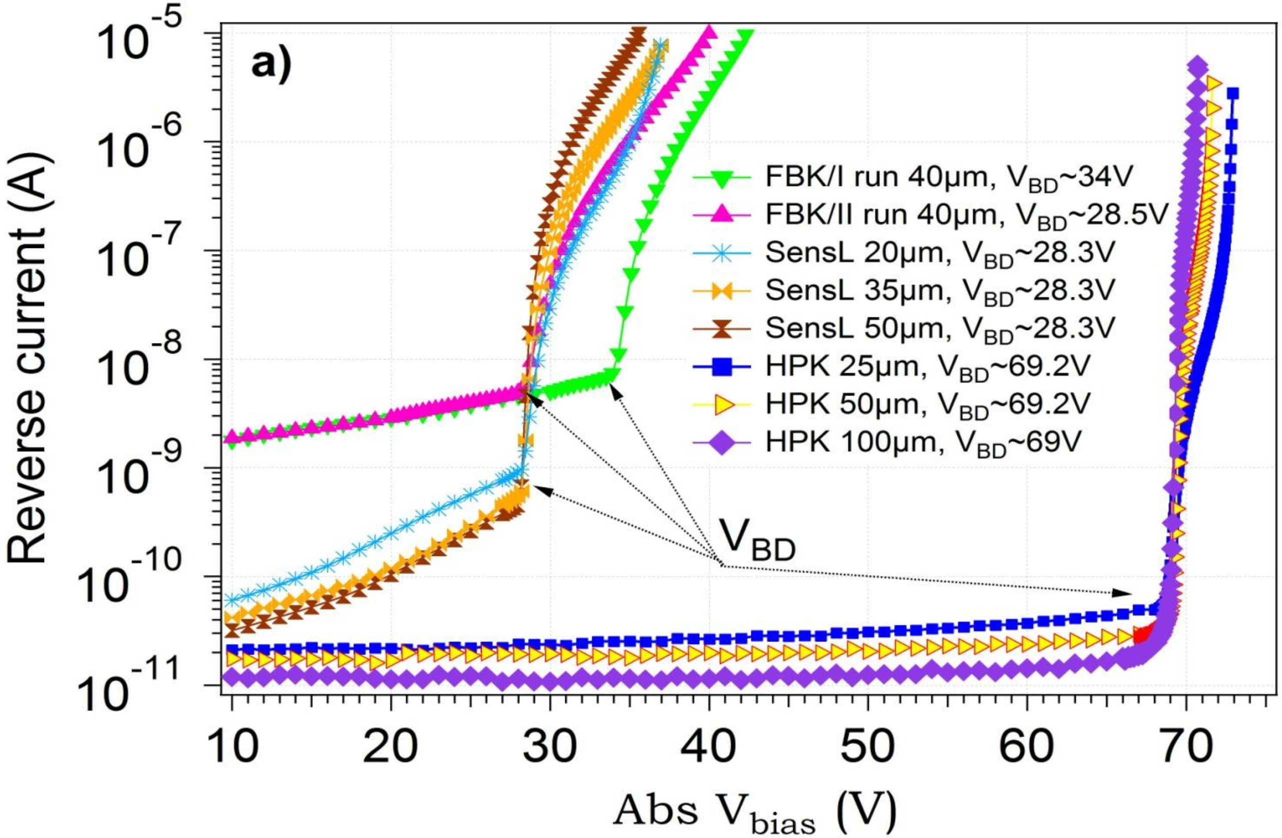
Working range defined by overvoltage: $\Delta V = V_{bias} - V_{bd}$

V_{bd}

SiPM reverse IV characteristics

Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013

SiPM's of 1x1 mm^2 with different technologies of 2007 productions

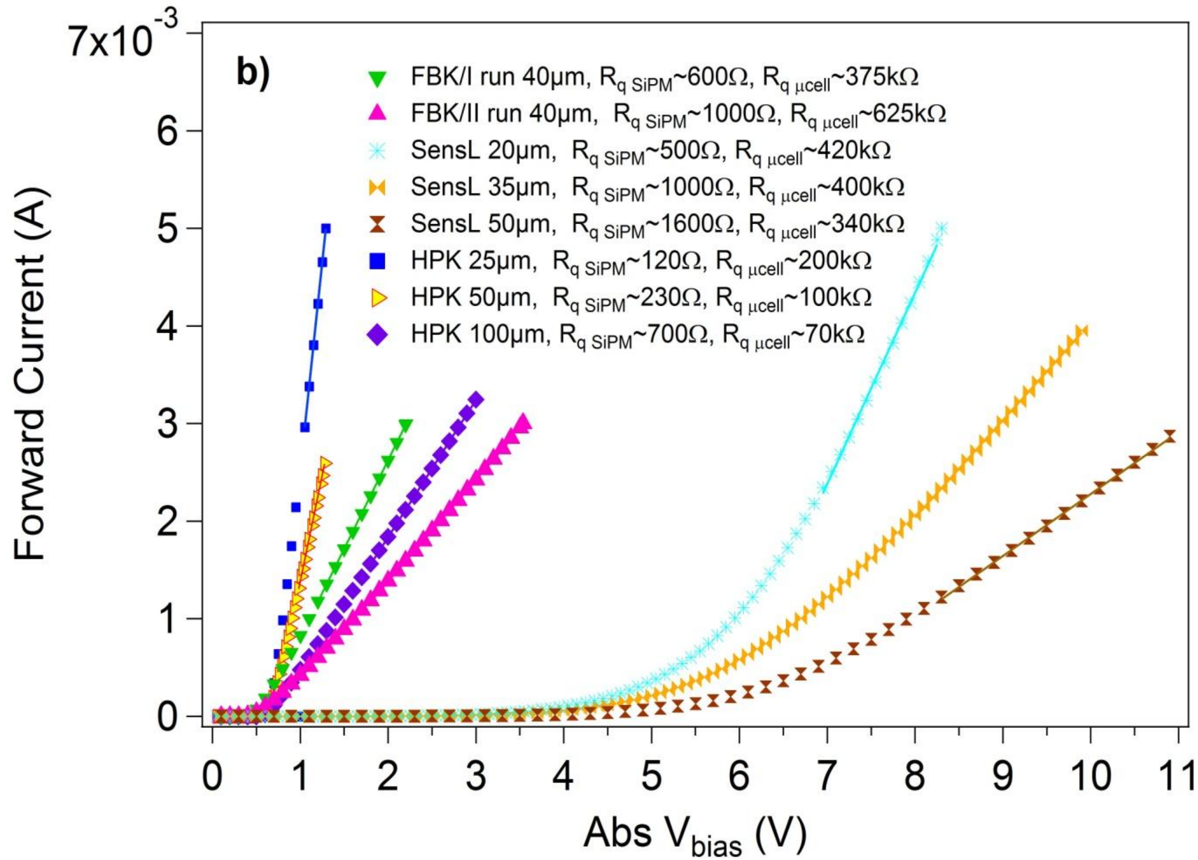


N.Dinu&al, NIMA 610, 2009

V_{bd} range: 15-70V, based on device technology

SiPM forward IV characteristics

SiPM's of 1x1 mm^2 with different technologies of 2007 productions

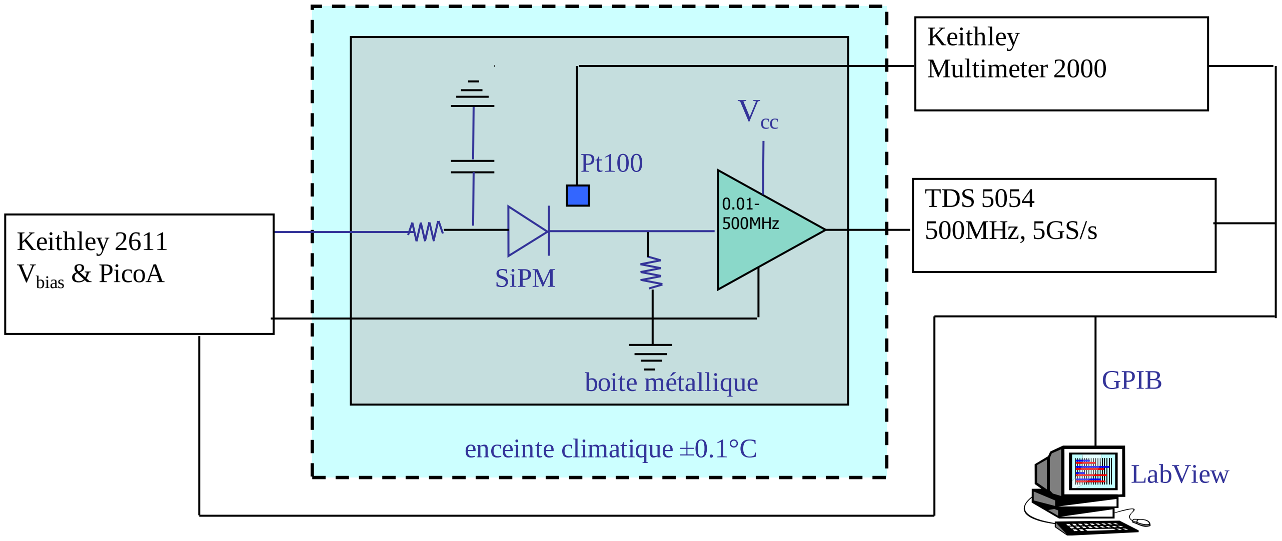


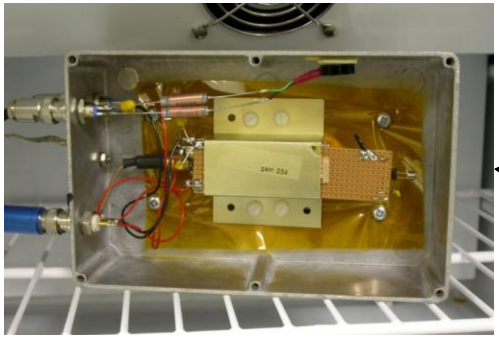
$R_{cell} = R_{measured}/N_{cells}$

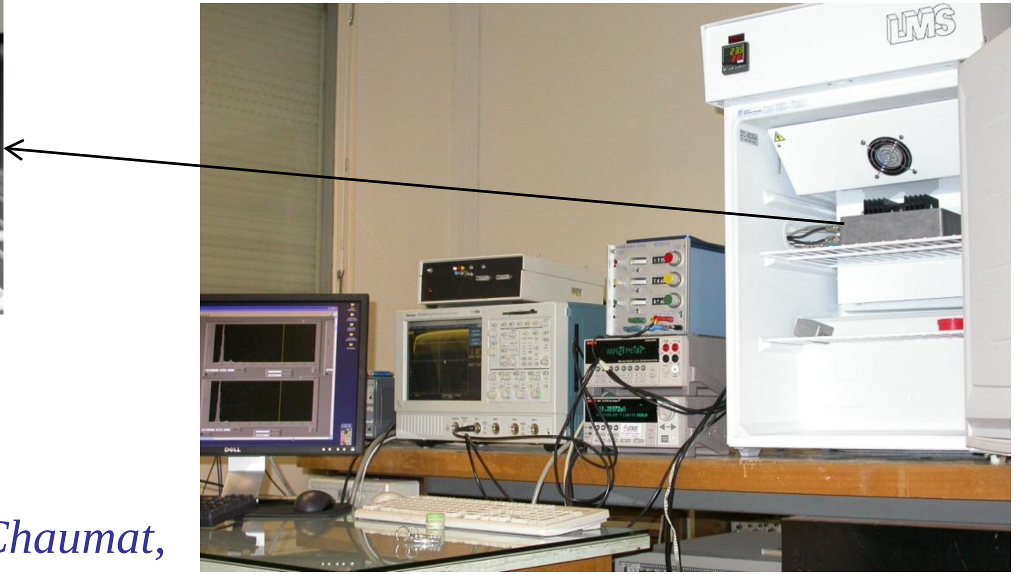
~ hundreds of kΩ: FBK, SensL, HPK

N.Dinu&al, NIMA 610, 2009

Dynamic measurements in the dark

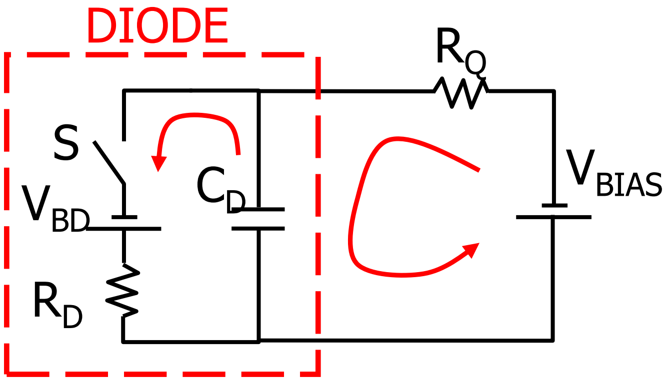


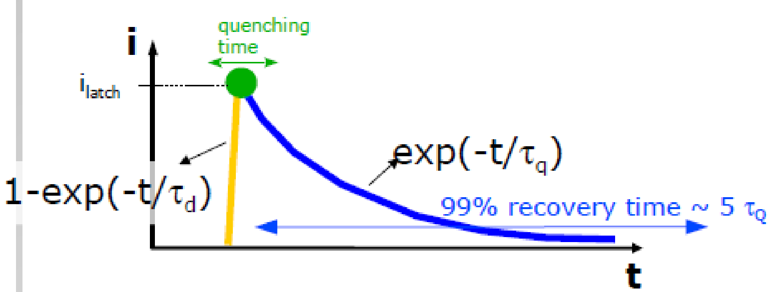




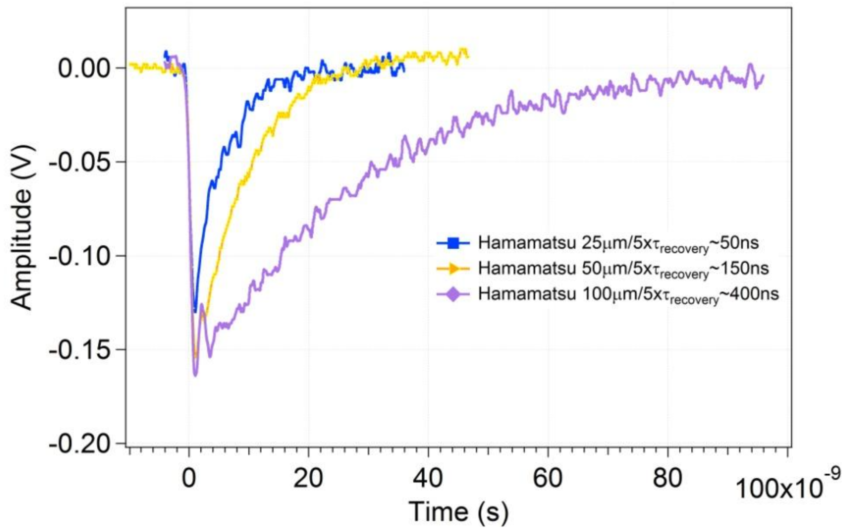
Thanks to all team: V. Puill, V. Chaumat, J.F. Vagnucci & C. Sylvia, C. Cheikali

SiPM's cell signal





Read-out by a voltage amplifier (500 MHz, 50 Ω, 45dB) on a scope (500 MHz)



N.Dinu&al, NIMA 610, 2009

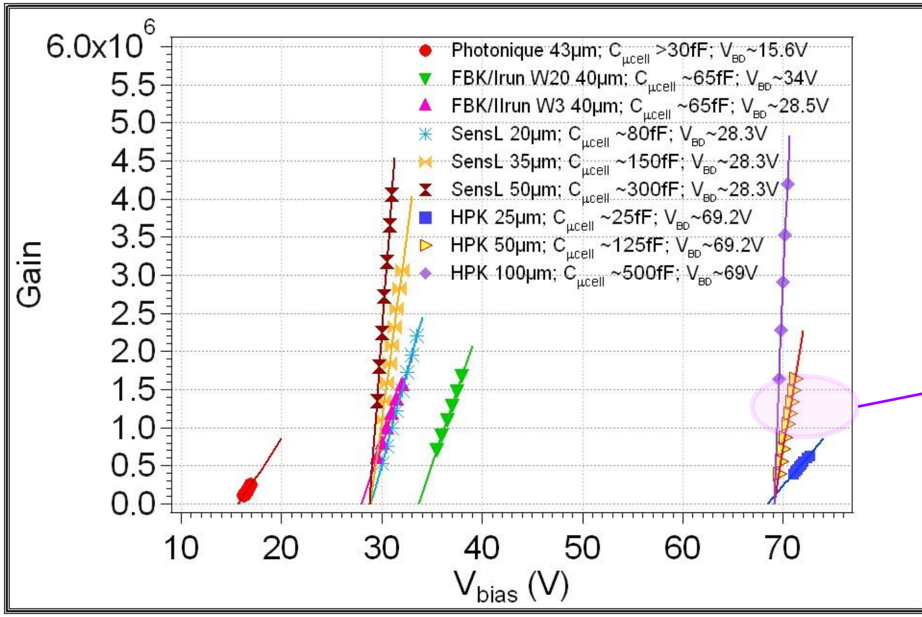
- Measured signals characteristics
  - rise time: $\tau_{rise} \cong R_D C_D$ ~ 1-3 ns (read-out chain should be taken into account)
  - recovery time $\tau_{recovery} \cong R_Q C_D$ (influence the dead time and dynamic range):
    - ~ tens of ns for FBK, HPK devices; up to 200ns for SensL devices

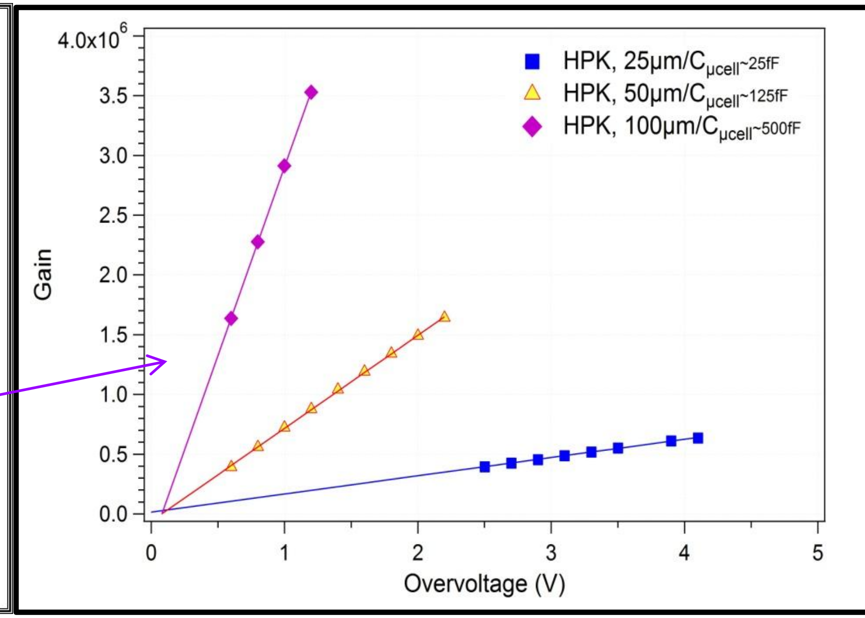
SiPM cell gain & capacitance

Defined as the charge developed in one cell by a primary charge carrier:

$$Gain = \frac{Q_{cell}}{e} = \frac{C_{cell} \times (V_{BIAS} - V_{BD})}{e} = \frac{C_{cell} \times \Delta V}{e}$$

N. Dinu & al, NIM A 610 (2009) 423–426

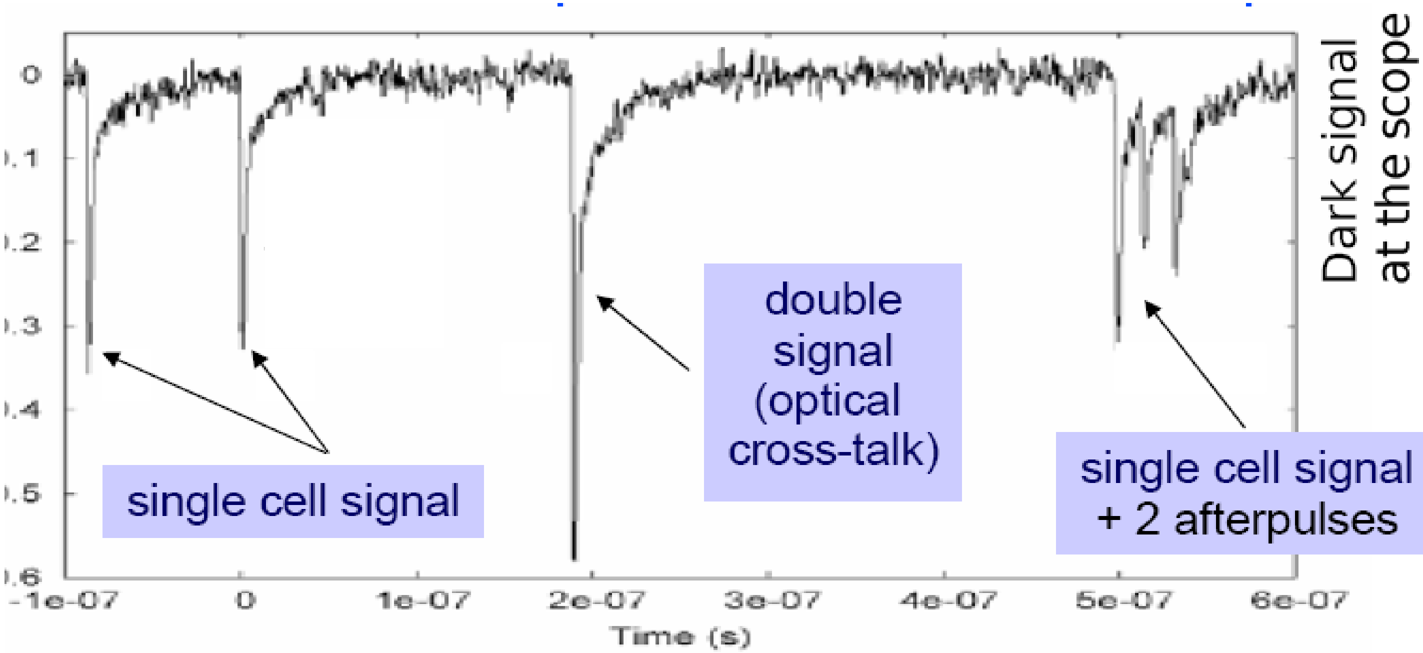




- G increases linearly with V_{bias} at a given V_{BD}
  - G: $5x10^5 – 5x10^6 \Rightarrow$ simple or no amplifier required
- The slope of the linear fit of G v.s. $\Delta V \Rightarrow$ cell diode capacitance
  - C_{pixel} : tens to hundreds of fF
- G and C_{pixel} increase with the cell geometrical dimensions
  - $C_{pixel} \sim \varepsilon_0 \varepsilon_r S/d$; S - cell junction surface; d - cell depletion thickness

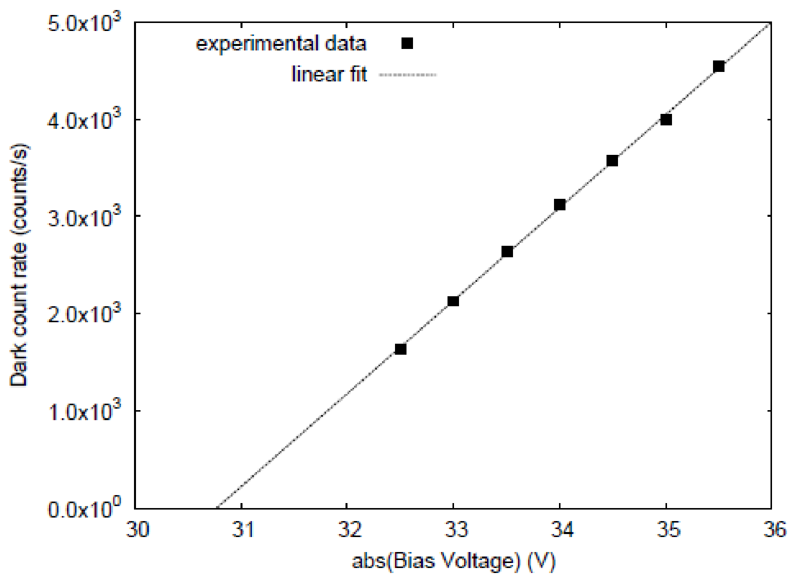
SiPM noise

- Dark count rate
  - the main source of noise limiting the SiPM performances (e.g. single photon detection)
  - the number of false photon counts/s registered by the SiPM in the absence of the light
  - three main contributions:
    - <u>thermal/tunneling</u> – charge carriers generation by thermal/ trap-assisted tunneling phenomena *– pulses looking the same as real photon pulses*
    - <u>afterpulses</u> – carriers trapped during the avalanche discharging and then released triggering a new avalanche
    - <u>optical cross-talk</u> – photo-generation during avalanche discharge (hot carrier luminescence phenomena)
      – these photons can trigger an avalanche in an adjacent µcell



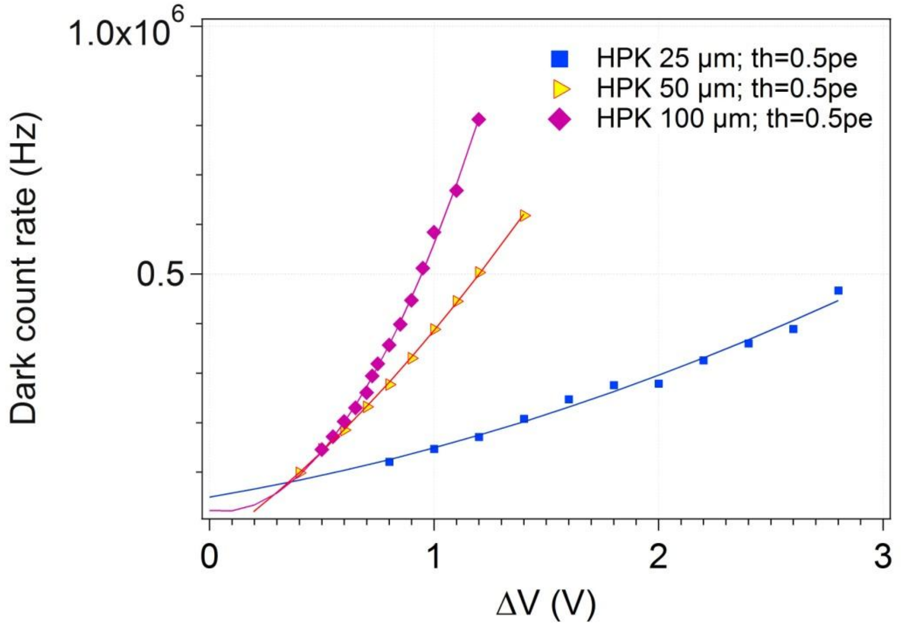
SiPM dark count rate

DCR of single cell of 40x40 μm² from FBK-irst



Piemonte & al., IEEE TNS, Vol. 54, Issue 1, 236-244

DCR of different SiPM's of 1x1 mm²



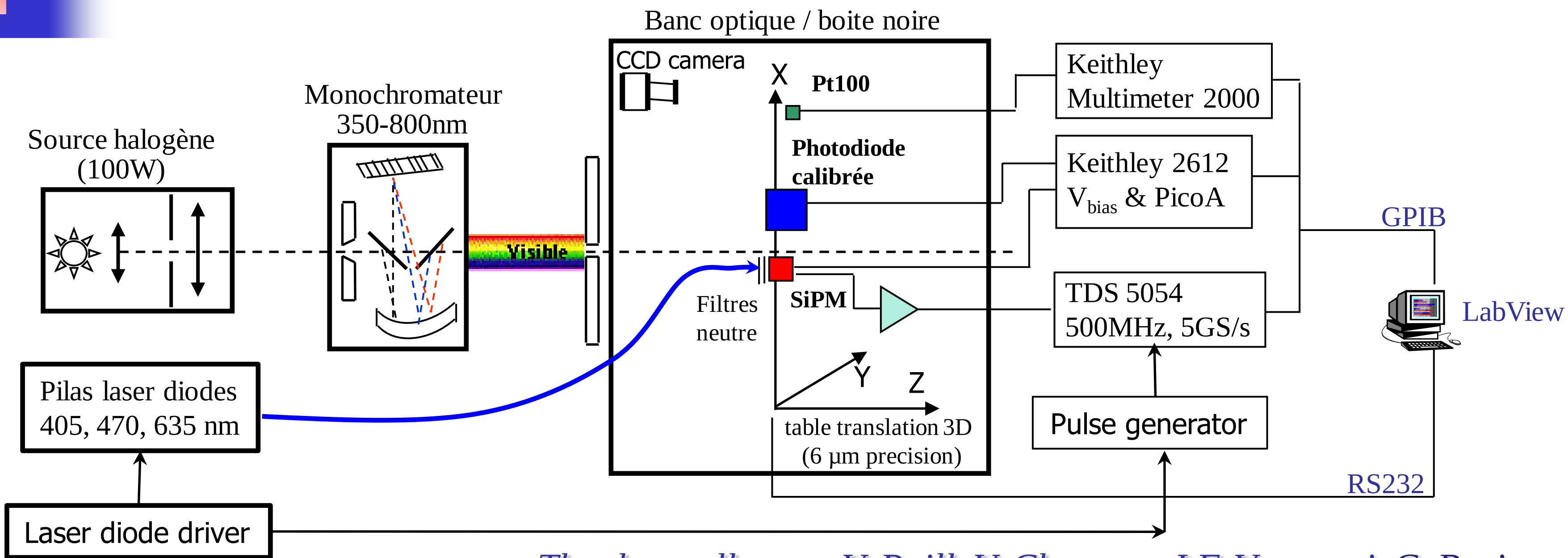
N. Dinu & al, NIM A 610 (2009) 423–426

- DCR – linear dependence due to triggering probability $\propto \Delta V$
  - non-linear at high ΔV due to cross-talk and after-pulses $\propto \Delta V^2$
- DCR scales with active surface

- Critical issues:
  - Quality of epitaxial layer
  - Gettering techniques

SiPM characteristics @ room temperature - light conditions -

Light measurements – continuous or pulsed light



Thanks to all team: V. Puill, V. Chaumat, J.F. Vagnucci, C. Bazin

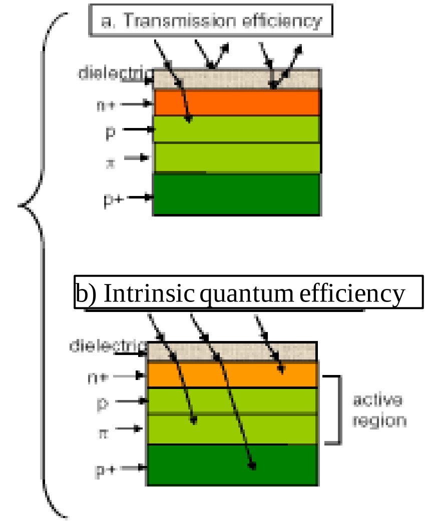
- Continuous light: PDE vs λ (350-800nm):
  - low incident flux (~ 10^7 incident photons /s/mm^2) – to avoid the SiPM saturation
  - calibrated photodiodes (HPK S3590-18, UDT Instrument 221)
  - the number of the photons recorded by the SiPM – evaluated by two methods:
    - DC method & AC counting methods
- Pulsed light: PDE, timing resolution, non-linearity
  - the number of the incident photons – evaluated with a PMT (HPK R614-00U)

Photon Detection Efficiency (1)

$$PDE = N_{output-pulses} / N_{incident-photons} = QE \cdot P_{01} \cdot \varepsilon_{geom}$$

QE = Quantum Efficiency

• probability for a photon to generate a carrier in the high field region



★

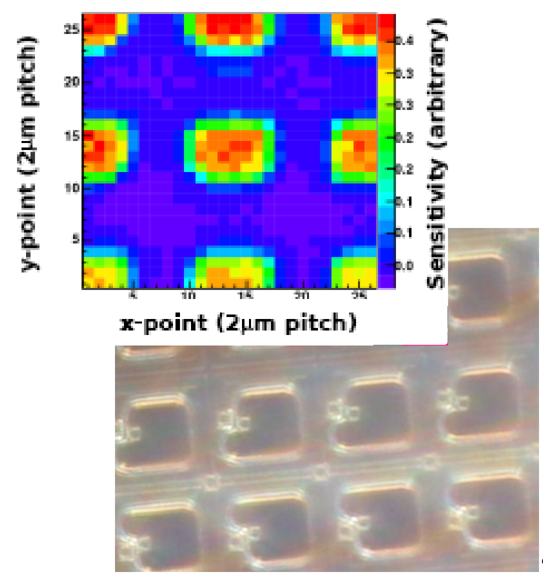
P_{01} = Triggering probability

• probability for a carrier traversing the high field to generate an avalanche

★

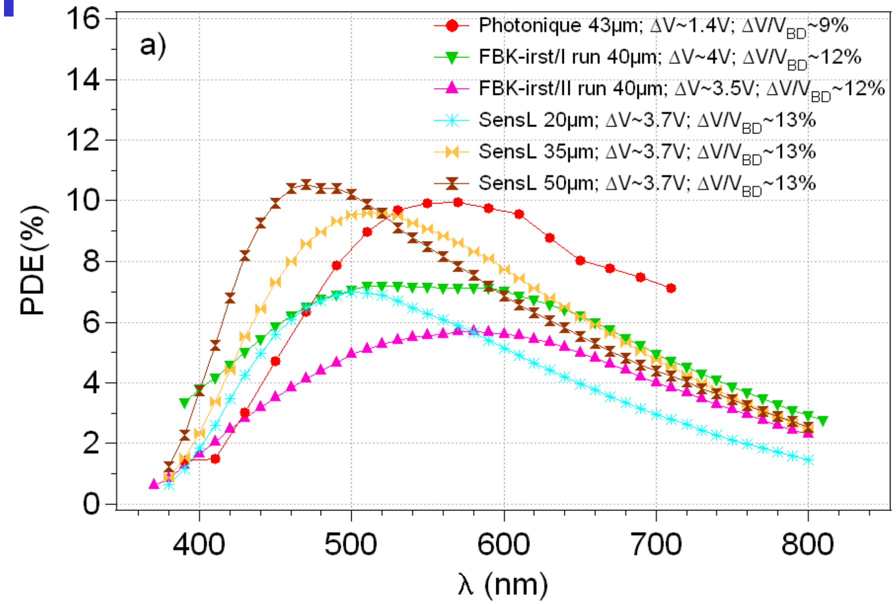
ε_{geom} = Geometrical fill factor

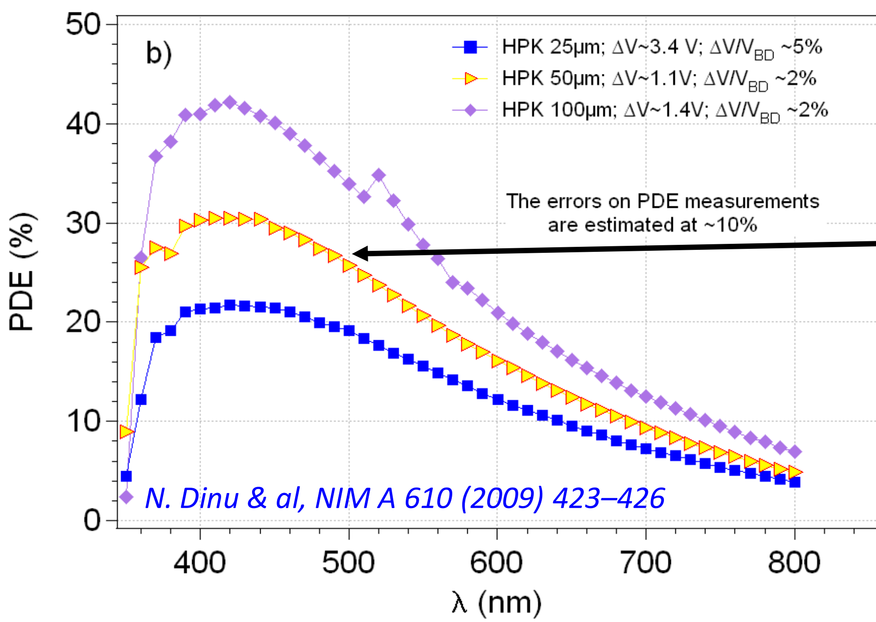
• fraction of dead area due to structures between the pixels e.g. grid lines, trenches, R_{quench}



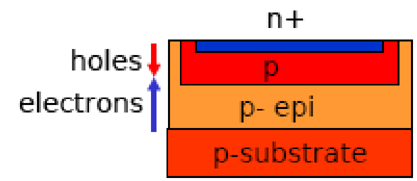
PDE of different SiPMs

Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013

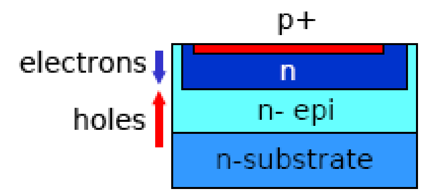




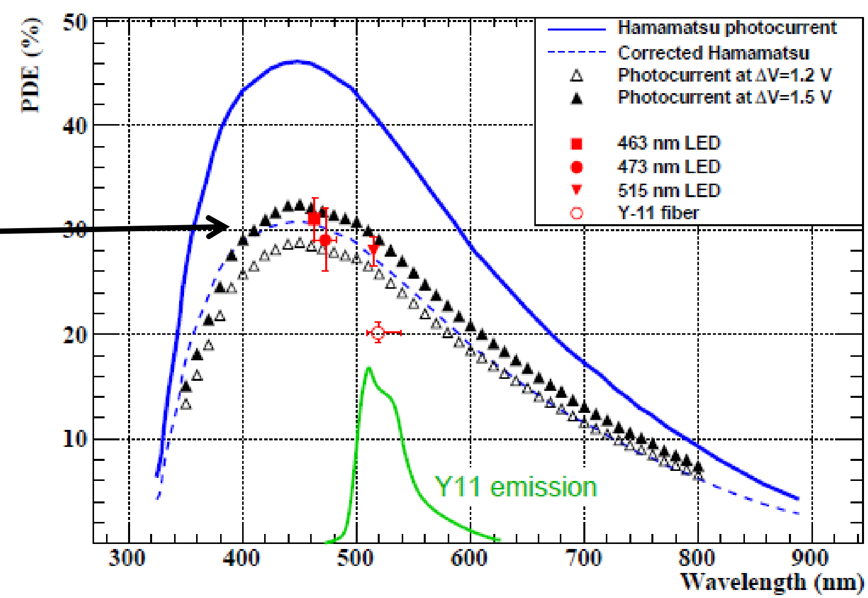
- PDE of Photonique, FBK, SensL



- PDE of HPK devices



A. Vacheret & al, arXiv:1101.1996v1

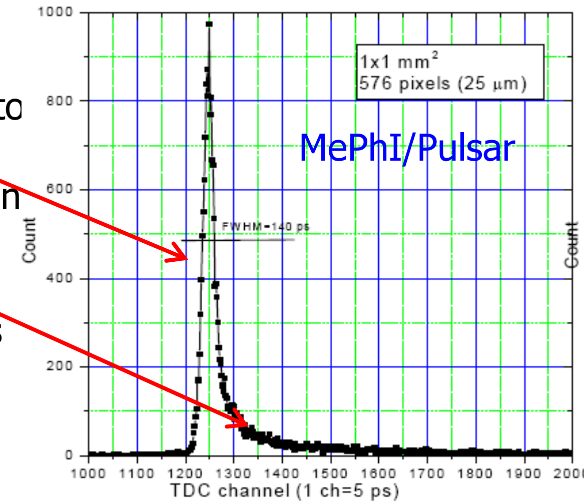


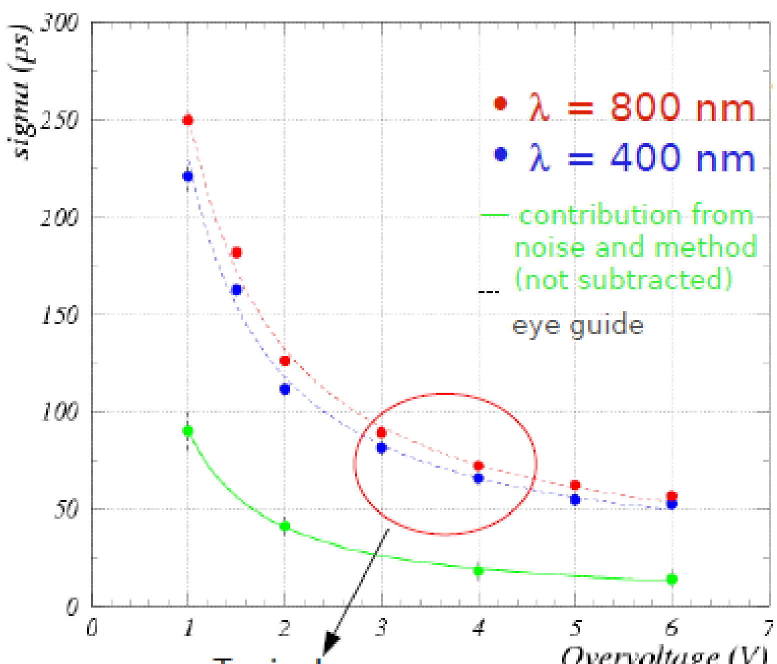
SiPM jitter or timing resolution (1)

Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013

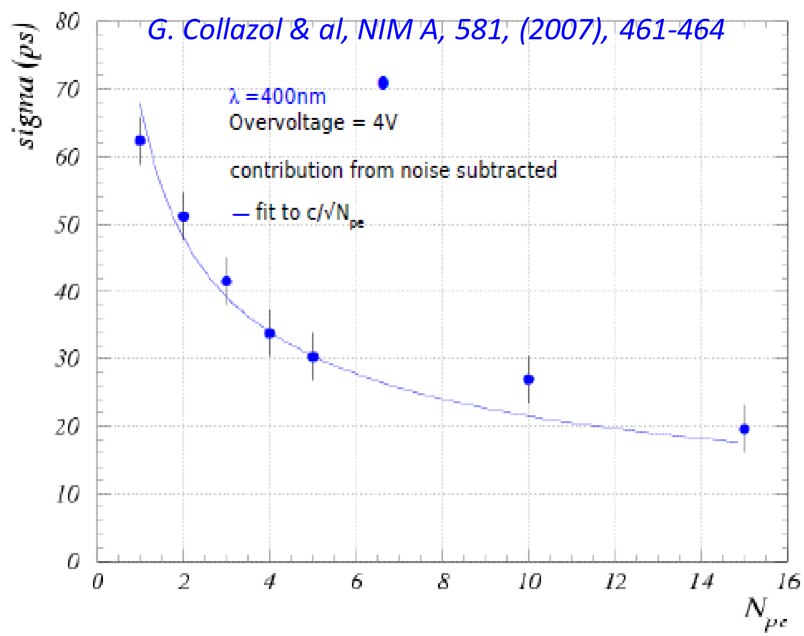
Two components :

- fast component of gaussian shape with σ $\mathcal{O}$(100ps)
  - variation of generated carrier transit time from depletion region to multiplication region (longitudinal propagation: $\mathcal{O}$(10ps))
  - statistical fluctuations of the avalanche build-up time (e.g. photon impact position → cell size; transversal propagation: $\mathcal{O}$(100ps))
- slow component: minor non gaussian tail with time scale of $\mathcal{O}$(ns)
  - due to minority carriers, photo-generated in the neutral regions beneath the depletion layer that reach the junction by diffusion (wavelength dependent)





Typical working region

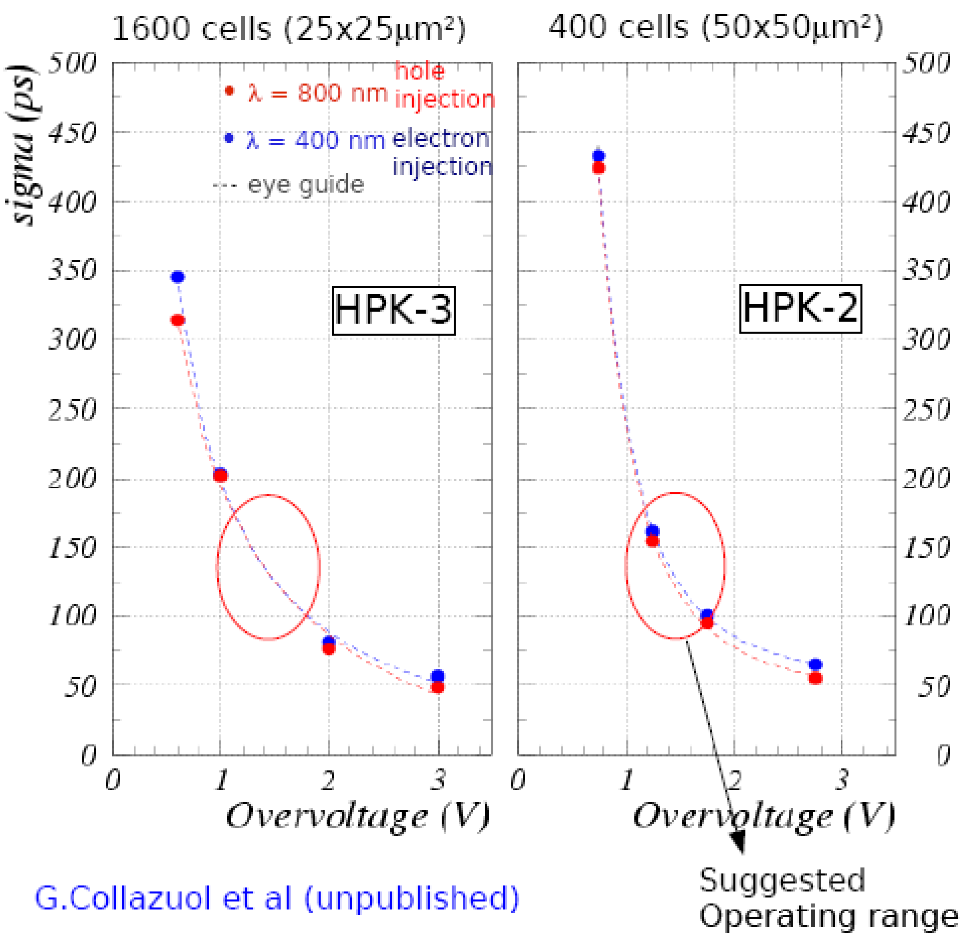


N of simultaneous photo-electrons

Poisson statistics: $\sigma \propto 1/\sqrt{N_{pe}}$

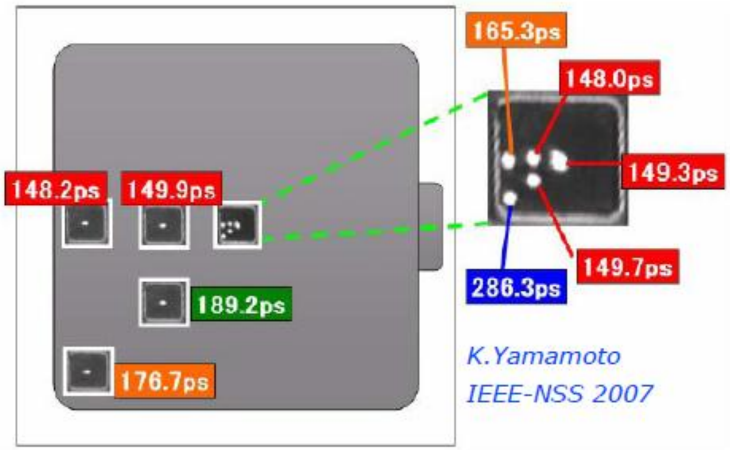
SiPM jitter or timing resolution (2)

SPTR – HPK devices



G.Collazuol et al (unpublished)

SPTR – position dependence



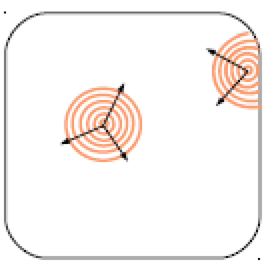
Data include the system jitter
(common offset, not subtracted)

Larger jitter if photo-conversion at the border of the cell

Due to:
1) slower avalanche front propagation

2) lower E field at edges

→ cfr PDE vs position



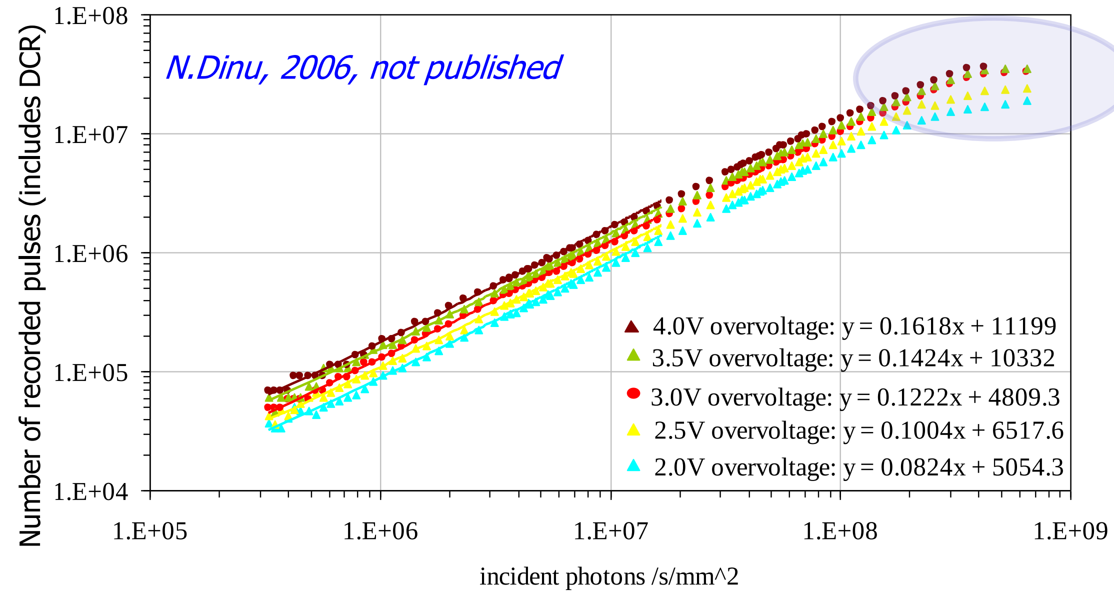
Detailed description of SPTR measurements and results:
G. Collazuol, Pixel Workshop, FermiLab, 2008

SiPM response non-linearity

Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013

The SiPM output signal is proportional to the number of fired pixels as long as the number of photons (N_{photon}) times the photon detection efficiency PDE is smaller than the number of the pixels N_{total}

FBK device, 1x1 mm^2, 625 cells; DCR = ~1-2x10^6 Hz



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

Main sources of non-linearity:

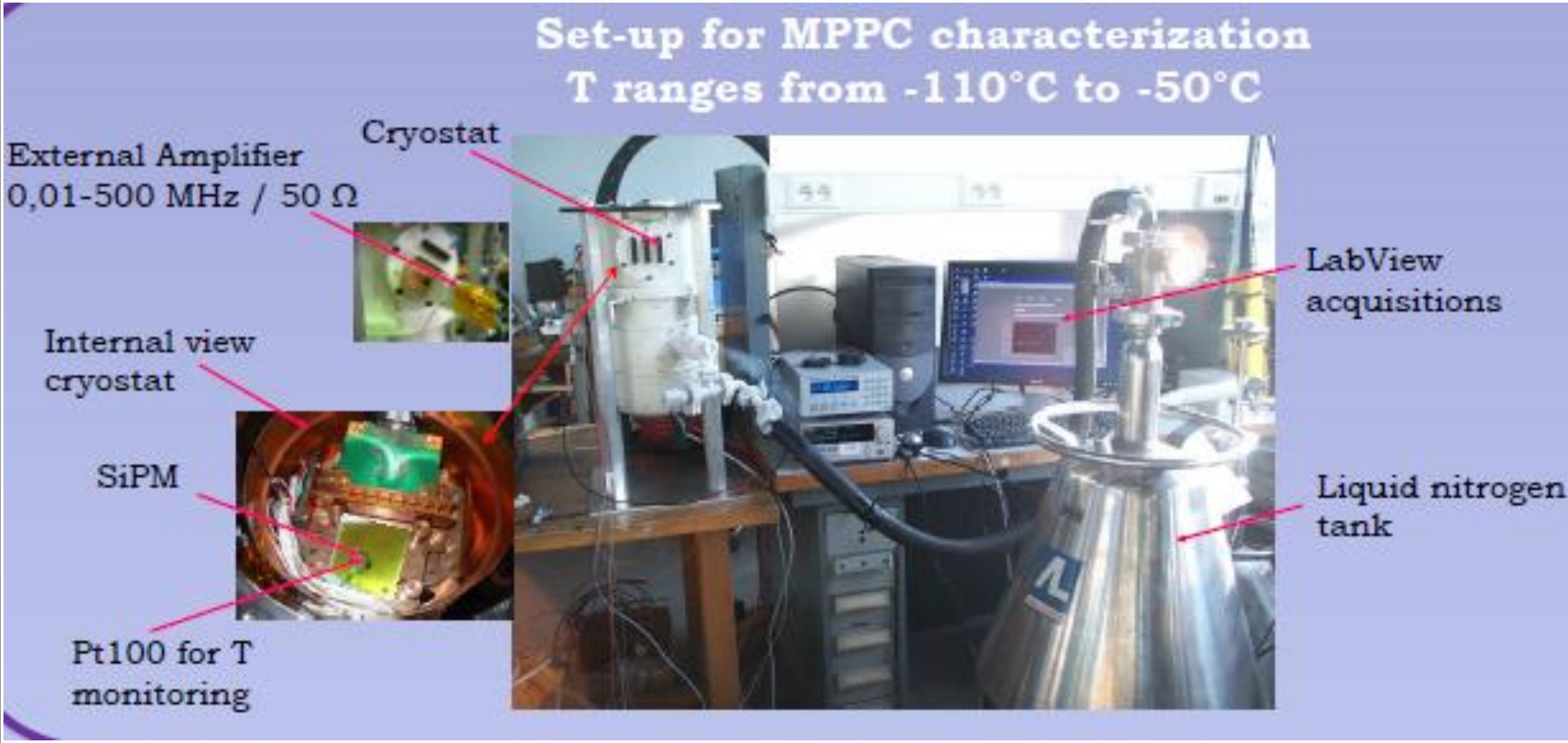
- finite number of pixels - main contribution when $N_{photons} \sim O(N_{cells})$
- finite recovery time
- afterpulses, cross-talk
- drop of ΔV during the light pulse due to relevant signal current on external series resistance

Symplified model: Stoykov, & al., JINST June, 2007

Detailed model to estimate non-linearity corrections: T. van Dam & al., IEEE TNS 57 (2010) 2254

SiPM characteristics as a function of temperature

LAL set-up



Thanks to all team: J.F. Vagnucci, C. Bazin, C. Cheikali, C. Sylvia, V. Puill, V. Chaumat,

Fermilab set-up

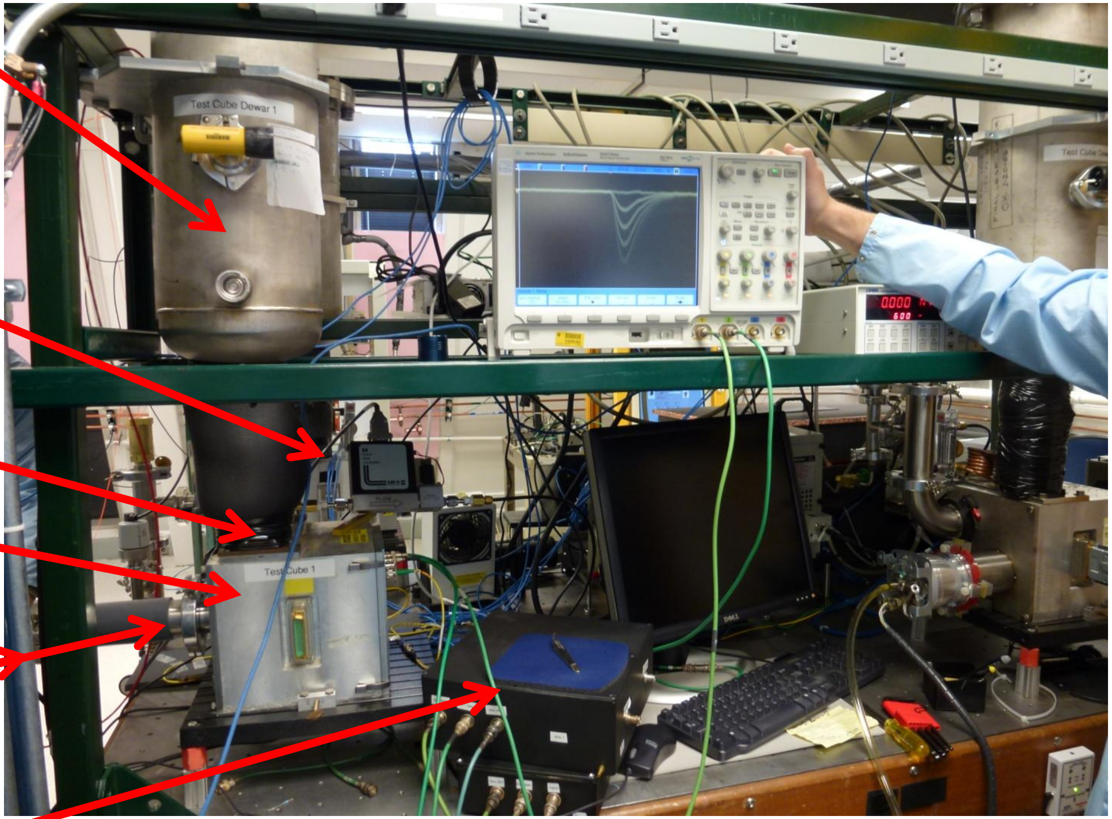
Vertical column automatic filling with N_2

System of N_2 flow control

Cold finger

Test vacuum cube
SiPM locations

Tubes connected to a vacuum pump

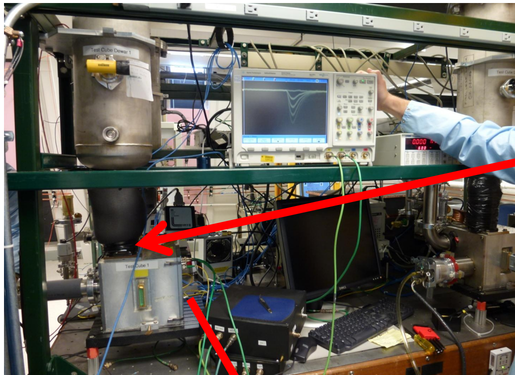


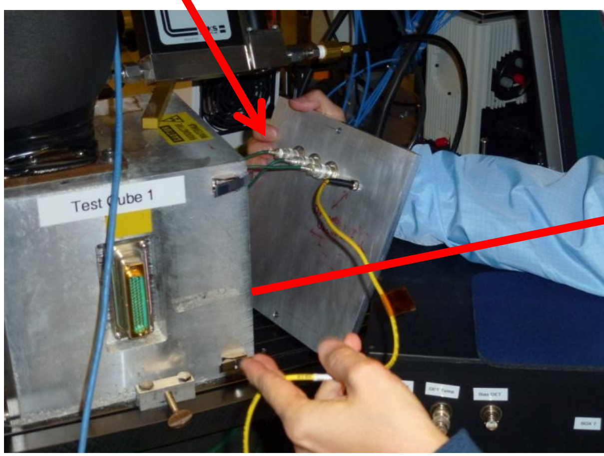
Box: read-out electronics

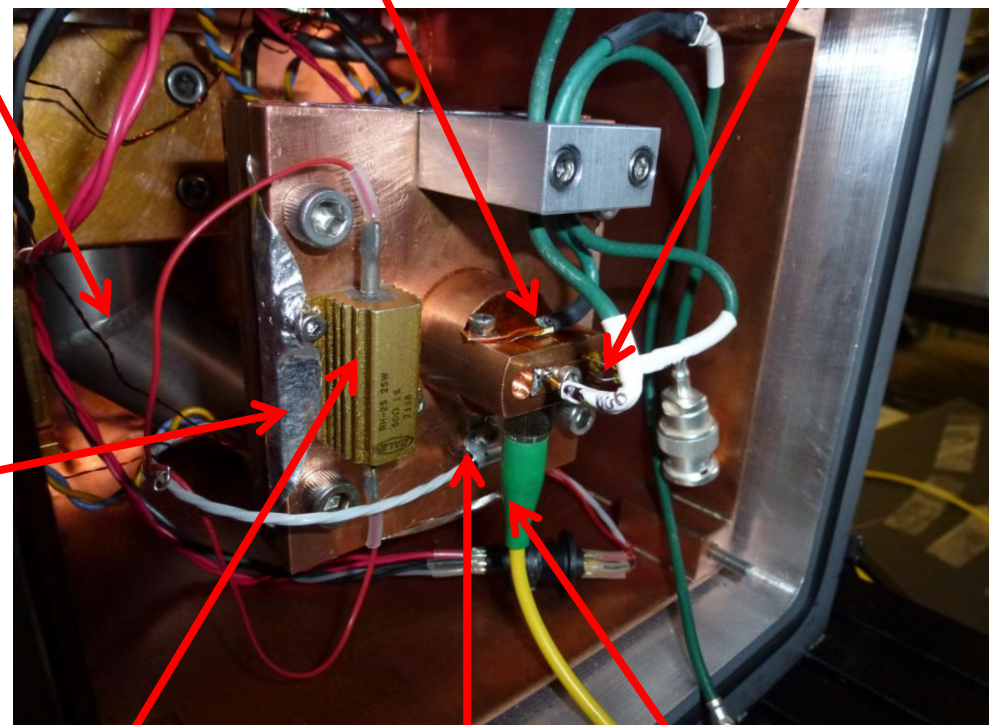
- T cryogenic control system Cryo.con + automatic flow control
- Keithley 2400 for SiPM bias
- CAEN digitizer – calibration (Vbd vs T)
- Agilent Oscilloscope – waveforms acquisition @ dV=const

Thanks to FermiLab team:
Adam Para, Paul Rubinov, Kelly Hardin, Cary Kendziora, Carlos Ourivio Escobar

Zoom inside of cube







Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013

Temperature dependence of SiPM parameters

- Few slides to be added

Arrays of SiPM
& multi-channels read-out electronics

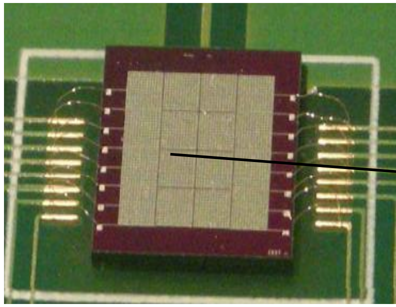
SiPM applications

- Calorimetry
- Cherenkov
- Medical
- Number of applications still growing….

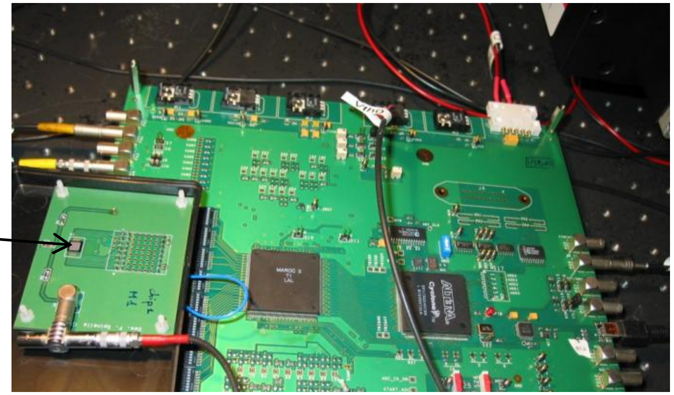
Strengths	Weaknesses
• Flexible design • High gain • Compact • Fast • High PDE → still growing • Insensitivity to magnetic fields • Low cost	• High dark rate @ room temp. • afterpulses & cross-talk • Still "small" area • Temperature dependence of some parameters • Radiation damage

SiPM arrays & multichannels read-out electronics

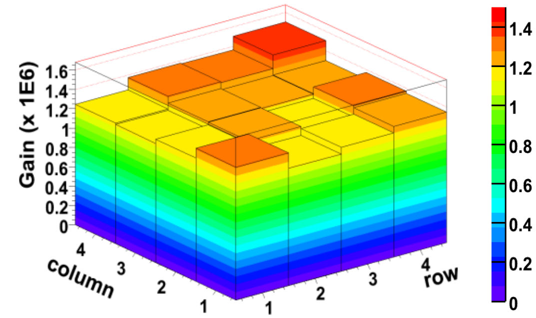
SiPM monolithic array of 4x4 channels from FBK-irst glued and wire bonded to a PCB @ Pisa



Each channel: 1x1 mm^2
625 cells, 40x40 µm^2/cell



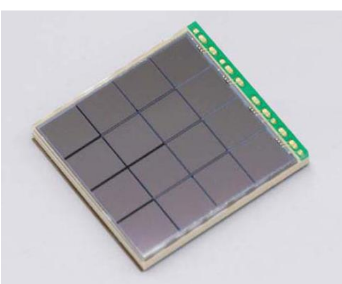
- SiPM matrix (16 channels)
- connected to MAROC2 chip (Omega Pole)

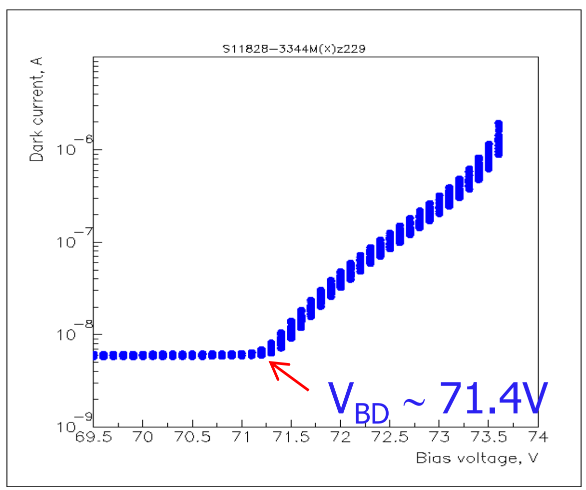


4% uniformity

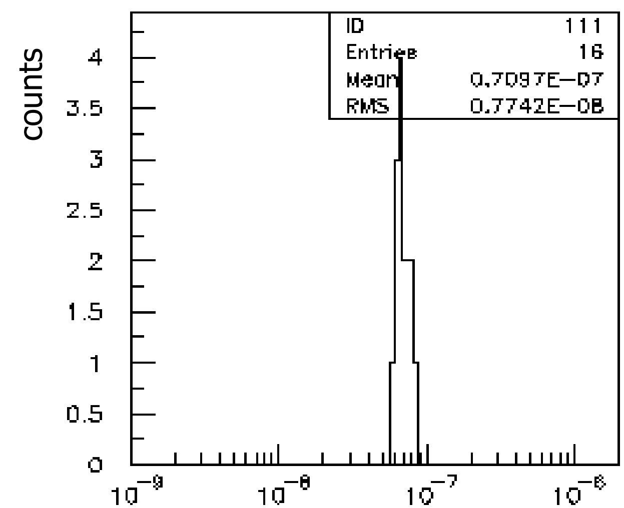
N. Dinu & al, NIM A 610 (2009) 101–104

SiPM monolithic array of 4x4 channels from Hamamatsu
Each channel: 3x3 mm^2, 3600 cells, 50x50 µm^2/cell





I_{dark} @ ΔV=0.7V ~ 71±8nA



Details on read-out electronics: see slides 40-42, SIPMED application

Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013

SiPM @ medical applications

Requirements

- Compact & cheap
- Fast → TOF-PET
- Insensitivity to magnetic field → PET/MRI

Applications

- Innovative detector systems
- Intra-operative probes, SPECT systems
- PET: Time-of-flight PET, PET/MRI

More details on PET applications: see G.Llosá, PhotoDet2012

SiPM @ intra-operative probes - SIPMED

- Aim of the project
  - Developement of a very compact intra-operative gamma probe based on arrays of SiPM coupled to scintillator and multi-channels read-out electronics
- Teams
  - IMNC & LAL
  - Omega Pole
  - L'Hôpital Lariboisière

From POCI to SIPMED (1)

POCI

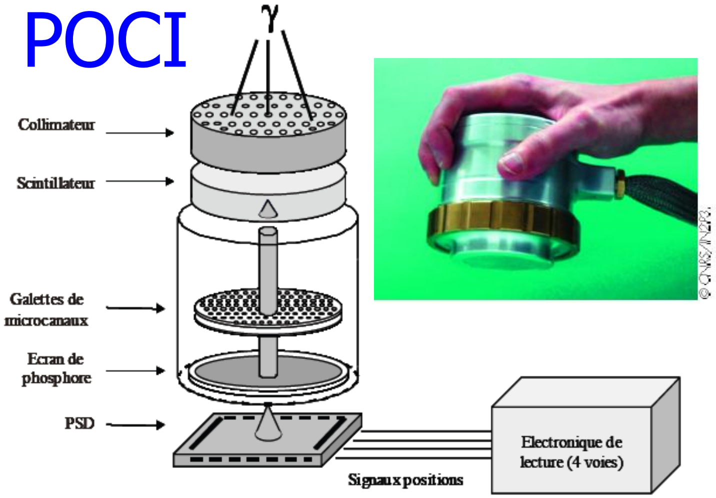
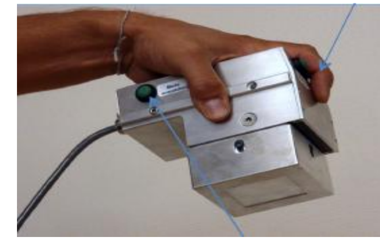
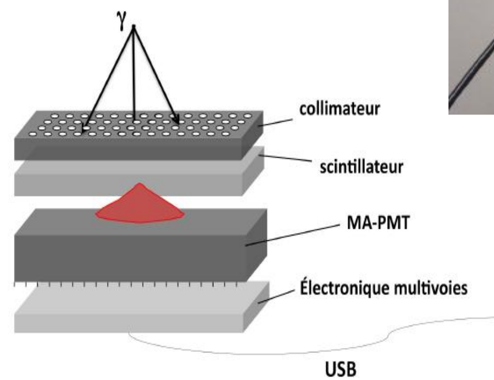


Figure II.1 : Représentation schématique de l'imageur POCI

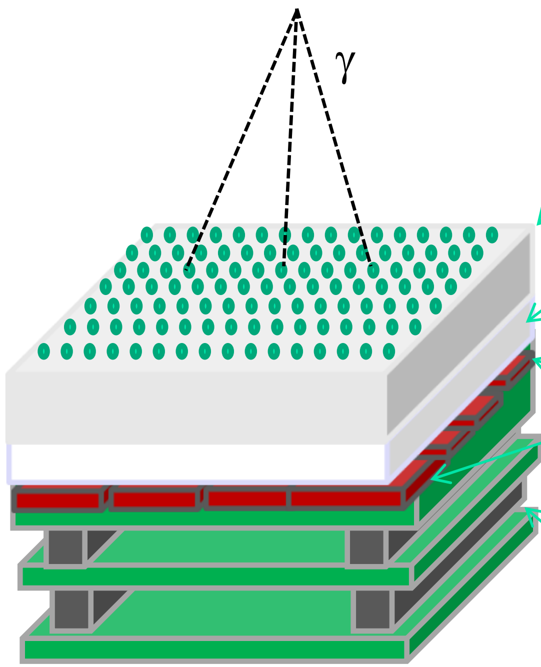
TreCam





	Spatial resolution	Efficiency	Energy resolution	Active surface	Dimension	Weight
POCI	3.2 mm (contact)	290 cps/MBq	32%	12.5 cm^2	h = 90 mm ϕ95 mm	1.2 kg
TReCAM	1.8 mm (contact)	300 cps/MBq	11.3%	25 cm^2	h = 117 mm 140 x 83 mm^2	2 kg

From POCI to SIPMED (2)



collimator

$LaBr_3(Ce)$ scintillator

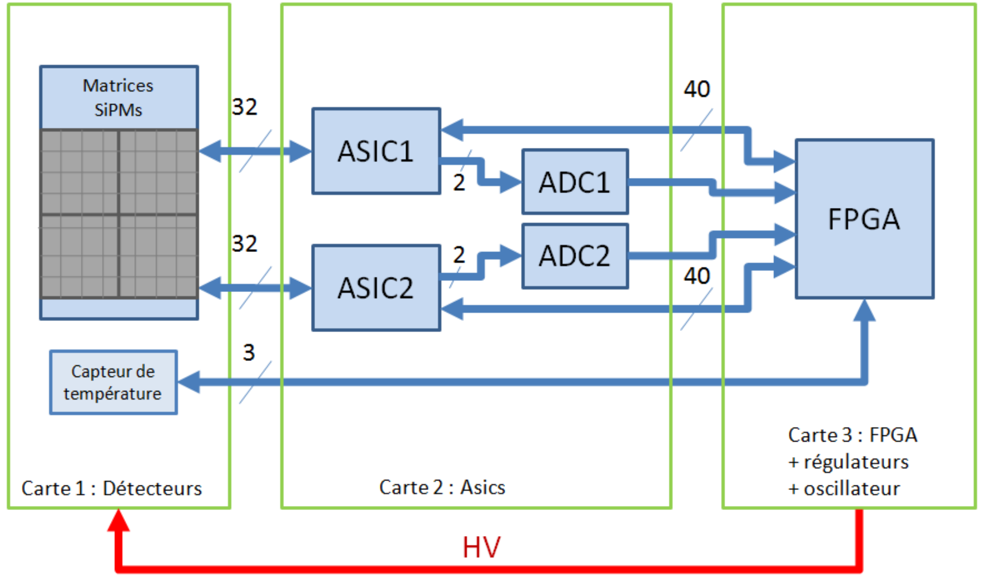
4x4 SiPM arrays (field of view: ~ 25 cm^2)
1 array: 4x4 SiPM's (13.6 x 13.7 mm^2)
1 readout channel = 1SiPM of 3x3 mm^2

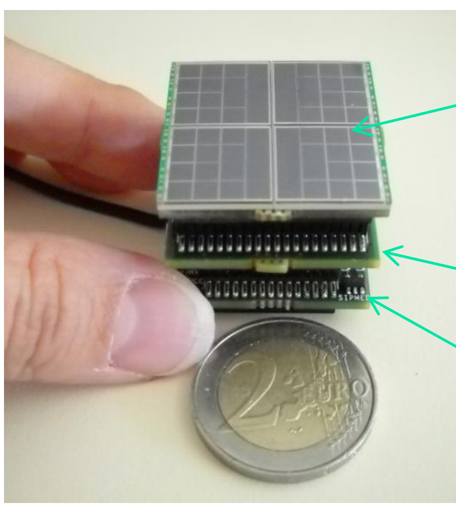
256 channels
miniaturized readout electronics

- SIPMED camera characteristics
  - Field of view 25 cm^2
  - Geometrical dimensions: 60x60x50 mm^2
  - Weight <1kg
  - 256 read-out channels

Characteristics of SiPM arrays

Elementary module SIPMED

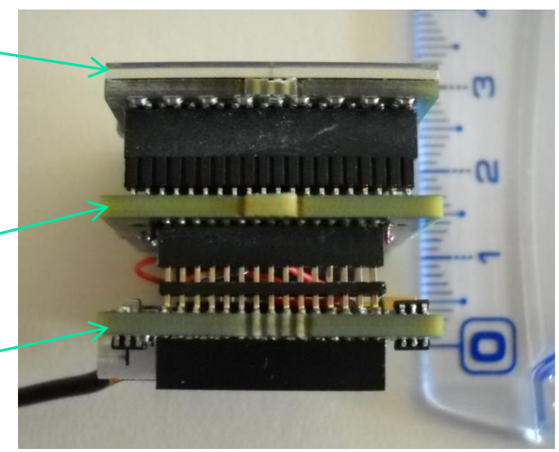




Carte 1 : matrices SiPM

Carte 2 : puces EASIROC
(Pole Omega)

Carte 3 : FPGA



First electrical tests – very satisfactory

Project under progress…..

SiPM @ calorimetry

Requirements

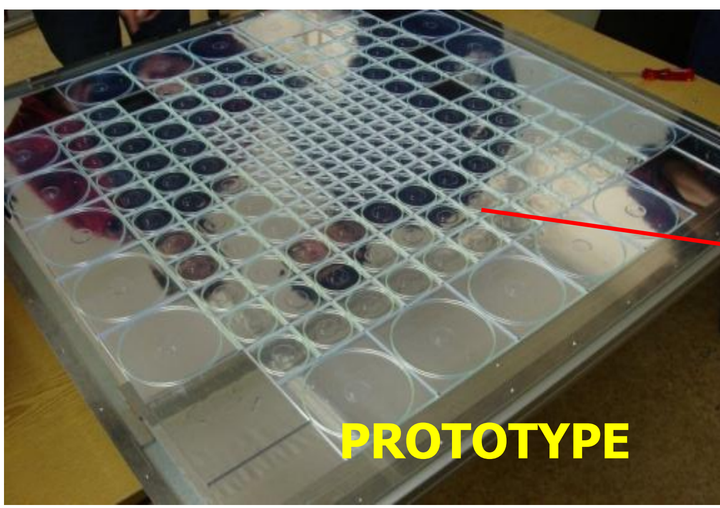
- Insensitivity to magnetic fields
- Radiation hardness
- Mass production with uniform properties and low cost

Applications

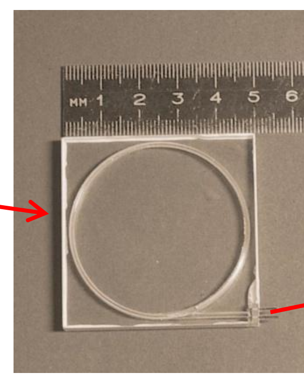
- Future applications (ILC, PANDA at Fair)
  - High granularity
  - Compactness, low weight (PEBS)
- Upgrade of future experiments
  - Replacing current photo-detectors (CMS)
  - Increasing granularity

SiPM @ ILC HCAL

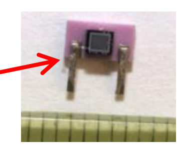
SiPM: tests with MePHI/PULSAR SiPM , HAMAMATSU MPPC



216 tiles/layer (38 layers in total) ~8000 channels



3 x 3 cm² plastic scintillator tile
with embedded WLS fiber + SiPM



SiPM
1 mm²

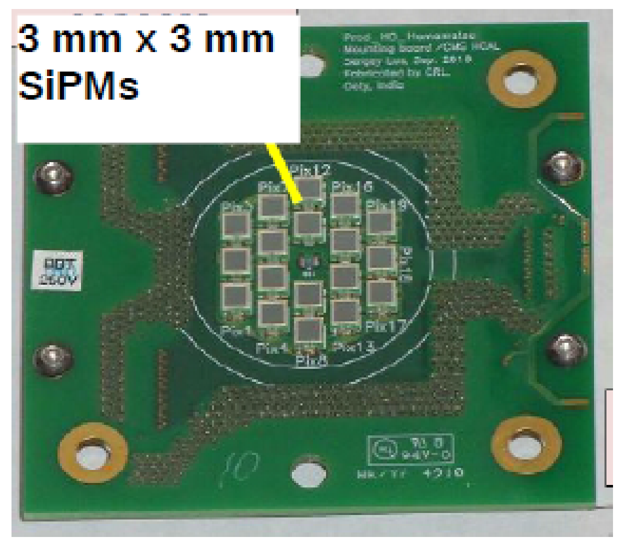
Readout of SiPMs by the SPIROC ASIC (Omega Pole)

CMS Outer Hadron Calorimeter (HO) upgrade

- Replace HO HPD (susceptible to discharge at intermediate B fields) with SiliconPhotoMultipliers (SiPM)
  - SiPM PDE >2x HPDs and gain a factor of 50 to 500 larger;
  - Compact and Vbias ~100V compared to ~10KV for HPDs;
  - Not affected by magnetic fields
- Scintillator/wavelengthshifting fiber.

Board with 18 MPPCs and Peltier on the back. Temp stabilization system.

• Components (2200 SIPMs, 160 SIPM Mounting Boards, 160 Control Boards) built and tested. Electronics will be complete by the end of 2012.
• The full HO SIPM system will be installed during the LHC LS1 shutdown in 2013.

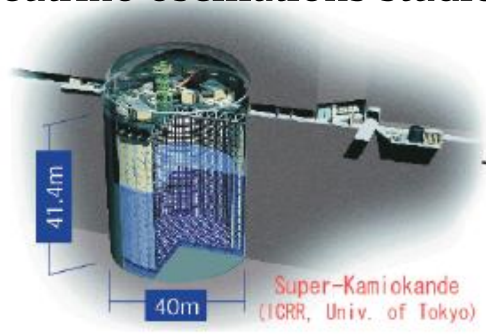


A. Sharma/Jim Freeman. FDFP 2012

Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013

SiPM @ Tokai-to-Kamioka

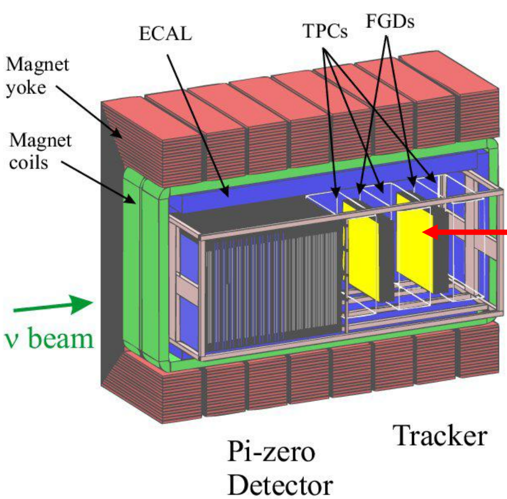
Neutrino oscillations studies

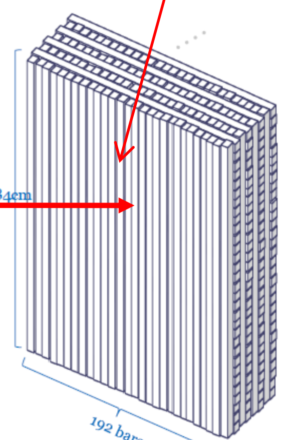


Far detector : Super Kamiokande

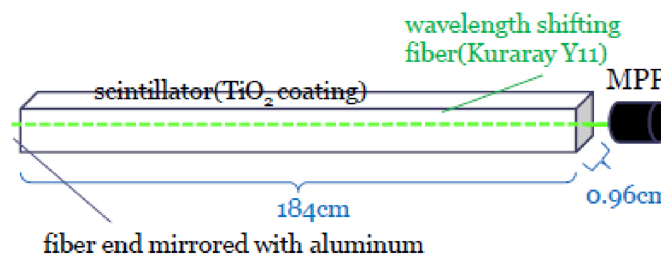
ν beam : J-PARC facility

ND280 : off axis neutrino beam flux and SuperK backgrounds measurements





Two Fine Grain Detectors (FGDs):



System	Channels	Bad channels	Fraction
ECAL (DSECAL)	22336 (3400)	35 (11)	0.16% (0.32%)
SMRD	4016	7	0.17%
P0D	10400	7	0.07%
FGD	8448	20	0.24 %
INGRID	10796	18	0.17 %
Total	**55996**	**87**	**0.16 %**

Total number of SiPM's used @ T2K

SiPM @ Cherenkov detectors

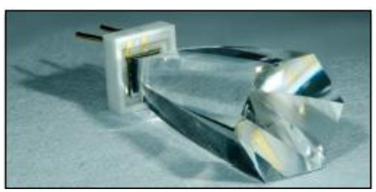
Requirements

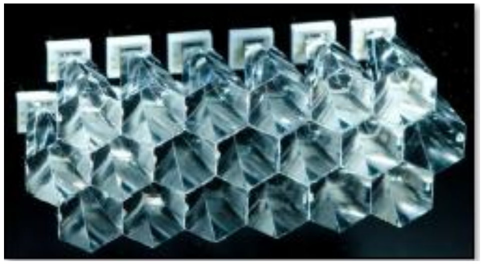
- Single photon detection
- High PDE
- Large area
- Low dark count rate
- Fast reponse

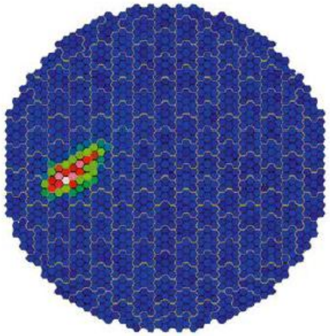
Advantages with respect to PMT

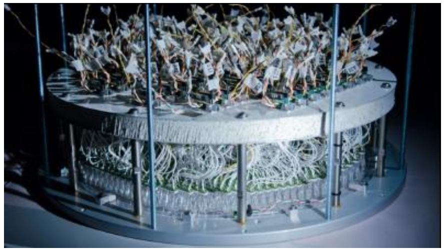
- Data analysis
  - Single photon resolution
  - High PDE
  - no known ageing
- For the construction
  - No need high voltage (~70 V vs kV)
  - More robust to light exposure

FACT – First G-APD Cherenkov Telescope









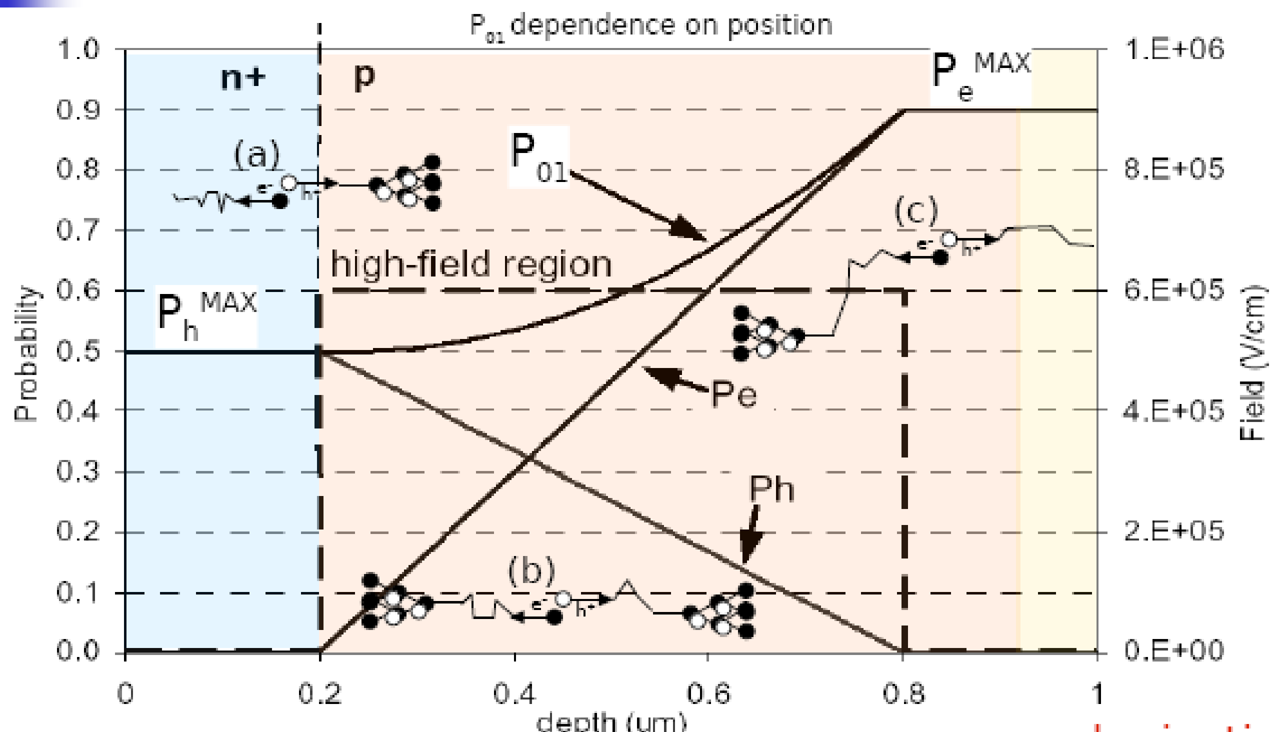
- First operation on the night of October 11, 2011 (full moon)
- Usually no operation of IACTs in full moon nights

1440 SiPM + light collecting cones

Conclusions

Additional slides

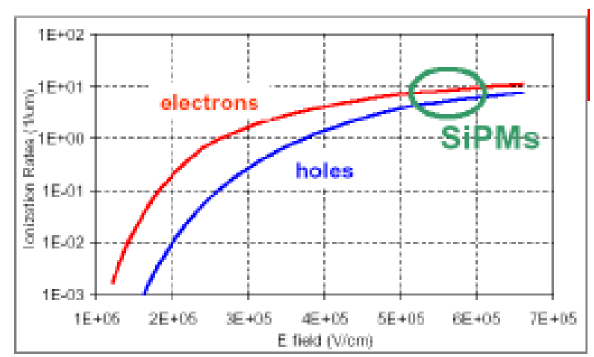
Avalanche triggering probability



C.Piemonte
NIM A 568
(2006) 224

Example with constant high-field:
(a) only holes may trigger the avalanche
(b) both electrons and holes may trigger
(but in afraction of the high-field region)
(c) only electrons may trigger

Ionization rate in Silicon



P_{01} optimization

- high over-voltage
- photo-generation in the p-side of the junction

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Avalanche triggering probability

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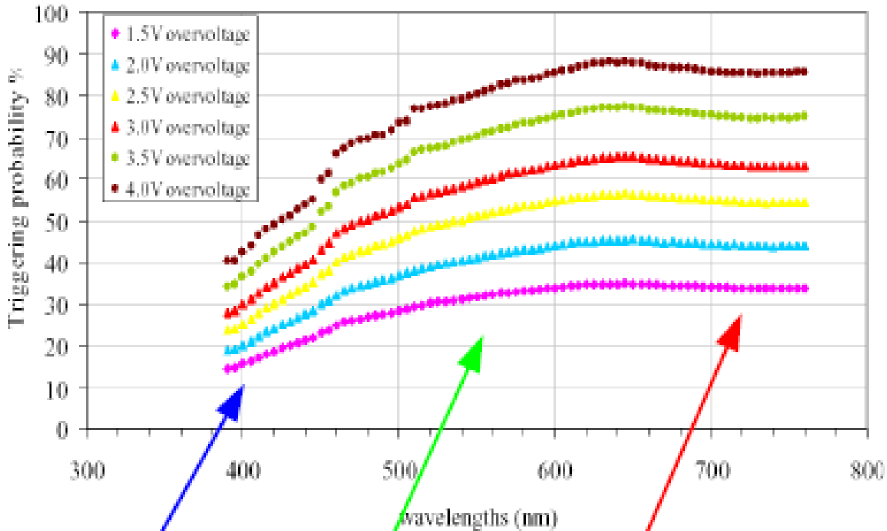
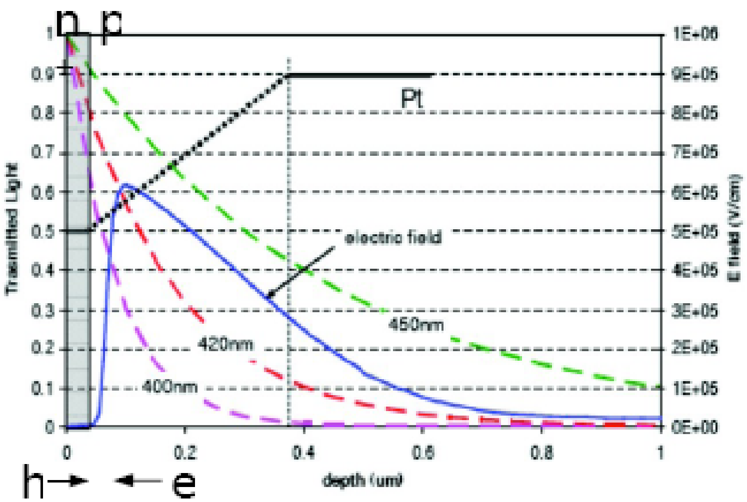
$P_{01} = PDE / QE / \varepsilon_{geom.}$





Only e⁻ cross the high E field region and trigger the avalanche

Both h⁺ and e⁻ might trigger the avalanche (but cross only a fraction of high field region)

Only h⁺ cross the high E field trigger the avalanche

IRST devices

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Radiation damage

- Bulk damage due to Non Ionizing Energy Loss (NIEL) ← neutrons, protons
- Surface damage due to Ionizing Energy Loss (IEL) ← γ rays
  (accumulation of charge in the oxide (SiO2) and the Si/SiO2 interface)

Radiation damage effects on SiPM

1) Increase of dark count rate due to introduction of generation centers

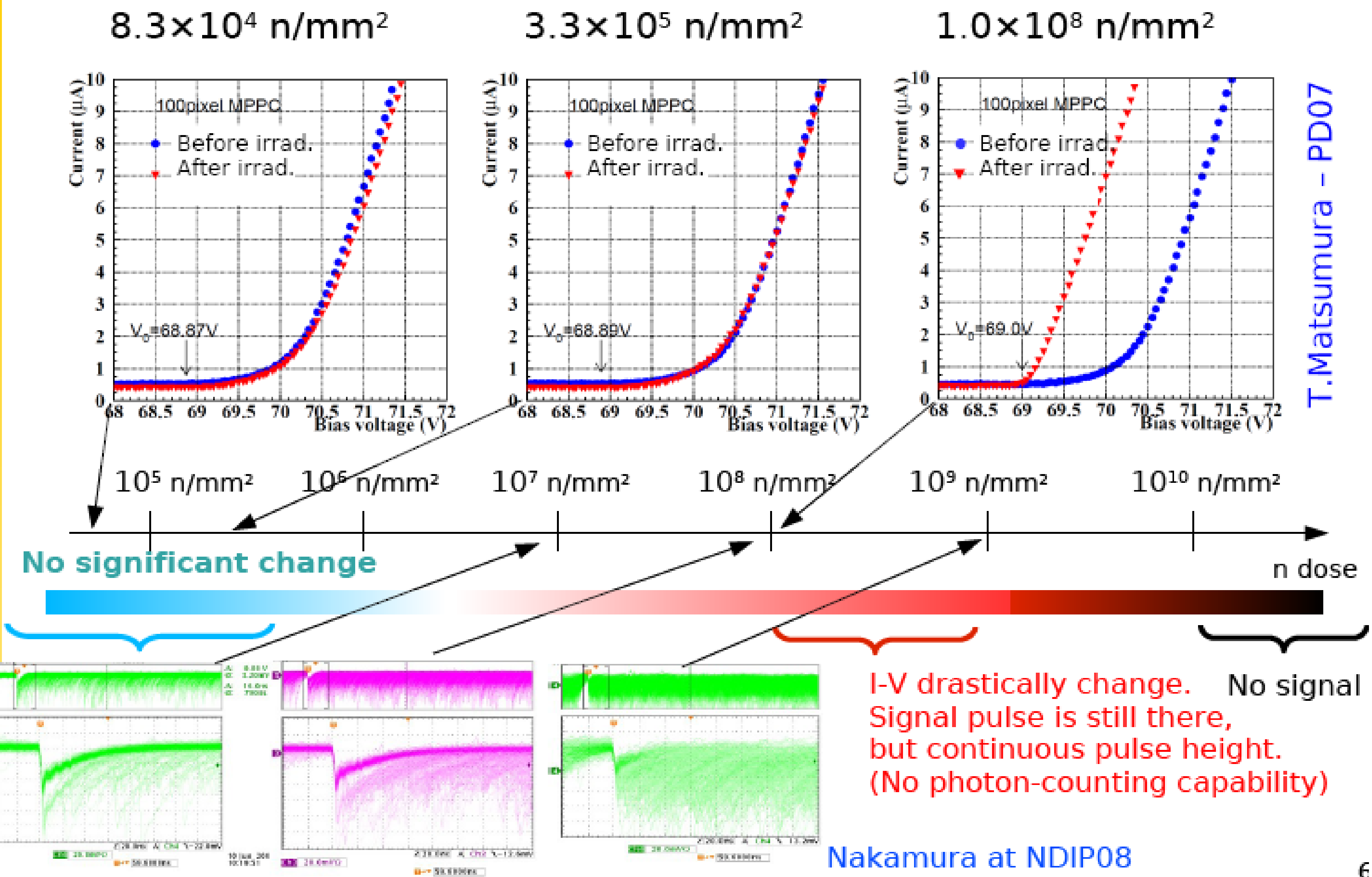
Increase (ΔR_{DC}) of the dark rate:
$\Delta R_{DC} \sim P_{01}\ \alpha\ \Phi_{eq}\ Vol_{eff}\ / q_e$
where $\alpha \sim 3 \times 10^{-17}$ A/cm is a typical value
of the radiation damage parameter for
low E hadrons and $Vol_{eff} \sim Area_{SiPM} \times \varepsilon_{geom} \times W_{epi}$

NOTE:
The effect is the same as in normal junctions:
- independent of the substrate type
- dependent on particle type and energy (NIEL)
- proportional to fluence

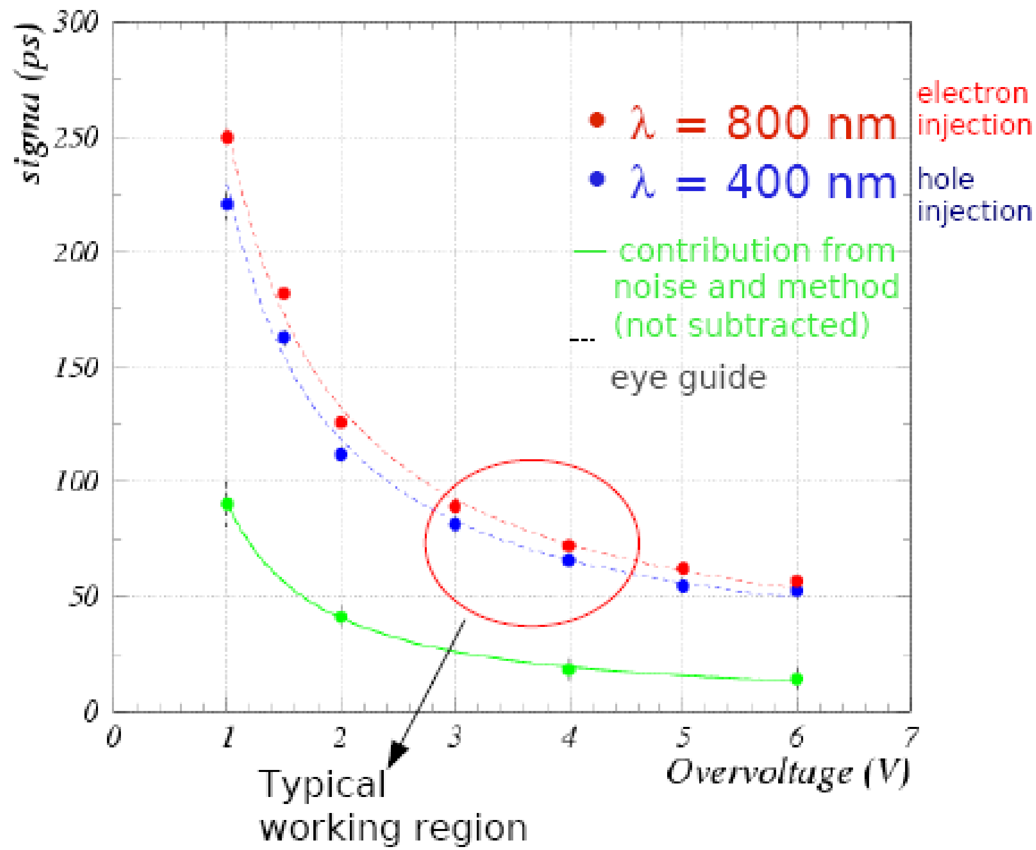
2) Increase of after-pulse rate due to introduction of trapping centers

→ loss of single cell resolution → no photon counting capability

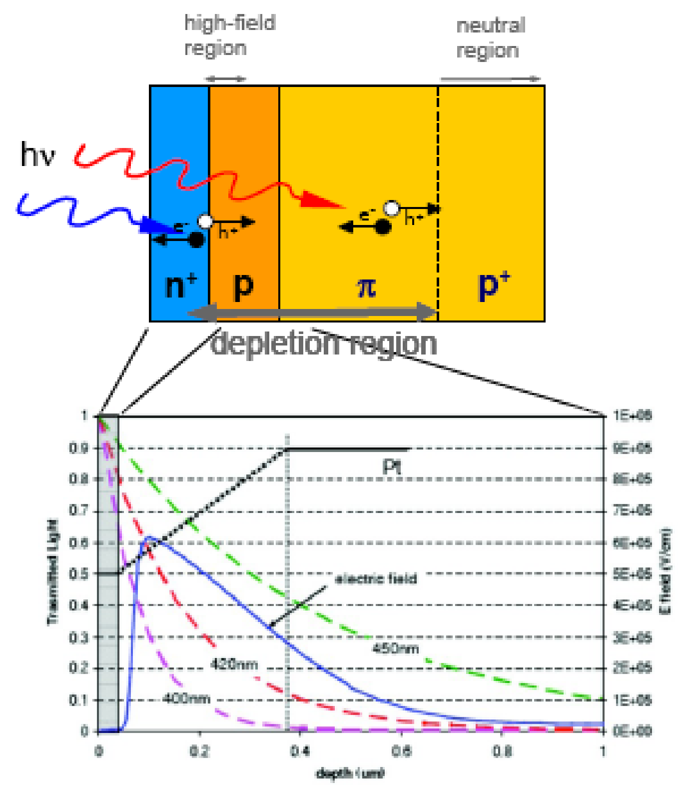
Radiation damage: neutrons (0.1-1 MeV)



IRST – single photon timing resolution (SPTR)



Better resolution for short wavelengths: carriers generated next to the high E field region



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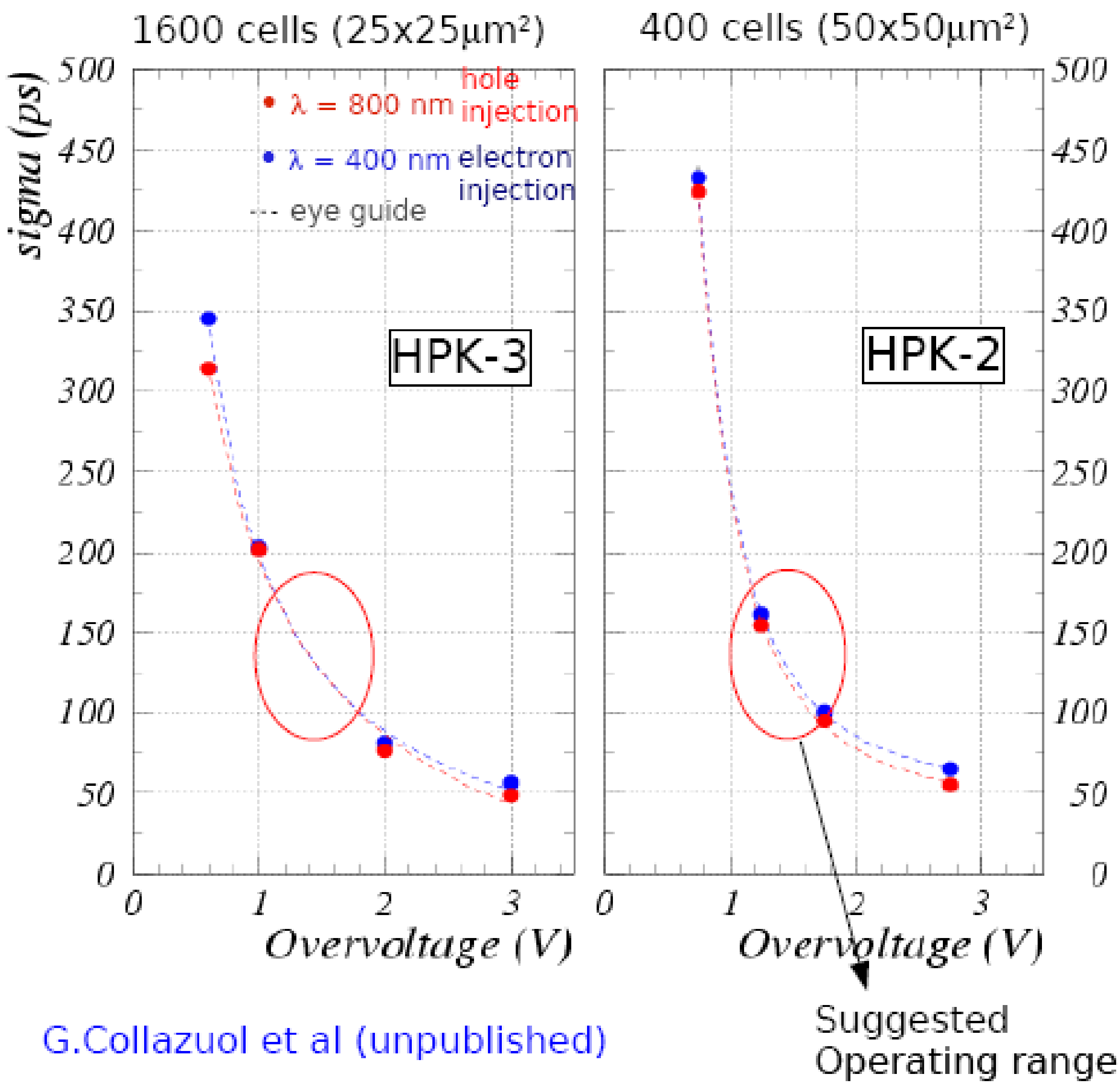
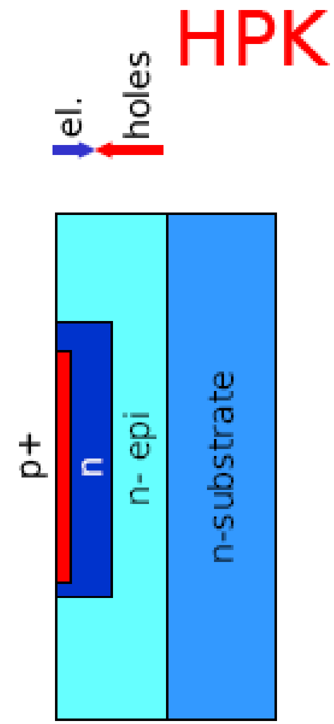
HPK – single photon timing resolution





G.Collazuol et al (unpublished)

Nicoleta Dinu, Ecole microelectronique IN2P3, 24.06.2013