SiPMs for Beam Instrumentation

Ideas From High Energy Physics

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IBIC16 – Barcelona – September 15th 2016

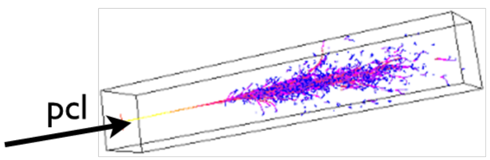
I. **Motivation**
II. SiPMs: state of the art
III. Signal conditioning
IV. Use cases in HEP
V. Possible applications for BI

I. Motivation: photodetectors in HEP

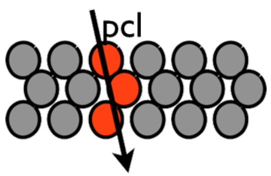
Where do we need photodetectors?

scintillators readout

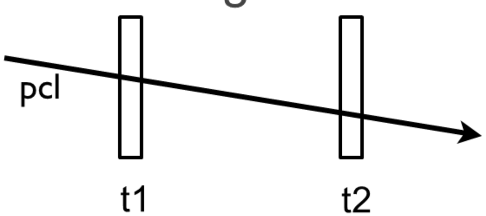
Calorimetry (elm & hadr)



Tracking (with scintillating fibers)



Time-Of-Flight i.e. PID

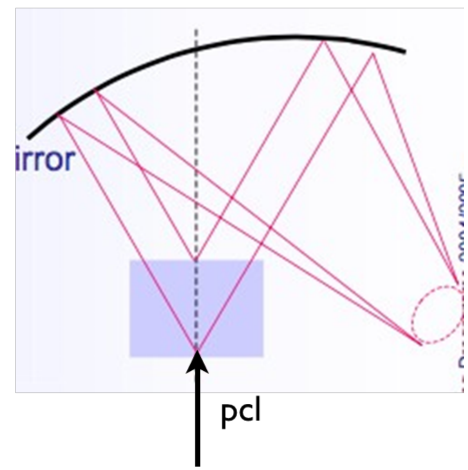


detection of Cherenkov light

PID (Particle ID)

Cherenkov Threshold detectors

or RICH
Ring
Imaging
CHerenkov



partially also in calorimetry

I. Motivation: photodetectors in HEP

photodetectors in HEP

for Cherenkov emission (namely RICH):

- blue / UV light sensitivity (large spectral response)
- single photons sensitivity
- optimize spatial resolution of single photons
- maximize number of detected photons
- large detector areas

} *Particle ID*

for scintillation: (most requirements here are specifically application-driven)

- visible light (mostly blue / green)

- nr. of photons
  for fibers => few photons } *Tracking*

  for large calorimeters => ~ 100s - 10000s photons
  depending on scintillator
  depending on energy deposition
  => large dynamic range

} *Calorimetry*

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SiPM becomes a competitor for PMTs in all domains

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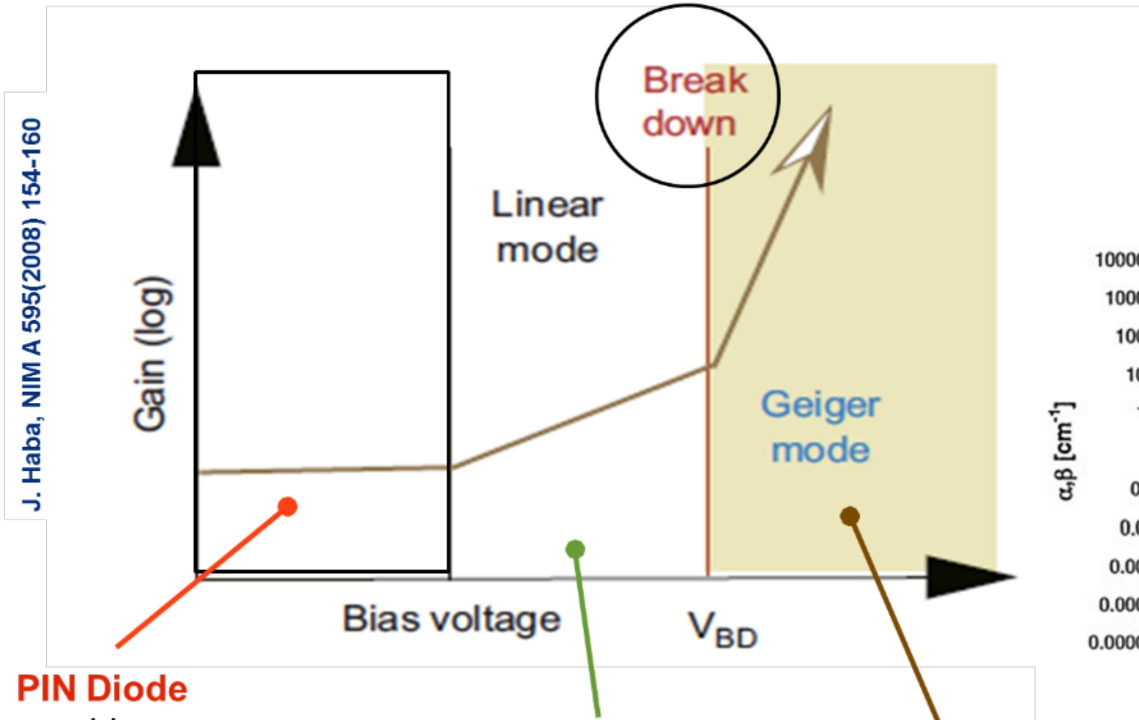
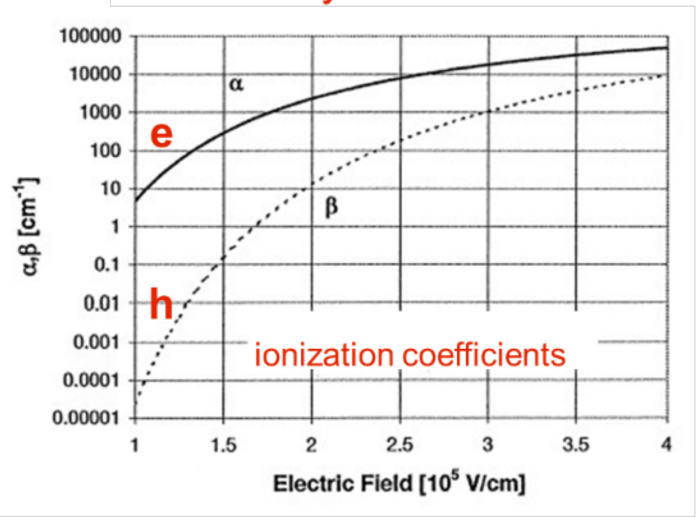
Reversed bias pn junction - Different regimes

Vbias :
- enlarge depletion region
- increase electric field
- secondary ionization



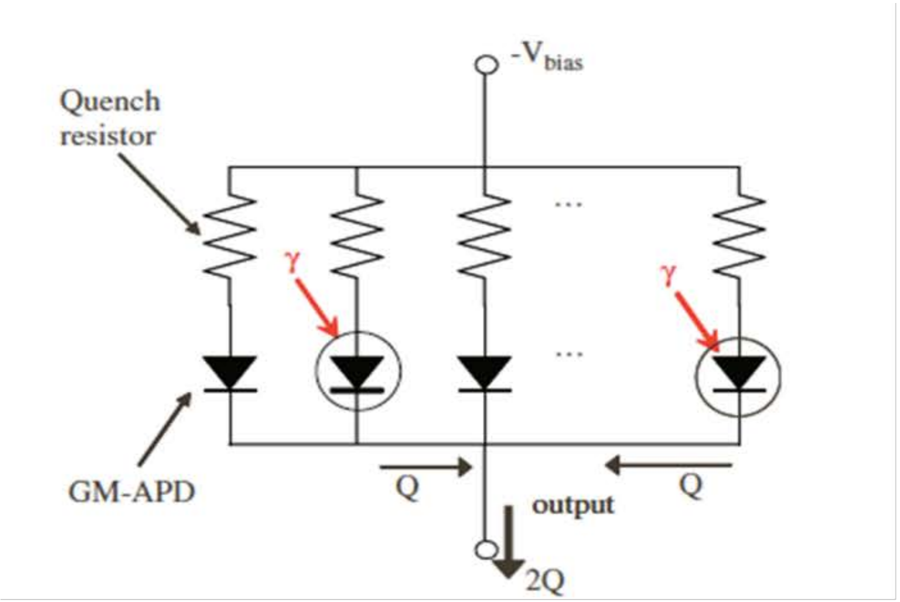


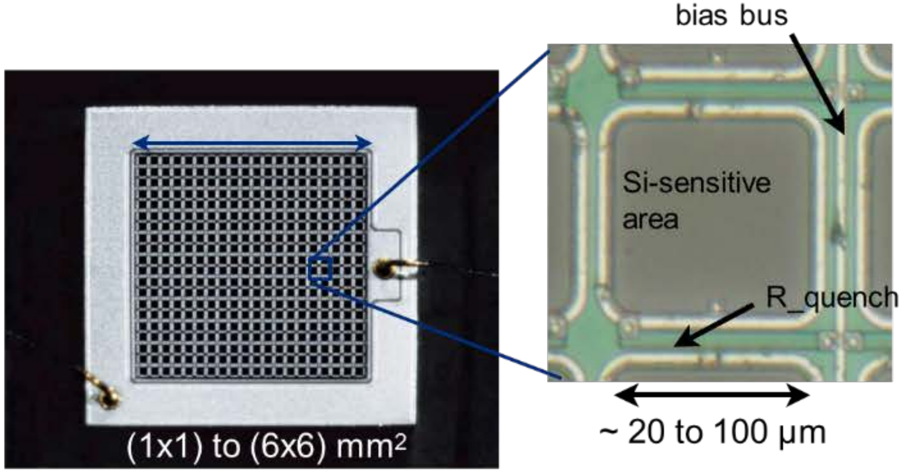
PIN Diode
- no bias
- no gain

AVALANCHE PHOTODIODE (APD)
- voltage
- secondary ionization from electrons
- avalanche
- linear regime

GEIGER MODE AVALANCHE (G-APD)
- V > V_breakdown
- secondary ionization from electrons and holes
- “broken” junction , avalanche
- Geiger regime, not linear anymore

SILICON PHOTOMULTIPLIER (SiPM) :
array of micro-cells operated in G-APD





nr cells ~ 100 to 15000 / mm^2

SiPM : array of micro-cells ***APD-like operated in G-mode*** connected to a **common bias** through **independent quenching resistors**, all integrated within a sensor chip.
The output is the **analogue sum of all cells**

individual cell (i.e. one diode, *APD-like*)

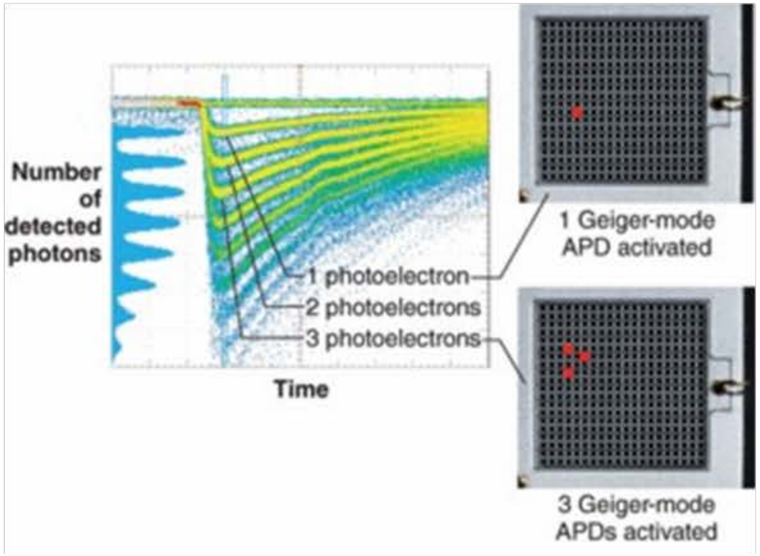
- Vbias > Vbreakdown
- Gain ~ 10^6 - 10^7
- Geiger regime (fully saturated)
- **No analogue info at the single cell level !**

- when hit by 1(2,3...n) photon(s)
  => full discharge
  => Qcell = Ccell (Vbias - Vbreakdown)

overvoltage

V_{OV}

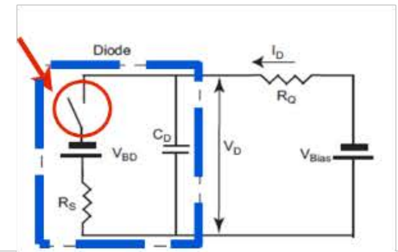
II. SiPMs: photon counting

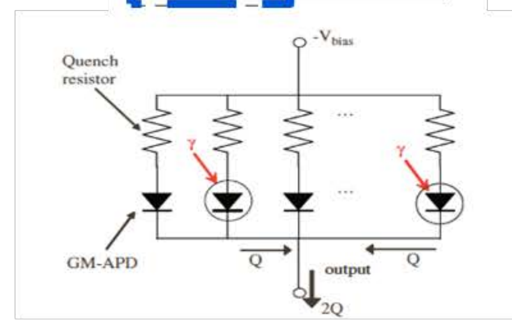


The output signal is 'quantized' and proportional to the Nr of fired cells

$$Q_{1cell} = C_{cell}\,\mathbf{V_{ov}}$$

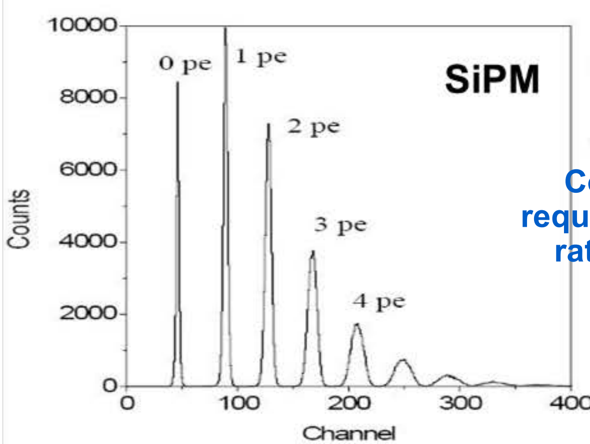
$$\mathbf{Q_{total} = N\,Q_{1cell}}$$



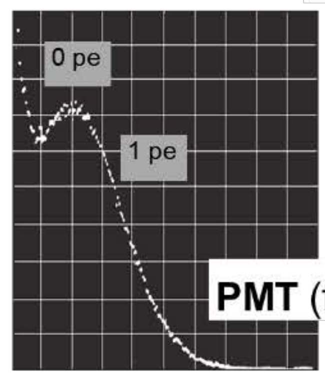


Excellent single photon counting capability

D. Renker, 2009 JINST 4 P04004

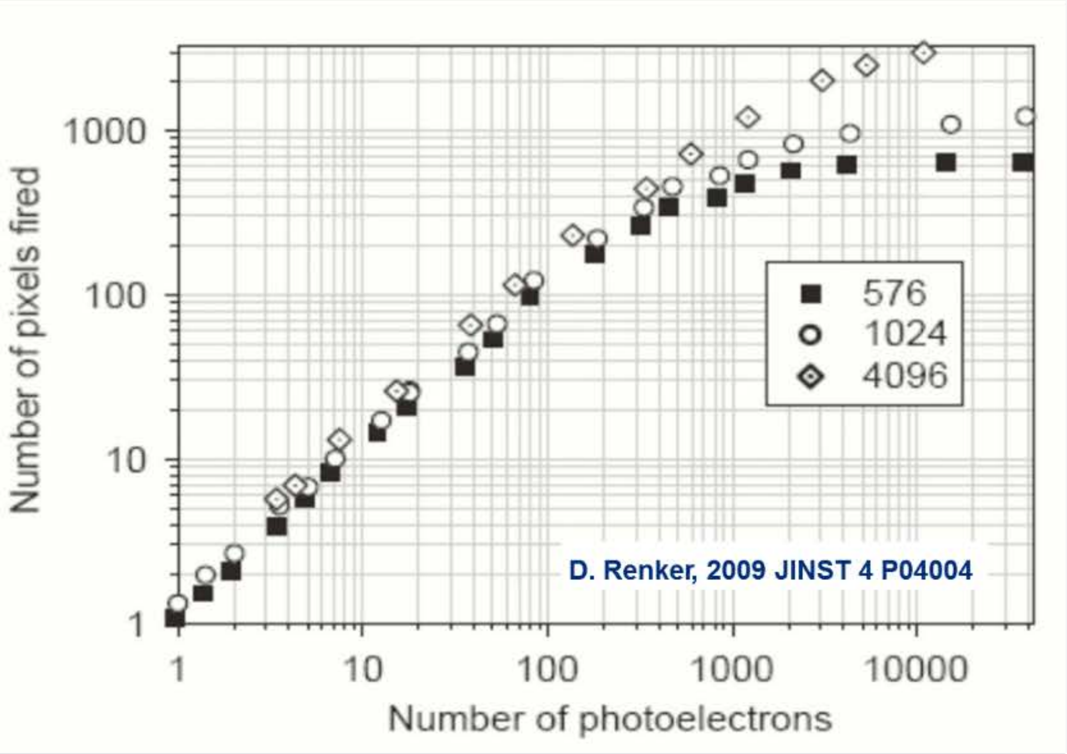


Cooling is required for low rates (DCR)



PMT (for comparison)

Intrinsic non-linearity in the response to high Nr incident photons

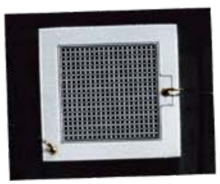


Linear but only as long as Nr_detected_photons < Nr_cells

after that : saturation

II. SiPMs: noise and drawbacks

the 'dark side' of SiPM



- dark counts
  impurities and/or thermal generation of free charges
  => permanent rate of avalanches not induced by photons

- cross-talk
  correlated noise : avalanches induced by the 'primary' avalanche in a neighbor pixel at the same time of the primary avalanche

- afterpulses
  correlated noise : avalanches induced by the 'primary' avalanche in the same pixel at a later time

Noise depends strongly on Vov and Temperature!

II. SiPMs: dark count

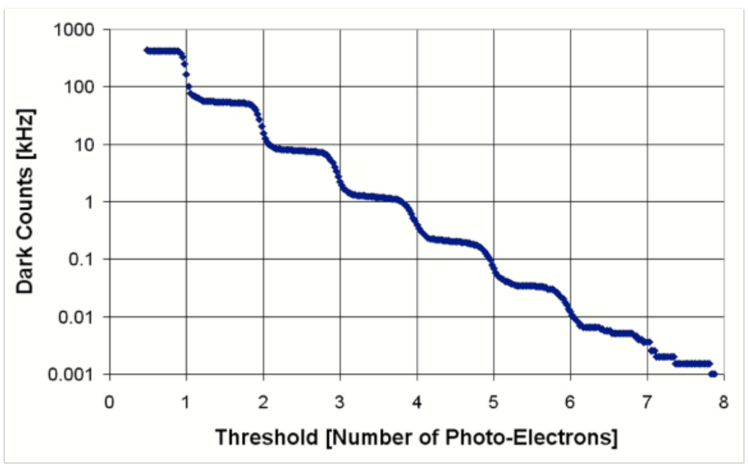
Counts registered by SiPM in absence of light
Due to **thermal generation** of charge carriers and/or tunnelling

typical values DARK COUNT RATES

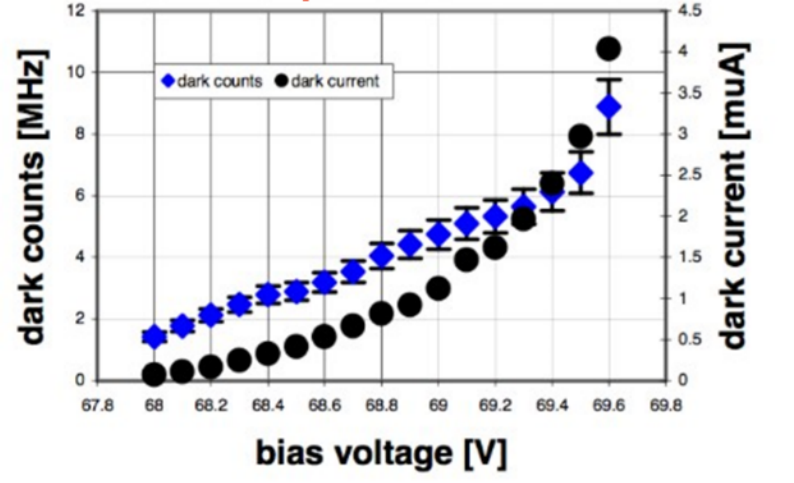
100 kHz - MHz / mm² (@0.5 pe thr)

- function of the triggering thr

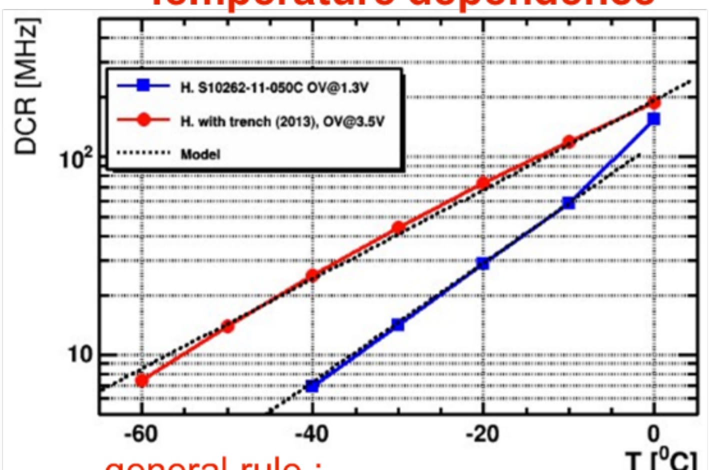
D. Renker, 2009 JINST 4 P04004



- Vov dependence



- Temperature dependence

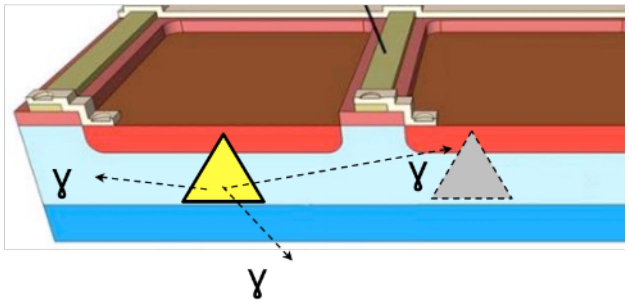


general rule :
dark rate is halved every ~ 8-10 K

Optical Cross Talk

During the avalanche a large nr of photons are produced { **O(1photon/10^5 charge carriers)** }
=> Reach neighbours pixels and start a second avalanche

correlated noise
contribution **added** to the primary signal
stochastic process => contributes to ENF

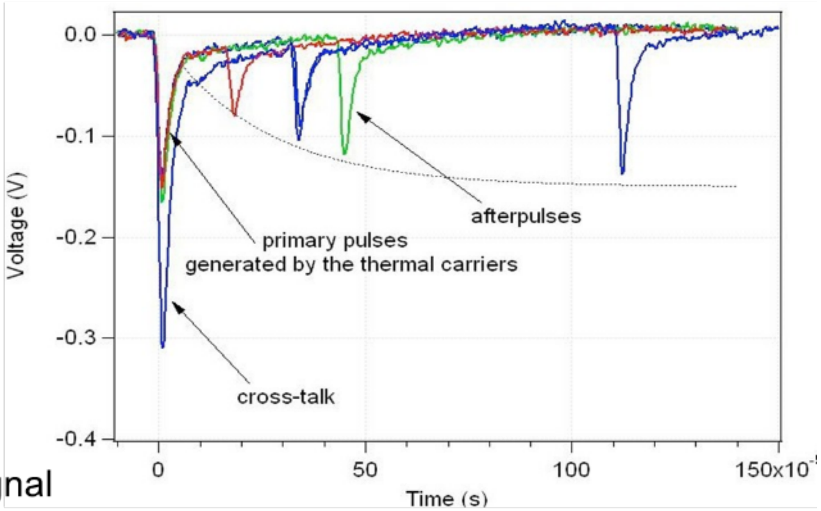


- larger Vov => larger gain => higher P_XT
- smaller pixel size => higher P_XT
- XT ~ 30 - 40 % (w/o trenches)
- significant impact of trenches = optical separation

Afterpulses

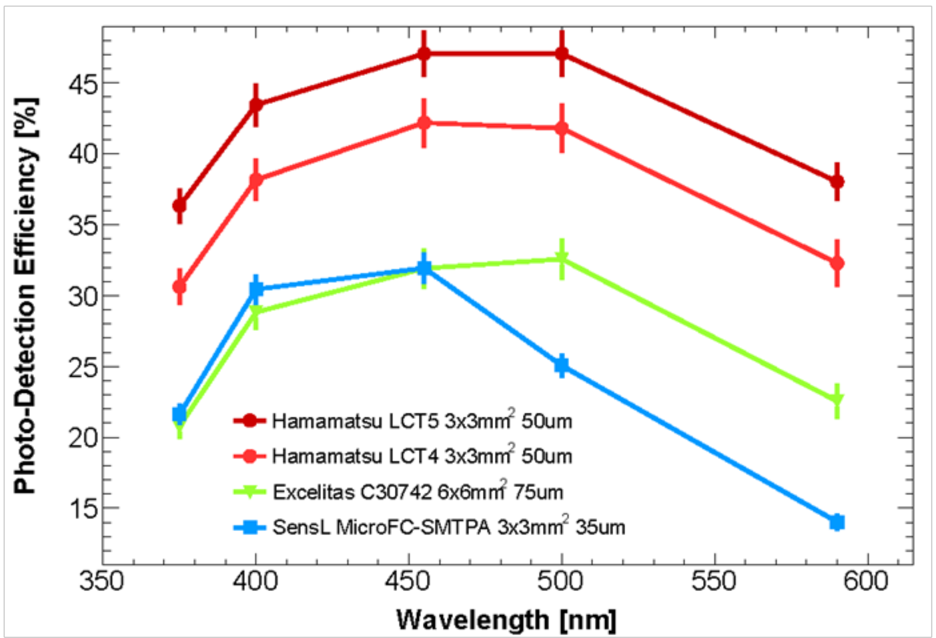
Charge carriers temporarily trapped in the lattice defects and released near the avalanche region (same cell) with some time delay

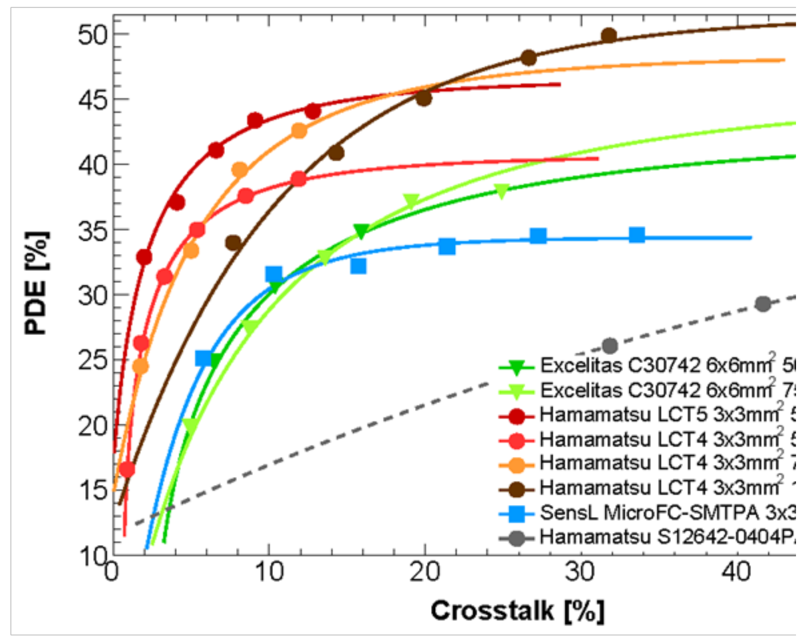
correlated noise
contribution delayed, occurring **after** the primary signal



II. SiPMs: state of the art

- High progress in SiPM technology: high PDE & low crosstalk
- DCR has been also reduced down to 100 KHz/mm^2
- Still a **trade-off between PDE and crosstalk** exists
- Also for other parameters: linearity, rate, etc
- **SiPM configuration** (pixel size, number, area, overvoltage, model) **has to been chosen accurately for each specific application**

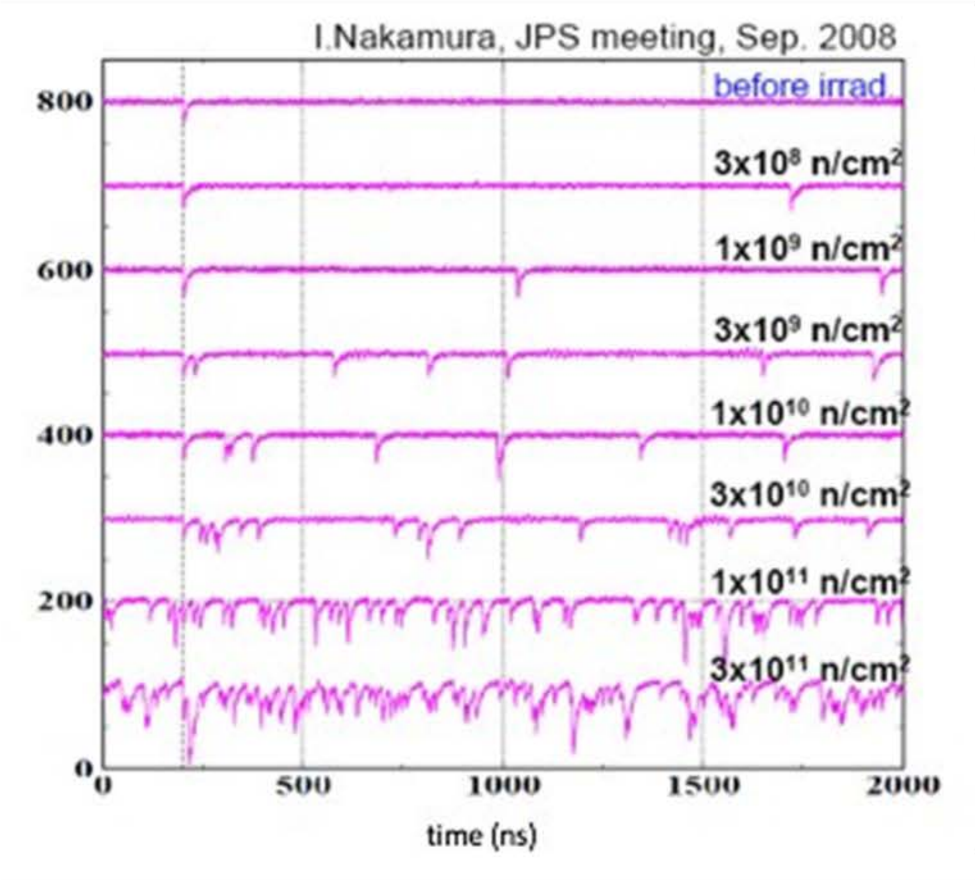


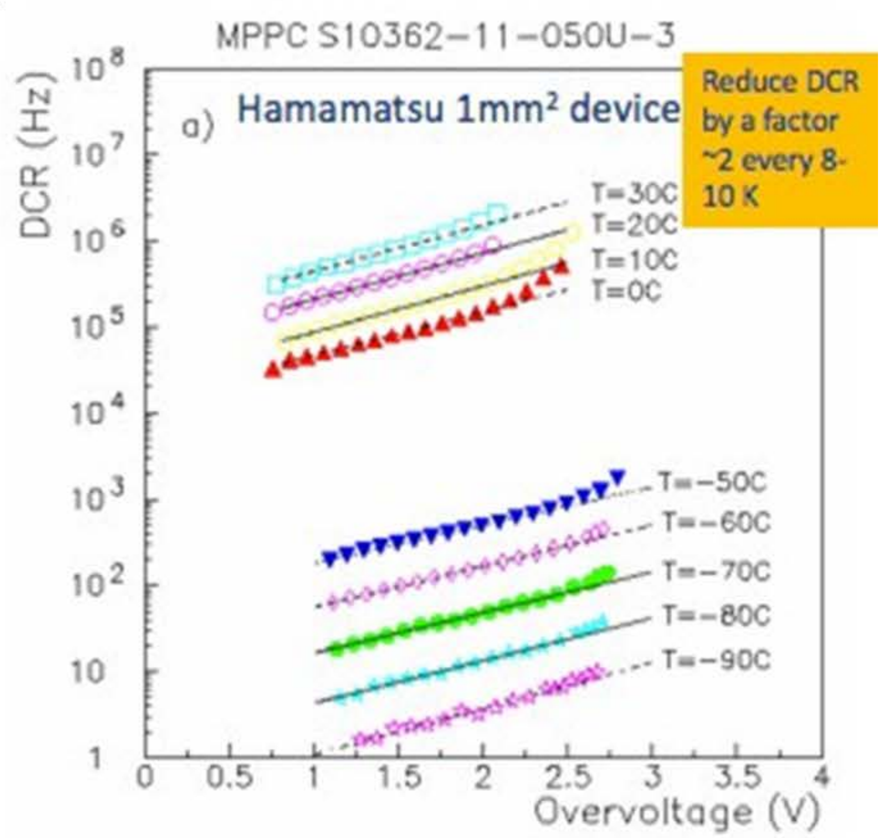


J. Biteau et alt. "Performance of Silicon Photomultipliers for the Dual-Mirror Medium Sized Telescopes of the Cherenkov Telescope Array", ICRC2015

II. SiPMs: radiation damage

Like the other Si devices, SiPM are sensitive to NIEL (Non Ionizing Energy Loss) damages by hadrons => damage of the Si lattice => increase in DCR and I_leakage





significant increase on DCR with irradiation

mitigated with COOLING !

II. SiPMs: solid state photodetectors

- PIN diodes
- APD (Avalanche Photo Diode)
- SiPM (Silicon Photomultiplier)

increasing gain ↓

increasing performance and technology ↓

time availability on the market ↓

Advantages wrt PMT

- **compact**
- **not sensitive to magnetic field**
- **robust**
- operated at low voltages
- high QE (lambda dependent)
- well established production methods
- integration in large system (large area)
- "pixelisation" (**high granularity device**)

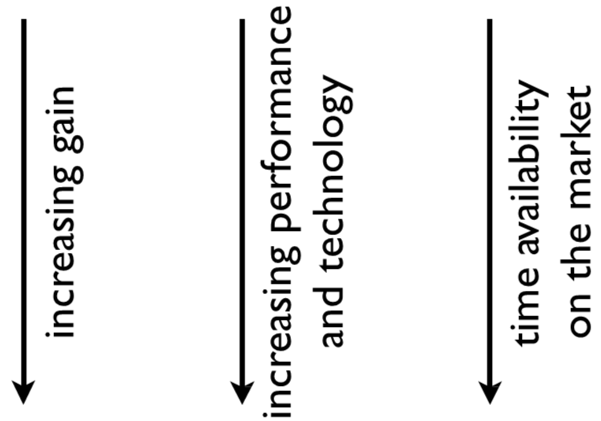
Disadvantages wrt PMT

- **dark rate**
- **temperature dependance** of response (gain) and noise

- PIN diodes

- APD (Avalanche Photo Diode)

- SiPM (Silicon Photomultiplier)



- detection of low light level (single photons detection)
- excellent timing performance

Applications in HEP

- **PIN / APD : Calorimetry**
- **SiPM : ~ Everywhere!! (compatibly with the maturity of the technology)**
  Calorimetry / Timing / Cherenkov single photon detection / Tracker...

note : not all applications are suitable for SiPM!!!

I. Motivation

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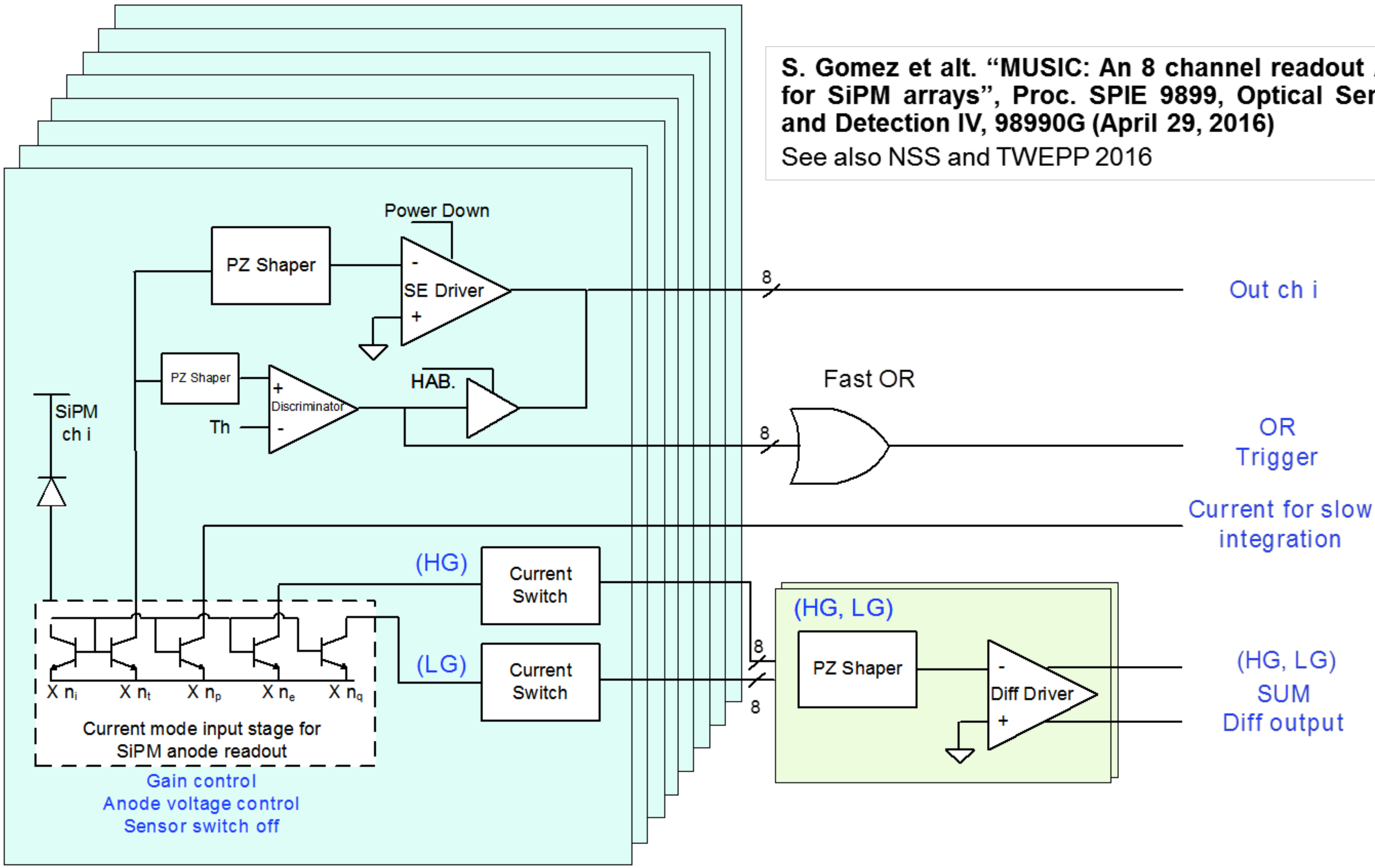
III. Signal processing: need

- Front end electronics for SiPM is needed to:
  - Adapt impedances
    - SiPM capacitances range from 30 pF to more than 1 nF
  - Preamplify to optimize the SNR
    - Even if "nominal" gain is in the order of 10^6 only a fraction of the charge is used for fast read-out systems
  - Shape the input signal
    - Large SiPM time constant may cause saturation or distortion because of pile up
  - Combine (sum) the signal of several SiPMs
  - Sometimes equalize over-voltage in SiPM arrays

III. Signal processing: example (MUSIC)

- MUSIC ASIC incorporates many of those functions:
  - It will be used to illustrate them

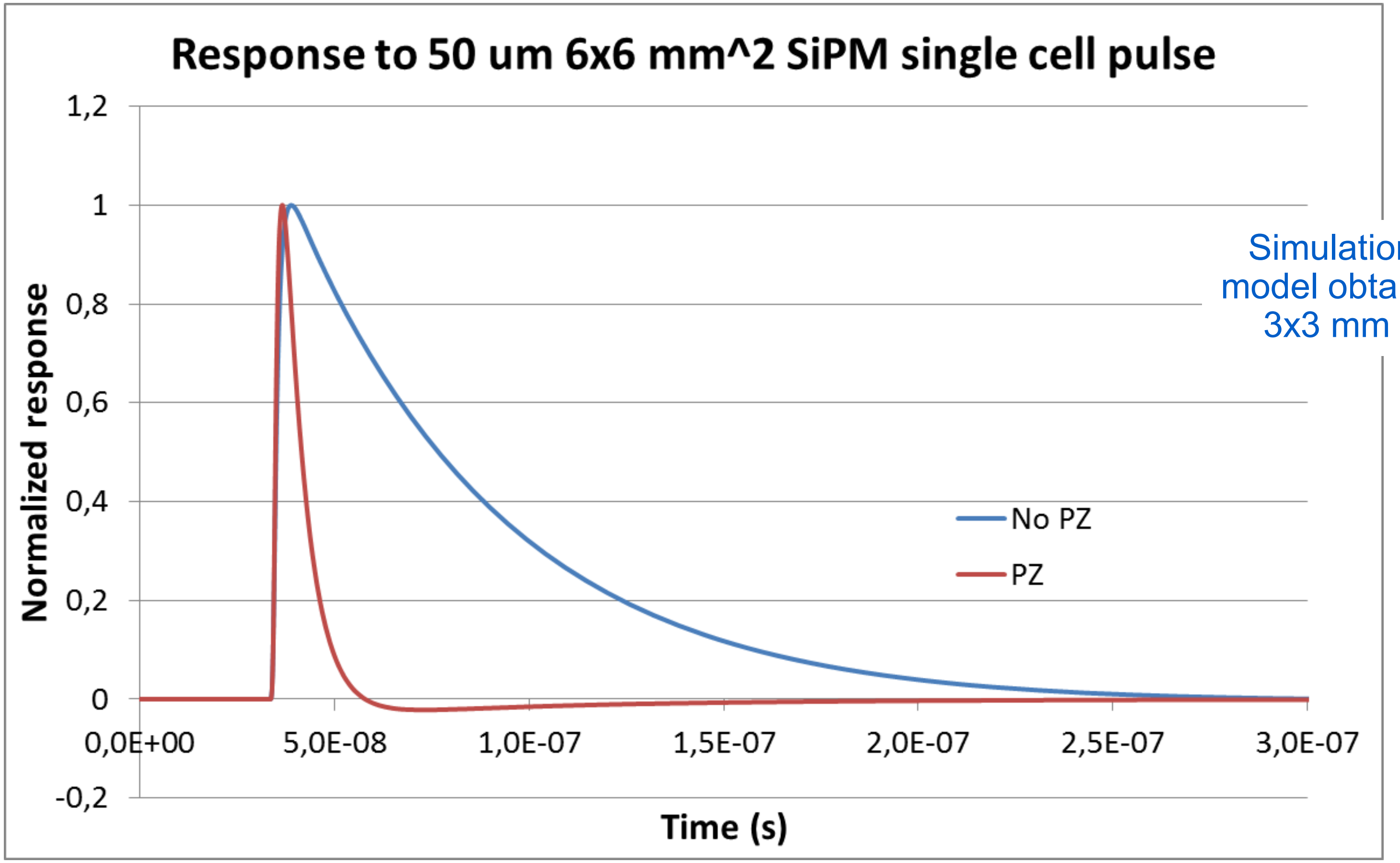


S. Gomez et alt. "MUSIC: An 8 channel readout ASIC for SiPM arrays", Proc. SPIE 9899, Optical Sensing and Detection IV, 98990G (April 29, 2016)

See also NSS and TWEPP 2016

Pole zero shaping

- Pole-Zero cancellation of the SiPM recovery time constant
- Parameters of the PZ cancellation are tunable to deal with different sensors
  - Up to 100 ns time constant
- After PZ cancellation: output pulse FWHM < 5 ns



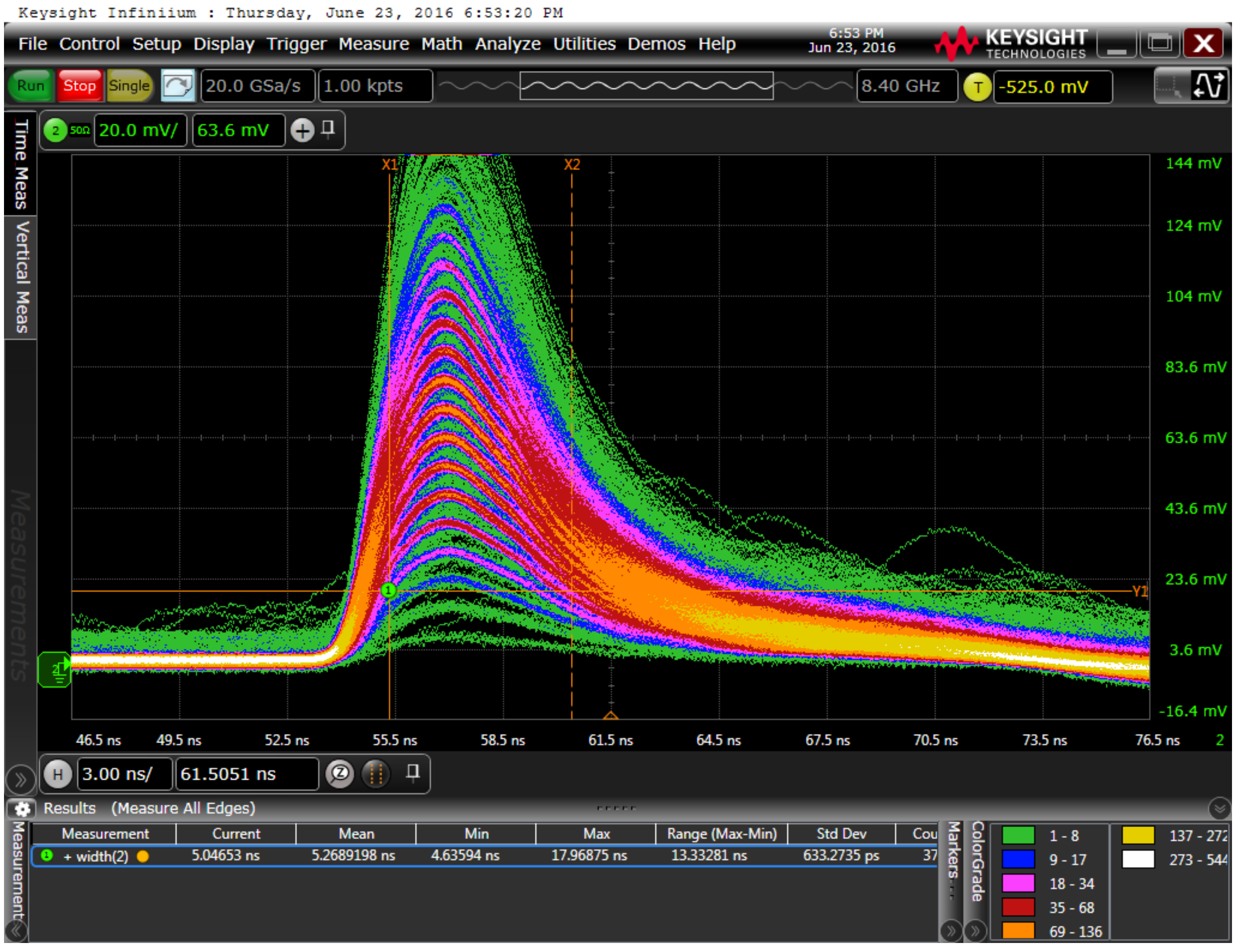
Simulation with a model obtained from 3x3 mm device

III. Signal processing: example (MUSIC)

- Output for a LCT4 MPPC (3x3 mm^2, 75 um cell)
- No pole-zero cancellation
- Large SiPM tail: pulse width > 100 ns

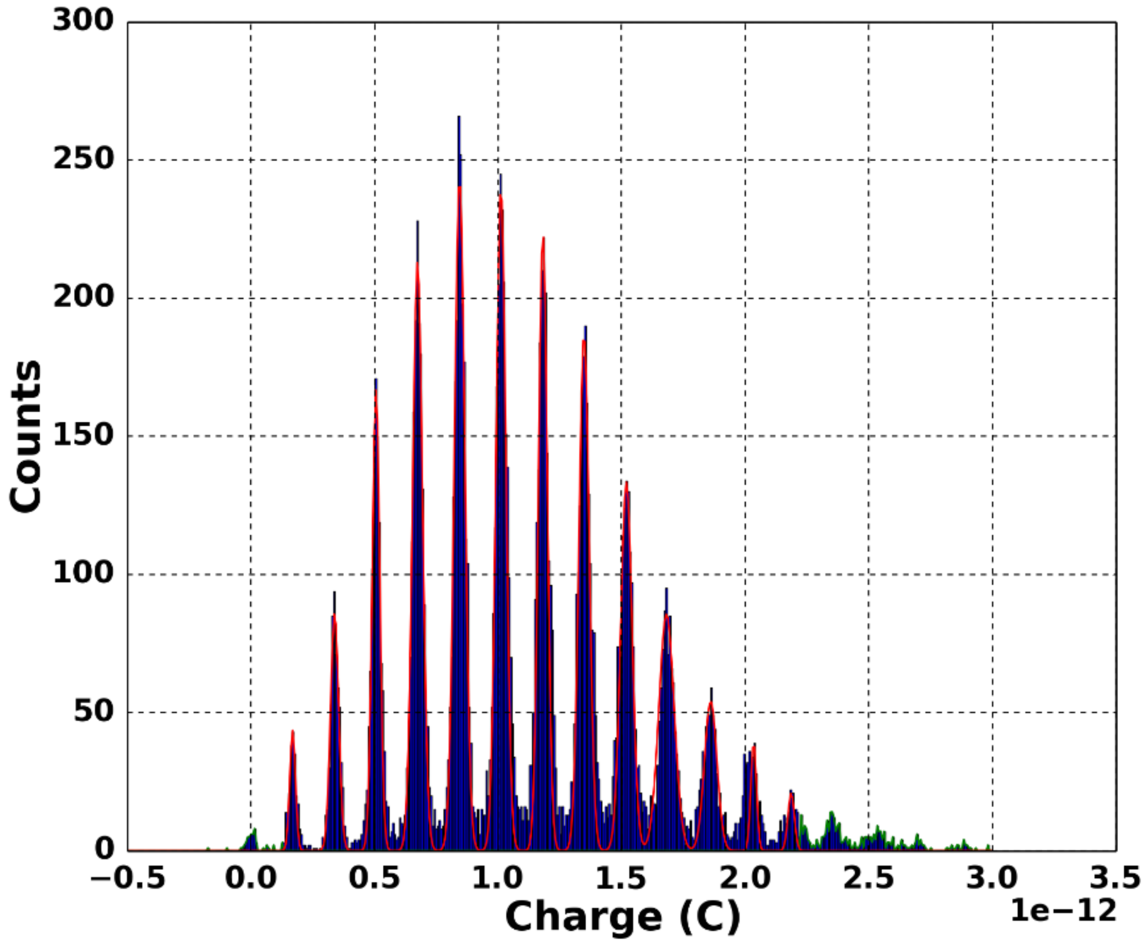
III. Signal processing: example (MUSIC)

- Output for a LCT4 MPPC (3x3 mm^2, 75 um cell)
- Pole-zero cancellation
- Excellent resolution with FWHM of about 5 ns
- Possible to reach 2-3 ns FWHM for other SiPM models



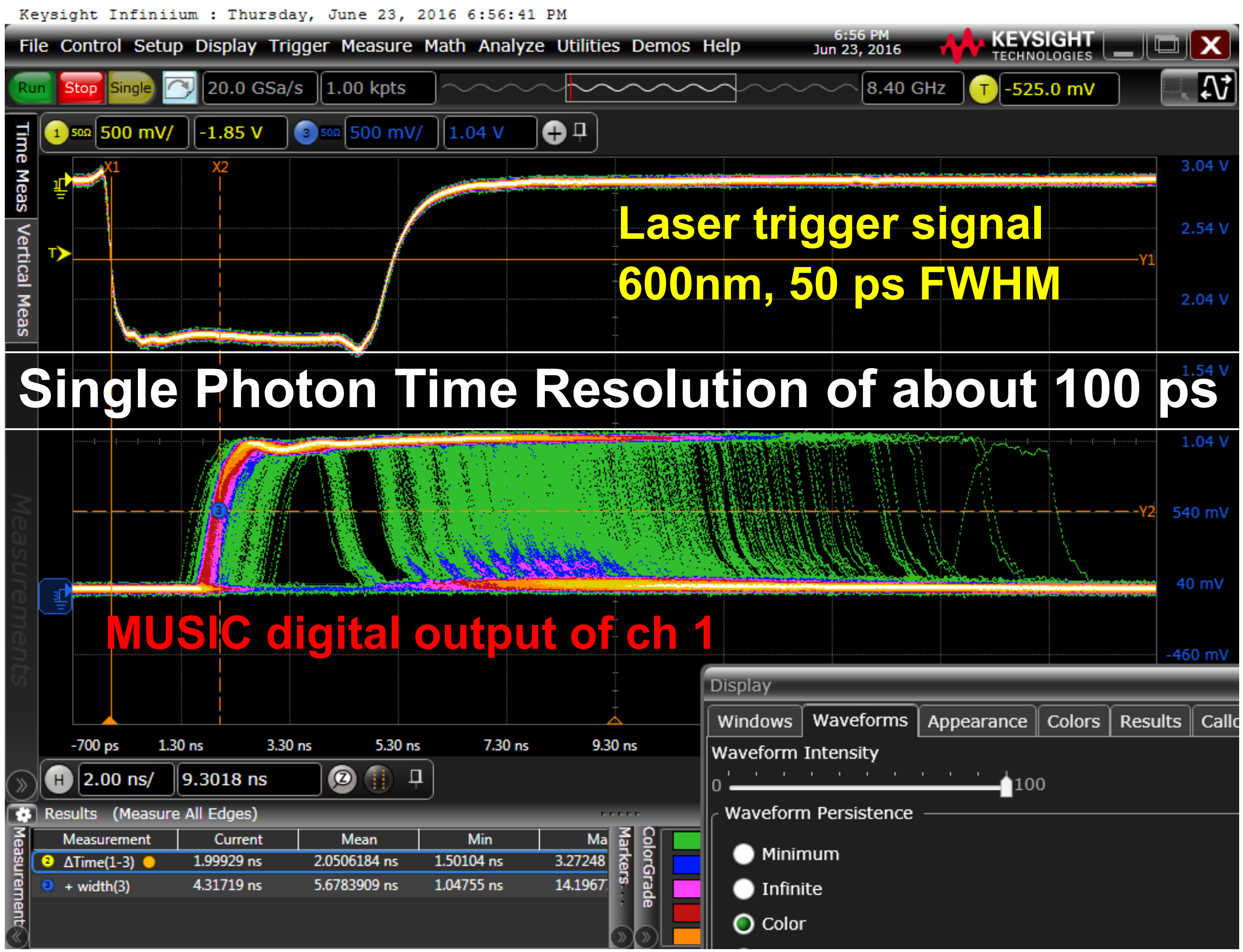
III. Signal processing: example (MUSIC)

- Charge spectrum for a LCT4 MPPC (3x3 mm^2, 75 um cell)
- Pole-zero cancellation
- Excellent resolution with FWHM of 5 ns



III. Signal processing: example (MUSIC)

- Binary output for a LCT4 HPKK MPPC (3x3 mm^2, 75 um cell)
- Pole-zero cancellation



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IV. Use in HEP: Scintillating Fiber Tracker

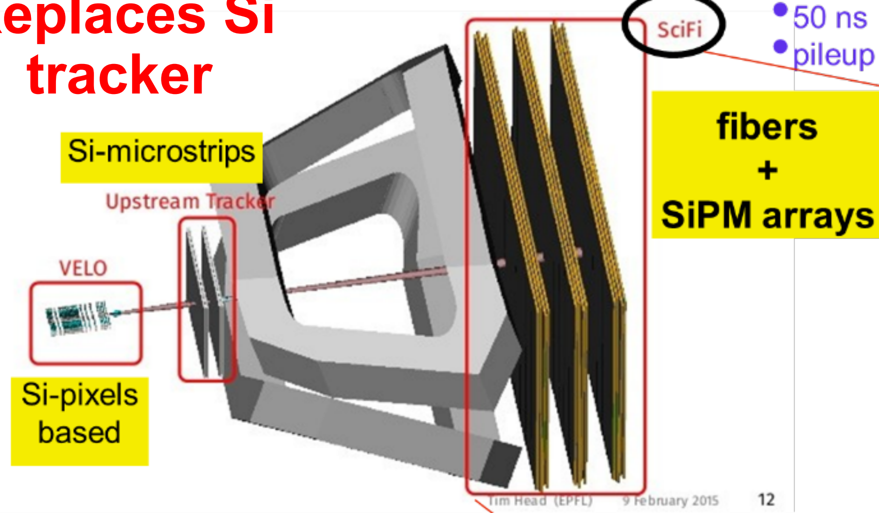
Institute of Cosmos Sciences

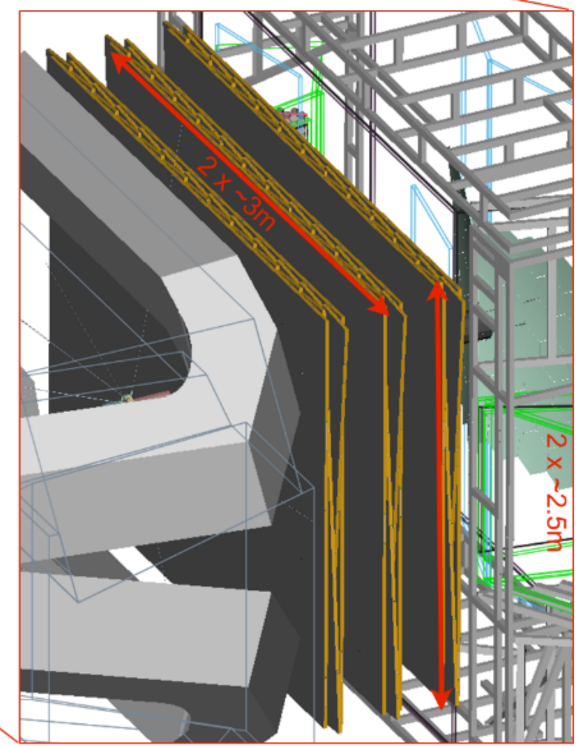
- **upgrade for the tracker system in LHCb experiment (LHC, CERN)**
- aim at the same performance as in current conditions with the high luminosity upgrade

current conditions	high luminosity upgrade
• $L < 4\ 10^{32}\ cm^{-2}s^{-1}$	• $L \sim 2\ 10^{33}\ cm^{-2}s^{-1}$
• 50 ns	• 25 ns
• pileup ~ 1.7	• pileup ~ 7.6
	• readout at interaction rate (40 MHz)

LHC Run3 (>2019)

Replaces Si tracker



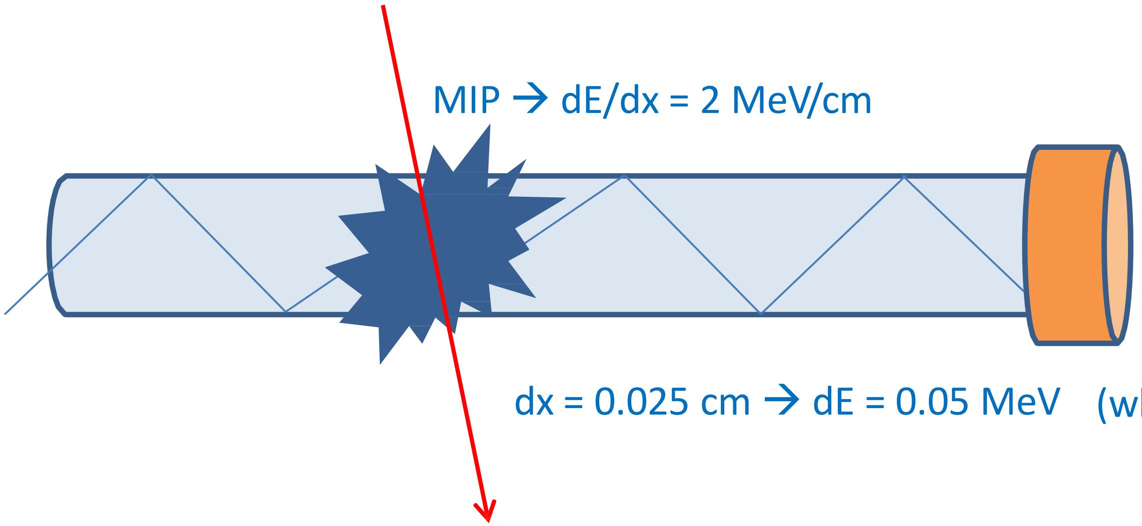


LHCb SciFi : not the first tracker based on scintillating fibers but the first one to face the demanding challenges of large dimensions / rates / radiation

Requirements :
- hit detection efficiency > 98% ; noise/signal cluster rate < 10%
- spatial resolution < 100 um
- 40 MHz readout
- radiation environment :
  scintillating fibers : up to 35kGy ionizing dose
  SiPM : $6\ 10^{11}\ n_{eq}\ /\ cm^2$ (with n shield) + 100 Gy ionizing dose

IV. Use in HEP: SciFi Tracker Fibers

Back-of-the-envelope estimate of photoelectric yield in a 0.25 mm double cladded fibre, 1 m from photodetector. <u>Non-irradiated.</u>



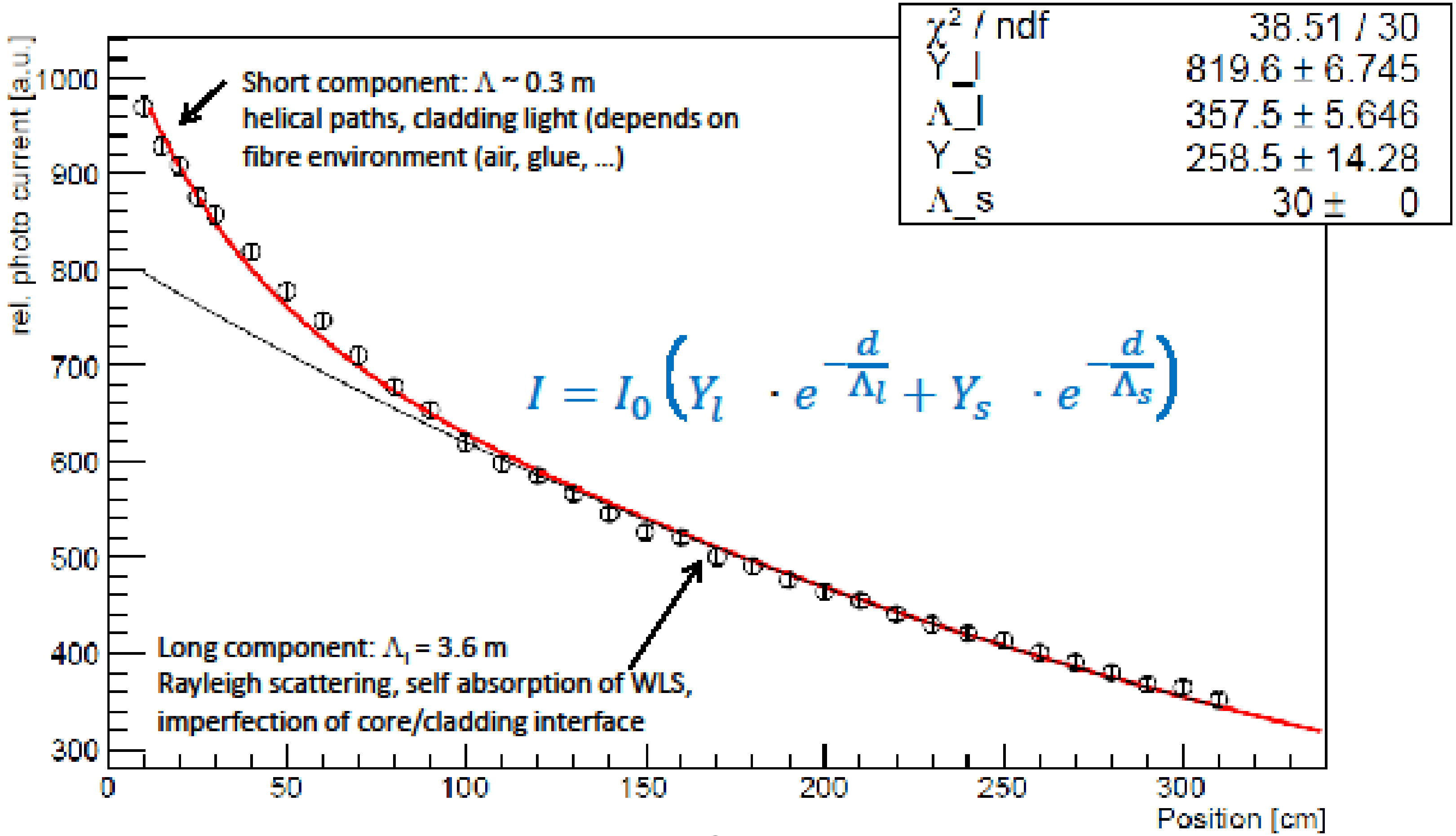
- Scintillation yield: dY_γ/dE = 8000 ph / MeV → Y_γ = 400
- Trapping inside fibre (1 hemisphere): 5.4% → $Y_\gamma \sim$ 20
- Attenuation losses over 1 m: 22% → $Y_\gamma \sim$ 16
- Efficiency of photodetector (typ. PMT): 25% → $Y_{p.e.} \sim$ 4

→ Need more traversed fibre thickness → increase thickness in particle direction (fiber stack)
→ Need higher photodetector efficiency → SiPM with PDE ~ 50 %
→ Need to recover light in the second hemisphere → mirror at the fiber end

IV. Use in HEP: SciFi Tracker Fibers

The majority of SciFi R&D and prototyping has been performed with SCSF-78MJ, Ø 0.25 mm, from Kuraray (JP).

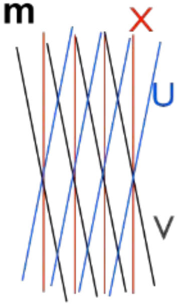
Attenuation in a 3.5 m long SCSF-78 fibre (Ø 0.25 mm) in air, averaged over emission spectrum



$$I = I_0\left(Y_l \cdot e^{-\frac{d}{\Lambda_l}} + Y_s \cdot e^{-\frac{d}{\Lambda_s}}\right)$$

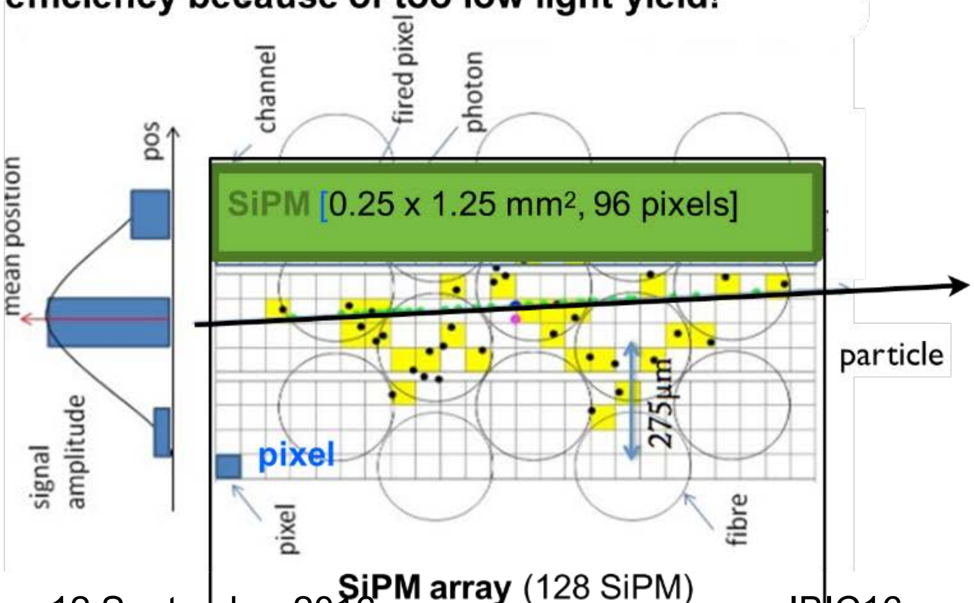
IV. Use in HEP: SciFi Tracker Modules

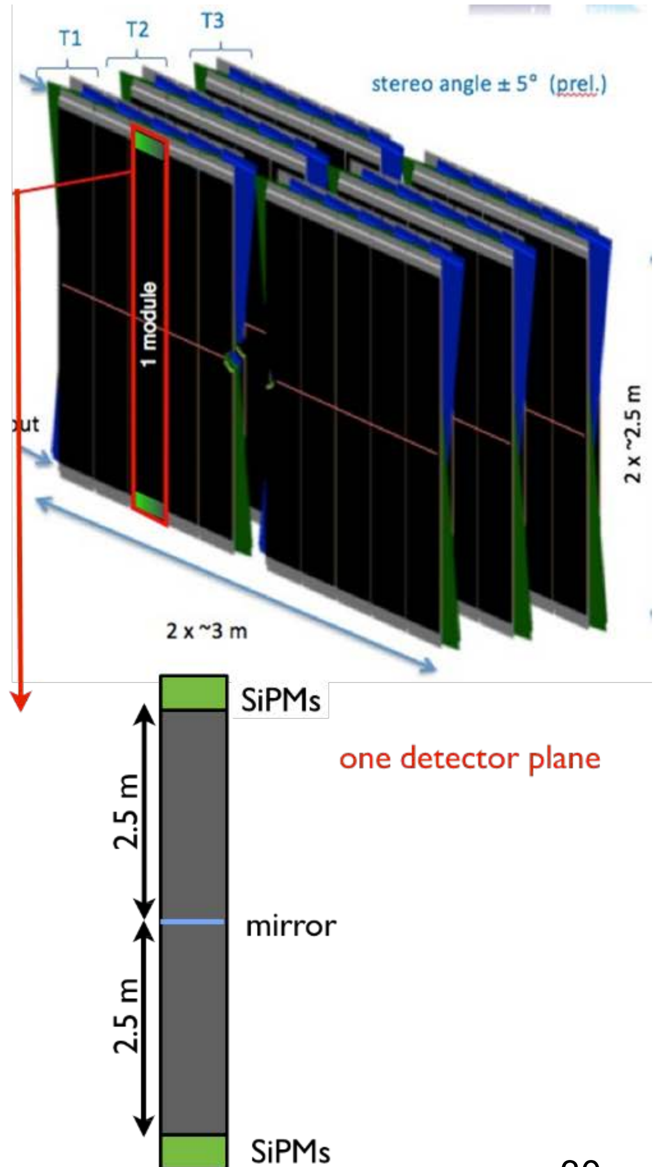
- **scintillating fibers ∅ = 250 µm ; L = 2.5 m**
- assembled in modular geometry :
  - 3 tracking stations
  - 4 planes / station ("XUVX" stereo)



- each plane : **stack of staggered layers**
  6 layers close to the beampipe
  5 layers elsewhere

A single fiber cannot guarantee 100% hit efficiency because of too low light yield!





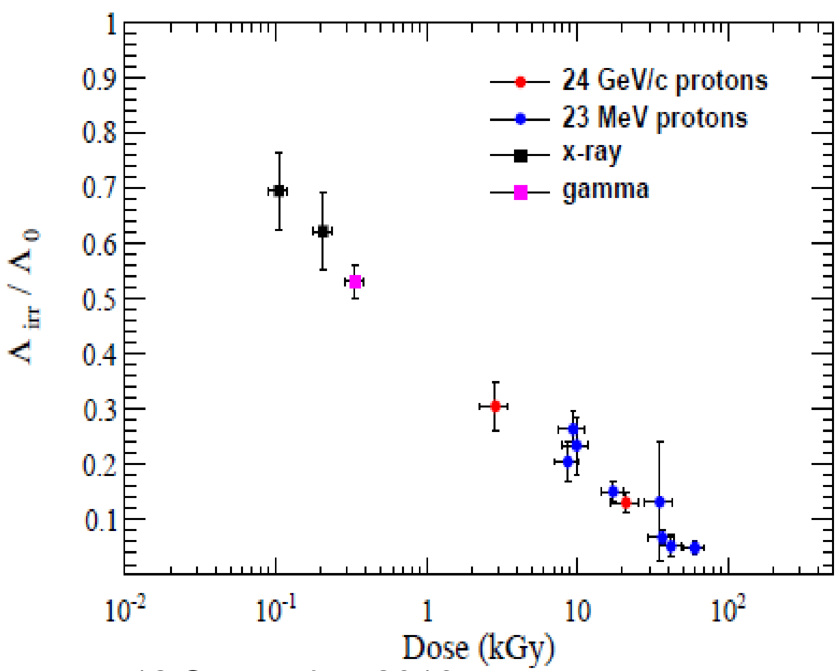
IV. Use in HEP: SciFi Tracker Radiation

Institute of Cosmos Sciences

Main radiation damage is transparency loss → decreasing attenuation length

Summary of SciFi irradiation experiments

Beam Type	Facility	Doses (kGy)	Dose rate (kGy/h)
24 GeV/c protons	CERN PS	3, 22	1.7, 0.4
24 MeV protons	KIT	9 – 60	$1.8 \cdot 10^3$
F^{18}(e^+ to 511 keV γ)	CERN/AAA	0.5	$\sim 2 \cdot 10^{-2}$
35 kV x-ray	Uni. HD	0.1, 0.2	$3.5 \cdot 10^{-3}$



The irradiation tests suggest

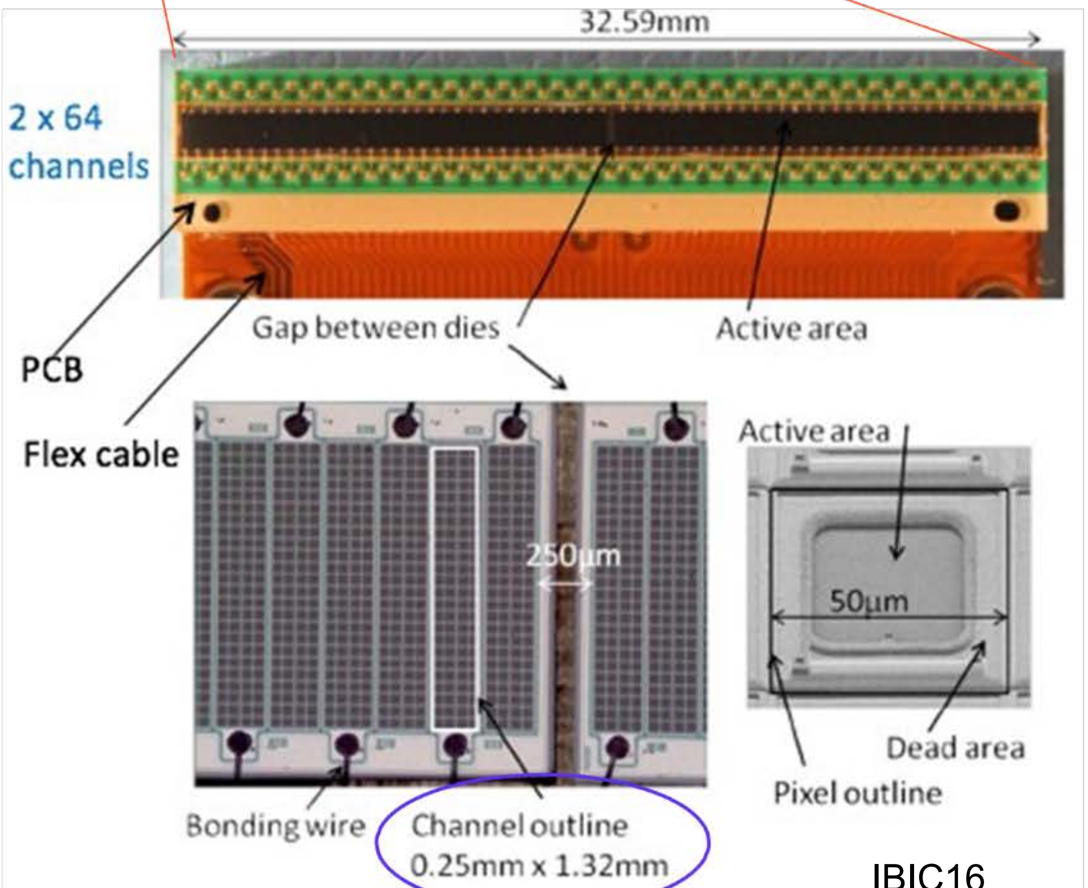
- A early onset of the damage (Λ/Λ_0 ~ log D)
- No strong effect of dose rate visible
- Recovery effects not clearly established

Combination of dose distribution and damage-vs-dose relation let us expect, at the end of the lifetime of the detector, a signal reduction by about 40%.

IV. Use in HEP: SciFi Tracker SiPMs

custom developments by **Hamamatsu** and **KETEK** are meeting the requirements

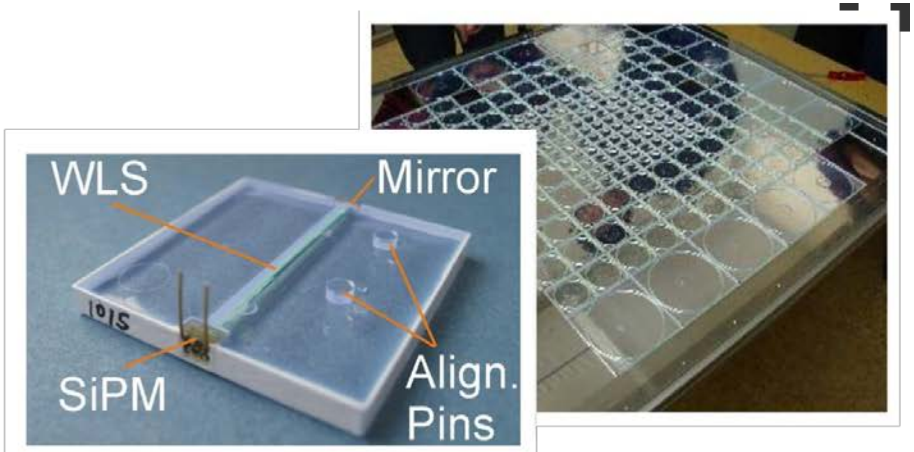
one SiPM array = 128 SiPMs (splitted in 2x64ch monolithic arrays)
for yield and reliability reasons



SiPM = "channel"

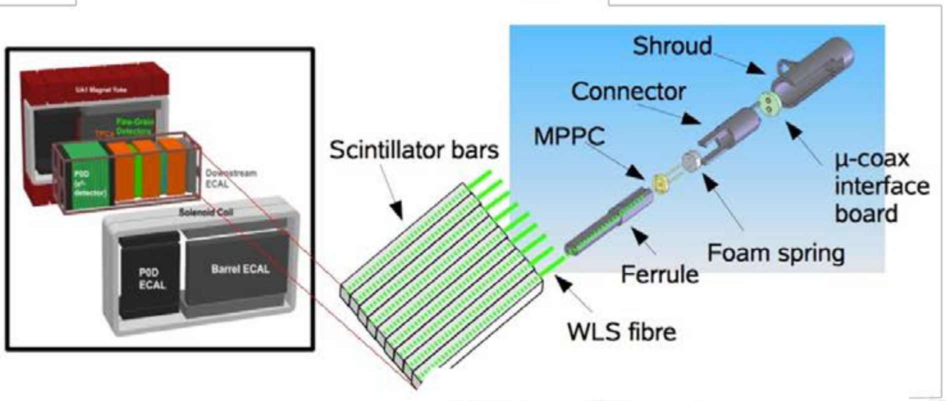
- 96 pixels/channel
- area/channel : 0.4 mm2
- pixel size ~ 50 µm (large=>PDE)
- **with trenches**
- **<100 µm epoxy (Hamamatsu) / glass (KETEK) protection layer**

IV. Use in HEP: **others**



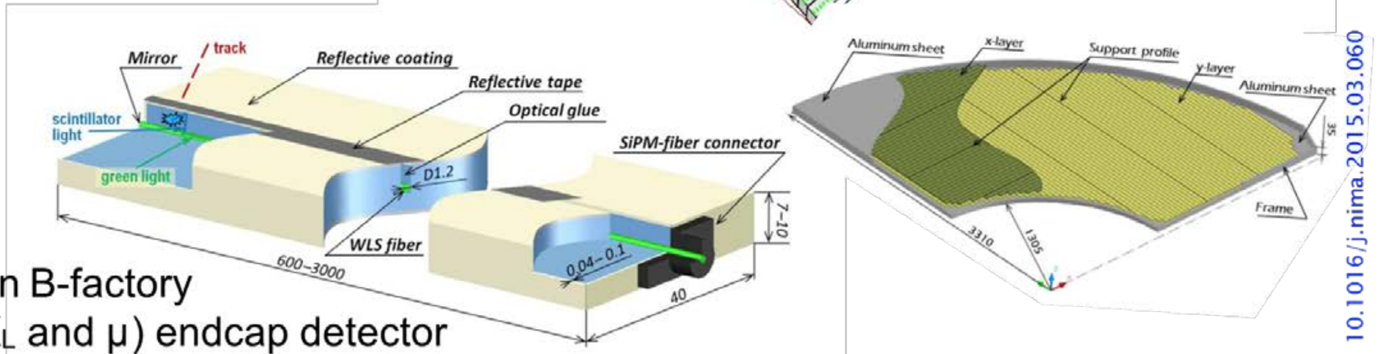
CALICE Analogue HCAL

- for future linear collider detectors
- high granularity calorimeter for particle flow applications
- scintillator tiles individually readout by SiPM through WLS fibers
- first large scale SiPM application in HEP



T2K experiment

- long-baseline neutrino experiment
- off-axis near detector
- electromagnetic calorimeter for the ND280



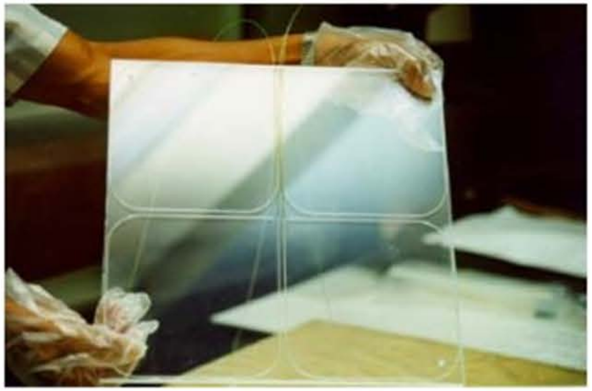
Belle II

- new generation B-factory
- for the KLM (K_L and μ) endcap detector

IV. Use in HEP: **others**

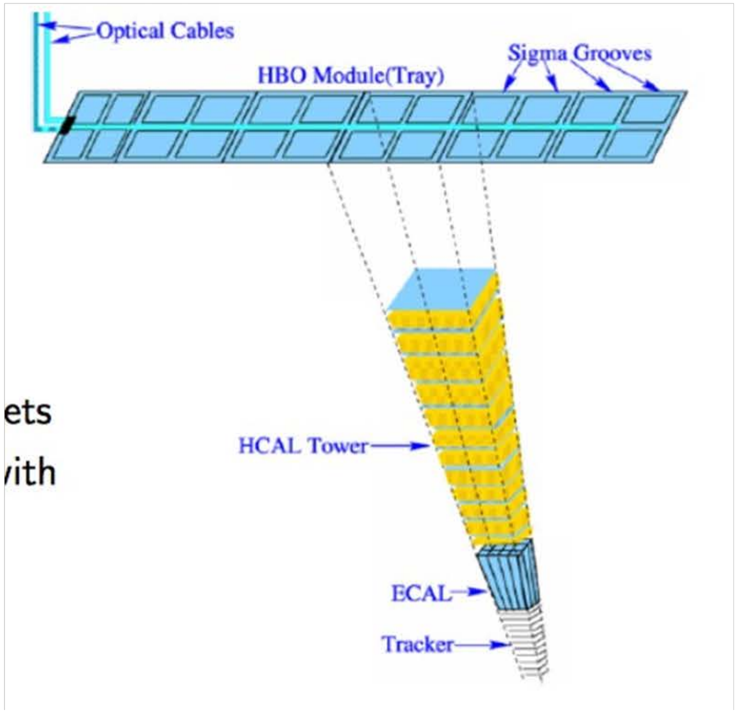
CMS HCAL HO (Outer Hadron Calorimeter)

- part of the HCAL as "tail catcher"
- outside magnet (still in return yoke field)
- actually the first large-scale (~ 1600 SiPM) operating in hadron collider
- replaced the HPD (during LS1)



arXiv:1408.5709

- scintillator tiles with WLS fibers



CMS HCAL UPGRADE

- SiPM will replace the HPD

I. Motivation
II. SiPMs: state of the art
III. Signal conditioning
IV. Use cases in HEP
V. Possible applications for accelerator beam instrumenation

V. Possible applications for accelerator BI

- SiPMs could be used in nearly any possible PMT application
  - Scintillator detectors:
    - Large dynamic range: 14-15 bits
  - Cherenkov detectors:
    - High PDE: near 50 %
  - Single photon detectors and photon counting
    - Short pulses (< 5ns) after correct shaping.
    - High time resolution (single photon time resolution around 100 ps)
- Possible exceptions:
  - Radiation damage:
    - SiPMs are very sensitive to NIEL
    - Can be alleviated: cooling (DCR), shielding, use optical fibres
  - Large area photo-detection:
    - Large area PMTs are still quite cost competitive
    - Depends on the evolution of the market

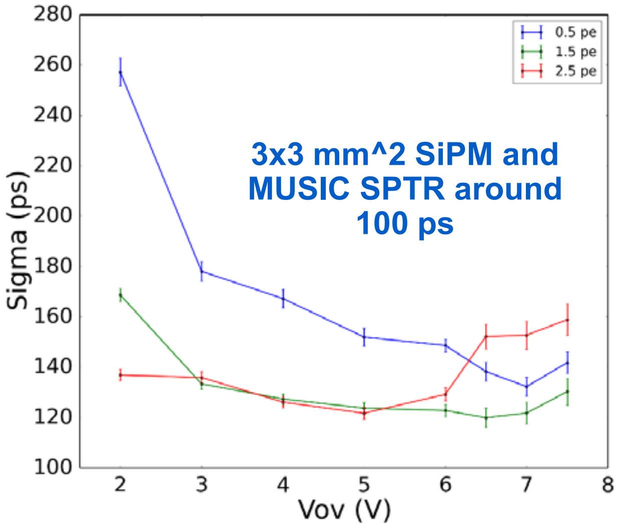
V. Possible applications for accelerator BI

- Beam loss monitors based on scintillators and Cherenkov effect
  - For Optical Fibre BLM based on Cherenkov effect, high PDE SiPMs can be very useful as Cherenkov light yield is rather low
  - An optical BLM based on scintillating fibres can be useful in low radiation environments
  - See 1962 - TUPG20 and 2060 - WEPG20
- Transverse Profile Monitors based on scintillating fibers and others
  - See 1691 - MOPG76, 2084 - WEPG64 and 2119 - WEPG70
- Can the experience from SciFi tracker be useful ?

E. Rojatti et al. "SCINTILLATING FIBERS USED AS PROFILE MONITORS FOR THE CNAO HEBT LINES" Proceedings of IPAC2015, Richmond, VA, USA

V. Possible applications for BI

- Time Correlated Single Photon Counting (TCSPC)
  - See 2104 - MOPG59
  - By correct choice of SiPM and front end electronics excellent performances can be obtained
  - Cooling might be required for low DCR



Martinenghi et al. "Time-resolved single-photon detection module based on silicon photomultiplier: A novel building block for time-correlated measurement systems", Rev. Sci. Instrum. 87, 073101 (2016)

TABLE I. Performances of the most commonly used PMTs for diffuse optics application and comparison with the SiPM module.

Manufacturer	Name	Area (mm^2)	QE 600 nm (%)	QE 800 nm (%)	SPTR (ps)	DCR (kcps)	Cooled
Hamamatsu Ltd.	R7400U-20	50.2	16.5	7.7	n.d.	<0.4	N
Hamamatsu Ltd.	R5900-20-M4	4 × 81	15.0	7.0	320	n.d.	N
Becker & Hickl	PMC-100	50.2	10.3	4.6	180	0.2-0.5	Y
Becker & Hickl	HPM-100-50	7.1	15.0	13.0	130	0.5-3	N
Picoquant	PMA-192	50.2	18.0	8.0	150	<3	Y
	SiPM module	1	29.9	10.1	100	~100	Y

Acknowledgements

- Many thanks to Chiara Casella (MIB) and Christian Joram (CERN) for the material on SiPMs and HEP applications
- And to the members of our team: A. Casajus, D. Ciaglia, G. Fernandez, D. Gascon, S. Gomez, R. Graciani, J. Mauricio, E. Picatoste, N. Rakotonavalona, D. Sanchez, A. Sanuy

Thanks a lot for your attention !!!

Questions ?

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