SiPM overview

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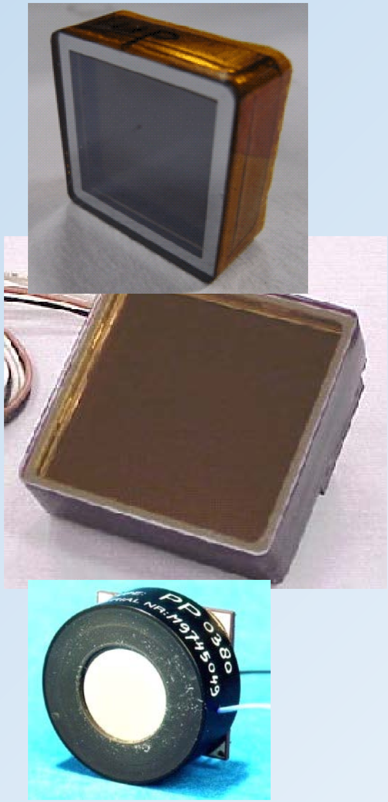
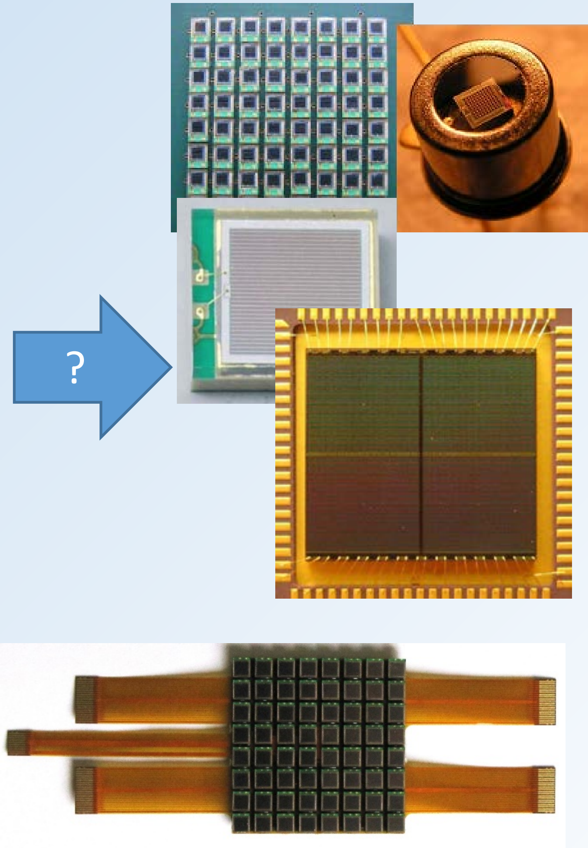
Outline:

- SiPM basics (operation, PDE, signal gain, noise ...)
- Detection of single Cherenkov photons with SiPM (ARICH, FARICH)
- TOF-PET coincidence timing with Cherenkov light
- Summary



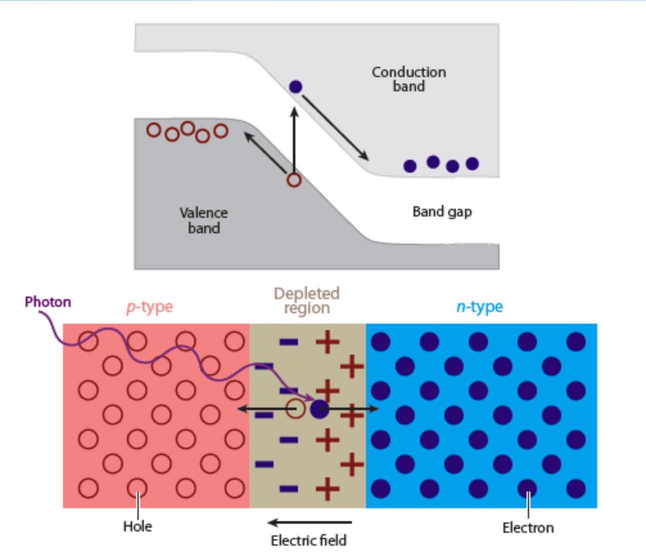


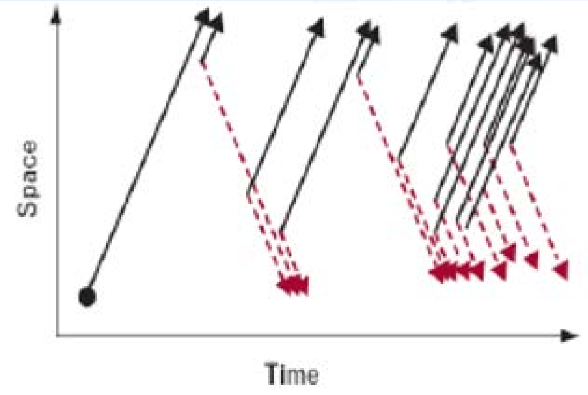
SiPM

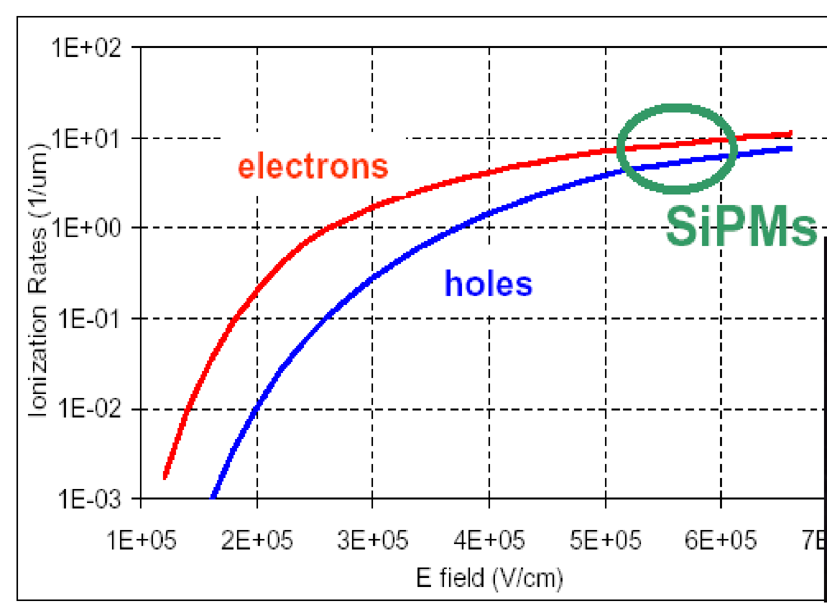
An array of APDs operated in Geiger mode – above APD breakdown voltage (microcells or SPADs – single photon avalanche diodes)

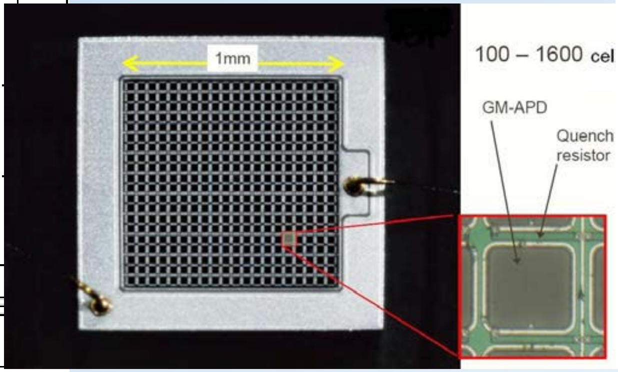
Detection of photons:

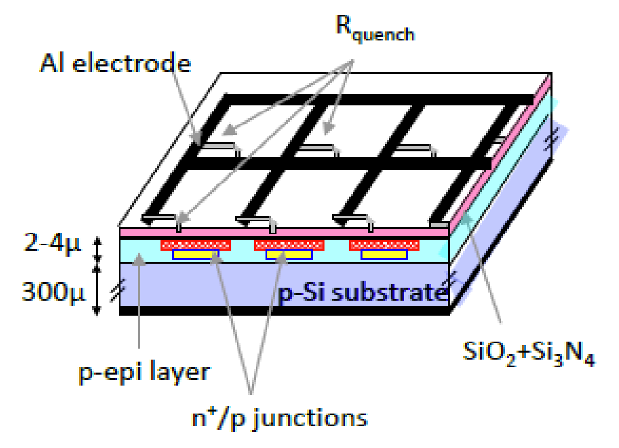
- absorbed photon generates electron-hole pair (QE,ϵ)
- avalanche is triggered by the carrier in the high field region $(P_{trig}) \rightarrow$ signal
- voltage drops below breakdown and avalanche is quenched (passive or active quenching)
- each triggered microcell contributes same amount of charge to the signal



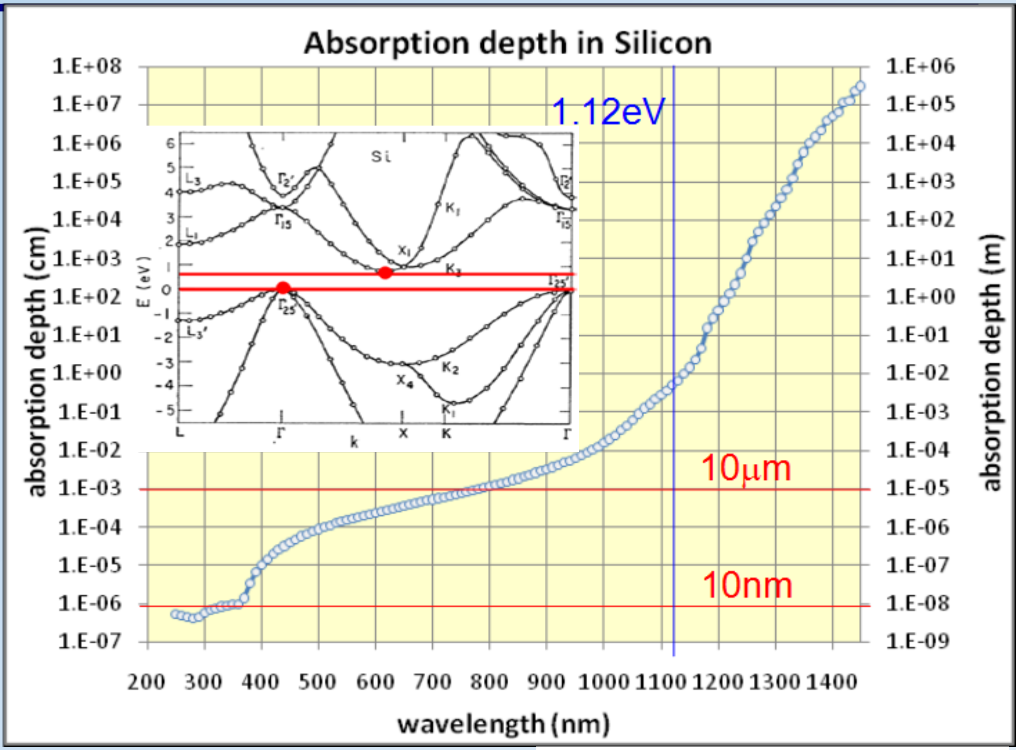








SiPM: PDE



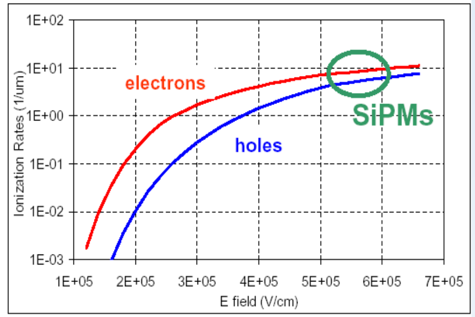
Three main contributions:

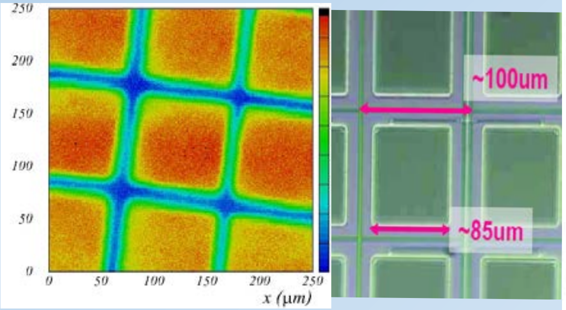
$$PDE = QE \times \epsilon_{geo} \times P_{trig}$$

- QE depends on surface reflections

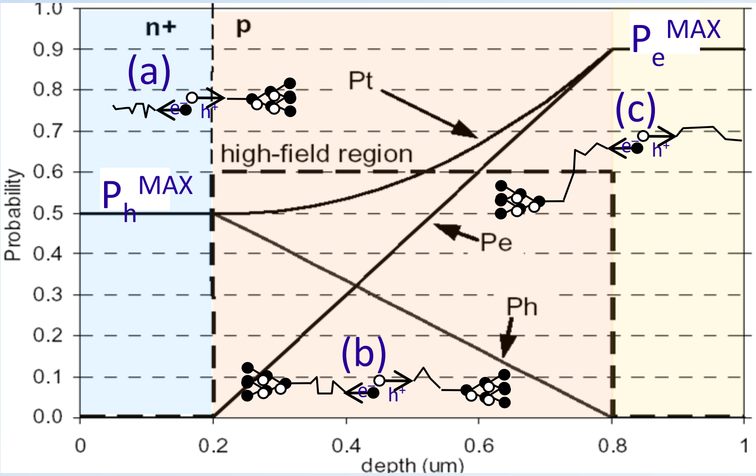
  $n \approx 5 \rightarrow R \approx \left(\frac{4}{6}\right)^2$ = 44%

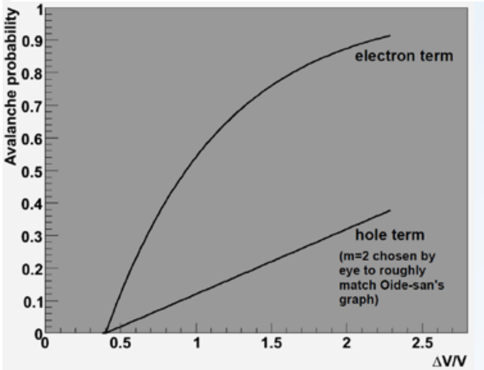
  → antireflective coating, large variation in absorption length → loss of efficiency:
  - absorption at the surface for short λ
  - transparent for long λ
- geometrical efficiency (ϵ_{geo})– active to total area, reduced by traces, quenching resistors, tranches ...
- triggering probability(P_{trig})





Hamamatsu

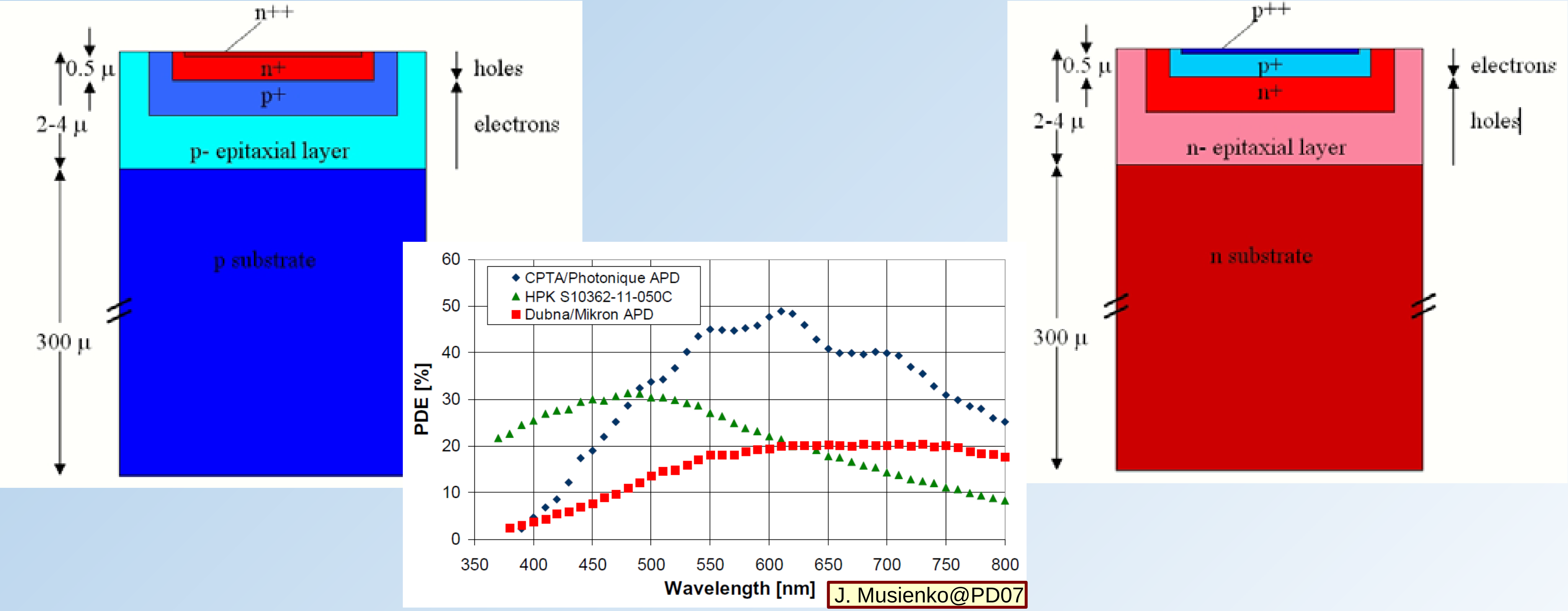




SiPM: p-on-n vs. n-on-p

n-on-p: green/red light sensitive:
- electrons drift to Geiger region from substrate and holes from surface side
- higher dark count rate – most of the thermally generated carriers arriving to Geiger region are electrons

p on n - green/blue light sensitive:
- electrons drift to Geiger region from surface and holes from substrate side
- lover dark count rate – most of the thermally generated carriers arriving to Geiger region are electrons



J. Musienko@PD07

SiPM: signal basics

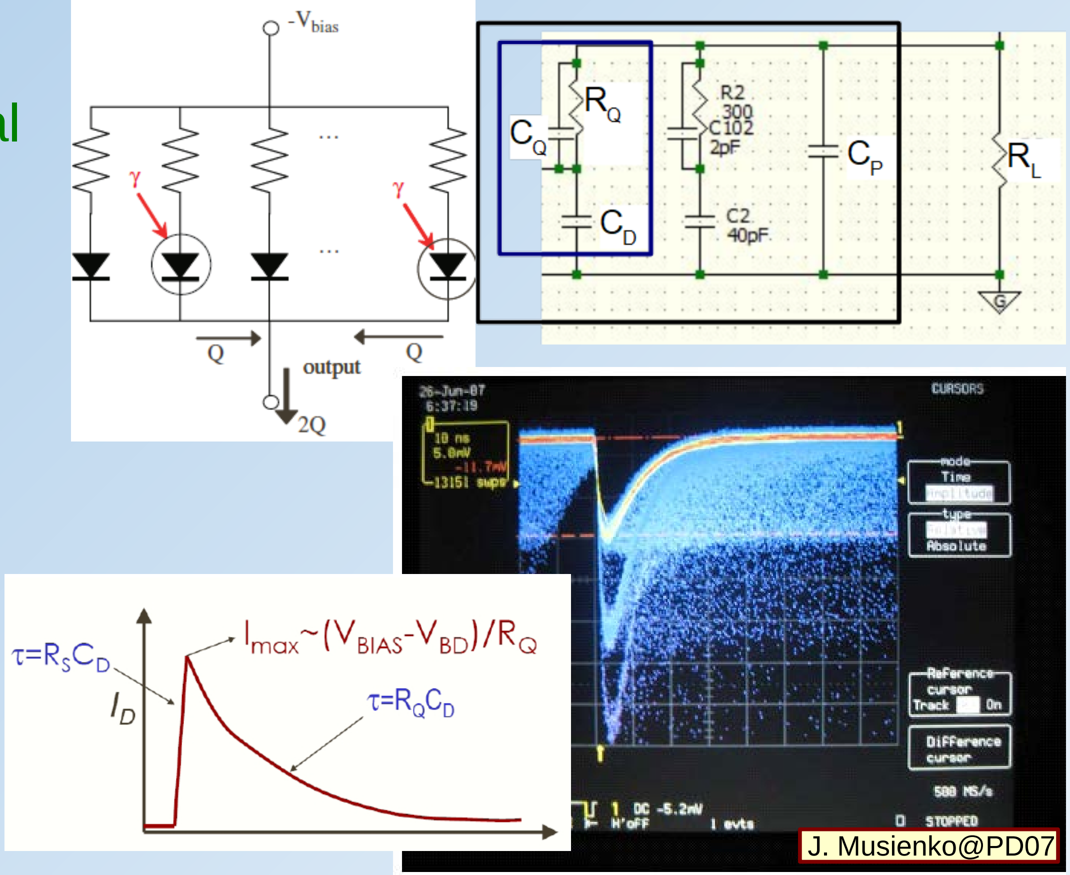
- each triggered microcell contributes equal amount of charge to the signal with a gain

$$G = C_{m.c.} \cdot (V_{bias} - V_{bd})/e_0$$

- large gain $\approx 10^5 - 10^7$
- fast rise time $\approx 100\ ps$
- relatively short signals, order of $10\ ns$
- total signal is the sum of the signals from all microcells – limited linear response to the light pulse intensity (by number of microcells)

$$n_{fired} = n_{all}\left(1 - \exp\left(-\frac{n_{phot.} \cdot PDE}{n_{all}}\right)\right)$$

- gain variations with temperature due to a break-down voltage shift, typical $\frac{dV_{bd}}{dT}$ about $10 - 100\ mV/^oC$



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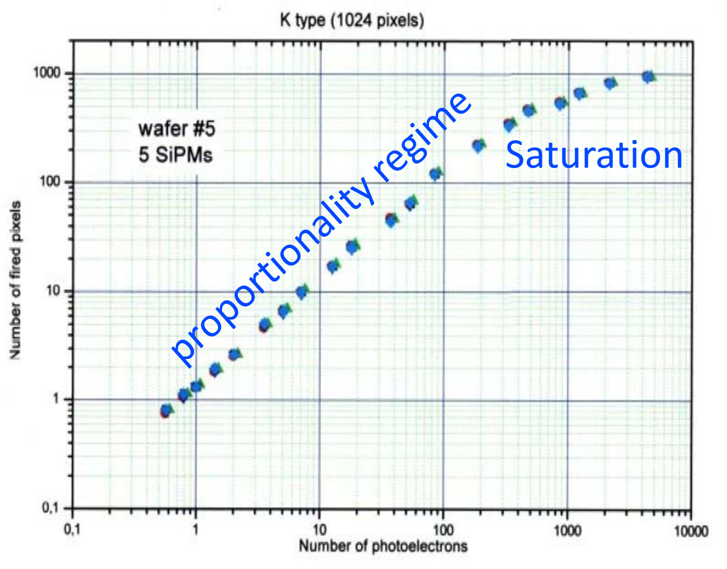
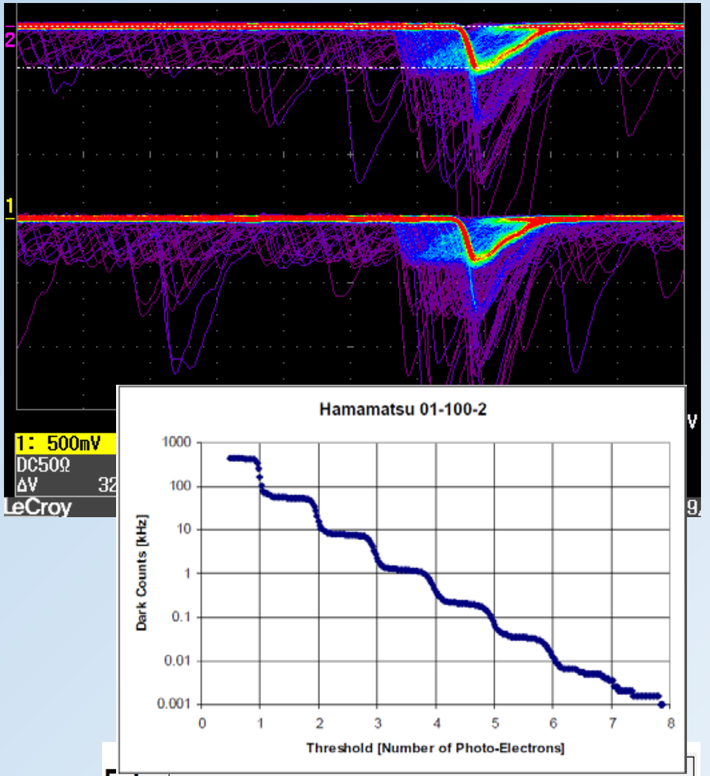
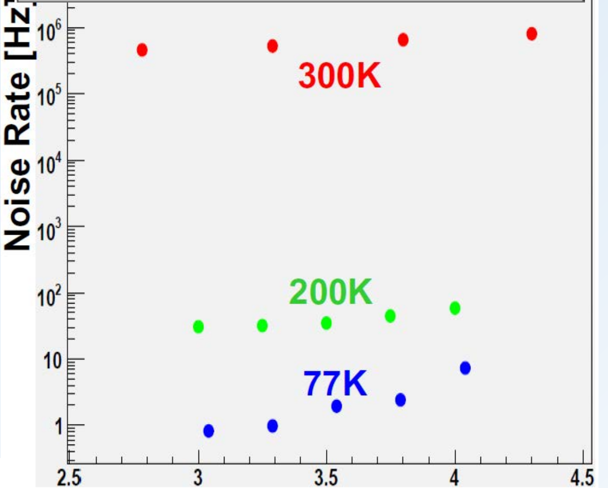
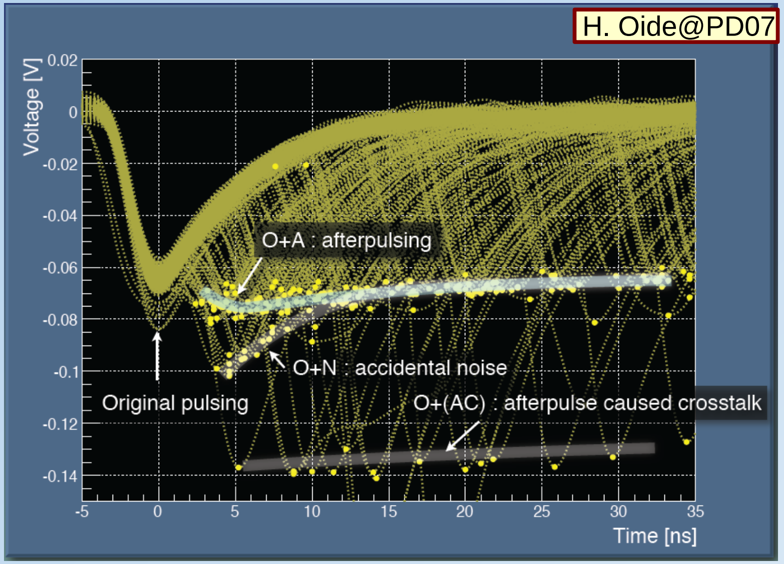


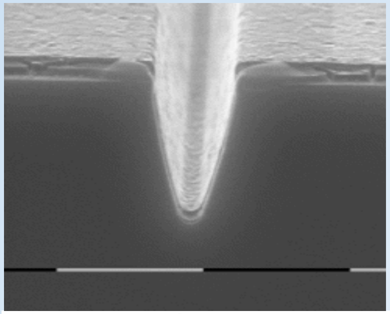
SiPM: noise

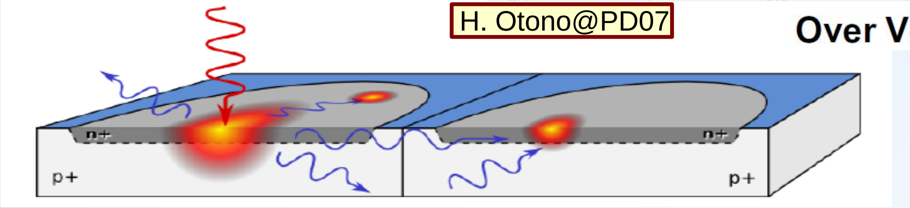
- dark counts are produced by thermal generation of carriers, trap assisted tunneling or band gap tunneling
- signal equal to single photon response
- typical rate went from $\approx 1MHz/mm^2$ to below $\approx 100kHz/mm^2$ for more recent samples
- roughly halved for every 8^oC
- increases linearly with fluence
- optical cross-talk produced when photons emitted in avalanche initiate signal in neighboring cell, reduced by screening – tranches
- after-pulses produced by trap-release of carriers or delayed arrival of optically induced carrier in the same cell







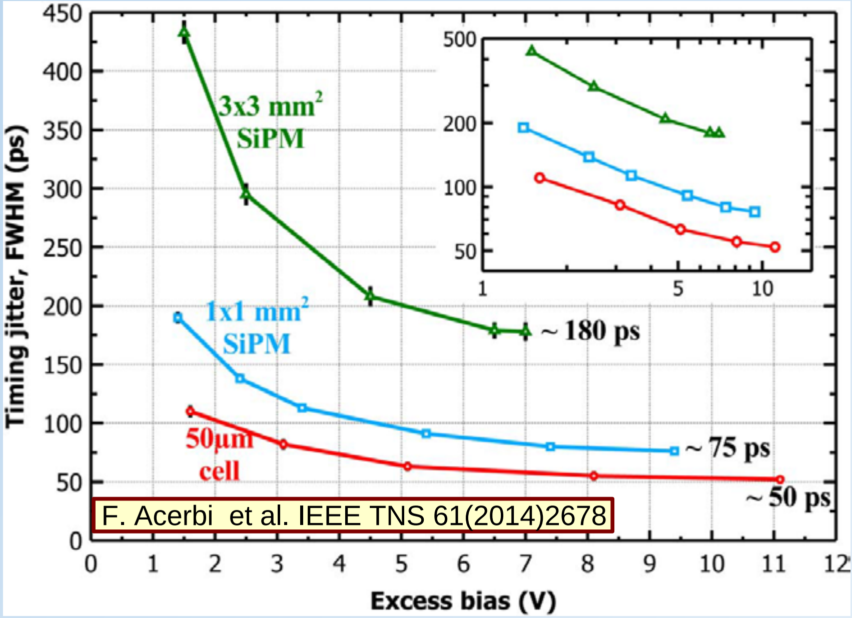




SiPM: single “photon” timing

Intrinsic TTS of SiPM microcells is extremely fast, $< 20\,ps$ for single SPAD, but timing deteriorates for larger devices. Main contributions:

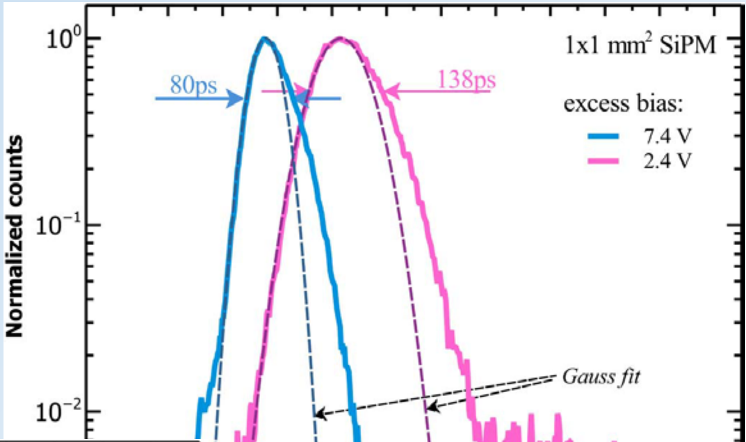
- nonuniformity within microcell (edges)
- spread between microcells
- overall SiPM capacitance
- λ dependence - tails

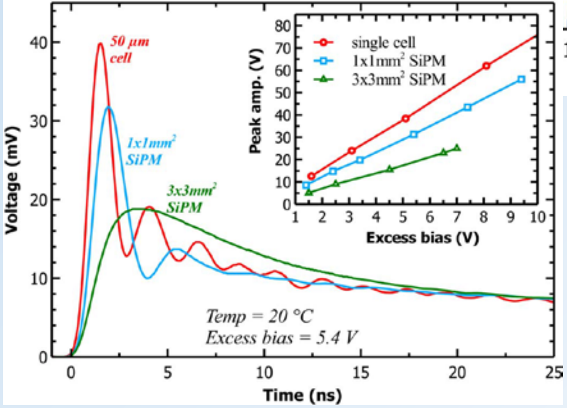


F. Acerbi et al. IEEE TNS 61(2014)2678

Comparison of timing properties for single $50\mu m$ SPAD, $1 \times 1\ mm^2$ and $3 \times 3\ mm^2$ SiPMs with the same SPAD for microcells:

- timing improves with higher overvoltage – larger pulses, at the expense of increased SiPM noise
- best timing resolutions for sing cell si are $\approx 21\ ps, 32\ ps\ and\ 77\ ps$
- TTS deterioration mainly due to larger overall capacitance reduced signal slope $\sigma_t \approx \sigma_e \left(\frac{dU}{dT}\right)^{-1}$



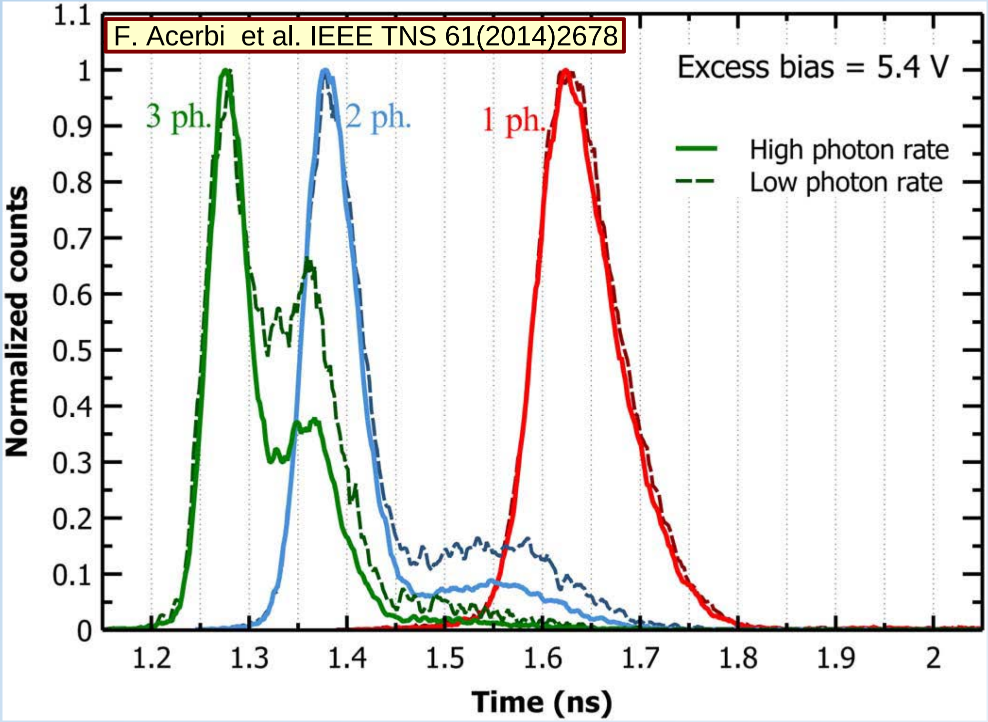


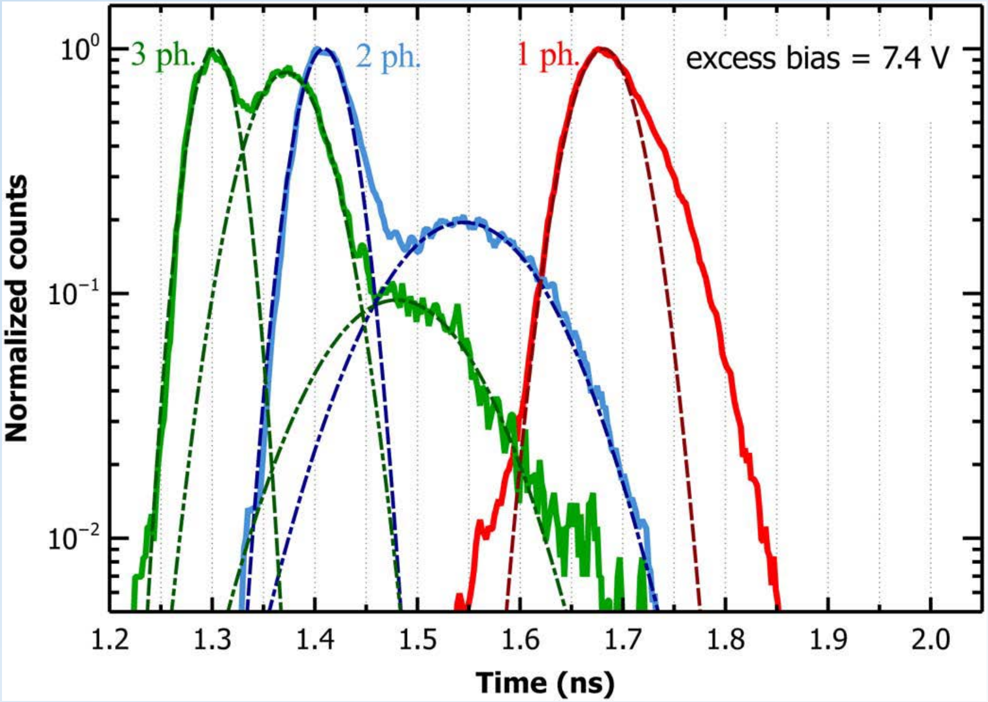
SiPM: timing for multi-cell signals

Optical cross-talk contribution to multi-cell signals spoils timing distribution – does not scale with $\frac{1}{N^2}$:

- two components for 2 m.c. signals:
  - double photon events – proper scaling
  - single photon with cross-talk, timing somewhere between single and double m.c. signals and resolution is worse
- ratio between contributions changes with light intensity confirming optical cross-talk origin
- even more components for larger signals

- may not be such a big effect for DIRC where single photon hits are well spaced in time and 2 m.c. signal would have only cross-talk peak – still worse resolution than sigl m.c. peak.

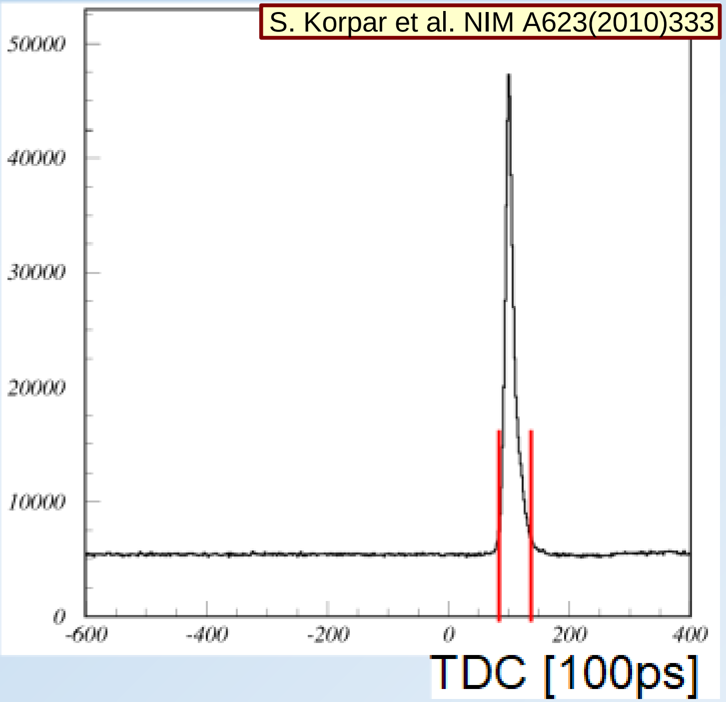

F. Acerbi et al. IEEE TNS 61(2014)2678

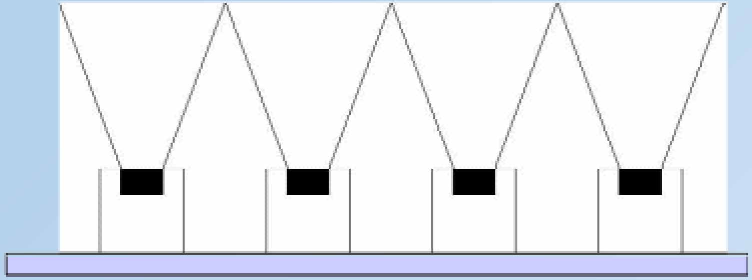


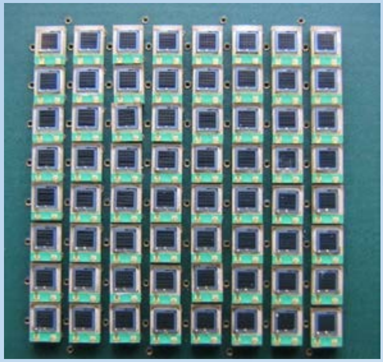
SiPM RICH: early study

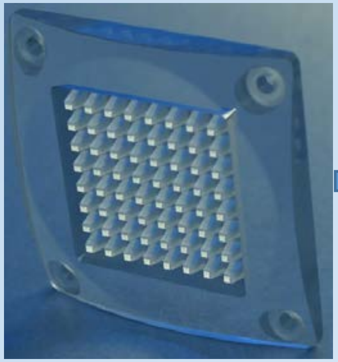
SiPM tests for focusing aerogel RICH, Belle II

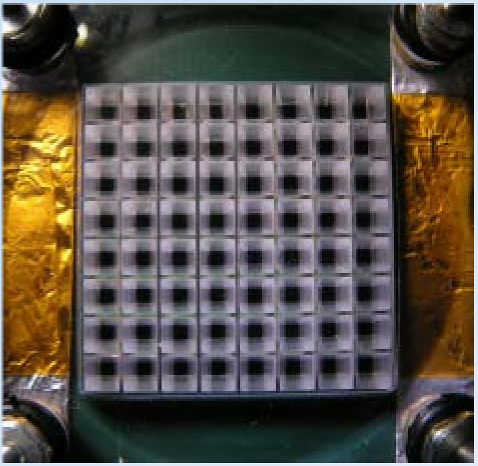
- aerogel $1\ cm, n = 1.03$
- 8×8 array of Hamamatsu S10362-11-100P
- Improve signal to noise ratio by:
  - narrow time window
  - use of light concentrators
- 3.7 photons/ring detected - ≈ 18 expected for $40\ mm, n = 1.05$ aerogel


S. Korpar et al. NIM A623(2010)333

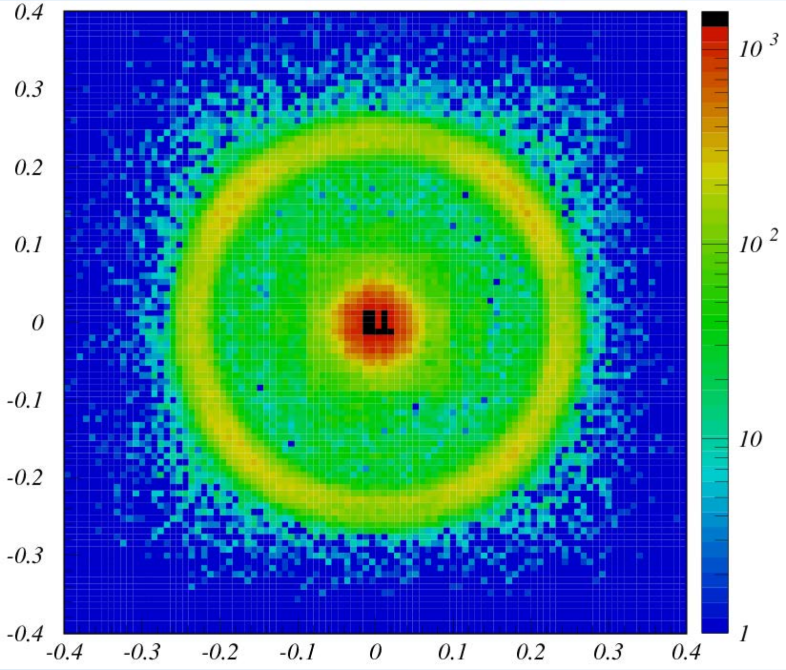








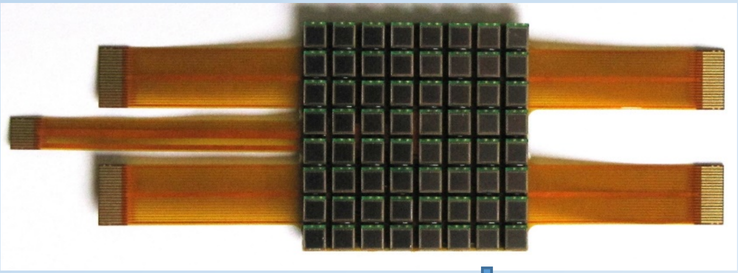
beam test result (1cm,n=1.03)

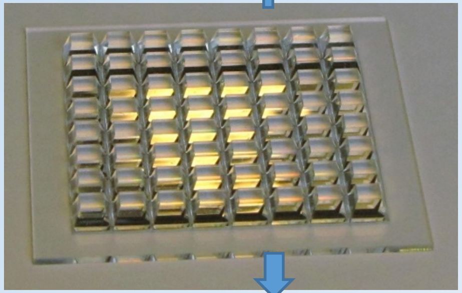


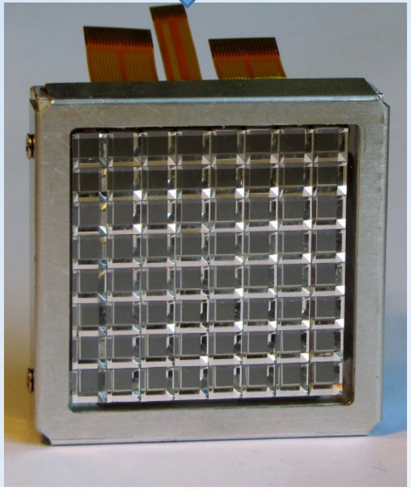
SiPM RICH: update

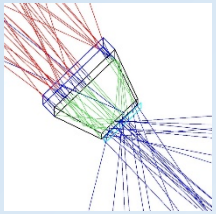
More realistic module prototype to be used for ARICH photon detector.

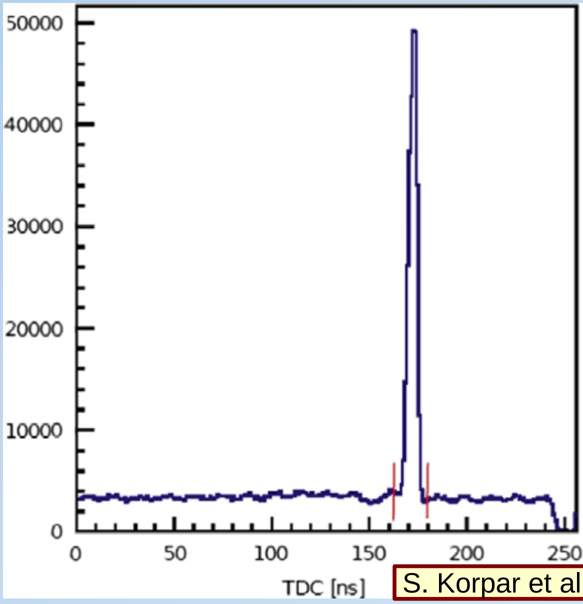
- Hamamatsu 64 channel MPPC module S11834-3388DF, 8×8 array of $3 \times 3\ mm^2$ SiPMs @ $5\ mm$ pitch
- matching array of quartz light concentrators used to
- two $20\ mm$ thick aerogel tiles in focusing configuration $(\mathrm{n} = 1.045, 1.055)$
- tested in $5\ GeV$ electron beam at DESY
- 36 hits/ring detected

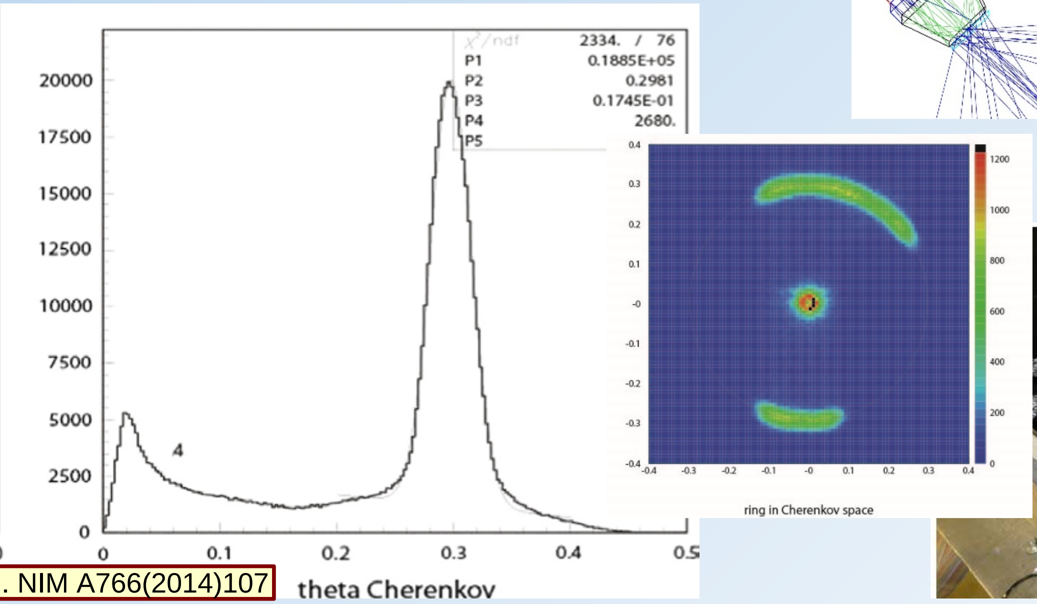




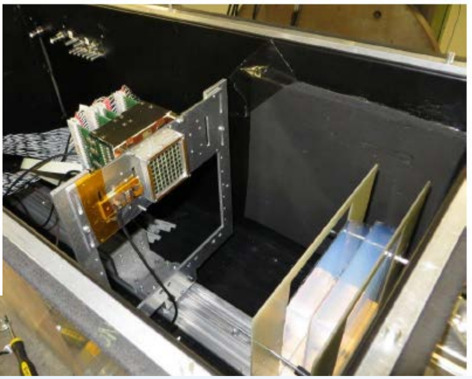








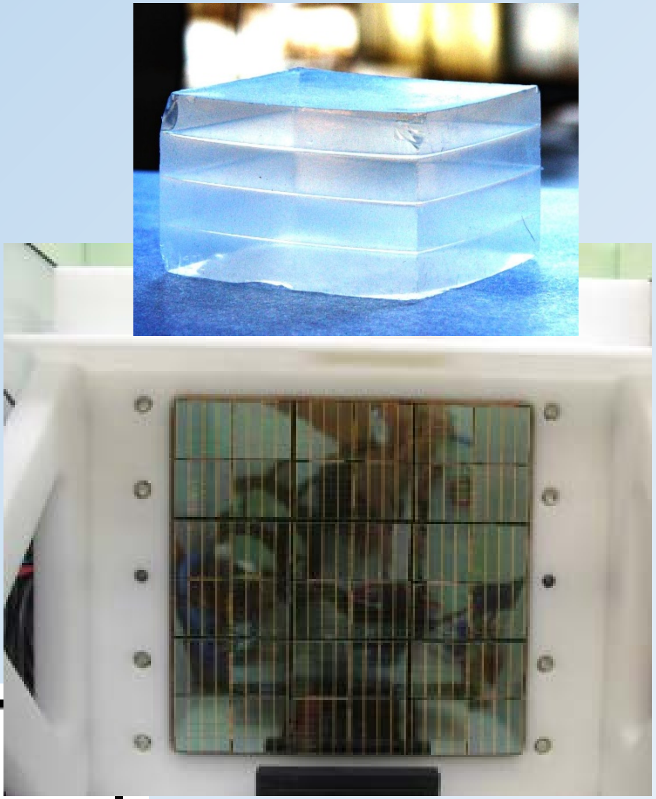
S. Korpar et al. NIM A766(2014)107

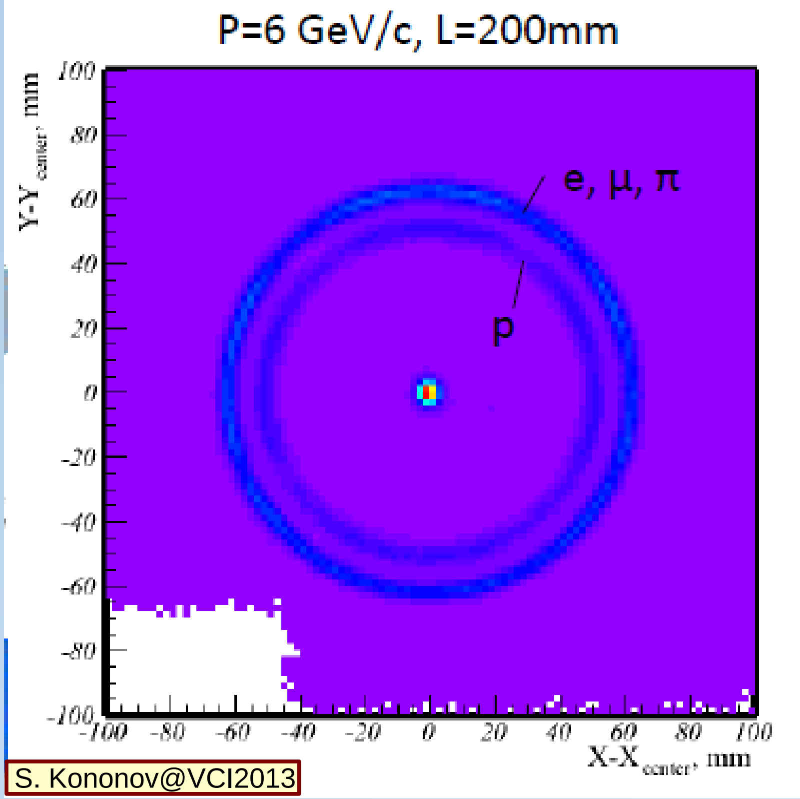


dSiPM RICH

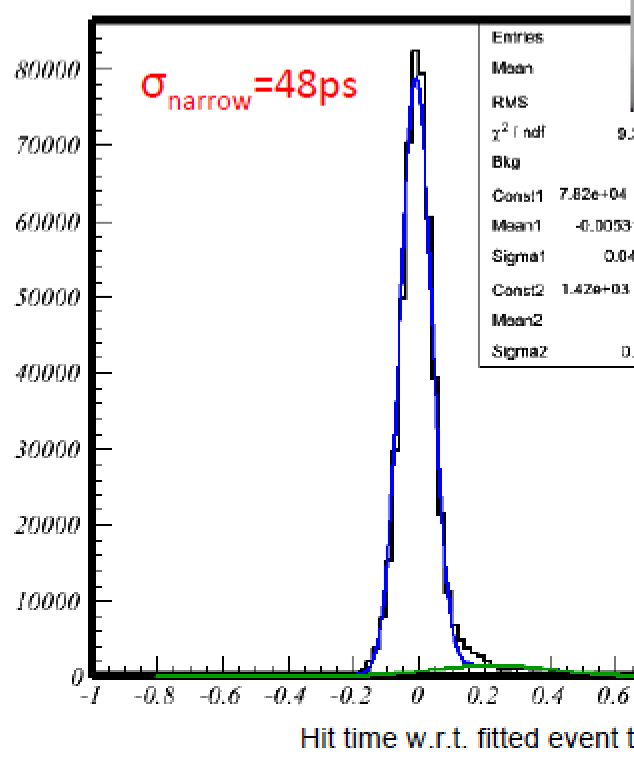
FARICH (Focusing Aerogel RICH) candidate for ALICE, PANDA, Super c-τ, (SuperB):

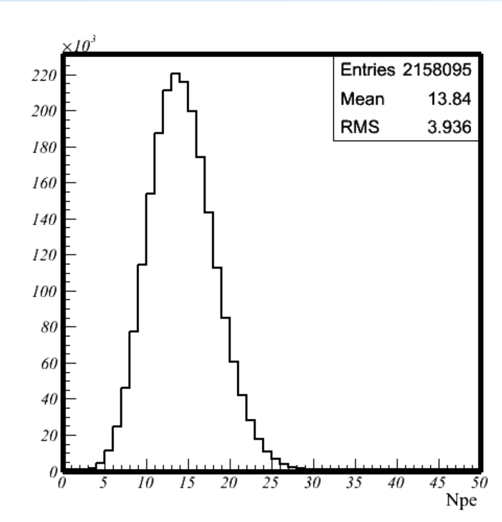
- another focusing aerogel development, 4 layer ($37.5\ mm, n_{max} = 1.046$
- dSiPM (DPC3200-22-44) photon detector 48×48 pixels ($20 \times 20\ cm^2$)
- first use of digital SiPMs from Philips for RICH
  - tested at CERN beam line (operated at -20^o)
  - excellent single photon timing $48\ ps$
  - ≈ 14 photons/ring





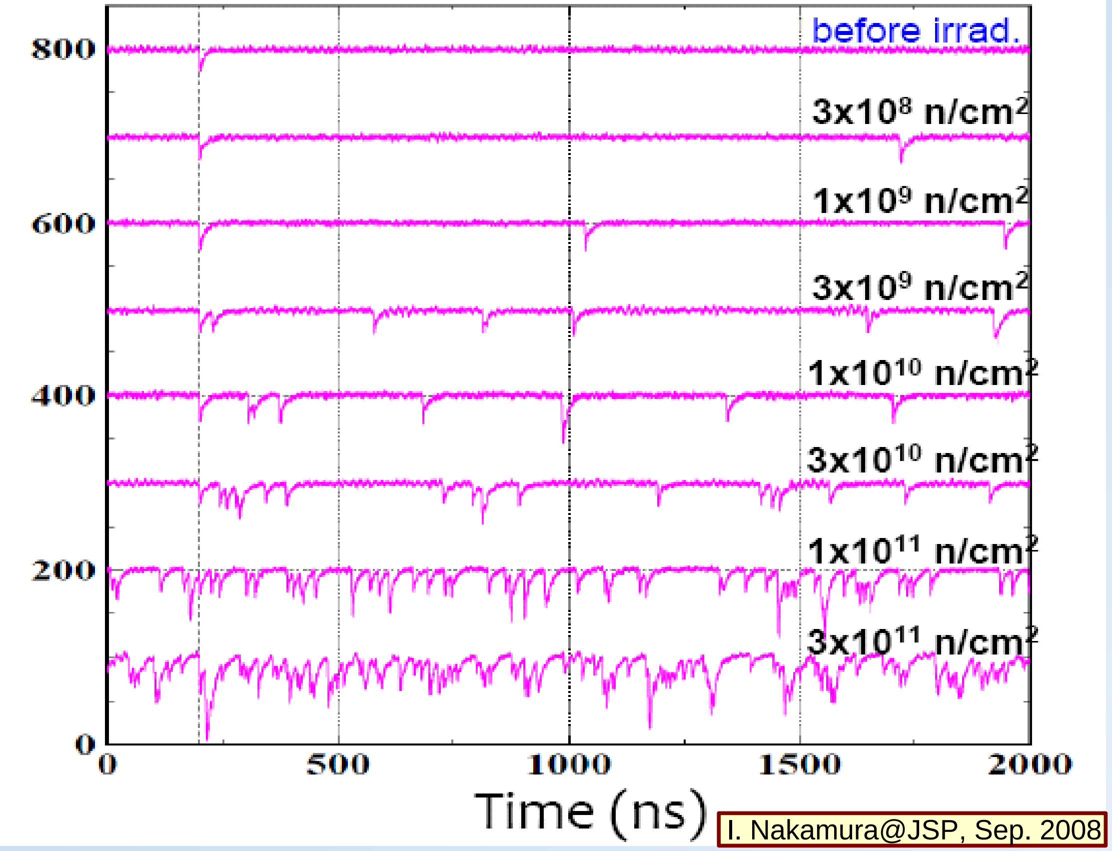
S. Kononov@VCI2013





Why didn't we use them? – radiation damage

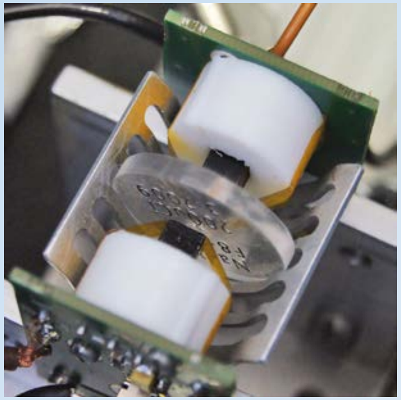
Bulk damage produced by radiation (n, p, ...) increases the dark current proportionally to fluence and eventually signals of Cherenkov photons can not be distinguished from noise.



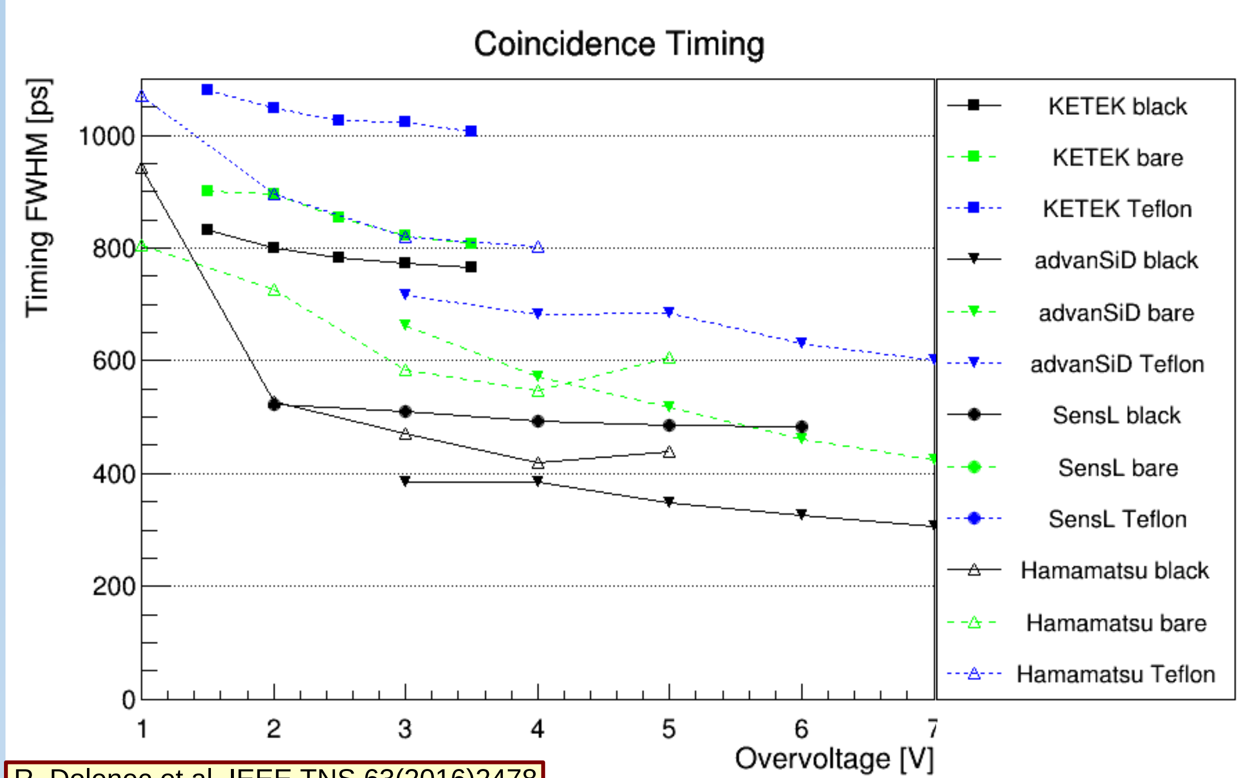
I. Nakamura@JSP, Sep. 2008

→ Very hard to use SiPMs as single photon detectors after fluence of $\approx 10^{11}\ n_{1MeV}/cm^2$ at room temperature!

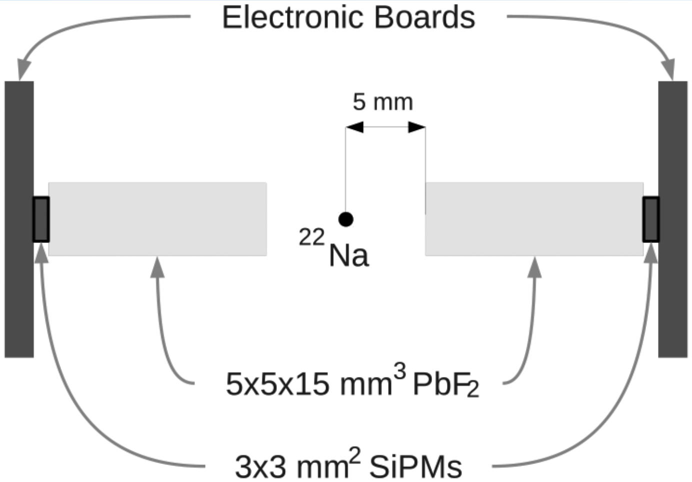
SiPM: TOF-PET timing with Cherenkov light



- 3x3 mm SiPMs from several producers were tested in Cherenkov TOF-PET setup and with pico-second laser source
- 5x5x15 mm^3 PbF_2 polished bare (black painted) crystals
- Teflon crystal support ~10mm deep
- custom board with NEC mPC2710TB amp.
- measured at $-25\ C^o$
- variation of bias - better PDE and timing
- best CRT achieved was $309\ ps\ FWHM$



R. Dolenec et al. IEEE TNS 63(2016)2478



Electronic Boards

5 mm

^{22}Na

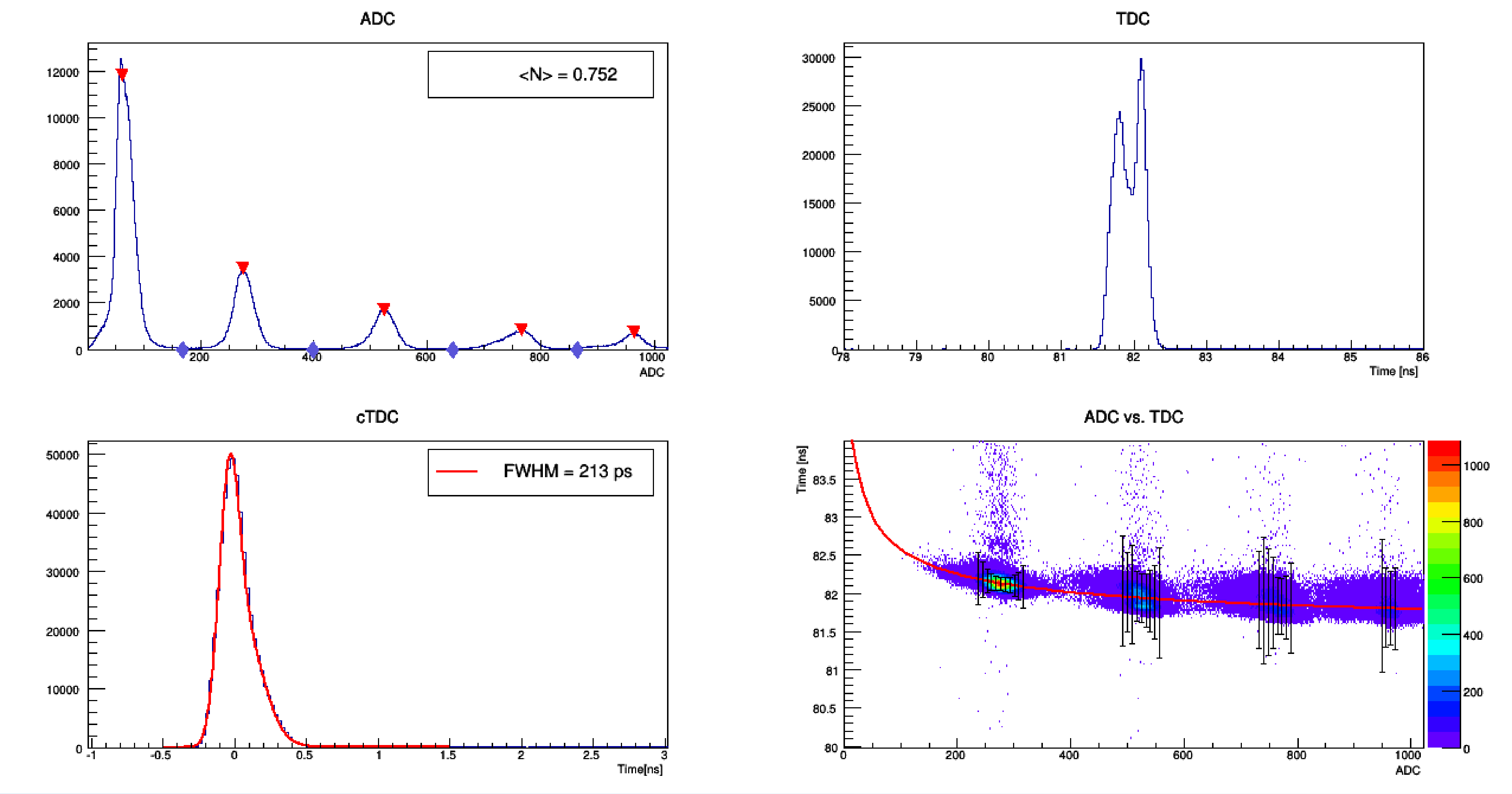
5x5x15 mm^3 PbF_2

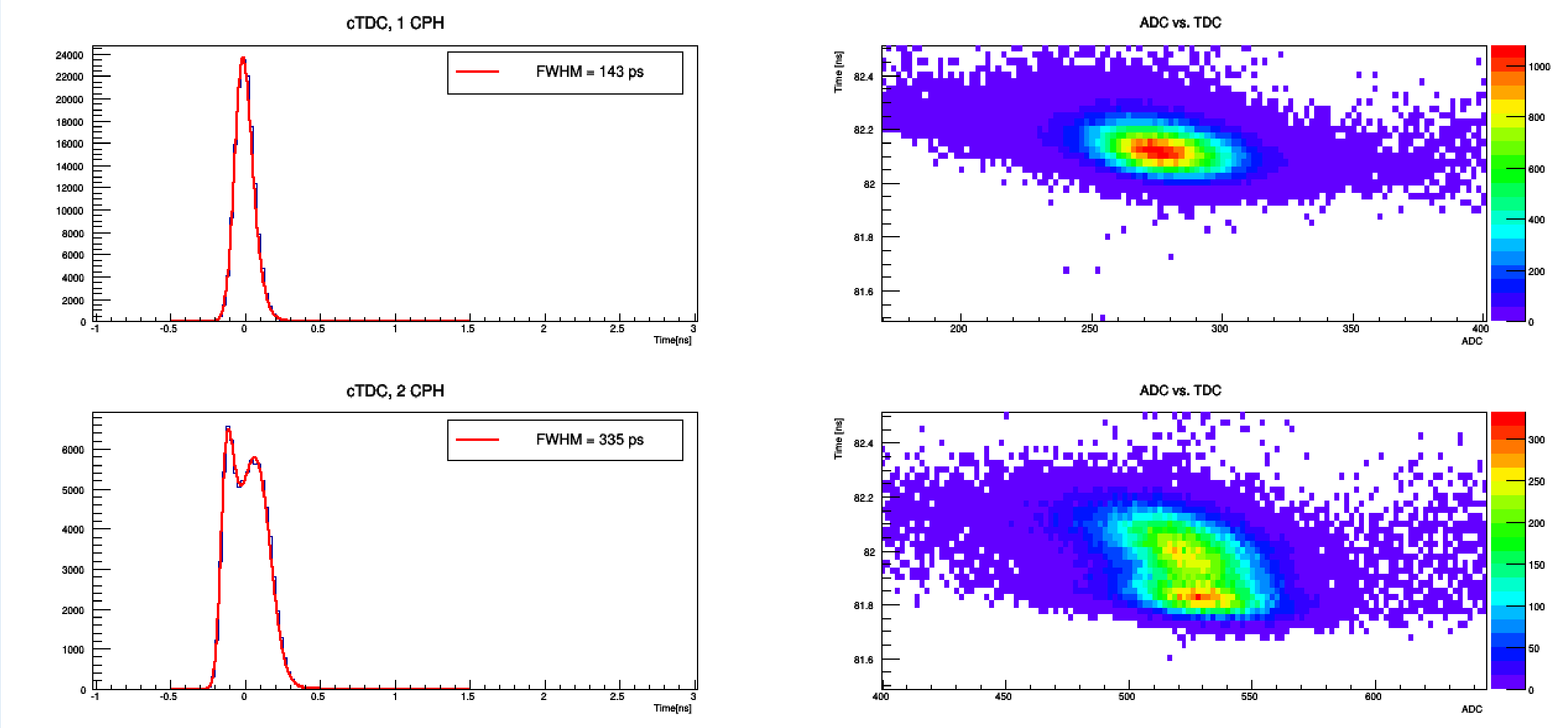
3x3 mm^2 SiPMs

Producer	Model	Pixel Pitch [µm]	Breakdown [V]
Hamamatsu	S12641-PA-50	50	65
AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK	PM3375TS-SBO	75	25
SensL	MicroFC-30050-SMT-GP	50	25

SiPM: timing test with pico-second laser

- AdvanSiD SiPM, OV=6V, T=-25° C
- blue laser λ =408nm, ~ 35ps FWHM




cTDC, 1 CPH
FWHM = 143 ps
24000
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
-1
-0.5
0
0.5
1
1.5
2
2.5
3
Time[ns]
ADC vs. TDC
Time [ns]
82.4
82.2
82
81.8
81.6
200
250
300
350
400
ADC
1000
800
600
400
200
0
cTDC, 2 CPH
FWHM = 335 ps
6000
5000
4000
3000
2000
1000
0
-1
-0.5
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1
1.5
2
2.5
3
Time[ns]
ADC vs. TDC
Time [ns]
82.4
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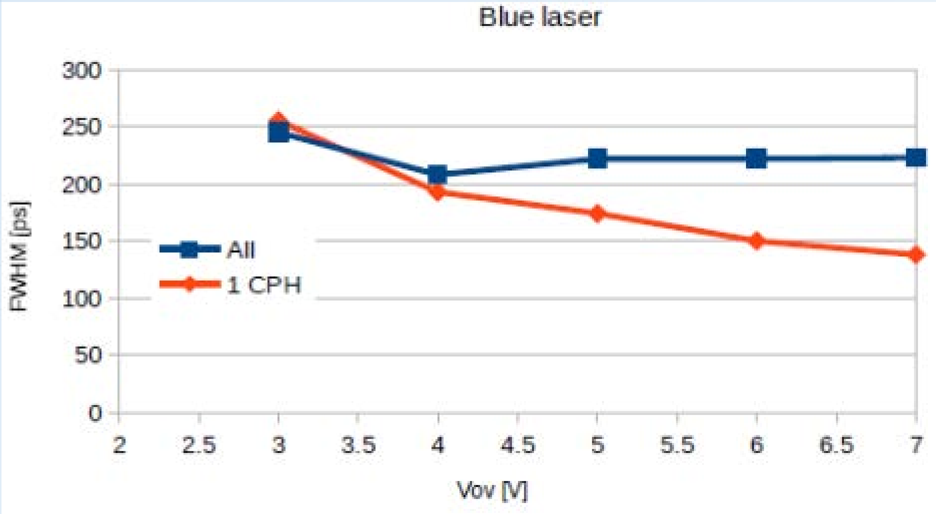
Blue laser
FWHM [ps]
300
250
200
150
100
50
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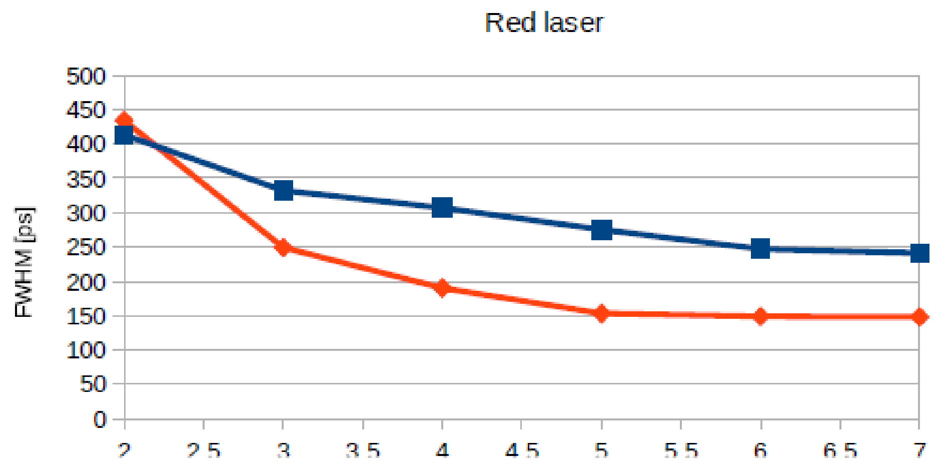
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
Vov [V]
All
1 CPH


Red laser
FWHM [ps]
500
450
400
350
300
250
200
150
100
50
0
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7

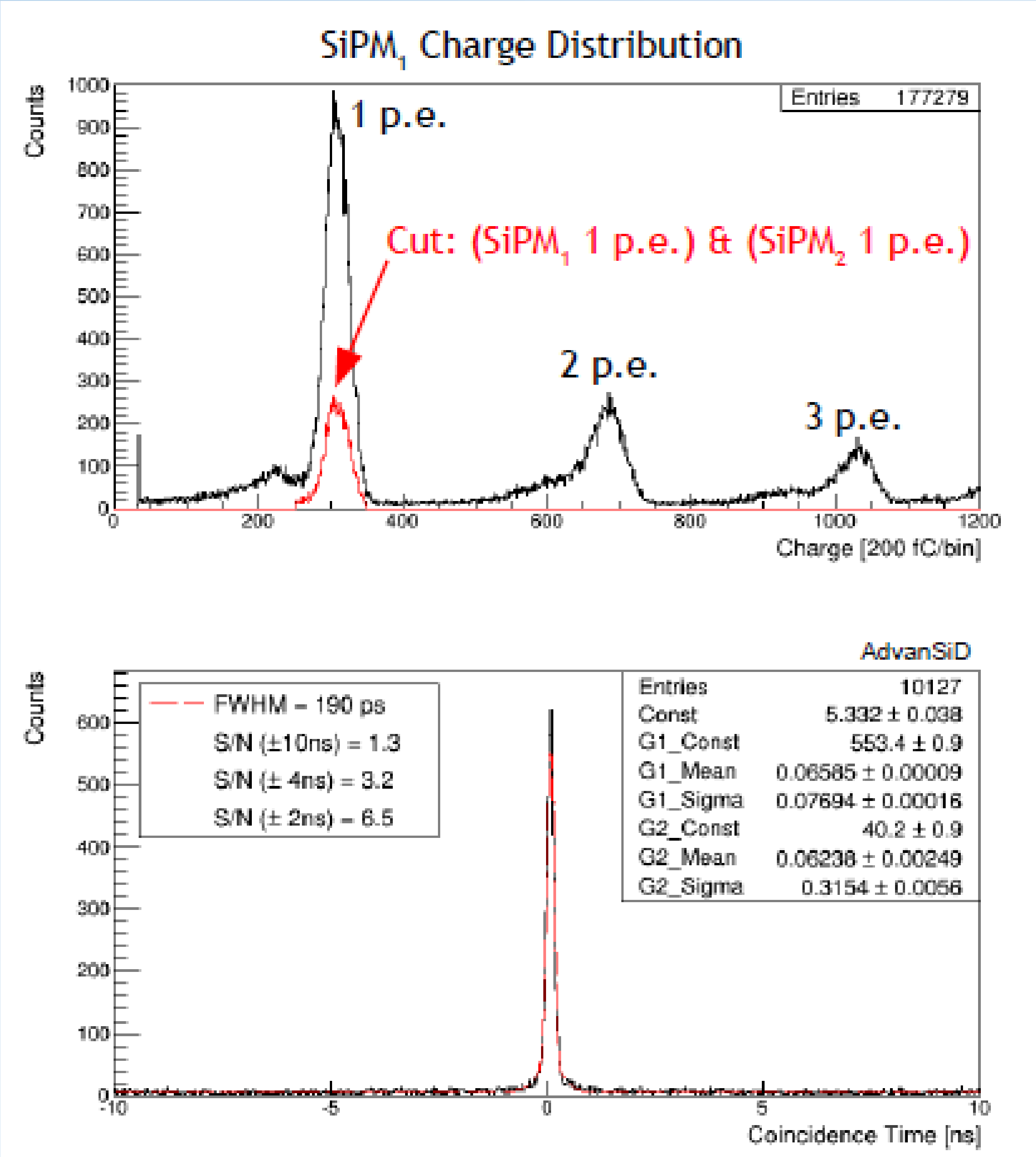
TOF-PET CRT wirh only 1 m.c. signals

- Using only events with single micro cell signal:

CRT= 190 ps FWHM

  - AdvanSiD,
  - V_{OV} =7V,
  - black-painted PbF_2 ,
  - T=-25º C

How to improve timing of events with optical cross-talk ?



Photosensors comparison table

🙂 😐 🙁

	Peak PDE	QE range	Gain	ENF	single photon?	TTS	B	Rad. Hard.	Ageing
PD	$\approx 100\%$	UV-IR	1	1	NO	-	OK	OK	OK
APD	$\approx 80\%$		< 1000	> 2	NO	-			
SiPM	$\approx 60\%$	UV-IR	$\approx 10^6$	$\approx 1 - 1.2$	YES (dark counts?)	$\approx 50ps$	OK	OK (gain, noise?)	OK
PMT	$\approx 35\%$	UV-IR	$\approx 10^7$	$\approx 1.1 - 1.5$	YES	$\approx 200ps$	$\approx 0.1\ mT$	HIGH	OK
MA-PMT			$\approx 10^7$	$\approx 1.1 - 1.5$		$\approx 150ps$	$\approx 10\ mT$		
MESH-PMT			$\approx 10^6$	$\approx 1.1 - 2$		$\approx 100ps$	$\approx 2\ T$ (axial)		
MCP-PMT	$\approx 25\%$	UV-IR	$\approx 10^6$	$\approx 1.1 - 2$	YES	$\approx 20ps$	$\approx 2\ T$ (axial)	HIGH	OK? (ALD)
VPT	$\approx 25\%$	UV-IR	≈ 10	≈ 2	NO	-	$\approx 2\ T$ (axial)		OK
HPD	$\approx 40\%$		≈ 5000	$\approx 1 - 1.1$	NO	-	OK (axial)	OK	OK
HAPD	$\approx 40\%$		$\approx 10^5$	$\approx 1 - 1.1$	YES	$\approx 30ps$ (@high gain)		OK (DC noise?)	
CsI MWPC	$\approx 25\%$	UV	$\approx 10^5$	≈ 2	YES	$\approx 10ns$	OK	HIGH	IBF?
CsI MPGD	$\approx 20\%$	UV	$\approx 10^6$	$\approx 1.2 - 2$	YES	$\approx 100ps$			

Summary and outlook

- SiPMs have some very nice properties: low operation voltage, high PDE, high gain, excellent timing, insensitive to magnetic field, easy to operate, not damaged by operation at ambient light ....,
- but also some drawbacks for single photon detections: high dark count rate, sensitive to neutron irradiation.

- To use SiPMs to detect single Cherenkov photons timing information is used to increase S/N.
- Light concentrators can further improve S/N
- Main problem is increase of dark count rate with neutron irradiation!
- Currently the only solution seams to be operation at cryogenic temperature.

- Intrinsic timing resolution ($< 20\, ps$) is comparable to MCP-PMT but timing resolution of SiPM is affected by large device capacitance and optical cross-talk effects.