Physics and Experimental Studies of SiPM Nonlinearity and Saturation

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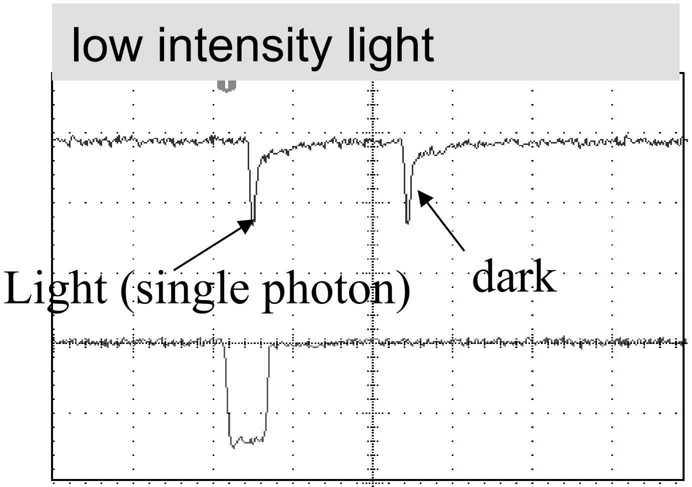
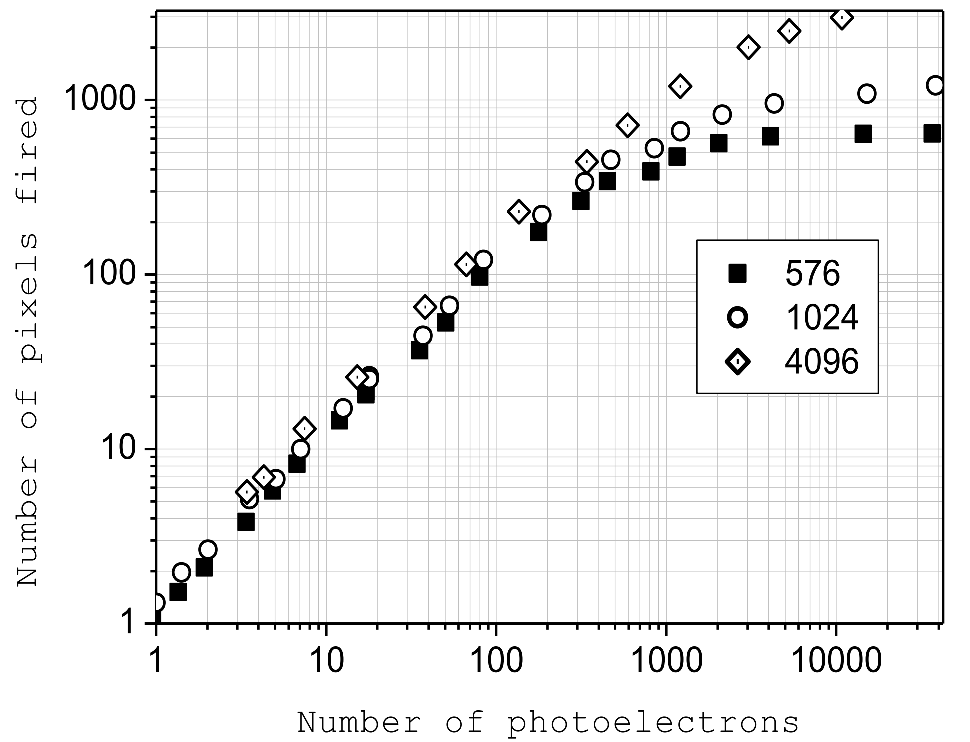
Silicon Photomultiplier – has been developed for single photon applications

BUT

Sometimes people use it for very high intensity light registration
Example : Calorimetry

V. Andreev et al. / NIM A 540 (2005) 368–380





For short light pulses
due to finite number of cells
charge signal (counted in number of fired cells) saturates

Binominal approach:
$$N_{firedcells} = N_{total} \cdot \left[1 - e^{-\frac{N_{photon} \cdot PDE}{N_{total}}} \right]$$

Saturation SiPM signal

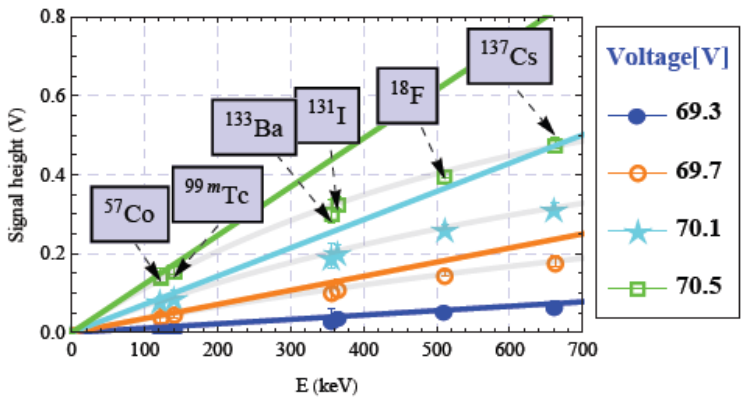


Figure 10. Dependency of the signal peak position from the deposited energy in the crystal for S10362-11-050C MPPC (400 $cells/mm^2$) coupled with the LYSO crystal at different voltages. Gray lines represent the exponential fit to measured data, while solid-coloured lines represent the Taylor expansion of the exponential model to the first order.

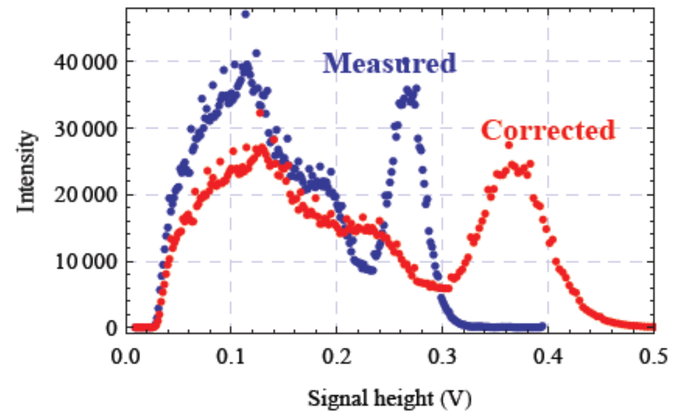


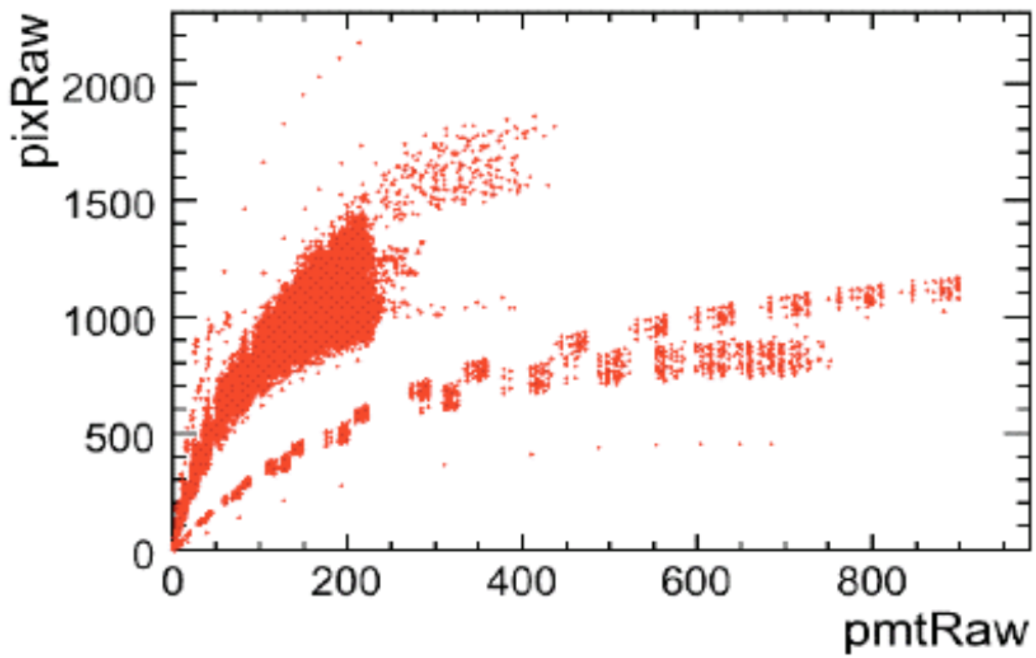
Figure 11. Measured spectra for S10362-11-050C MPPC coupled to the LYSO crystal at 70.1 V at room temperature. Radioactive source was ^{18}F. Energy resolution without correction for nonlinear effects of 14% becomes in reality 21% after the correction.

A Monte-Carlo model of a SiPM coupled to a scintillating crystal
2012 JINST 7 P02009
(http://iopscience.iop.org/1748-0221/7/02/P02009)

Correction for the SiPM non-linearity
(new perspective on saturation curve)

for AHCAL SiPM with scintillator tile
Shaojun Lu
Shaojun.lu@desy.de

SiPM response curve (ITEP measurement)



- That is real life!
- What we have to do, was not only what you have seen on this plot!
- Some improvement has been done day after day.

Correction for the SiPM non-linearity

(new perspective on saturation curve)

for AHCAL SiPM with scintillator tile

Shaojun Lu

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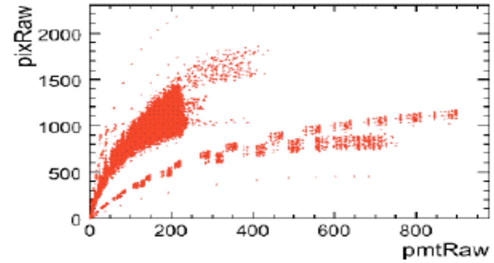
Natural units

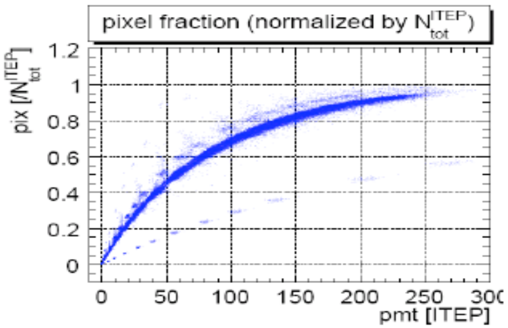
- In physics, natural units are physical units of measurement defined in such a way that certain selected universal physical constants are normalized to unity; that is, their numerical value becomes exactly 1.

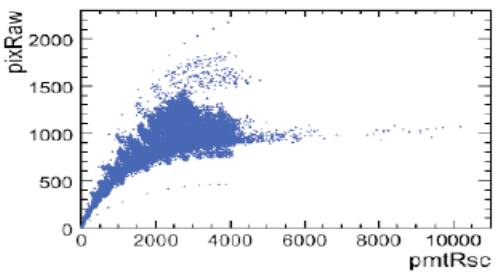
-- From wikipedia

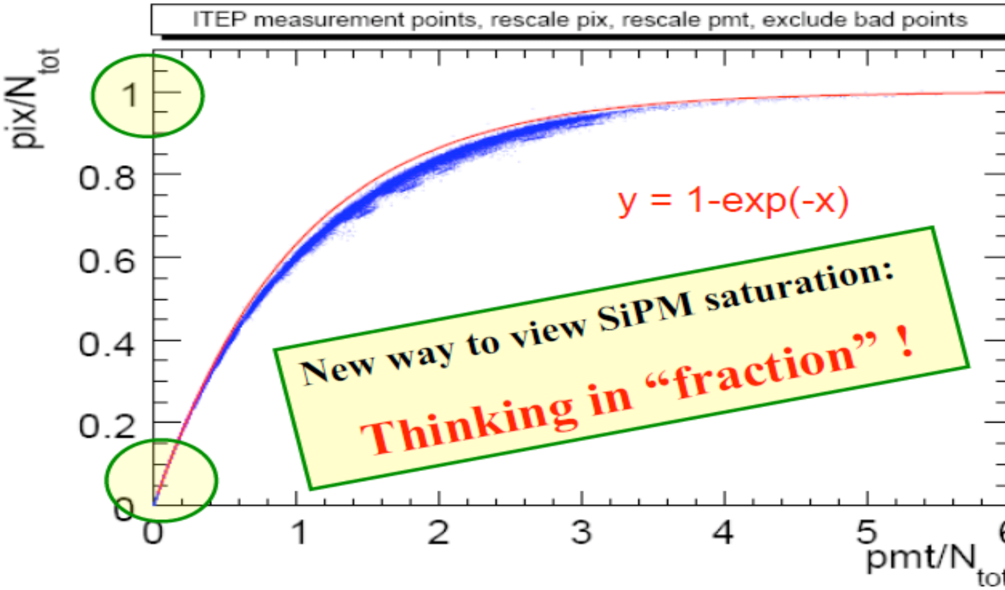
Shaojun Lu

SiPM response curve (ITEP measurement)









- Total pixel numbers: extracted by fitting the last 5 ITEP measurement points
- Slope: corrected by fitting the first 10 ITEP measurement points
- Bad points: removed base on double exponential fit

6

If we are studying SiPM properties we have to think in the coordinates of
•fired pixels (together with correlated pixels) – Y
•Number of phe assuming ideal conditions with infinite number of pixels inside SiPM) – x

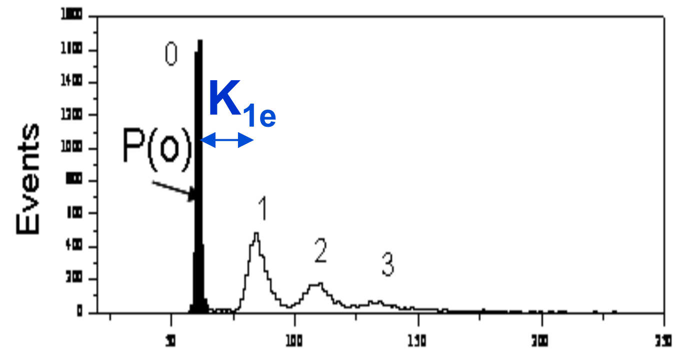
How to normalize the SiPM saturation curve?

Amplifier and SPE spectra (low intensity light)

$X_i = \langle N_{phe} \rangle = -\ln P(0)$

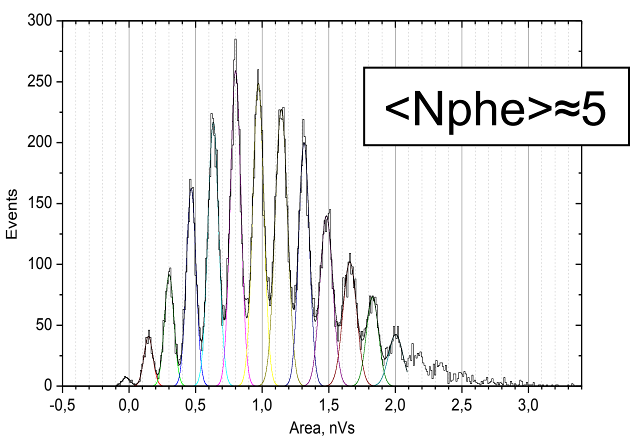
$Y_i = \langle N_{fired\_pixels} \rangle = \frac{Mean}{K_{1e}}$ Mean= Mean(whole distribution)-Ped_position

Z_i = signal from the reference photodetector, units

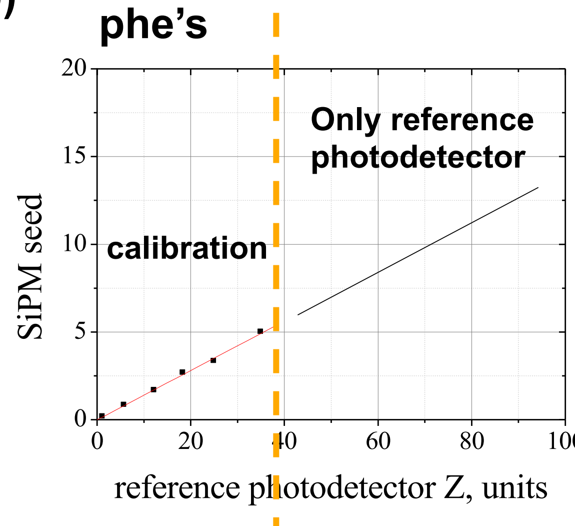


We need several Light intensity points provide us enough value of P(0)

Maybe last intensity calibration point (too low P(0))

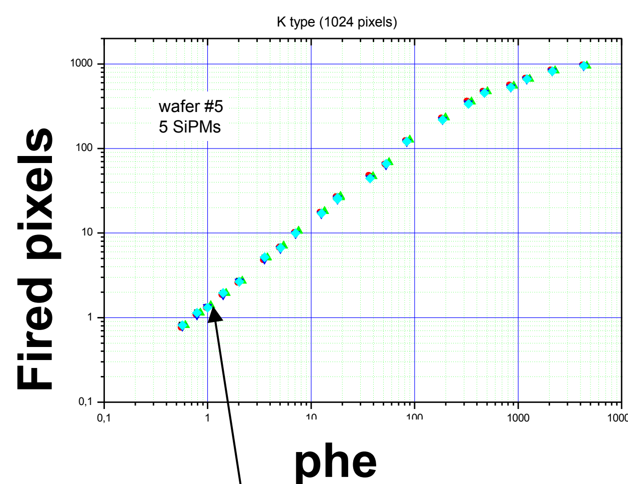


Calibration of reference photodetctor in number of phe's



Extraction number of seeds

5 SiPM samples

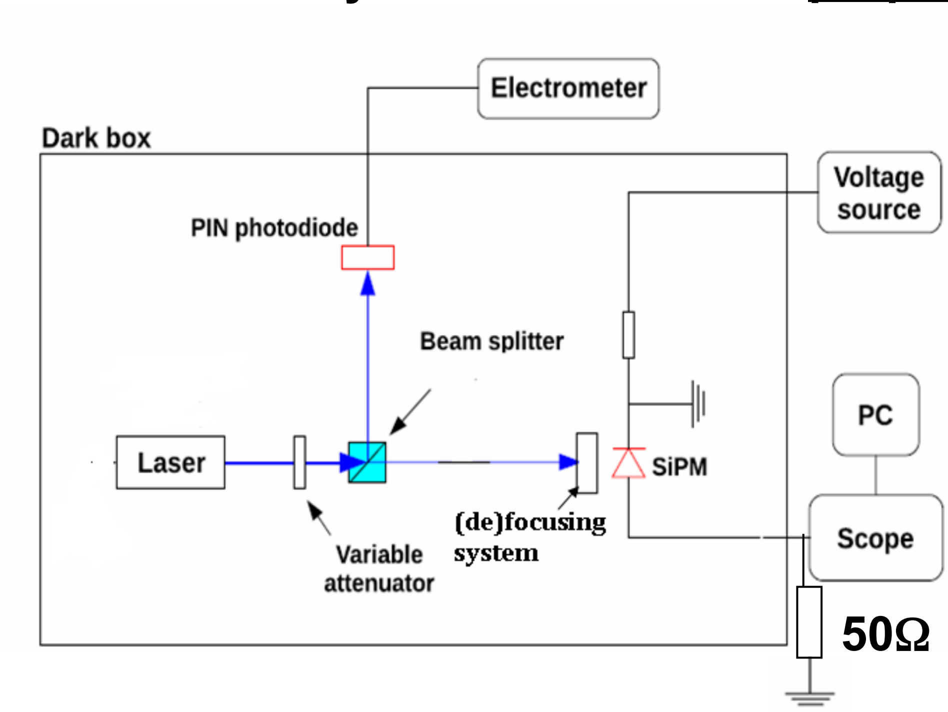


SiPM Crosstalk is visible

Fired pixels>phe

1. Firstly we need to have a <u>proper</u> experimental setup

Example of the setup



1. Light source, operated in stable mode (no changes in an electrical pulse)
2. Light intensity is changed by filters
3. Uniformly distributed light over the SiPM surface* (over surface with desired number of investigated pixels)
4. Reference stable linear photodetector (the best choice is PIN-diode)
5. Amplifier to obtain SPE spectra for low light intensity (bypassed for high intensity light)
6. Temperature and voltage must be stable and better controlled with needed accuracy

The proper experimental setup

1. Light source, operated in stable mode (no changing of electrical pulse)
2. Light intensity is changed by filters

Due to changing of electrical pulse light pulse shape, wavelength and distribution of correlated photons might be changed too

3.Uniformly distributed light over the SiPM surface* (over surface with desired number of investigated pixels)

Saturation (nonlinearity) depends on pixel load (number of photons/number pixels (think in fraction)

4. Reference stable linear photodetector -the best choice is PIN-diode (dynamic range of about 10^8)

PMT is not the best choice for the reference detector. It has own nonlinearity, especially for pulse signals (parameters of the specific PMT should be checked)...

7.Then we need to understand what we want to study– amplitude (A) or charge (Q)? A and Q are different and have a different behavior

8. Important – we need to know exactly pulse shape corresponded to our task and the best situation when it can be reproduced exactly in the test setup

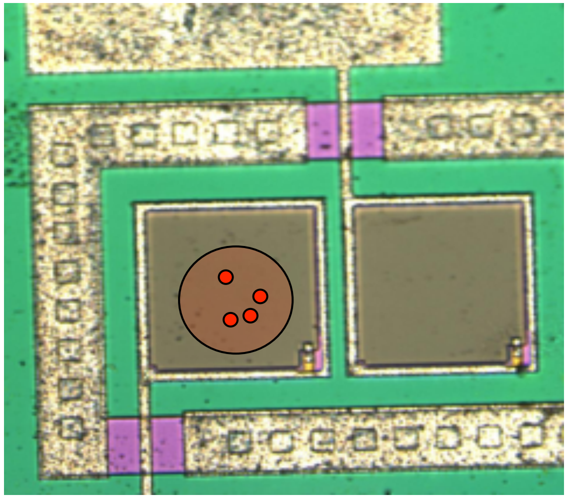
9. We need to know real operation conditions of SiPM (applied voltage, light distribution over the SiPM area, load and serial resistances of a connection scheem)

Amplitude (A) or Charge (Q)?

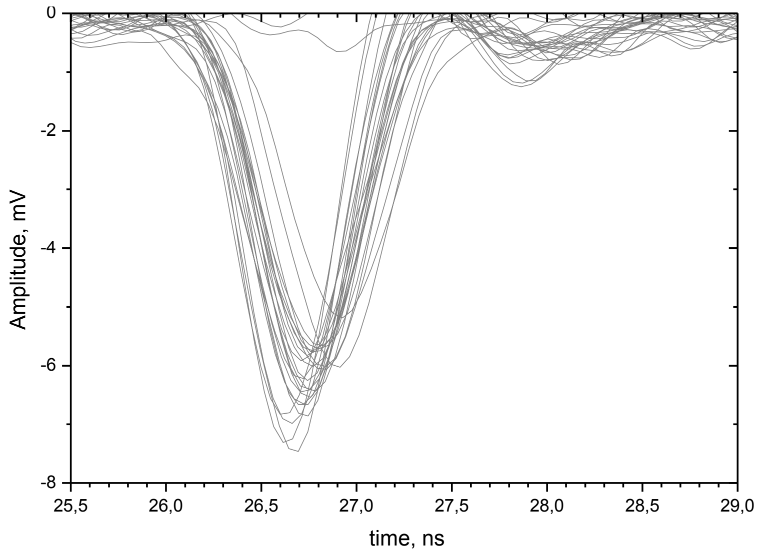
Before saturation doesn't matter. But if you have more then one phe/pixel:

Single stand alone cell. Moderate light (several photons/flash) intensities

Focused laser light at the center of the cell, 40ps, 660nm
Scope LeCroy WaveRunner 620Zi 2GHz



MEPHI cell



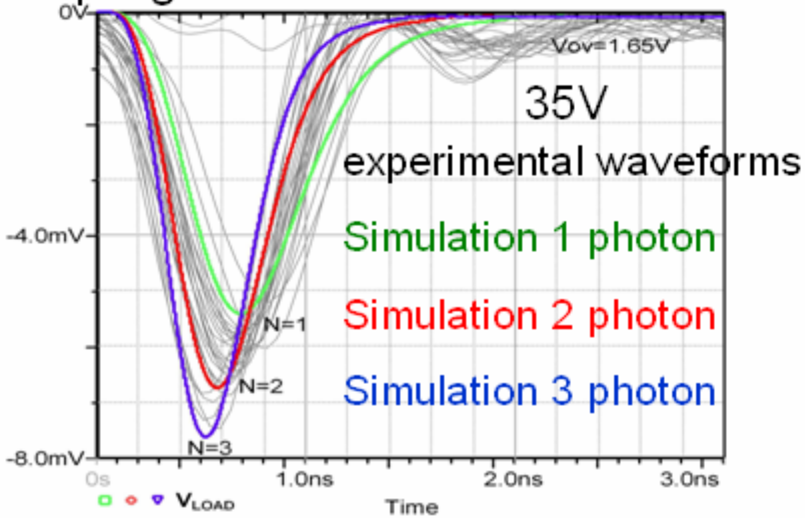
Why so significant dispersion of signals amplitudes?
It is exactly one fired cell (stand alone)

Suggestion – Geiger discharge starts from several points inside of the cell

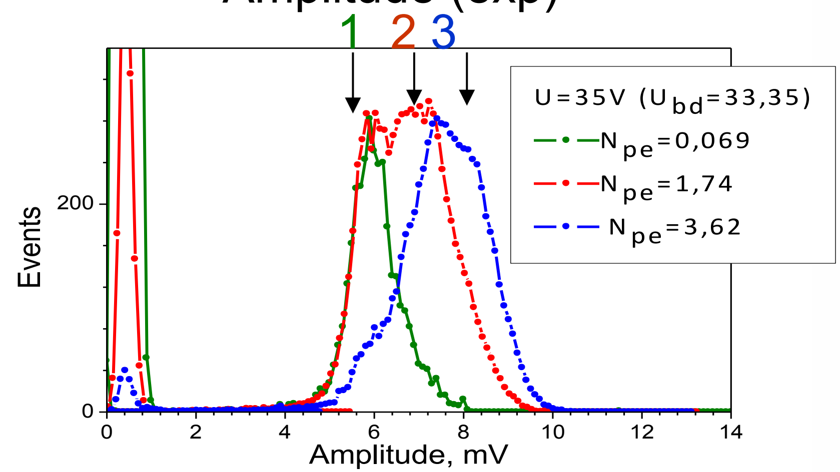
Signals from stand alone cell

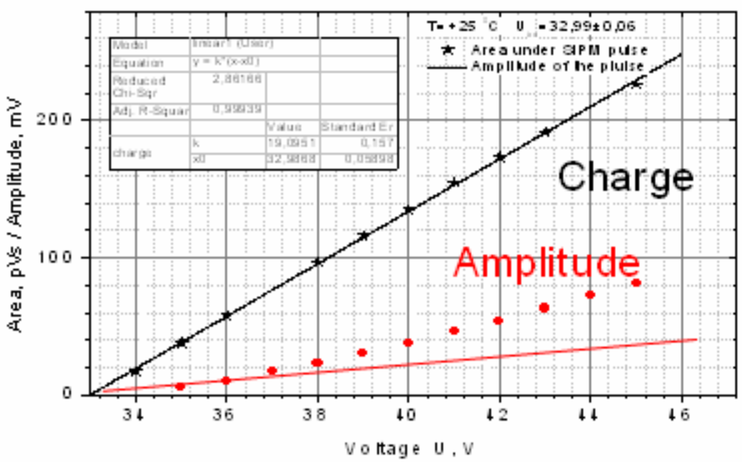
Fixed overvoltage ΔU=1.65V, different light intensity

Exp signals & SPICE simulations

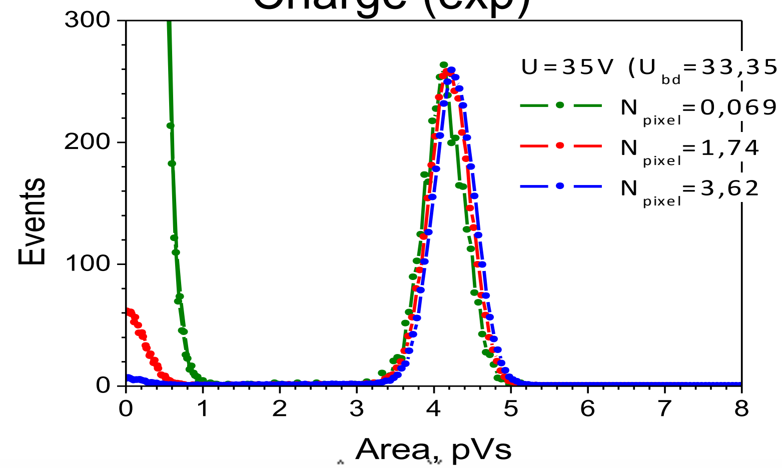


Amplitude (exp)

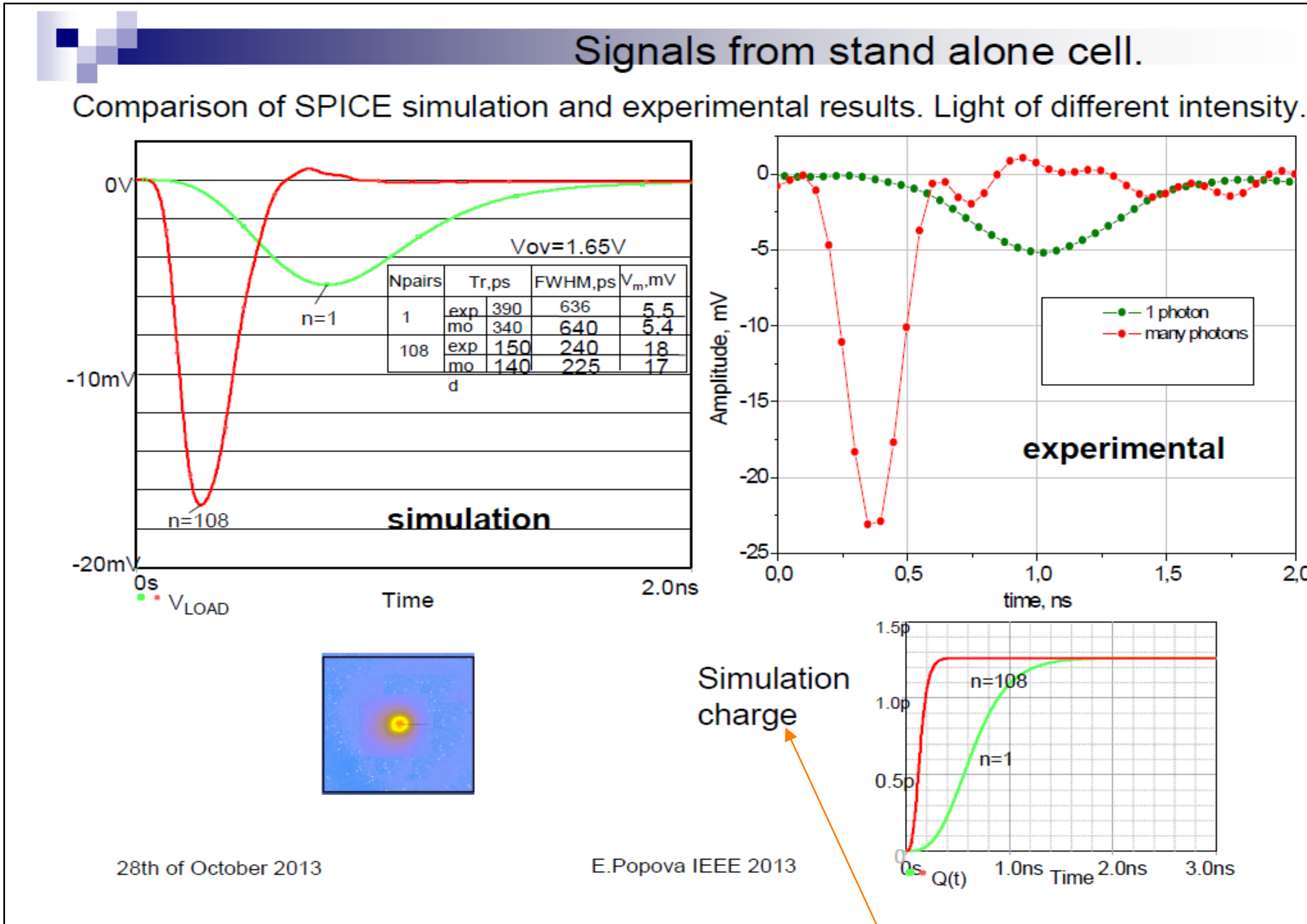




Charge (exp)



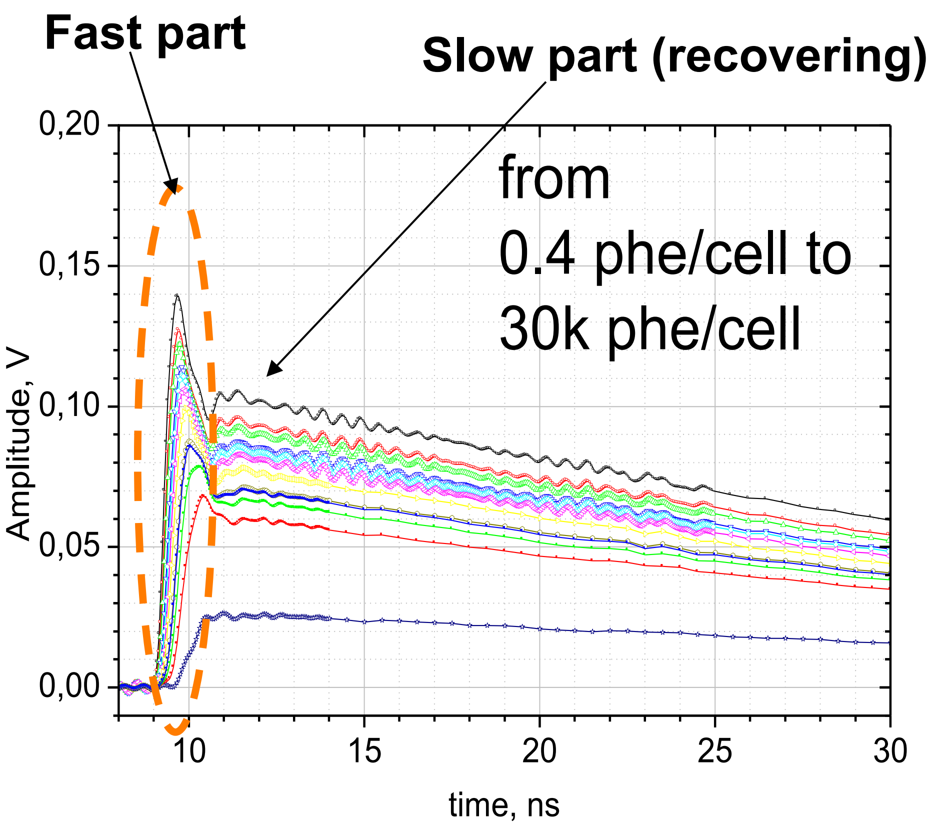
Even for very low light intensity we have "2-photons" amplitudes from cell -> it maybe an evidence of photon assisted discharge propagation

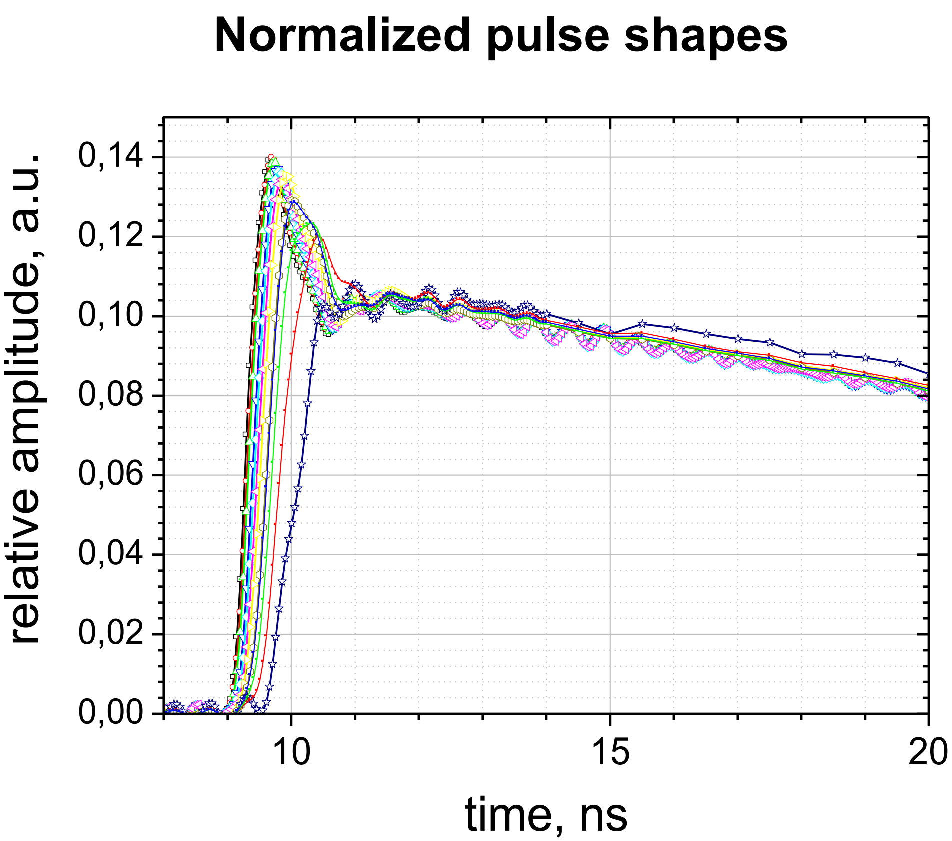


But what is about cell charge for high intensity light in reality?

Pulse shape for different light Intensities. MEPHI data

Hamamatsu S10362-11-100U No.50, Ubreakdown=68.4V, U=69.5V

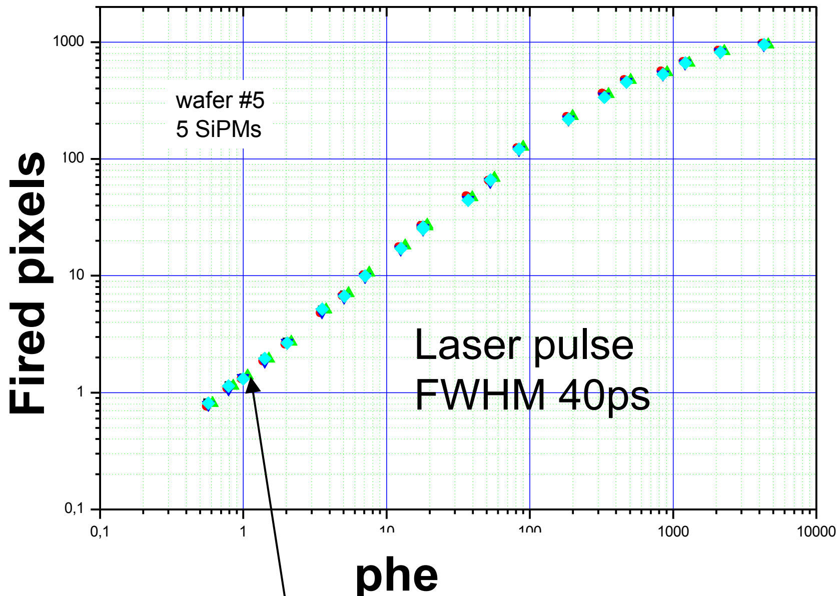




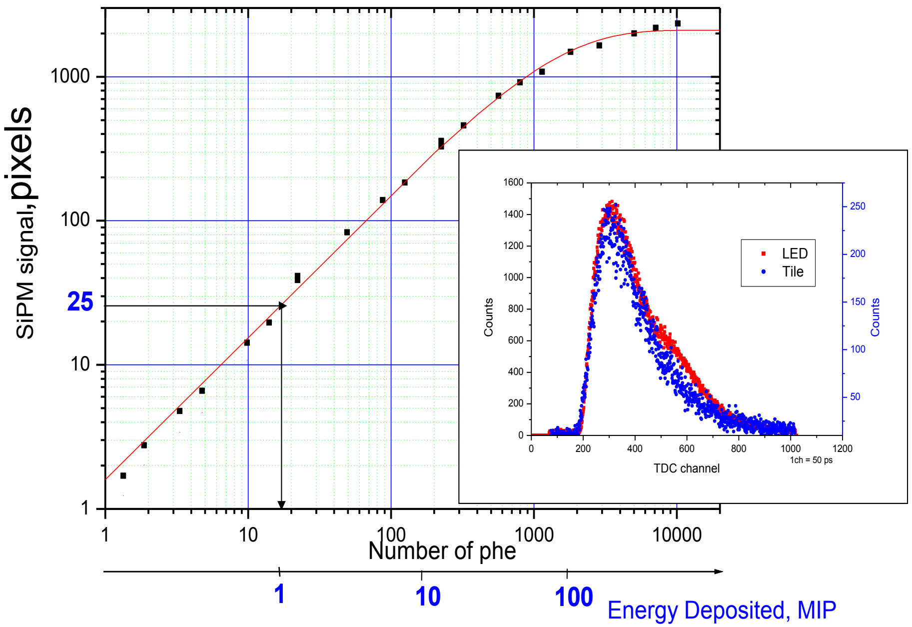
3.Important – we need to know exactly pulse shape corresponded to our task and the best way – it should be reproduced exactly in the experimental setup

The same SiPM type

5 SiPM samples



Individual tile energy reconstruction using calibration curve SiPM signal vs energy deposited:



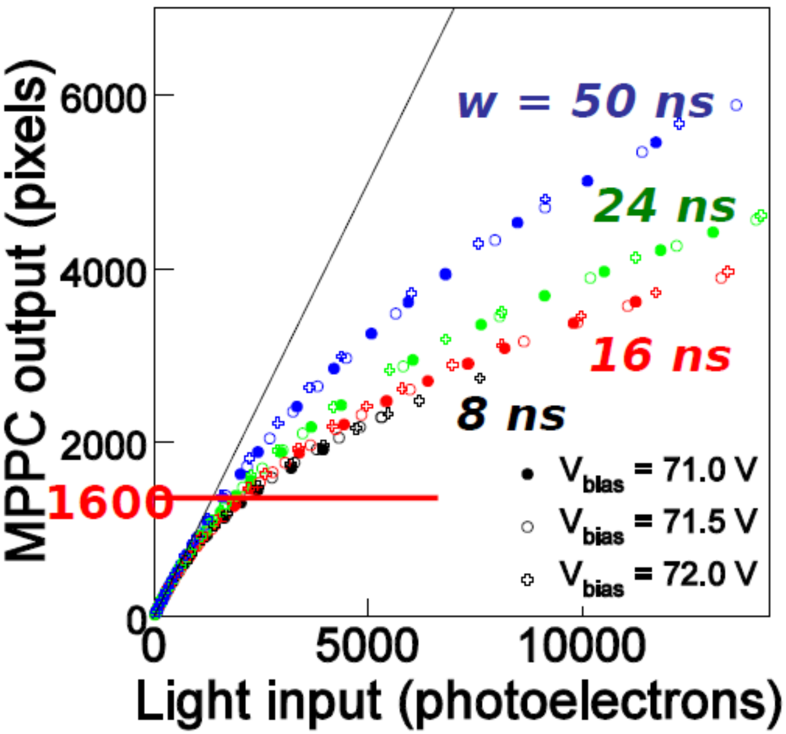
1024 pixels in saturation

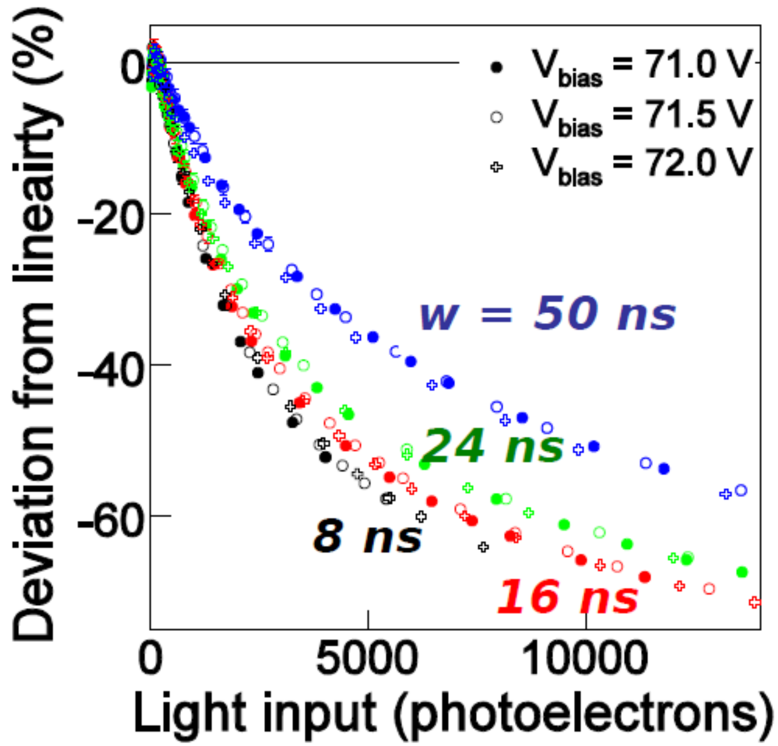
~2000 pixels in saturation

Pulse shape depended – recovery during pulse duration!!!

Response Curve

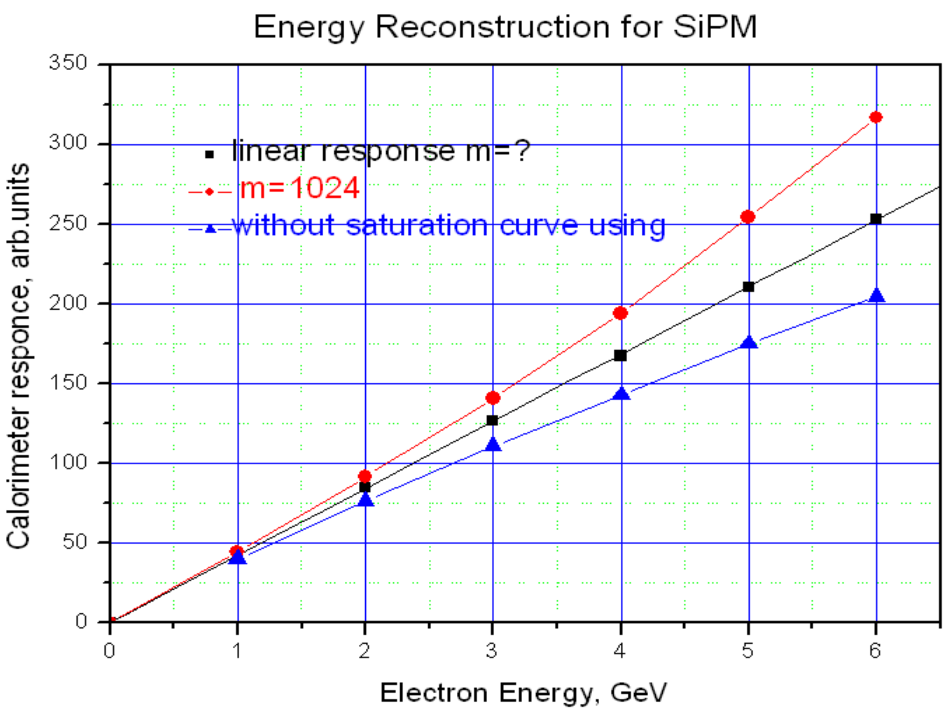
Response curves taken with various width of LED light pulses. (gate width = 100 ns)

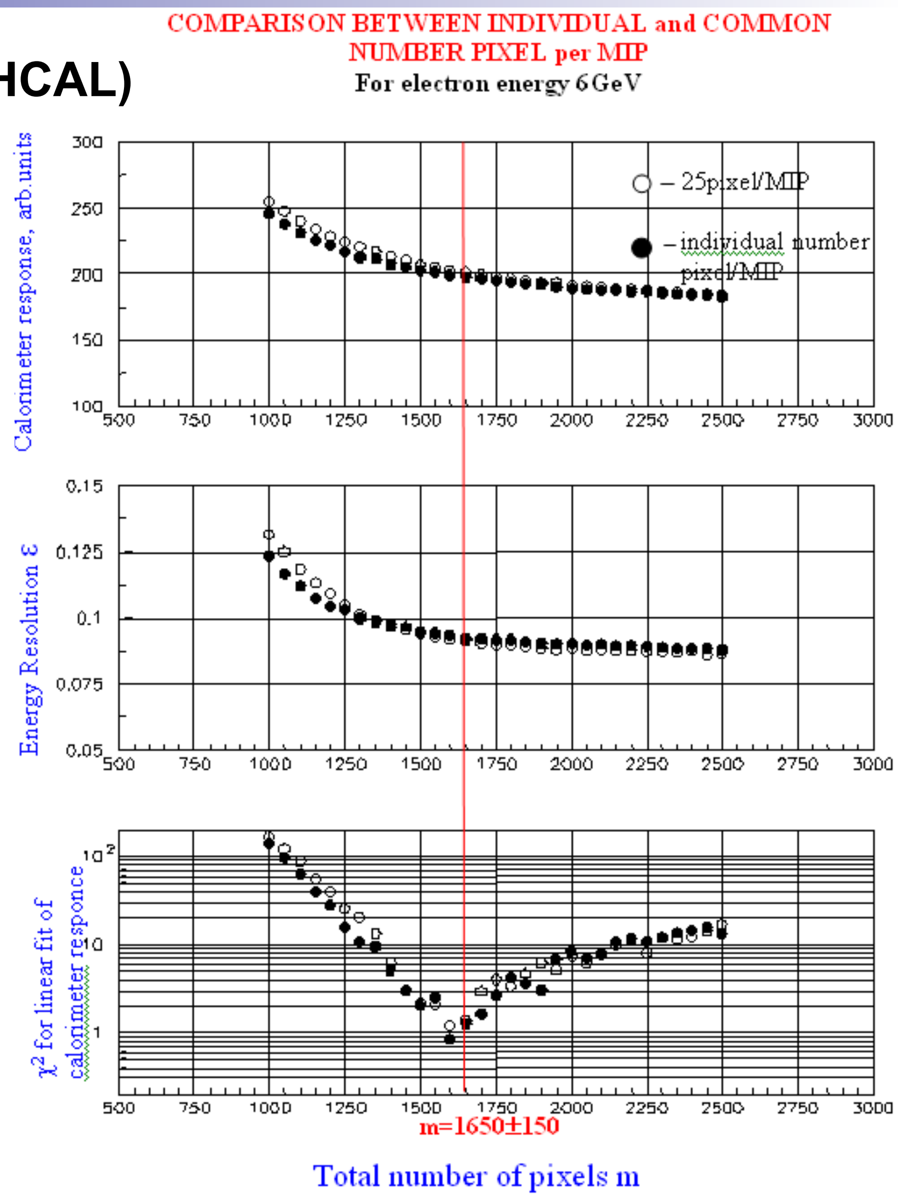




- Dynamic range is enhanced with longer light pulse
- Time structure of the light pulse gives large effects in non-linear region.
- No significant influence with changing bias voltage.
- Knowing time structure of scintillator/WLS light signal is crucial

CALICE MINICAL (preprototype of the tile HCAL)
100 SiPMs individually read out tile+WLS





1024 real pixels inside (agrees with saturation curve for 40ps light)

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

Effective Ntotal is 1650+-150

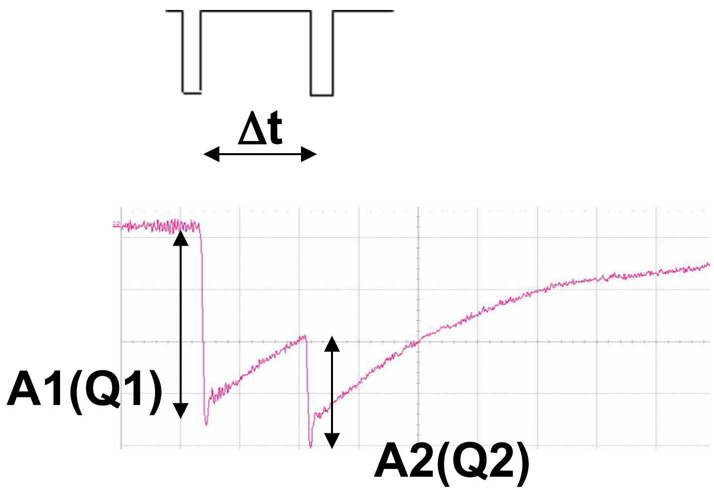
SiPM Recovery

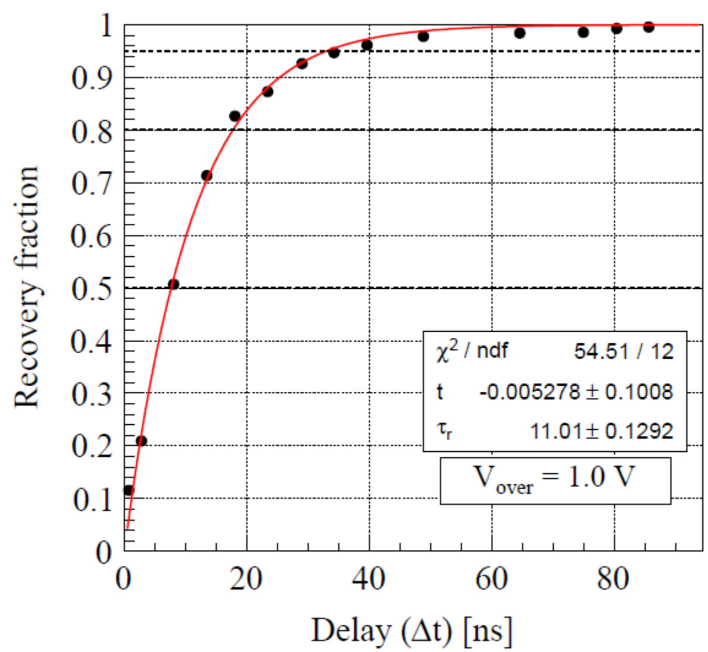
Double light pulses method. 2 short pulses with high intensity to fire all SiPM cells
Uniforme illumination over SiPM area

$y(\Delta t) = A2/A1$

Fixed intensity

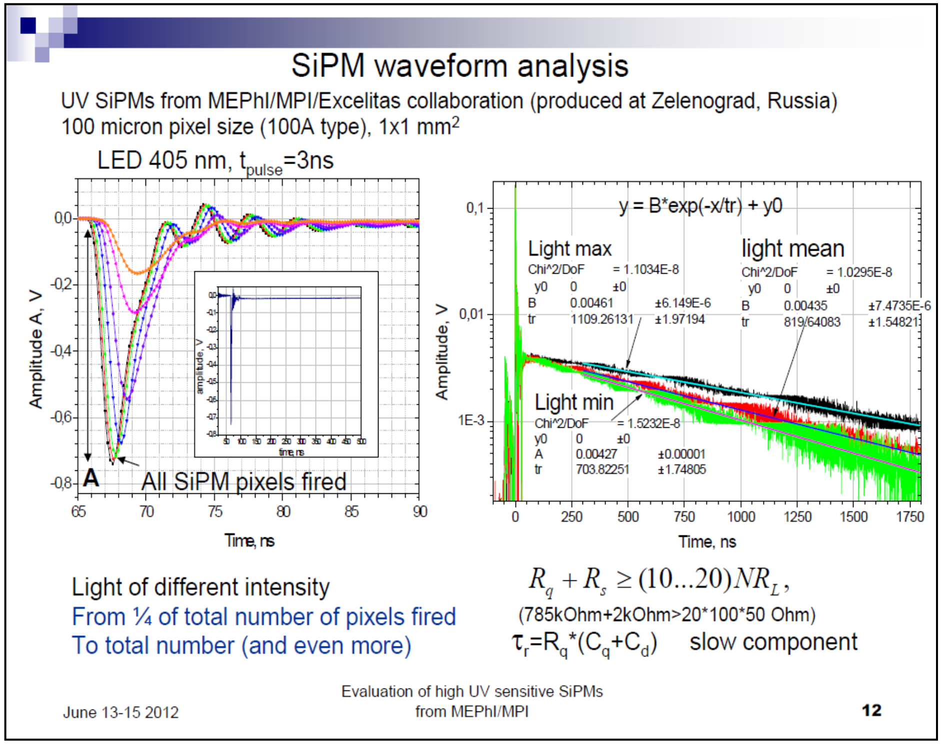
$$y(\Delta t) = 1 - \exp[-(\Delta t - t)/\tau_R]$$

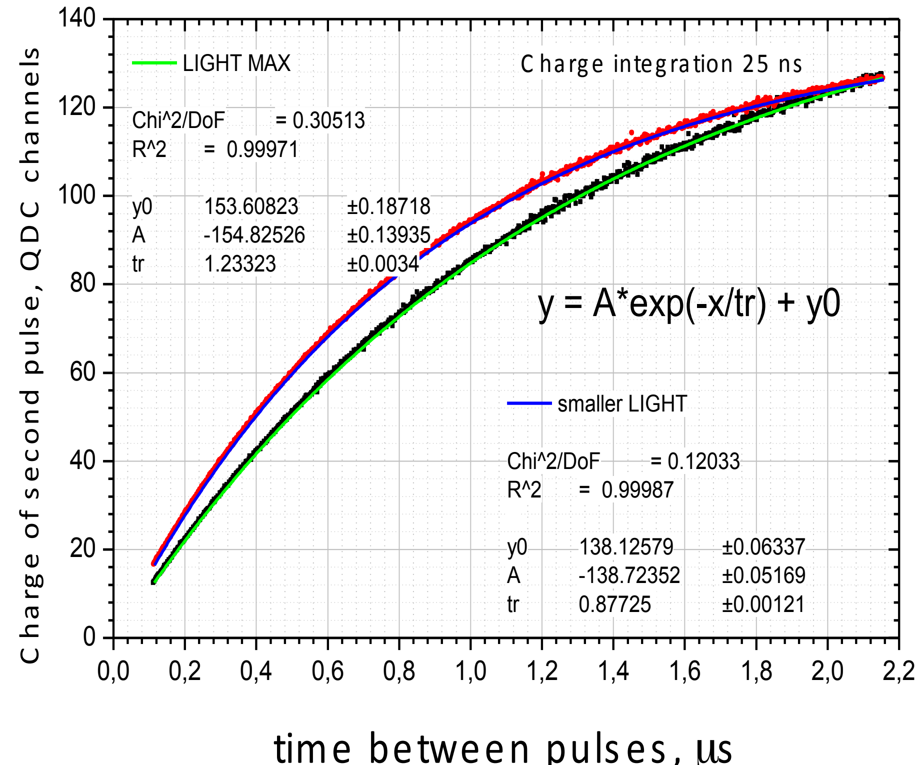




But one should be carefull – recovery might depends on light intensity (pixel load) - oversaturation

SiPM recovery time. Pulse shape analysis and double light pulses method for charge Q



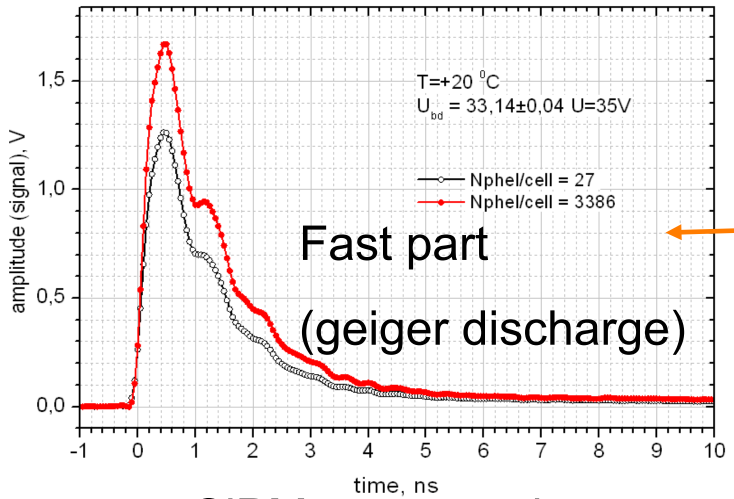


Light MAX	**τr=1233±4ns**
Smaller light (but still with SiPM saturation)	**τr=877±2ns**

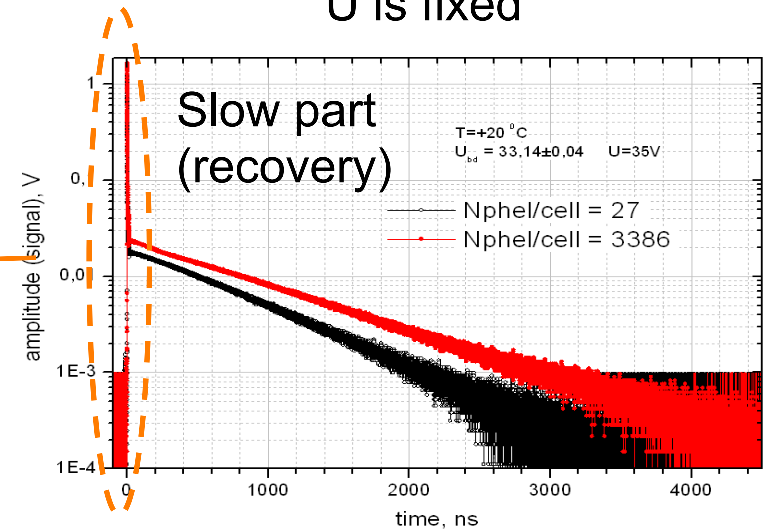
Both methods give the same results for recovery time vs light intensity
Drawback – no light intensity monitor

We have repeated our measurements with 1x1 mm² MEPHI SiPM (pitch 100μm) under control of light intensity

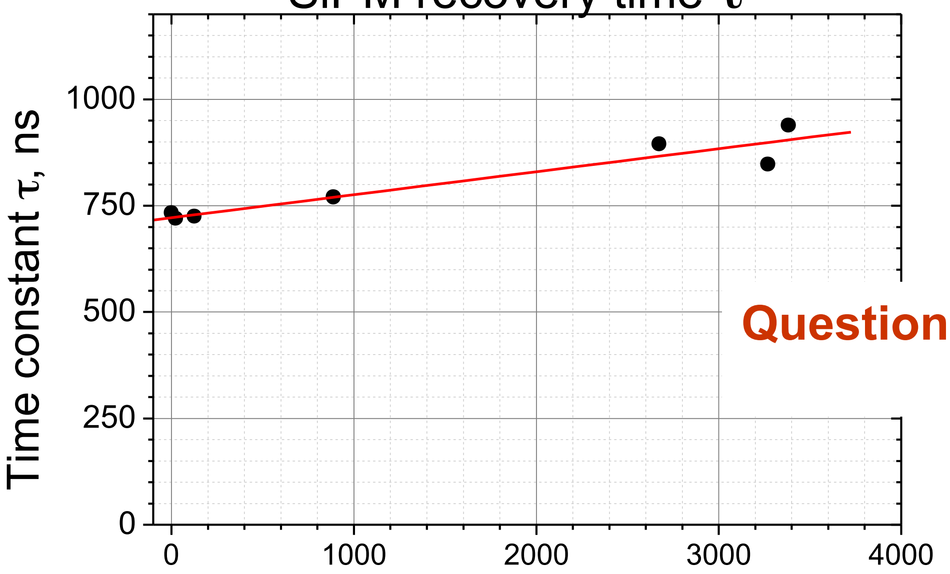
SiPM pulse for saturation conditions



U is fixed



SiPM recovery time τ



Amplitude, Charge and τ increase with light intensity

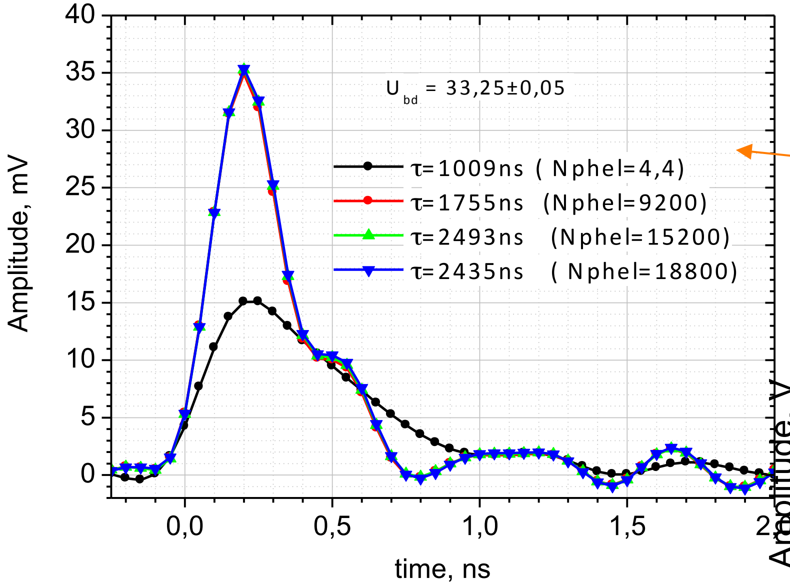
Question – what is (are) the reason(s) for this?

Group effect?

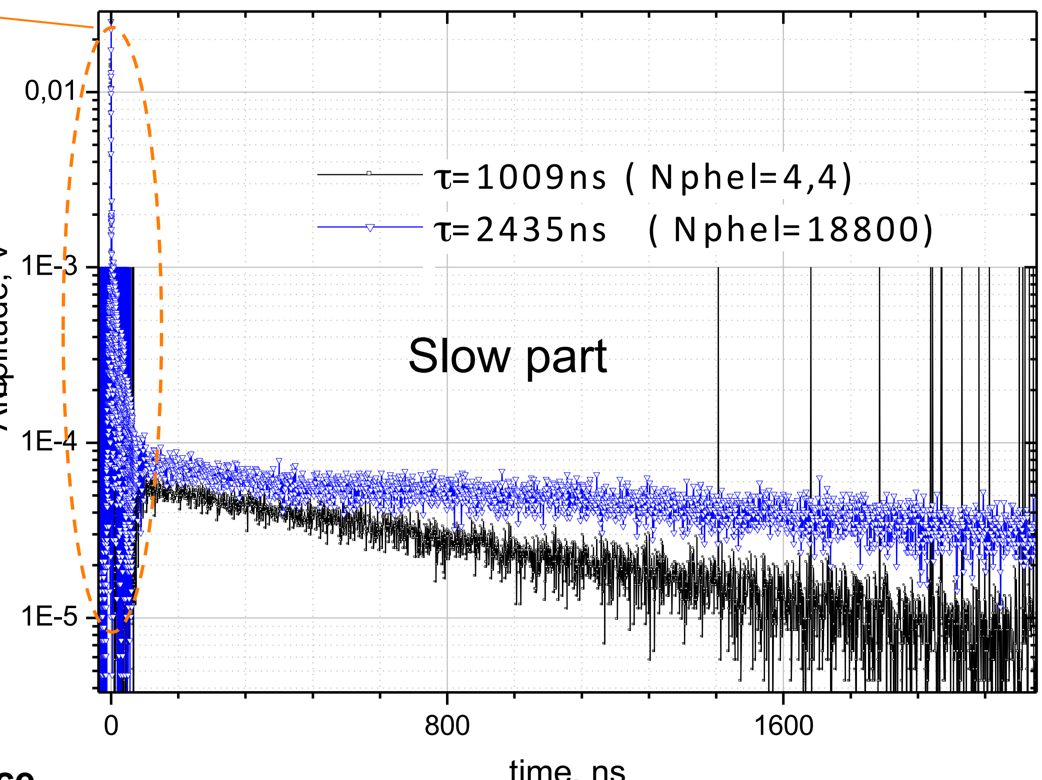
SiPM gain ~10^7

Single cell pulses for high intensities light (fixed voltage U=35V). MEPHI cell (100x100μm^2)

Fast part



SiPM cell pulse for saturation conditions



$$Q = (C_{fast} + C_{slow}) * (U - U_{br})$$

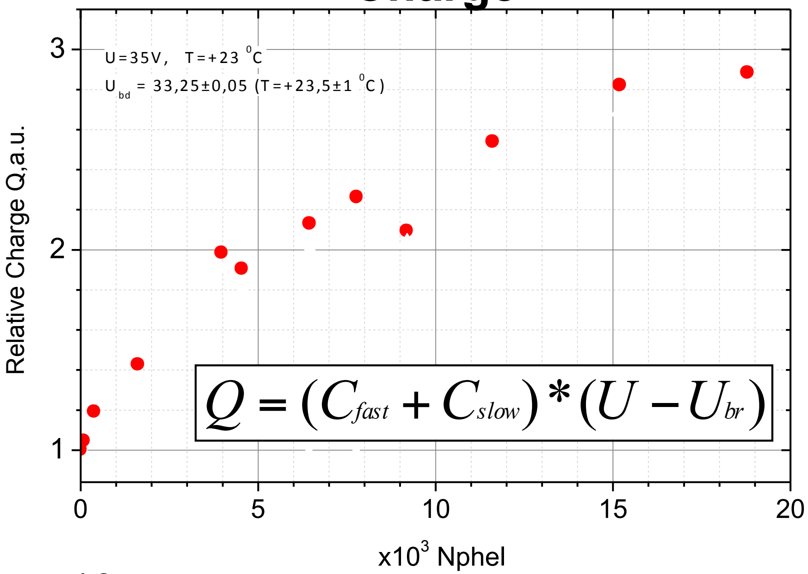
Total charge

$$\tau = R_{quench} * (C_{fast} + C_{slow})$$

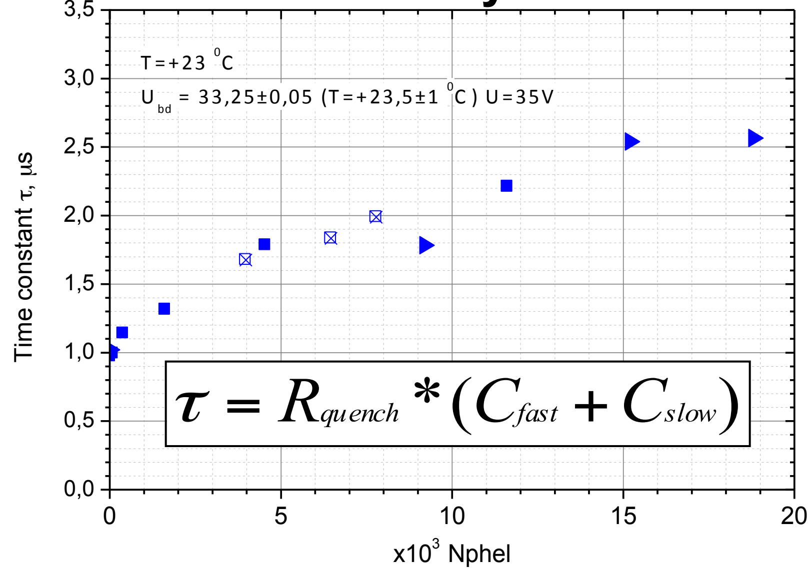
C_{fast} – readout (parasitic) cell capacitance
C_{slow} – cell p-n junction capacitance

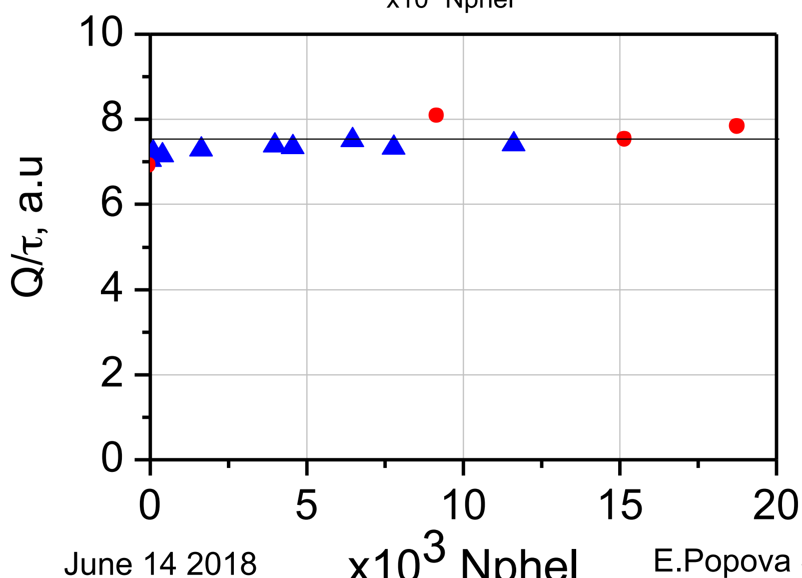
*Single cell pulses for high intensities light (for **fixed voltage**). MEPHI cell (100x100μm^2)*

Charge



Recovery time





$$Q / \tau = (U - U_{br}) / R_{quench} = const$$

$$U - U_{br} = const$$

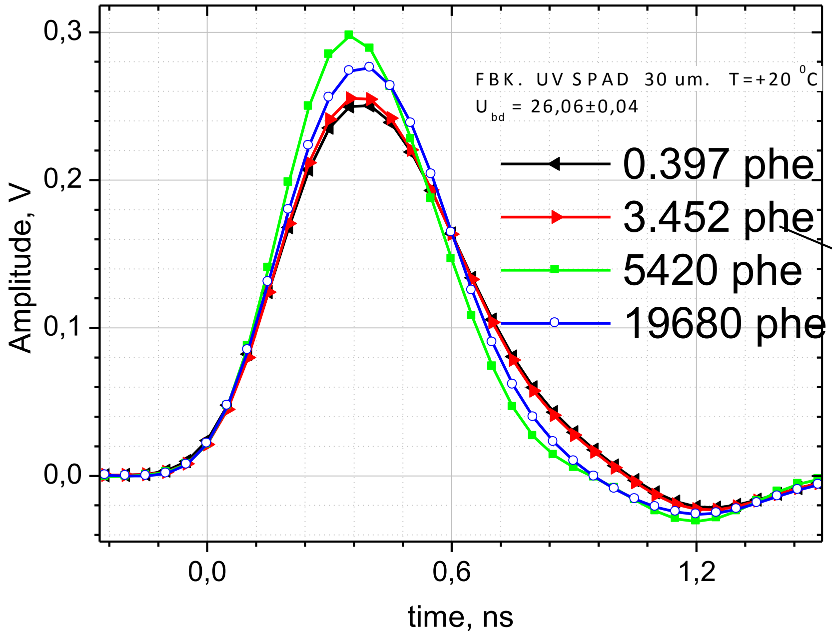
U-Ubreakdown doesn't change

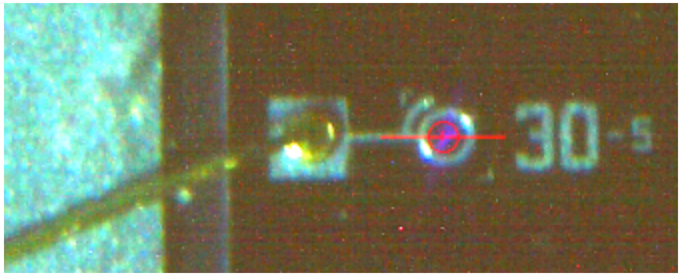
Q increases due to increasing of C_{fast}+C_{slow}

Specific technology?

Single cell pulses for high intensities light (for fixed voltage U=38V). FBK UV SPAD. Dia 30 μm

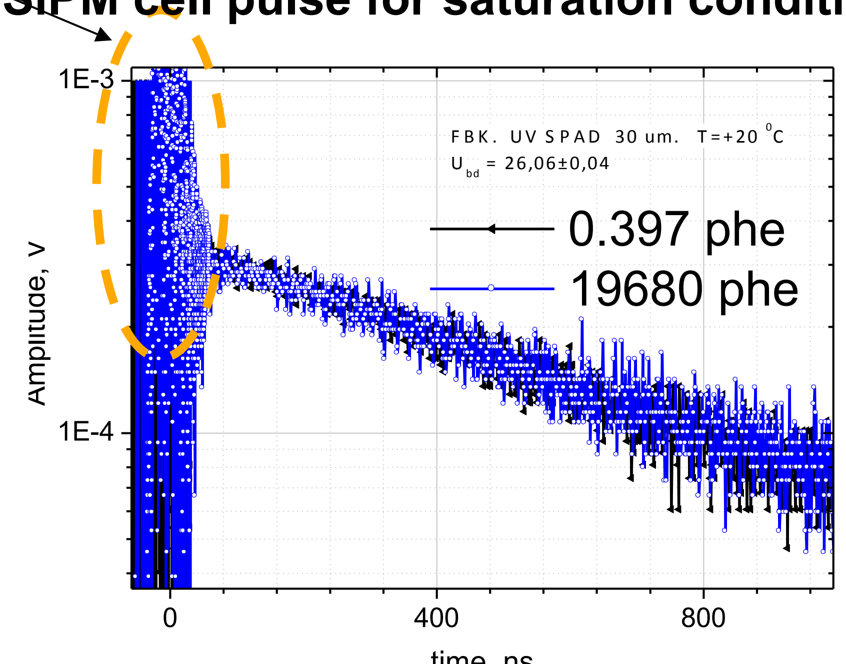
ΔU=12V





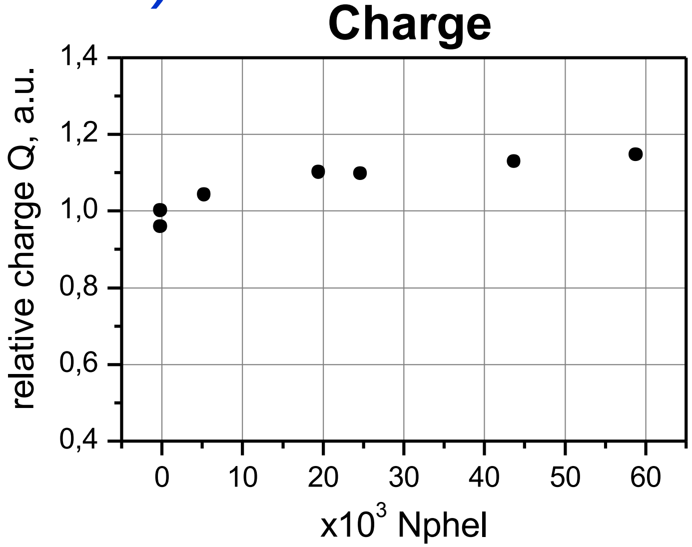
Thanks to F.Acerbi

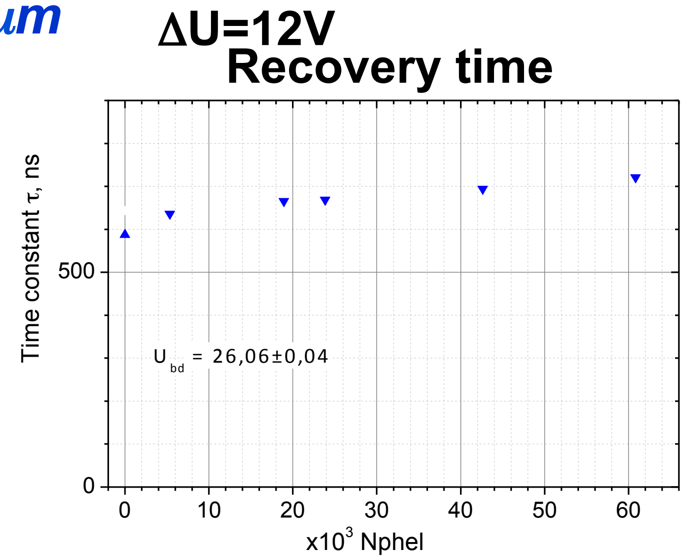
SiPM cell pulse for saturation conditions



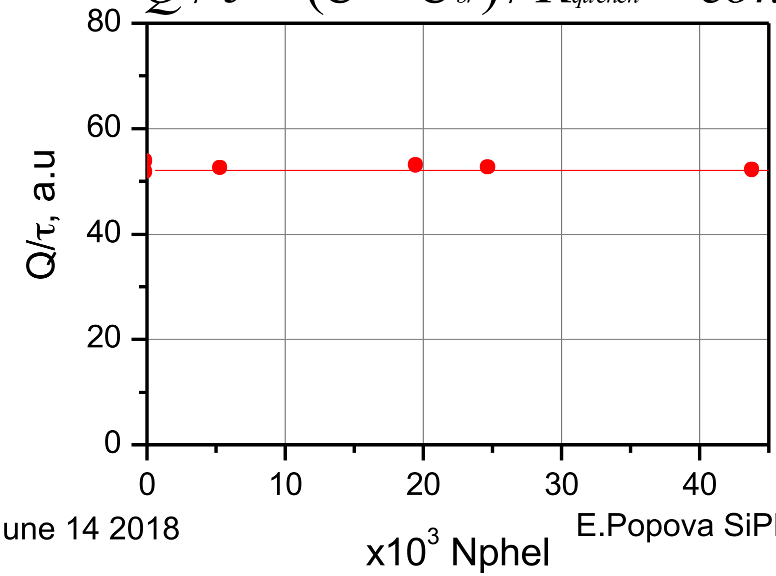
Very small difference in pulse shapes for different light intensities

Single cell pulses for high intensity light (for fixed voltage U=38V). FBK UV SPAD. Dia 30 μm





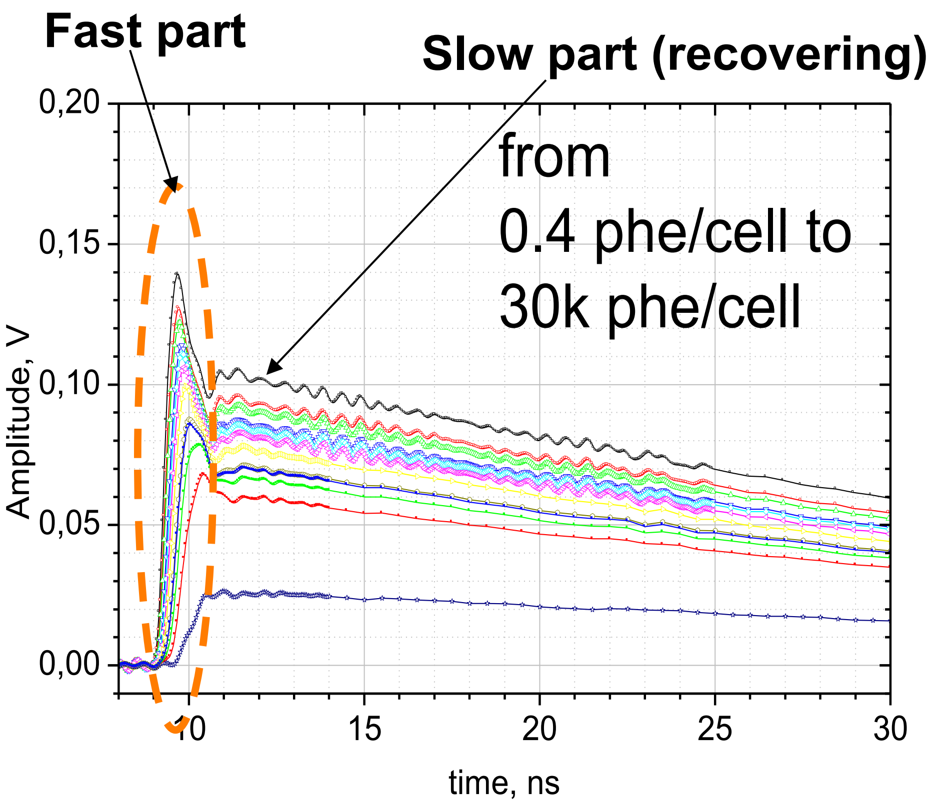
$$Q/\tau = (U - U_{br})/R_{quench} = const$$



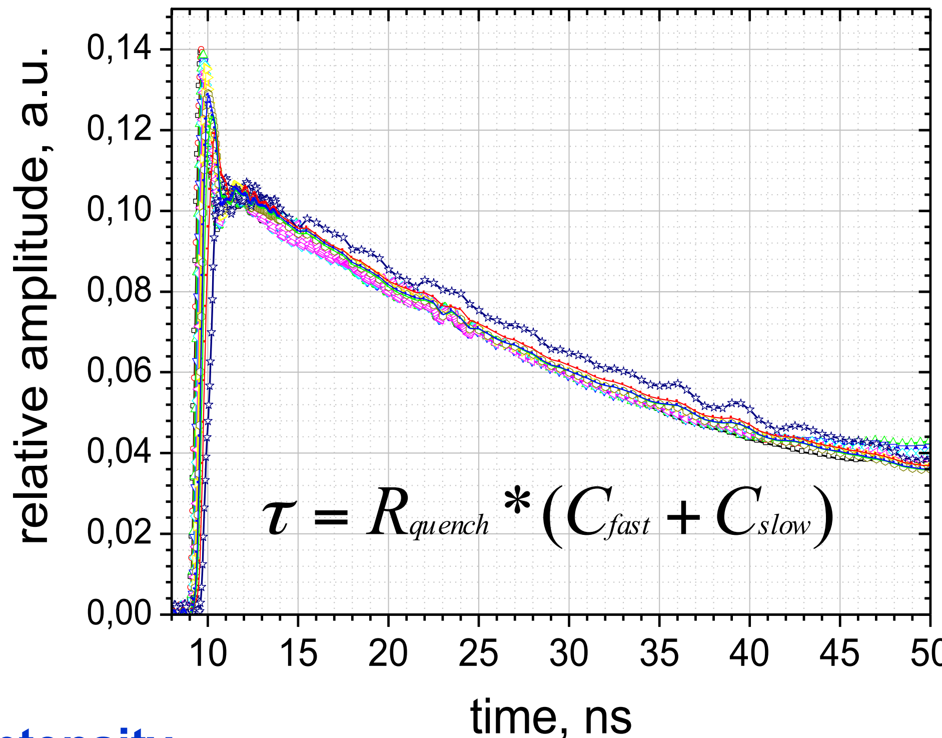
U-$U_{breakdown}$ doesn't change
Q increases due to increasing of C_{fast}+C_{slow}

Pulse shape for different light Intensities. MEPHI data

Hamamatsu S10362-11-100U No.50, Ubreakdown=68.4V, U=69.5V



Normalized pulse shapes



$Q = (C_{fast} + C_{slow}) * (U - U_{br})$ **Q changes with intensity**

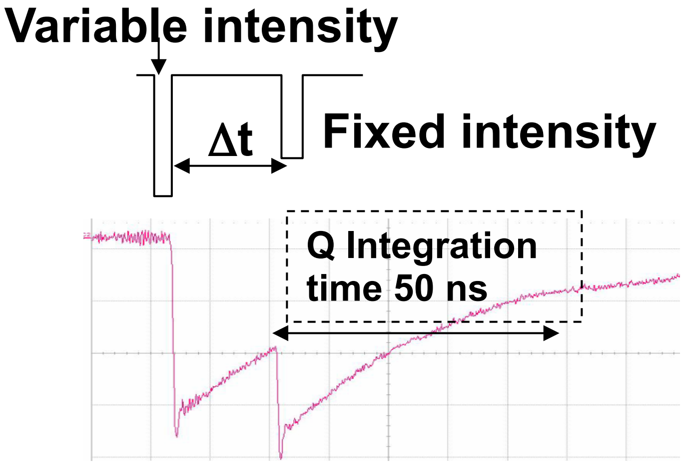
τ doesn't change with intensity

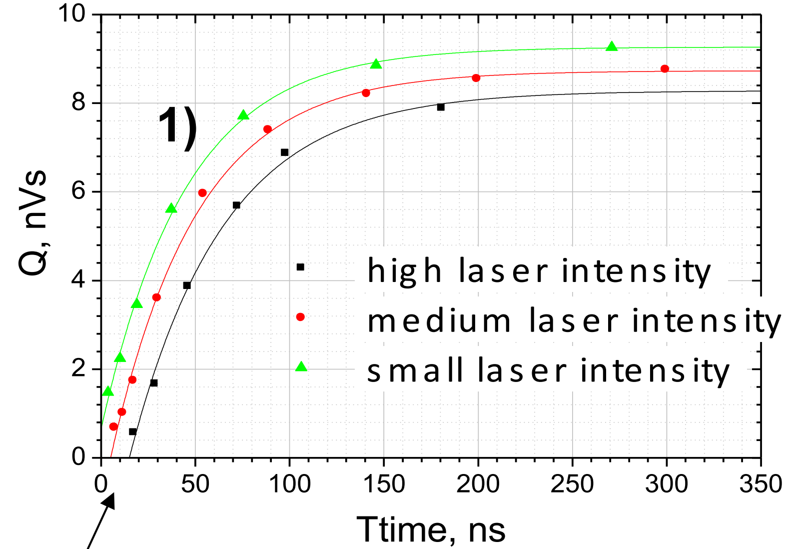
$A = N_{total\_cell} * \Delta U / R_{quench} * 50[Ohm]$

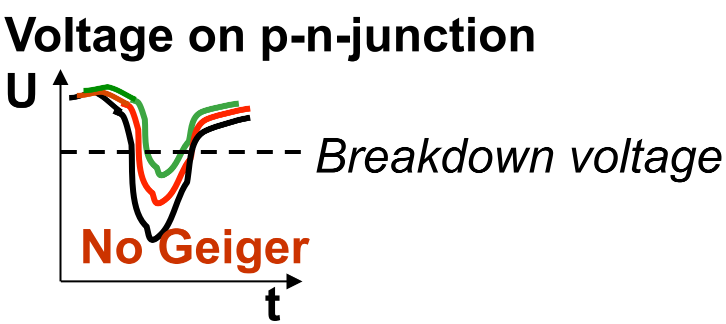
ΔU changes with intensity – potential drops on cell p-n-junction below $U_{breakdown}$

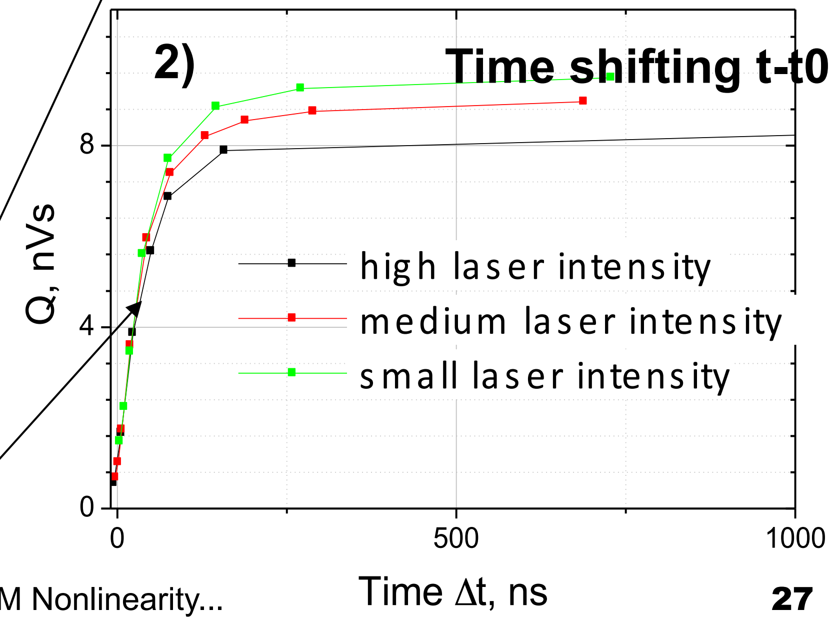
Recovery time for high light Intensities (many phe/cell). Double light pulses method

Hamamatsu S10362-11-100U No.50, $U_{breakdown}$=68.4V, U=69.5V





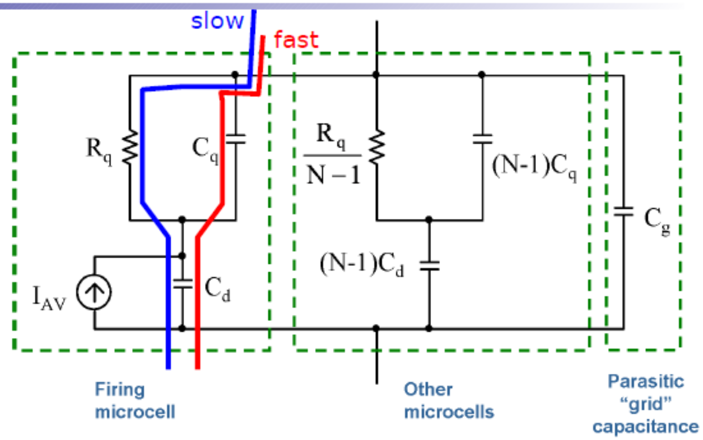




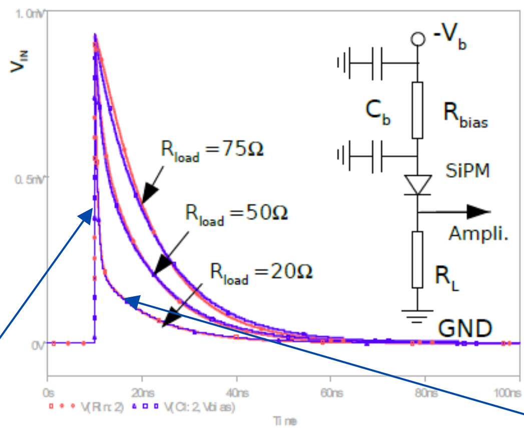
As higher intensity of the first pulse as longer time Δt before second pulse starts to give Geiger discharge (1); But recovery constant is the same (2)

Electrical model of a SiPM

R_q: quenching resistor (hundreds of kΩ)
C_d: junction capacitance (few tens of fF)
C_q: parasitic capacitance in parallel to R_q (few tens of fF, $C_q < C_d$)
I_{AV}: SiPM ~ ideal current source
current source modeling the total charge delivered by a cell during the avalanche $Q=\Delta V(C_d+C_q)$
C_g: parasitic capacitance due to the routing of Vbias to the cells (metal grid, few tens of pF)



N- total number of cells in SiPM



1) the peak of V_{IN} is independent of R_s

A constant fraction Q_{IN} of the charge Q delivered during the avalanche is instantly collected on $C_{tot}=C_g+C_{eq}$. where Ceq= N*[CqCd/(Cq+Cd)]

2) The circuit has two time constants:

- $\tau_{IN} = R_L\ C_{tot}$ (fast)
- $\tau_r = R_q(C_d+C_q)$ (slow)

In case of Rq>>N*R_L

R_L

Decreasing R_s, the time constant τ_{IN} decreases, the current on R_s increases and the collection of Q is faster

F. Corsi, C. Mazzocca et al.

G.Collazuol - IPRD08 4/10/2008

10

Fast component (geiger discharge)

Slow component (pixel recovery)

Important image!
To analyze SiPM waveform one needs to be sure that there are no external network influence

Recovery time depends on number of fired pixels and load resistor

Studying Voltage Recovery Processes on Silicon Photomultipliers
Instruments and Experimental Techniques, 2013, Vol. 56, No. 6, pp. 697–705

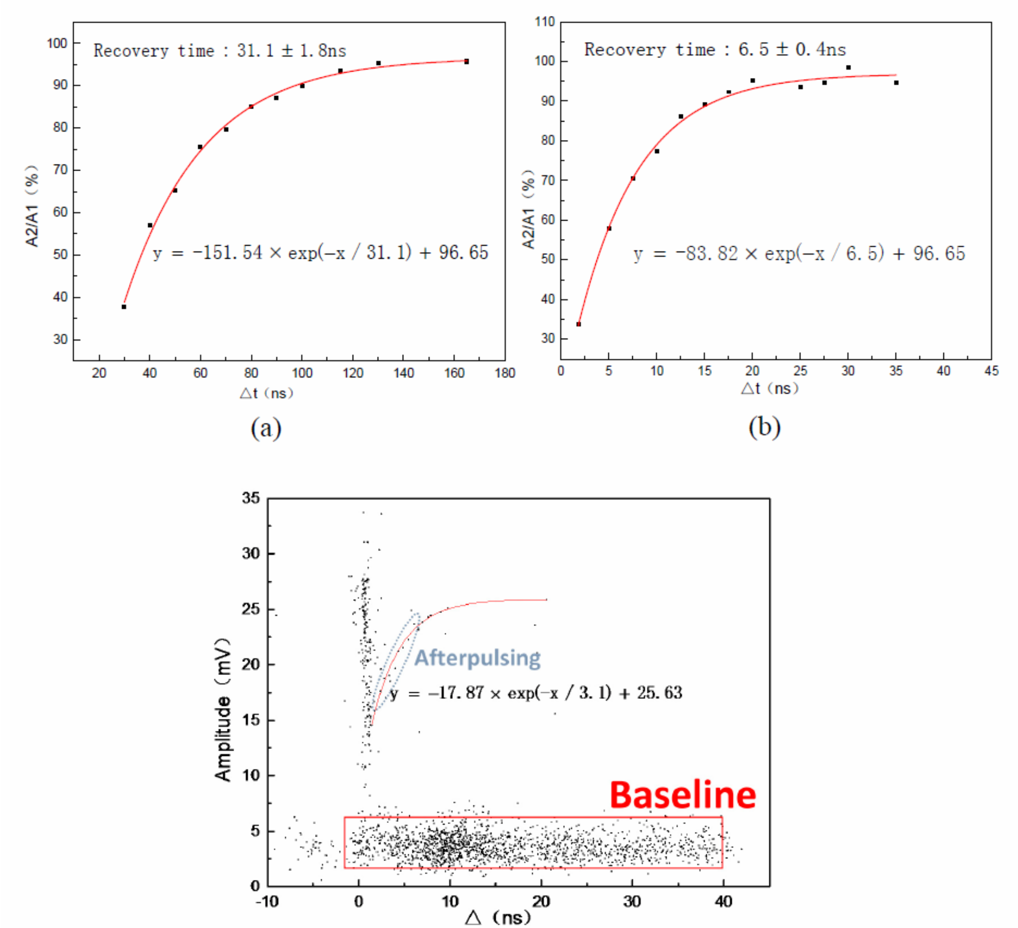
$$\Delta V_{ov}(t,n,N) \approx V_{ov}^{0}\left[\left(1-\frac{n}{N}\right)e^{-t/\tau_1}+\frac{n}{N}e^{-t/\tau_N}\right],$$

$$\tau_1 = (R_q + R_s)C_p + R_q C_f,$$
$$\tau_N = (R_q + R_s + NR_L)C_p + R_q C_f.$$

If $R_q + R_s \geq (5-10)NR_L$

$$\tau_r \approx \tau_1 \approx \tau_N \approx (R_q + R_s)C_p + R_q C_f$$

Experimental study of a SiPM recovery time



For 3 x3 mm2 SiPM, with 90 000 pixels the

90000 pixels the recovery time is 31.1 +-1.8 ns;
2000 pixels 6.5 +-0.4 ns
one fired pixel 3.1 +- 0.2 ns.

For 1.4 x1.4 mm2 device, ~20 000 pixels
15 000 pixels the recovery time is 15.2 +-0.5 ns

Recovery Time of Silicon Photomultiplier with Epitaxial Quenching Resistors
Instruments **2017**, 1, 5; doi:10.3390/instruments1010005

Summary:

For Geiger discharge in oversaturated conditions (>>1 phe/SiPM cell)

•SiPM charge, recovery time and amplitude depend on light intensity;

•Depending on SiPM cell construction (technology used) high light intensities may affect cell capacitance and/or cause enhanced voltage drop on cell pn-junction (below $U_{breakdown}$);

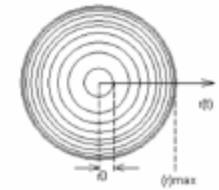
Possible reasons for such behavior:

•conventional feedback between ionization rates and instant pn-junction overvoltage becomes too “slow” for extremely fast and strong Geiger discharge development

•very local feedback due to screening effect of free carriers produced during ionization in depletion region starts play a role in this case.

Work has been supported by Megagrant 2013 program of Russia, agreement № 14.A12.31.0006 from 24.06.2013

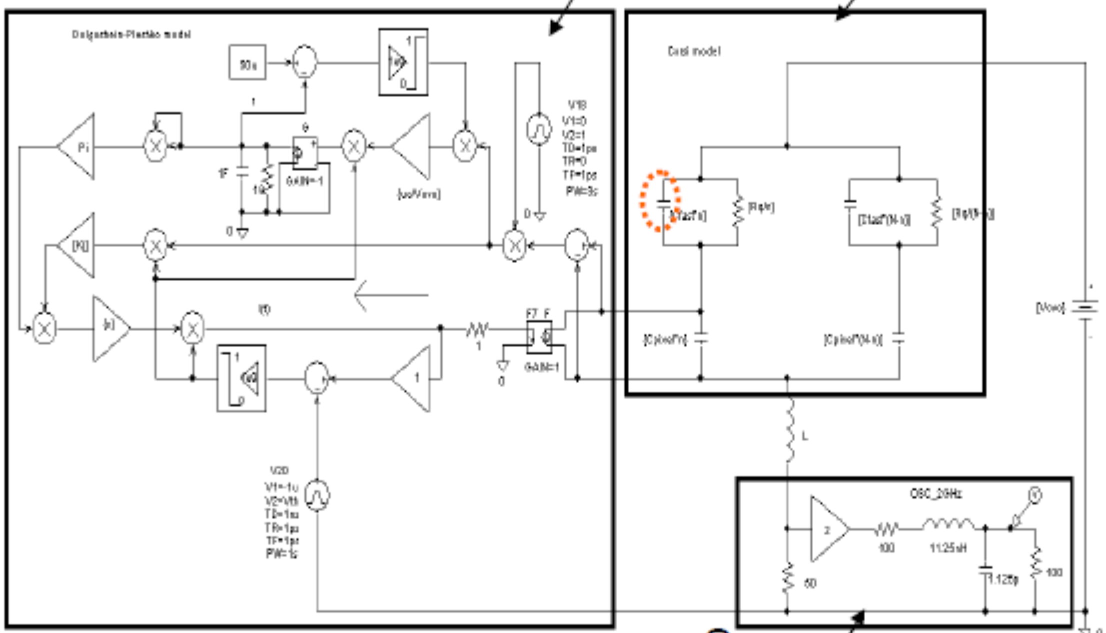
Spice model of avalanche development in a SiPM cell (transversal propagation)



Transversal avalanche propagation & Avalanche current selfquenching

Corsi model

Dolgoshein-Pleshko model



Scope

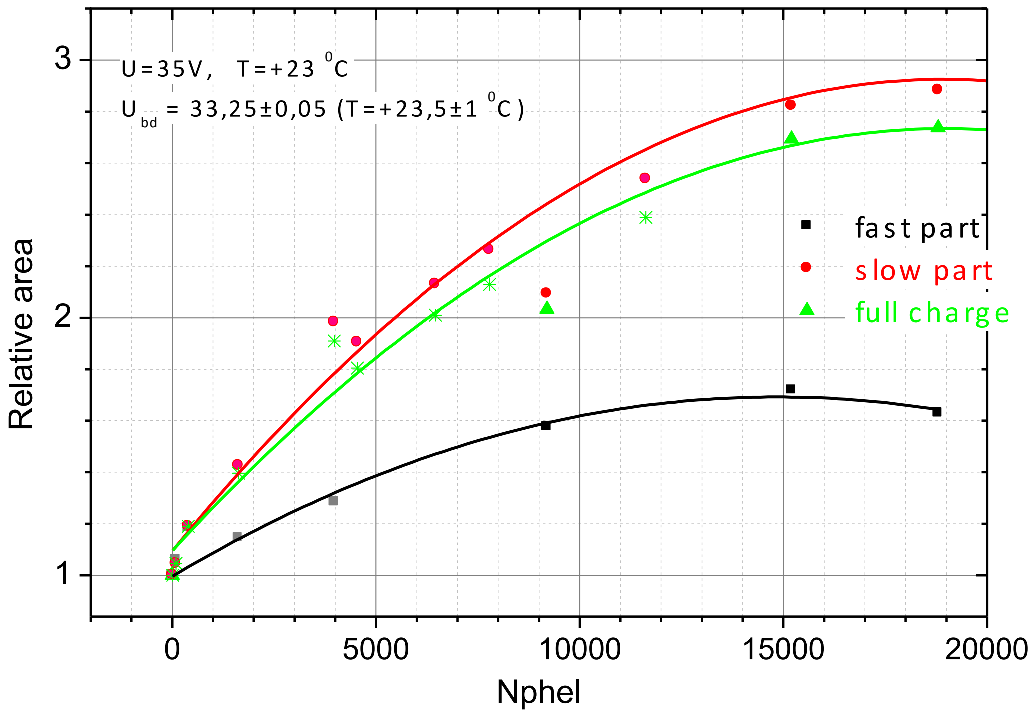
- Geiger discharge starts in a tiny spot inside a cell (1st disk)
- Current $J(t)=K_J*V_{ov}(t)$, where Kj- is disk specific conductivity
- Discharge spreads from spot to 1st elementary ring, 2^{nd},..., with velocity $u(t) = u_0 \times V_{OV}(t)/V_{OVO}$,
- The capacitor of the cell discharges through the Geiger-avalanche current, after a while overvoltage drops down to 0

C_{fast} – important parameter!

V_{OVO}-initial overvoltage, $V_{OV}(t)$ – momentary overvoltage

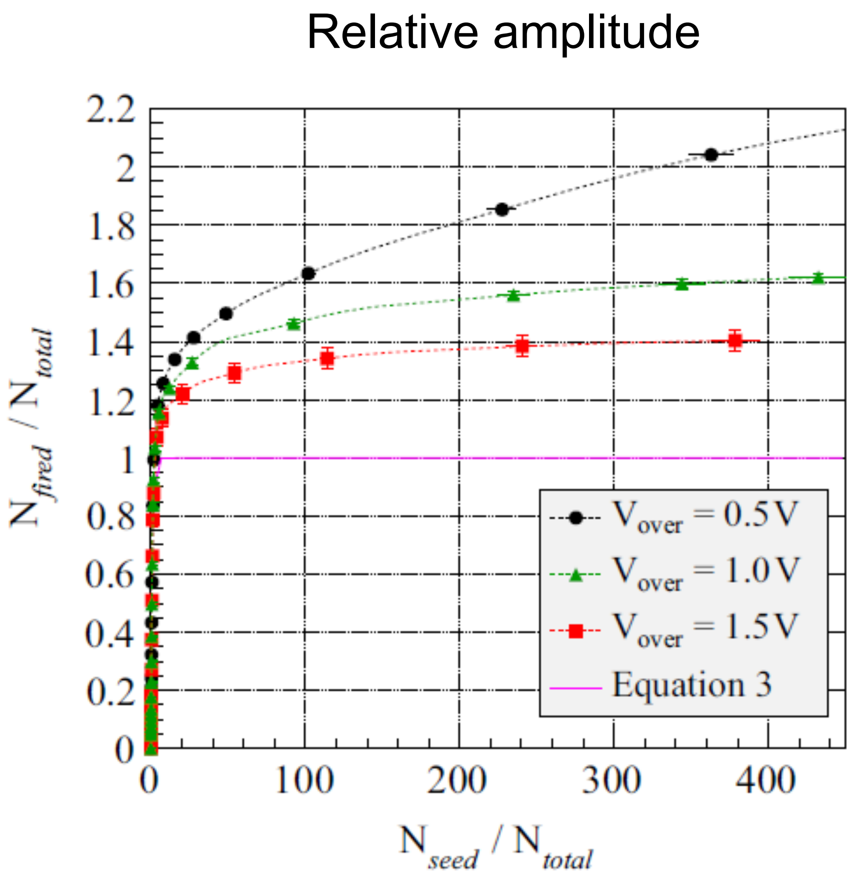
***K_j, u_0** - are experimental parameters*

$$I(t) = J(t)S(t) = J(t)\times \pi r^2(t) = \pi k_J V_{ov}(t)[\int_0^t u_0 \frac{V_{ov}(t')}{V_{ov0}}]^2 dt'$$



U=35V, T=+23 °C
U bd = 33,25±0,05 (T=+23,5±1 °C)
fast part
slow part
full charge
Relative area
Nphel
3
2
1
0
5000
10000
15000
20000

Hamamatsu MPPC 100U 1x1mm2



"One possible explanation could be that a very high number of input photons per pixel may trigger several avalanches simultaneously, giving rise to a slightly higher output signal compared to the single photon signal." L. Gruber et al.NIM A737 (2014) 11–18

Novel approach for calibration breakdown voltage of large area SiPM

Sergei Dolinsky[1]
GE Global Research Center
One Research Circle, Niskayuna NY, USA
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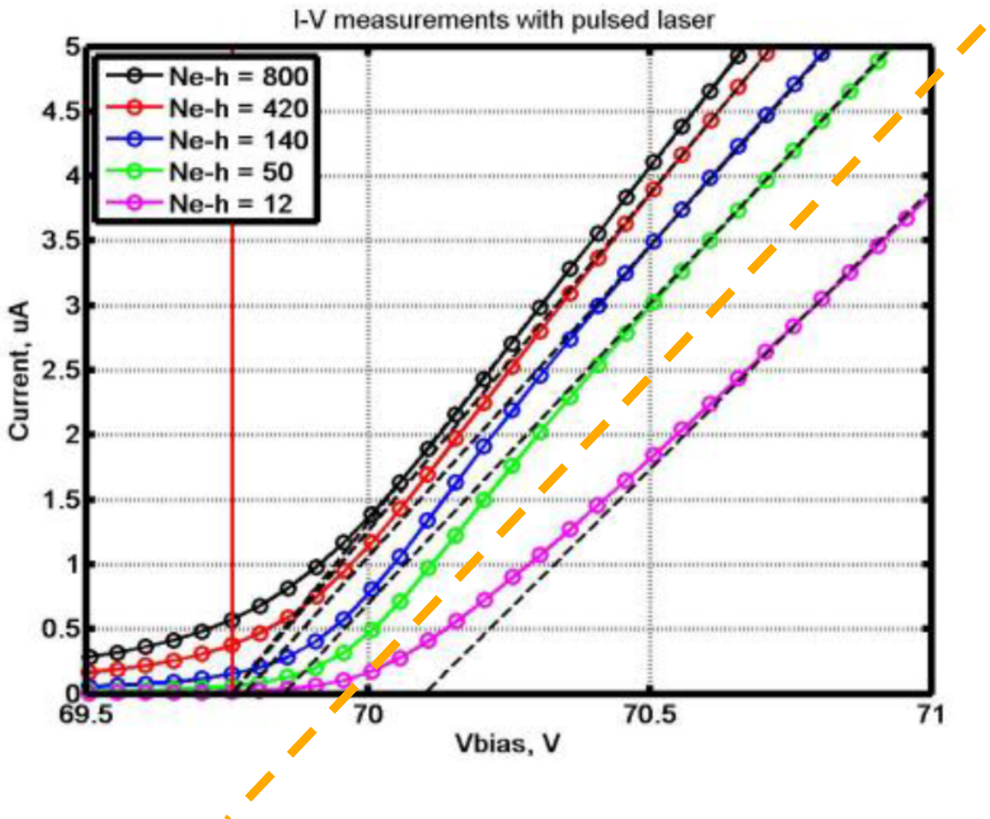
N_{e-h}/u-cell/pulse	Effective C_{u-cell} (fF)	$V_{br(V)}$	dVpeak/dVbias
800	152 fF	69.76	0.9
420	145 fF	69.76	-
140	132 fF	69.78	0.75
50	122 fF	69.85	-
12	97 fF	70.05	0.6

Table1 The results of the measuretments for different intensities



$$Q = (C_{fast} + C_{slow}) * (U - U_{br})$$

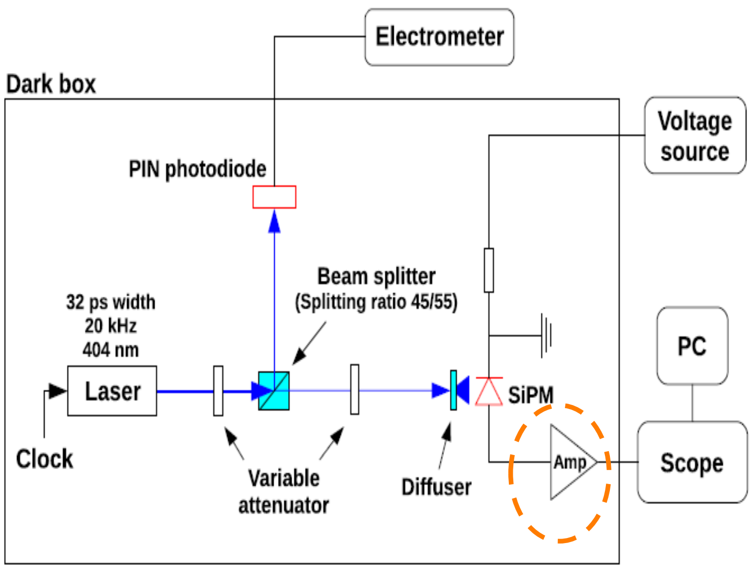
$$C_{microcell} = (C_{fast} + C_{slow})$$

$$dI / dU = N_{cell} * C_{microcell} * F_{rep}$$

Not C but Q

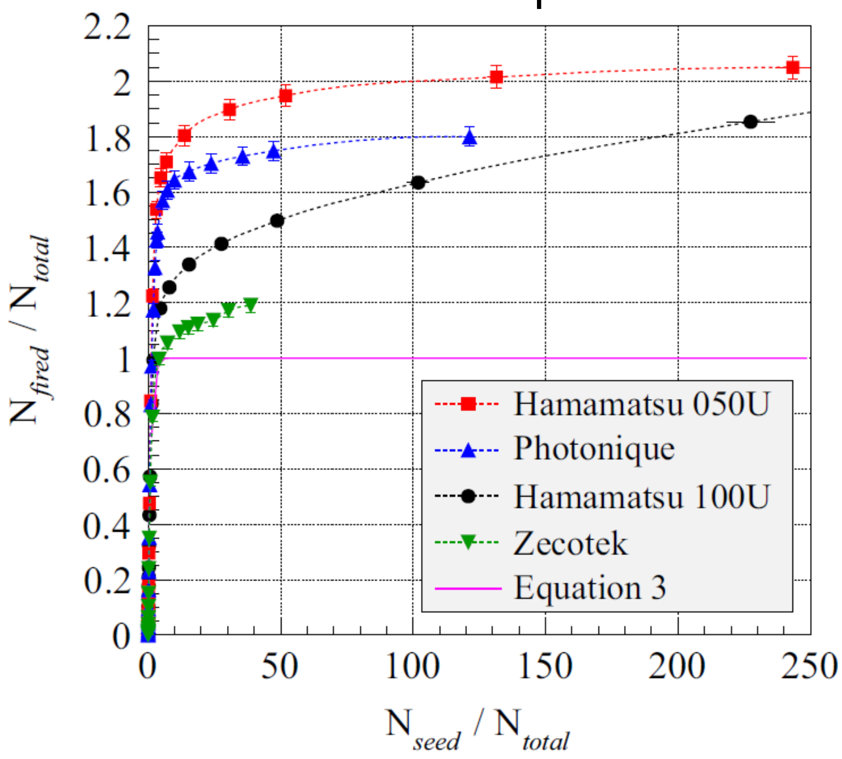
dI/dV = Ncell·d(ΔQ/ Δ t)/ /dV

Over saturation behavior of SiPMs at high photon
L. Gruber et al./NIM A737 (2014) 11–18



Amplitude analysis of 1x1mm^2 different SiPMs

Relative amplitude



Advanced Laser Diode Systems
(PIL040) 404 nm, 20kHz,FWHM 32 ps

It has been reported that MPPC pulse shape doesn't depend on light intensity
Used Amp might be the reason for that