VSiPMT Prototype Tests

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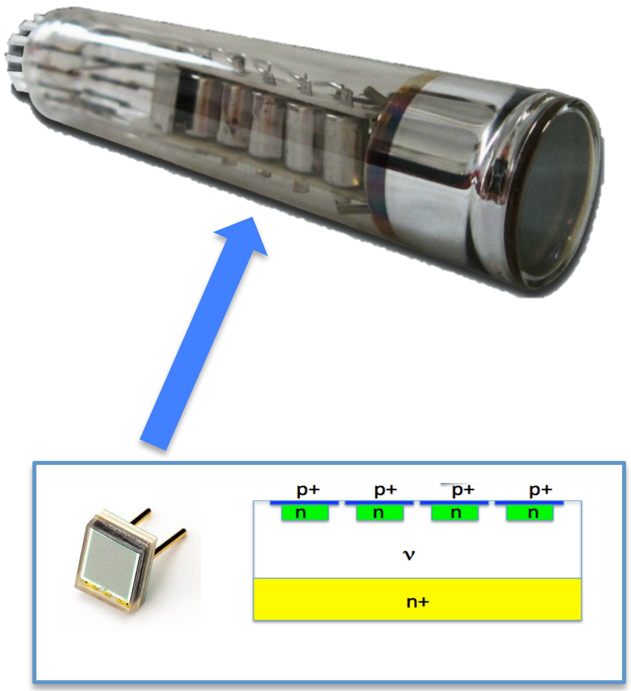
Outline

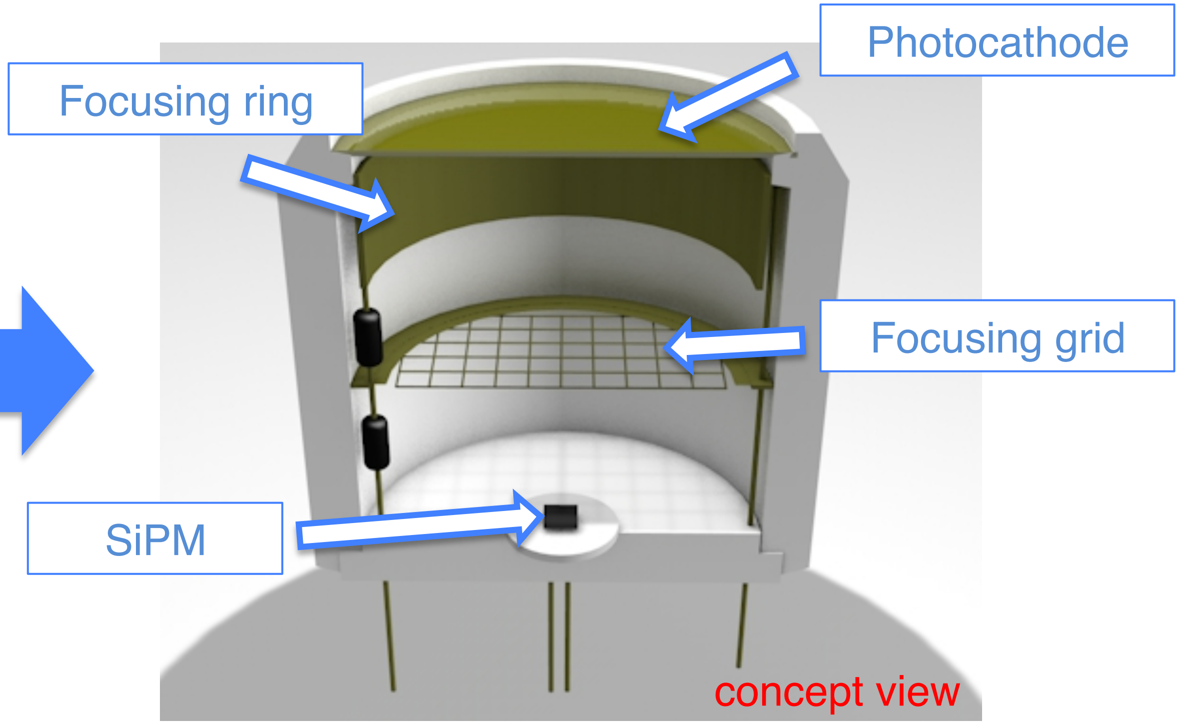
1. Introduction
2. The prototypes
3. Experimental setup
4. Characterization
5. Conclusions

Introduction

Vacuum Silicon PhotoMultiplier Tube (VSiPMT)

An innovative design for a modern hybrid photodetector based on the combination of a Silicon PhotoMultiplier (SiPM) with a Vacuum PMT standard envelope





The classical dynode chain of a PMT is replaced with a SiPM, acting as an electron multiplying detector.

An attractive solution for cryogenic applications

Requirements for next generation DM experiments

- Good bg discrimination → High S/N ratio and high SPE resolution;
- Low radioactive bg → PMTs < 1mBq/(3" PMT);
- Low power consumption;
- Stable operation at LAr/LXe temperature.

Uranium, Thorium and Potassium from ceramics/metal parts in a standard PMT are the main source of background in DM noble liquids experiments

VSIPMT

Unrivalled performances optimal solution for next generation DM experiments

Unprecedented features wrt cryogenic PMTs:

- Photon counting capability;
- Low power consumption;
- Silicon virtually **free of radioactivity** (in addition reduced mass);
- Excellent timing performances (low TTS);
- **High stability (not depending on HV)**;
- Excellent SPE resolution.

Timeline

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 594, Issue 3, 11 September 2008, Pages 326–331

Review

A new high-gain vacuum photomultiplier based upon the amplification of a Geiger-mode p–n junction

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...ngs
...ors (IPRD08)

A new Design for an High Gain Vacuum Photomultiplier: The Silicon PMT Used as Amplification Stage

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Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
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In Press, Corrected Proof — Note to users

VSiPMT for underwater neutrino telescopes

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Proof of feasibility of the Vacuum Silicon PhotoMultiplier Tube (VSiPMT)

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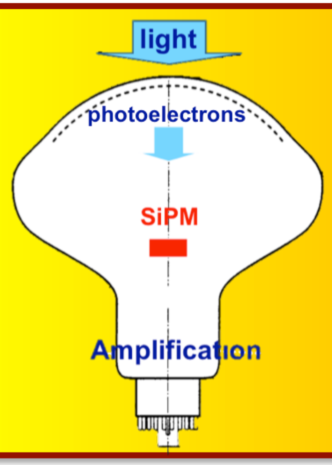

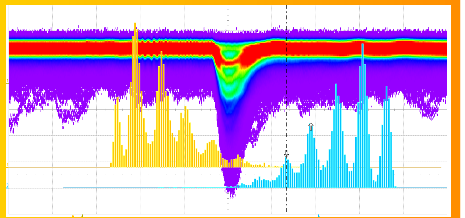

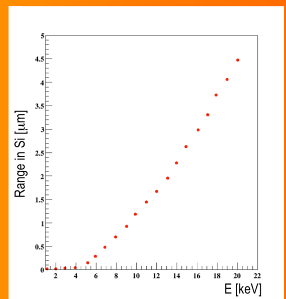

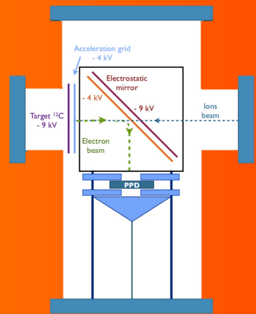

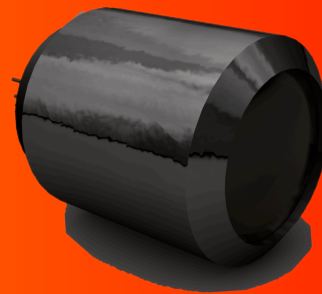

2007

2013

Physics Procedia
Volume 37, 2012, Pages 703–708
Proceedings of the 2nd International Conference on Technology and Instrumentation in Particle Physics (TIPP 2011)

High Gain Hybrid Photomultipliers Based on Solid State p-n Junctions in Geiger Mode and Their use in Astroparticle Physics

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Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
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Vacuum silicon photomultipliers: Recent developments

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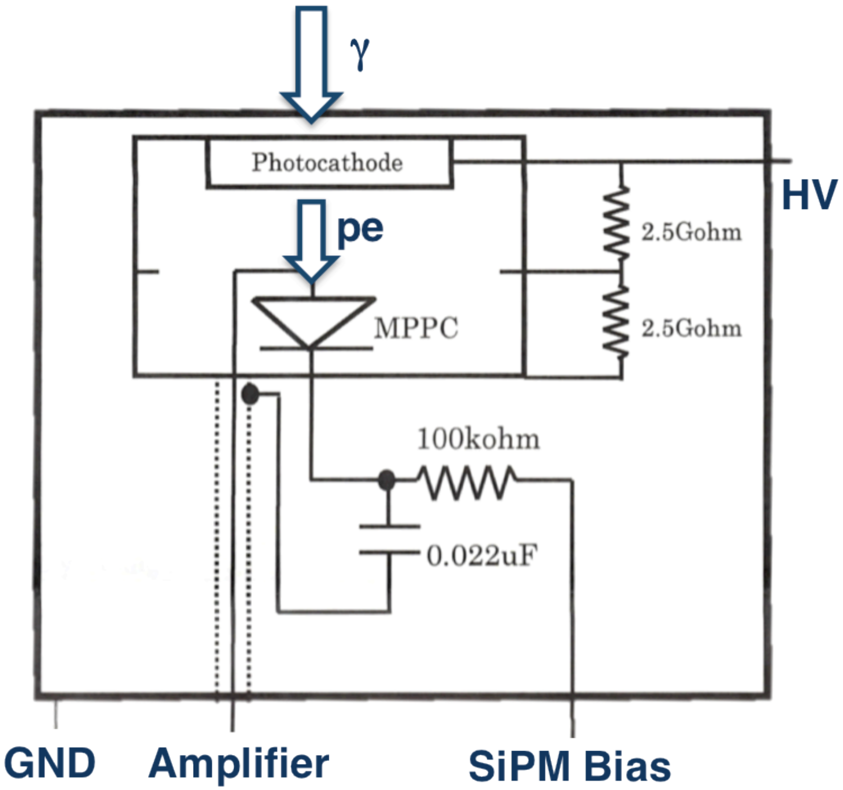
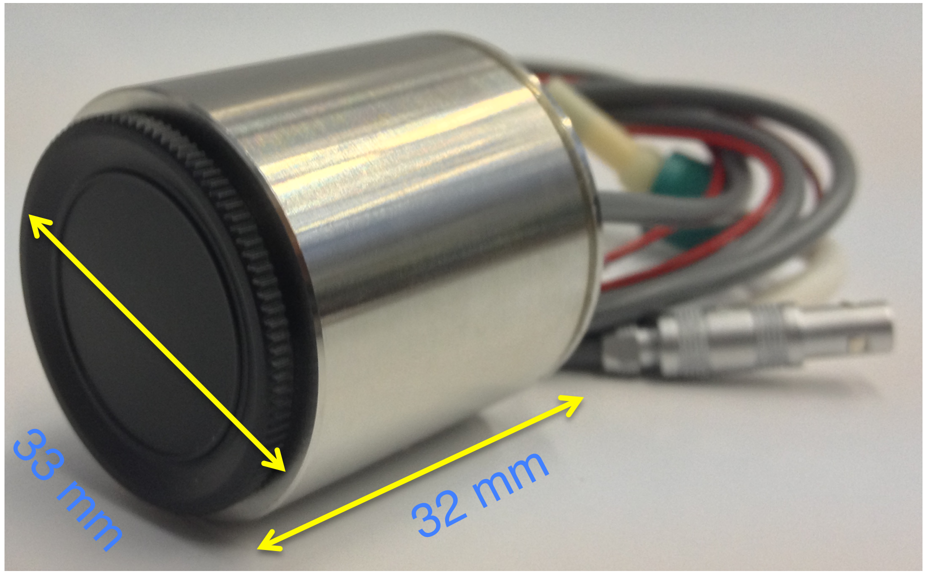
The prototypes

HAMAMATSU
PHOTON IS OUR BUSINESS



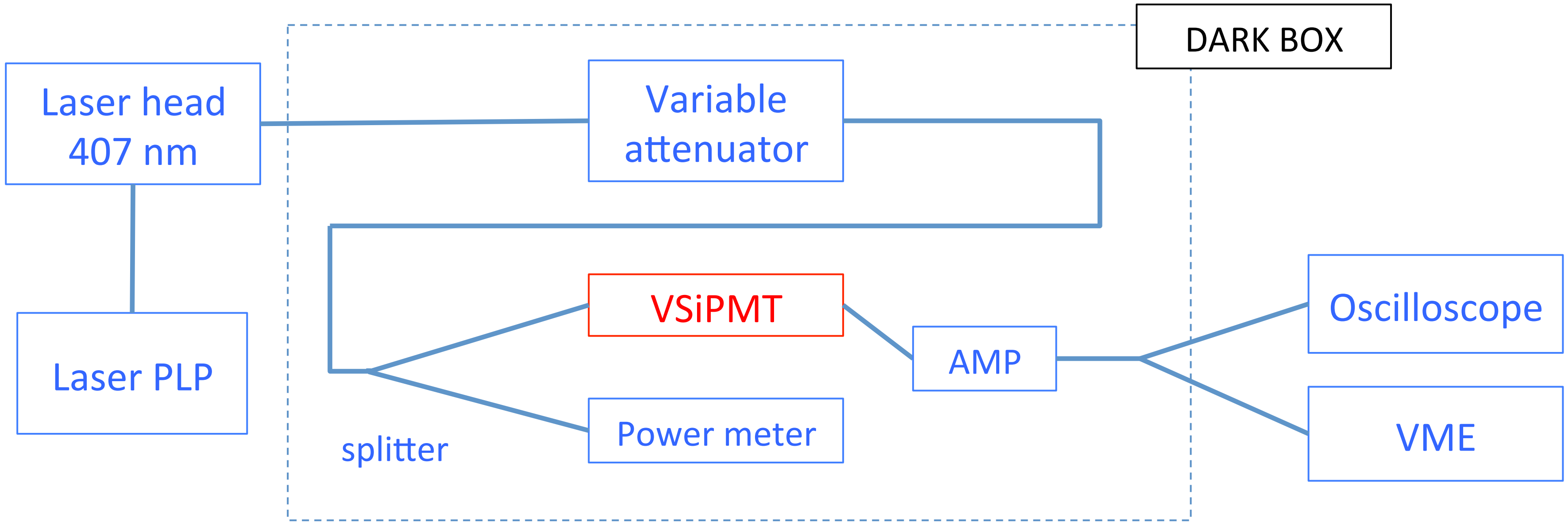


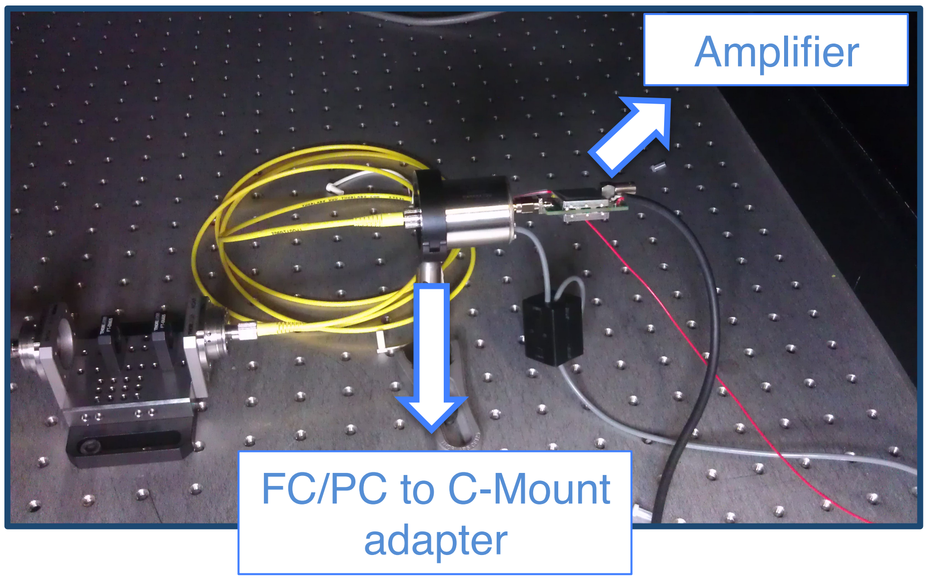
7x7 mm^2 entrance window
3 mm diameter GaAsP photocathode
2 protoyopes:
MPPC 1 mm^2 / 50 μm / 400 cells
MPPC 1 mm^2 /100 μm / 100 cells

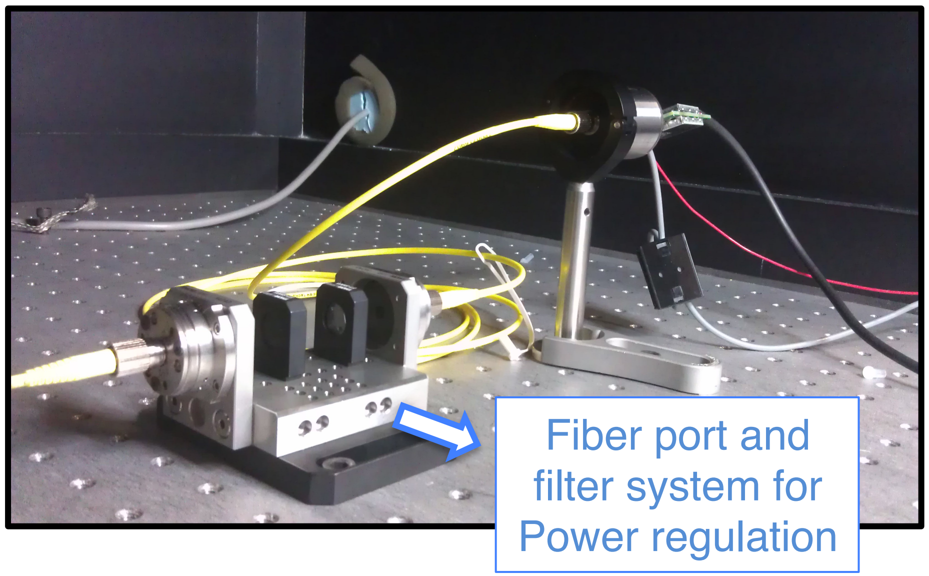
$p^+n\nu n^+$ configuration, special non-windowed series for ε optimization.
Lower voltage required (-2,5/3 kV expected).

No voltage divider: no power dissipation nor complicated circuits to reduce the dissipation
Only a very simple amplifier is required (typ. < 5mW).

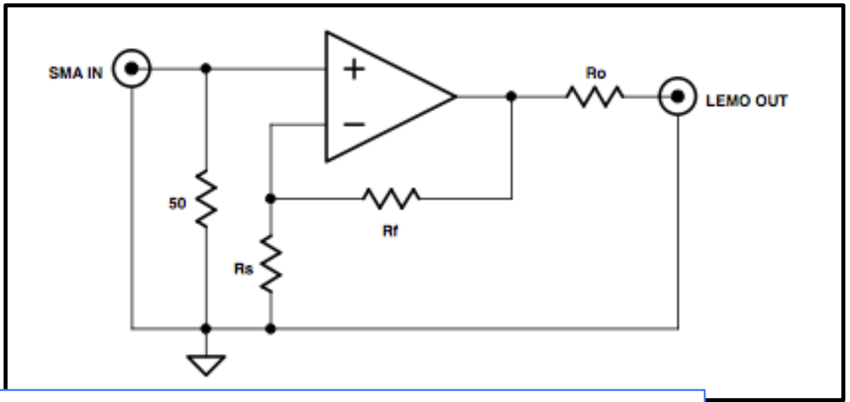
Experimental setup





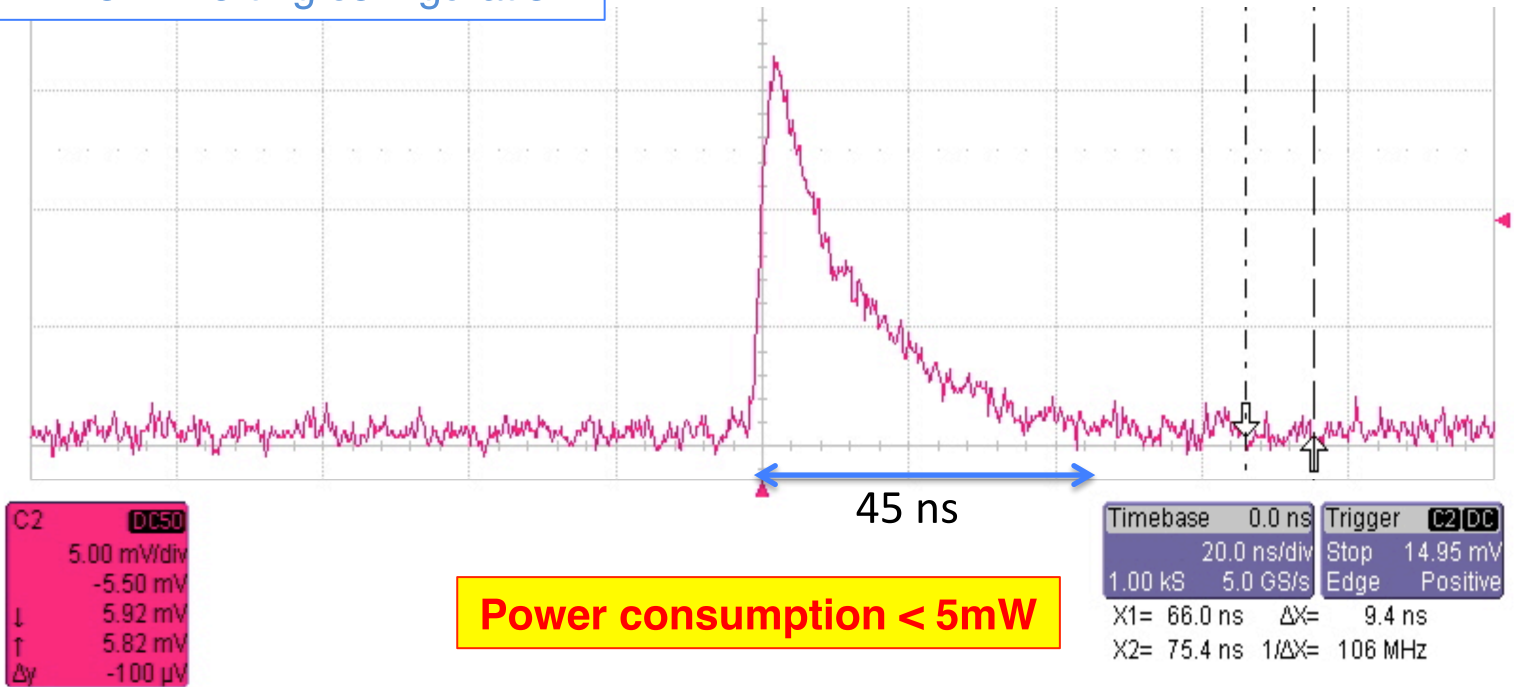


Amplification



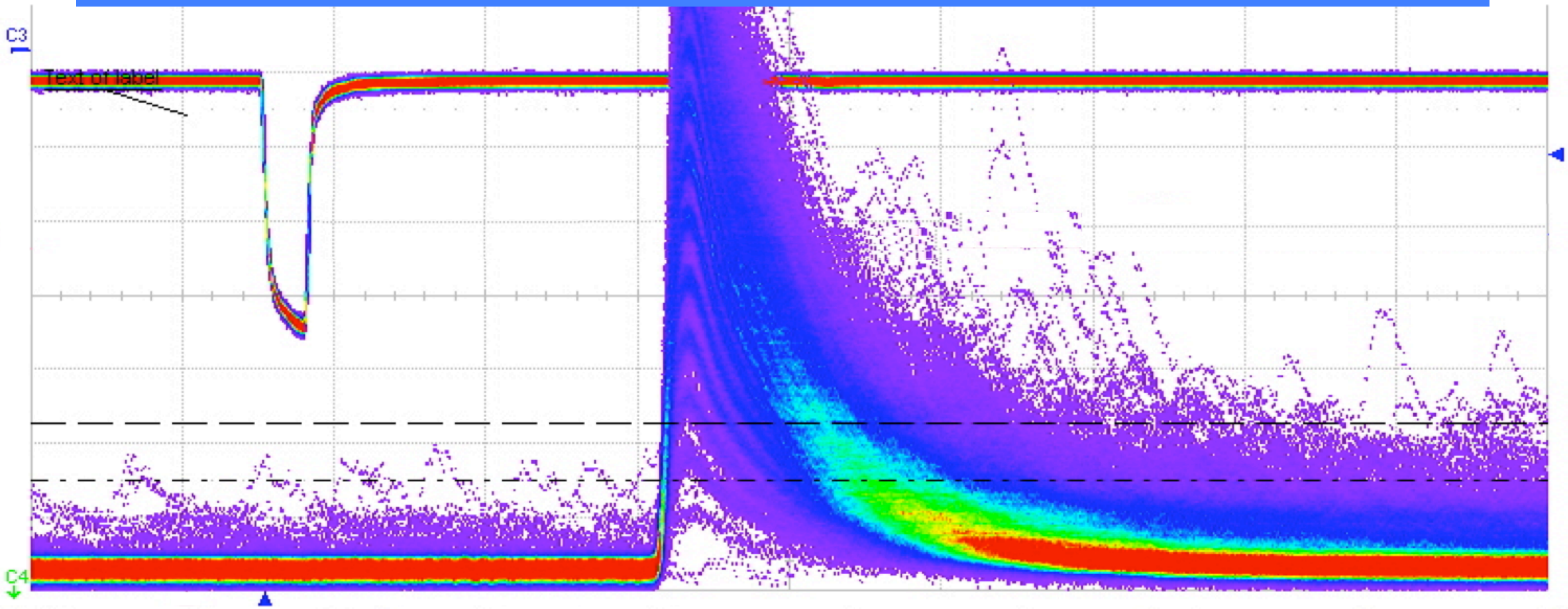
Single-state amplifiers based on an OP-AMP in non inverting configuration.

Three different gains: 10, 15, 20.



Power consumption < 5mW

Waveforms



C3 DC50
200 mV/div
658.0 mV
-1.160 V
-1.004 V
Δy 156 mV

C4 DC50
5.00 mV/div
-26.90 mV
14.35 mV
18.25 mV
Δy 3.90 mV

→ 5 mV/div

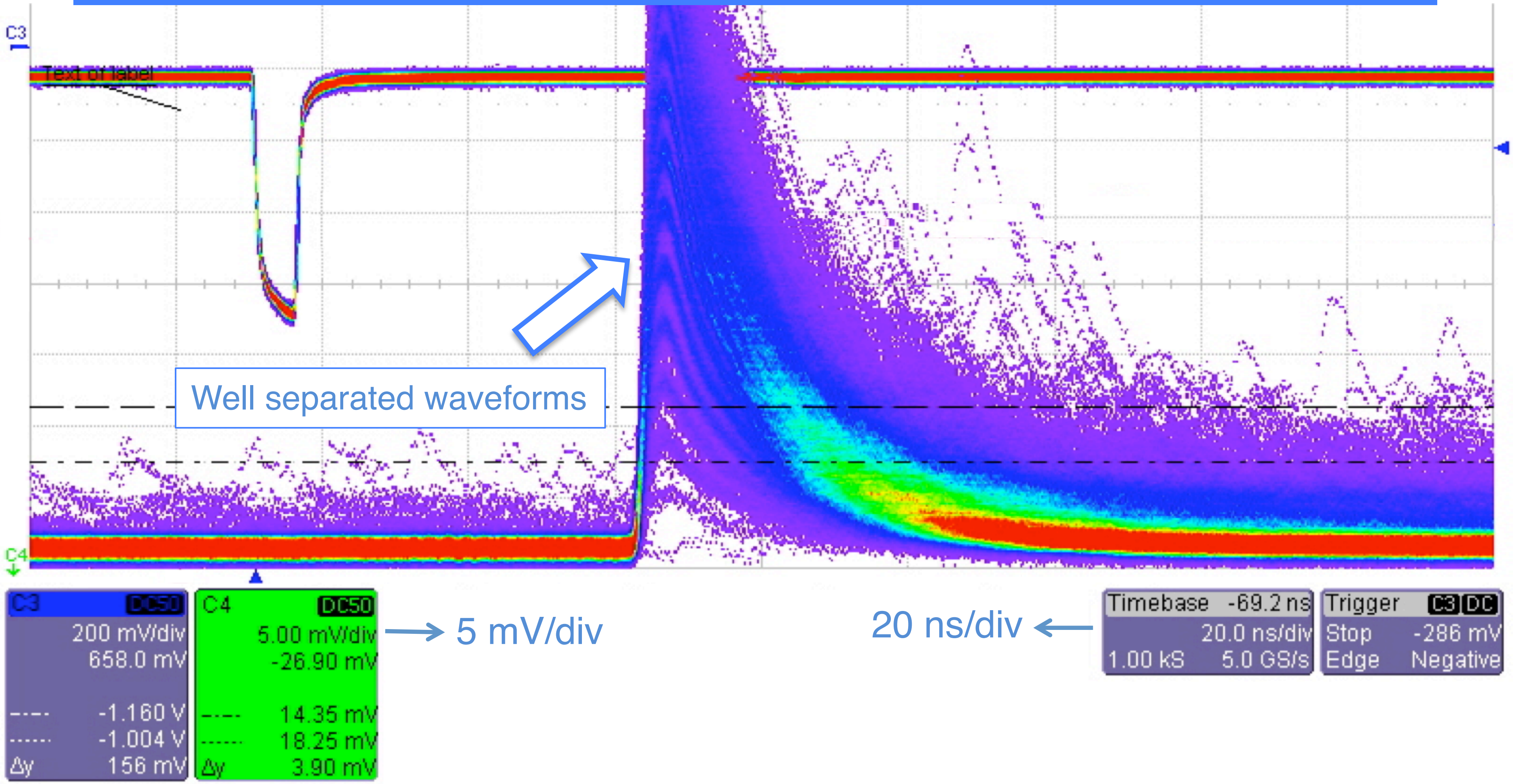
20 ns/div ←

Timebase -69.2 ns
20.0 ns/div
1.00 kS 5.0 GS/s

Trigger C3 DC
Stop -286 mV
Edge Negative

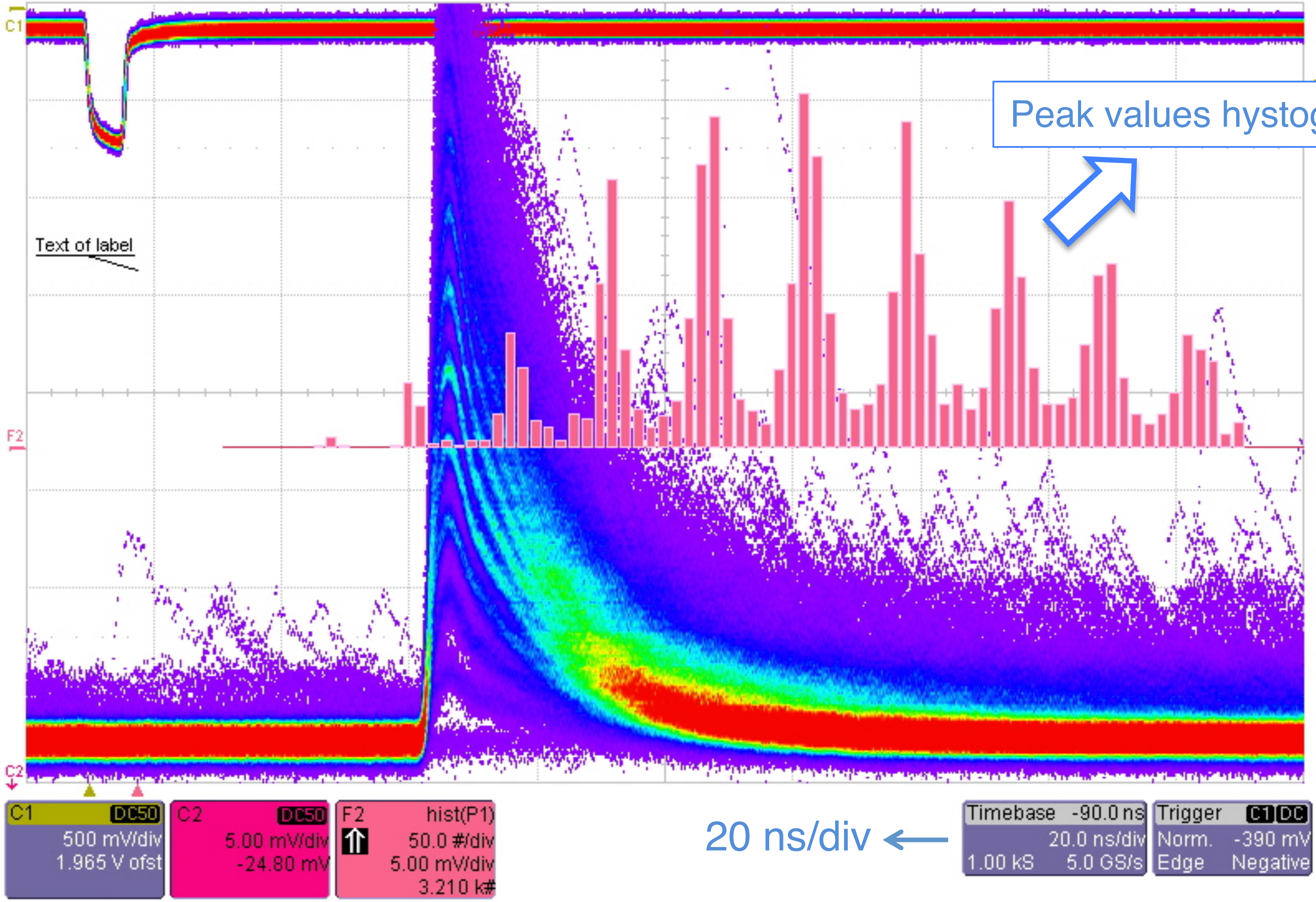
- VSiPMT illuminated by a pulsed laser light at low intensity (407nm)
- oscilloscope triggered in synch with the laser
- Responses for multiple triggers are overlaid

Waveforms



Excellent photon counting capabilities

Waveforms

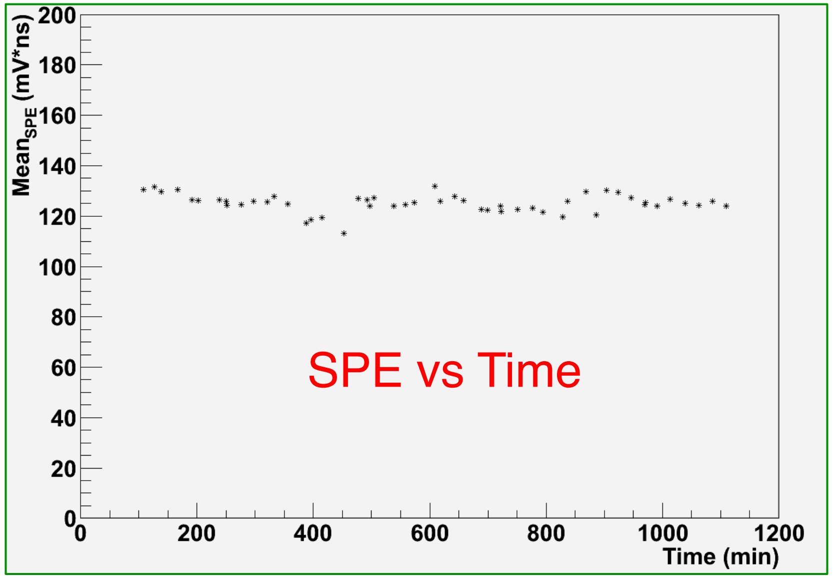


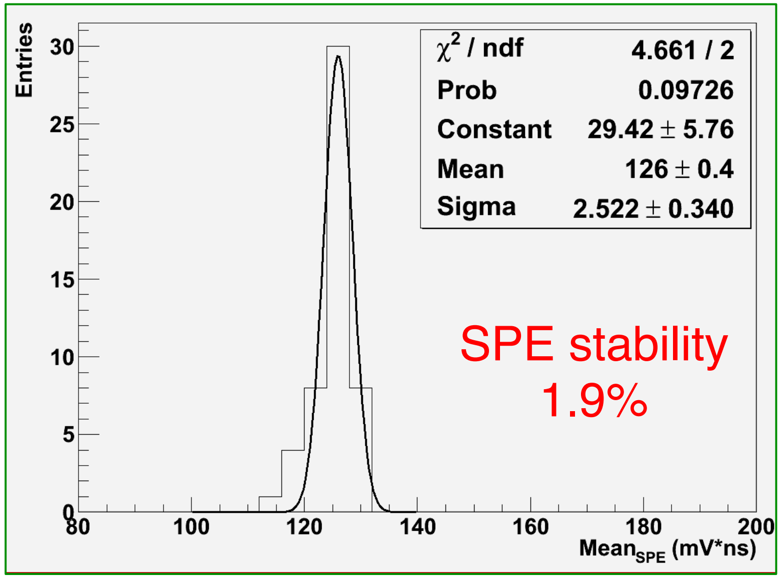
Excellent photon counting capabilities

Time stability

100.000 waveforms with low intensity laser light have been acquired every 20 min for 20 hours to study the stability in time of the following parameters:

1. Single photo electron response ($Mean_{SPE}$)
2. Resolution of the SPE ($RMS_{SPE}/Mean_{SPE}$)
3. Peak-to-Valley ratio





Time stability

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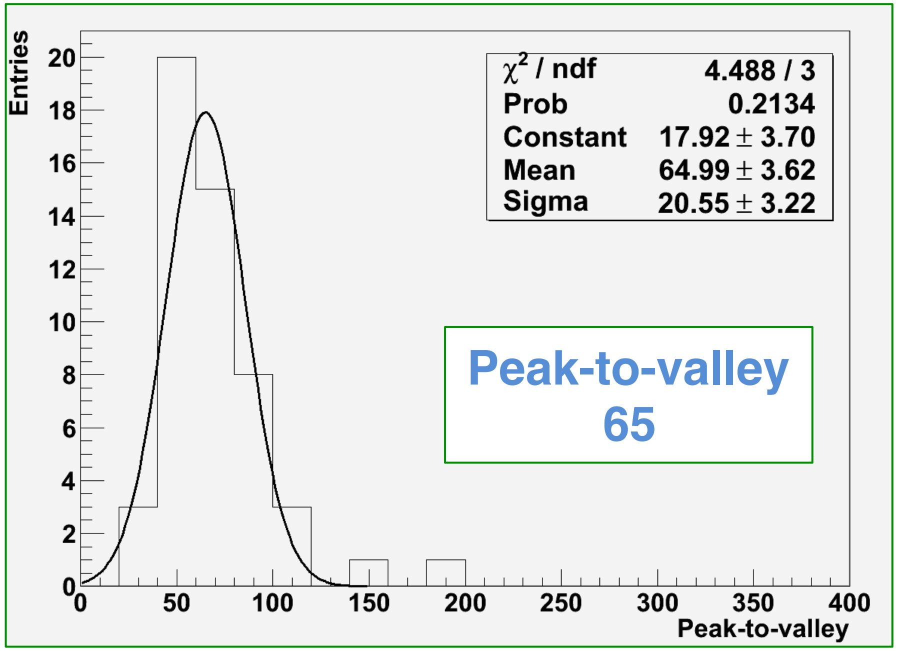
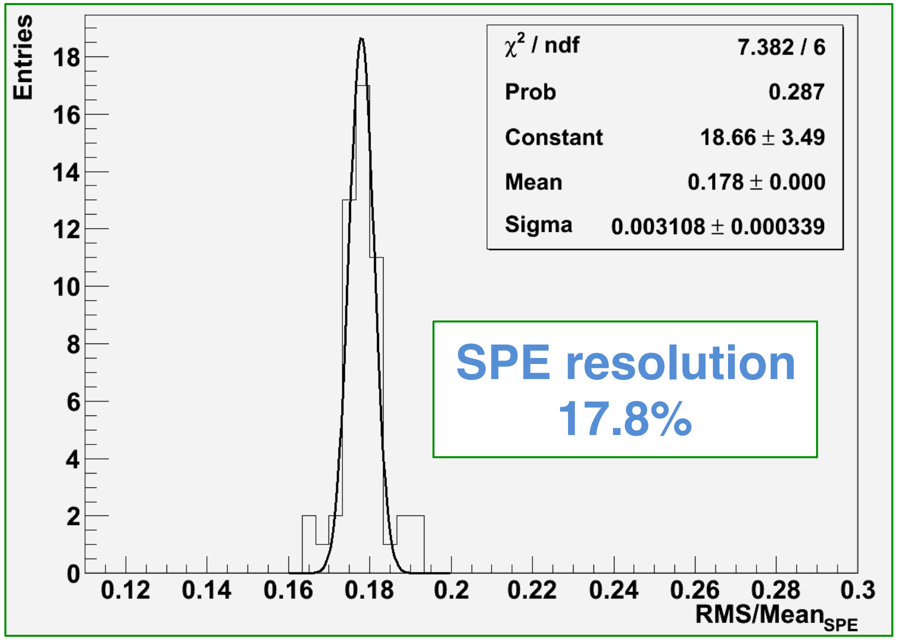




SPE spectra

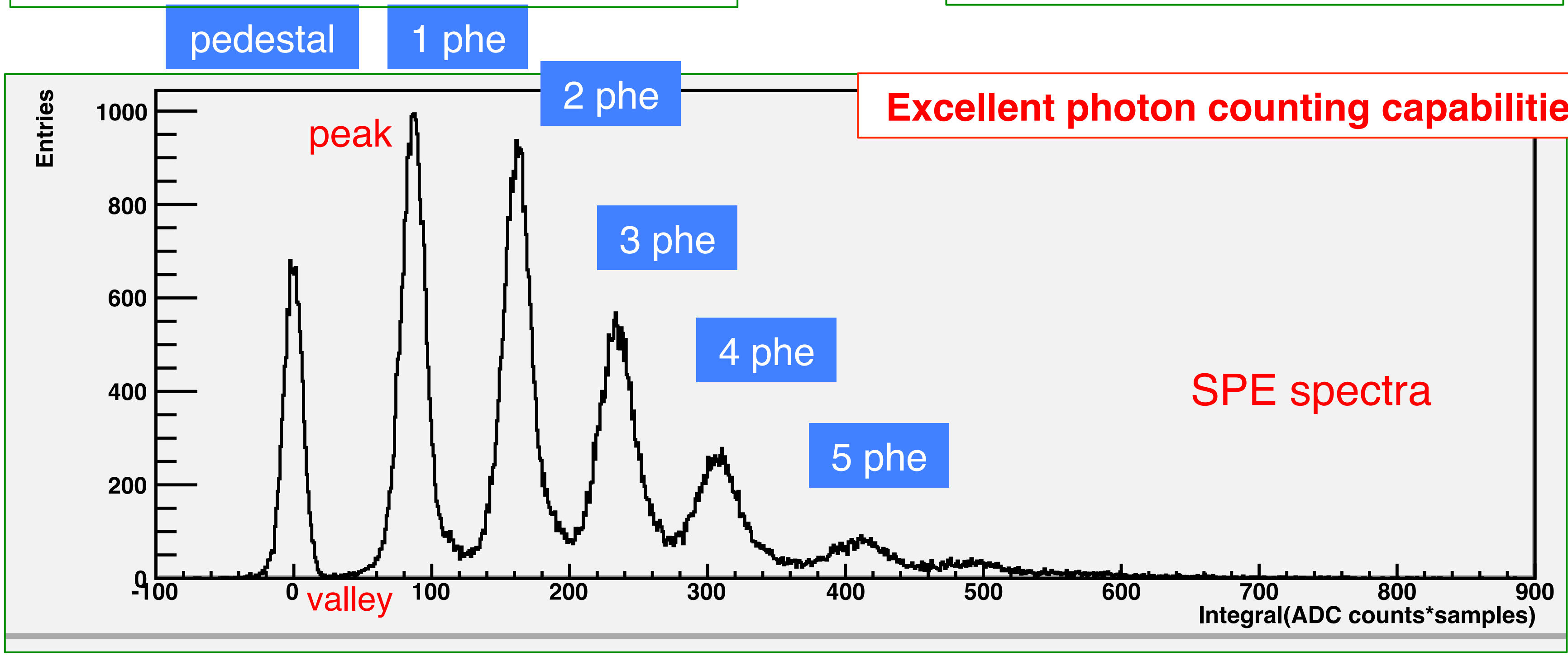
100.000 waveforms for each acquisition run with low laser intensity.

Integral of the waveform in a window of 100 ns after subtracting the baseline.

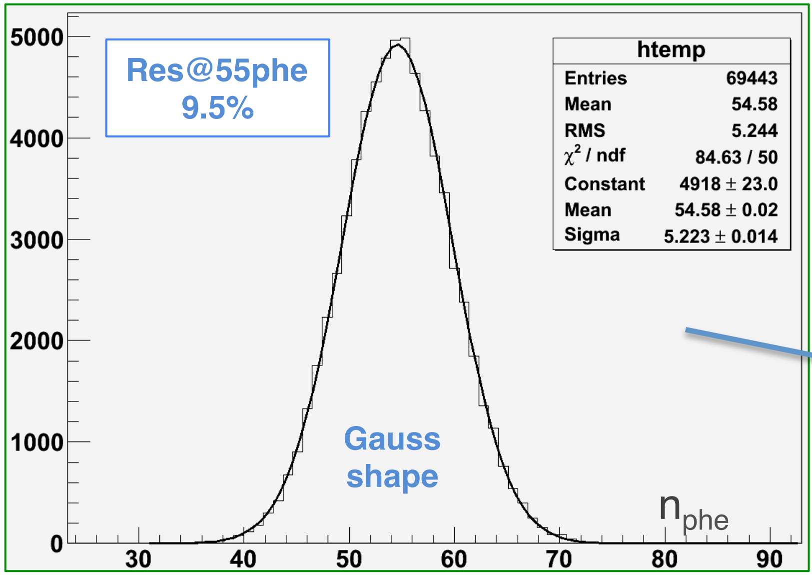
DAQ ADC CAEN V1720E
12 bit – 4 ns sampling
Laser TRG 10kHz

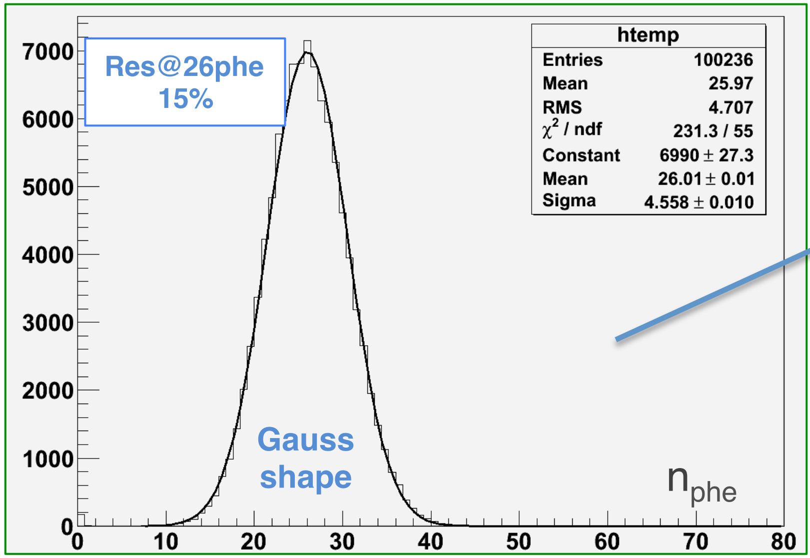
VSiPMT working point
V_{bias}= 72.5 V – HV = 4 kV
Amplification x20

Excellent photon counting capabilities

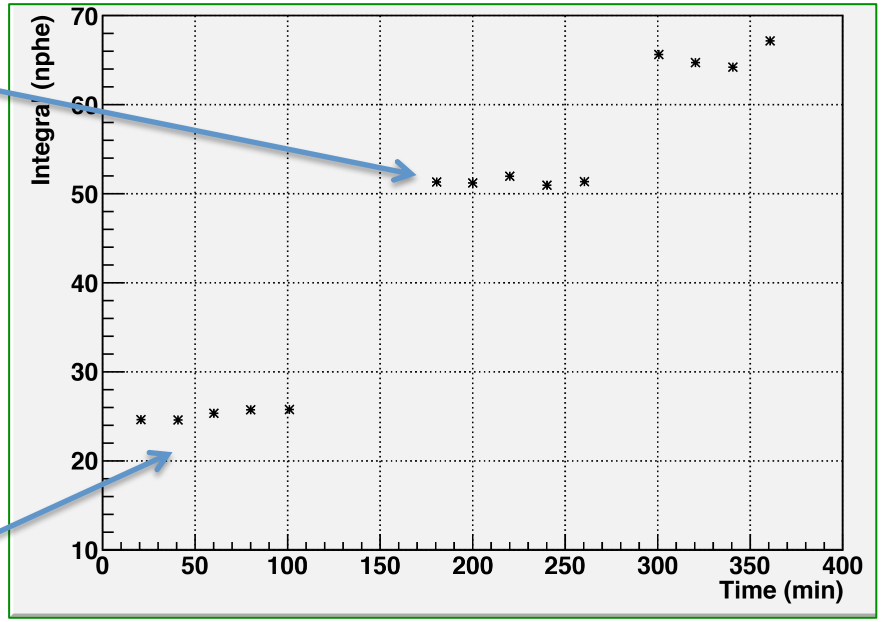


Multi photon response and stability



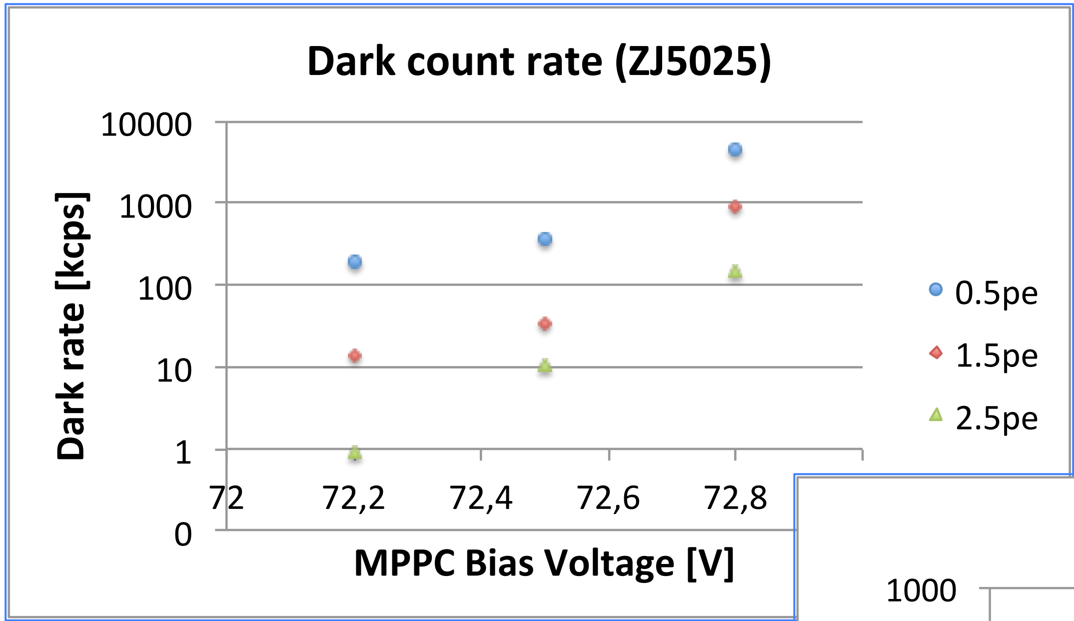


NO drop in the MPE response on 100 min

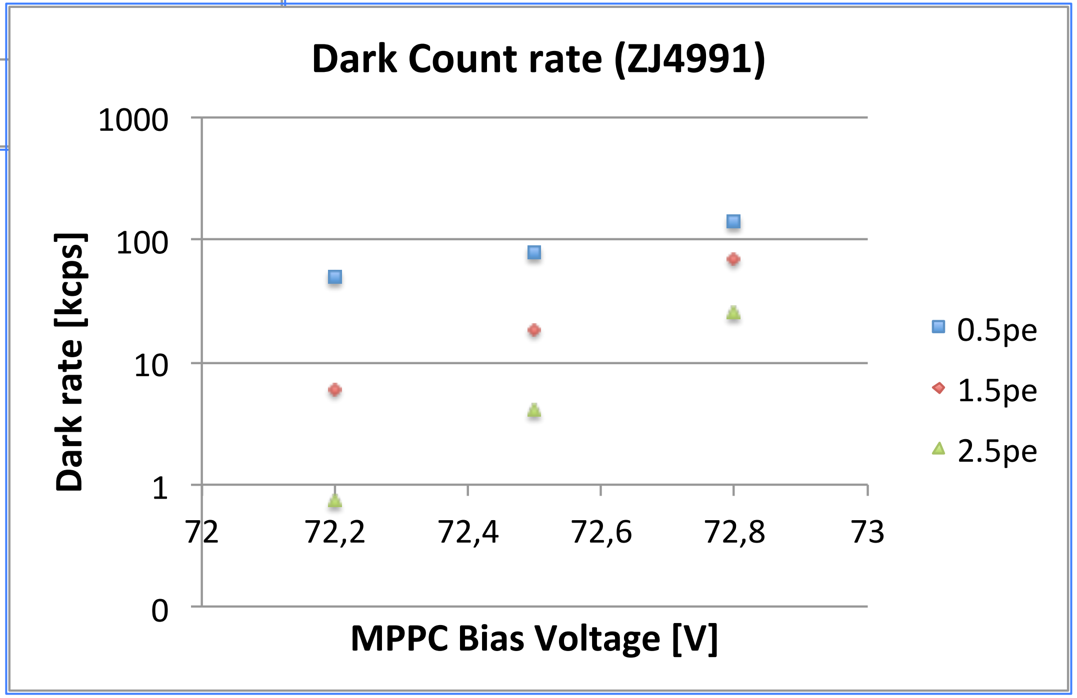


NO fatigue effect on high illumination

Dark counts/1



High DC rates
100 – 1000 kcps

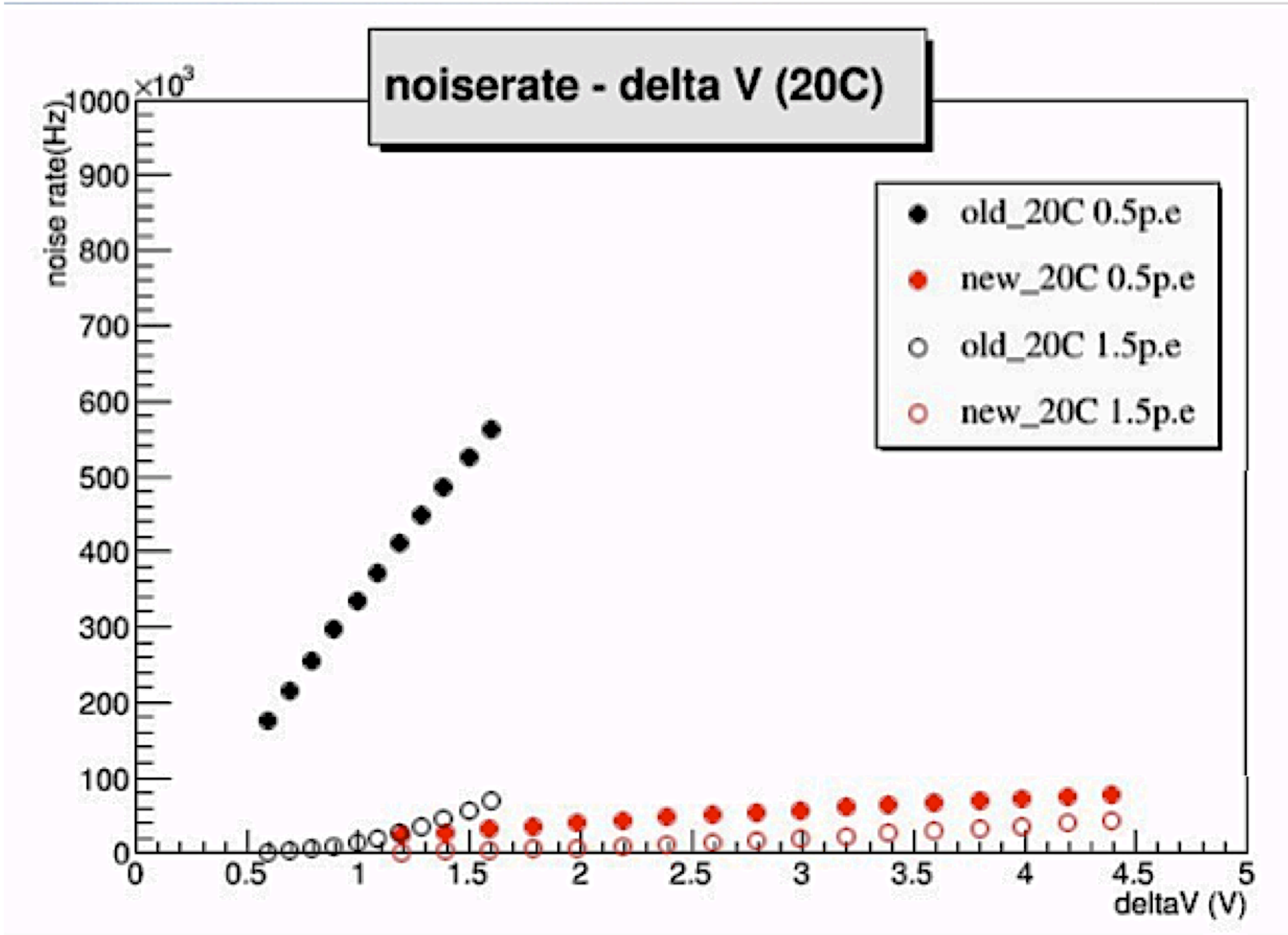


Decisively looks like a weak figure

However...

Dark counts/2

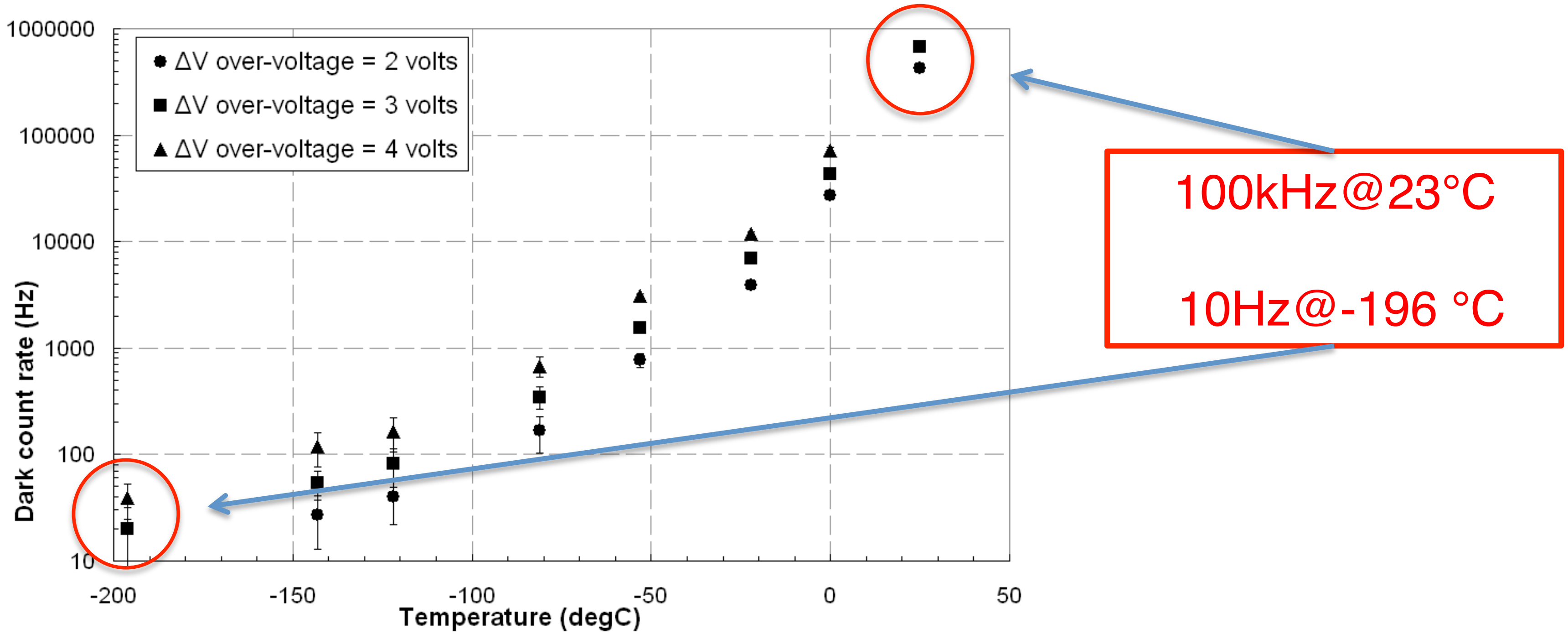
New generation Hamamatsu MPPCs



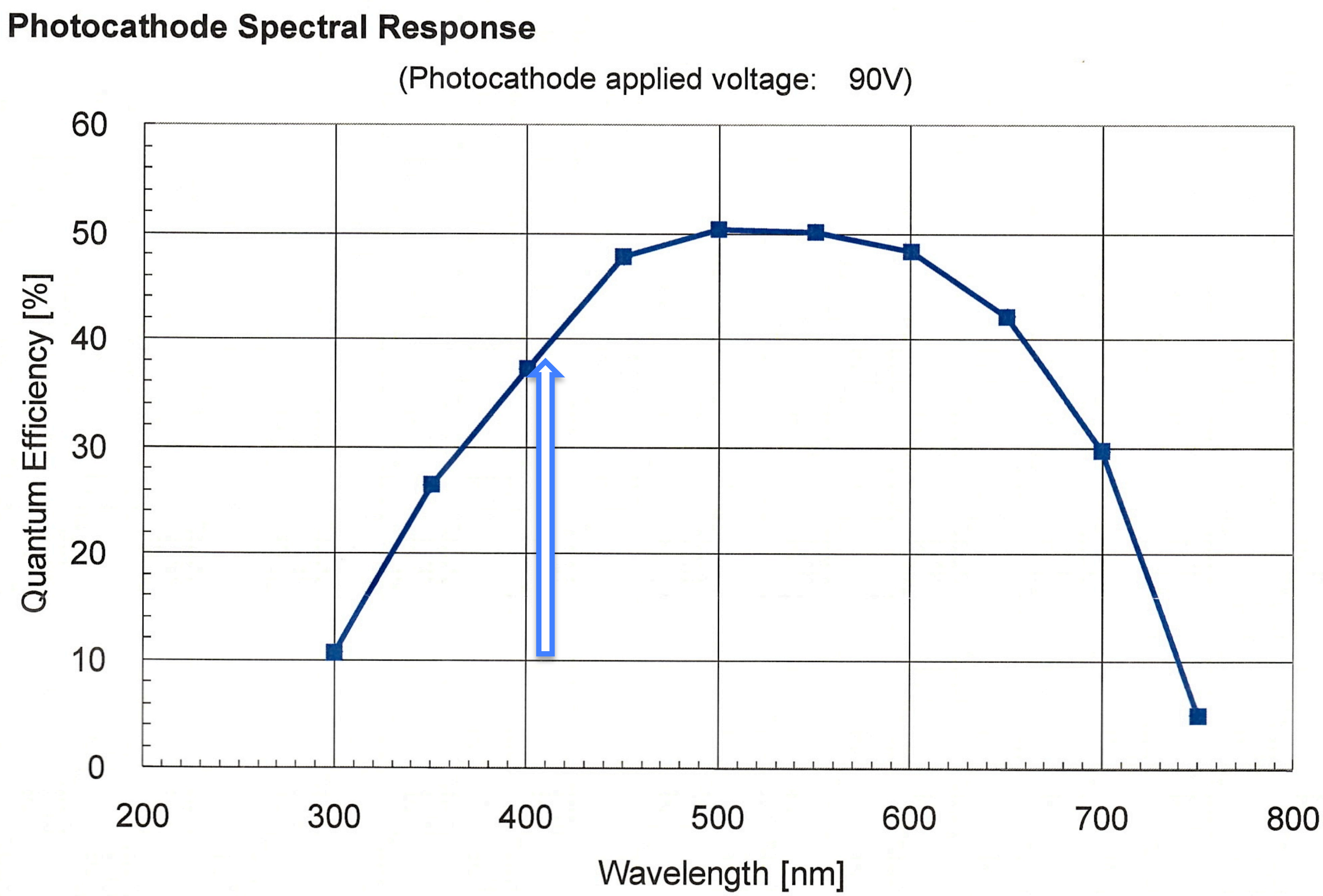
Advantages at low temperature

Cryogenic application would reduce drastically the dark rate

P.K. Lightfoot, Characterization of a silicon photomultiplier device for applications in liquid argon based neutrino physics and dark matter searches, JINST 3 P10001, 2008.

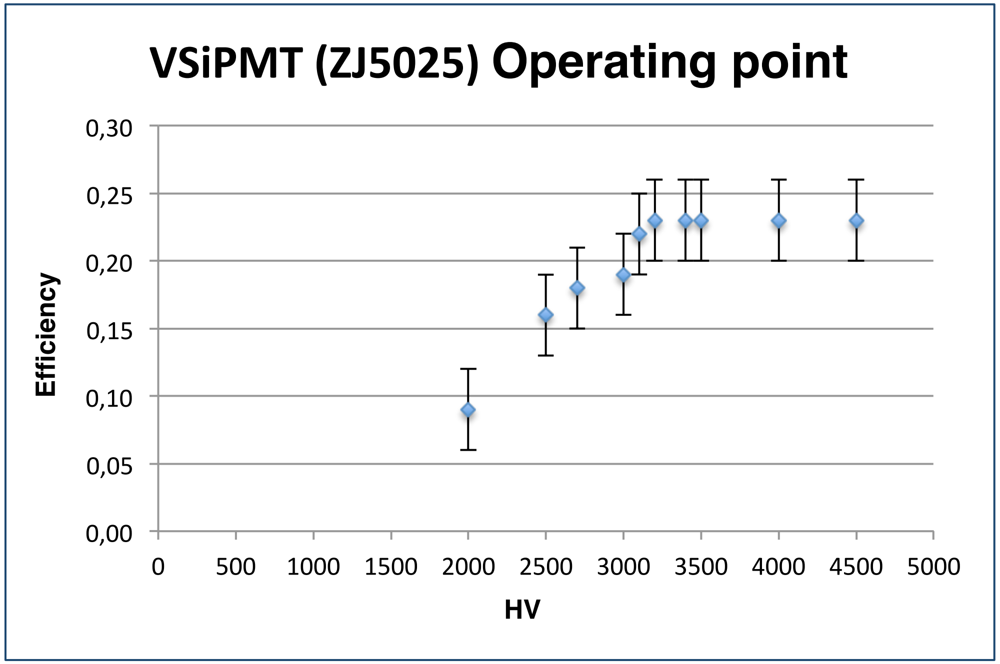


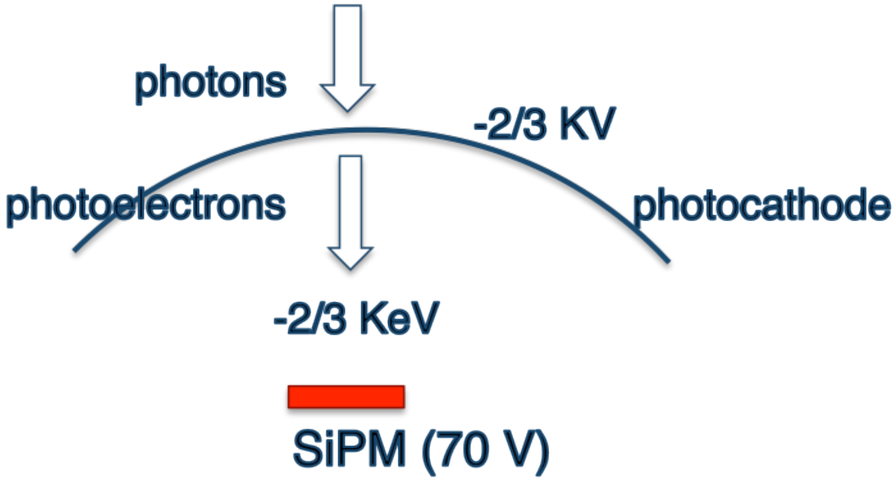
Efficiency



Photocathode Spectral Response
(Photocathode applied voltage: 90V)
Quantum Efficiency [%]
0
10
20
30
40
50
60
200
300
400
500
600
700
800
Wavelength [nm]

Efficiency





$$\varepsilon = \varepsilon_{\text{photocathode}} \times \varepsilon_{\text{SiPM (50)}}$$

$$\mathbf{0{,}23} \approx 0{,}38 \quad \times \quad 0{,}61$$

↘ Fill factor

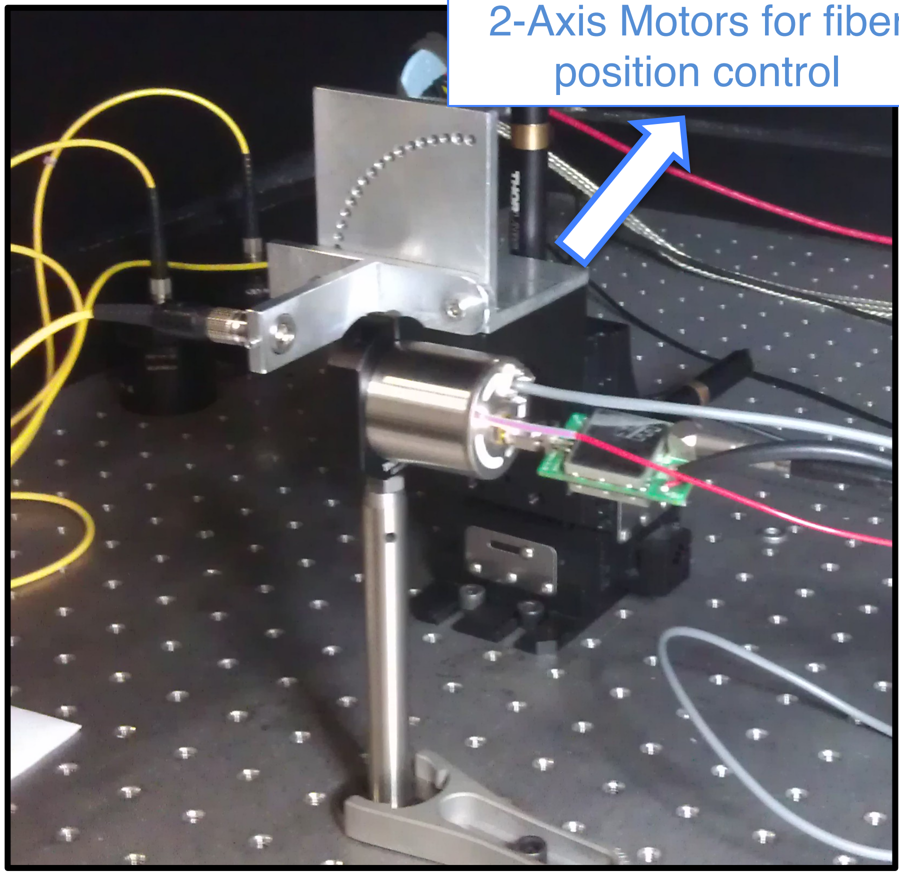
VSiPMT (ZJ5025) measured efficiency $\varepsilon = 0.23$

in agreement with expectations

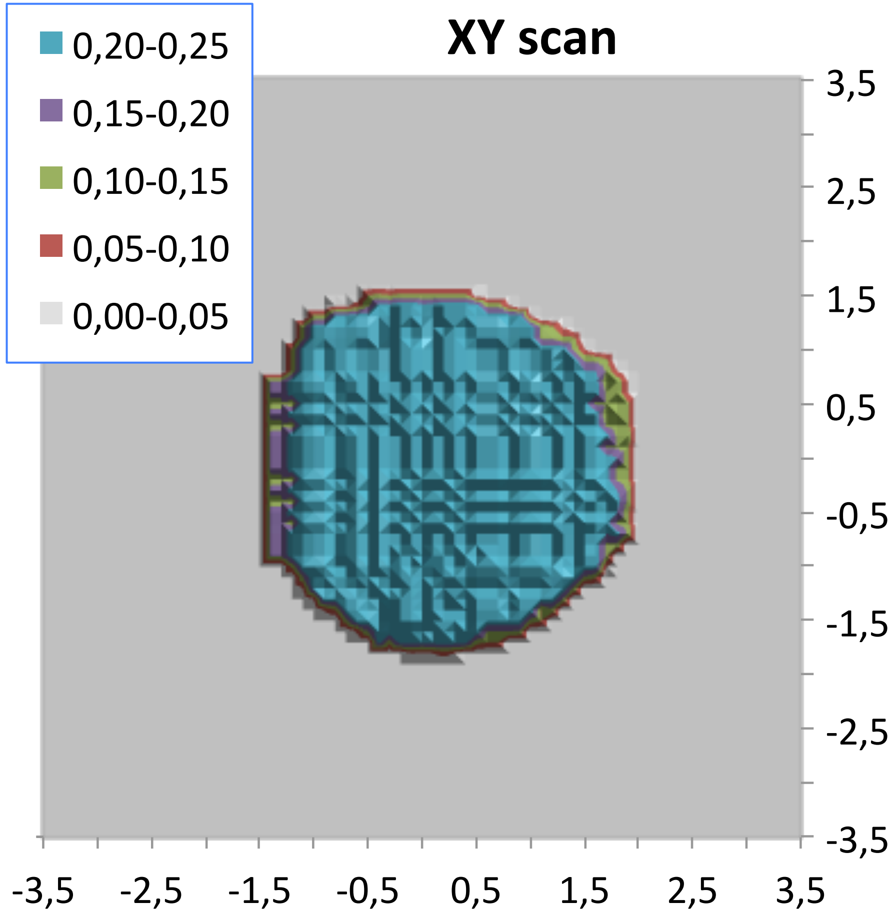
Efficiency is highly stable over 3200 V.
No need for high voltage stabilization.

- Reducing the SiO_2 coating layer it will be possible to reach the plateau region at even lower voltages.
- The HV implies NO power consumption (NULL current) unlike PMTs. Moreover, for PMTs the power consumption increases with the rate!

XY scan



2-Axis Motors for fiber position control

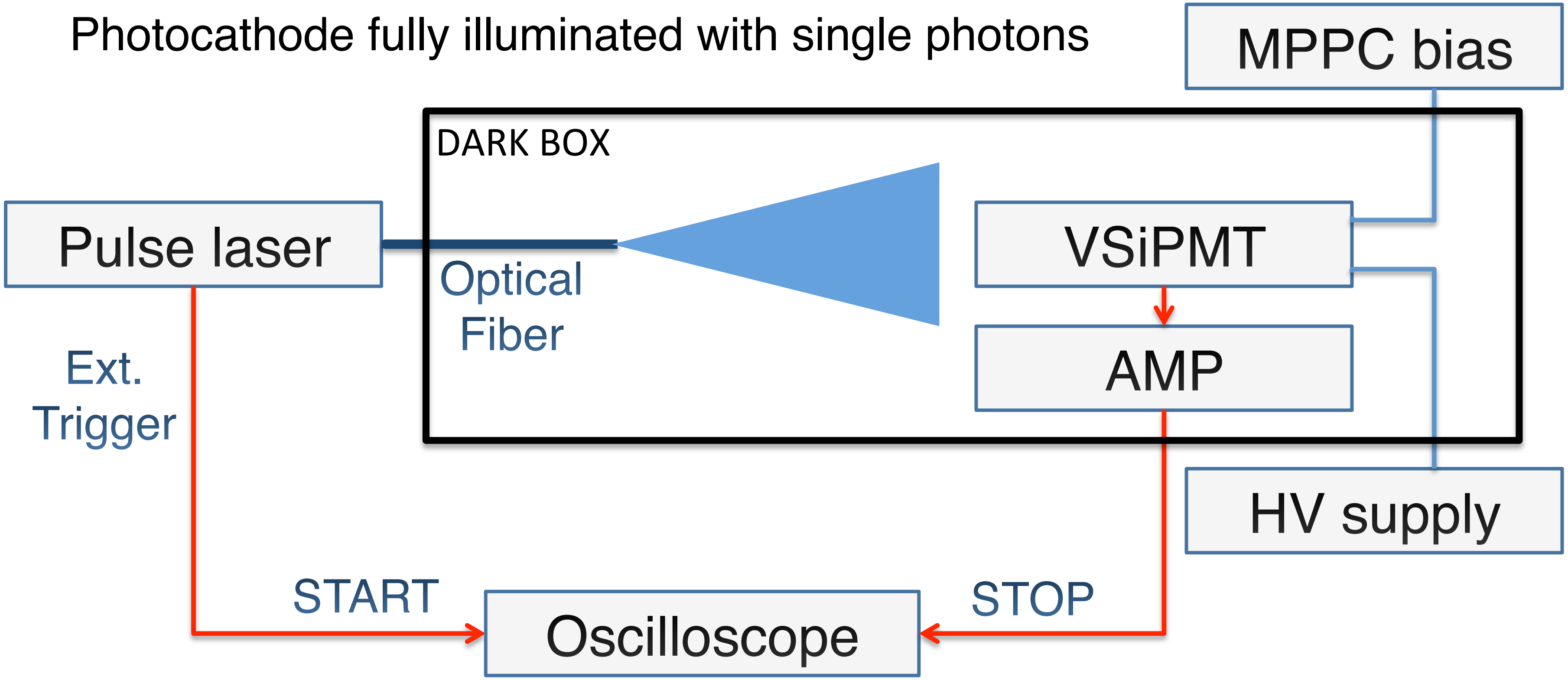


Homogeneous efficiency
≈ 0.2 over a 7mm^2 surface

Surface increase factor ≈ 7

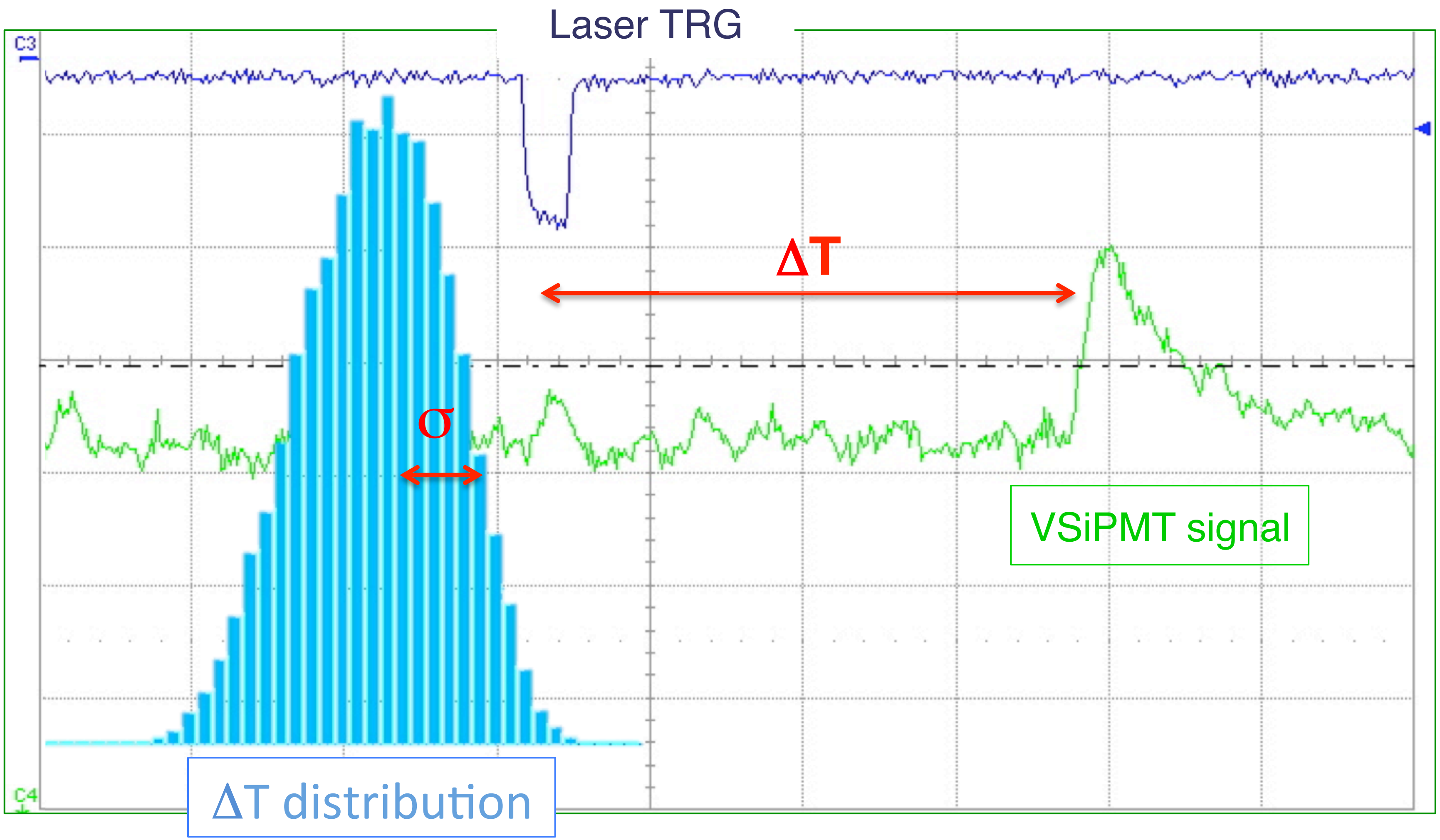
TTS

Photocathode fully illuminated with single photons



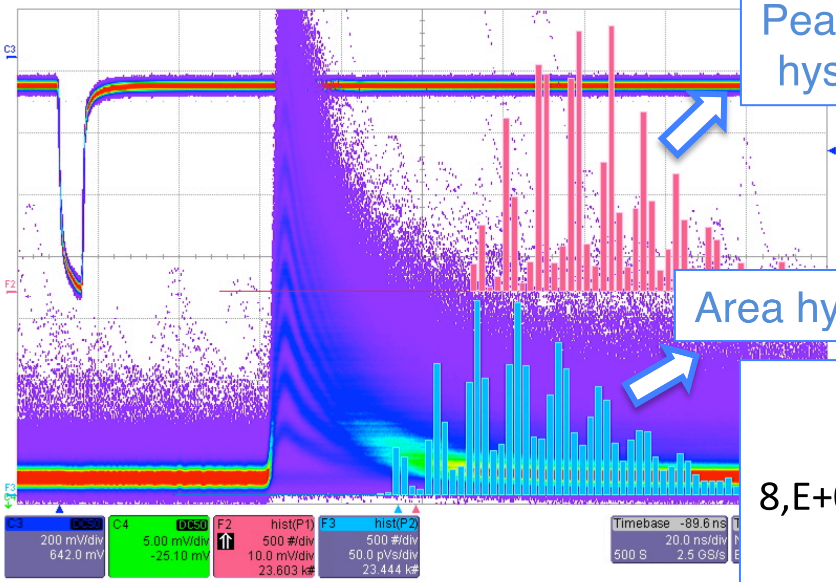
- The output from the VSiPMT is fed as the stop signal via a discriminator;
- We measure the time interval between the "start" and "stop" signals.

Transit Time Spread



VSiPMT
TTS (sigma) < 0.5 ns

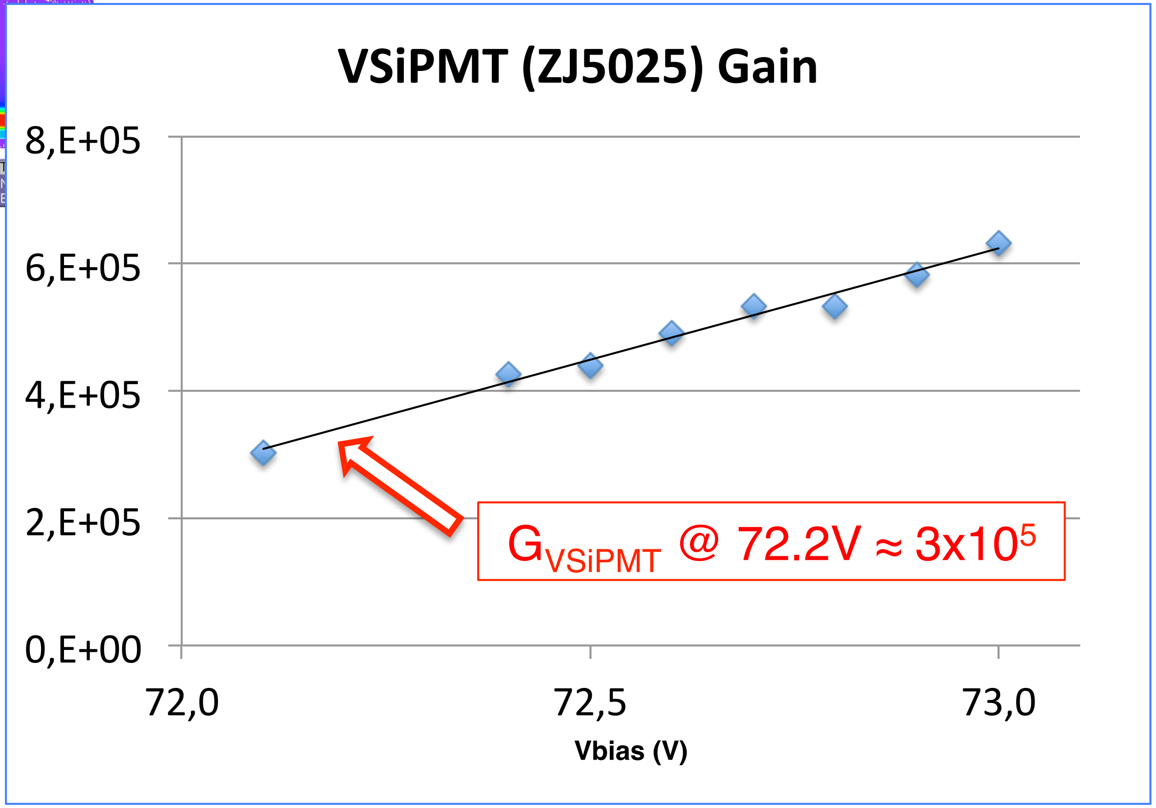
Gain



Measure of the charge corresponding to 1 pe (peaks in area hystogram)

High gain (10^5–10^6), linear trend

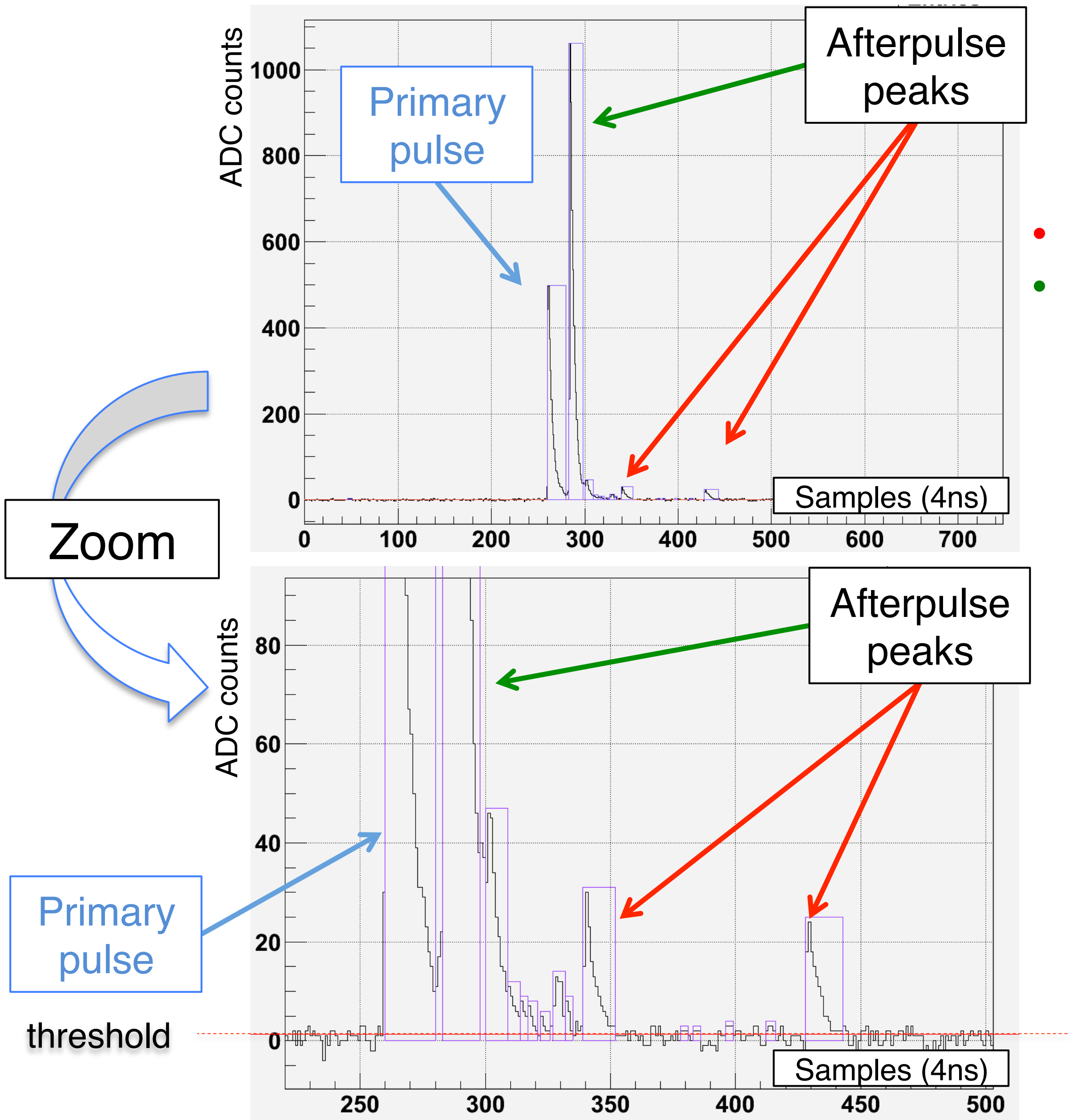
Total Gain = G_{VSiPMT} x G_{AMP}



Ideal Working Point: 72.2V

- **G ≈ 6x10^6 (G_{AMP} = 20);**
- **Dark Count ≈ 60 kcps;**
- **TTS < 0.5ns.**

Afterpulses



2 Afterpulse classes:

- SiPM afterpulses (1-3 pe, ≈ 10%)
- "Vacuum" afterpulses (gas residuals contribution, high intensity, ≈ 0.02%)

Peak finder:

Searches for peaks above 3 RMS of the noise level distribution

For each peak we reconstruct:

Arrival time

Integral

Pulse height

Afterpulse rate

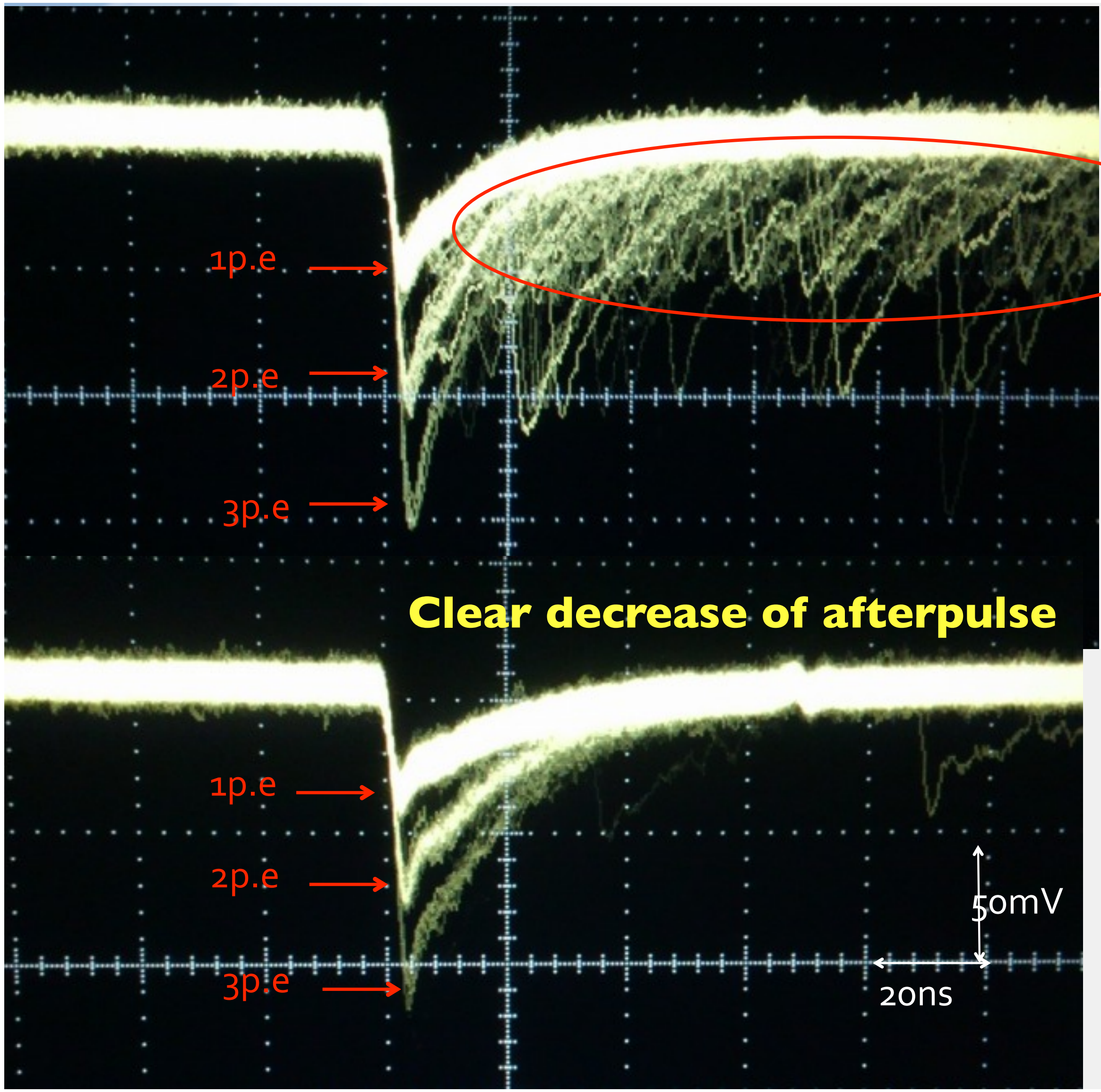
$$R_{AP} = \frac{\sum I_{AP}}{\sum I_{MP}}$$

R_{AP}: afterpulse rate;
I_{AP}: sum of the intensities of each afterpulse peak found in 100.000 waveforms;
I_{MP}: sum of the intensities of the primary pulses of 100.000 waveforms;

Afterpulse rate Table summary

Threshold (pe)	Afterpulse rate
>0.50	10.41%
>0.75	9.40%
>1.00	7.34%
>2.00	2.38%
>5.00	0.23%
>10.00	0.02%

Afterpulse rate



Persistence = 1.1sec
Gain = 9×10^5

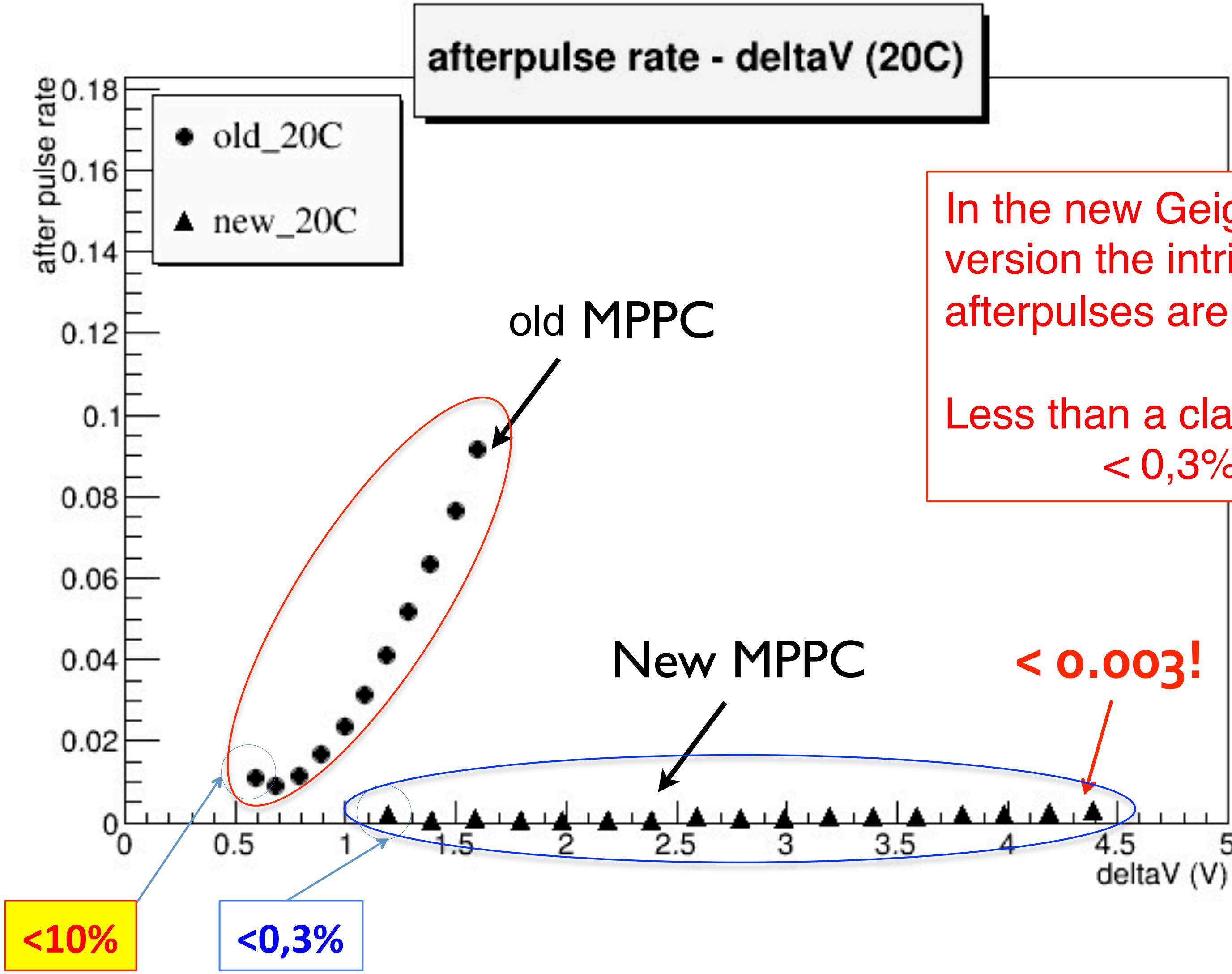
afterpulse and dark noise

old version

new version

3

Afterpulse rate

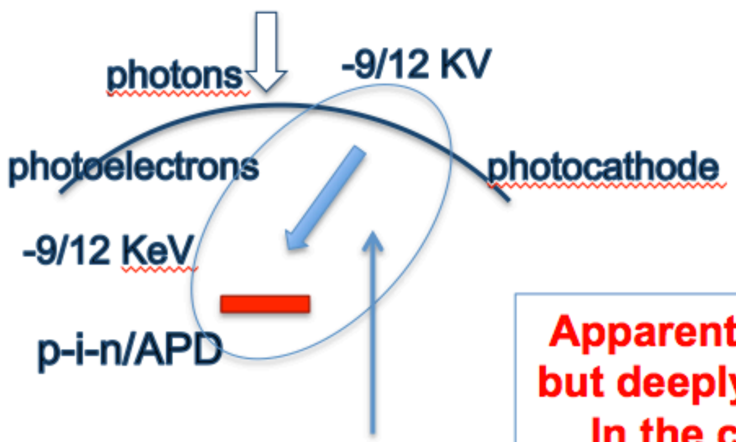


In the new Geiger diode version the intrinsic afterpulses are negligible

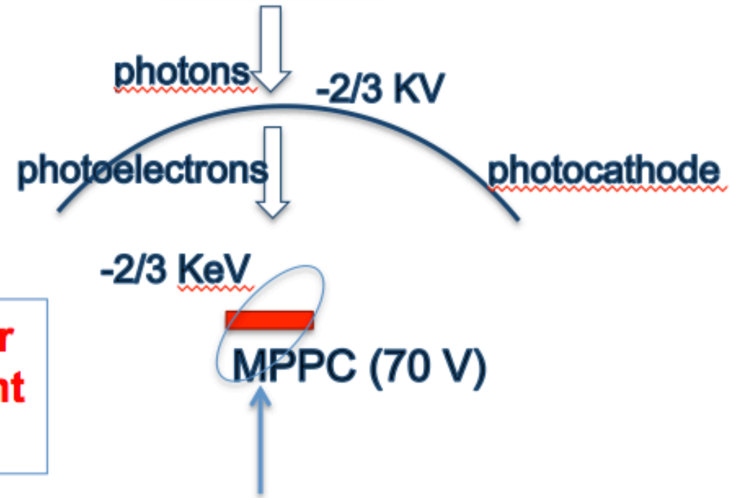
Less than a classical PMT
< 0,3% !!!

VSiPMT vs HAPD

HAPD



VSiPMT



Apparently similar but deeply different In the concept

Need of HV to obtain a high gain

High gain obtained with low voltage in the SiPM

Drawbacks of the APD solution

- $G=E_{phe}/E_{e,h}\approx10^4\text{-}10^5$
- too **low Gain. HV gain required**
- G **depending** on HV
- Need a strong HV critical **stabilization.**
- Difficult **and expensive insulation**

Advantages in the VSiPMT solution

- **G > 10^6** : a factor 10 higher.
- **Low HV, no need for bombardment gain** only energy for photoelectron transfer
- **Low voltage Gain: easy to stabilize**
- **Normal insulation**

VSIPMT VS PMT

	PMT	VSiPMT	comparison
Efficiency	Photocathode x 1st dynode	Photocathode x Fill factor MPPC (➔1)	**≈ comparable (slightly worse)**
Gain	10^5 - 10^6	10^5 - 10^6	**≈ equivalent**
Timing	nsec	fractions of nsec (no spread dynodes)	**+ VSiPMT**
Power Consumption	Divider Dissipation	No dissipation: just amp. G=10-20 (<5mW)	**+VSiPMT**
Stability H.V.	H.V. stabilization for stable gain	No H.V. stability (plateau)	**+VSiPMT**
Dark counts	≈ kHz @ 0.5pe	**VLT** ➔≈10Hz	**+VSiPMT**
Photon counting	difficult	excellent	**+VSiPMT**
Peak-to-valley ratio	≈ 3 (typ.)	> 60	**+VSiPMT**
Afterpulse (@0.5pe)	≈ 10%	Next gen. MPPC <0.3%	**+VSiPMT**
SPE resolution	≈ 30% (typ.)	≈ 17.8%	**+VSiPMT**

Conclusions and Perspectives

VSiPMT is an innovative design for a modern hybrid photodetector based on the combination of a Silicon PhotoMultiplier (SiPM) with a Vacuum PMT standard envelope

It has many **UNPRECEDENTED** features, such as:

- Photon counting capability;
- Low power consumption;
- Excellent timing performances (low TTS);
- Virtually **free of radioactivity;**
- Excellent SPE resolution;
- High stability (not depending on HV).

making it a very attractive solution for next generation DM experiments

STILL IMPROVABLE!!!

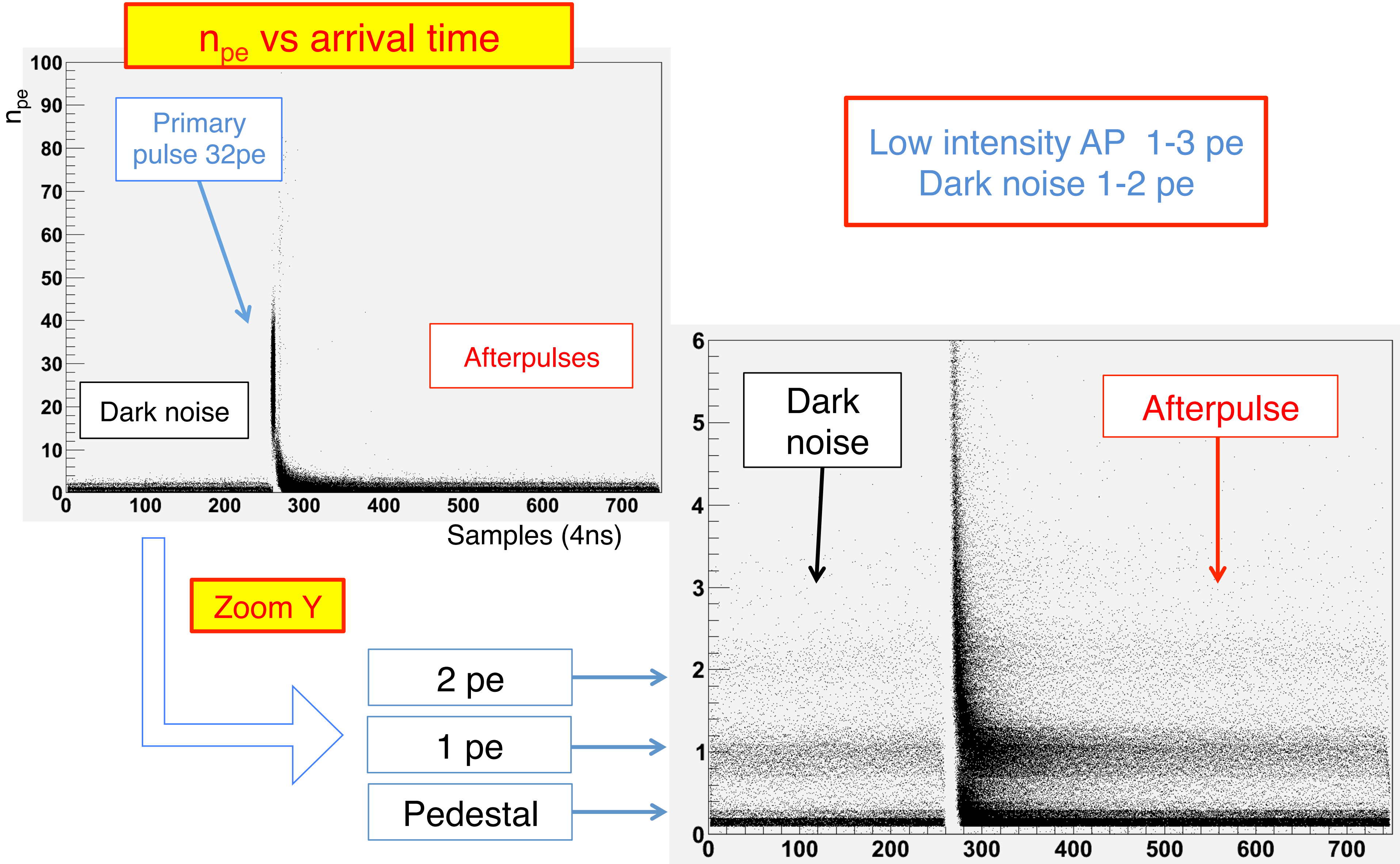
New generation of Hamamatsu MPPCs:

- sensibly lower afterpulse rates;
- lower noise: much reduced dark counts;
- higher gain → no amplification required (persp.), even lower power consumption

Thank you

Backup slides

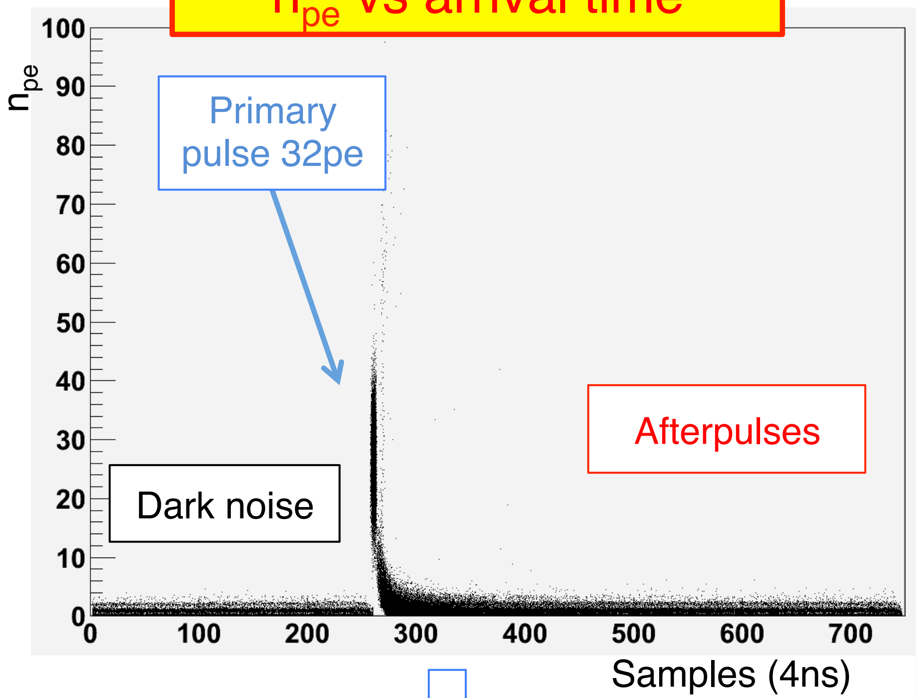
AP typical amplitude/1



Low intensity AP 1-3 pe
Dark noise 1-2 pe

AP typical amplitude/2

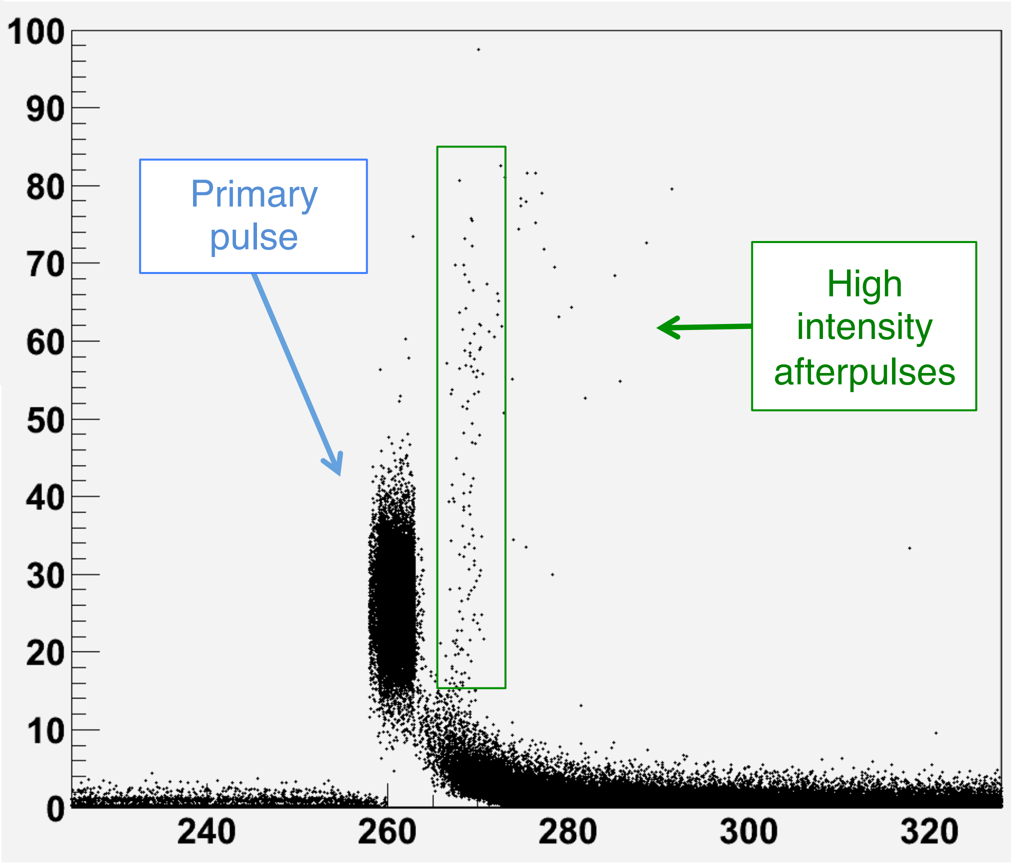
n_{pe} vs arrival time



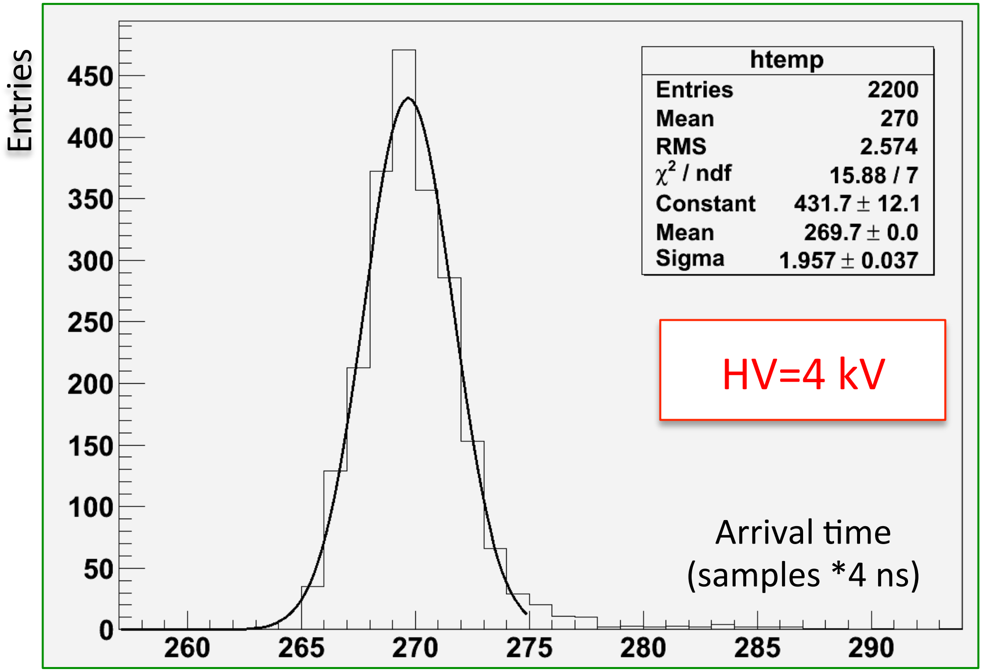
Zoom X

High intensity AP band
20-80 pe

Ionization of residual gases??



High intensity AP time distribution

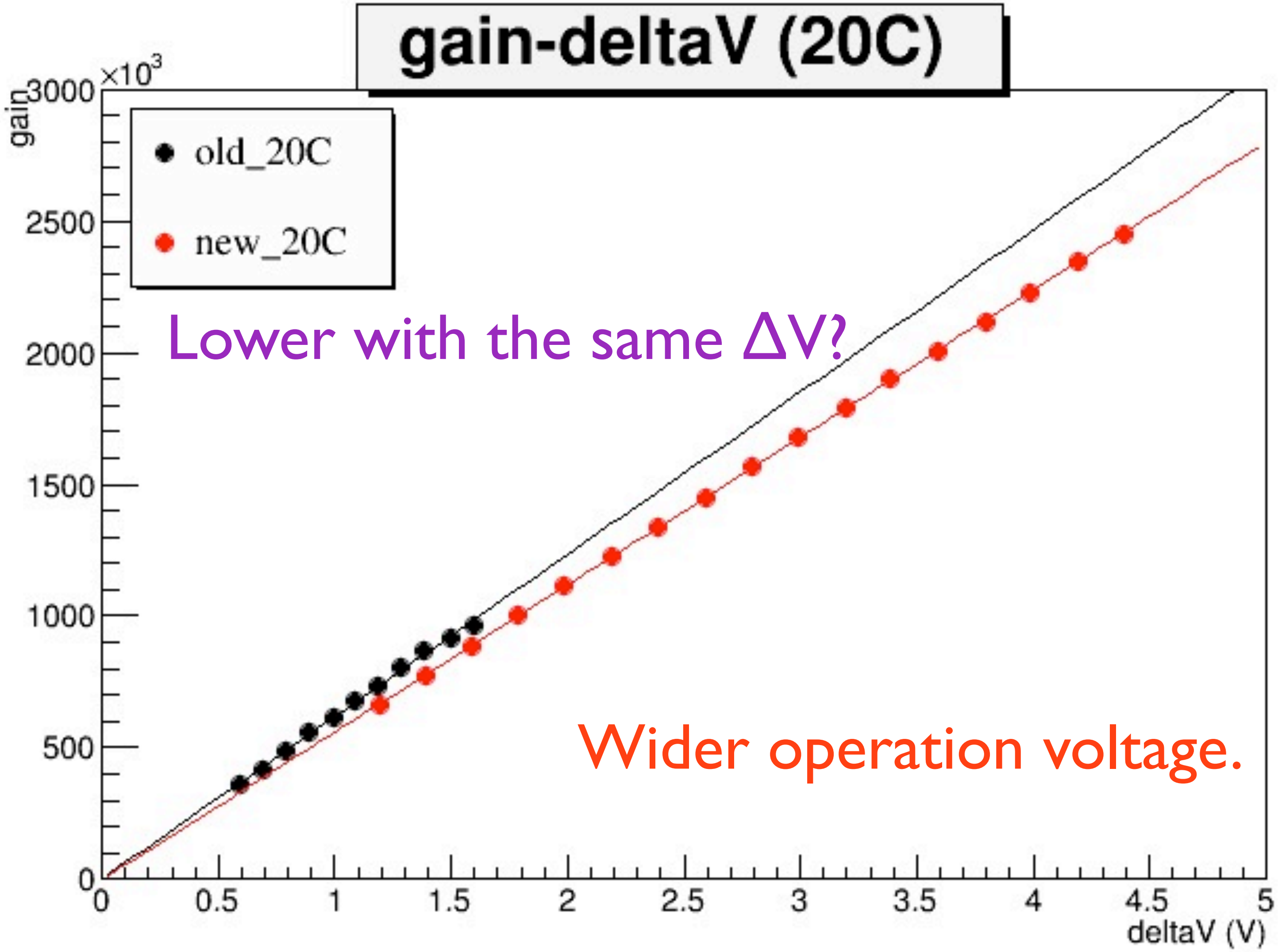


>10 pe, 0.02%

HV (kV)	Delay (ns)	Intensity (pe)
2	52.8	10-25
3	43.6	18-70
4	38.4	22-80

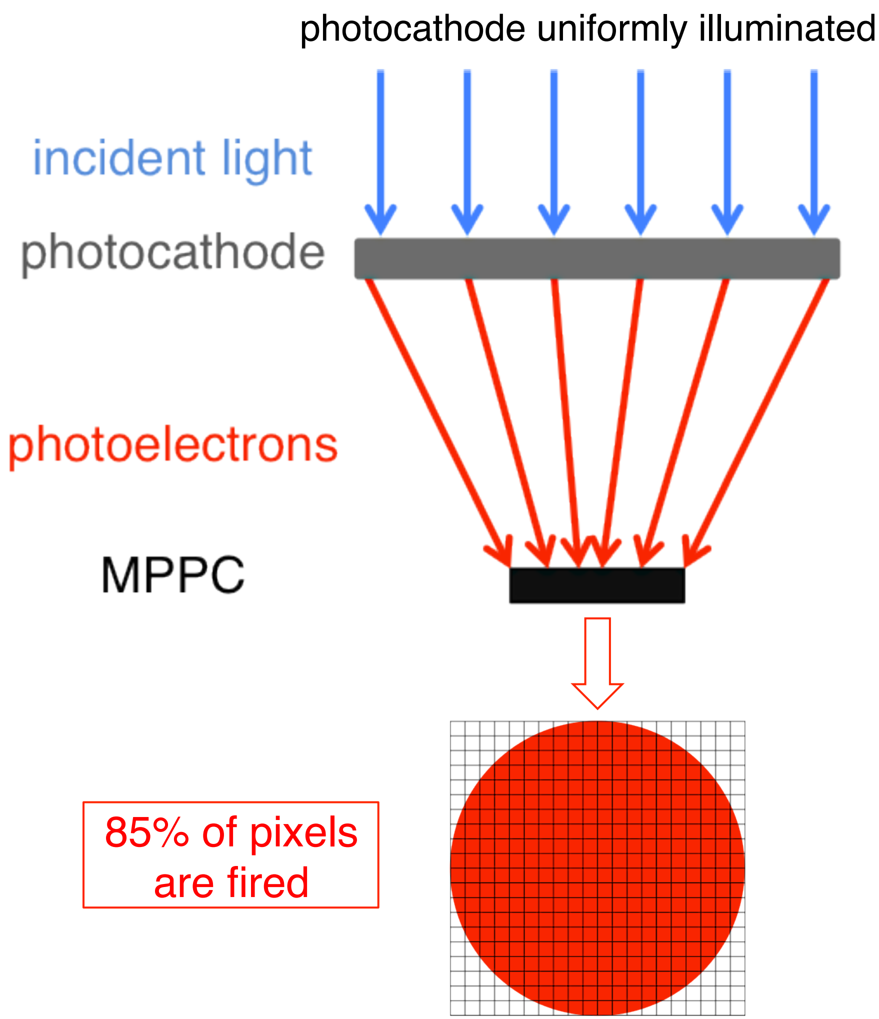
Strong hint for ionization of residual gases

New generation MPPC gain

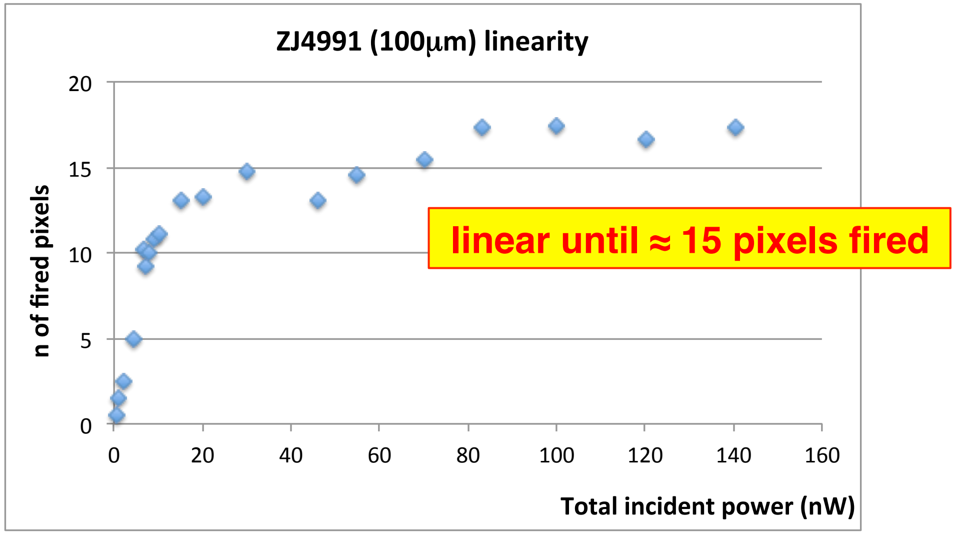


Linearity

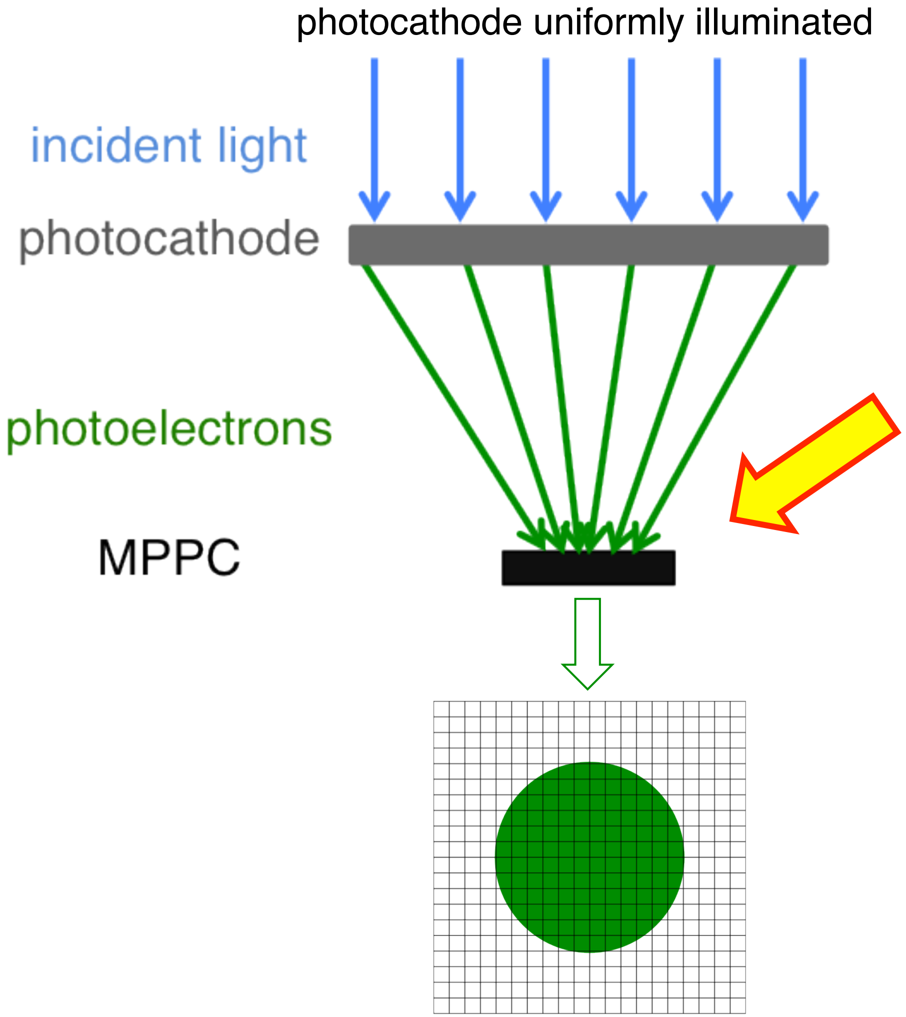
The ideal case



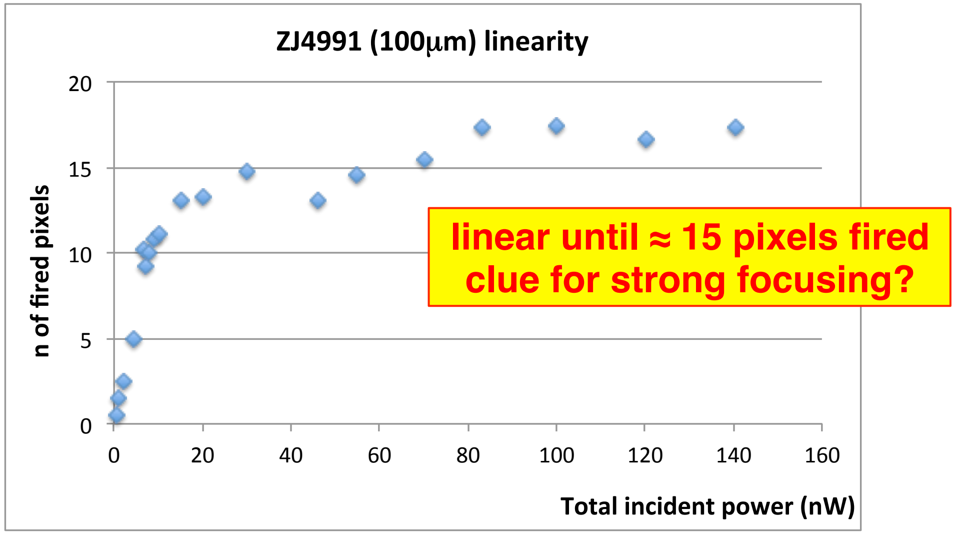
What we measured



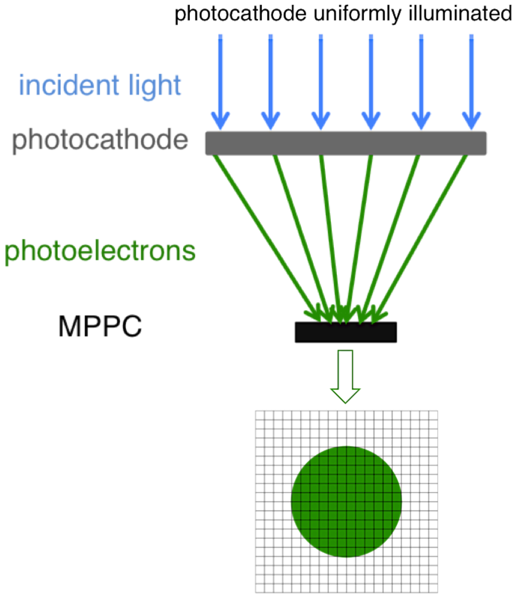
Linearity

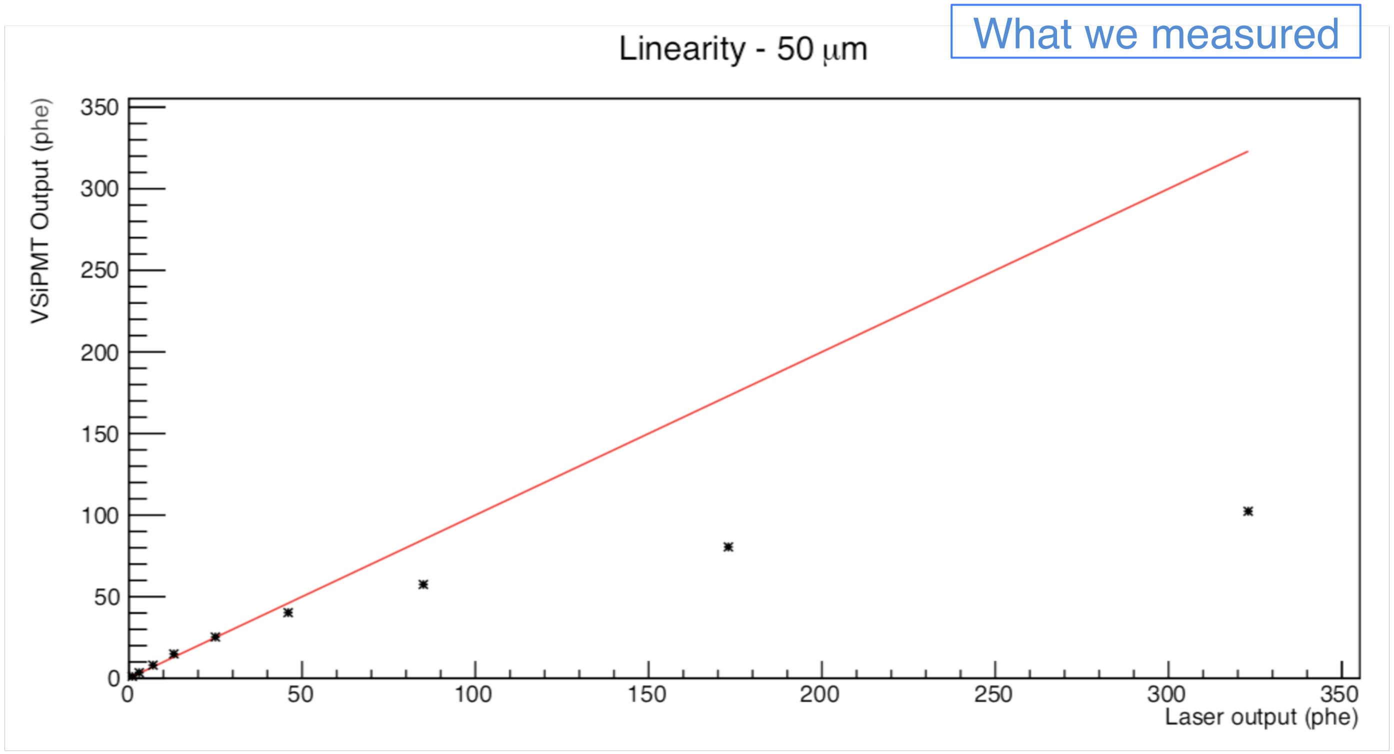


What we measured



Linearity





ZJ4991 (100μm) has a too limited linearity

Optimal solution: 25μm – 50μm pixel size MPPC with improved Fill Factor for QE maximization

Time structure of afterpulses