VSiPMT Prototype Tests

Daniele Vivolo
Università degli Studi di Napoli “Federico II” and INFN Napoli

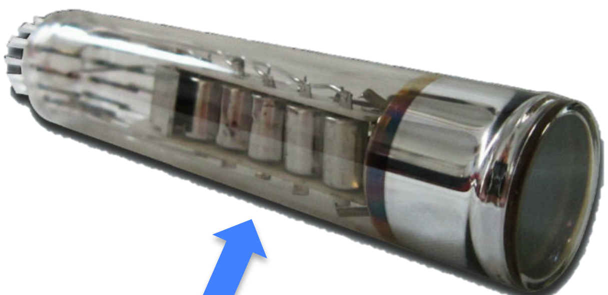
Outline

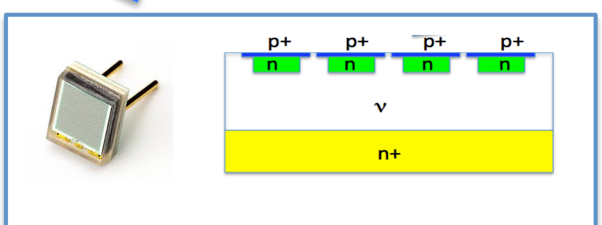
1. Introduction
2. The prototypes
3. Experimental setup
4. Characterization
5. Conclusions

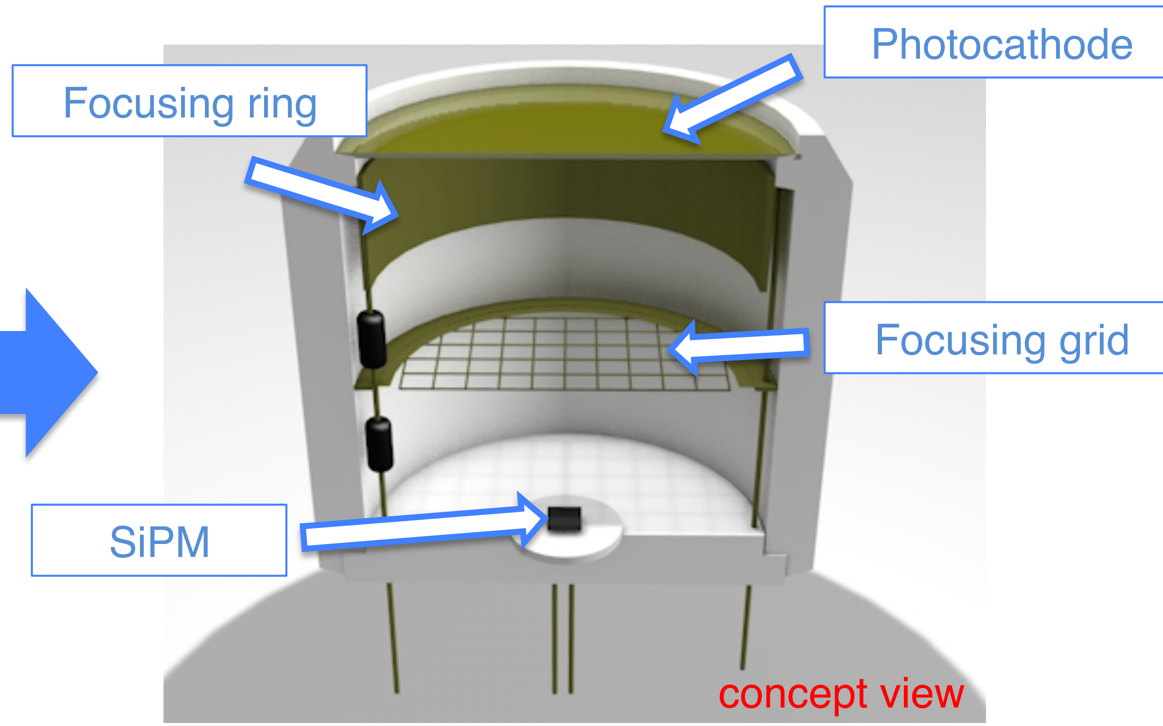
Introduction

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 Cherenkov experiments

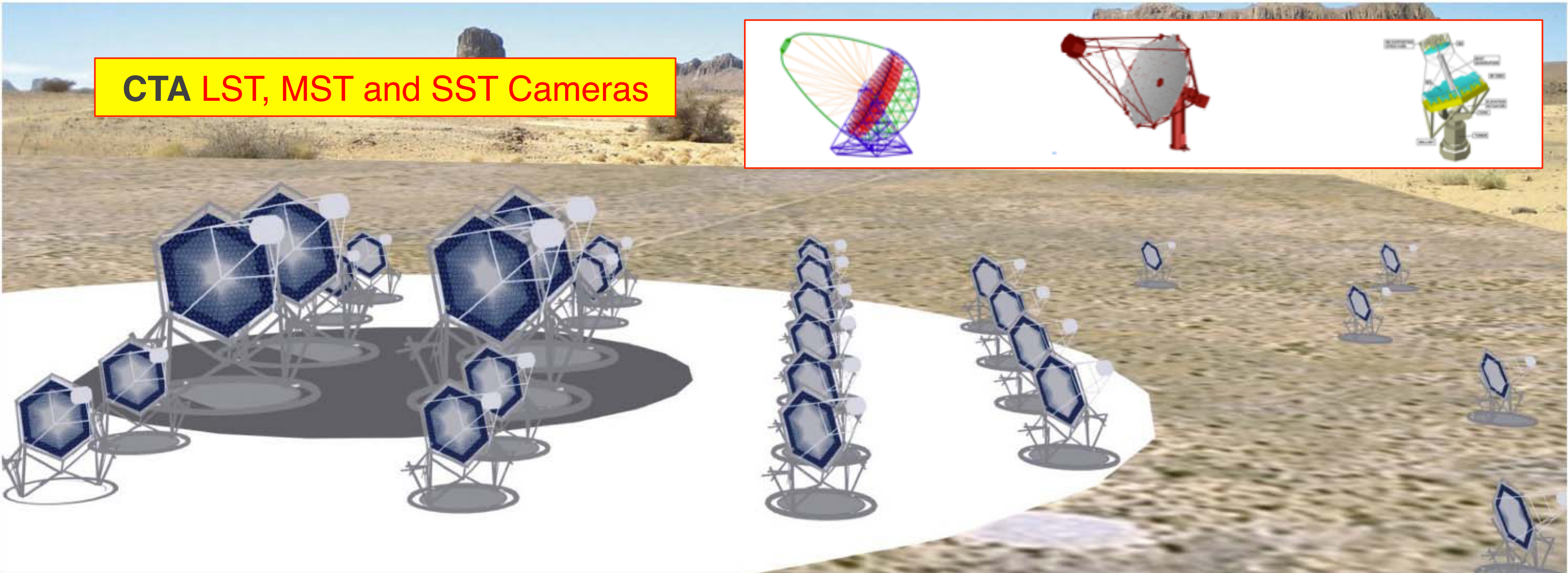
VSIPMT

Unrivalled performances
optimal solution for Cherenkov experiments

Unprecedented features:

- Photon counting capability;
- Low power consumption;
- Large sensitive surface;
- Excellent timing performances (low TTS);
- High stability (not depending on HV).

Application to atmospheric Cherenkov telescopes



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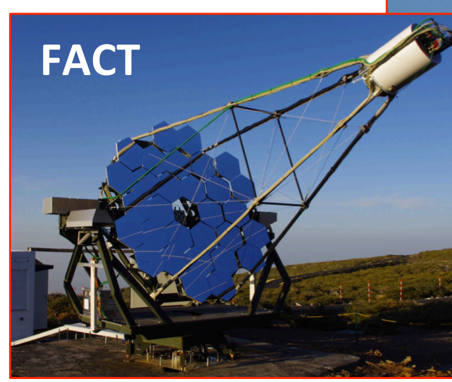
Application to atmospheric Cherenkov telescopes

VERITAS, MAGIC, HESS, FACT
Cameras



An attractive solution for Cherenkov experiments

VSIPMT

Unrivalled performances
optimal solution for Cherenkov experiments

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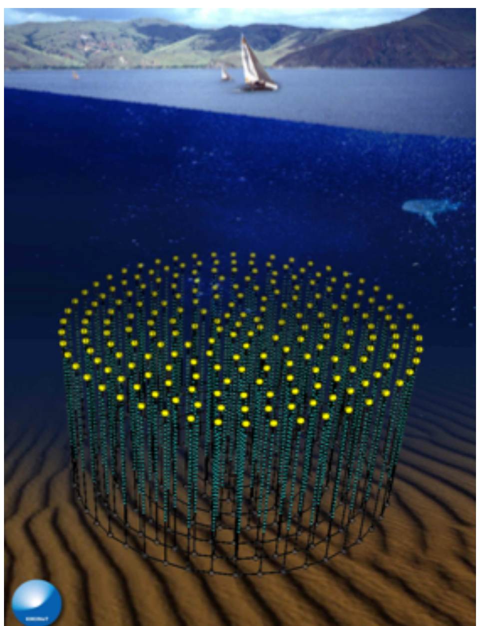
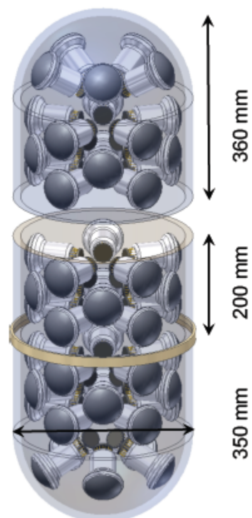
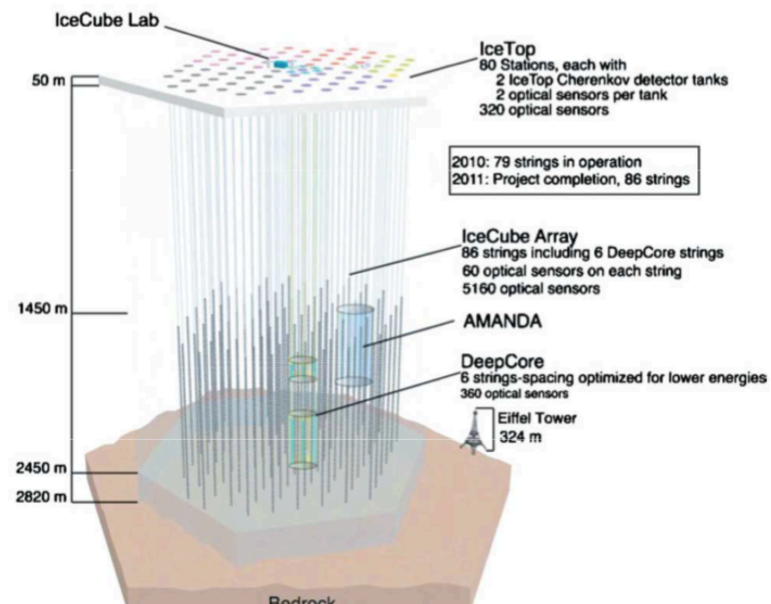
- Low power consumption;
- Large sensitive surface;
- Excellent timing performances (low TTS);
- High stability (not depending on HV).

Application to under-water/under-ice neutrino telescopes



KM3NeT/Icecube (m)DOM





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

Giancarlo Barbarino[a], Riccardo de Asmundis[b], Gianfranca De Rosa[b], Giuliana Fiorillo[a], Valentina Gallo[b], Stefano Russo[a]
[a] Università di Napoli "Federico II", Dipartimento di Scienze fisiche, via Cintia 80126, Napoli, Italy
[b] Istituto Nazionale di fisica Nucleare, sezione di Napoli, Complesso di Monte S. Angelo Ed. 6, via Cintia 80126, Napoli, Italy

...ngs
...66
...ors (IPRD08)

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

Giancarlo Barbarino[a], Riccardo de Asmundis[b], Gianfranca De Rosa[b], Giuliana Fiorillo[a], Stefano Russo[a]
[a] Università di Napoli "Federico II", Dipartimento di Scienze fisiche, via Cintia 80126 Napoli, Italy
[b] Istituto Nazionale di fisica Nucleare, sezione di Napoli, Complesso di Monte S. Angelo Ed. 6, via Cintia 80126 Napoli, Italy

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Available online 1 January 2013
In Press, Corrected Proof — Note to users

VSiPMT for underwater neutrino telescopes

Giancarlo Barbarino[a], Riccardo de Asmundis[b], Gianfranca De Rosa[a], Carlos Maximiliano Mollo[b], Daniele Vivolo[a, b]
[a] Università di Napoli Federico II, Dipartimento di Scienze Fisiche, via Cintia 80126 Napoli, Italy
[b] Istituto Nazionale di fisica Nucleare, sezione di Napoli, Complesso di Monte S. Angelo Ed. 6, via Cintia 80126 Napoli, Italy

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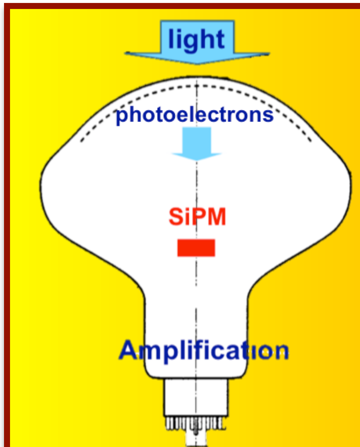
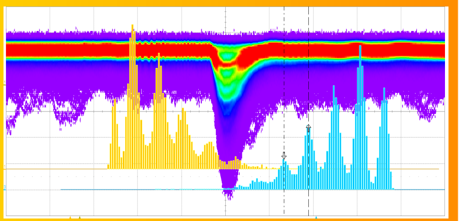
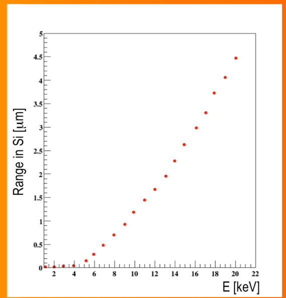
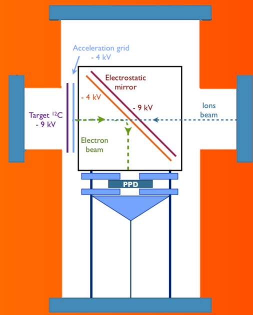
Proof of feasibility of the Vacuum Silicon PhotoMultiplier Tube (VSiPMT)

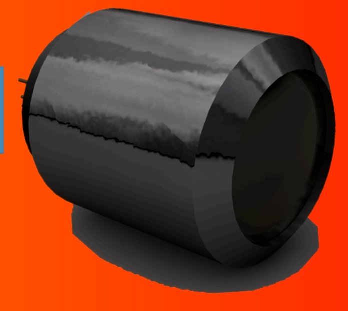
G. Barbarino,[a,b] L. Campajola,[a] R. de Asmundis,[b] G. De Rosa,[a,b] G. Fiorillo,[a,b] P. Migliozzi,[b] F.C.T. Barbato,[a,b] C.M. Mollo,[b] A. Russo[a,b] and D. Vivolo[a,b,1]
[a] Università degli Studi di Napoli "Federico II", Dipartimento di Fisica, via Cintia 80126 Napoli, Italy
[b] Istituto Nazionale di Fisica Nucleare — Sezione di Napoli, Complesso di Monte S. Angelo Edificio 6, via Cintia 80126 Napoli, Italy
E-mail: vivolo@na.infn.it











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

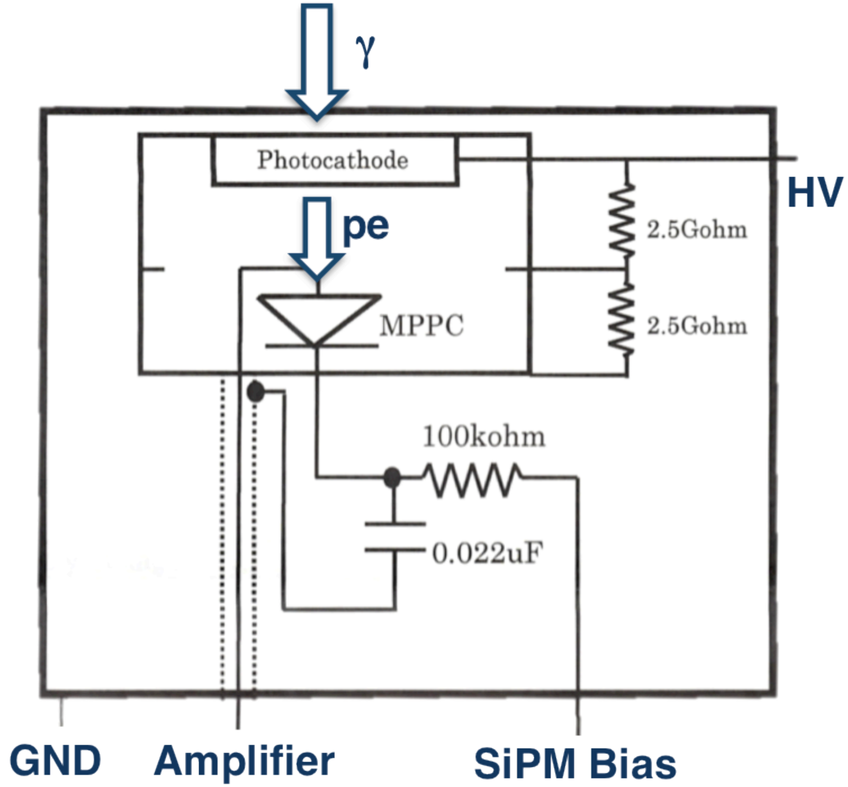
Giancarlo Barbarino[a], Riccardo de Asmundis[b], Gianfranca De Rosa[a], Carlos Maximiliano Mollo[b], Stefano Russo[a], Daniele Vivolo[a, b]
[a] Universit'a di Napoli Federico II, Dipartimento di Scienze Fisiche, via Cintia 80126 Napoli, Italy
[b] Istituto Nazionale di fisica Nucleare, sezione di Napoli, Complesso di Monte S. Angelo Ed. 6, via Cintia 80126 Napoli, Italy

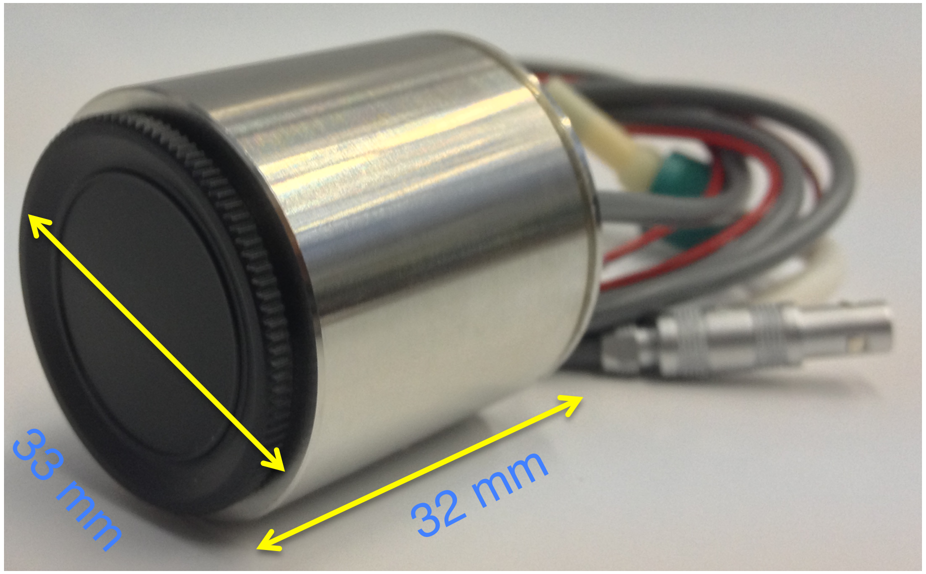
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Available online 5 December 2012
In Press, Corrected Proof — Note to users

Vacuum silicon photomultipliers: Recent developments

Giancarlo Barbarino[a, b], Felicia Carla Tiziana Barbato[b], Luigi Campajola[a], Riccardo de Asmundis[b], Gianfranca De Rosa[a], Carlos Maximiliano Mollo[b], Daniele Vivolo[a, b]
[a] Dipartimento Scienze Fisiche, Università "Federico II" Napoli, Italy
[b] INFN Napoli, Italy

The prototypes



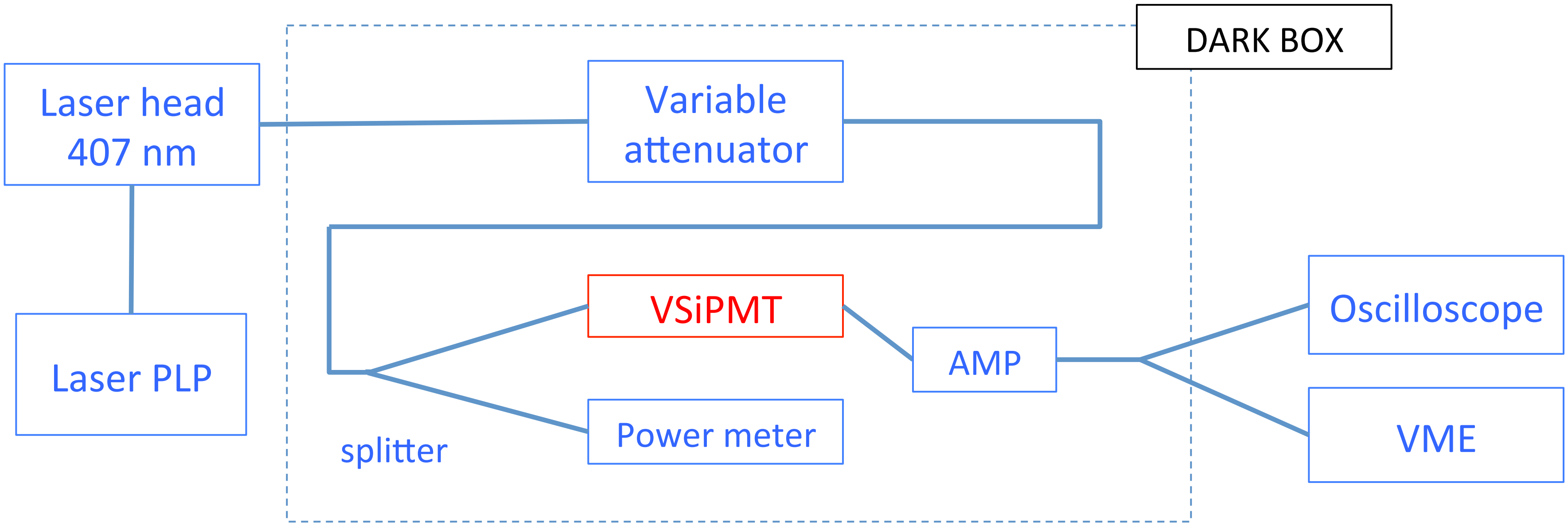


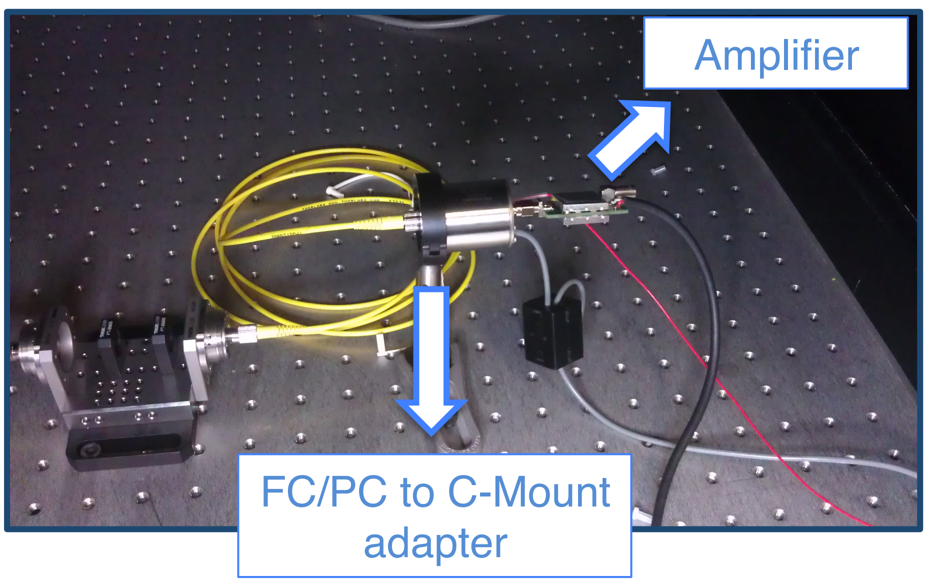
7x7 mm^2 entrance window
3 mm diameter GaAsp photocathode
2 protoyopes:
MPPC 1 mm^2 / 50 μm / 400 cells
MPPC 1 mm^2 /100 μm / 100 cells

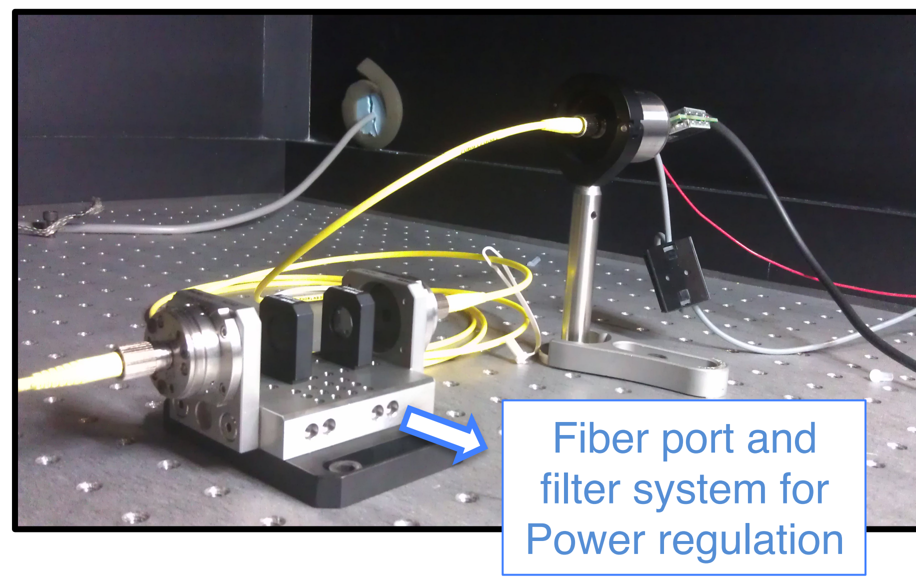
$p^+n\nu n^+$ configuration, special non-windowed series for ε optimization.
Lower voltage required (-2,5/3 kV expected).

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

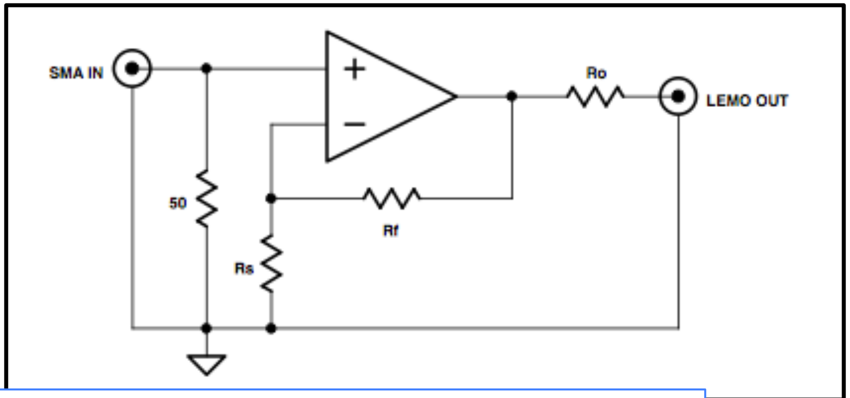
Experimental setup





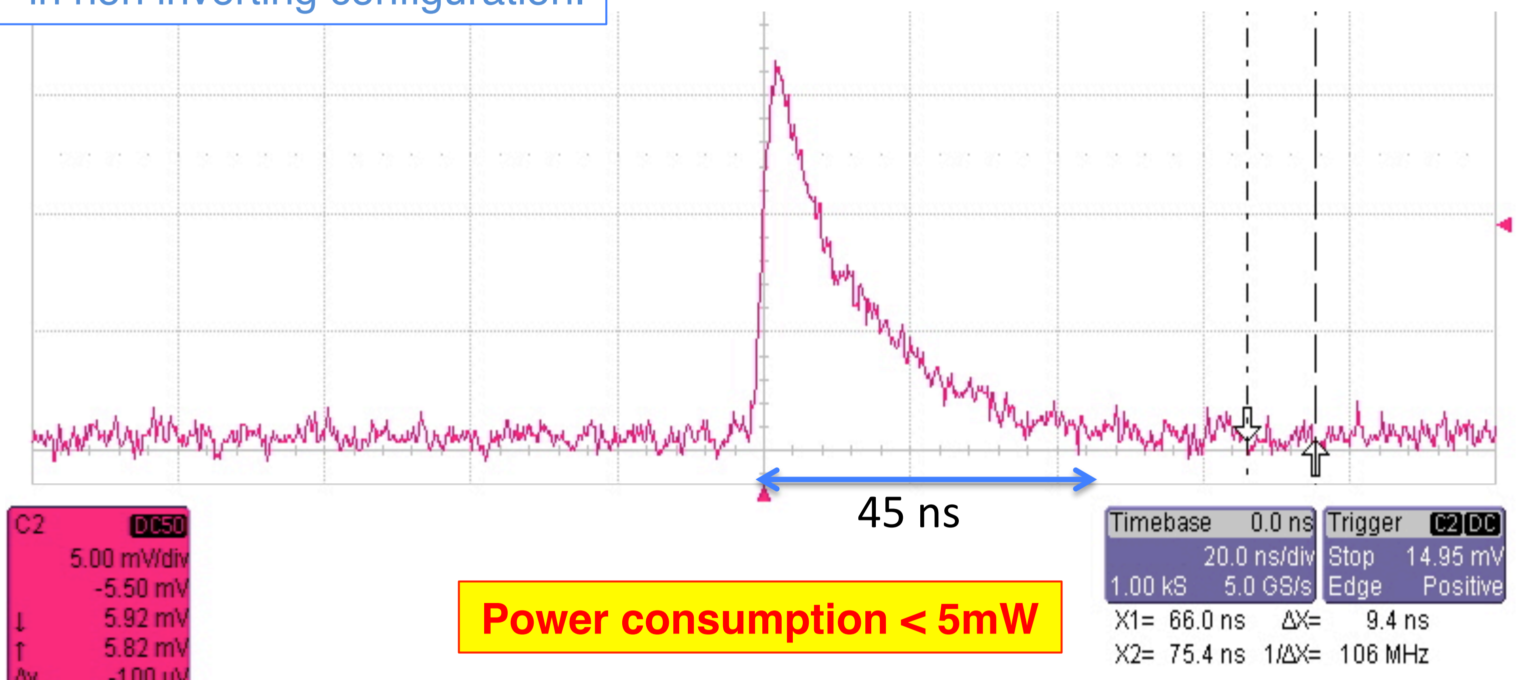


Amplification



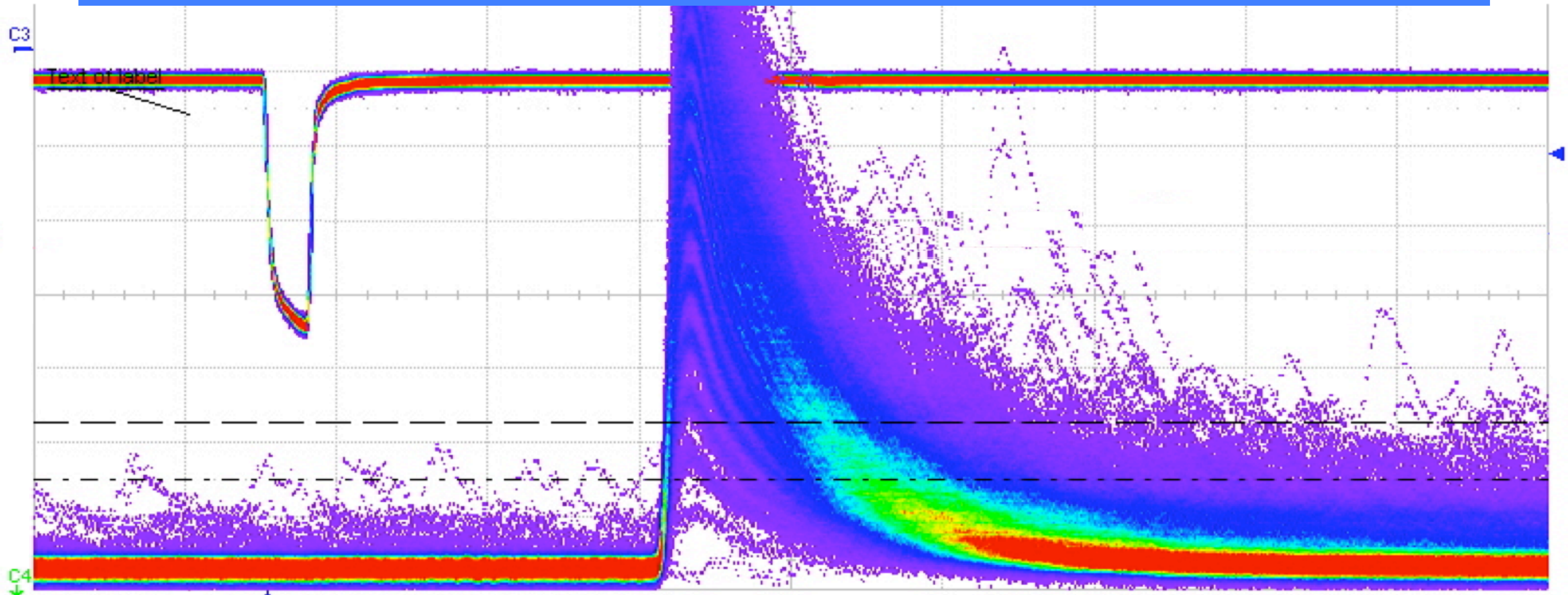
Single-state amplifiers based on an OP-AMP in non inverting configuration.

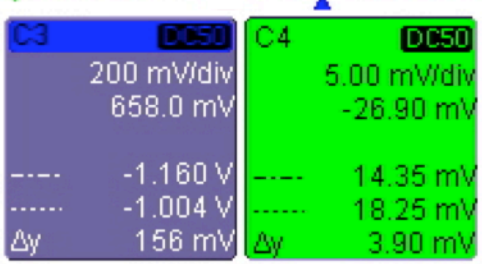
Three different gains: 10, 15, 20.



Power consumption < 5mW

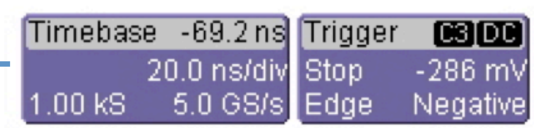
Waveforms





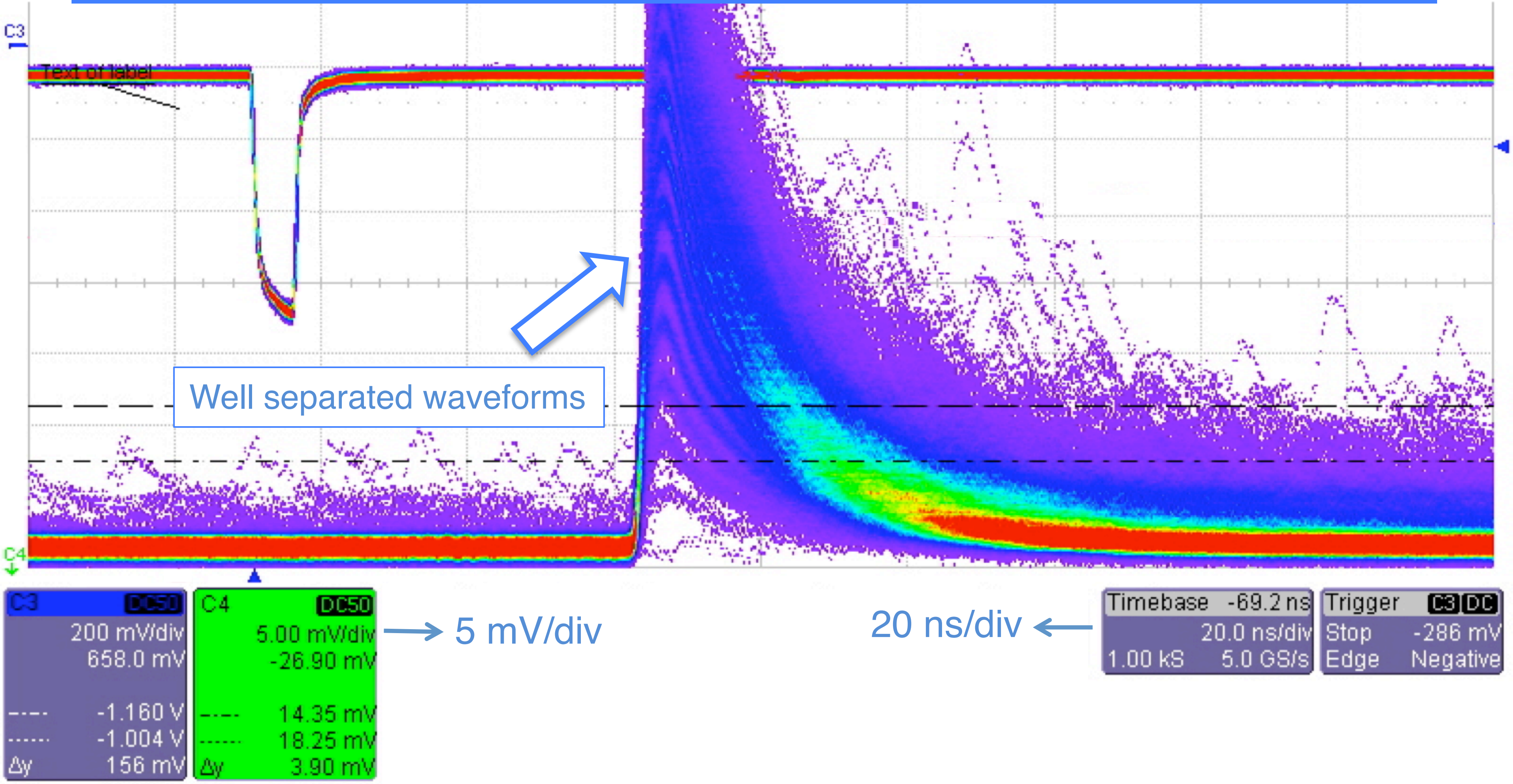
→ 5 mV/div

20 ns/div ←



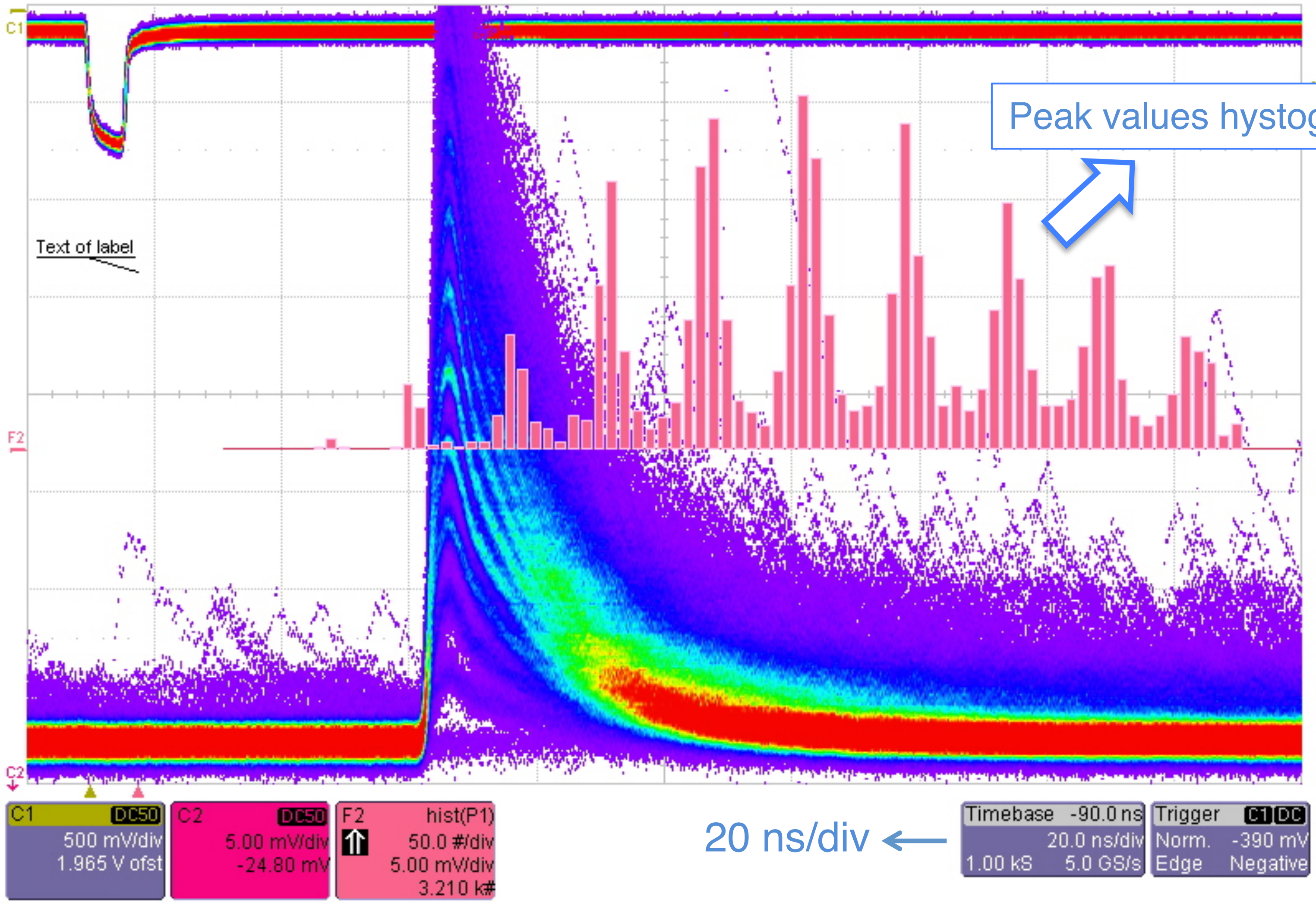
- VSiPMT illuminated by a pulsed laser light at low intensity (407nm)
- oscilloscope triggered in synch with the laser
- Responses for multiple triggers are overlaid

Waveforms



Excellent photon counting capabilities

Waveforms



Peak values hystogram

20 ns/div

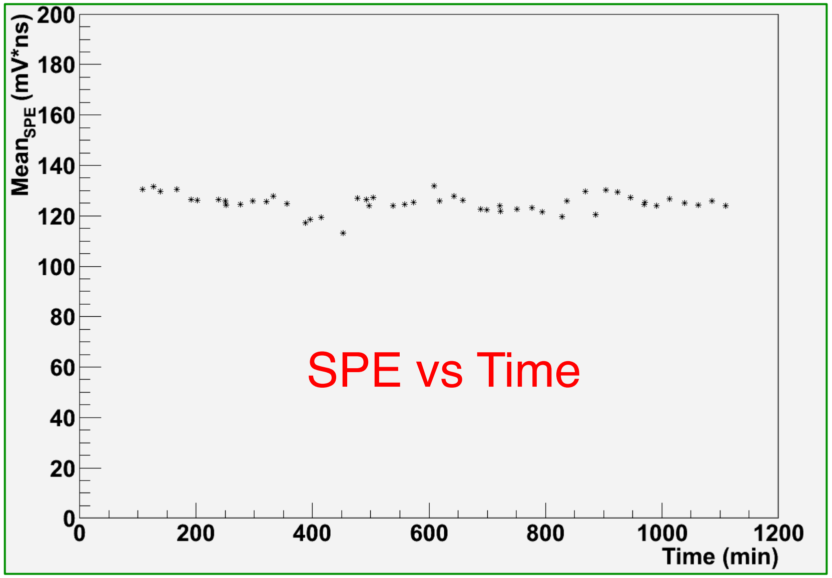
5 mV/div

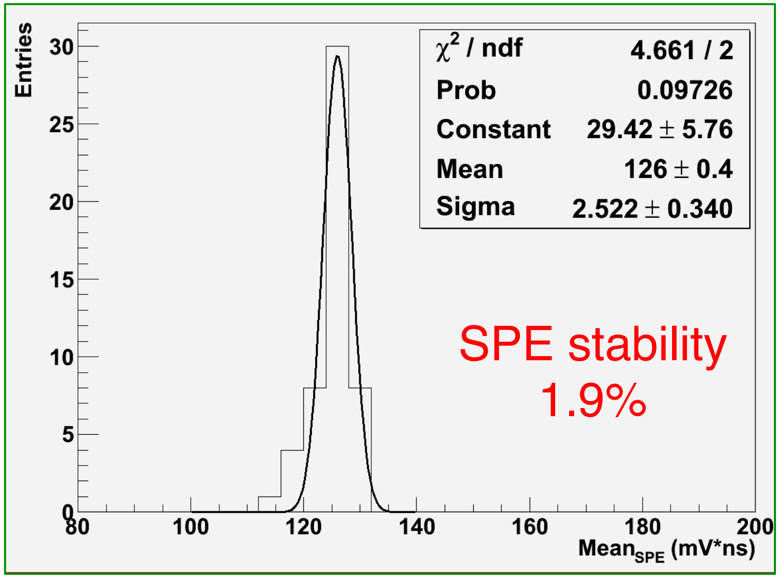
Excellent photon counting capabilities

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





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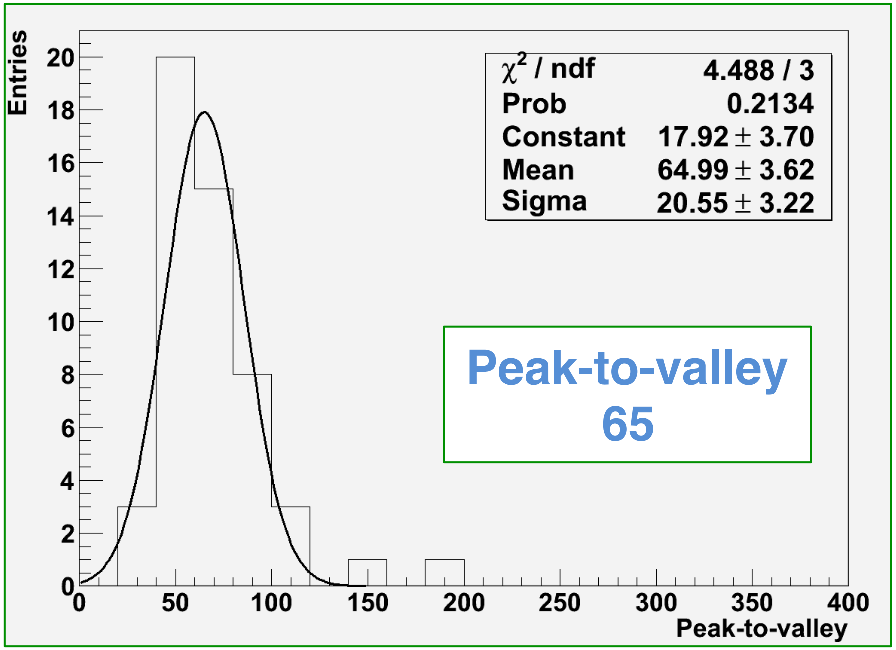
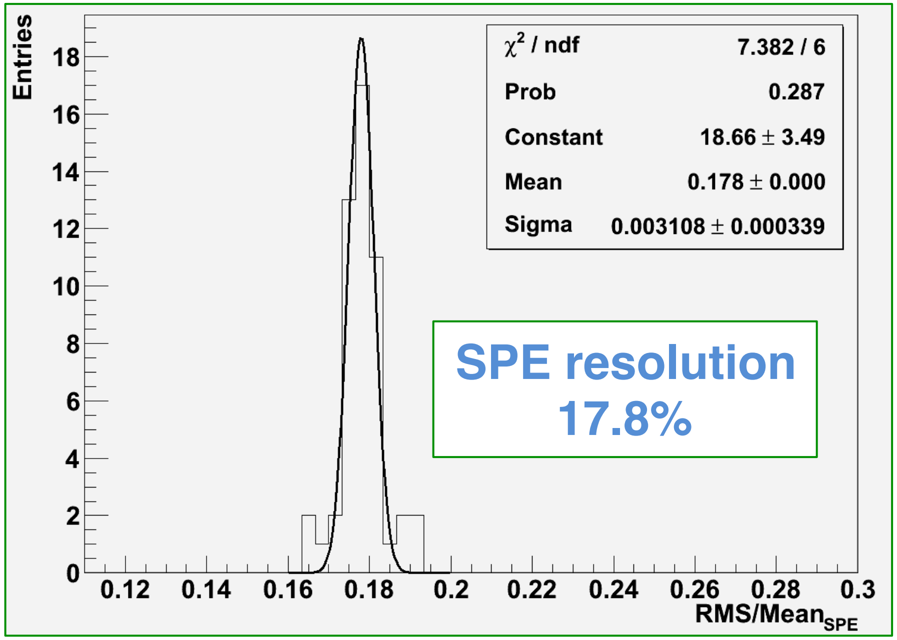




SPE spectra

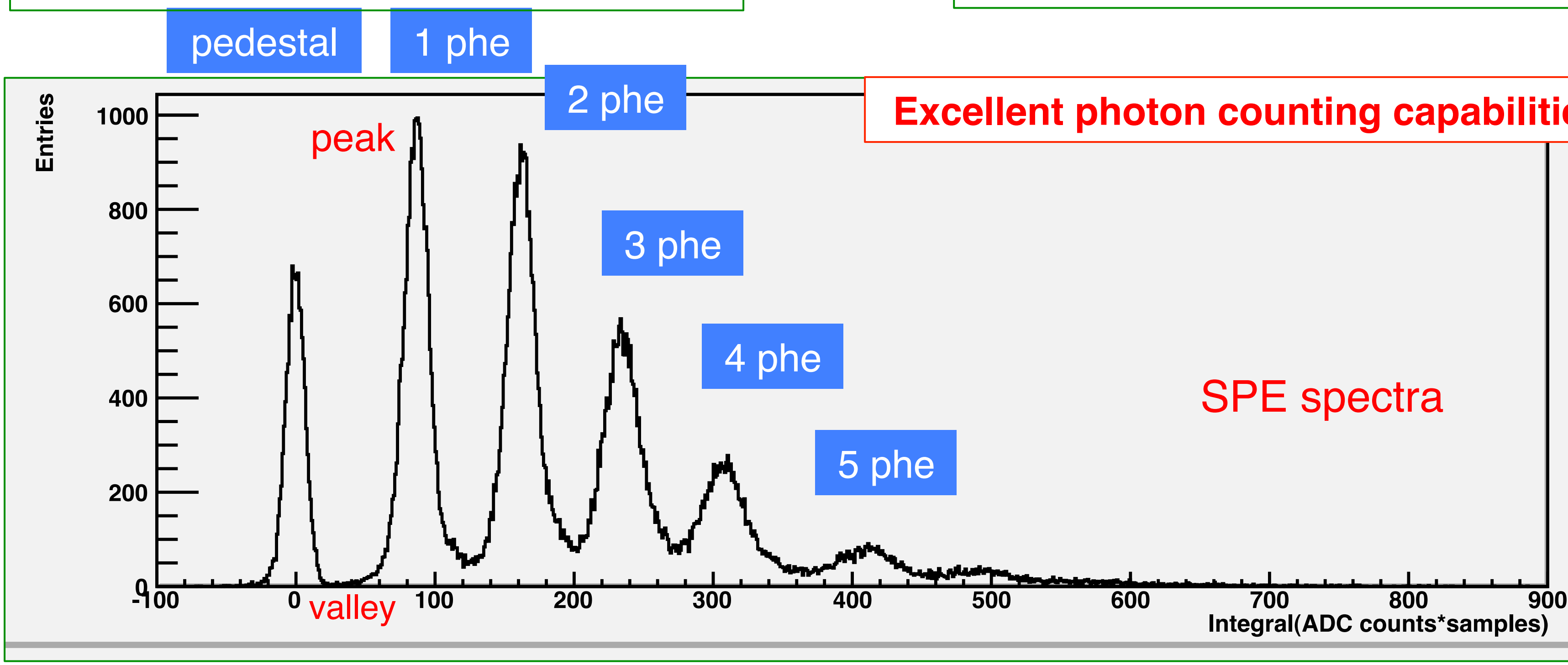
100.000 waveforms for each acquisition run with low laser intensity.

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

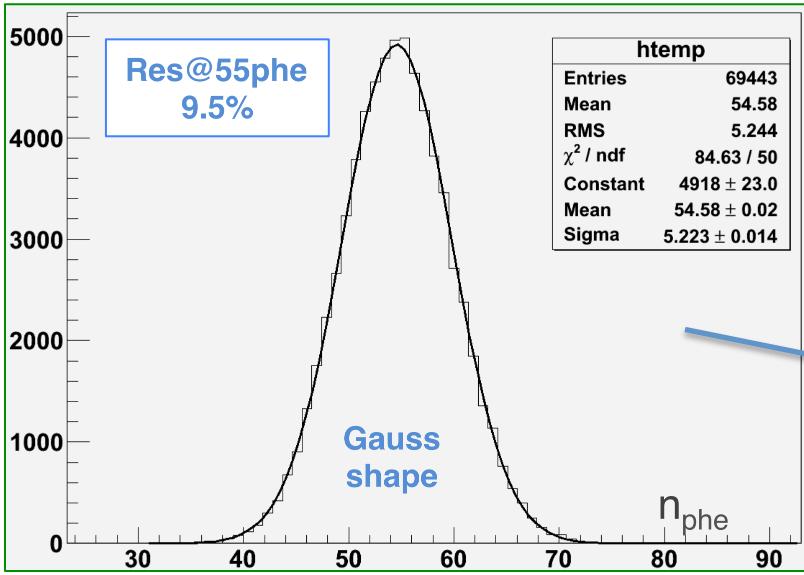
DAQ ADC CAEN V1720E
12 bit – 4 ns sampling
Laser TRG 10kHz

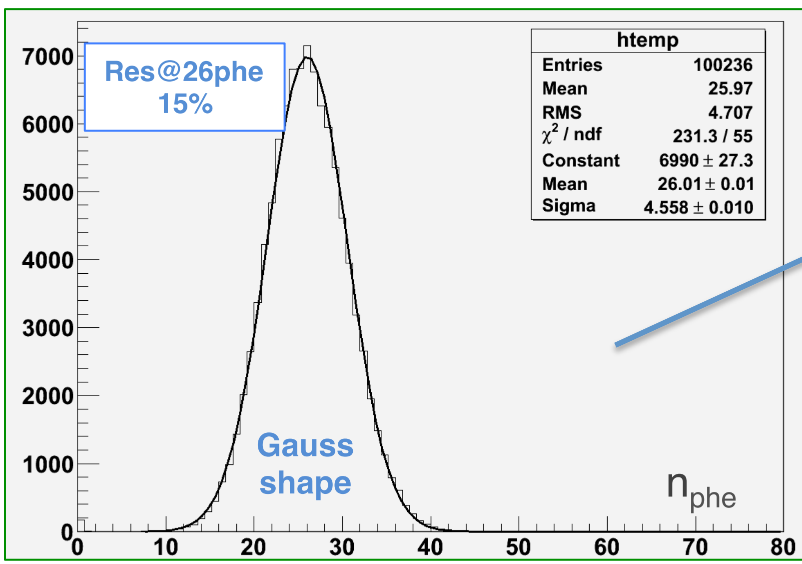
VSiPMT working point
V_{bias}= 72.5 V – HV = 4 kV
Amplification x20

Excellent photon counting capabilities

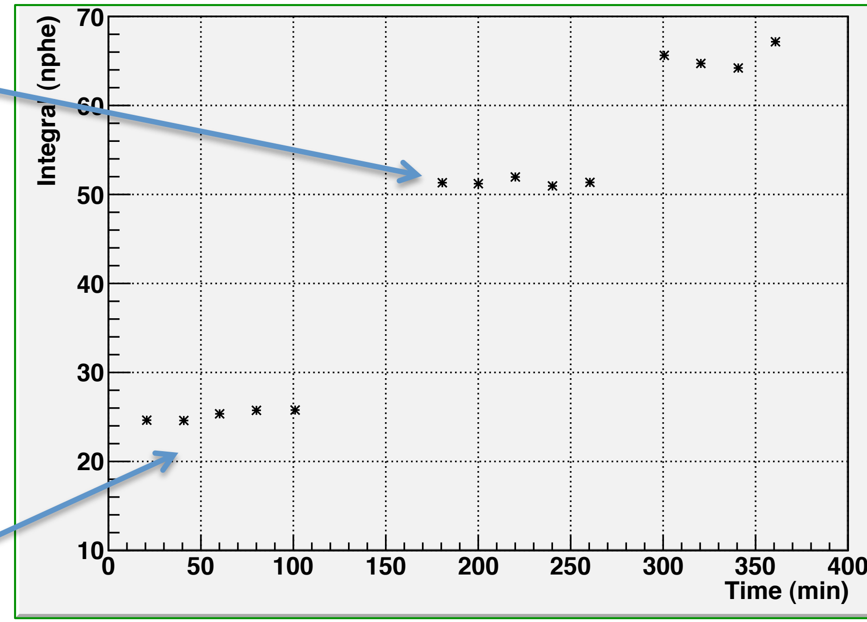


Multi photon response and stability



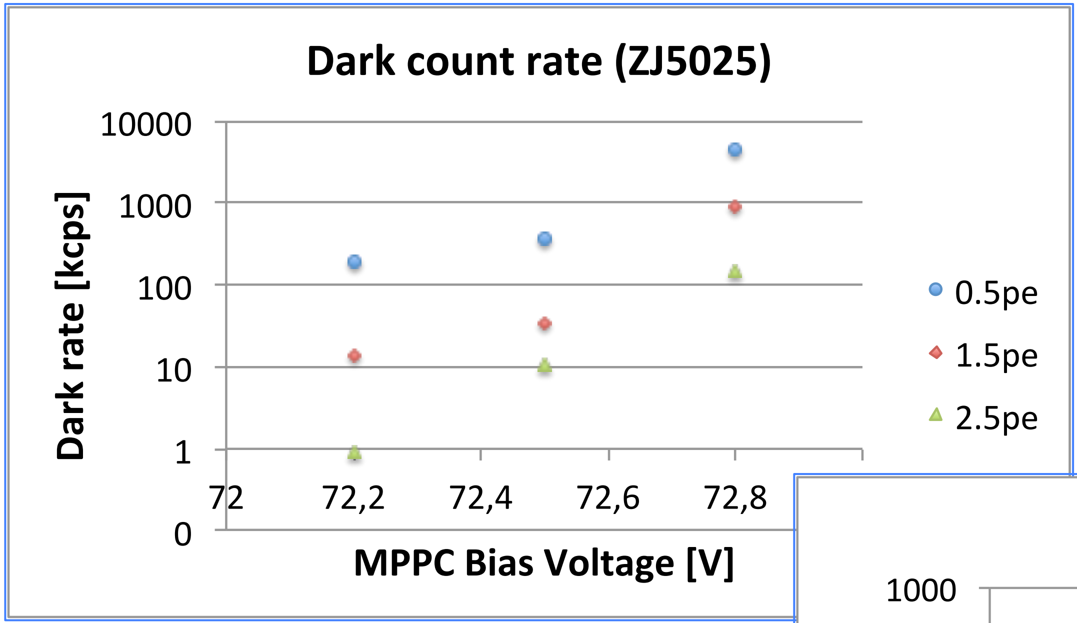


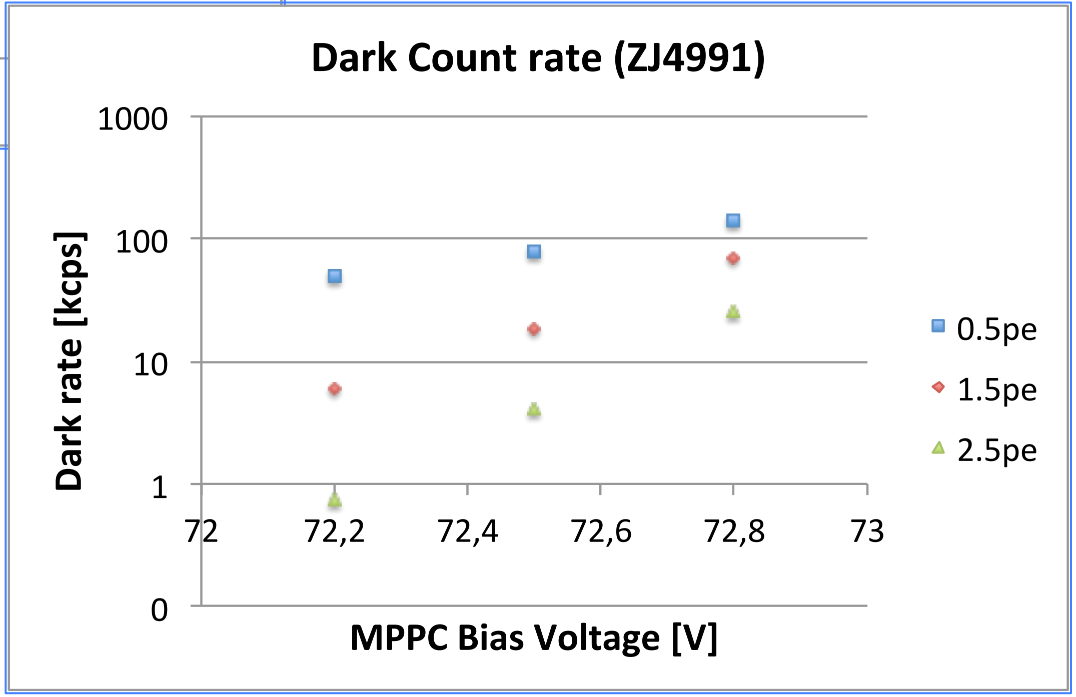
NO drop in the MPE response on 100 min



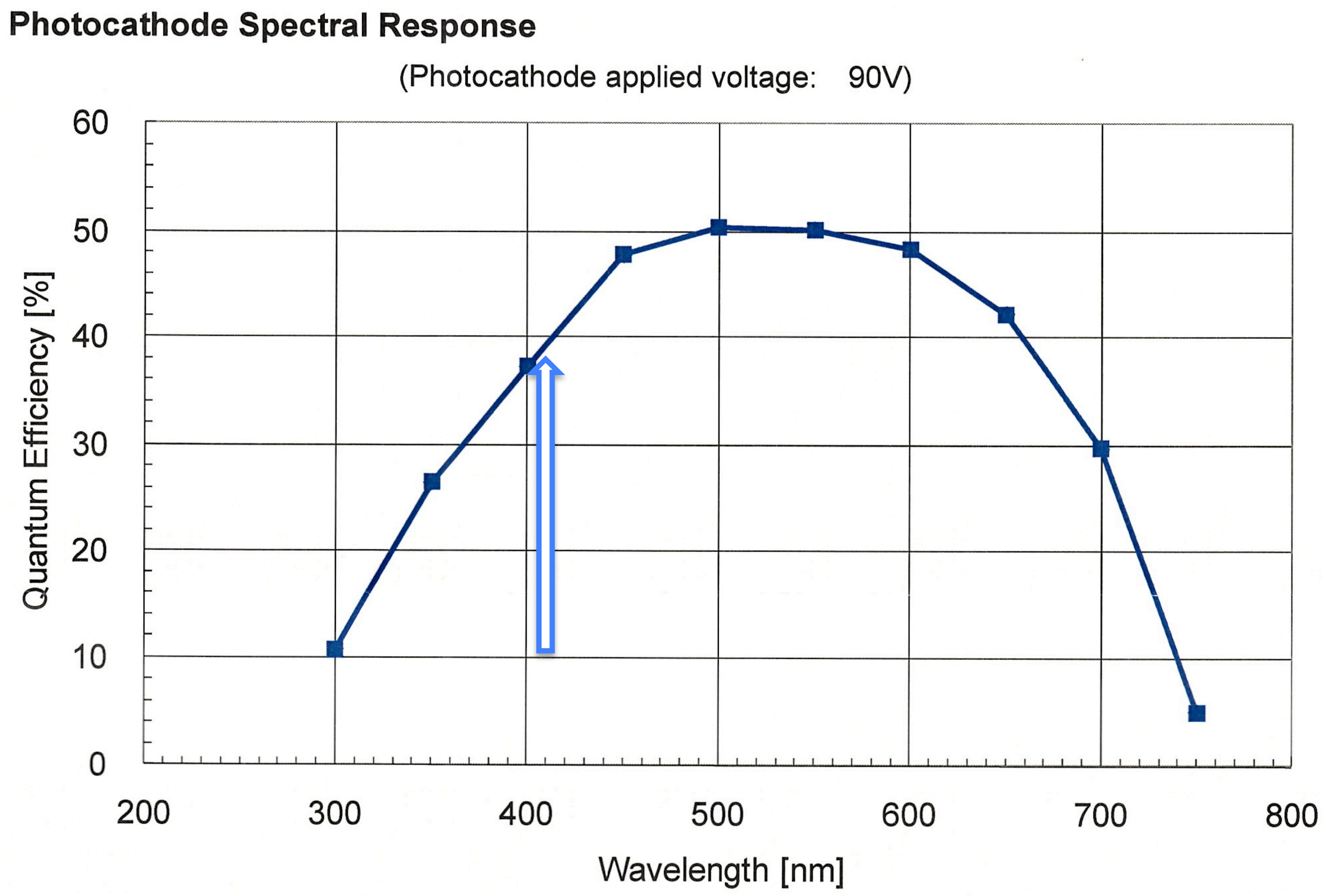
NO fatigue effect on high illumination

Dark count


Dark count rate (ZJ5025)
10000
1000
100
10
1
0
Dark rate [kcps]
72
72,2
72,4
72,6
72,8
MPPC Bias Voltage [V]
0.5pe
1.5pe
2.5pe

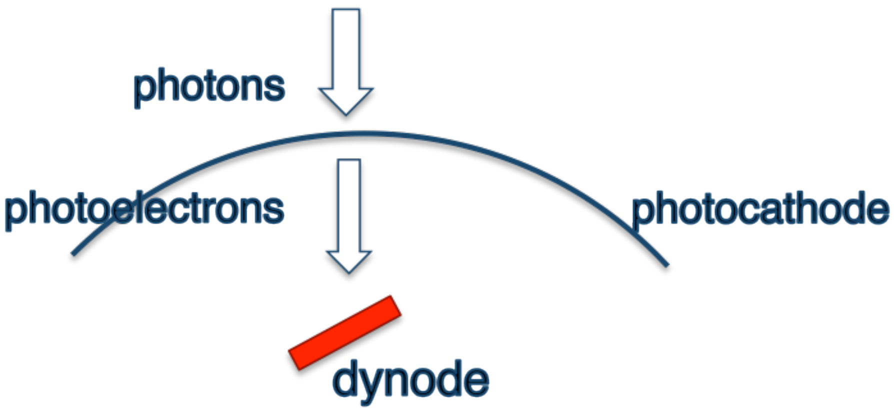

Dark Count rate (ZJ4991)
1000
100
10
1
0
Dark rate [kcps]
72
72,2
72,4
72,6
72,8
73
MPPC Bias Voltage [V]
0.5pe
1.5pe
2.5pe

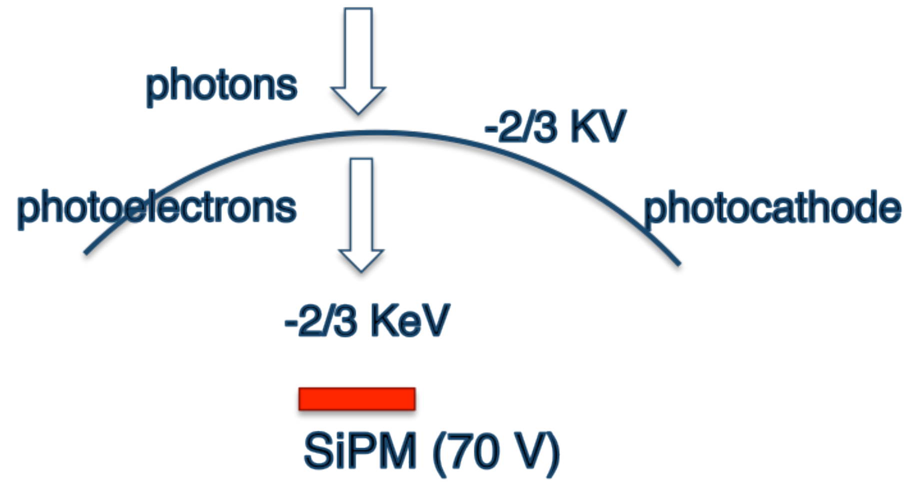
Efficiency



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

Efficiency: VSiPMT vs PMT





PMT Efficiency

$\varepsilon = \varepsilon_{\text{photocathode}} \times \varepsilon_{\text{1st dynode}}$

0,30 ≈ 0,38 x 0,8

VSiPMT Efficiency

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

0,23 ≈ 0,38 x 0,61 ↘

Fill factor

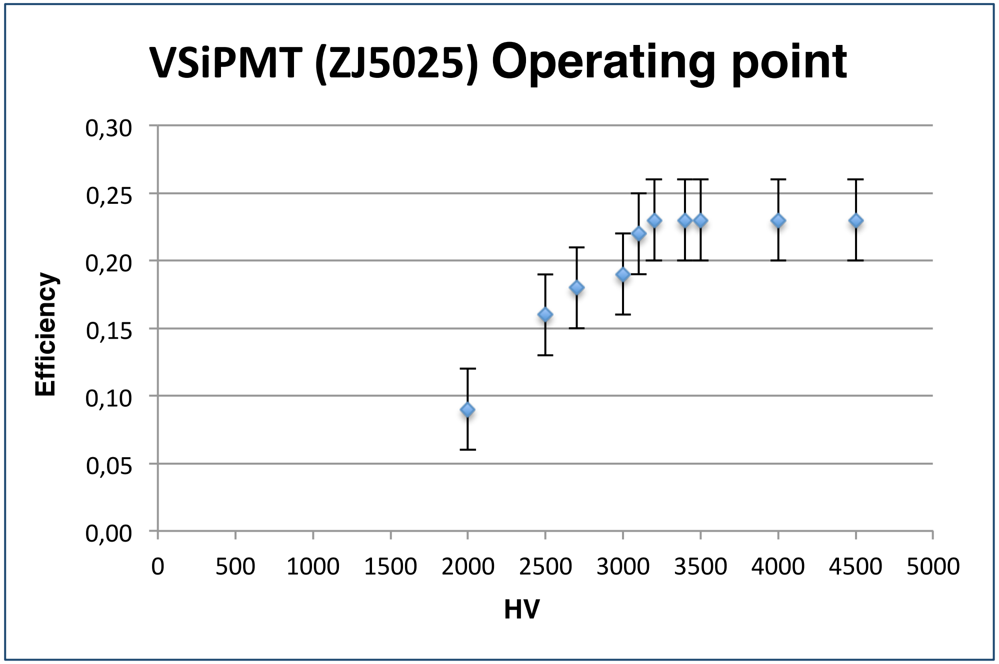
↗ $\varepsilon = \varepsilon_{\text{photocathode}} \times \varepsilon_{\text{SiPM (100)}}$

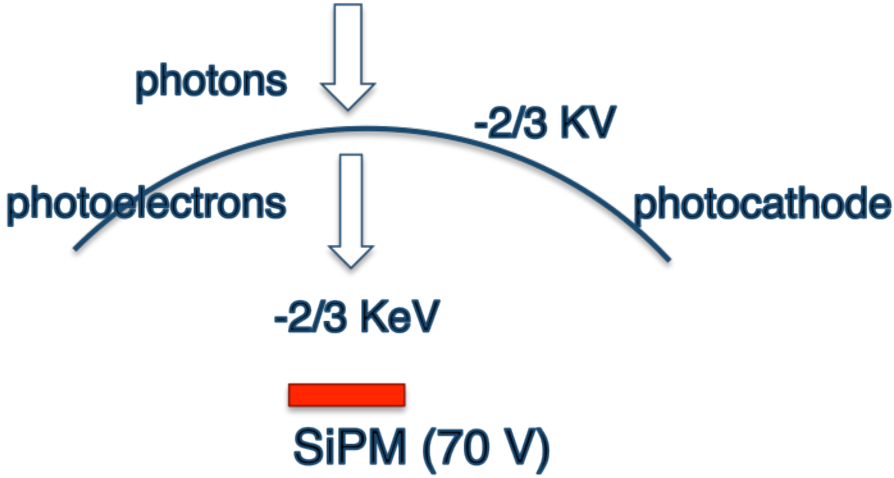
0,30 ≈ 0,38 x 0,78

The expected efficiencies for PMT and VSiPMT are comparable

VSiPMT efficiency further improvable with fill factor

Efficiency





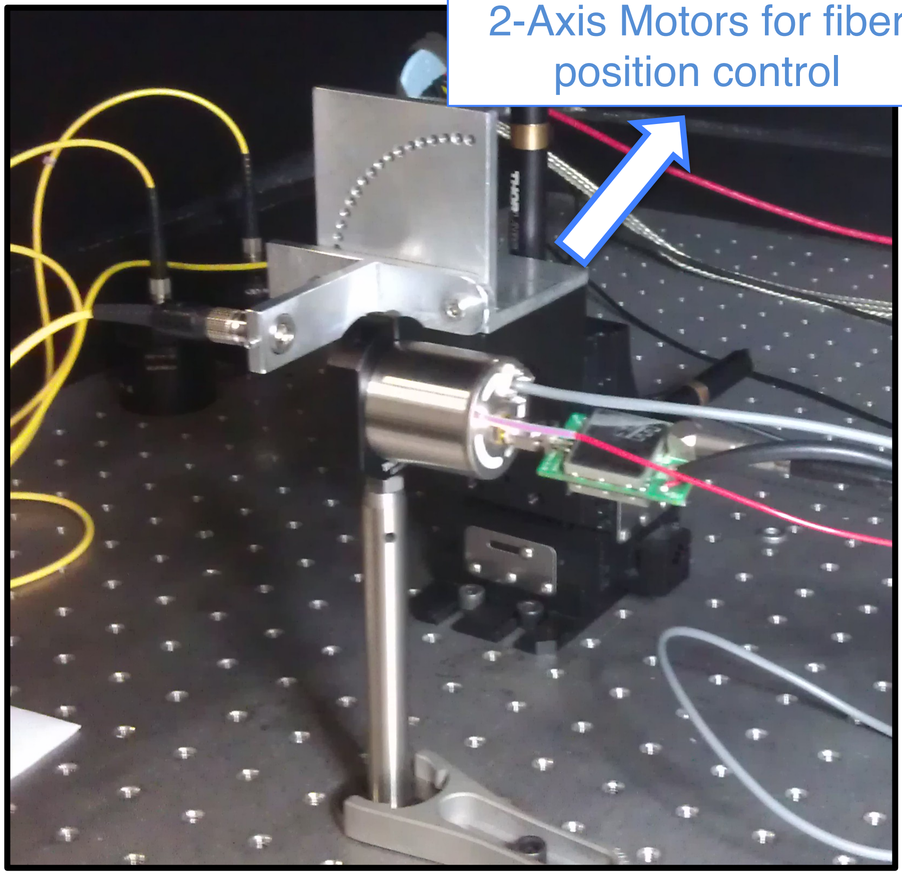
VSiPMT (ZJ5025)
measured efficiency
$\varepsilon = 0.23$

in agreement with expectations

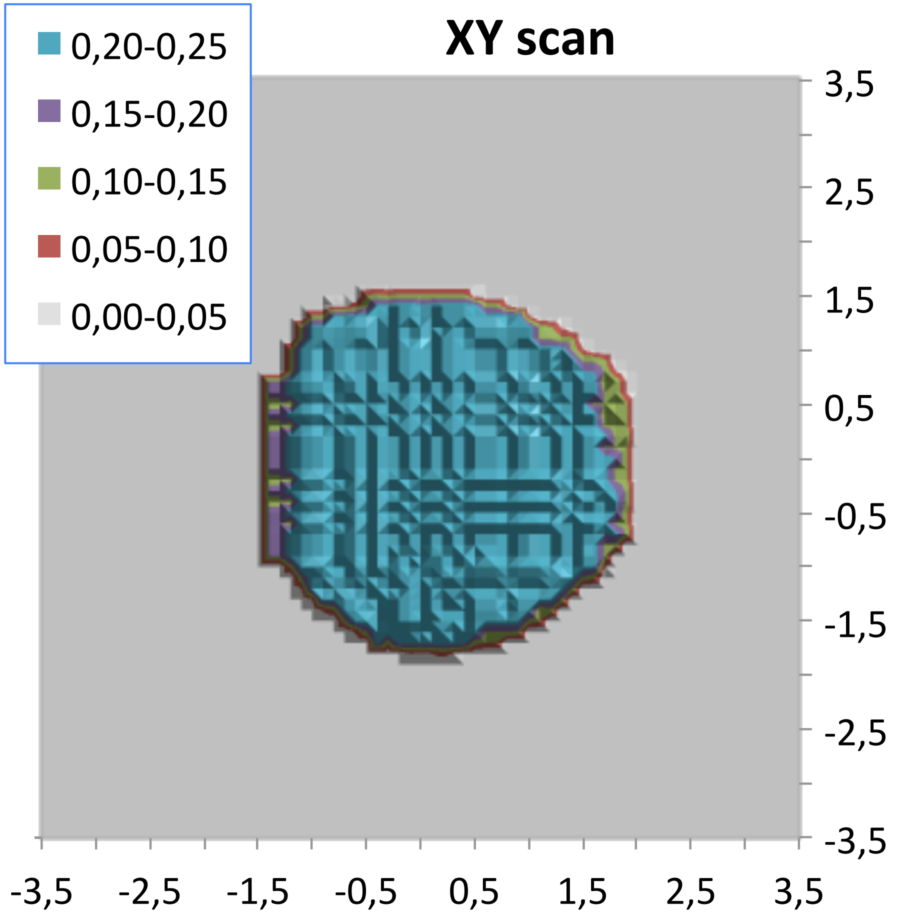
Efficiency is highly stable over 3200 V.
No need for high voltage stabilization.

- 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

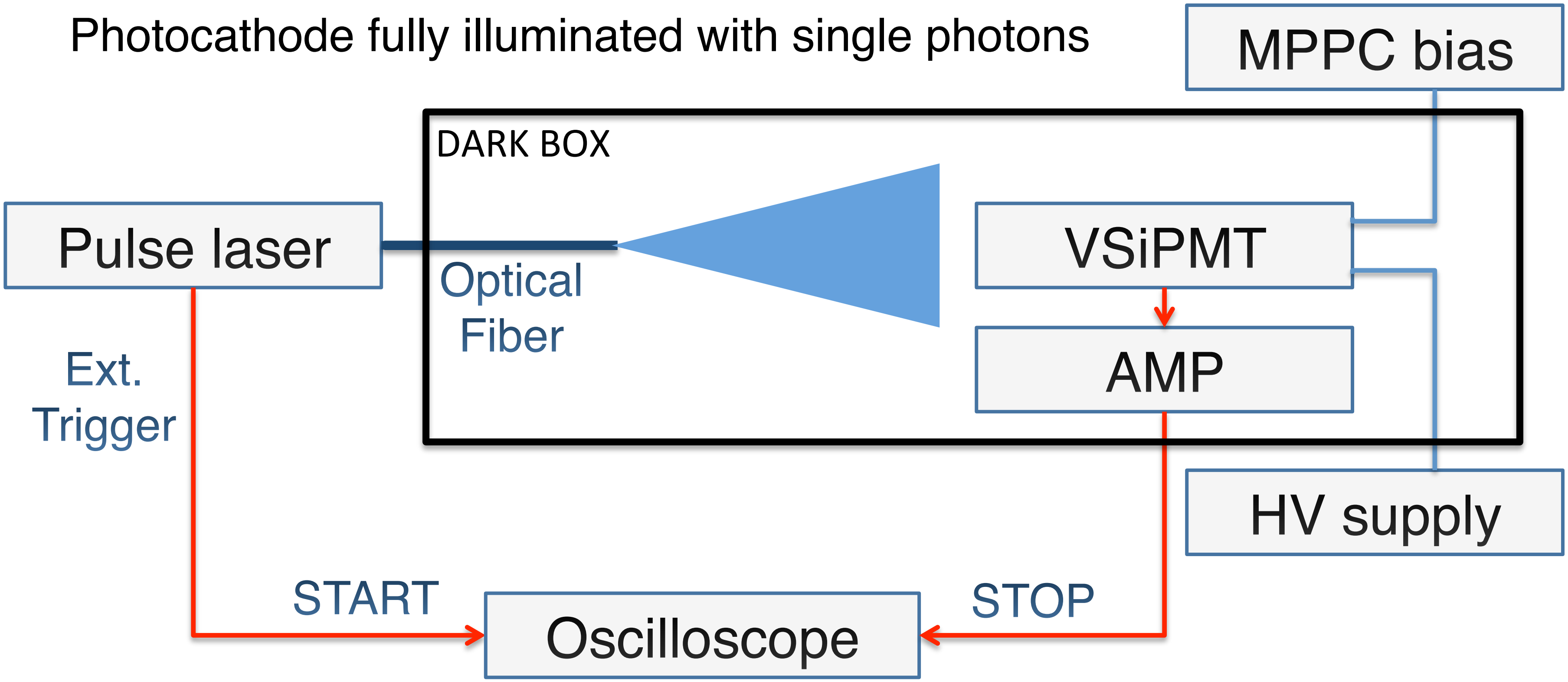


Homogeneous efficiency
≈ 0.2 over a 7mm^2 surface

Surface increase factor ≈ 7

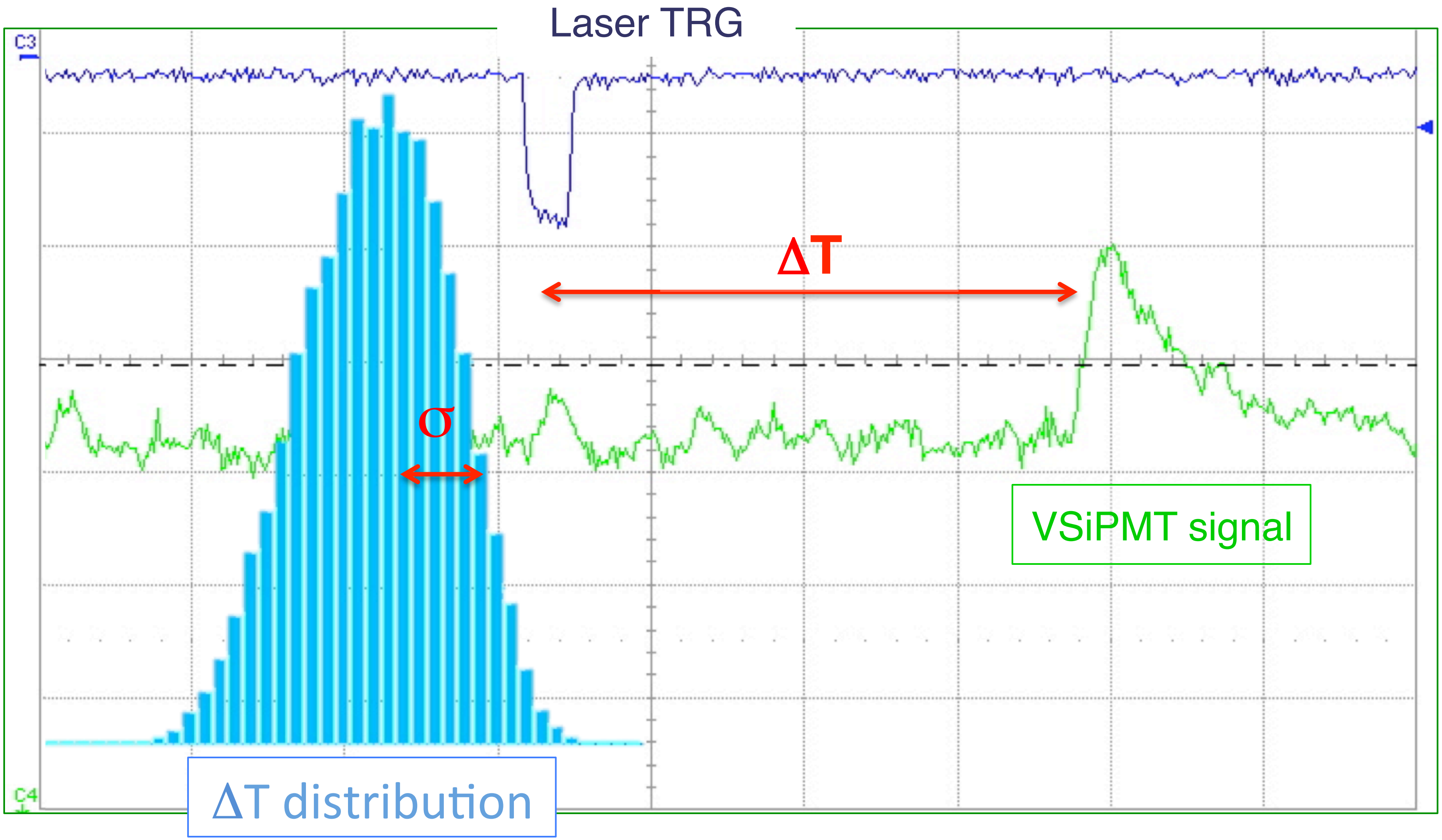
TTS

Photocathode fully illuminated with single photons



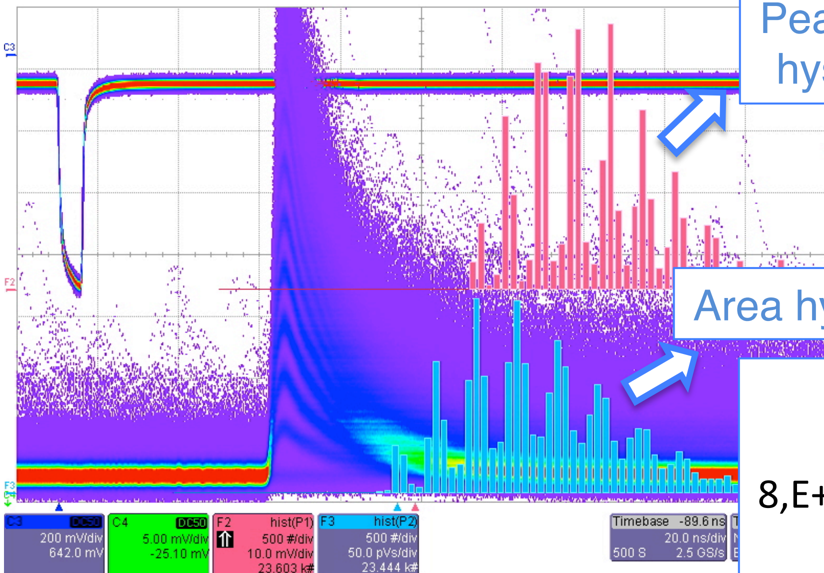
- The output from the VSiPMT is fed as the stop signal via a discriminator;
- We measure the time interval between the "start" and "stop" signals.

Transit Time Spread



VSiPMT
TTS (sigma) < 0.5 ns

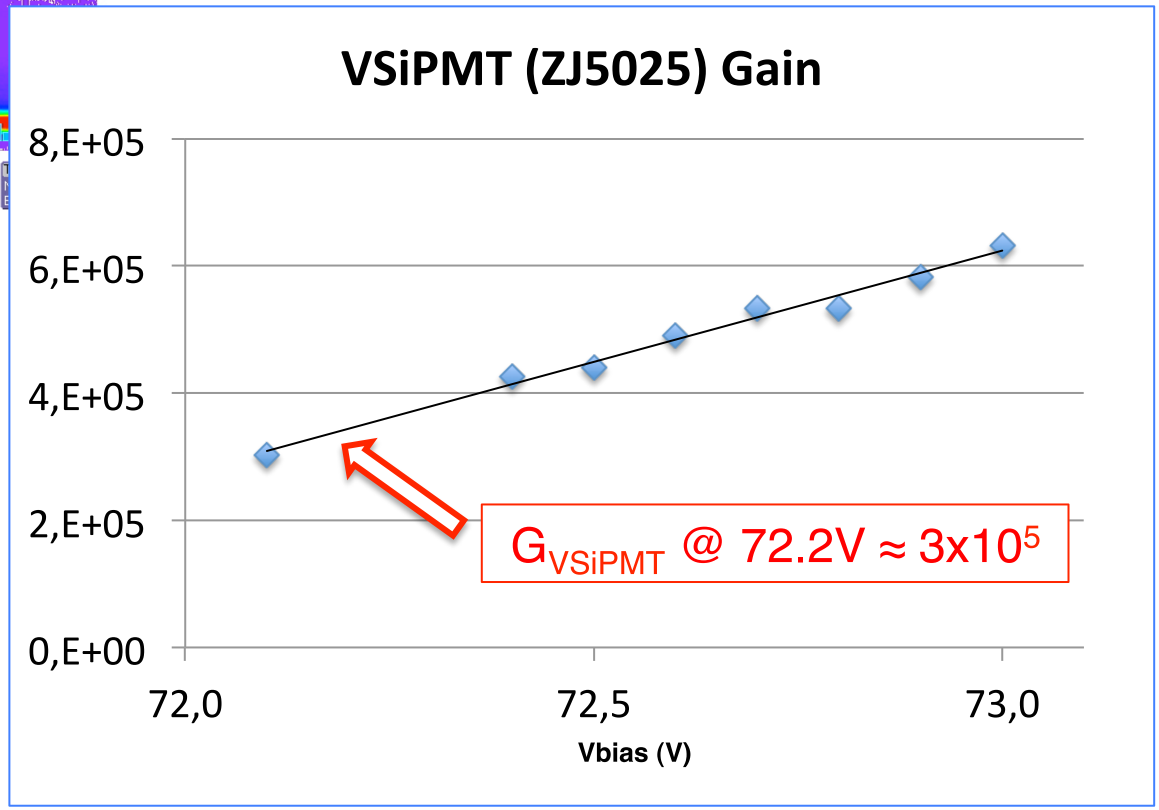
Gain



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

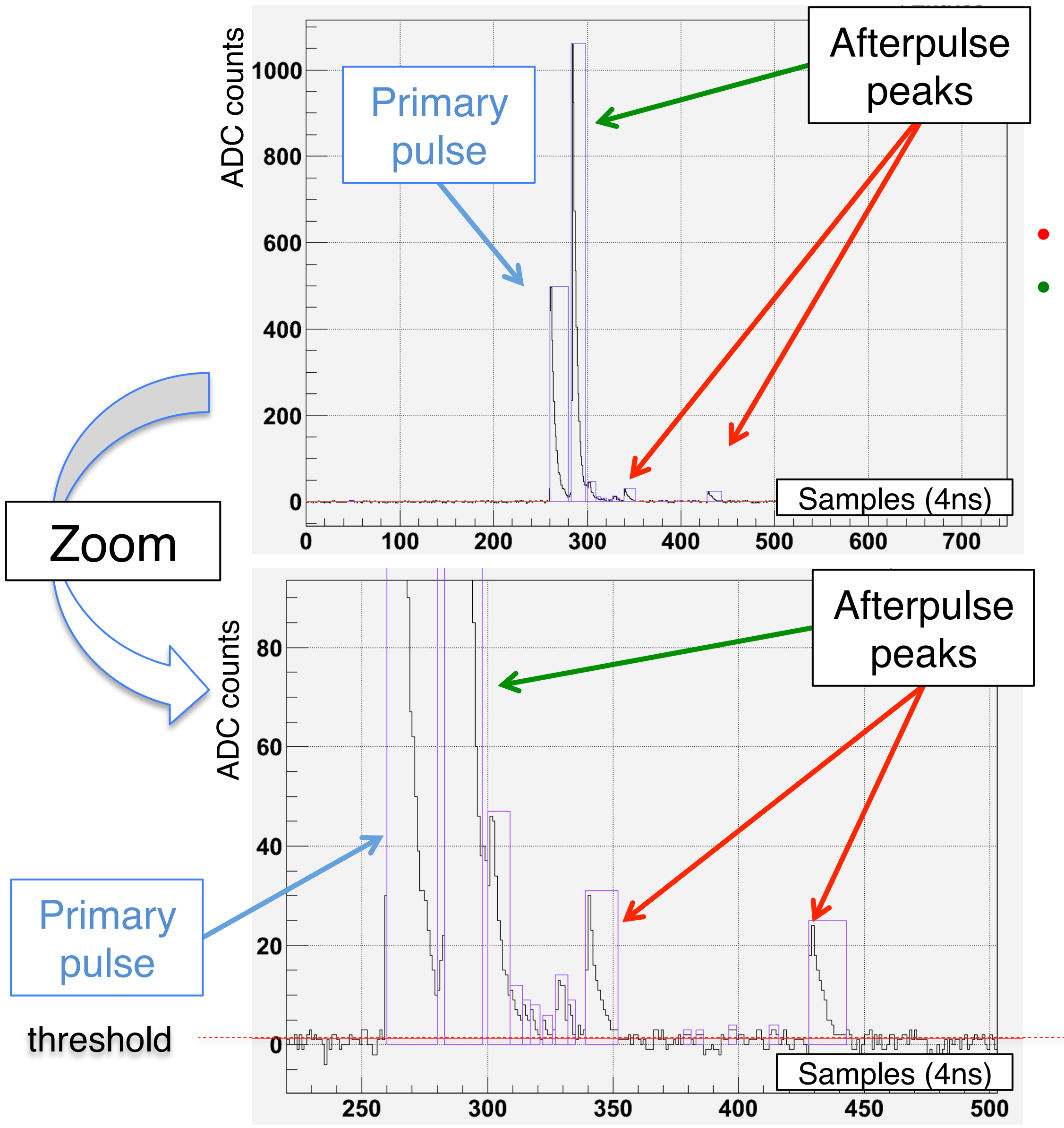
High gain (10^5–10^6), linear trend

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



Ideal Working Point: 72.2V
- **$G \approx 6 \times 10^6$ (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

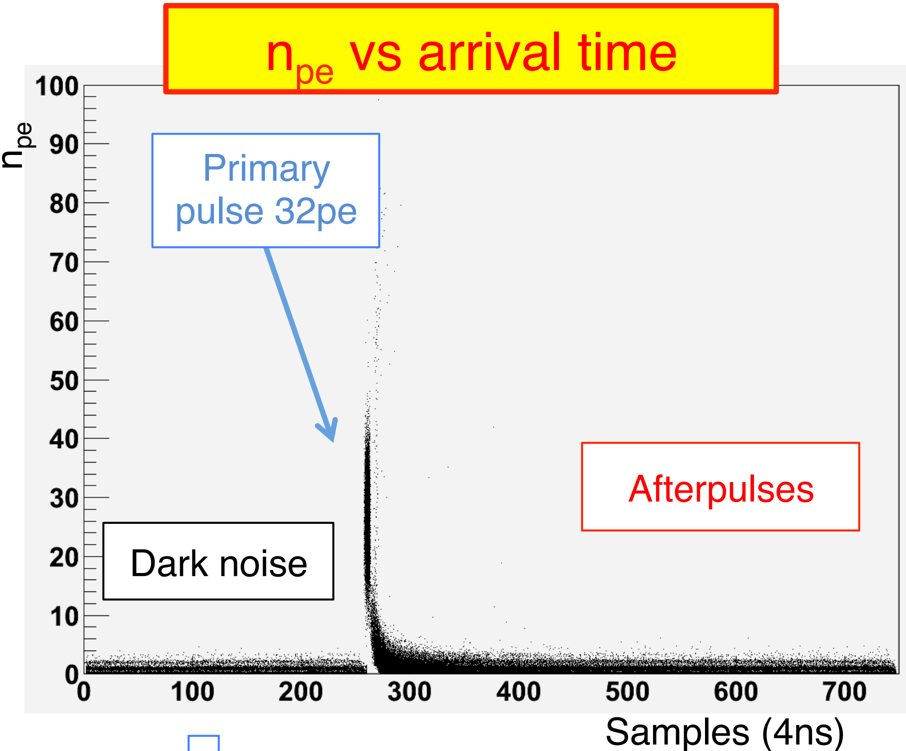
For each peak we reconstruct:

Arrival time

Integral

Pulse height

AP typical amplitude/1



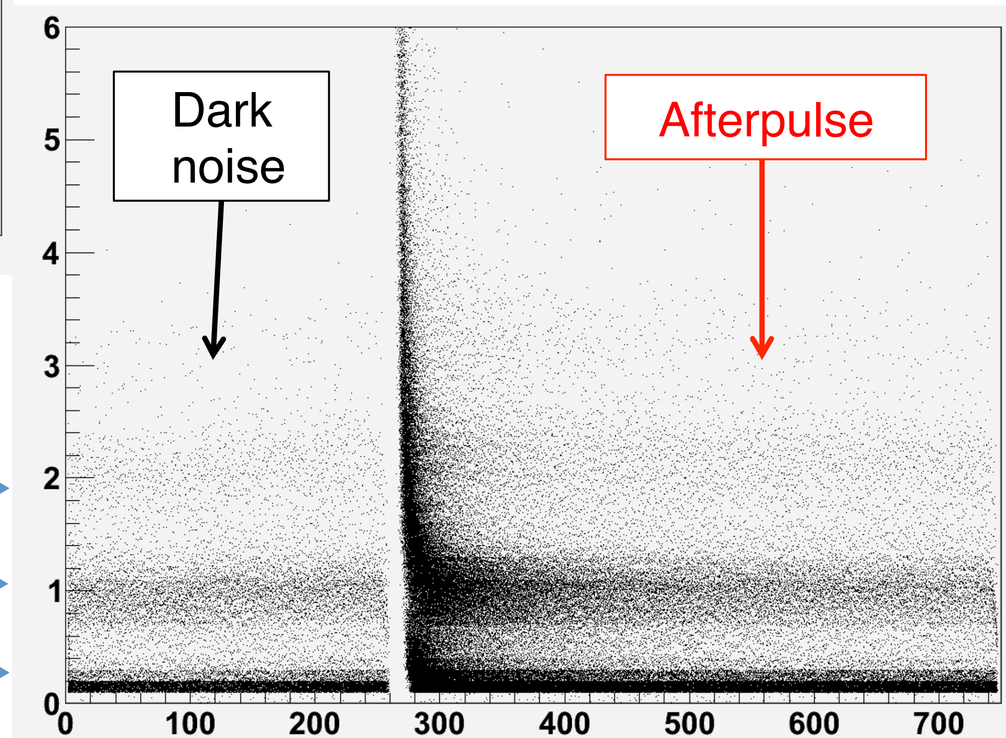
Low intensity AP 1-3 pe
Dark noise 1-2 pe

Zoom Y

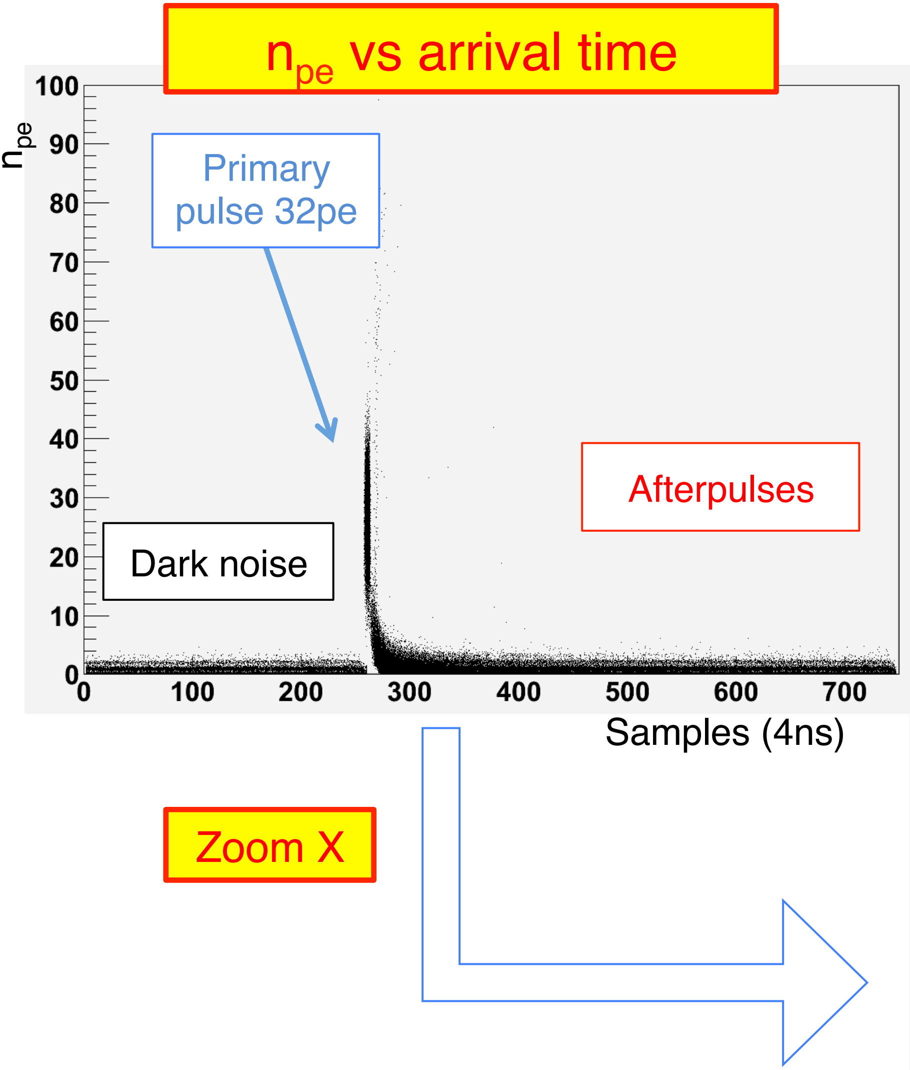
2 pe

1 pe

Pedestal

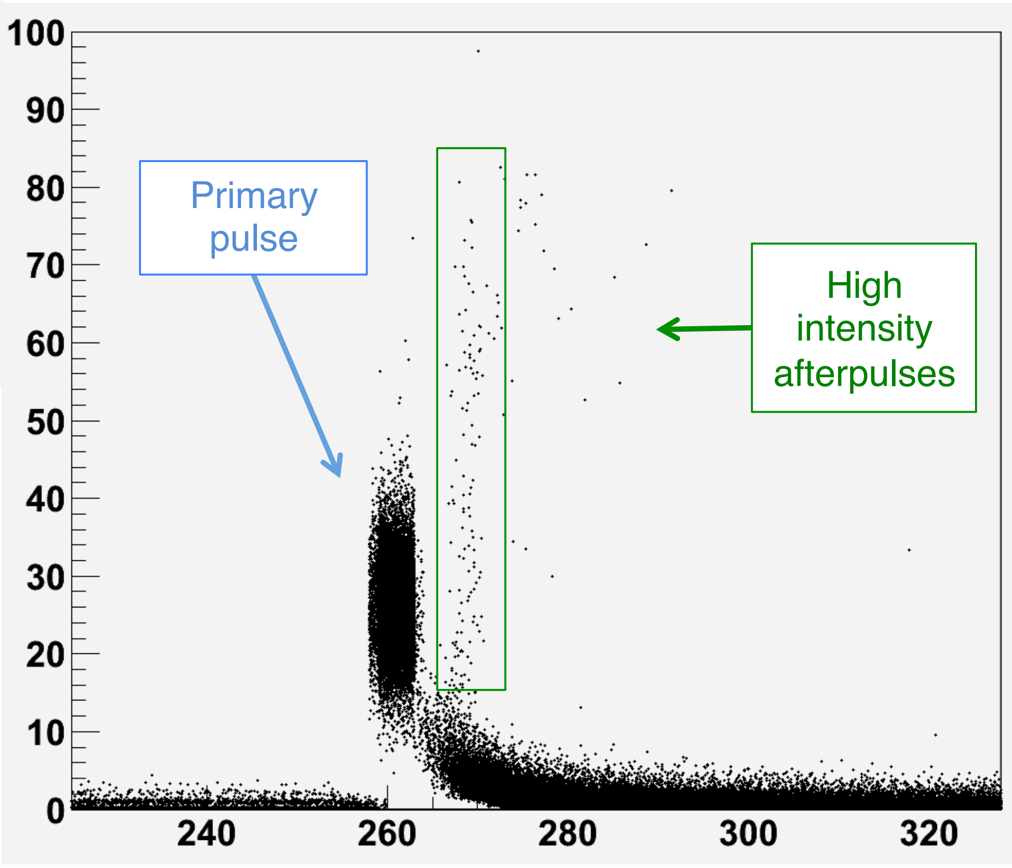


AP typical amplitude/2

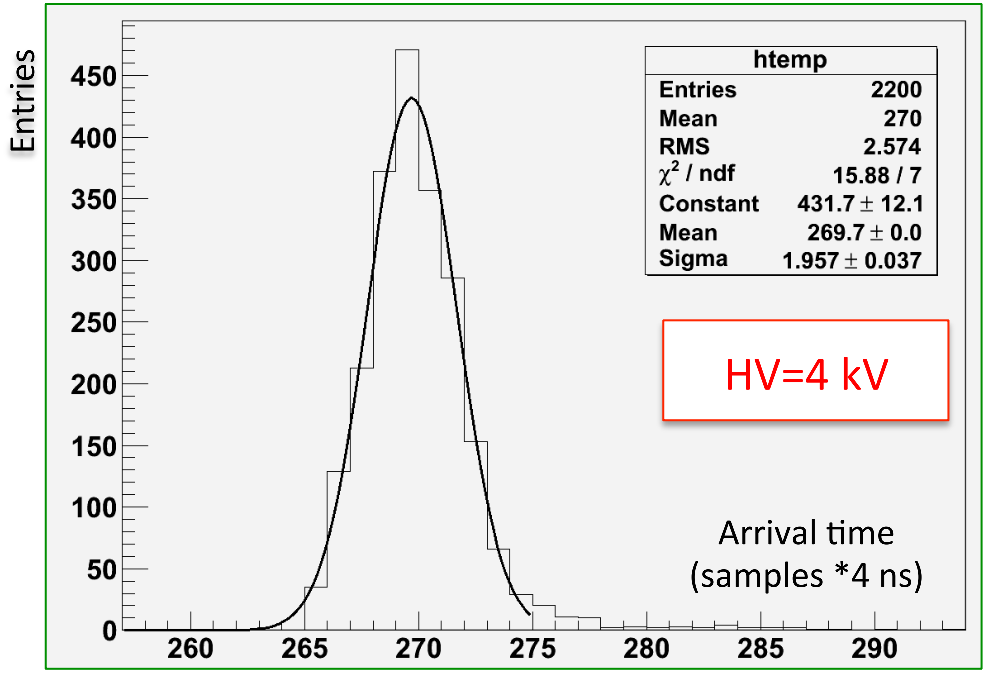


High intensity AP band
20-80 pe

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

Afterpulse rate

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

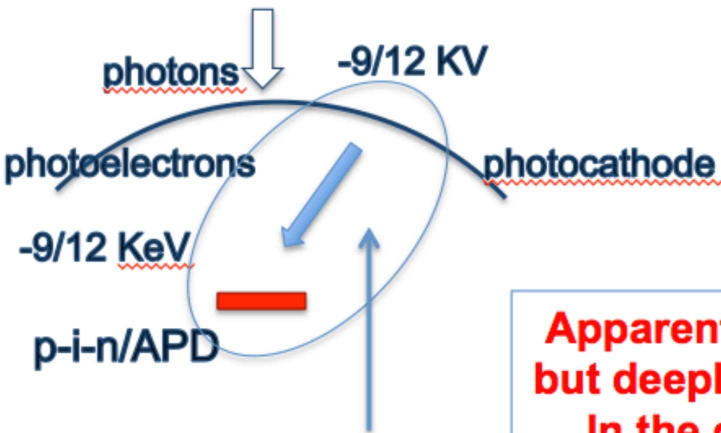
R_{AP}: afterpulse rate;
I_{AP}: sum of the intensities of each afterpulse peak found in 100.000 waveforms;
I_{MP}: sum of the intensities of the primary pulses of 100.000 waveforms;

Afterpulse rate Table summary

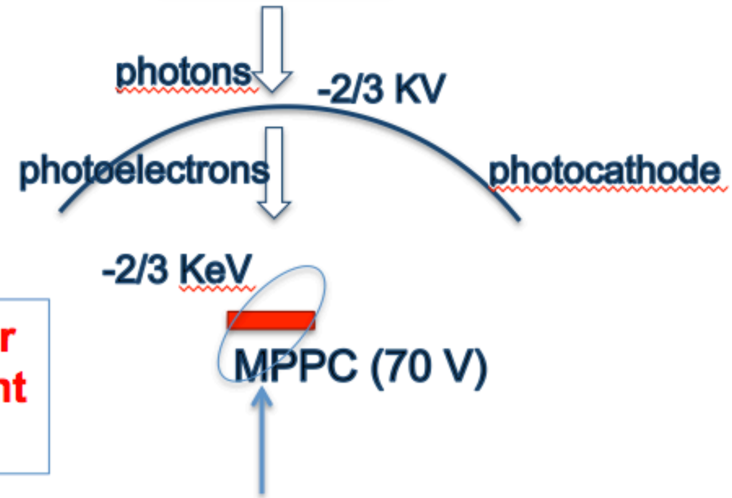
Threshold (pe)	Afterpulse rate
>0.50	10.41%
>0.75	9.40%
>1.00	7.34%
>2.00	2.38%
>5.00	0.23%
>10.00	0.02%

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

- $G=E_{phe}/E_{e,h} \approx 10^4-10^5$
- 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 (0,8)	Photocathode x Fill factor MPPC (➔1)	**≈ equivalent**
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	≈ 10^2 kHz @ 0.5pe	**+PMT**
Photon counting	difficult	excellent	**+VSiPMT**
Peak-to-valley ratio	≈ 3 (typ.)	> 60	**+VSiPMT**
Afterpulse	≈ 10% @ 0.5pe	≈ 10% @ 0.5pe	**≈ equivalent**
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;
- Large sensitive surface;
- Excellent timing performances (low TTS);
- High stability (not depending on HV).

making it a very attractive solution in many Cherenkov experiments

STILL IMPROVABLE!!!

New generation of Hamamatsu MPPCs:

- sensibly lower afterpulse rates;
- lower noise: much reduced dark counts;
- higher gain ➔ no amplification required (persp.)

Thank you