VSiPMT

The VSiPMT project: characterization of the second generation of prototypes

TIPP 2017 - International Conference on Technology and Instrumentation in Particle Physics

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INFN Section of Naples

VSiPMT

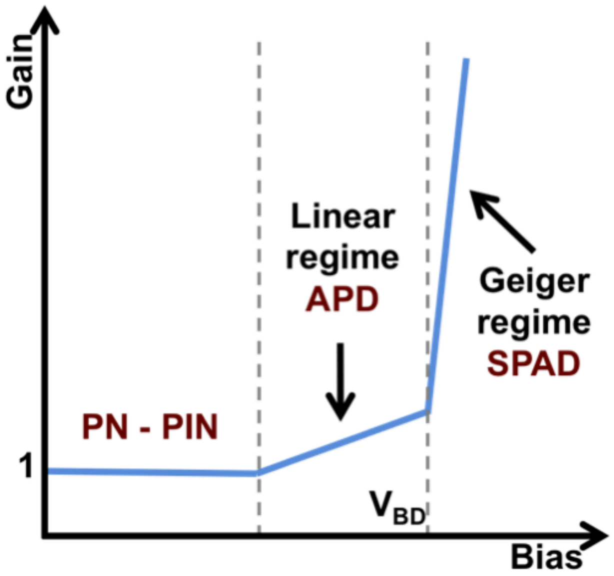
- Introduction
- Timeline
- The EB-MPPC100 prototype
- Characterization:
    - experimental setup
    - photon spectra
    - dark noise
    - gain
    - efficiency
    - focusing
    - linearity
    - timing
    - photocathode homogeneity
- Conclusions and perspectives

VSiPMT

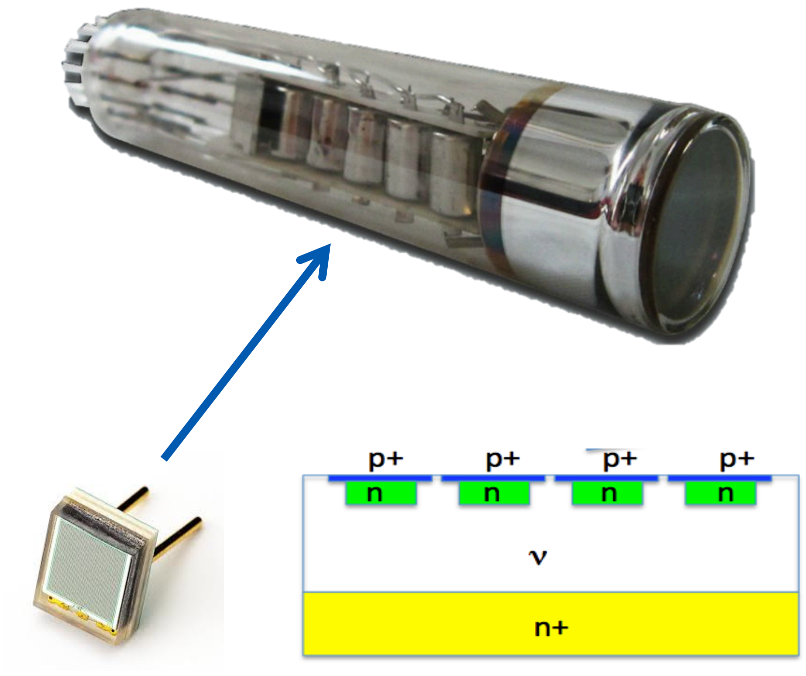
- fluctuations in the first dynode gain ➔ single photon counting difficult;
- linearity strongly related to the gain (decreases as gain increases);
- transit time spreads over large fluctuations;
- complex and expensive mechanical structure;
- sensitivity to magnetic fields;
- need of voltage dividers ➔ power consumption and failure risks increase.

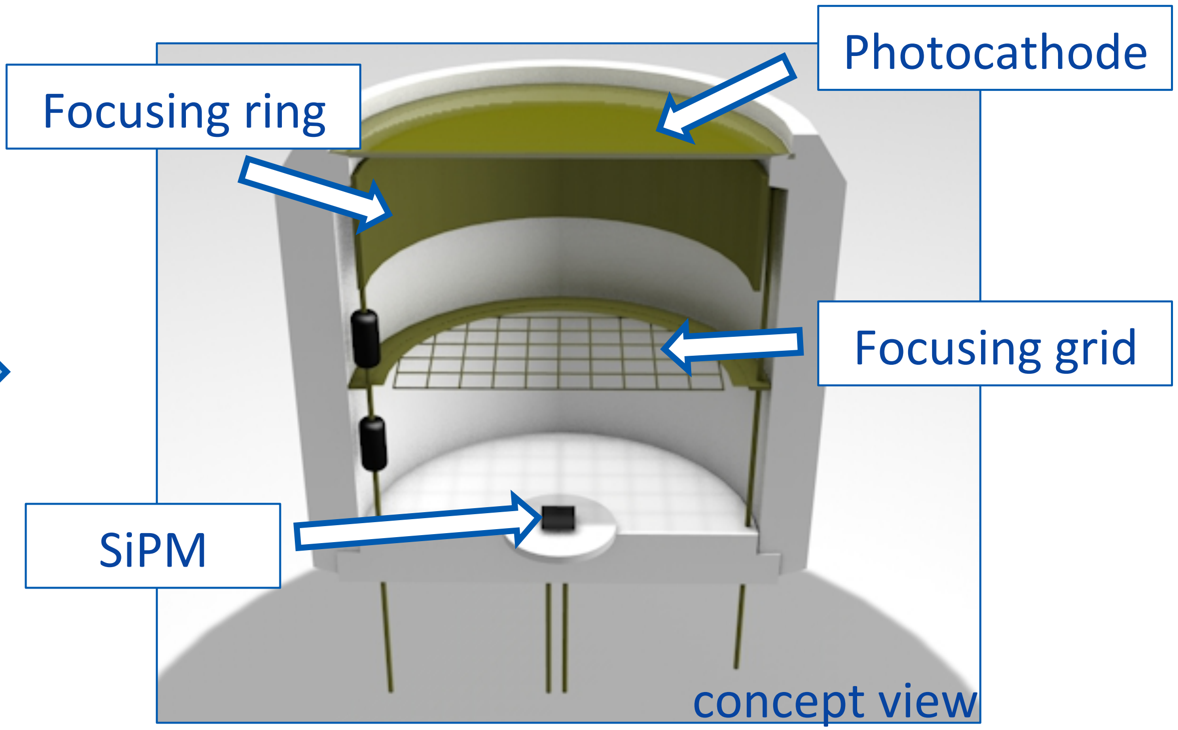
New generation of semiconductor photodetectors, based on inverse p–n junction:

- PIN photodiodes: no gain;
- avalanche photodiodes (APD): gain of few hundreds;
- avalanche photodiodes in linear Geiger-mode (GM-APD, or SiPM): gain of $10^5 - 10^6$.



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

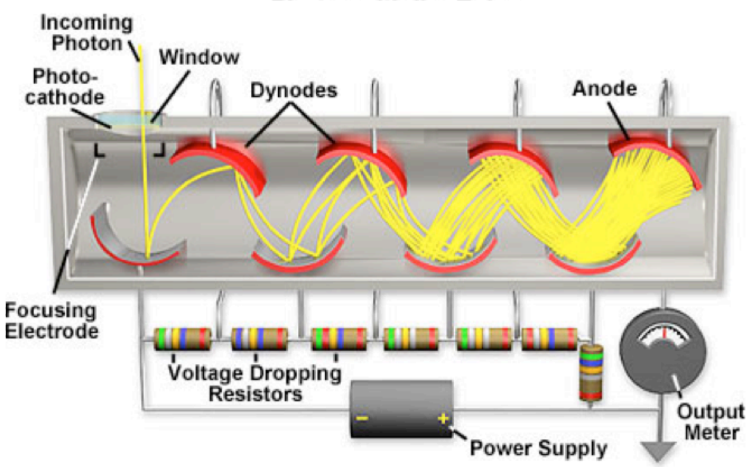


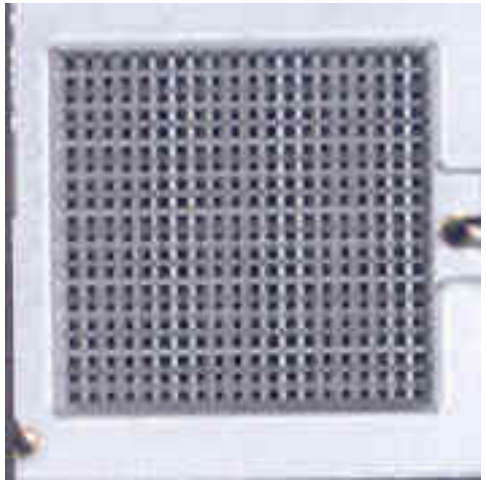


The classical dynode chain of a PMT is replaced with a SiPM, acting as an electron multiplying detector.

VSiPMT

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





• **Photon counting**	Multiplication gain (series) Energy resolution α $1/(d^{1st})^{-1/2}$ $G=d^n=(kV_d)^n$	"Parallel" gain (digital) no statistic fluctuations
• **Time resolution**	$\sigma^2_{total}=\sigma^2_{pc\_em}+\sigma^2_{em}$ $\sigma_{pc\_em}\ \alpha\ (V_{pc\_em})^{-1/2}$ $\sigma_{em}\ \alpha\ (d^{1st})^{-1/2}$	$\sigma^2_{total}=\sigma^2_{pc\_em}+\cancel{\sigma^2_{em}}$
• **Gain stabilization**	$dG/G=n\ dV_d/V_d= n\ dV_b/V_b$	easy, low voltage

VSiPMT

The VSiPMT follows a technology path **pioneered by HAPDs**

Both hybrid photodetectors, based on the combination of photocatdode and semicon. technologies. Anyway…

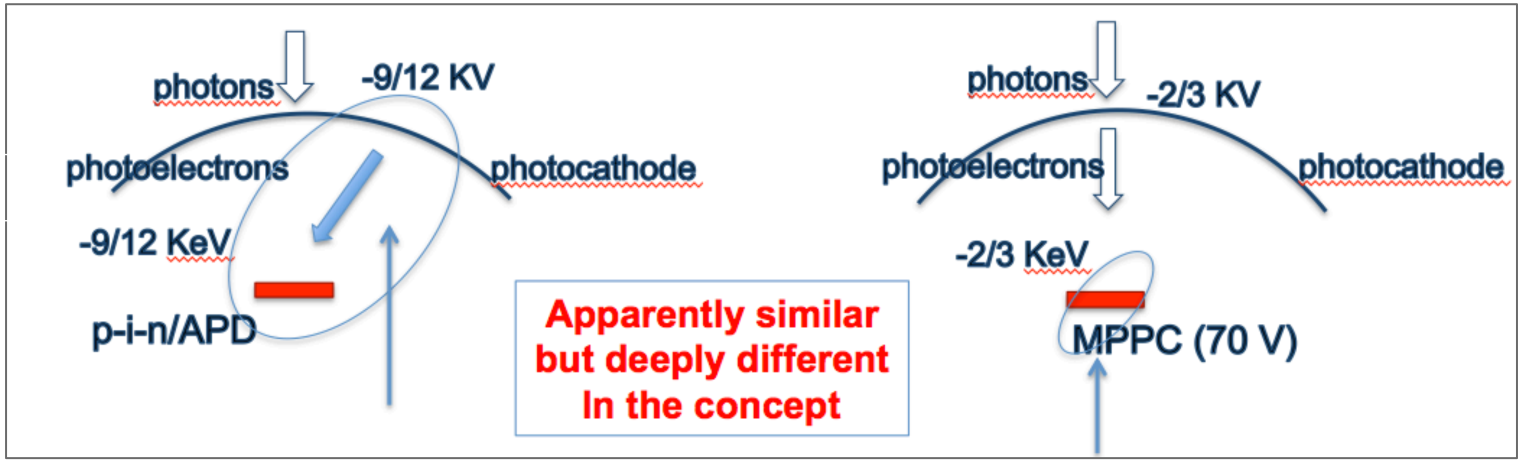
In a HAPD bombardment gain is required

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

In a VSiPMT the gain is made by the amplification stage only, as for **PMTs**.

VSiPMT advantages:
- **$G > 10^6$**: a factor 10 higher.
- **Low HV, no need for bombardment gain**
- **Low voltage Gain: easy to stabilize**
- **Normal insulation**

HAPD



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Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

ELSEVIER

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]
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...ngs

...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]
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Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

ELSEVIER

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VSiPMT for underwater neutrino telescopes

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

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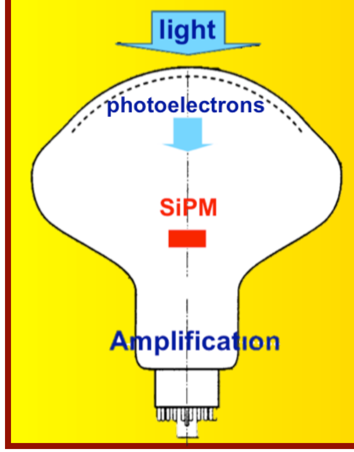
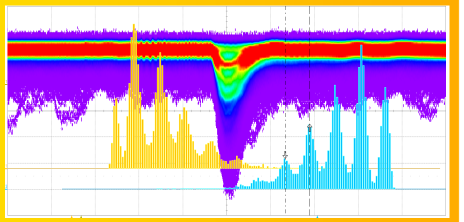
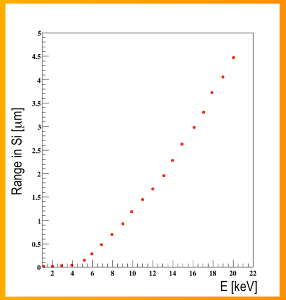
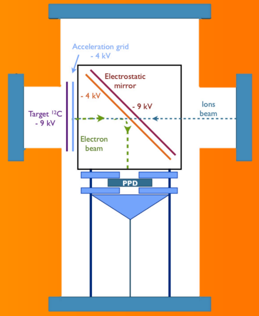
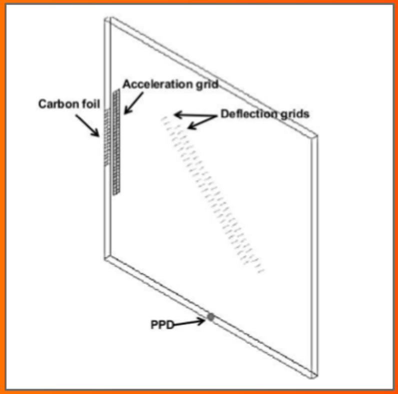
2014











2007

Physics Procedia

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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

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]
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Astroparticle Physics

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A new generation photodetector for astroparticle physics: The VSiPMT

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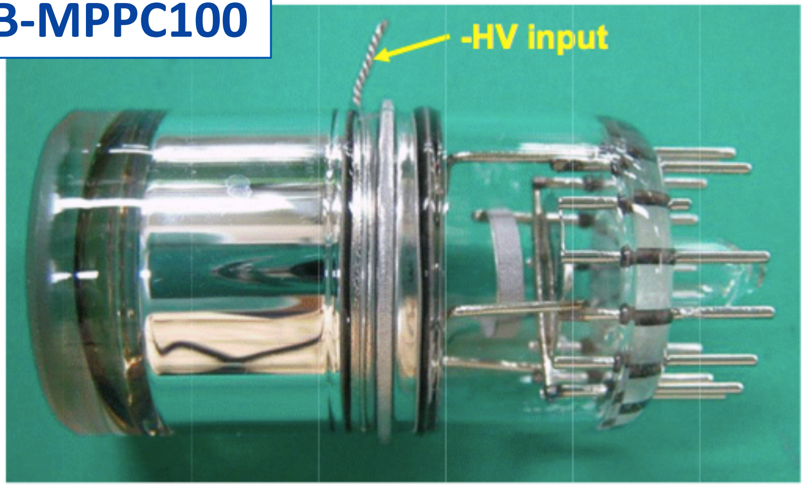
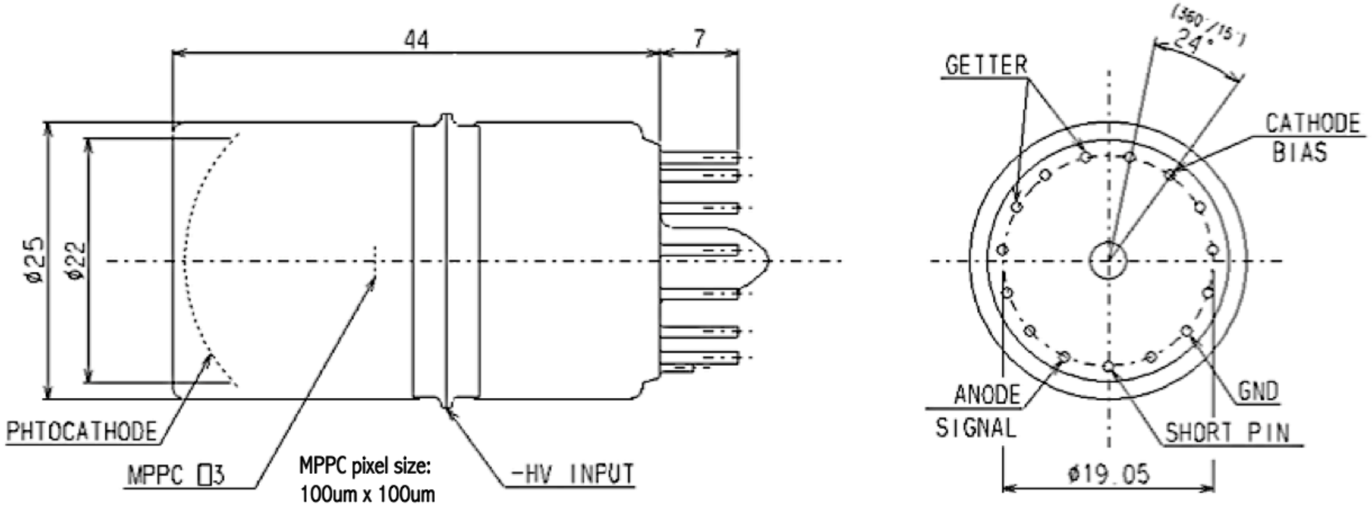
Today: second generation of VSiPMT prototypes

Side view

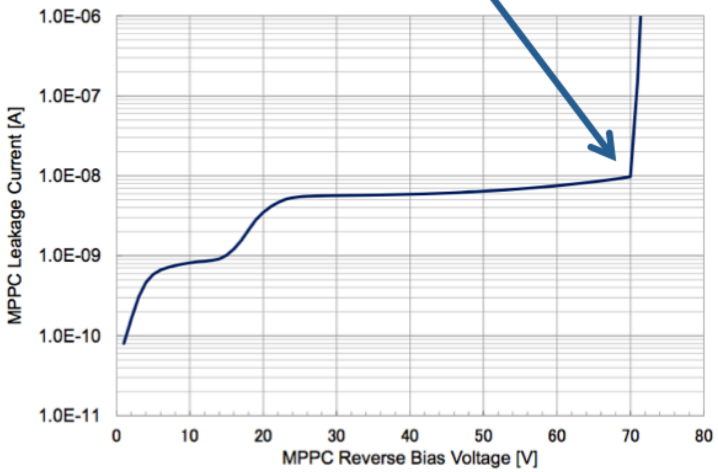
EB-MPPC100



Dimensional outlines



V_{bd} = 70V



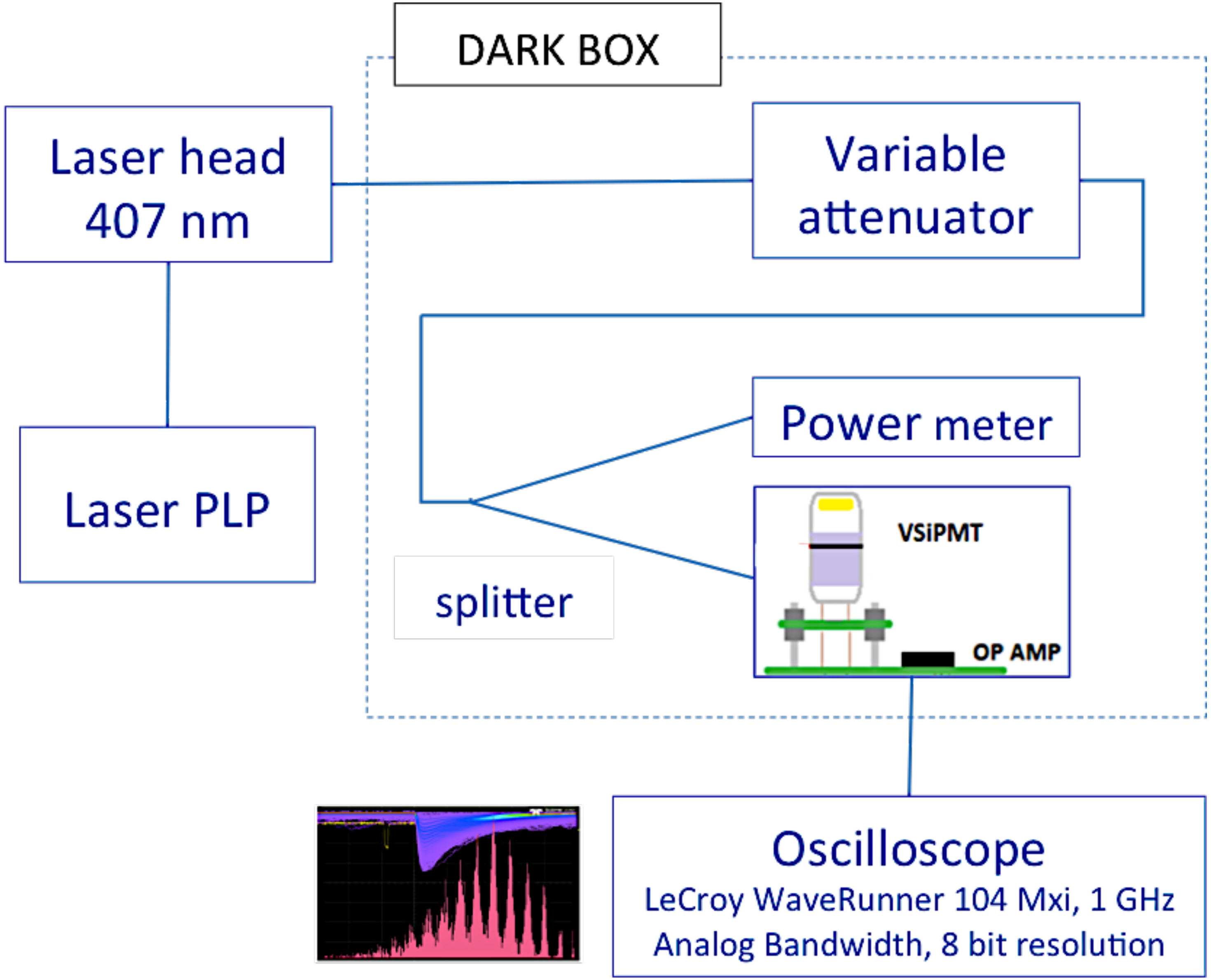
Specifications

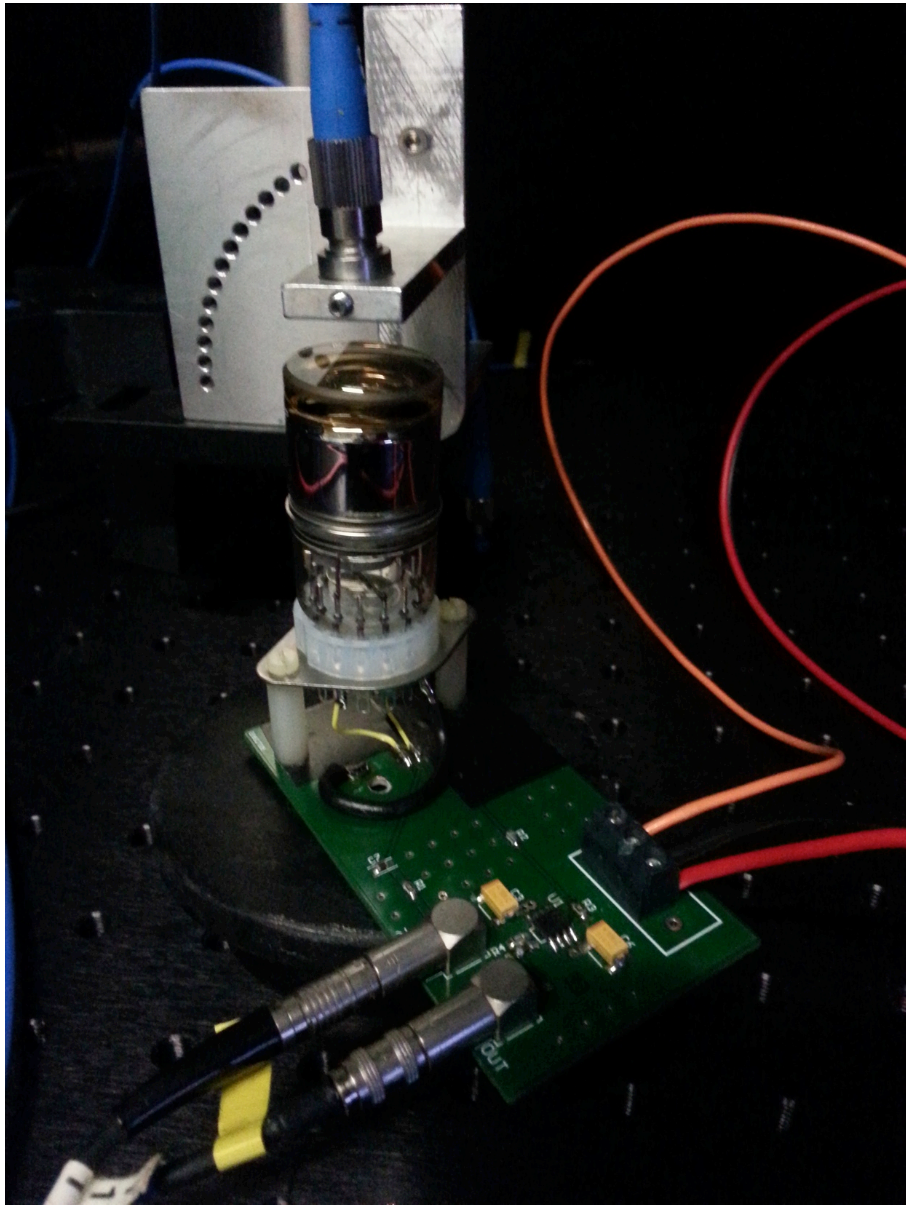
Parameter		Value	Unit
Spectral Response		200 to 650	nm
Photocathode	Material	Bialkali	-
	Effective Area	Φ22	mm
Window Material		Borosilicate Glass	-
Target		MPPC 3x3 mm	-

Maximum Ratings (Absolute Maximum Values)

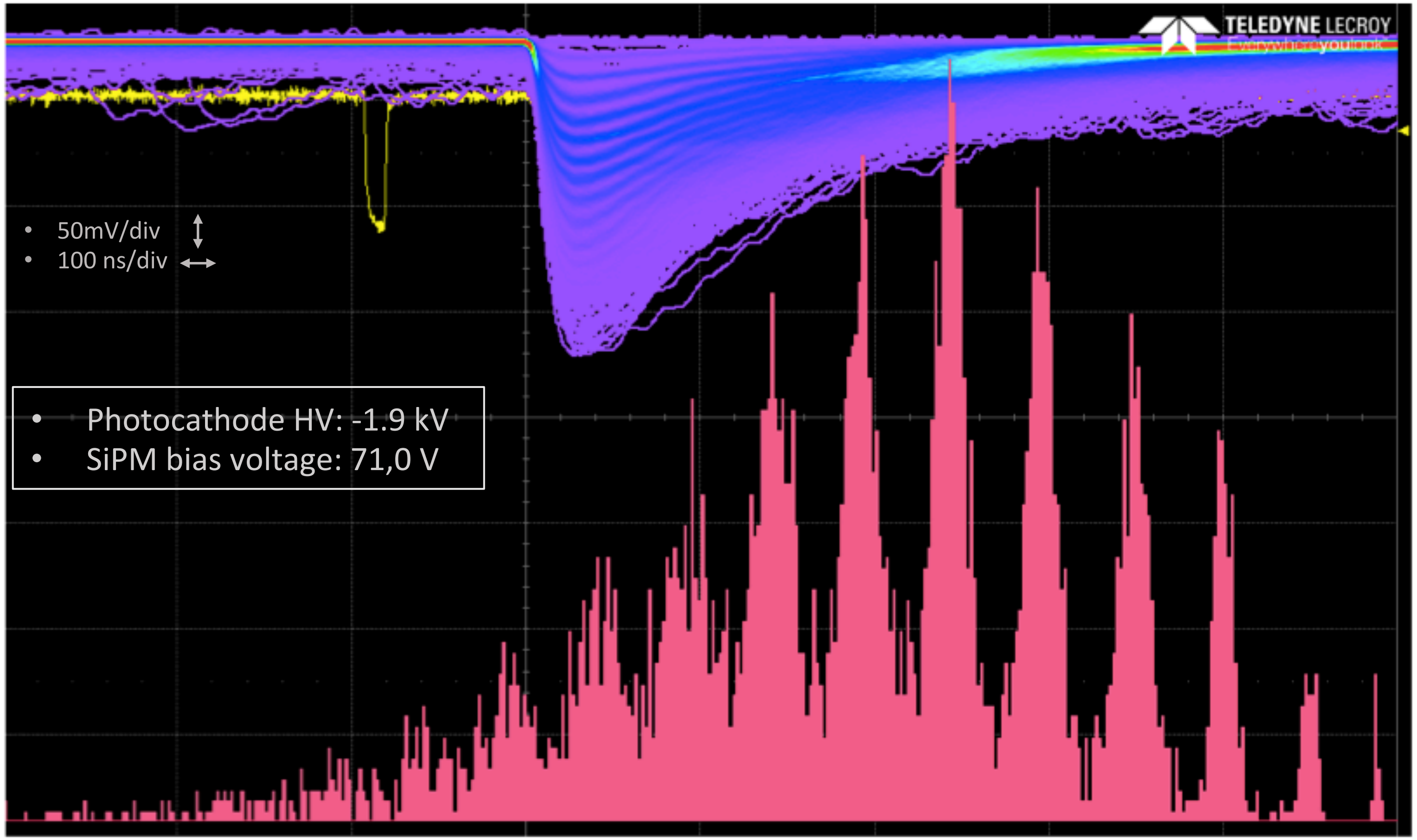
Parameter	Value	Unit
Photocathode Voltage	-2000	V dc
MPPC Reverse Bias Voltage at 25°C	+72.0	V dc

VSiPMT

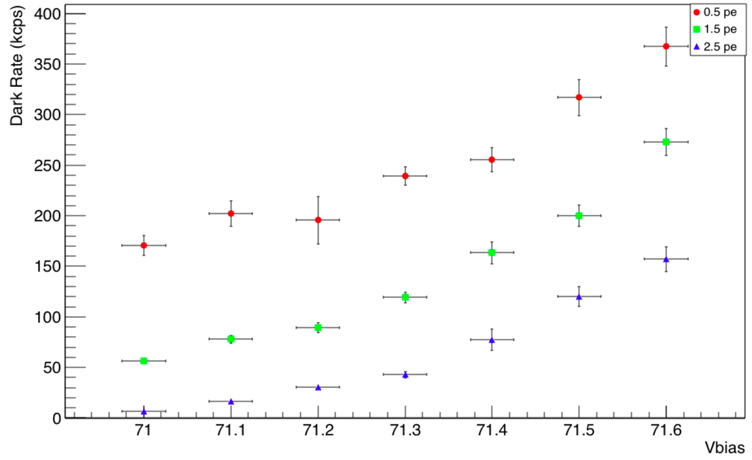

DARK BOX
Laser head
407 nm
Variable
attenuator
Laser PLP
Power meter
VSiPMT
splitter
OP AMP
Oscilloscope
LeCroy WaveRunner 104 Mxi, 1 GHz
Analog Bandwidth, 8 bit resolution



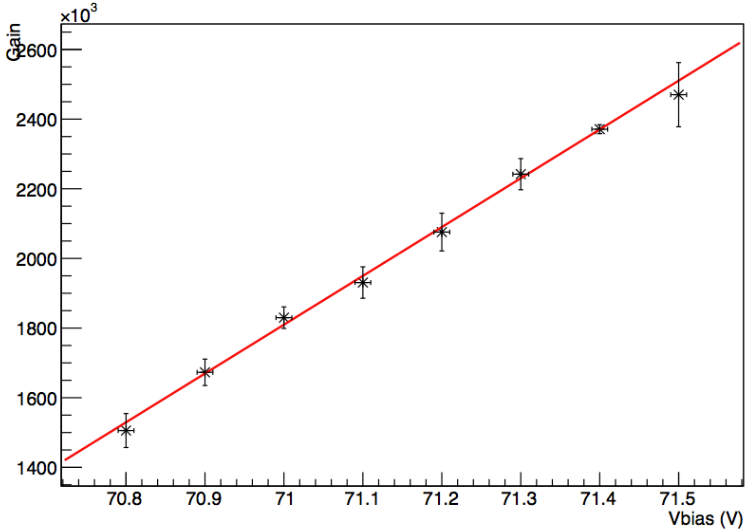
Photon spectra



Dark noise



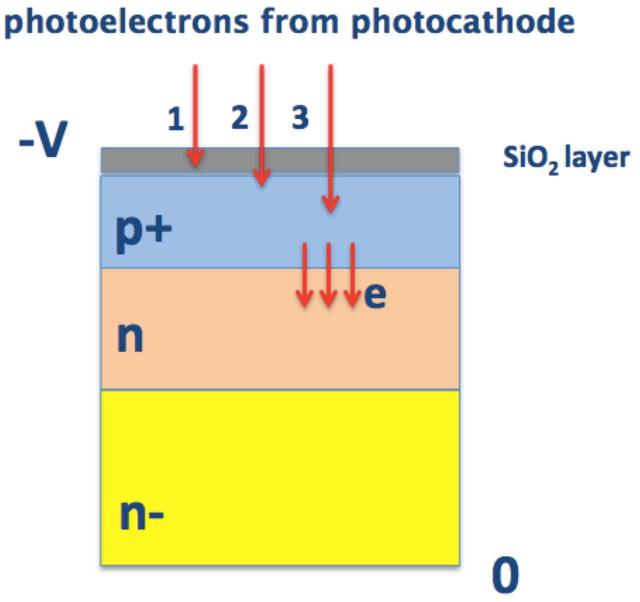
Gain



- **Excellent photon counting capability!**
- **Dark noise and gain exhibit no significative difference between HV on (-1.9kV) and HV off**

VSiPMT

Phenomenology



1. photoelectron with not enough energy to enter in depletion region (p^+n) and to trigger Geiger avalanche.
2. photoelectron with very marginal energy to enter in depletion region (p^+n) and to trigger Geiger avalanche.
3. photoelectron with enough energy to enter in depletion region (p^+n) and to trigger Geiger avalanche.

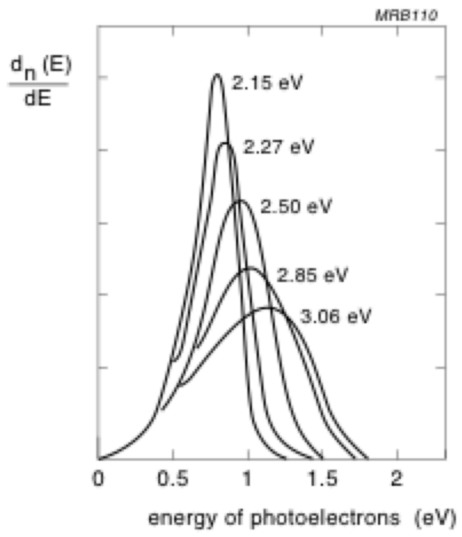
Definition

$$\varepsilon_{total}(PDE) = \varepsilon_{photocathode} \times \varepsilon_{fill\text{-}factor\text{-}SiPM} \times \varepsilon_{trigger} \times \varepsilon_{focusing}$$

- $\varepsilon_{photocathode}$ = photocathode efficiency (fixed number @fixed λ)
- $\varepsilon_{fill\text{-}factor\text{-}SiPM}$ = geometrical efficiency (fixed number)
- $\varepsilon_{trigger}$ = trigger efficiency (depends on the High Voltage)
- $\varepsilon_{focusing}$ = focusing efficiency

When the high voltage gives to all the photoelectrons enough energy to penetrate inside the p-region of the SiPM, the behaviour of $\varepsilon_{trigger}$ as a function of high voltage becomes flat (plateau $\varepsilon_{trigger}$ =1) and the total efficiency will be a fixed number (@fixed λ).

SiPM photoelectron trigger efficiency

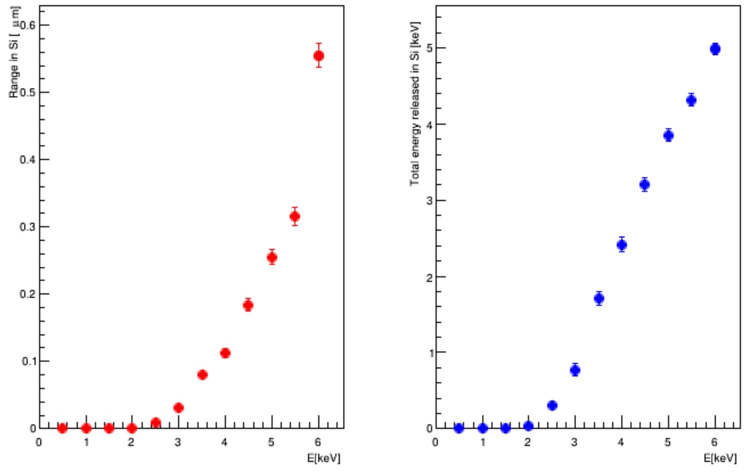


Simulations

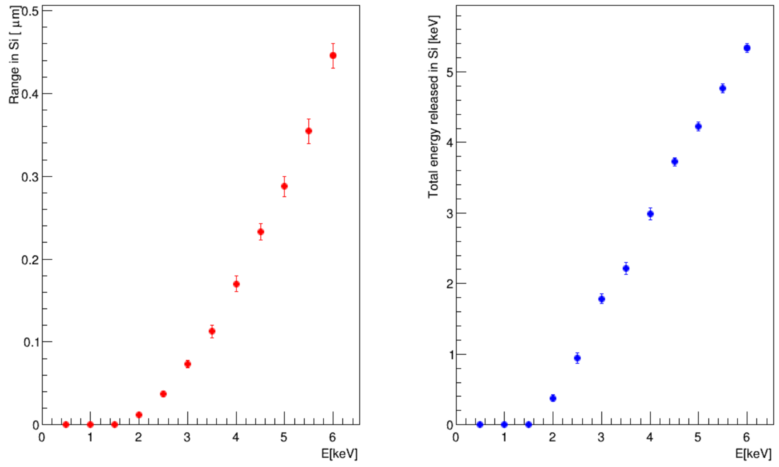
Range and **energy deposit** of the photoelectrons in the SiPM as a function of SiO_2 passivation layer thickness have been simulated (range: 150 to 15nm).

Assumption: the average energy of photoelectrons outcoming from the photocathode is 1 eV.

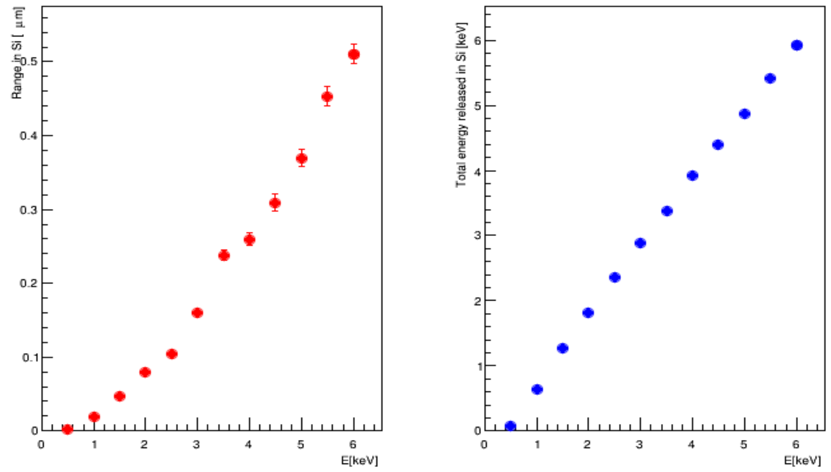
150 nm passivation layer



100 nm passivation layer



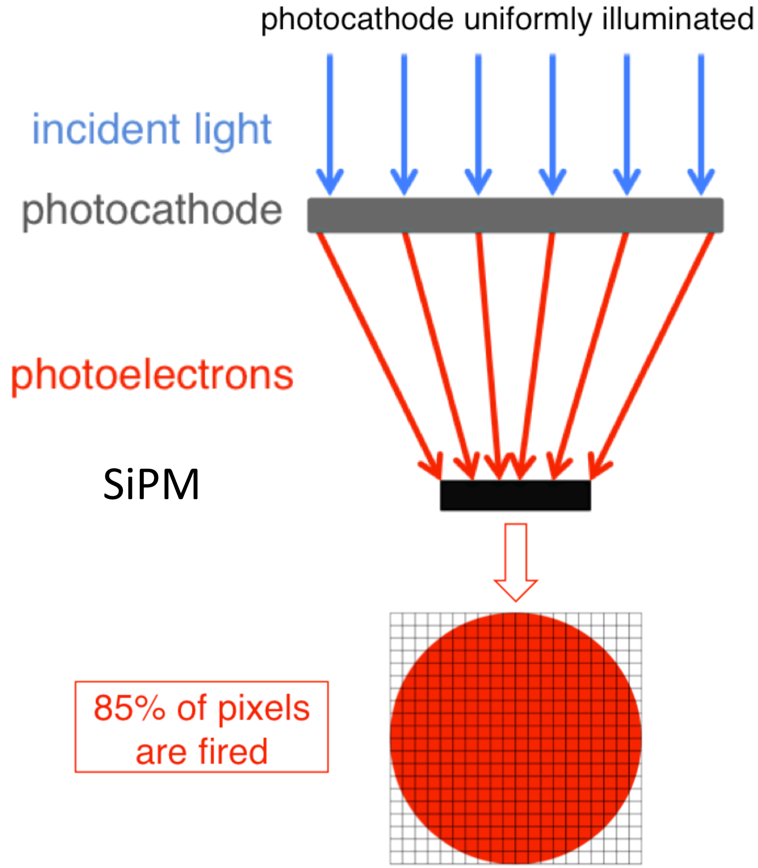
15 nm passivation layer



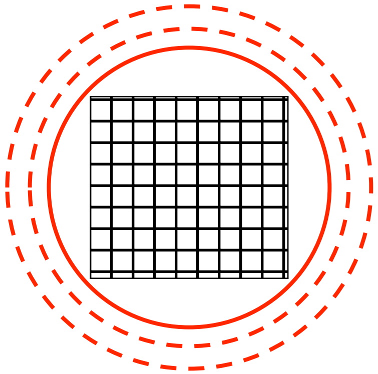
Simulations show that the HV to have $\varepsilon_{trigger}$ =1 rises with the passivation layer thickness.

Focusing efficiency (and linearity, as well) are maximized if in a condition of uniformly illuminated photocathode all the SiPM pixels are hit by the accelerated photoelectrons.

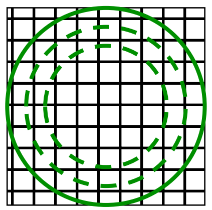
The ideal case:
focusing efficiency = 1 , optimized linearity



- If the photoelectron spot is larger than the SiPM size, some photoelectron will systematically miss the target ➔ focusing efficiency < 1



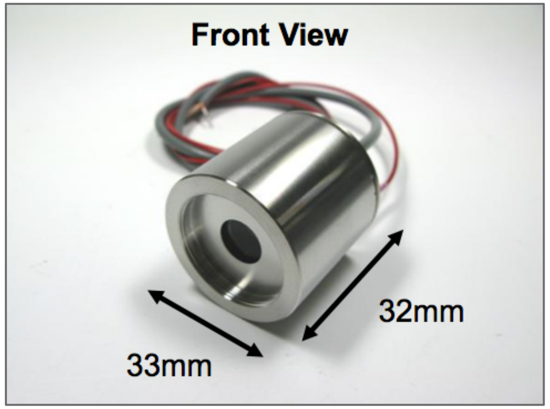
- On the other side, if the photoelectron beam is too much "squeezed", the focusing efficiency will still be 1 but the device will lose linearity

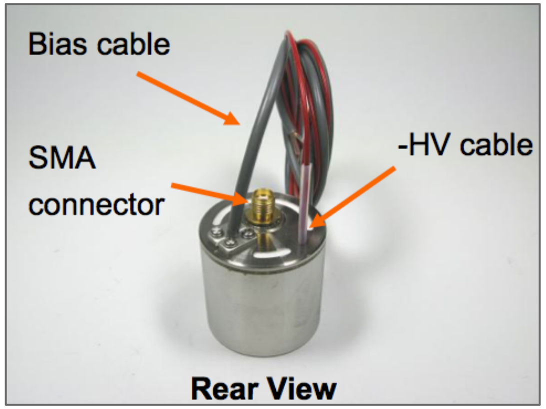


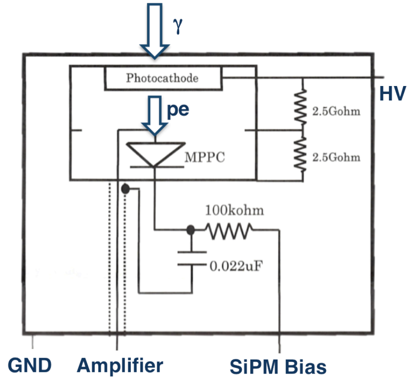
Even in the ideal case, the SiPM pixels that are not involved in the detection process are still contributing to dark noise!

VSiPMT

HAMAMATSU
PHOTON IS OUR BUSINESS

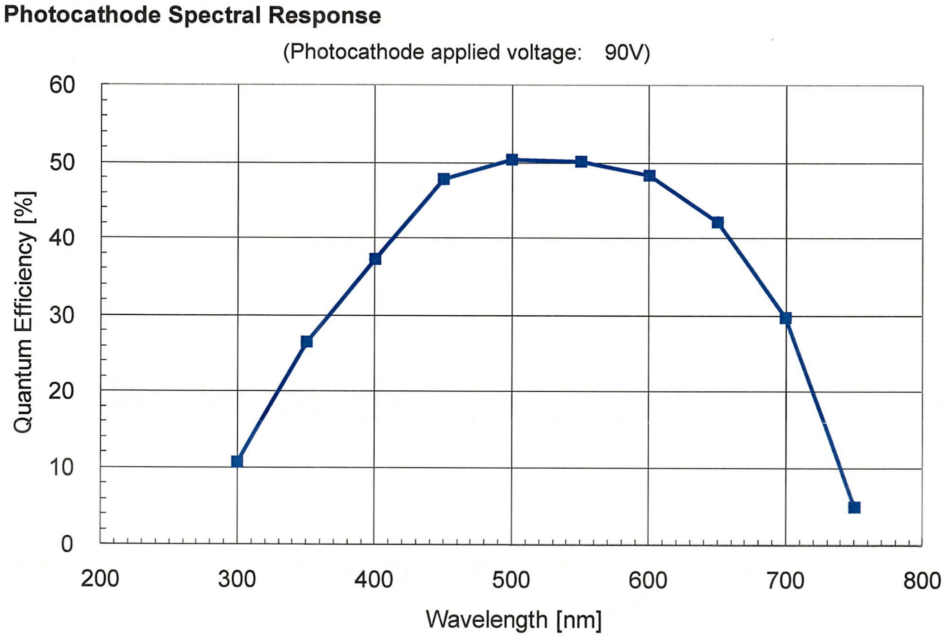


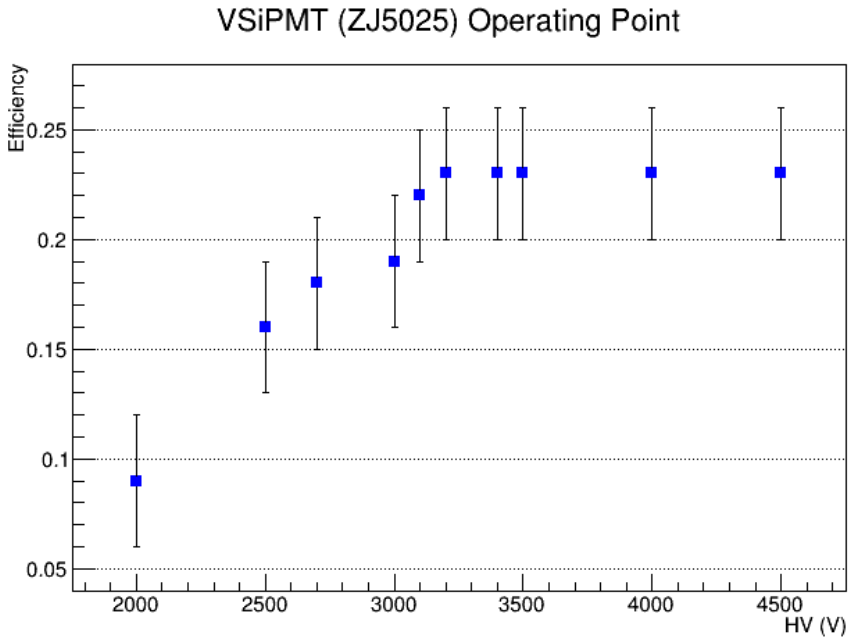




7x7 mm^2 Borosilicate glass entrance window
3 mm diameter GaAsP photocathode
2 protoypes:
MPPC 1 mm^2 / 50 mm / 400 cells
MPPC 1 mm^2 /100 mm / 100 cells

Special non-windowed series for e optimization.
Low photocathode voltage (-2,5/3 kV expected).





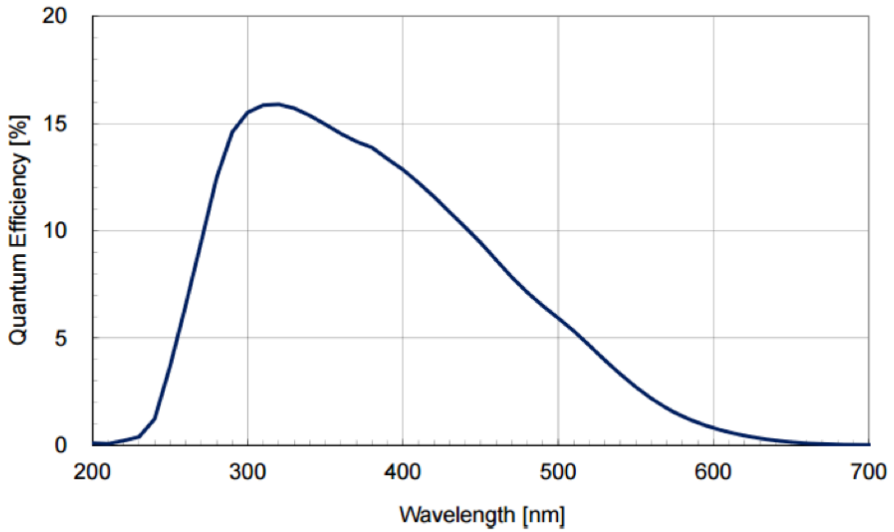
$\varepsilon = \varepsilon_{\text{photocathode}} \times \varepsilon_{\text{SiPM (50)}}$

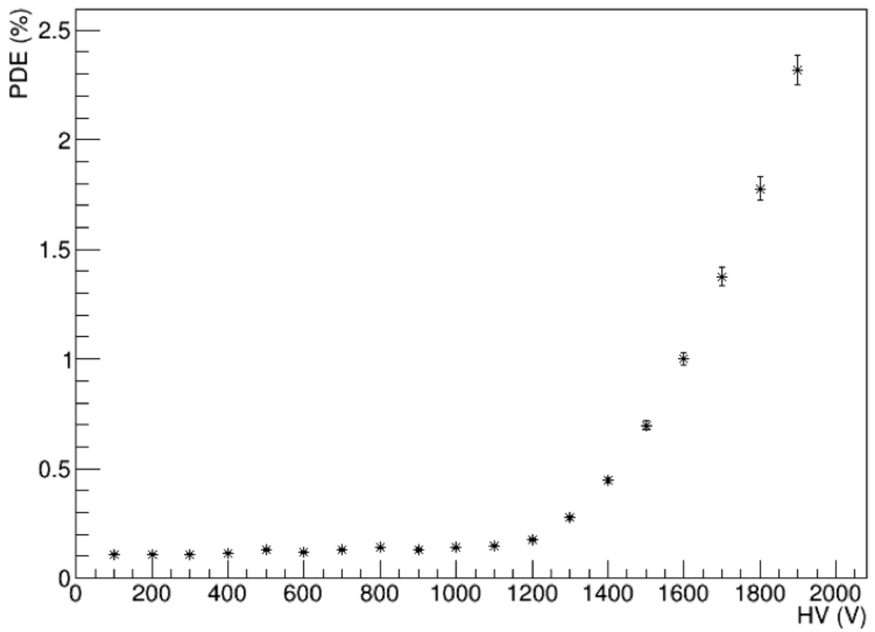
0,23 ≈ 0,38 x 0,61 ↘

Fill factor

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

VSiPMT





Assuming a plateau region working regime and an optimized focusing

$$\varepsilon_{total}(PDE) = \varepsilon_{photocathode} \times \varepsilon_{fill\text{-}factor\text{-}SiPM} \times \varepsilon_{trigger} \times \varepsilon_{focusing}$$

$$0{,}09 = 0{,}12 \times 0{,}78 \times 1 \times 1$$

- The maximum PDE measured for the prototype is ≈ 2%
- The plateau region is not reached!

Reason: maximum rating for PMT HV is -2kV! (insulation issue)

$$\varepsilon_{total}(PDE) = \varepsilon_{photocathode} \times \varepsilon_{fill\text{-}factor\text{-}SiPM} \times \varepsilon_{trigger} \times \varepsilon_{focusing}$$

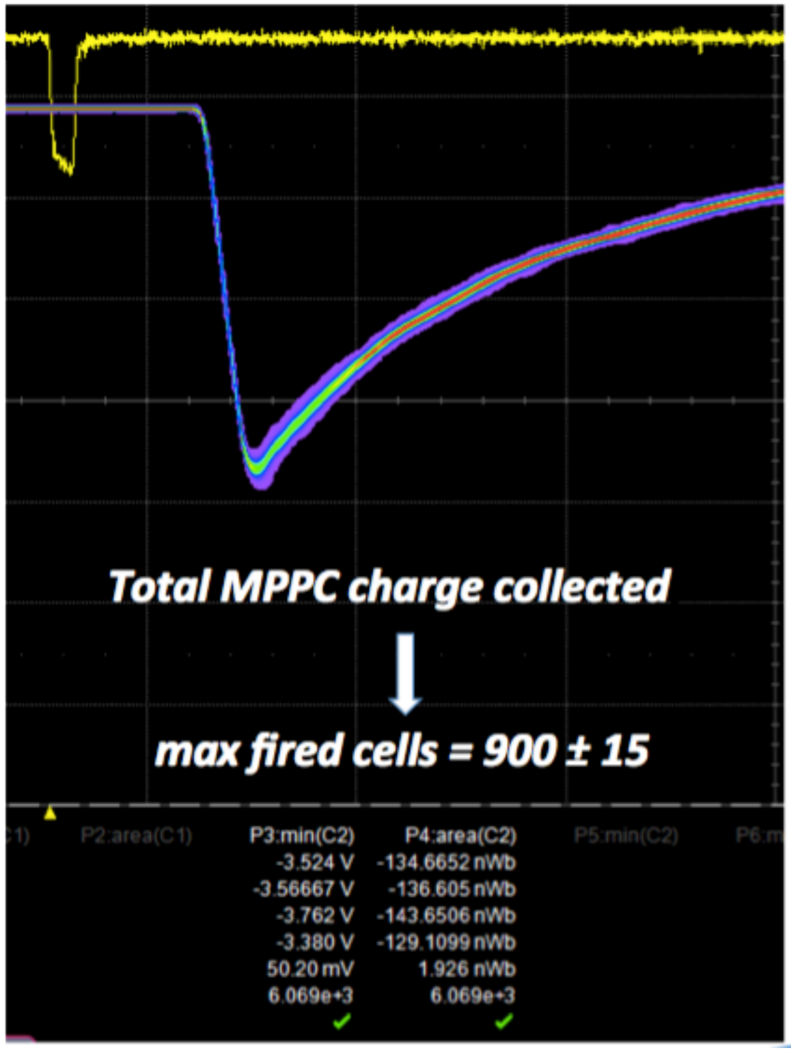
$$0{,}02 = 0{,}12 \times 0{,}78 \times ? \times ?$$

No clue about the characteristics of the SiPM inside the prototype.

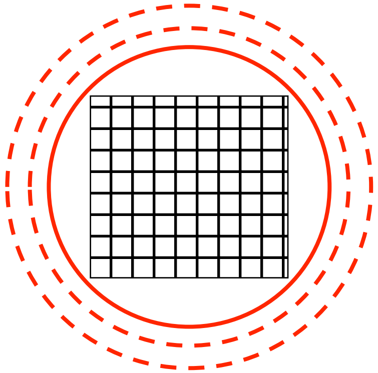
Measurement of focusing efficiency is done as follows:

- the photocathode is illuminated with high photon number.
- Under this condition, the SiPM is saturated.
- Number of maximum fired cells is calculated as:

$$\textit{max fired cells} = \frac{Q\ (\textit{total MPPC charge collected})}{Q\ (\textit{single MPPC charge})}$$



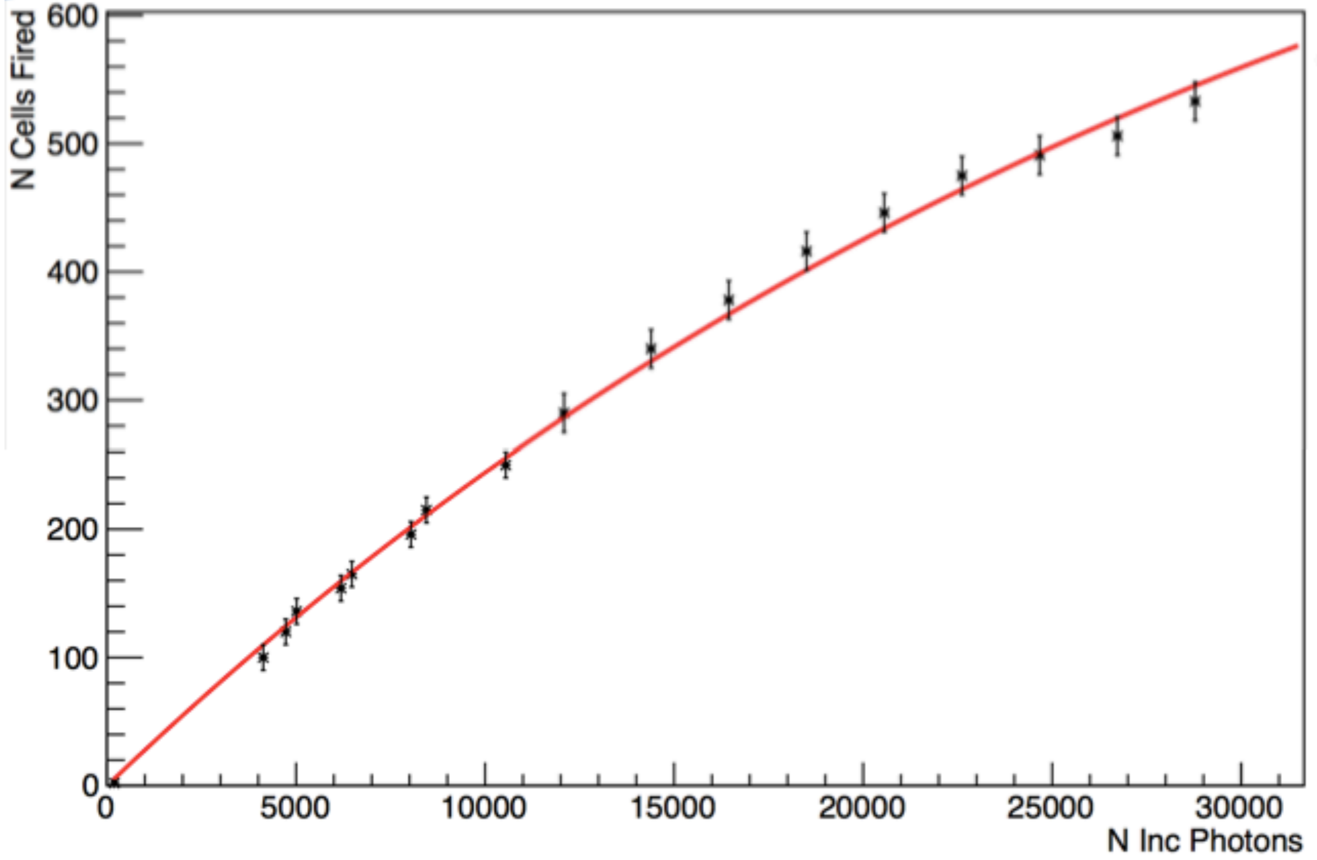
Results: **max fired cells = 900 ± 15**
over a total MPPC cells = 900



Radius of photoelectron focusing area circumscribes the MPPC square shape or is outside the square. The system is UNDERFOCUSED.
Not possible to say how much! $\varepsilon_{focusing} < 1$

The linearity curve of a SiPM follows the well-known formula:

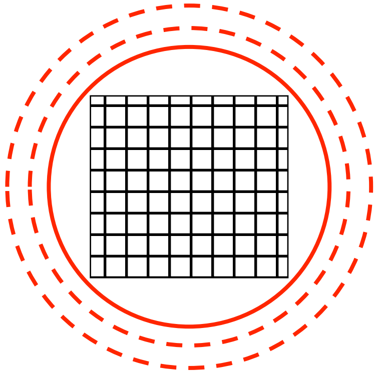
$$\mathrm{Nfired} = \mathrm{Ntotal} \times \left[1 - \exp\left(\frac{-\mathrm{Nphoton} \times \mathrm{PDE}}{\mathrm{Ntotal}}\right)\right]$$



From the linear fit:

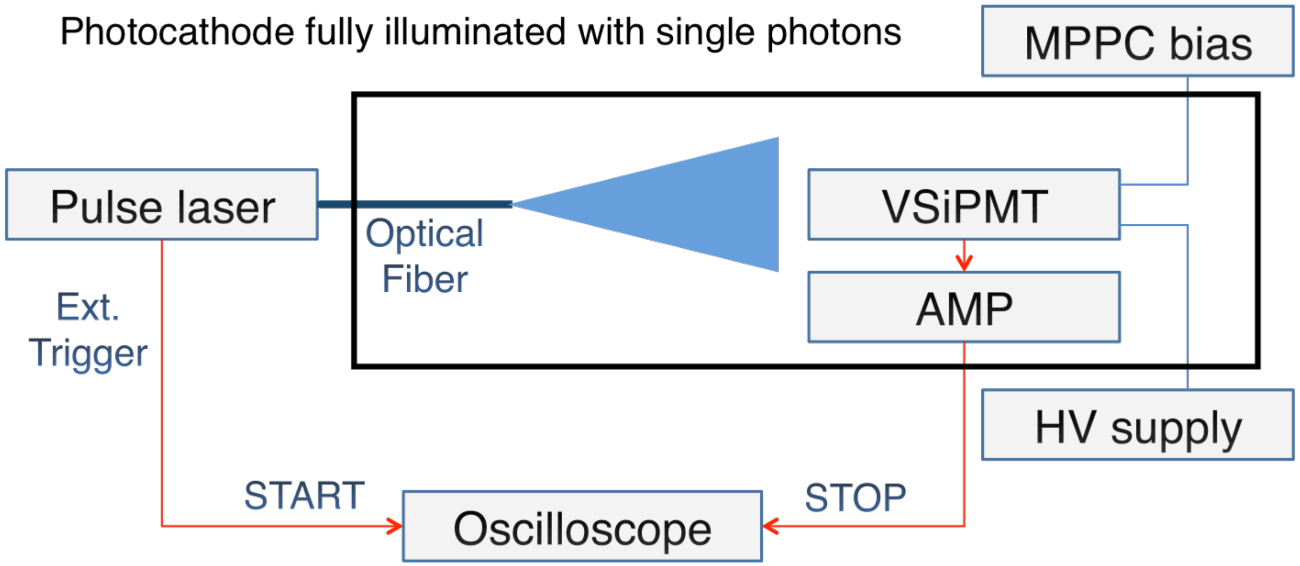
- **Ntotal (max fired cells) = (9.40 ± 1.0) x 10^2**
- **PDE = (2.77 ± 0.12) %**

in quite good agreement with the measured PDE

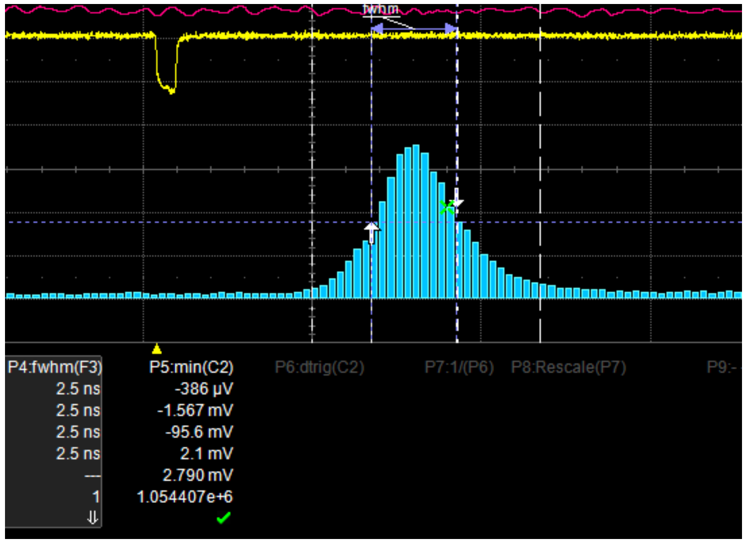


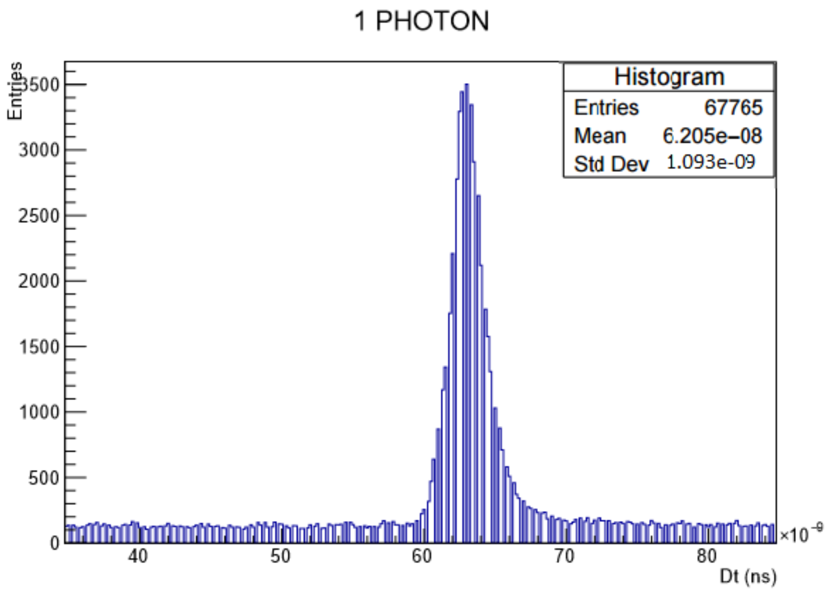
UNDERFOCUSED system
($\varepsilon_{focusing} < 1$)
A well-focused devise would have Ntotal (max fired cells) ≈ 700

VSiPMT



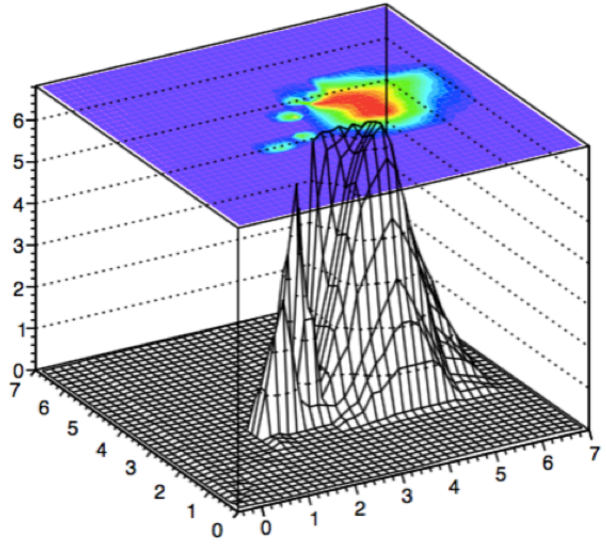
- The output from the VSiPMT is fed as the stop signal via a discriminator;
- We measure the time interval between the "start" and "stop" signals.

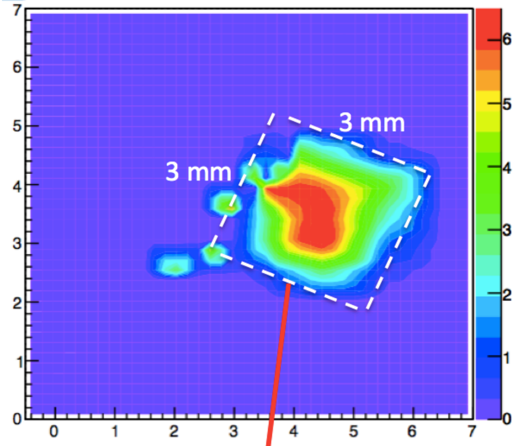




TTS = 2.58 ns (FWHM)

VSiPMT

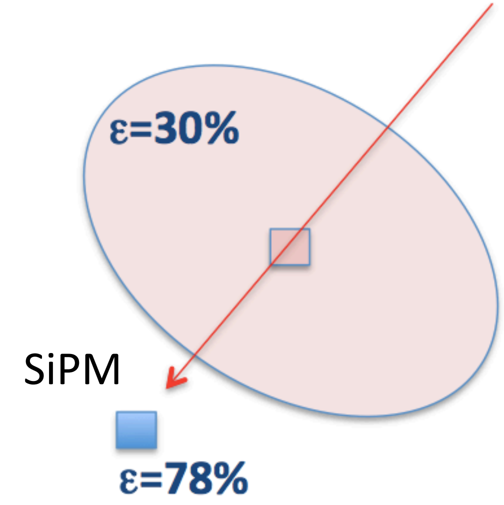


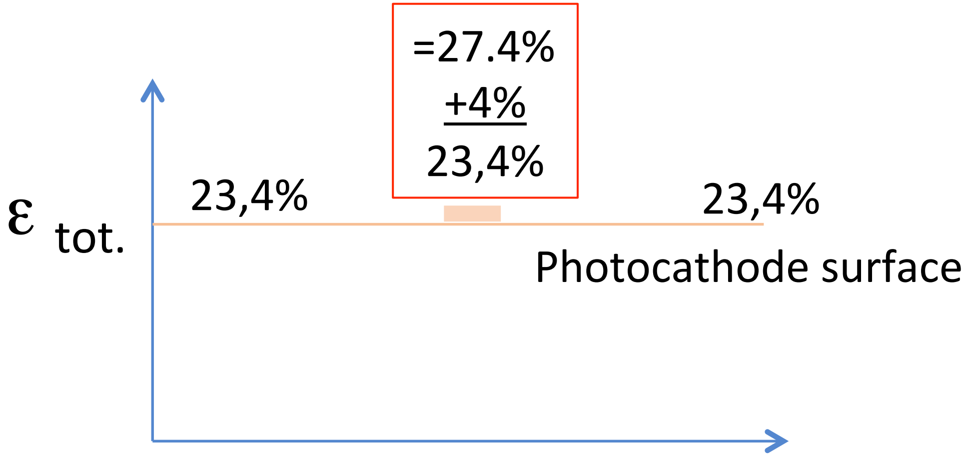


projection of 3x3 the SiPM on the photocathode obtained by direct photon detection when H.V. is off

4% of over-efficiency for photon transparency only at center of photocathode. Negligible effect in all usual photodetection applications

Projection:
optimized device (photocathode QE ≈ 30%, $\varepsilon_{focusing}$=1)





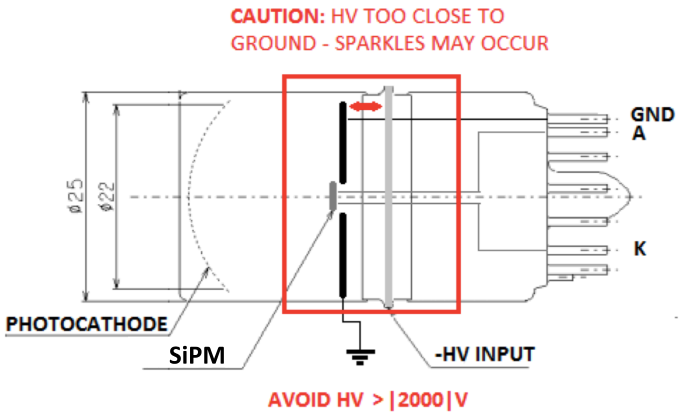
Quantitative effect:
+4% of over-efficiency in 1,7% of total 1 inch photocathode surface area
⬇
2 inch photocathode: less and less effect

VSiPMT

The aim of the EB-MPPC100 1INCH prototype is the proof of feasibility of an inch-size VSiPMT. Results are excellent!

The device exhibits outstanding features:

- Excellent photon counting capability
- Large sensitive surface (first inch-size prototype)
- Challenging time performances
- Major limit: High Voltage limited to 2000 Volt.
  The drawback is the low efficiency. The energy inferred by HV to the photoelectrons is not enough to overcome the SiPM entrance window and to penetrate in the p-region of the SiPM (absence of a plateau in the efficiency plot). Consequently, also stability is affected.
- Also the underfocusing of the photoelectrons could be improved by a better spatial positioning of the SiPM. Undramatic: easy to solve (not optimized device).



An optimized insulation or an improved design can help to bring the HV at the correct point, thus allowing to work in the PDE plateau region and so at the maximum efficiency.

Ready for the next step!