Characterization of Hamamatsu MPPC for use in liquid xenon scintillation detectors

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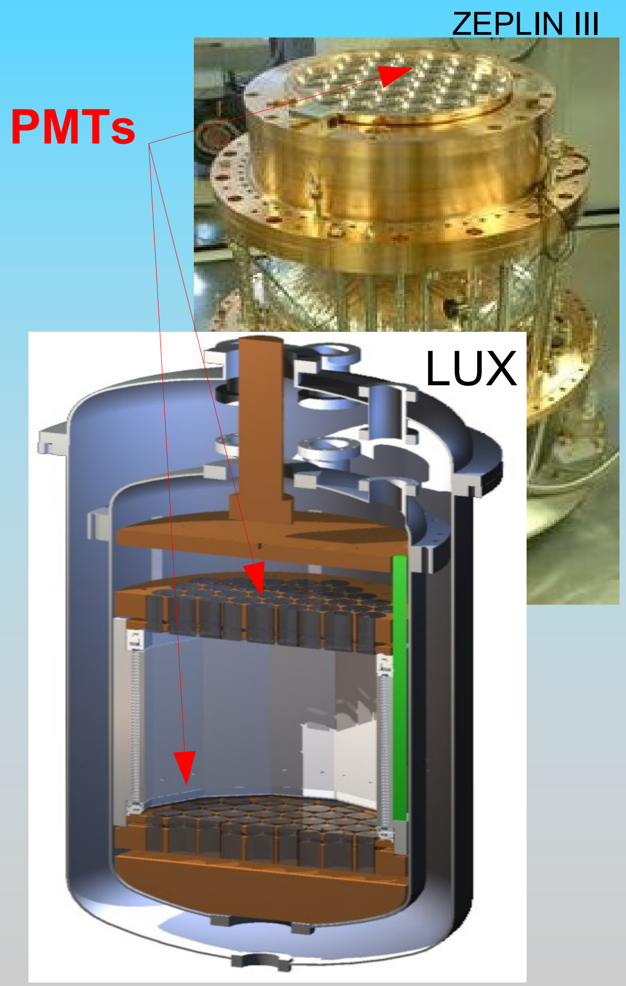
Motivation

Liquid xenon (LXe) is a very good medium for detectors of ionising radiation:

- Large atomic number (A = 131 $g.mol^{-1}$);
- High density (ρ = 2.9 $g.cm^{-3}$);
- High light output (W_S = 23 eV for 1 MeV e^-);
- Fast decay time (2.2, 27 and 45 ns);

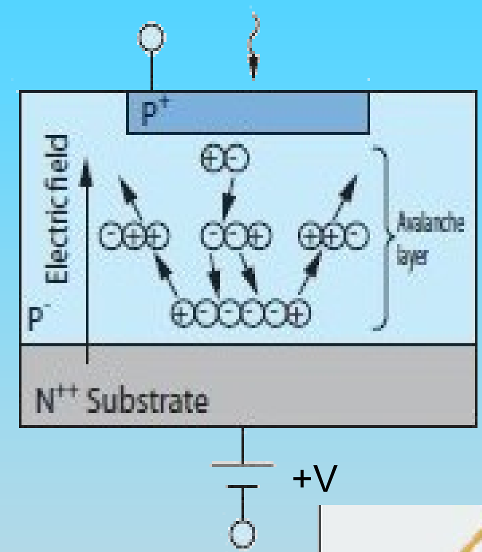
The LXe scintillation (175 nm) is usually detected by photomultiplier tubes (PMTs). However, for some applications (e.g. Dark Matter search), PMTs are one of the dominant sources of background. This points to the need of alternative, more radio-pure readout techniques:

- Micro-structures devices: Micromegas, GEMs;
- Solid state devices: APDs, **SiPMs**;
- ...



SiPM in LXe: Pro & Contra

A SiPM is an array of **avalanche photodiodes** (pixels) working Independently in **Geiger mode**. The device output signal is the linear sum of all pixels.

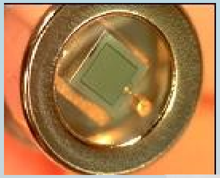


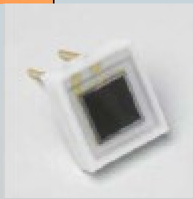
Advantages:

- ✓ High gain;
- ✓ Good single photoelectron resolution;
- ✓ Low noise at low temperatures;
- ✓ High radio-purity and low mass;
- ✓ Insensitive to external electric fields;

Disadvantages:

- ✗ Low linearity range (dependent on the number of pixels);
- ✗ Crosstalk and afterpulsing (but devices are evolving...);
- ✗ Small area (growing and arrays are already available...);



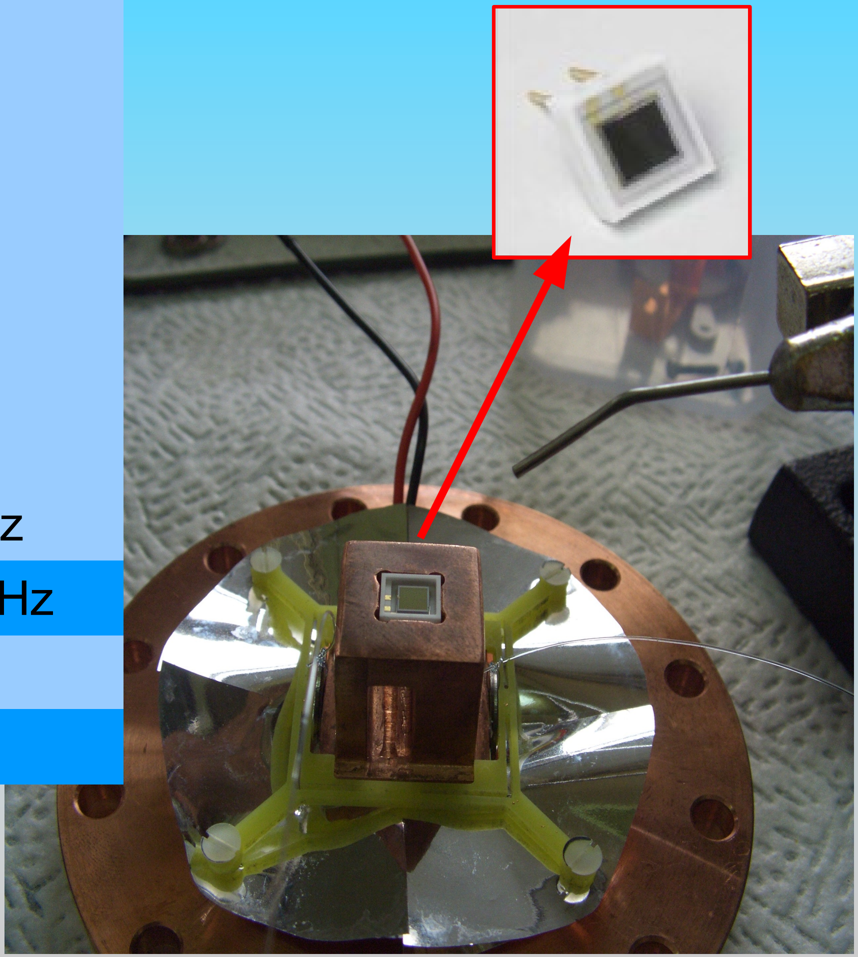


Unknowns:

- QE/PDE @ 175 nm?
- Robustness (cooling/warming, pressure variations)
- Xe purity impact

Windowless SiPM

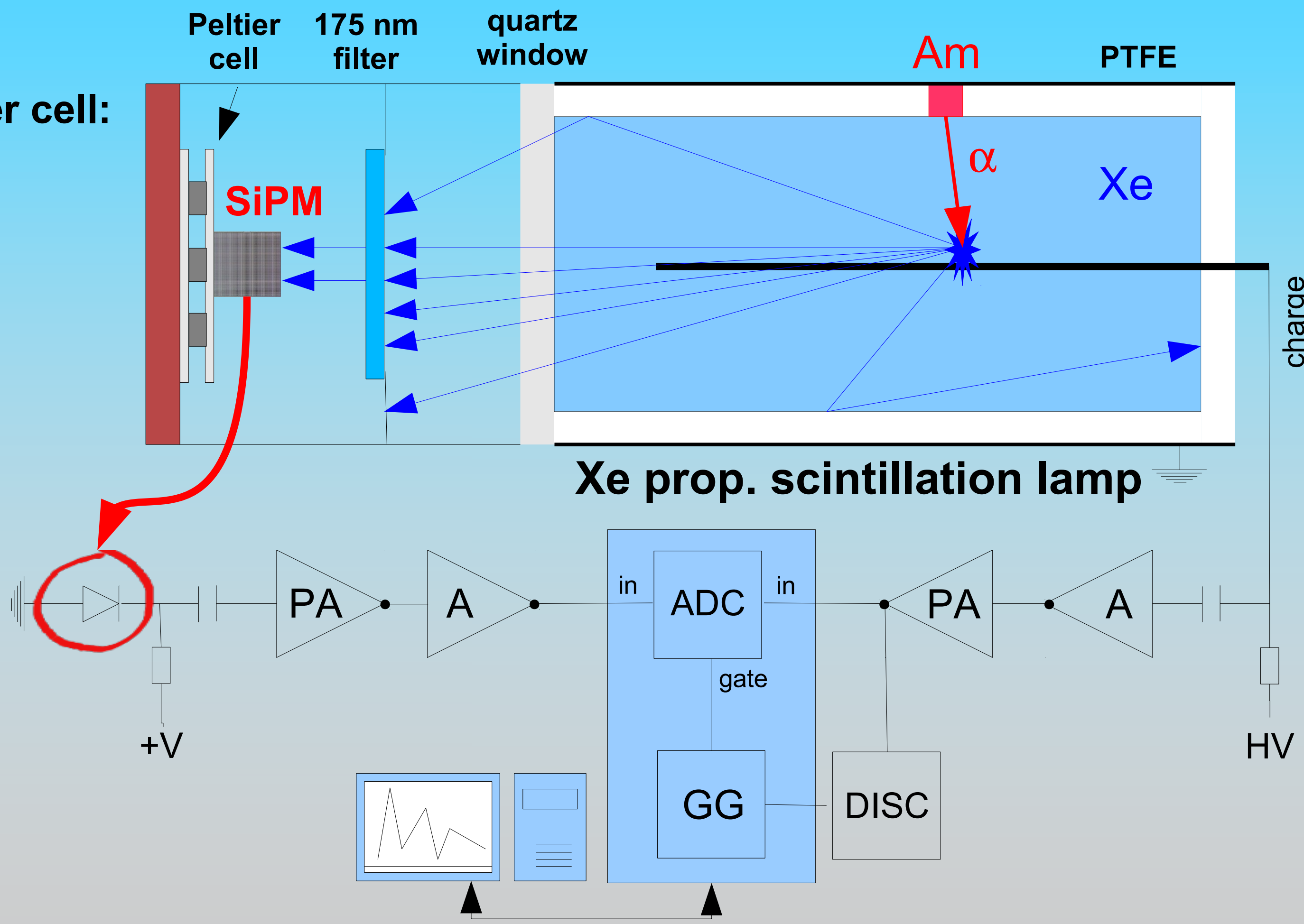
Manufacturer	Hamamatsu	
Type	S10362-33-100X	
Number of pixels	30x30	
Effective active area	3x3 mm	
Fill factor	78.5 %	
Peak sensitivity	440 nm	
Spectral response range	320-900 nm	
Dark counts	room	~2 MHz
	-35 °C	12.7 KHz
Time resolution (1 pe)	0.6 ns (FWHM)	
Gain	2×10^6	



QE measurement: SiPM

Cooling with a Peltier cell:
- Single stage: 17W;
- ΔT = -62 ºC (2.5W);
- Prec: 0.02 ºC rms.

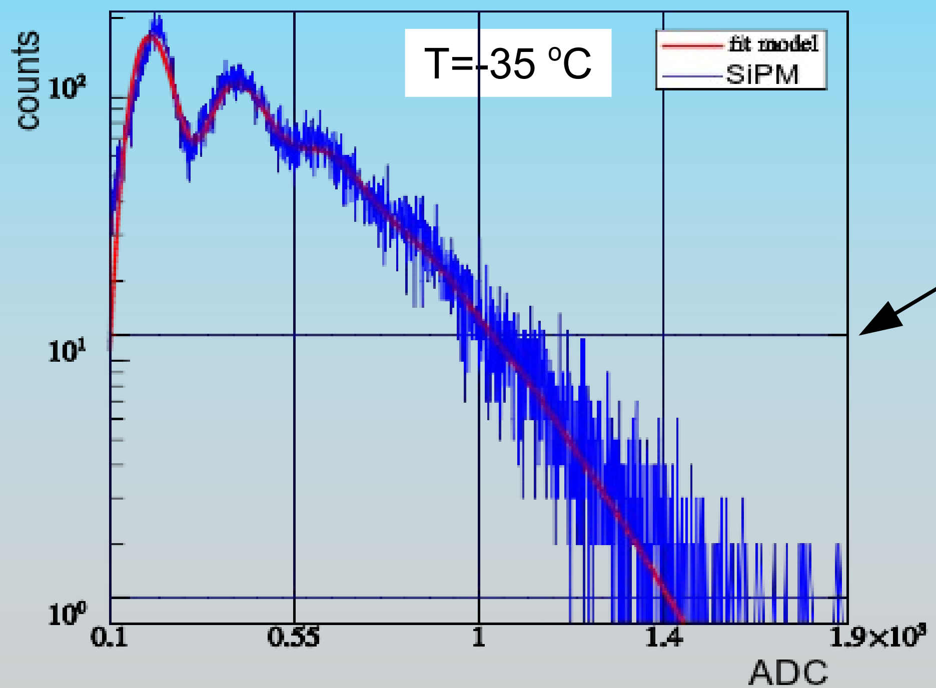
Signal formating:
- Shaping: 2 μs;
- Gate: 6 μs.

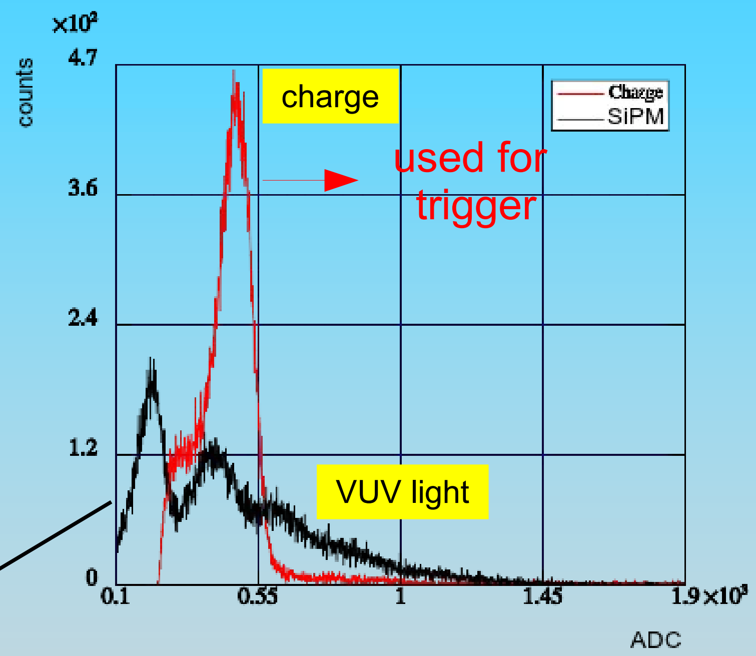


SiPM spectrum

$N_{photoelectron}$ [VUV light] = 2.1 (stat/fit)

$N_{electron}$ [charge] = 84,5 x 10^3



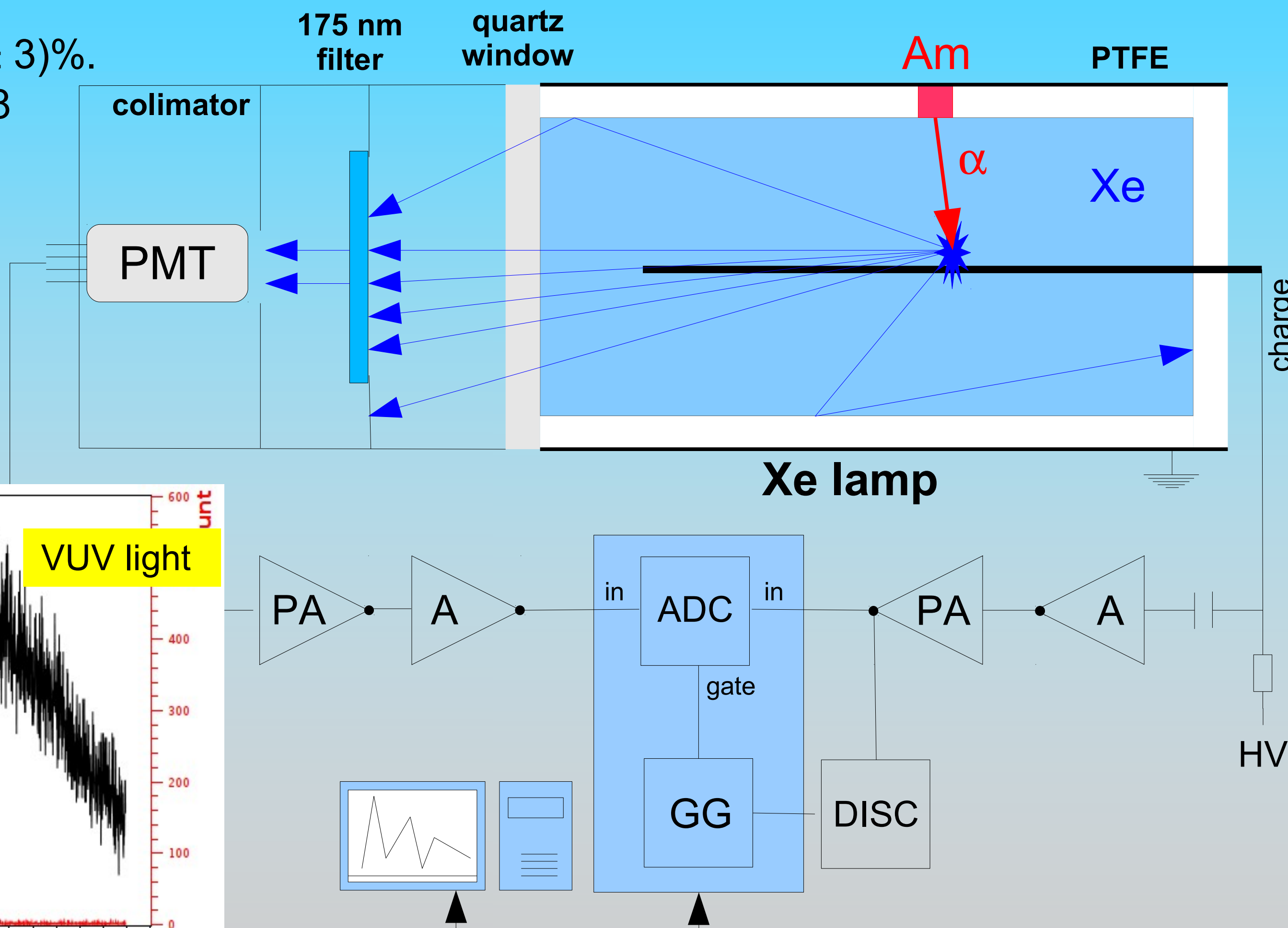


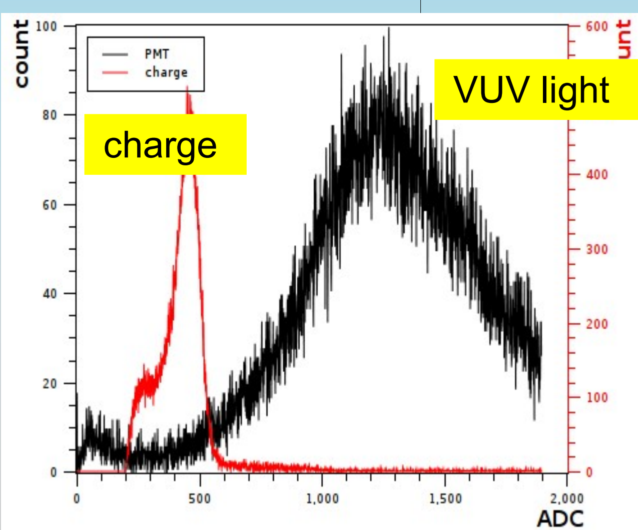
Gain = $2x10^6$
Shaping = 2 μs; Gate = 6 μs
Trigger = charge (Xe lamp)

QE measurement: PMT

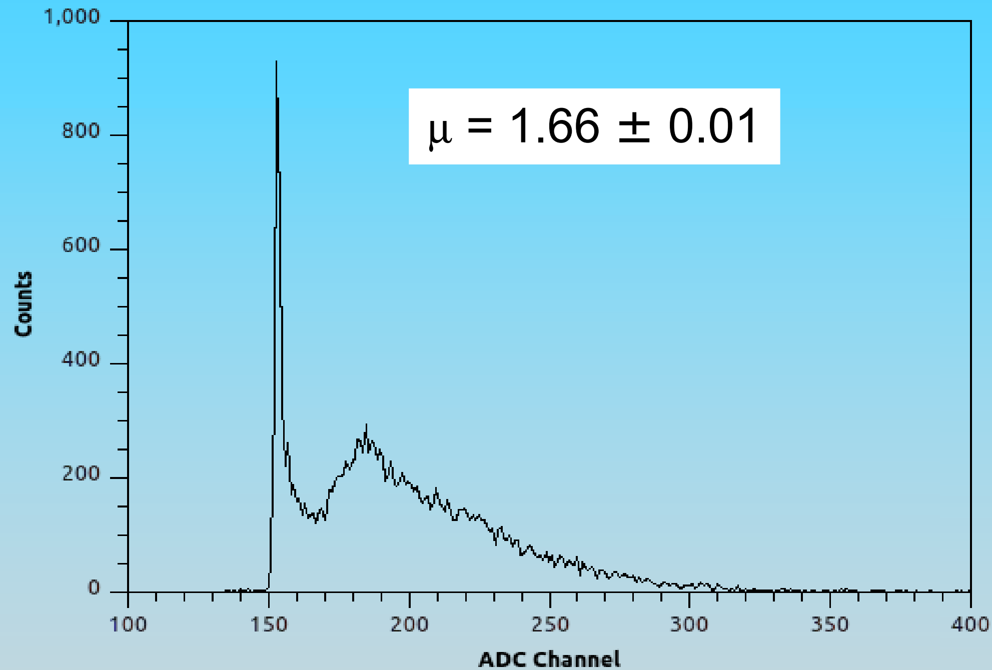
Hamamatsu R1668:
- QE (175 nm) ~ (20 ± 3)%.
- e^- collection eff. ≅ 0.8

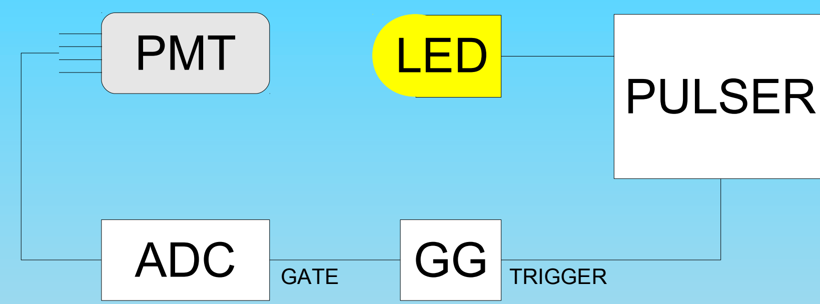
Signal formating:
- Shaping: 2 μs;
- Gate: 6 μs.

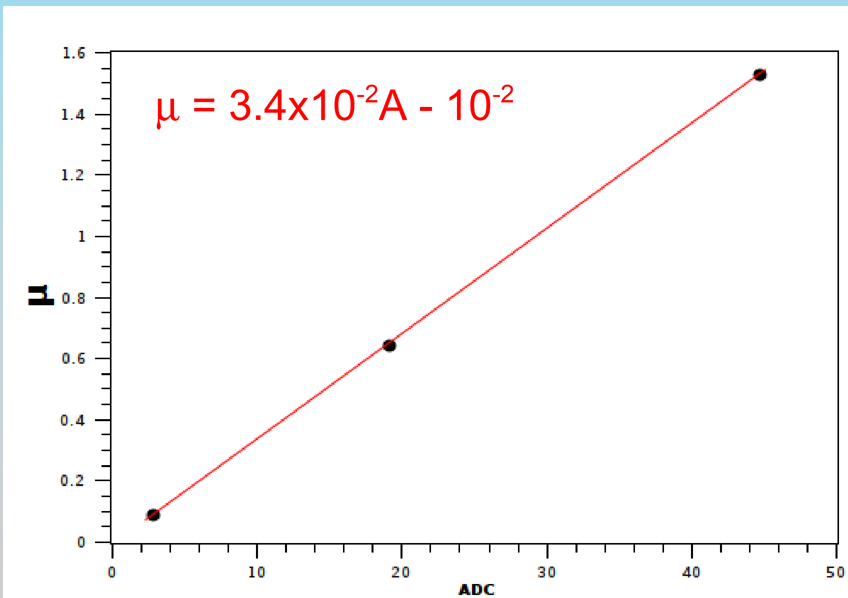




PMT: SER / calibration







$$\frac{P(\mu,0)=N_0}{\sum_{k=0}^{+\infty} P(\mu,k)=N}=e^{-\mu}\Rightarrow\mu=-\ln\left(\frac{N_0}{N}\right)$$

Where P(μ,k) is the Poisson distribution.

SiPM PDE & QE estimate

λ=175 nm, T=-35°C

	N_{phe}	QE	PDE
PMT	20.4	20%	
SiPM	2.1	**2.6%**	**2.0%**

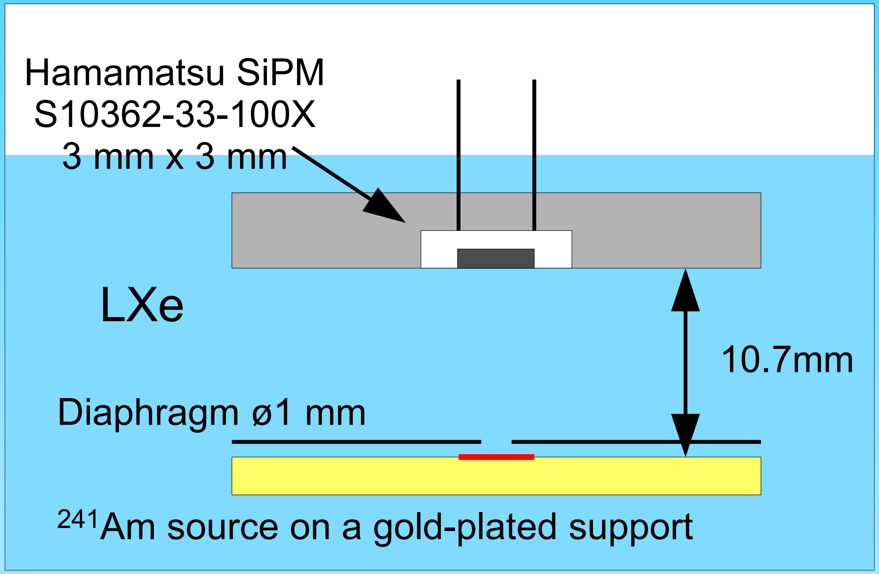
What about liquid xenon?

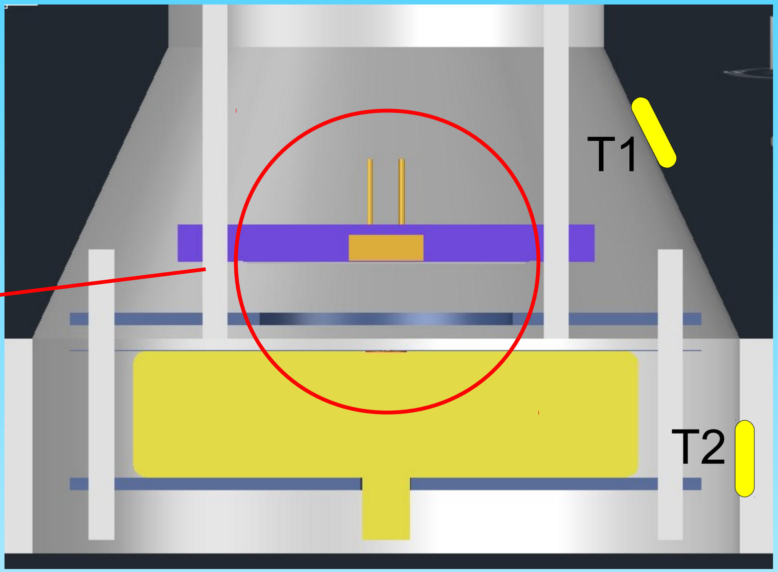
Aprile *et al.*,
Nucl. Instr. Meth. A556 (2006) 215-218
PDE = 5.5% → QE = 22%

VS

Akimov *et al.*,
Nuc. Exp. Tech., v.52 (2009) 345-351
PDE < 1% for the same SiPM!

SiPM in LXe



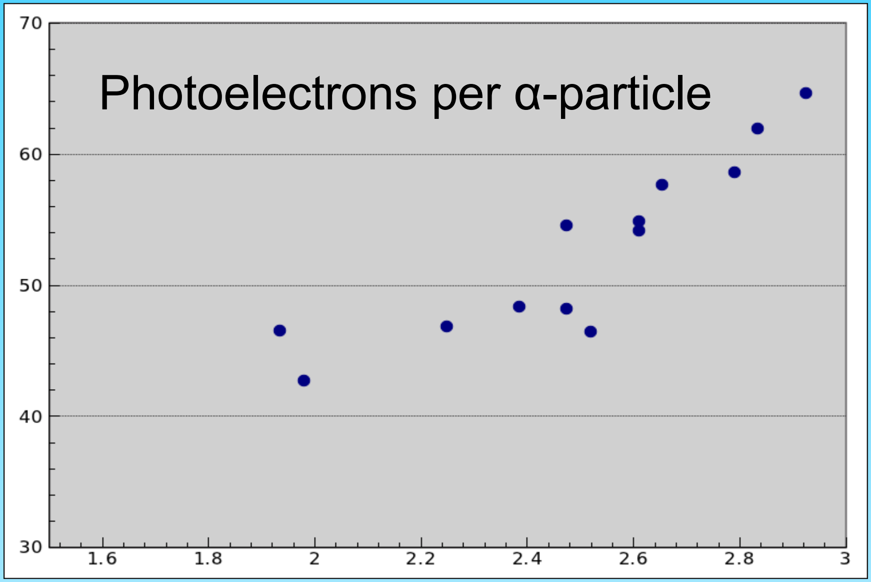


T1, T2 – PT100 thermosensors

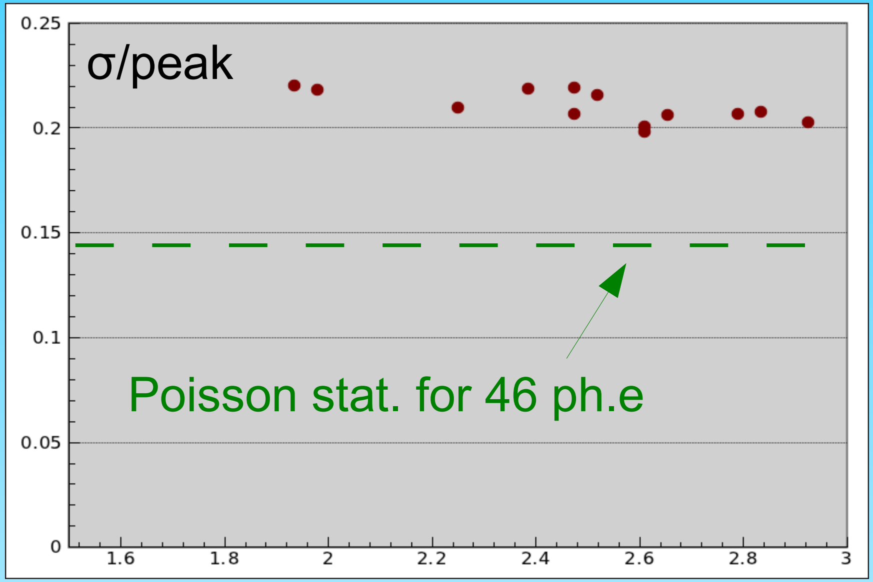
Number of VUV photons reaching SiPM sensitive area:

$$N_{ph} = \frac{E_\alpha}{W_s}\frac{\Omega}{4\pi} \approx \frac{5.49\times10^6\times3^2}{16.3\times10.7^2\times4\times3.14} \approx 2100$$

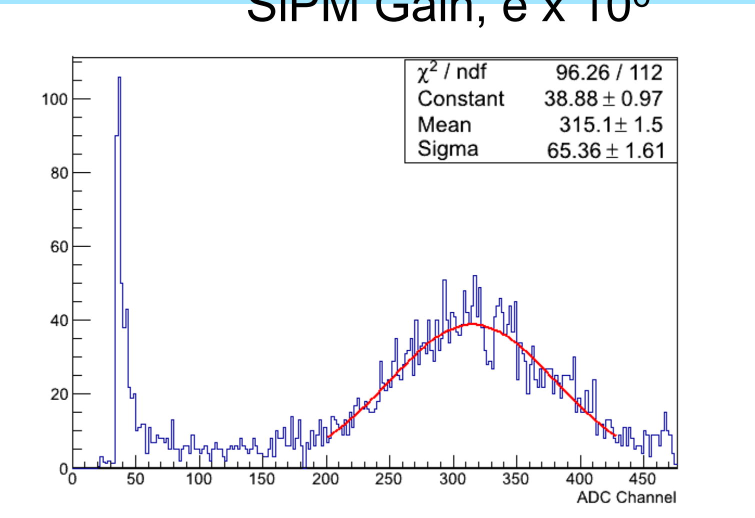
SiPM in LXe



SiPM Gain, e x 10^6



SiPM Gain, e x 10^6

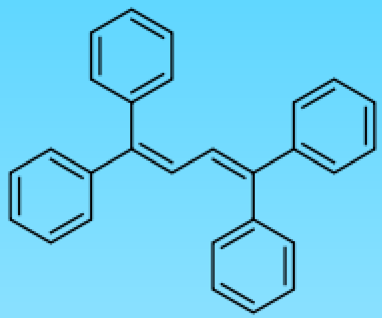


At the gain of 2×10^6 and T=-106.5°C

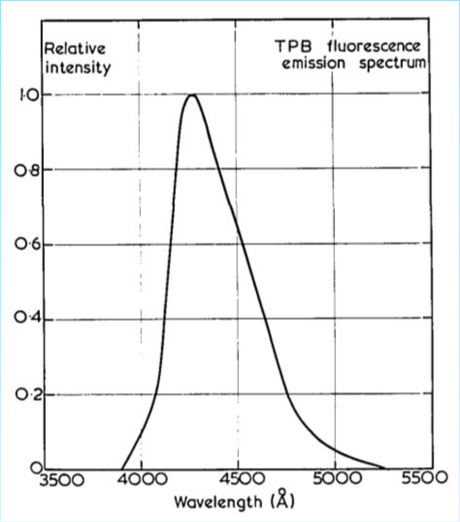
46 ph.e per α-particle are measured
PDE = 46/2100 = 2.2%
Agrees with Xe lamp result

WLS coating

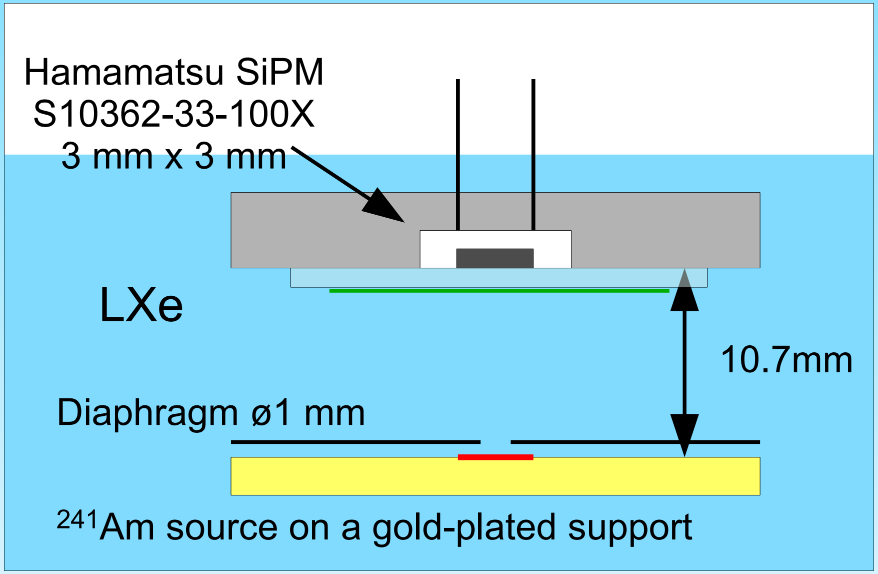
TPB (Tetraphenyl butadiene)



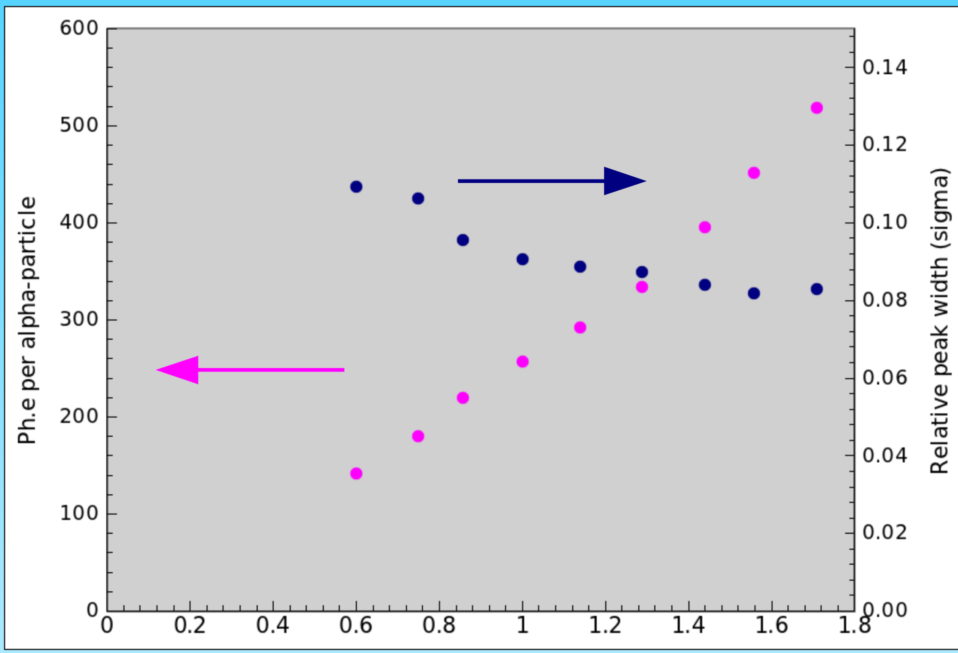
•Efficiently absorbs VUV and re-emits in blue region
•QE of ~100% for 175 nm incoming light (C.H. Lally et al., Nucl. Instr. Meth. - B, v.117, pp. 421–427)
•Successfully used in LAr (P K Lightfoot et al., 2009, JINST 4 P04002)



Emission spectrum of TBP (W. M. Burton and B. A. Powell Appl. Opt. v.12, pp. 87-89)



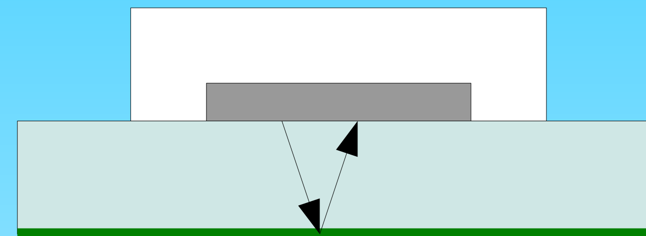
WLS coating



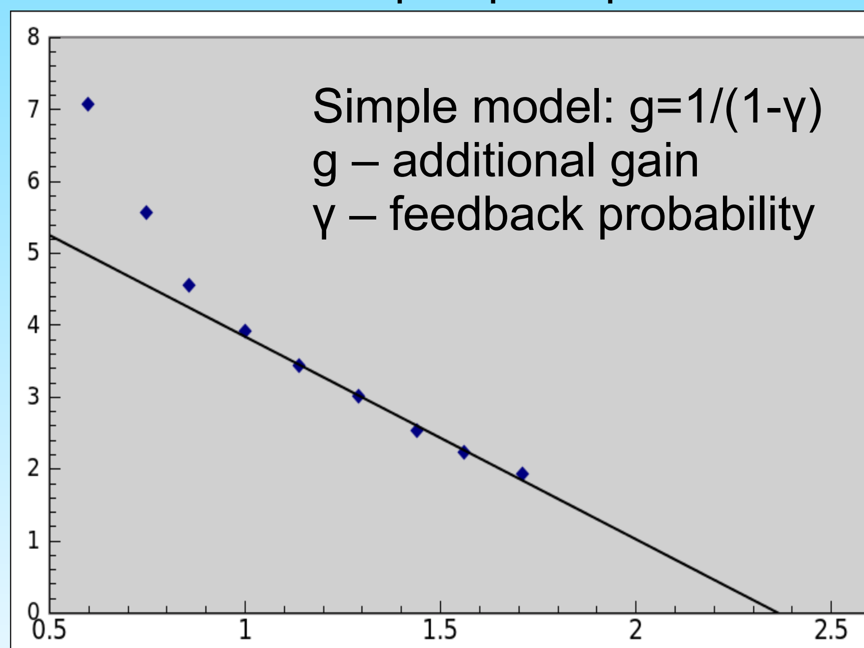
SiPM Gain, e x 10^6

γ = 1 @ SiPM gain of ~2.4

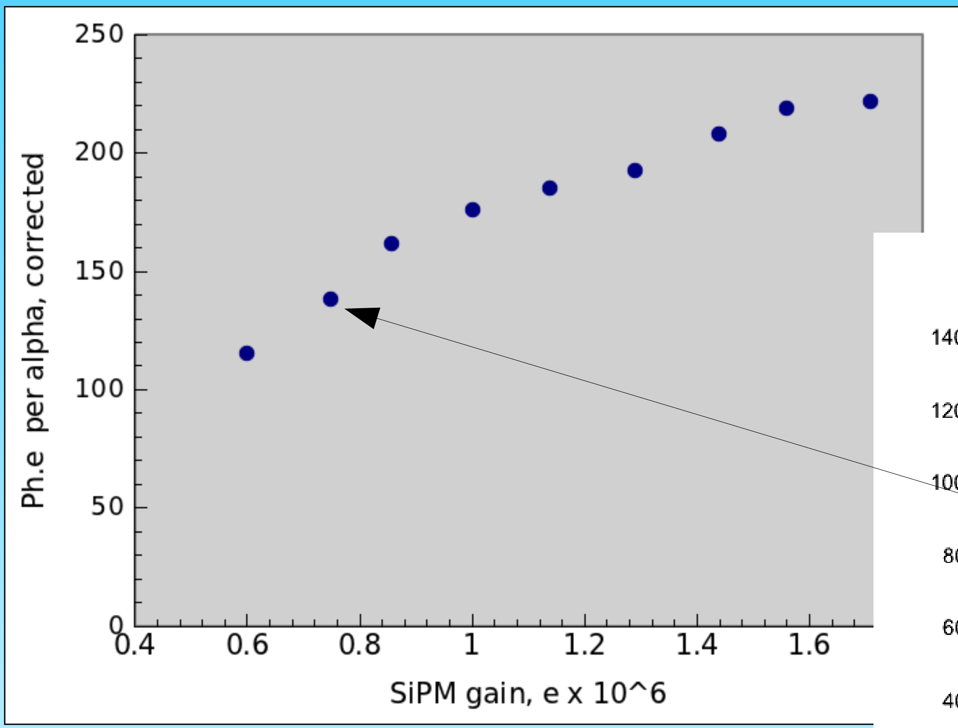
Is it optical feedback?

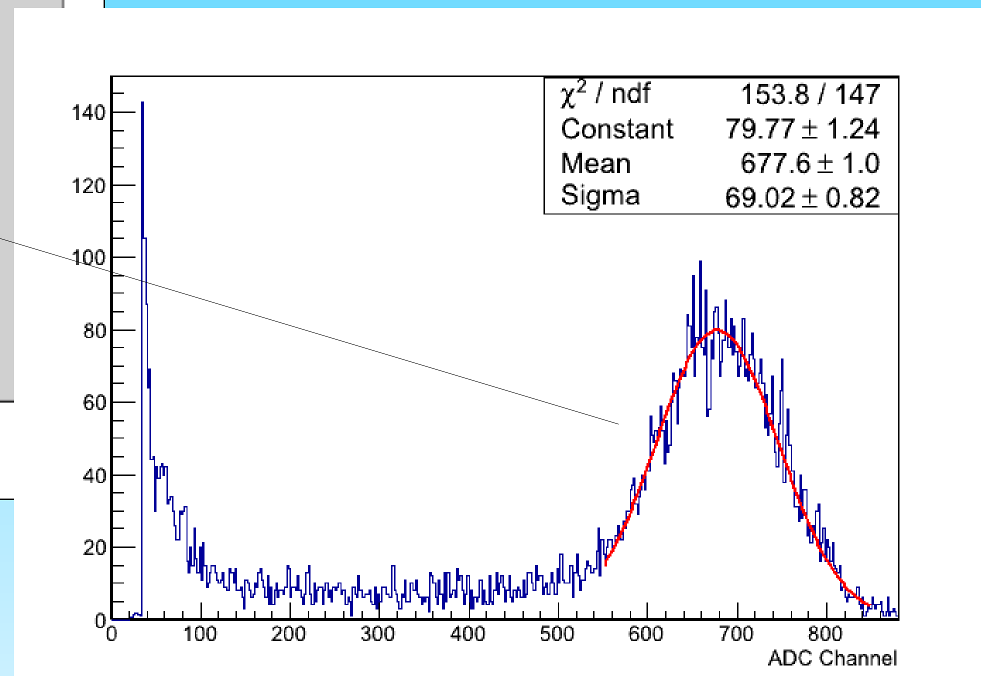


Inverse of alpha peak position



WLS coating





@ SiPM gain of ~2 x 10^6 :
46 ph.e / α – uncoated
220 phe / α – TPB uncoated

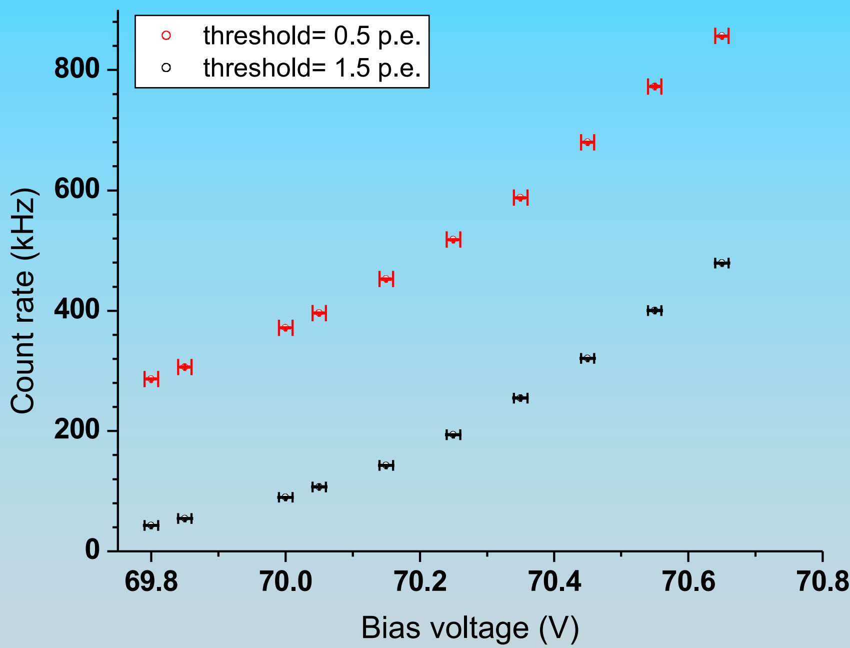
About x5 improvement

Summary

In this work we present the performance results for windowless SiPM (Hamamatsu) operating at temperatures down to -100ºC:

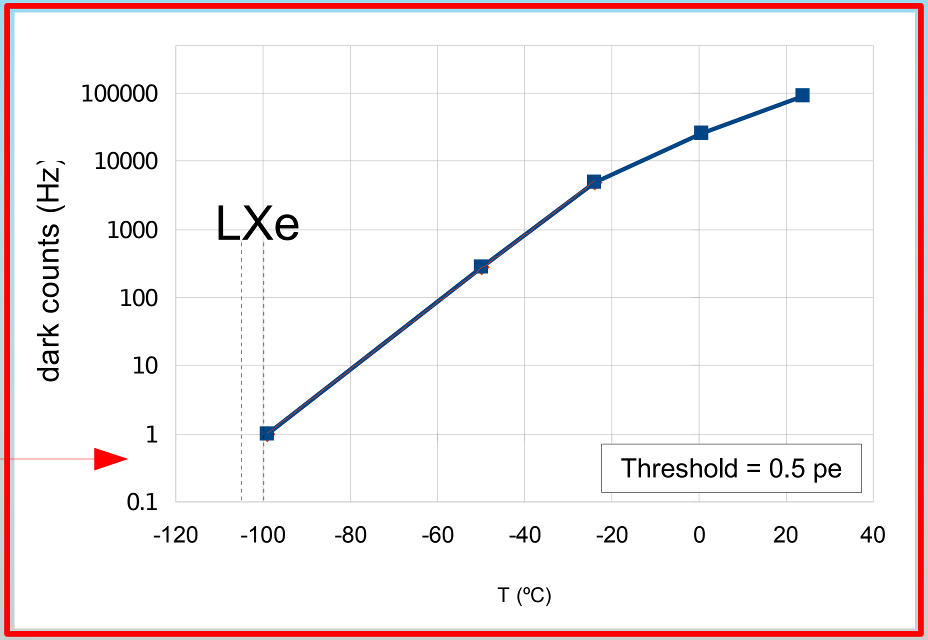
- **A intrinsic noise of <1 Hz for a threshold of $\geq$1 pe has been measured at -100ºC;**
- **The SiPMs maintain a good single electron response at high gain (>10^6) and low temperature;**
- **The standard SiPM with window is not sensitive to xenon light;**
- **A QE of ~2.6% (PDE ~ 2%) at 175 nm has been measured using xenon proportional scintillation light source;**
- **Works immersed in liquid xenon with the same estimated PDE (2%)**
- **A glass plate coated with TPB in front of SiPM improves PDE by at least a factor of 5, but probably causes optical feedback**

SiPM @ low T: noise

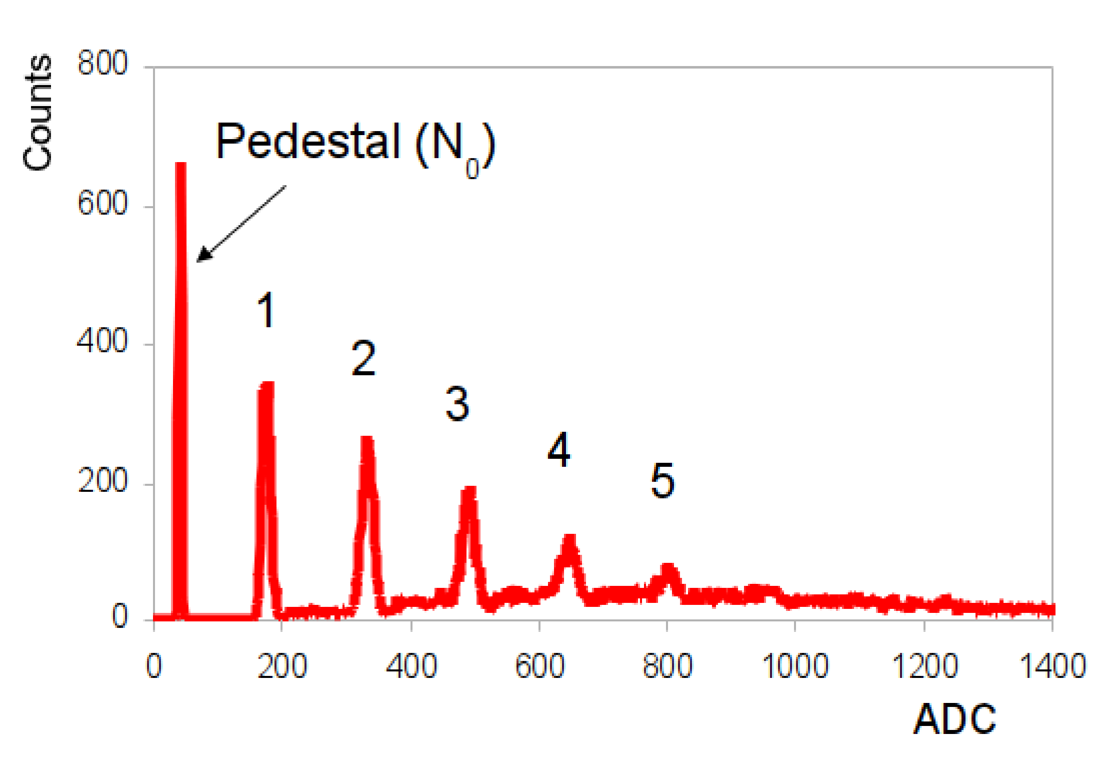


Hamamatsu, S10362-11-100U
Number of pixels= 100
Array total area = 1 mm2
Active Pixel area = 78 μm^2

≈10x the typical noise (per unit area) from a bialkali PMT...



SiPM @ low T: afterpulsing



- T = -100 ºC;
- Blue LED (20 ns);
- Charge PA + A (μ = 250 ns;)

$$afterpulse = \frac{N_1' - N_1}{N_1'} \sim 0.2(1\ pe)$$

$$N_1' = P(-\log(N_0/N), 1)$$

P(μ,i) → Poisson Distribution;
N → number of light pulses;
N_0 → counts in the pedestal;
N'_1 → 1 fired pixel (expected);
N_1 → 1 fired pixel (observed);

Hamamatsu, S10362-11-050U
Number of pixeis= 400
Array total area = 1 mm2
Active Pixel area = 61.5 μm^2