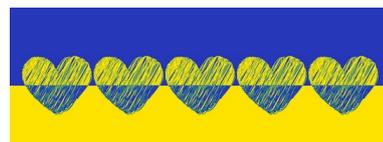




A SiPM based camera for the Terzina telescope on board the NUSES space mission

L. Burmistrov, M.Heller, T. Montaruli, C. Trimarelli, Jan Swakon (for IFJ PAN proton facility)
(on behalf of NUSES collaboration)



Outline:

The NUSES mission.

Intro.

The Terzina telescope

SiPM intro.

Simulation of the instrument

Radiation hardness

Annealing





The NUSES Collaboration

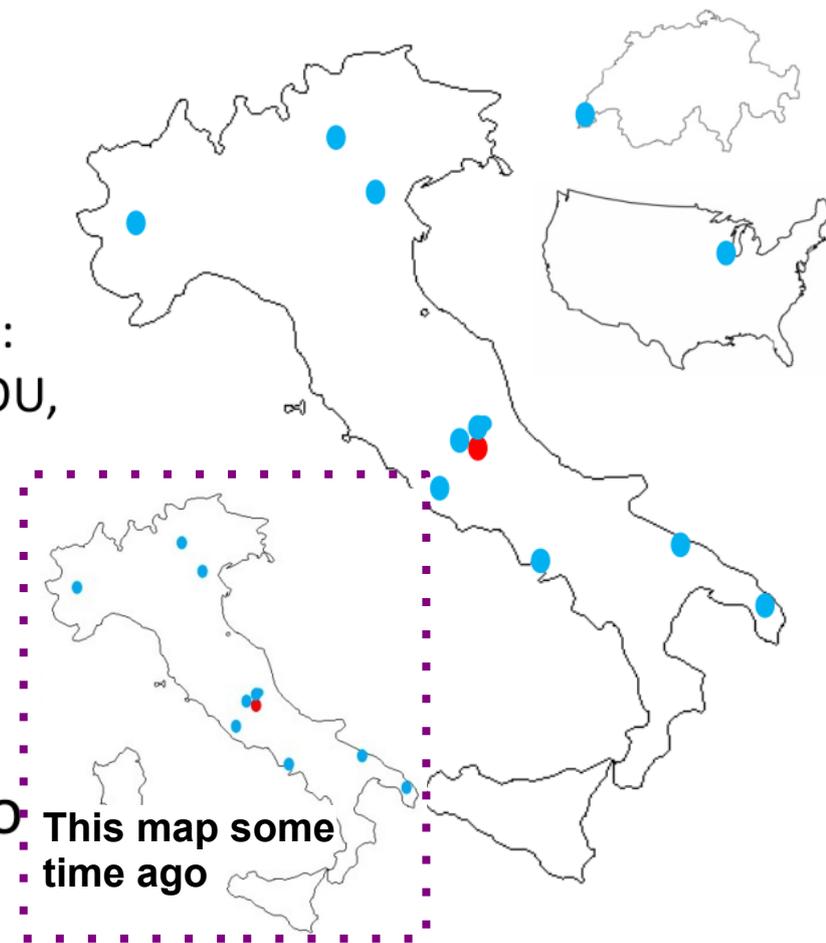
60+ persons from many institutions.

Large expertise (and synergies) from space missions/R&D :
AMS, DAMPE, eASTROGAM, FERMI, GAPS, HERD, LIMADOU,
PAMELA, POEMMA, SPB2 ,

GSSI is leading the mission

Current list of the italian groups:

- Gran Sasso Science Institute
- INFN – Laboratori Nazionali del Gran Sasso
- Università dell’Aquila
- Università di Roma “Tor Vergata” and INFN-Roma2
- Università di Torino and INFN Torino
- Università di Trento and INFN-TIFPA
- Università di Bari and INFN
- Università di Padova and INFN
- Università “Federico II” and INFN Napoli
- Università del Salento and INFN



University of Geneva +
University of Chicago +
Possible interests from:
- other US institutions
- Spain
-



The NUSES mission: two payloads

Terzina

Pathfinder for future missions devoted to **UHE cosmic rays and neutrino astronomy** through space-based atmospheric **Cerenkov light** detection.

See talks from:
R.Aloisio and L.Burmistrov

Zirè

Measure the fluxes of **low energy (<250 MeV) CR**, mainly electrons and protons, to study cosmic rays, Van Allen belts, space weather and the magnetosphere-ionosphere-litosphere couplings (MILC) in case of seismic / volcanic activities.

Detect **0.1-10 MeV photons** for the study of transient (**GRB**, e.m. follow up of GW events, SN emission lines,...) and steady gamma sources.

See talks from :
Ivan De Mitri
Riccardo Nicolaidis

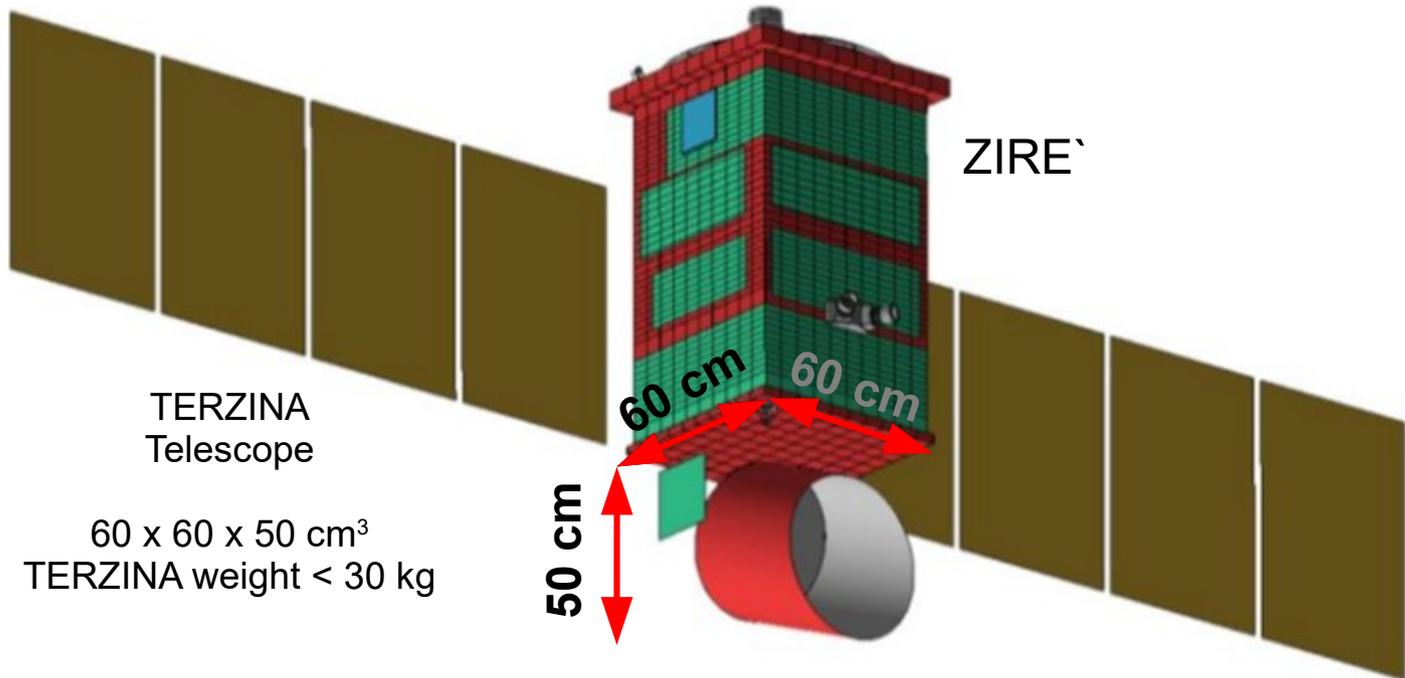
New technologies and approaches

Developement of new observational techniques , testing new sensors (e.g. **SiPM**) and related electronics/DAQ for space missions. New solutions for the satellite platform.

Poster by : Pillera (zirè-FTK)

See talks from :
Andrea Di Salvo

The NUSES mission composed of two payloads.



Two main components :

ZIRE

TERZINA

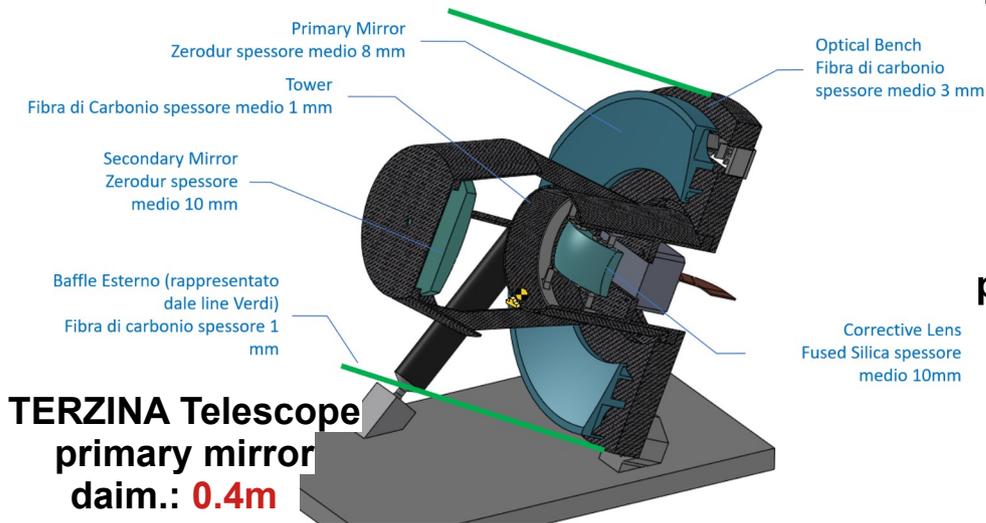
TERZINA

Demonstrator of Cherenkov light detection produced by Extensive Air Showers
First measurement of showers with Cherenkov light from space ($E > 100 \text{ PeV}$)
Proves the technology for detecting Earth skimming muon and tau neutrinos
Measure the background conditions
Further Development of SiPM technology for space

ZIRE`

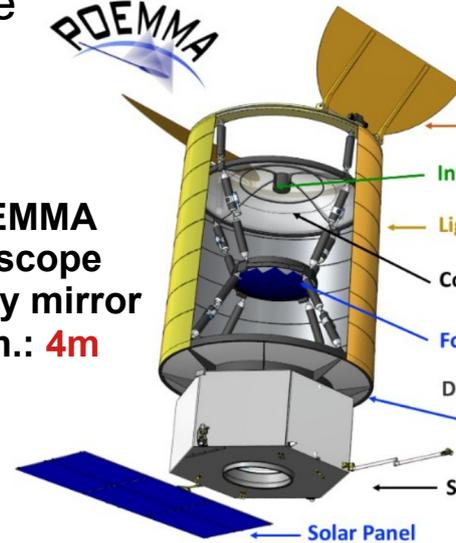
Monitors the fluxes of low energy cosmic rays ($< 250 \text{ MeV}$),
Electrons and protons to study Van Allen radiation belts
Space weather and the magnetosphere-ionosphere-litosphere couplings
And much more

Camera vs POEMMA



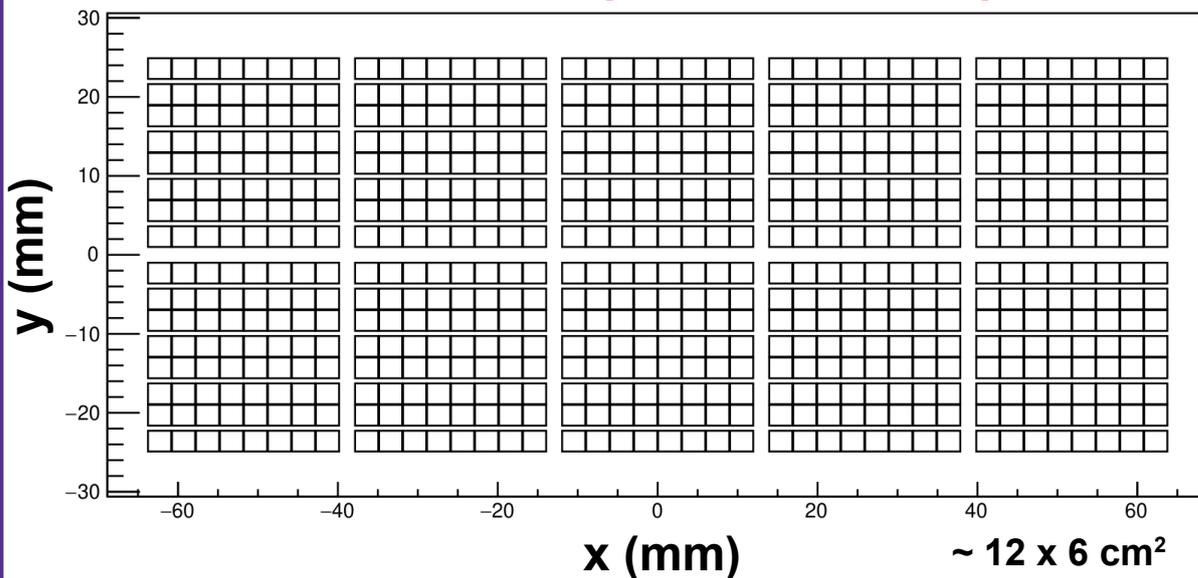
Probe
POEMMA

POEMMA Telescope primary mirror daim.: 4m

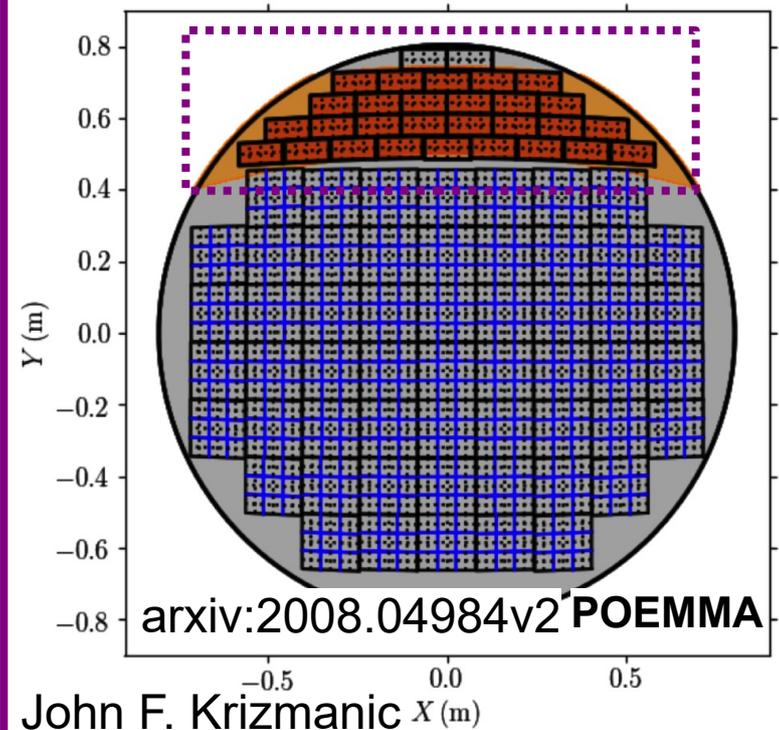


Telescope:	Instrument	
Optics	Schmidt	45° full FoV
	Primary Mirror	4 m diam.
	Corrector Lens	3.3 m diam.
	Focal Surface	1.6 m diam.
	Pixel Size	3 × 3 mm ²
	Pixel FoV	0.084°
PFC	MAPMT (1μs)	126,720 pixels
PCC	SiPM (20 ns)	15,360 pixels
Observatory	Each Telescope	
	Mass	1,550 kg
	Power (w/cont)	700 W
	Data	< 1 GB/day
Mission	(2 Telescopes)	
Lifetime	3 year (5 year goal)	
Orbit	525 km, 28.5° Inc	
Orbit Period	95 min	

TERZINA SiPM photo detection plane



SiPM part (Detection of Cherenkov light)

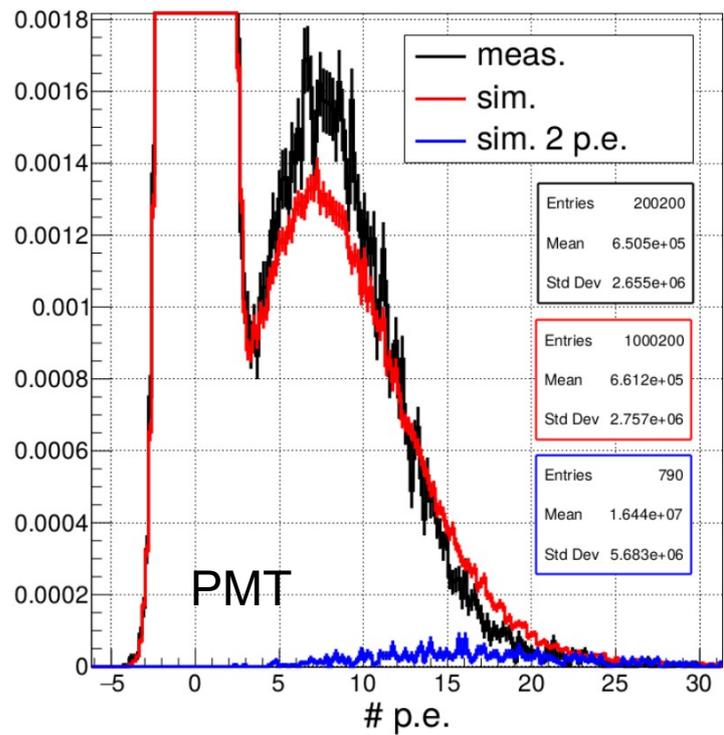
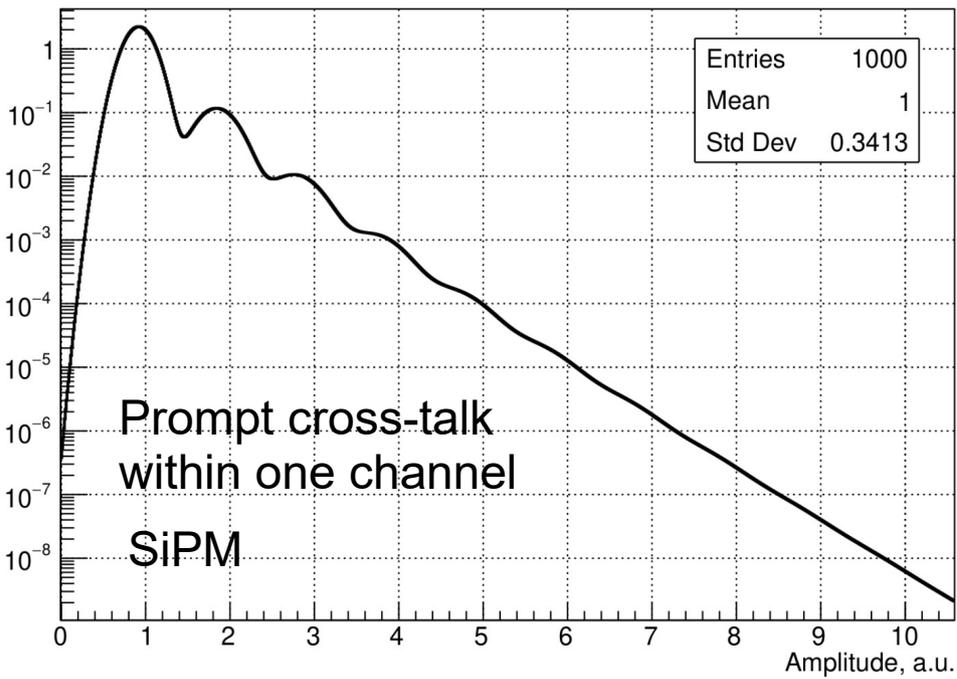


SiPM vs ma-PMT (PMT)

Operation voltage	<100 V	~1000V
Currents	~1 μ A	~100 μ A
Power per cm^2	~mW	~0.1W
Weight per cm^2 of sensitive area	~10 g	~100g
Total integrated charge	infinite	200 Q
Time resolution	<100 ps	< 1 ns
Special resolution	~1 mm	~10 mm
Photo detection efficiency @ 400 nm	> 50 %	< 50 %
Variation with temperature	very sensitive	low
Need of pre-amplifier/PMT gain	0.1 mV	5 mV
Radiation resistance	low	good

PMT

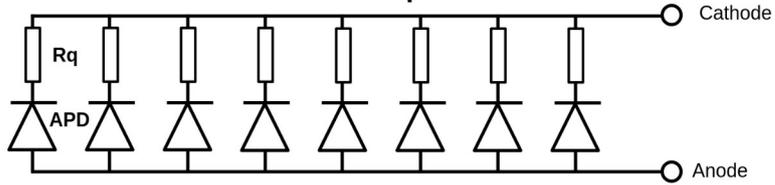
Single photon response PMT vs SiPM



→ Change sharing between anodes.

→ Large variation of the response defined by secondary emission

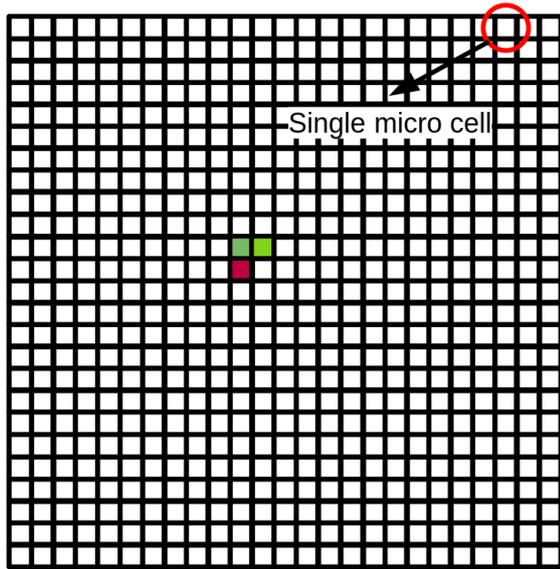
SiPM all the cells are connected in parallel



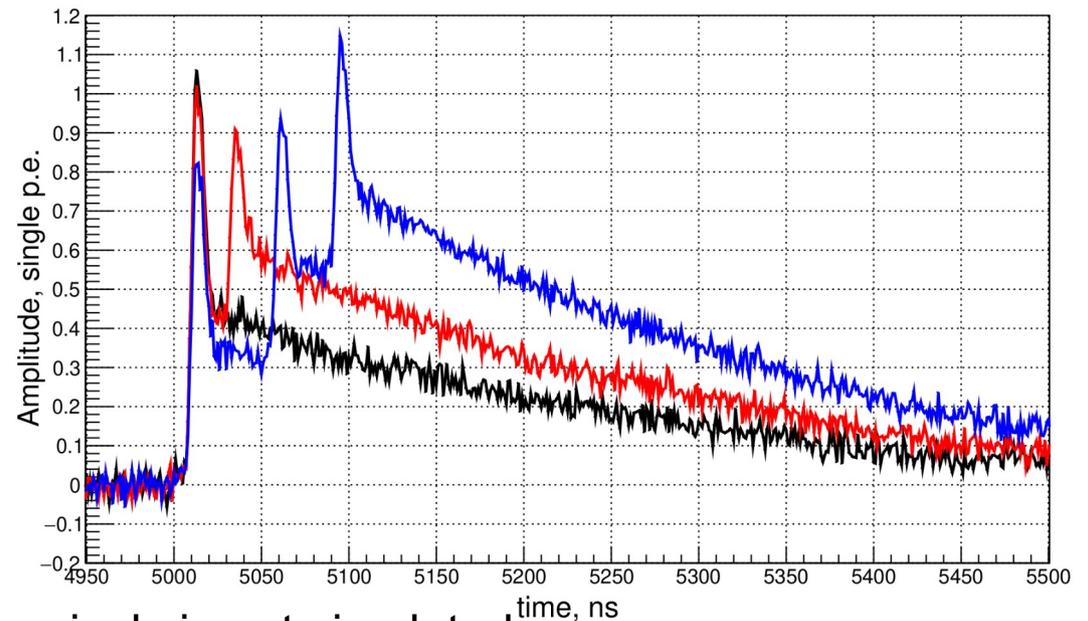
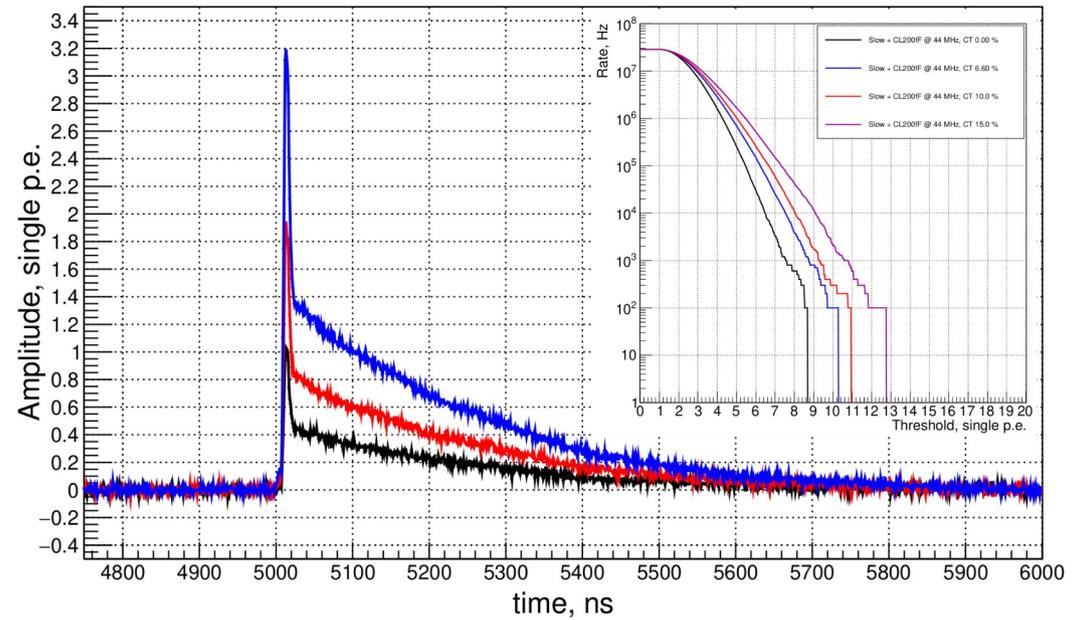
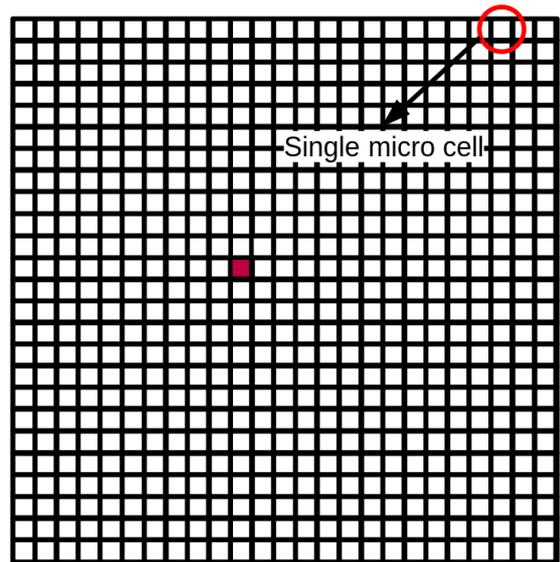
Parametric SiPM simulation

In simulation we include as well :
Gain variation, electronic noise, pre-amplifier, ADC.

Prompt cross talk.

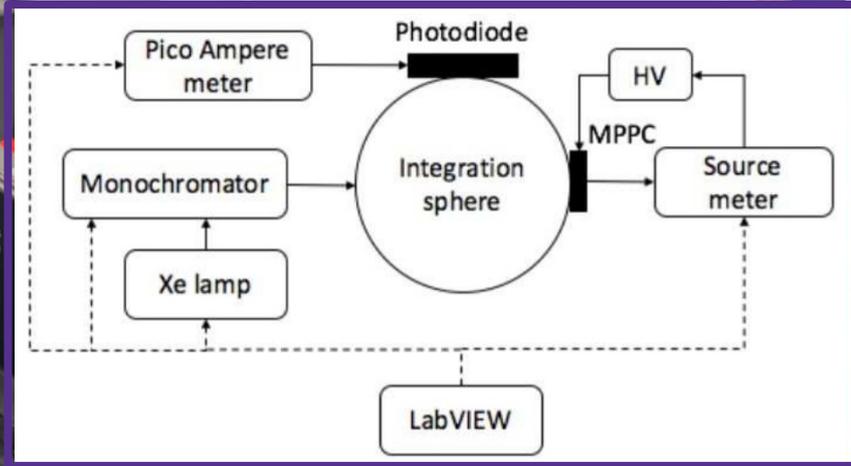


After pulsing

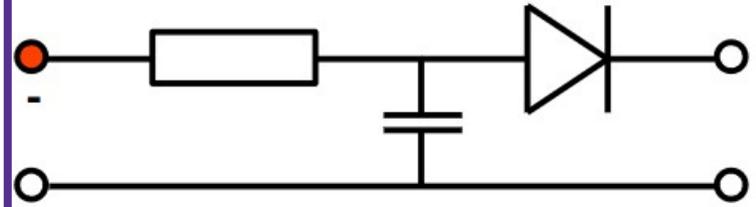


L. Burmistrov Delayed crosstalk imposed in other pixels is not simulated.

Experimental setup

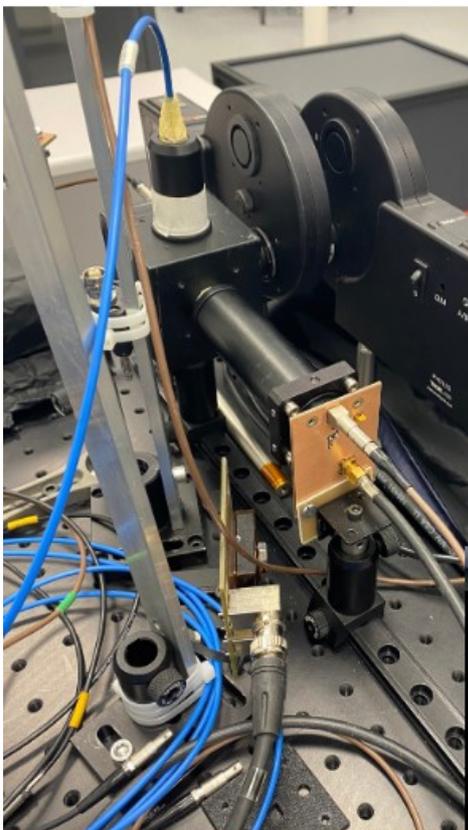
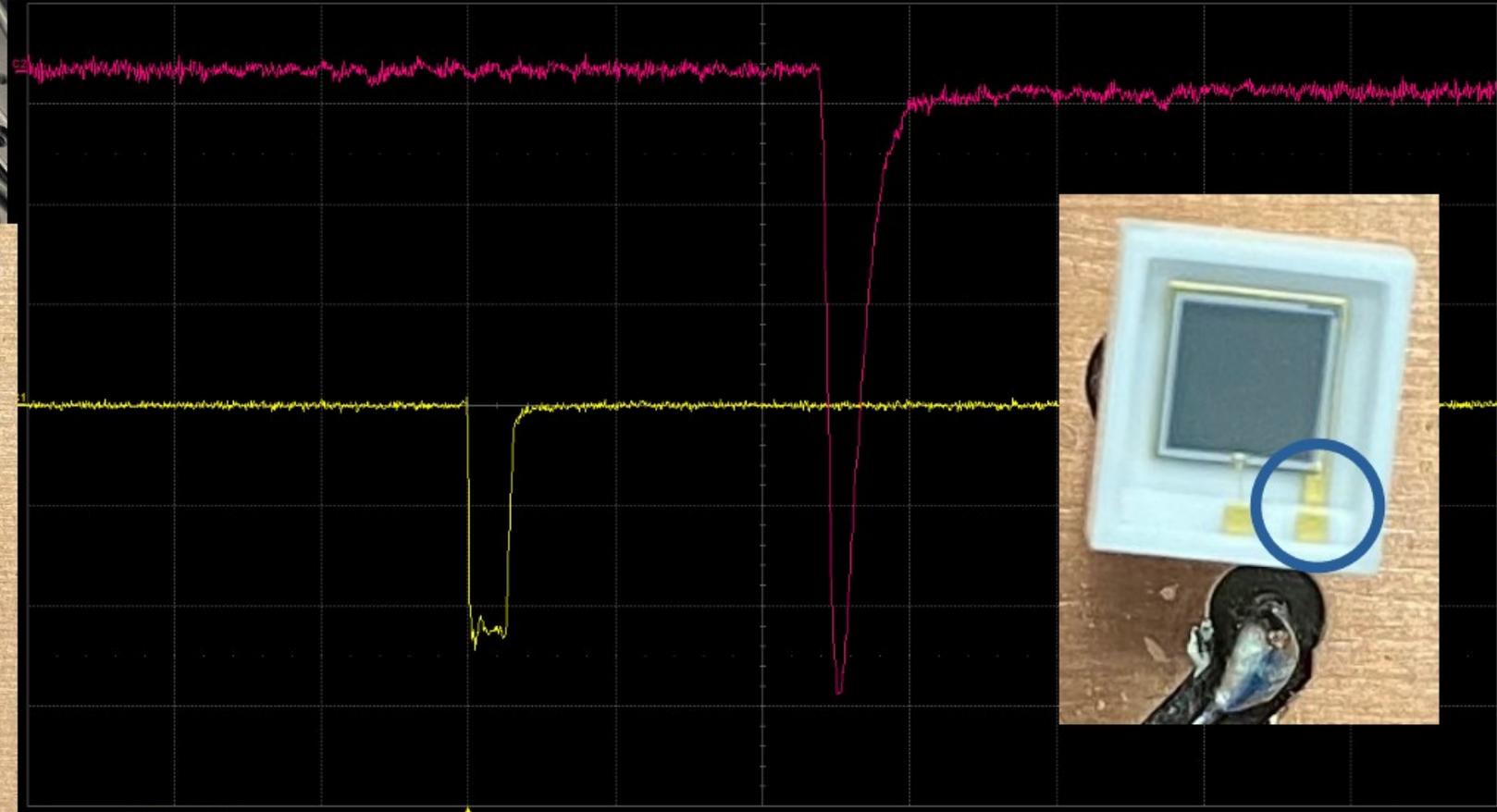


Hamamatsu 2021 (Vbias -54 V)



Read cathode

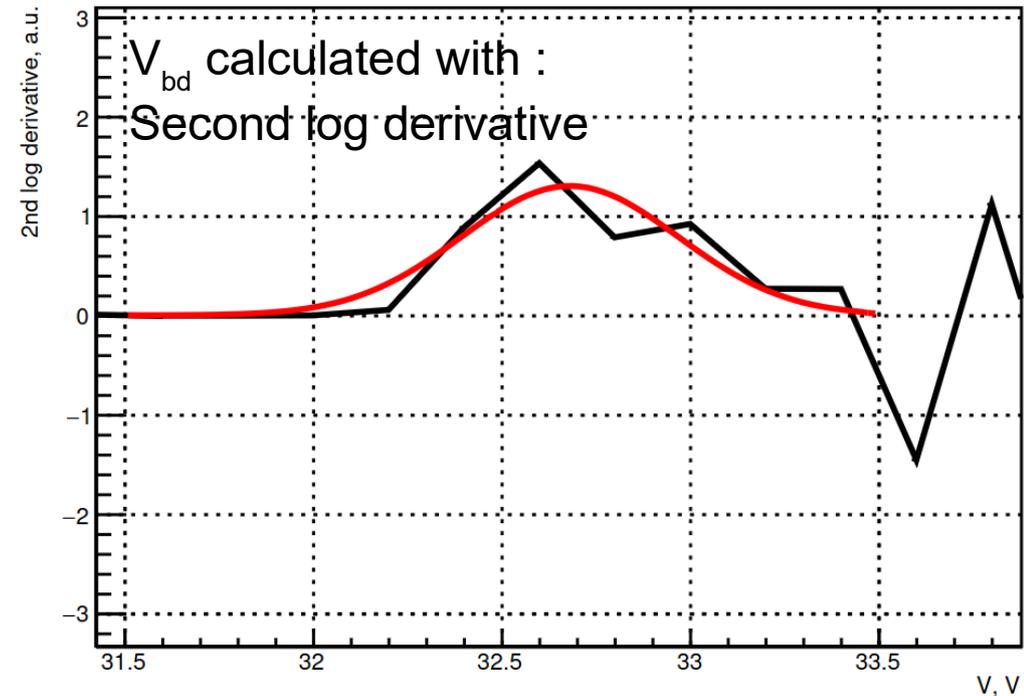
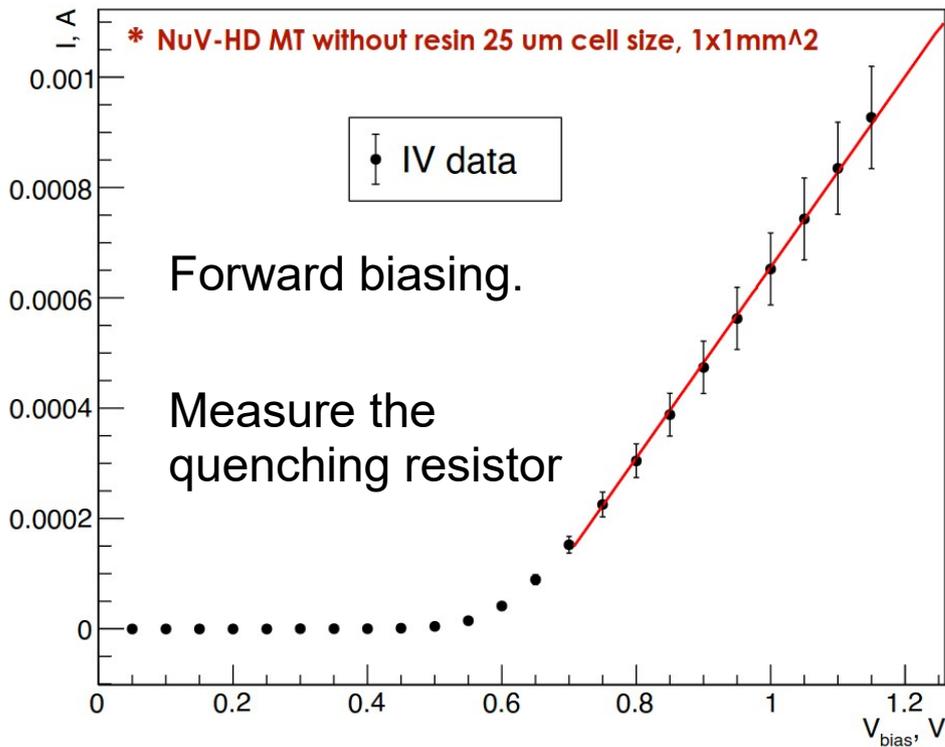
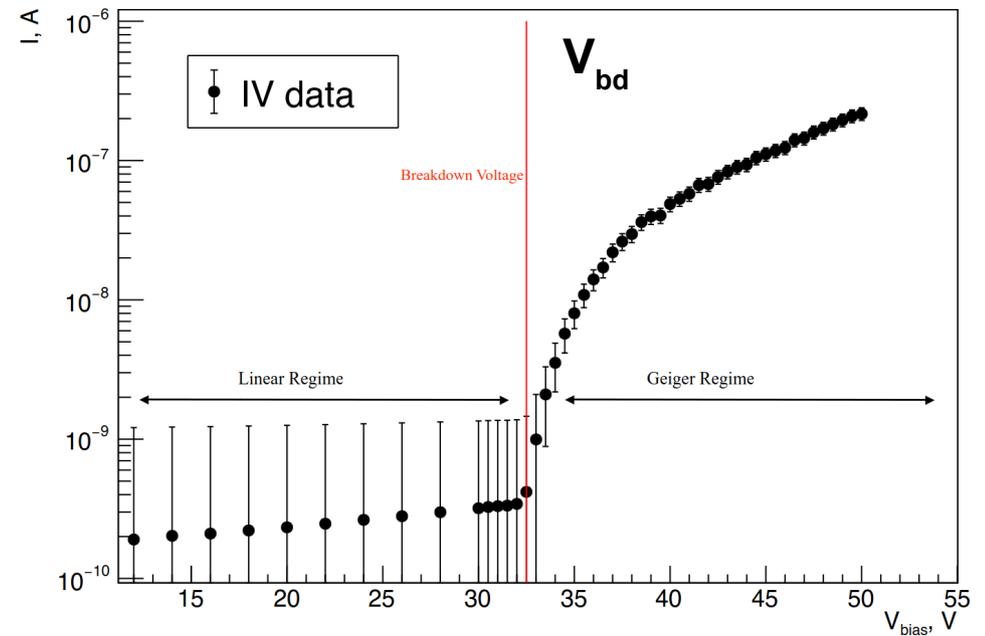
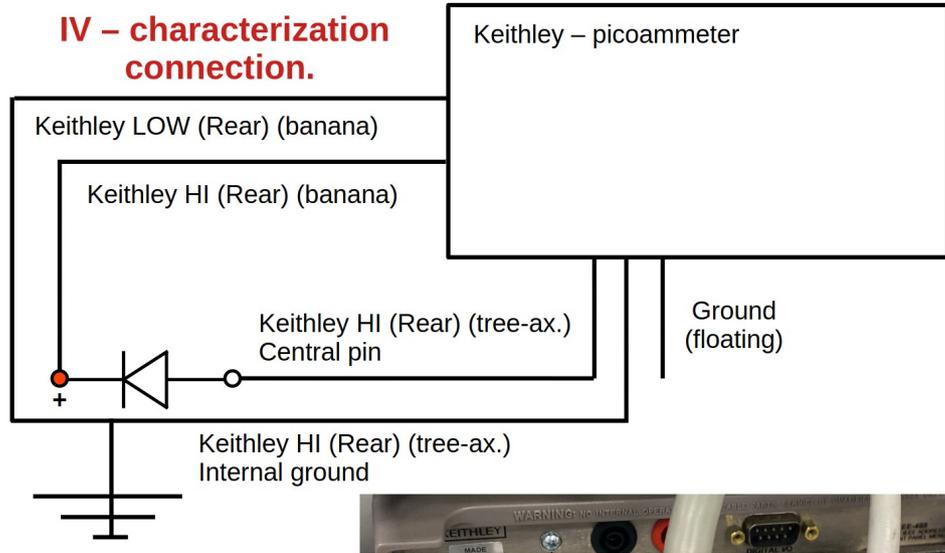
File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Support



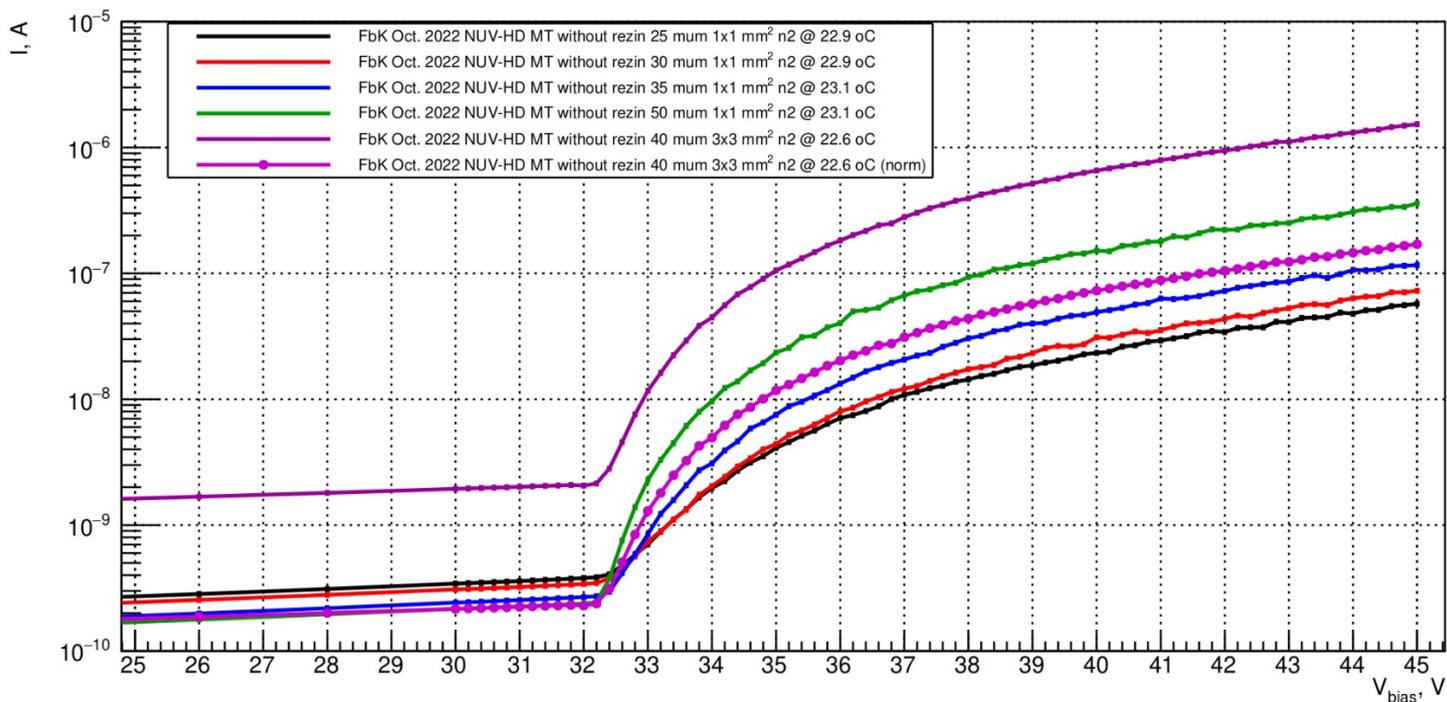
TELEDYNE LECROY
Tbase -40.0 ns Trigger C1 DC
2 kS 20.0 ns/div Auto -240 mV
10 GS/s Edge Neg
1/11/2023 9:51:08 PM

SiPM characterization : $V_{\text{break down}} (V_{\text{bd}})$

Break down voltage – defines when SiPM start to detect light. It is a function of a temperature.

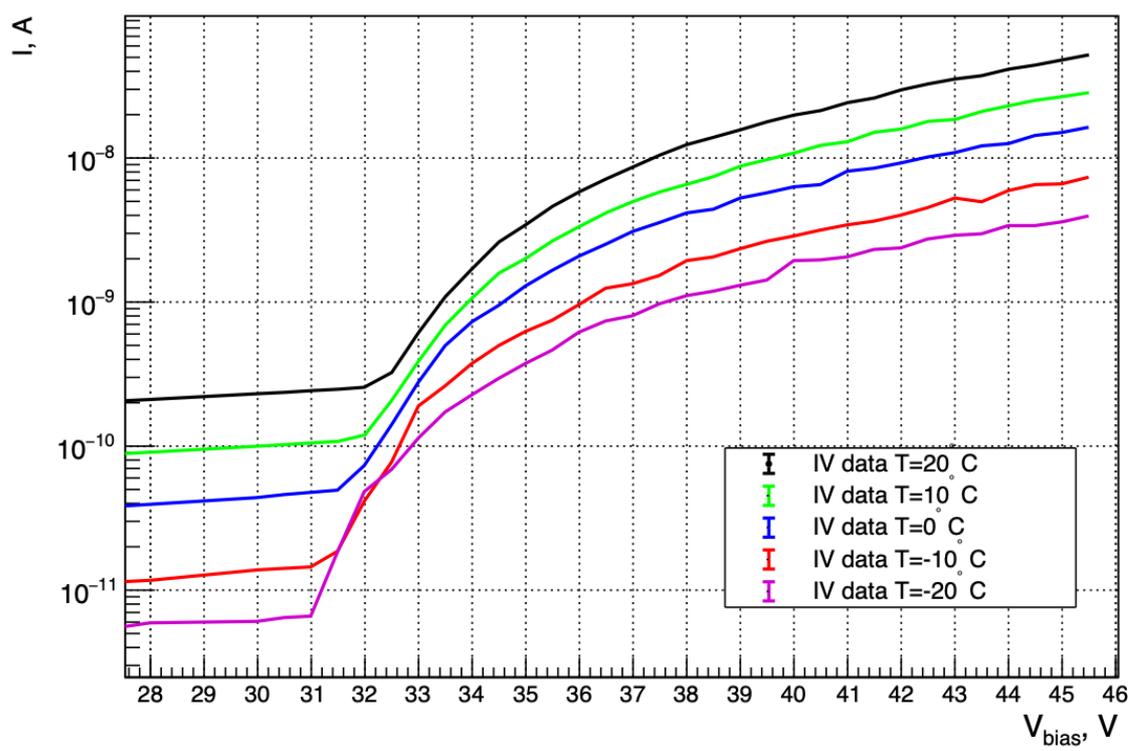


SiPM characterization : IV curves for different mu-cell sizes.



Cell size ↑

Current at same V ↑



V_{bd} as a function temperature

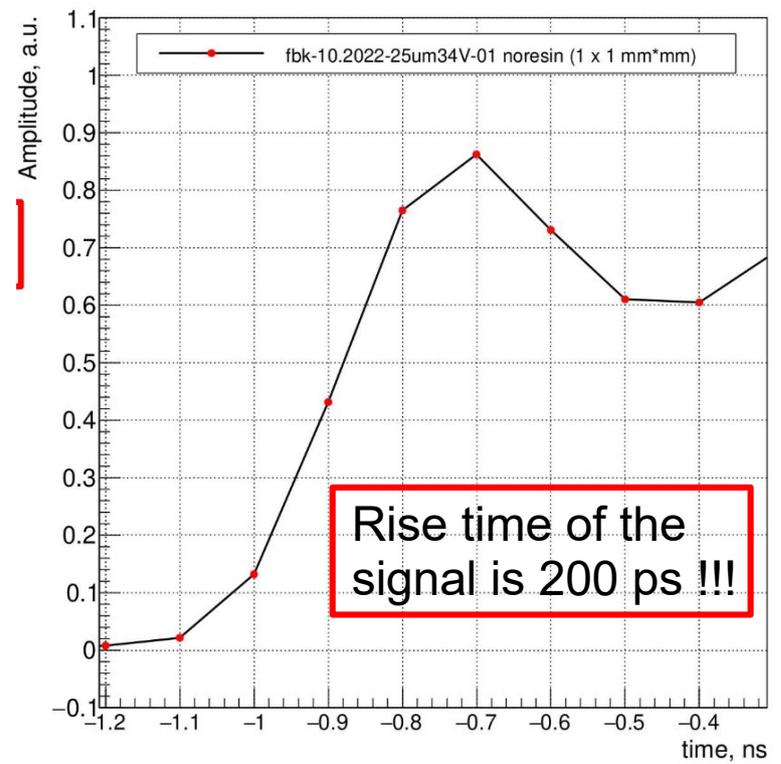
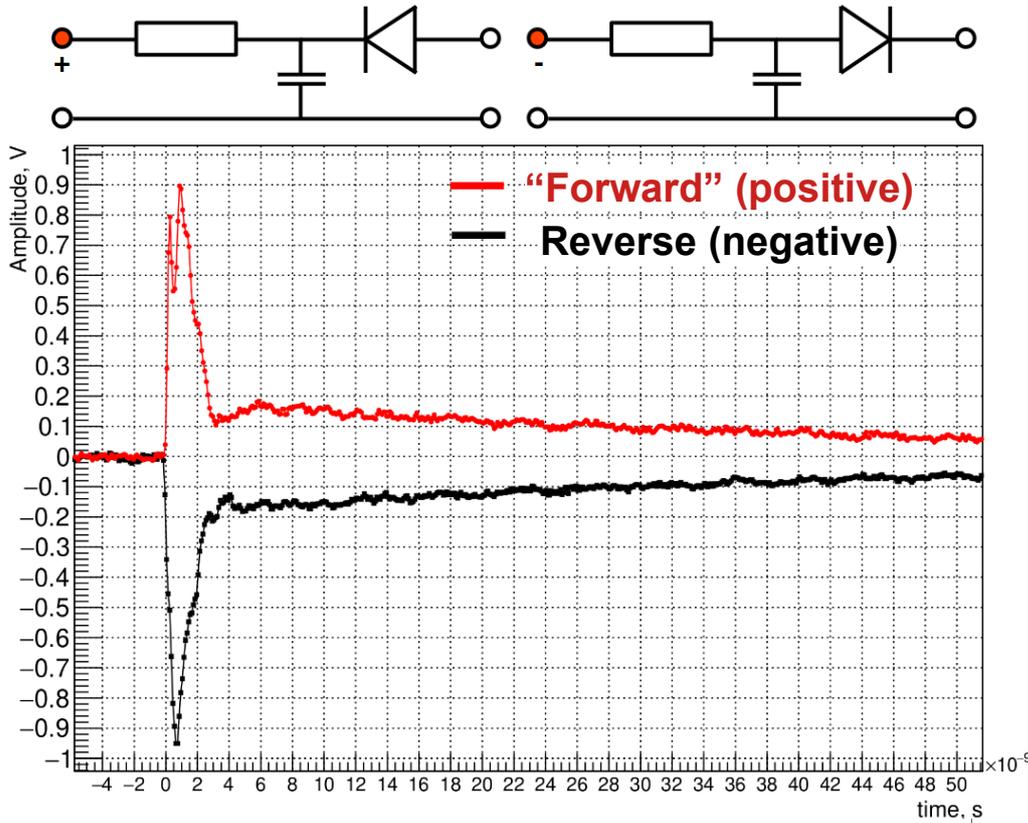
Temperature ↑

V_{bd} ↑

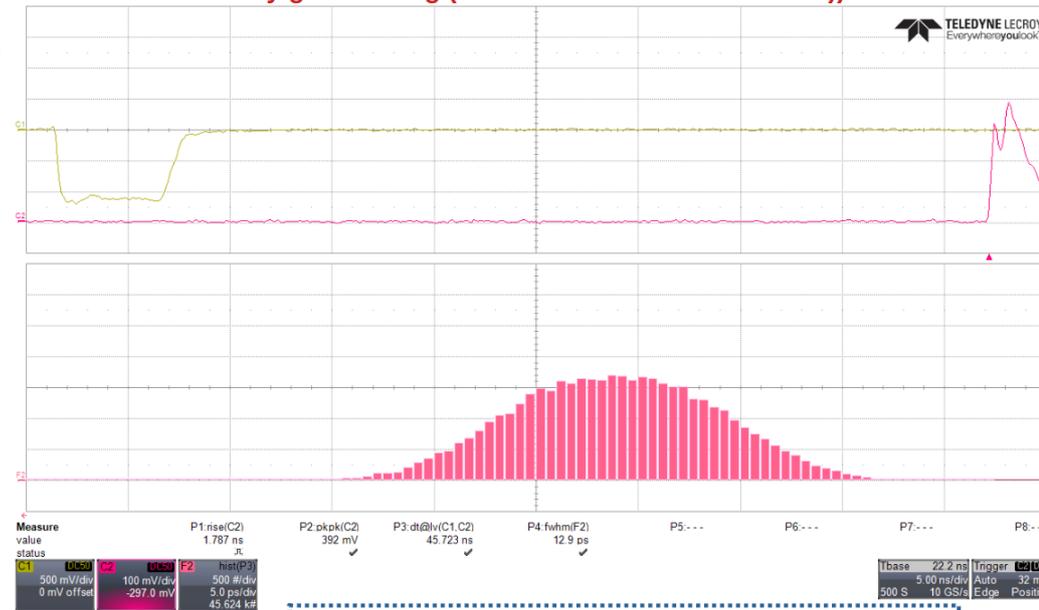
~32.6 V (20°C)
~31.2 V (-20°C)

Temperature coefficient is 33mV/°C

SiPM characterization : response on very large number of photons from laser (~10 ps).

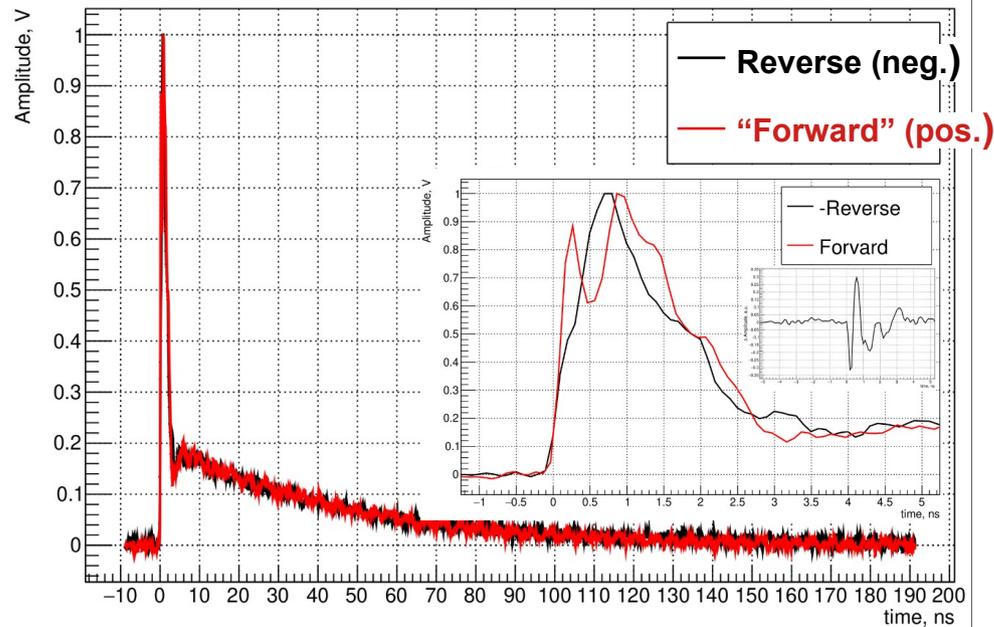


Very good timing (the record I have measured :-))

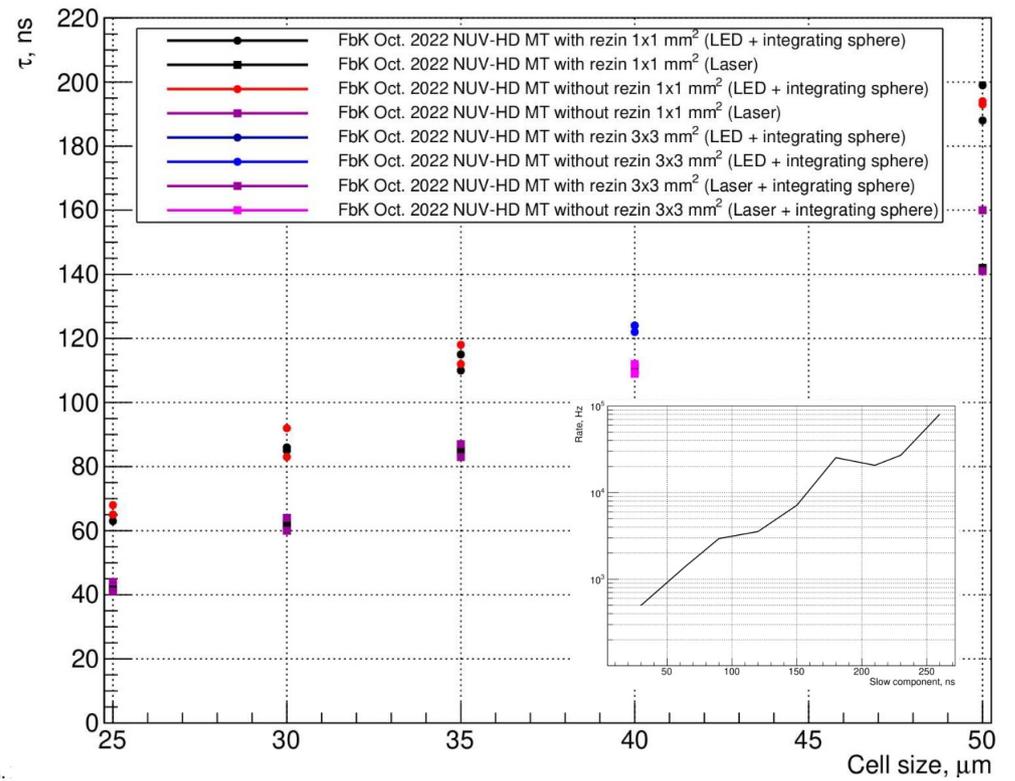
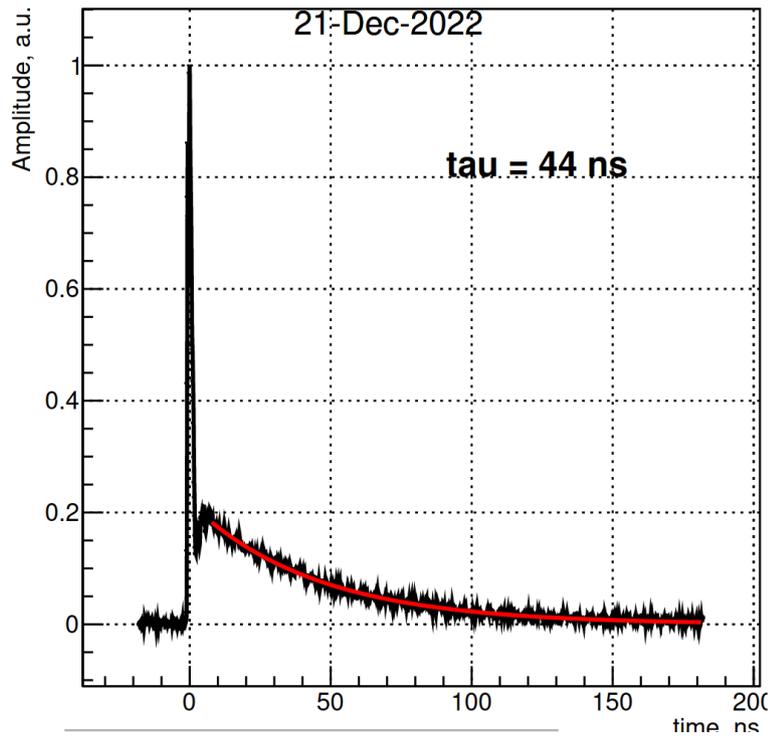


Time resolution (σ) = $12.9/2.35/\sqrt{2} \sim 4$ ps

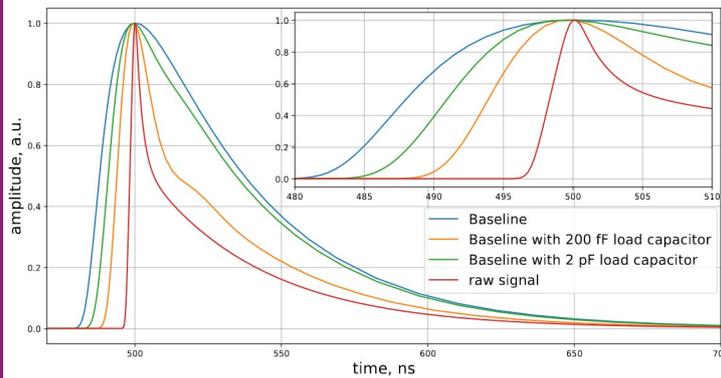
This time resolution with a very good amplifier can be potentially obtain for single p.e. (for a given peak).



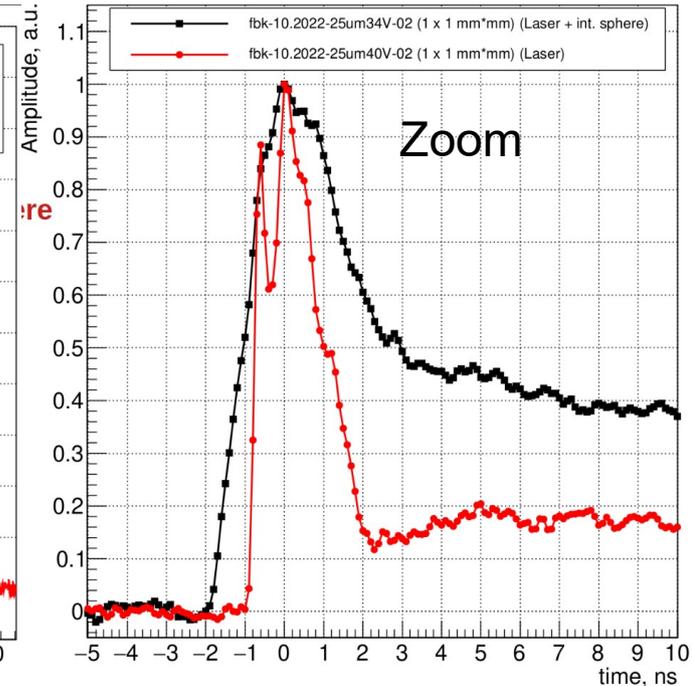
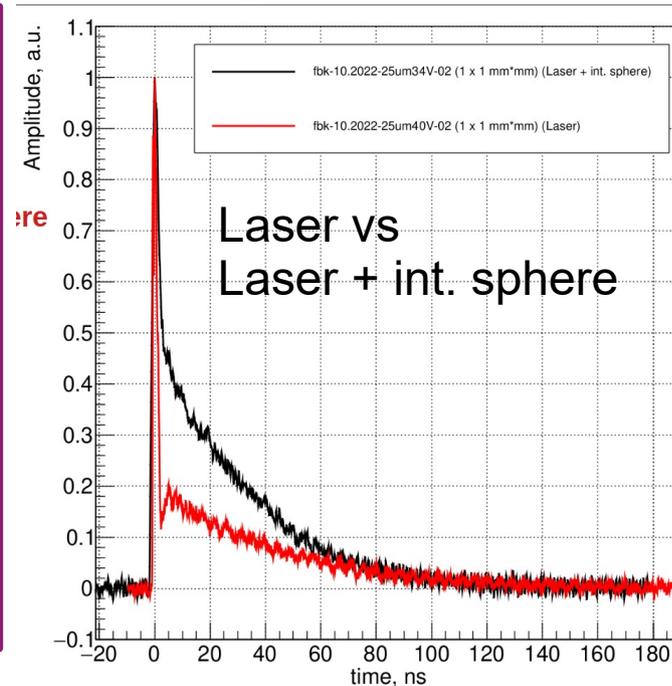
SiPM characterization : decay time of the slow component. Pre-amplifier optimization.



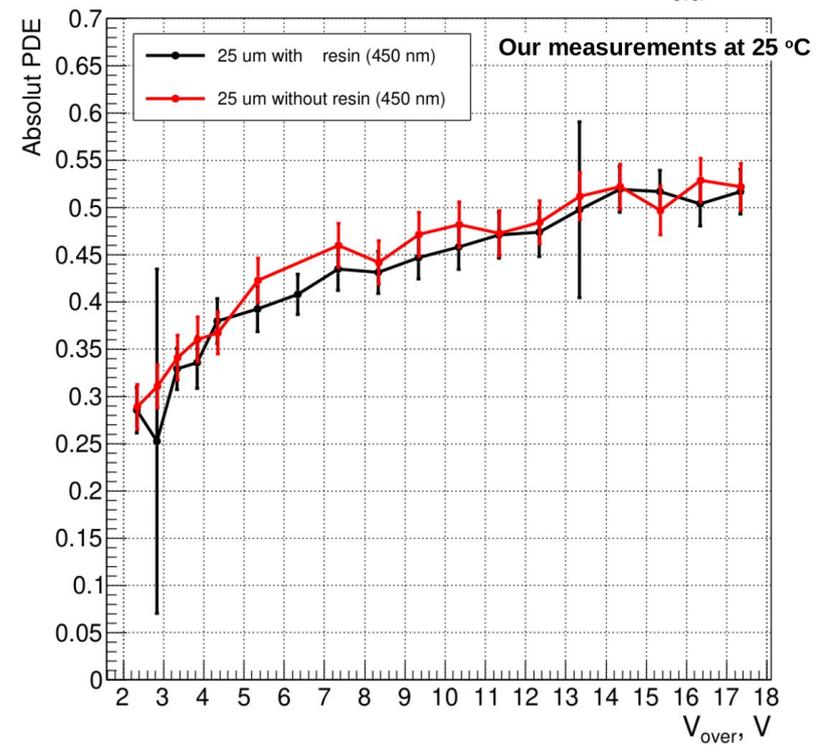
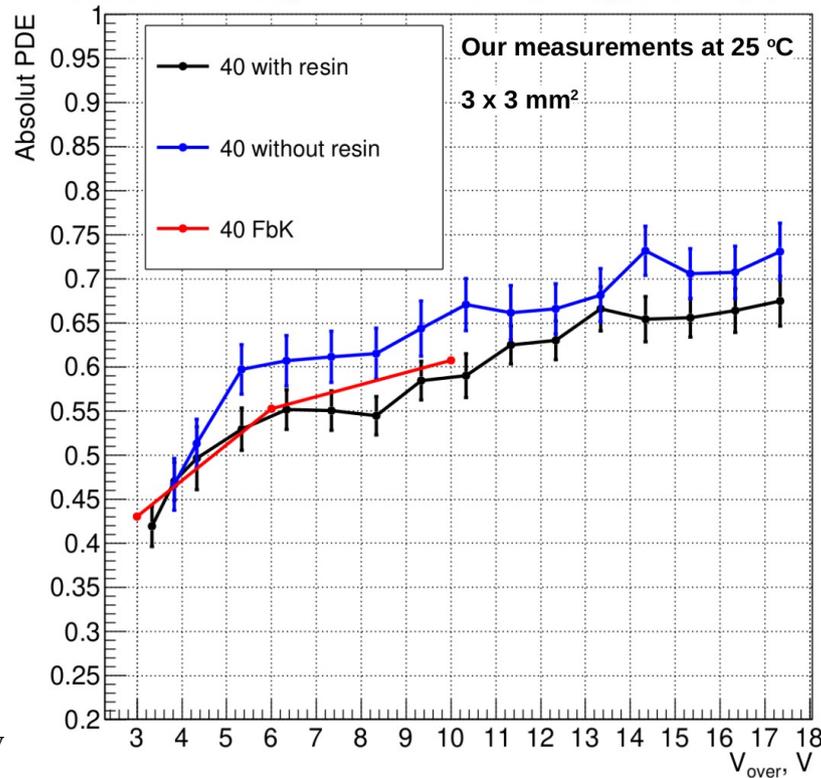
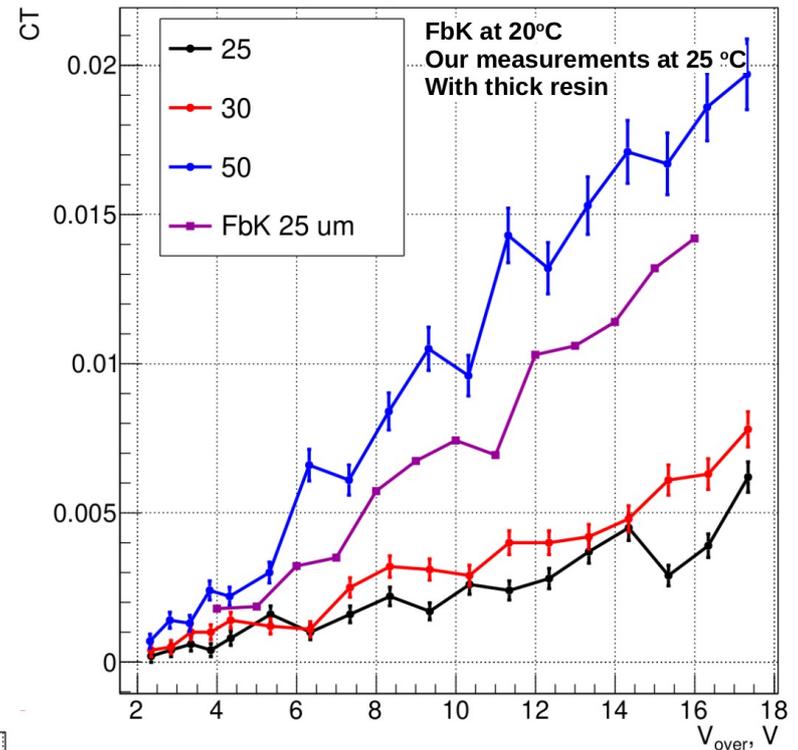
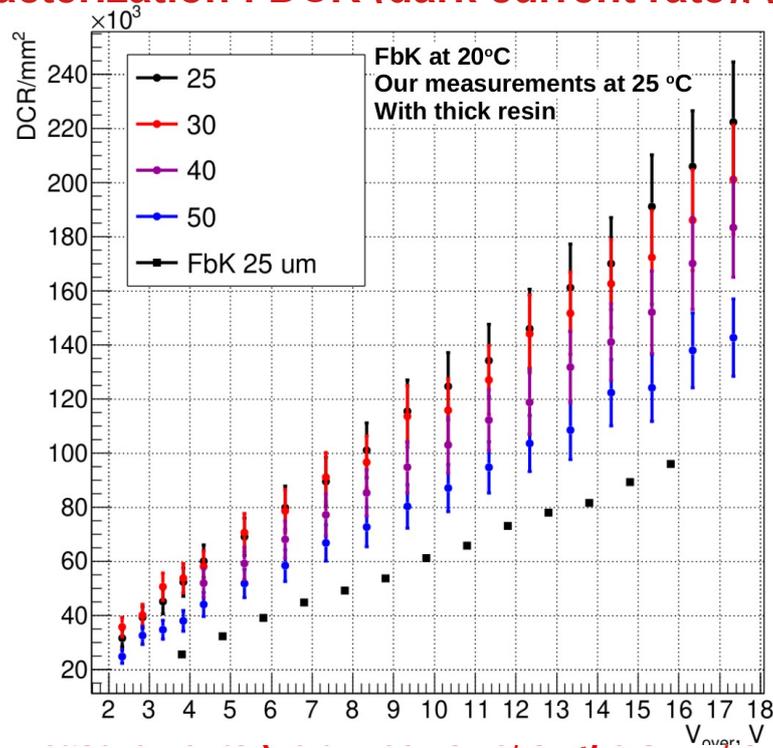
Normalized single p.e.
shape after amplification.



L. Burmistrov



SiPM characterization : DCR (dark current rate). (CT) optical cross-talk, PDE(photo detection eff.)



Irradiation facility with horizontal beam line (AIC-144 cyclotron)

<https://web.infn.it/EURO-LABS/>

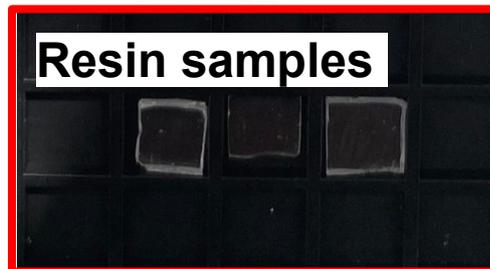
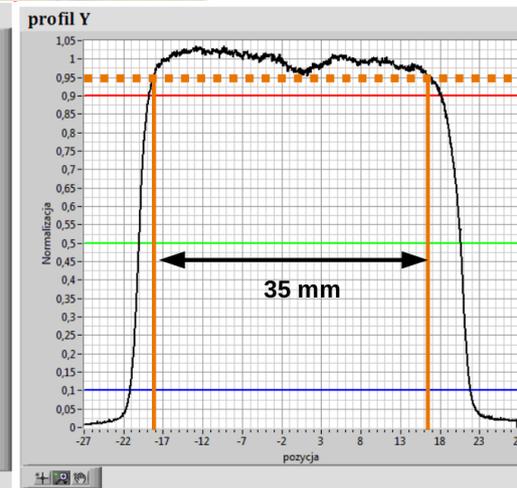
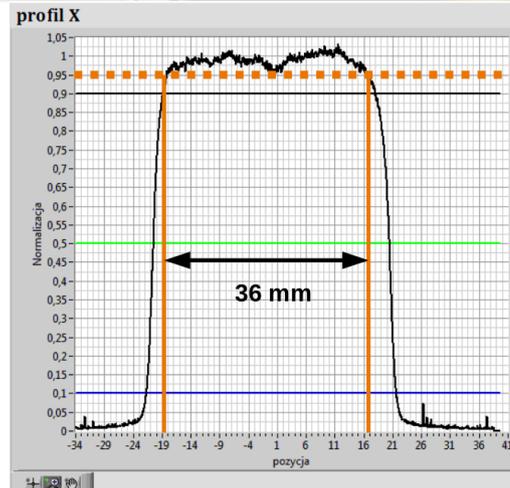
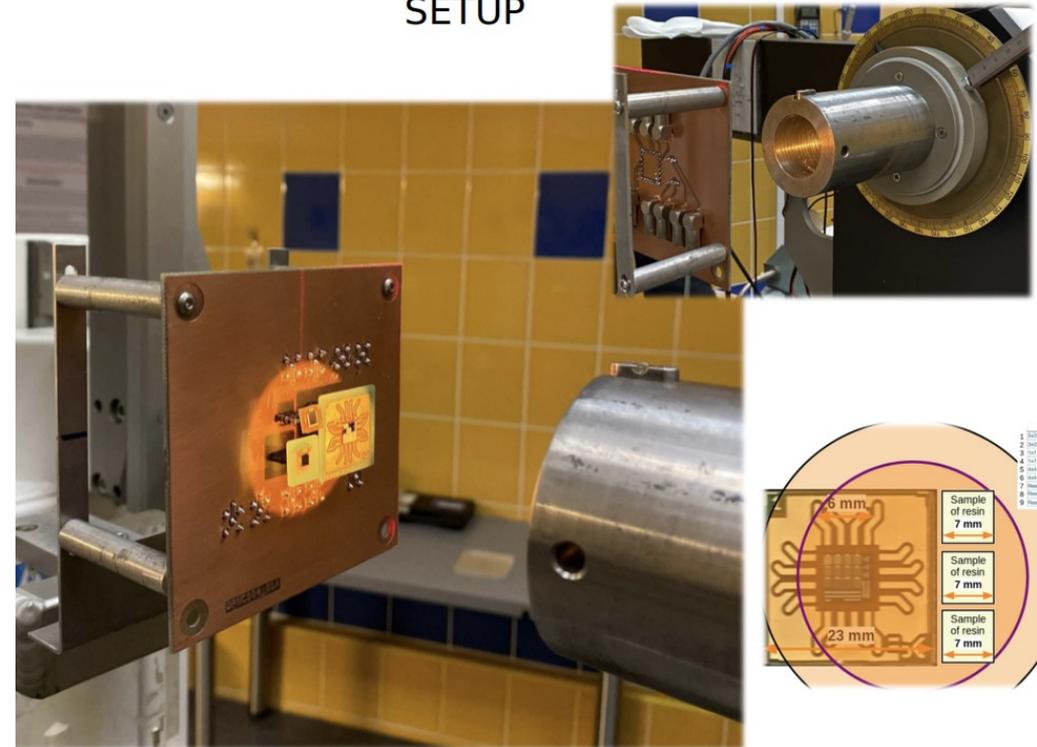
<https://www.ifj.edu.pl/>

EXPERIMENTAL
SETUP

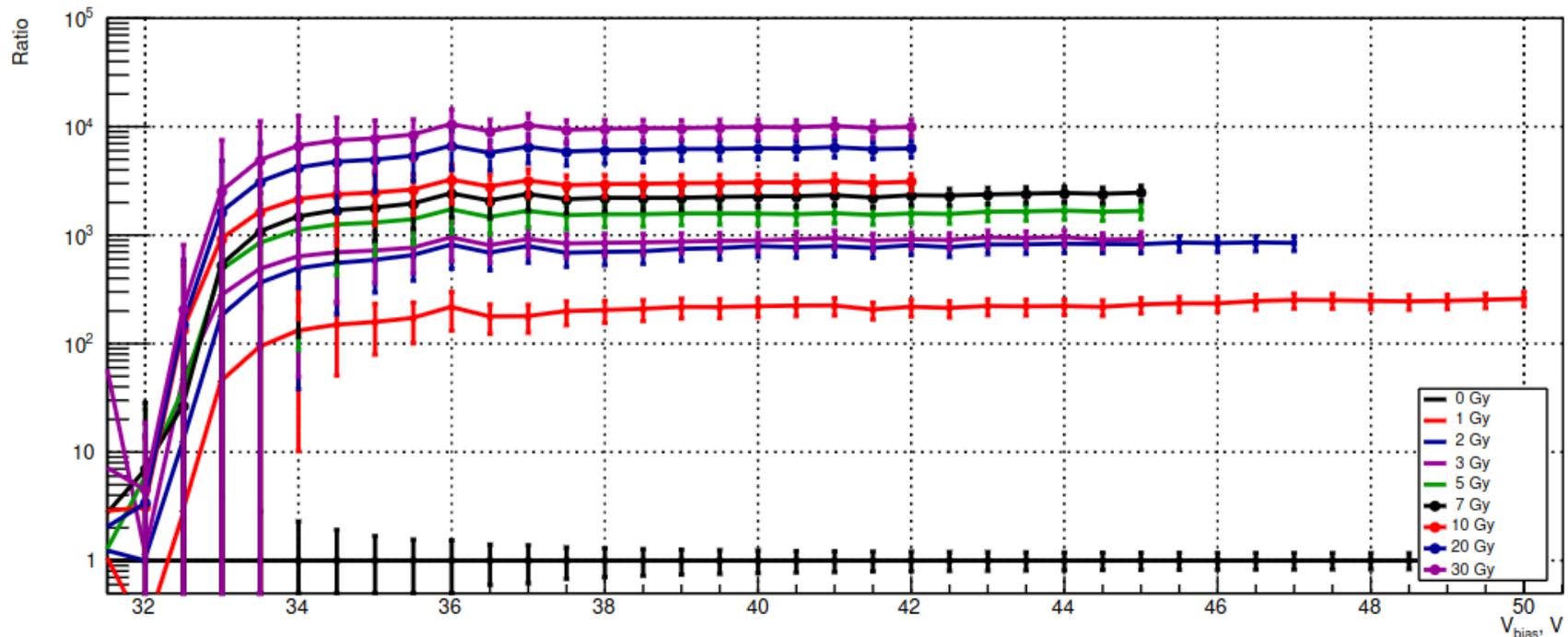
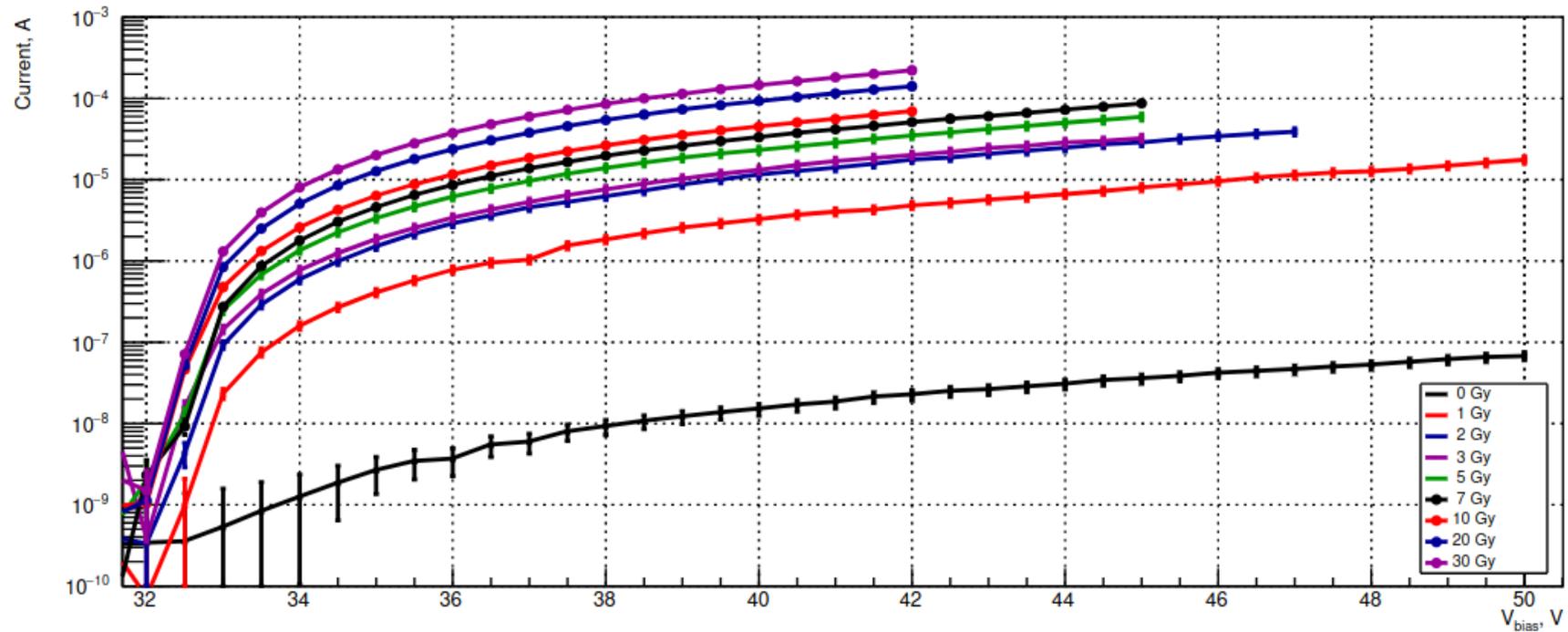


**Acknowledgments: IFJ-PAN and Jan Swakon
(responsible for proton irradiation campaign).**

- Energy: 0-58 MeV;
- Dose rate: 0.001 – 1 Gy/s (measured in water);
- Single scattering;
- Beam field size: ≤ 40 mm;
- Field homogeneity $\geq 5\%$;
- Min flux of protons: $5e5$ p/cm²·s (50MeV);
- Typical flux: $10e8$ – $10e9$ p/cm²·s;
- Irradiation in SOBP available;
- Sample positioning precision (> 0.1 mm);
- It is not possible to deposit high doses (>1 kGy);



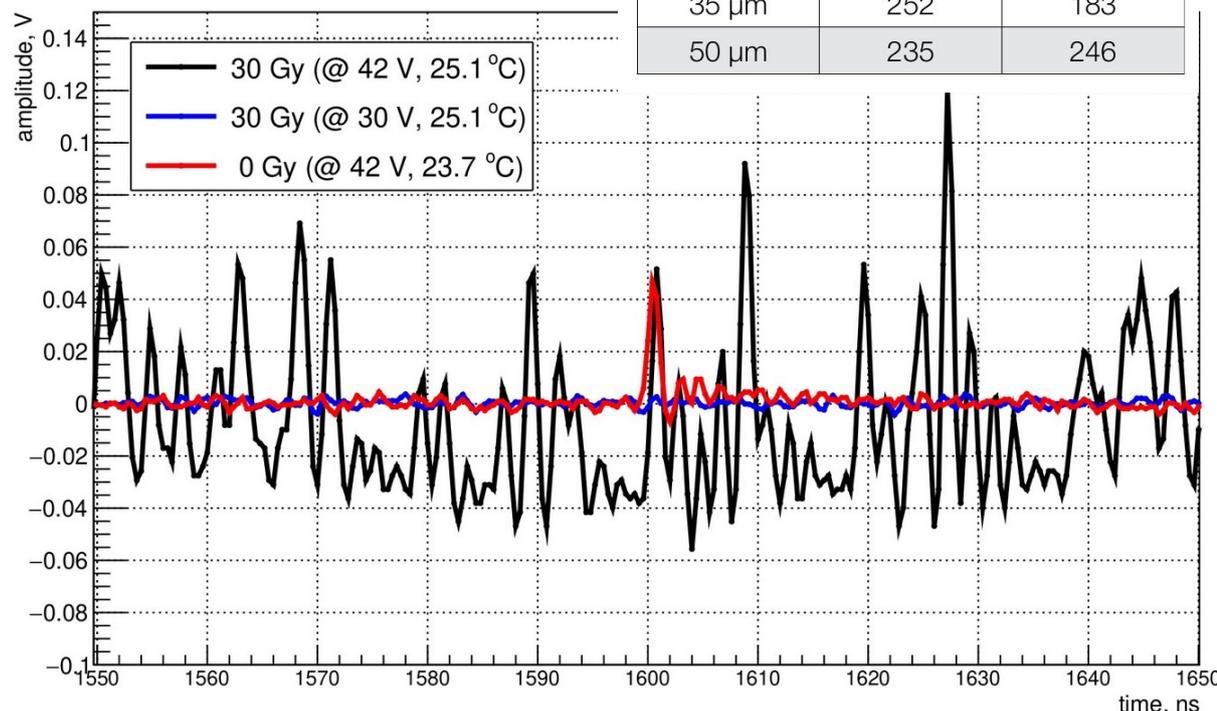
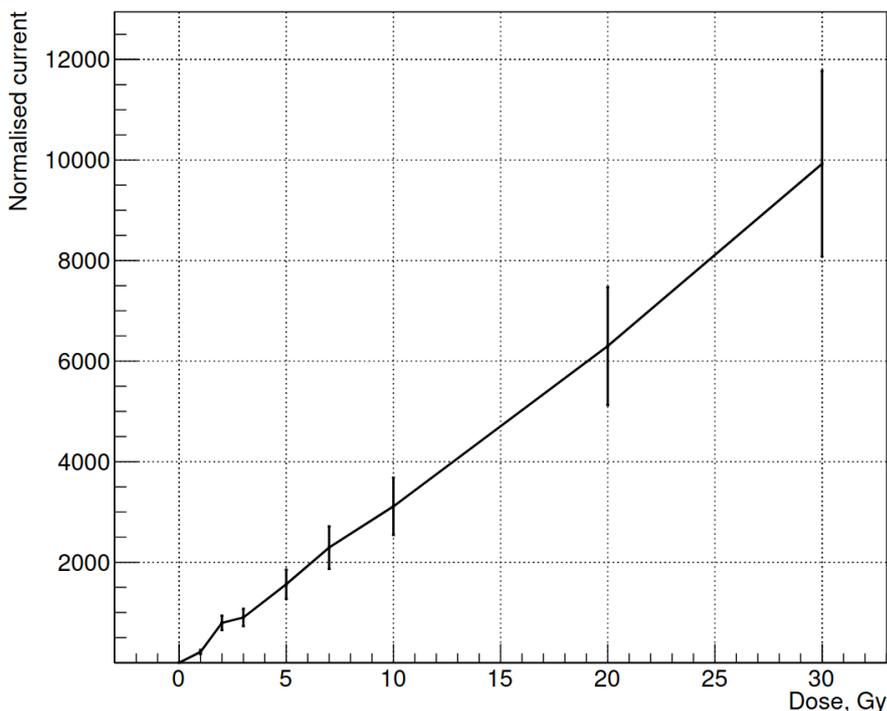
IV measurements after each irradiation step



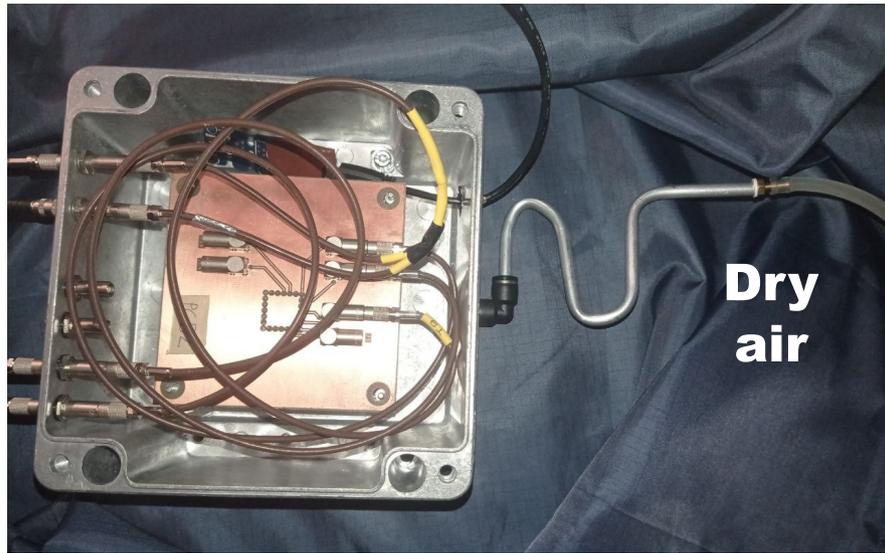
Results after irradiation test

- ➔ We observe linear increase of the DCR with irradiation dose.
- ➔ Standard characterization of the SiPM is impossible after irradiation.
- ➔ The PDE measurements can be done only with large number of photons, as a consequence large systematical are expected for this measurements.
- ➔ 30 % of the expected dose are coming from protons.
- ➔ We “simulate” 10 years on the orbit (planned mission duration is 3 years).
- ➔ No optical degradation of the resin samples have been observed.
- ➔ No change of the quenching resistor has been observed.
- ➔ No change of the V_{bd} behavior as a function of temperature measured.

Current multiplication per Gy		
	wo resin	resin
25 μm	350	100
30 μm	475	173
35 μm	252	183
50 μm	235	246

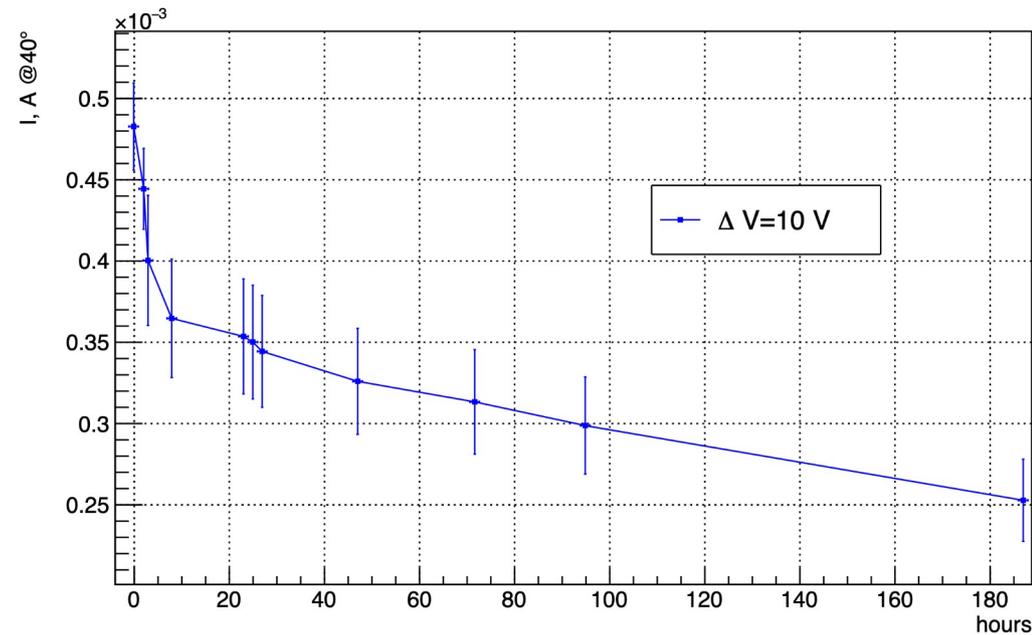
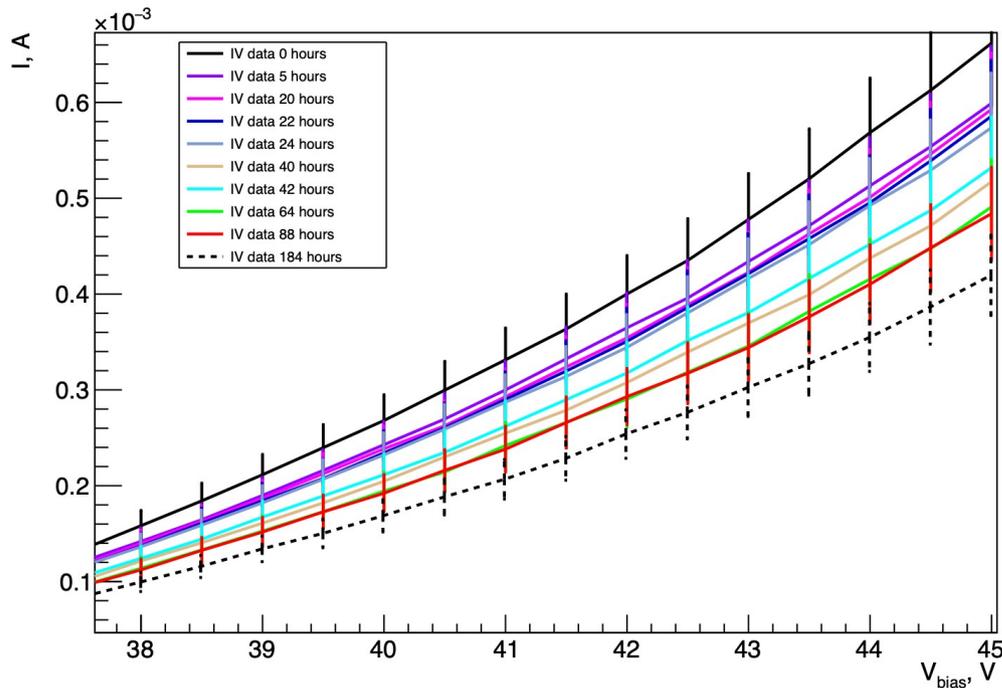


Annealing at 40 °C

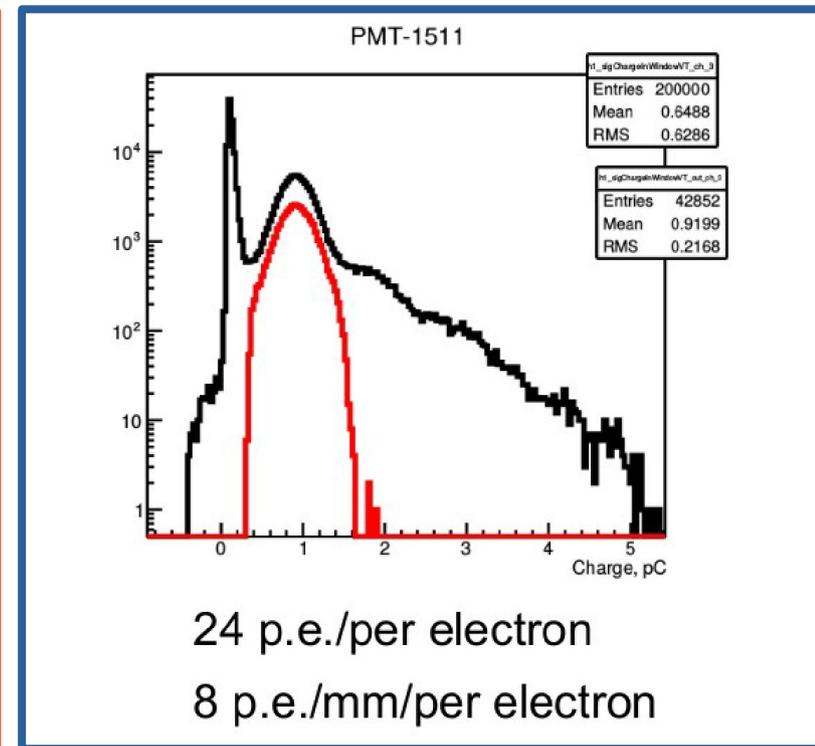
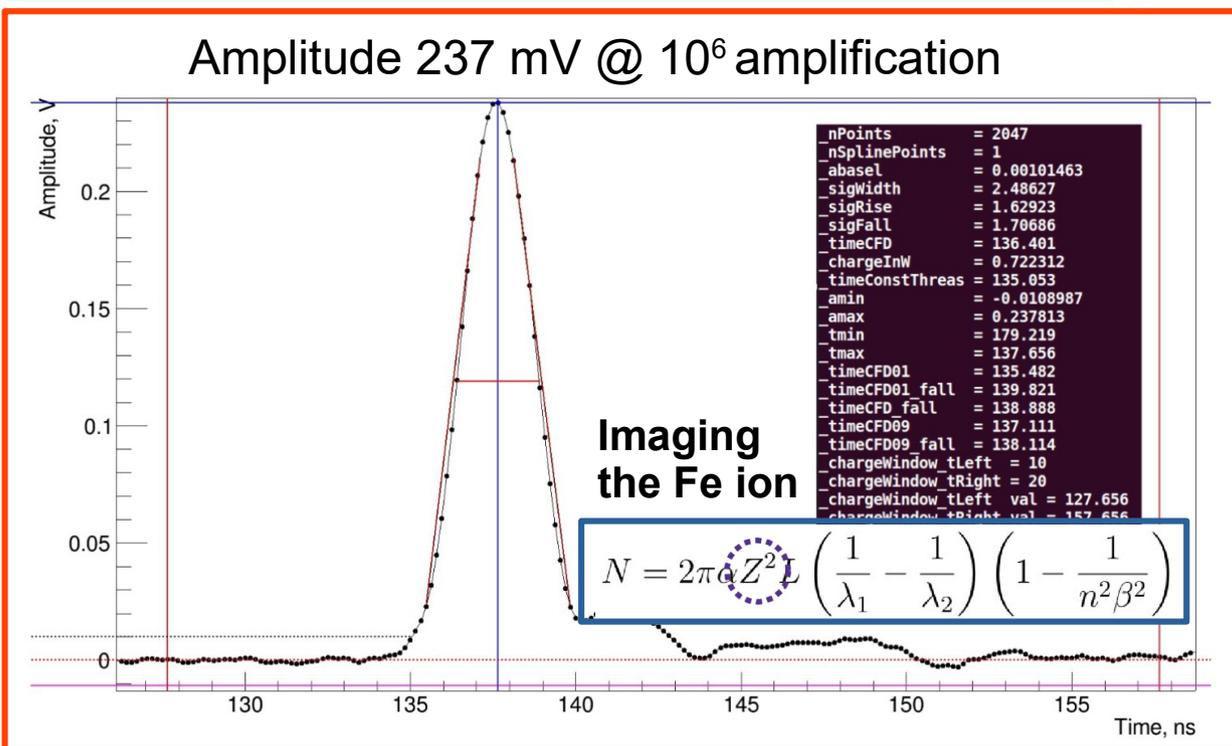
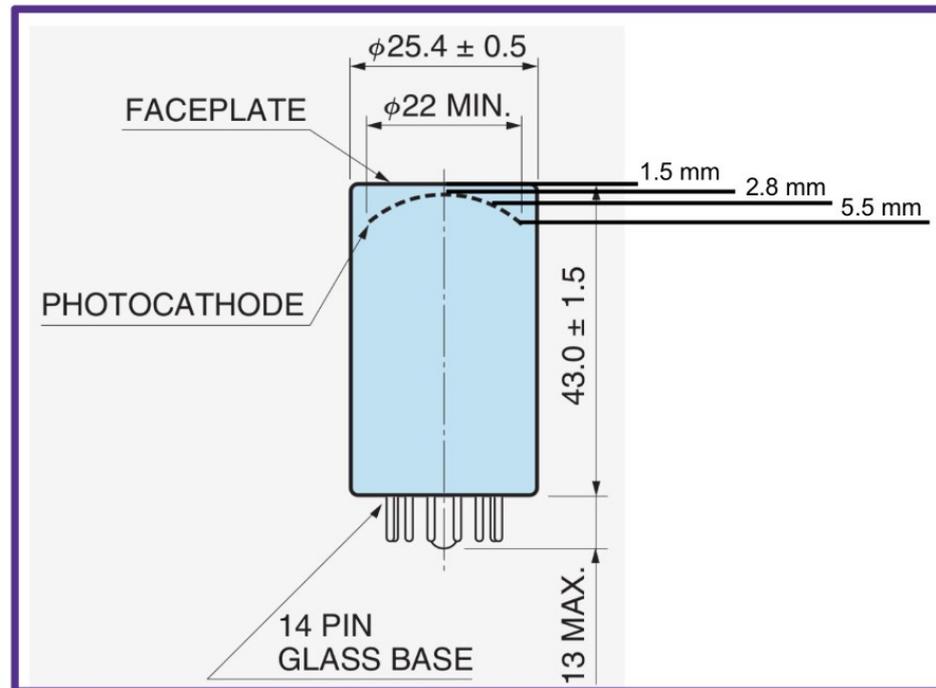
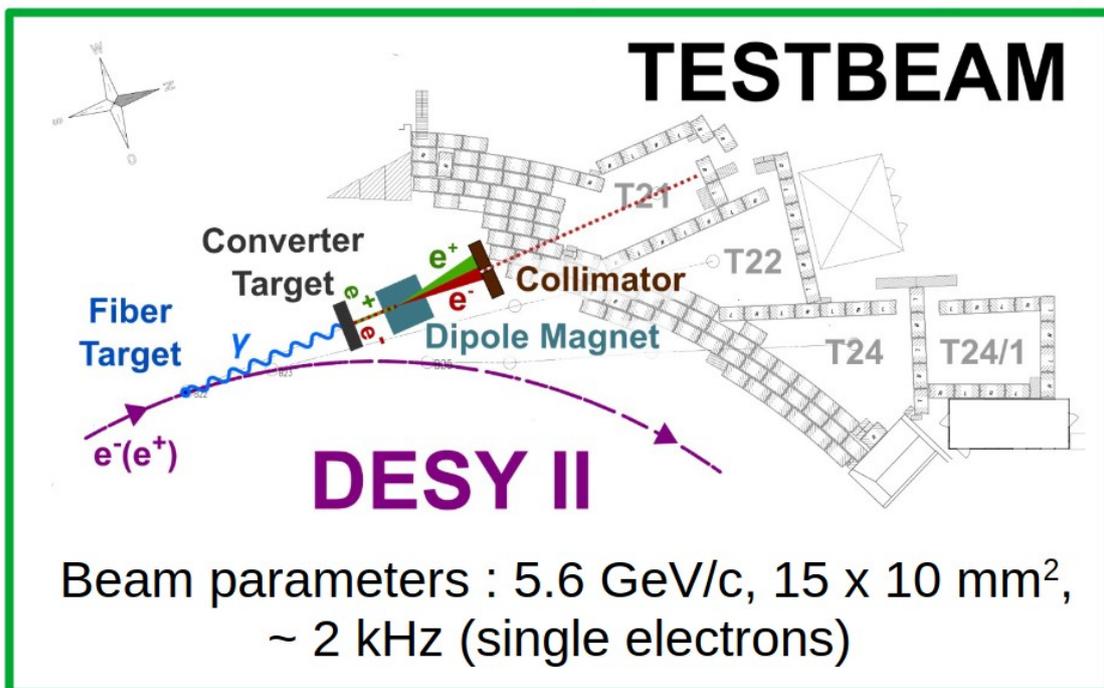


Climatic box, where we can vary the temperature from -20 to 80 °C

- The irradiated samples are stored at -20 °C to avoid room temperature annealing.
- We use the climatic chamber for temperature control.
- Measurements IV measurements were done every 2-5 hours (excluding nights).



How much light do we produce in the photo sensor window

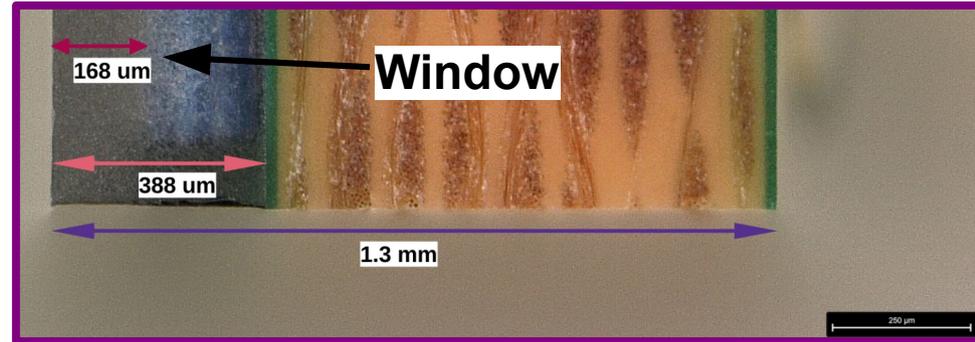


Bare SiPM or SiPM with thin window ?

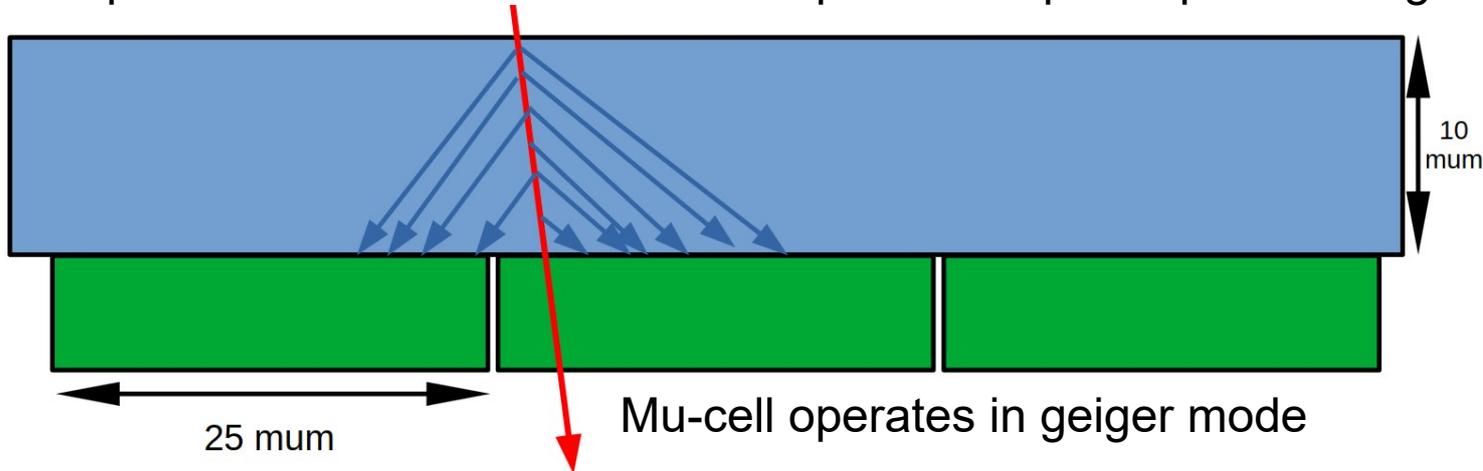
Thickness of the protective window 400 – 40 μm

Can we make it thinner ? 10 μm ?

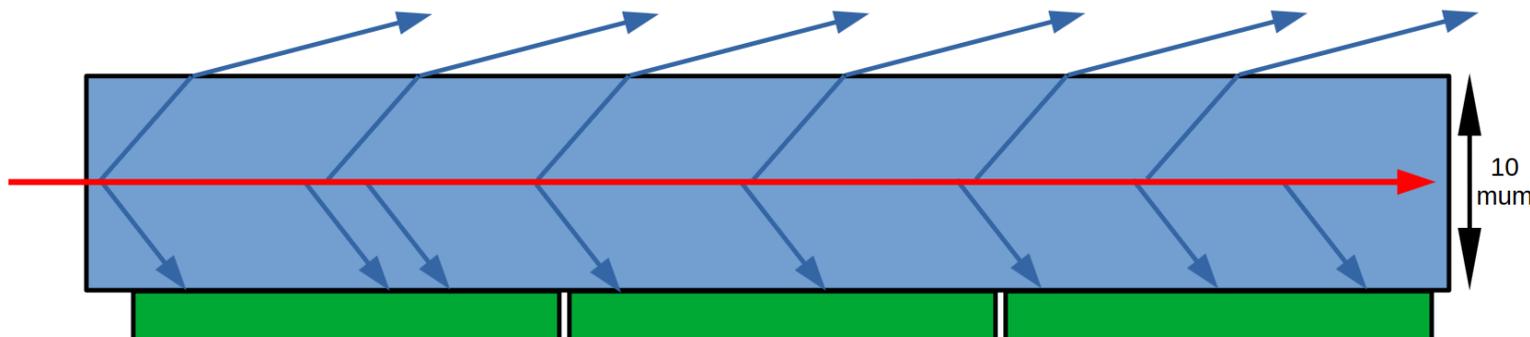
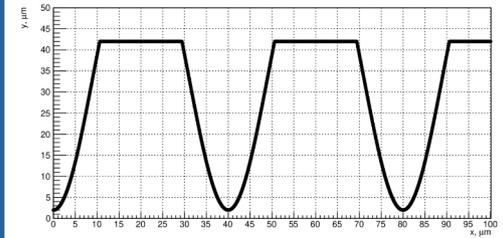
Can we completely remove it ?



Perpendicular track at maximum will produce 4 p.e. equivalent signal



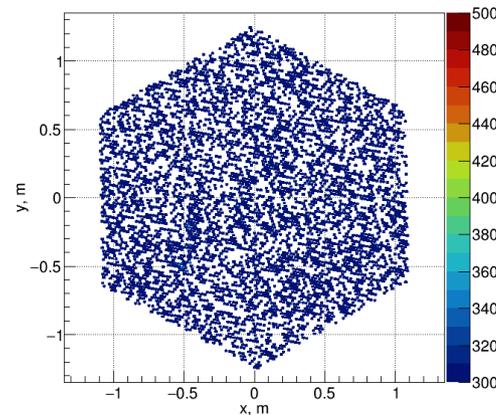
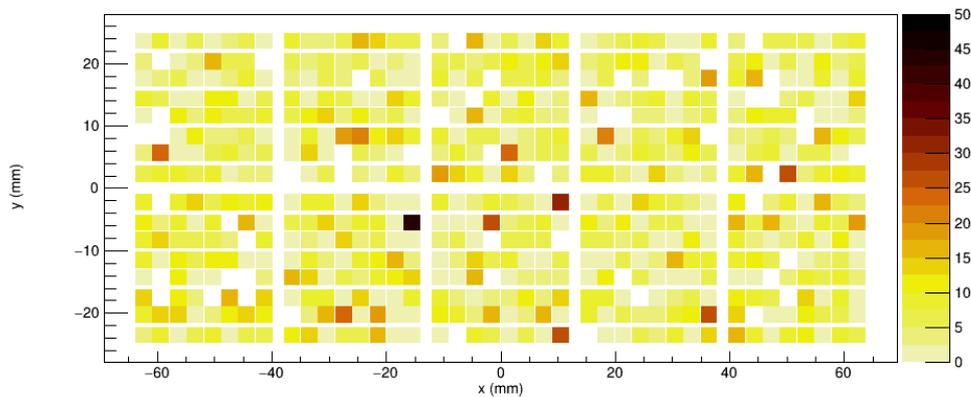
If the bare surface is not planar very thin resin can form micro-lenses need to have additional R&D.



This effect can be vanished by removing the window :-)

Conclusions

- ➔ SiPM are promising photo sensors to be used for space base experiments.
- ➔ We present full chain of different activities for Terzina telescope on board the NUSES space mission.
- ➔ We present the parametric simulation of the SiPM used in the full simulation chain.
- ➔ We characterize SiPM with different mu-cell sizes with and without resin.
- ➔ The radiation test with 50 MeV protons up to 30 Gy integrated dose (corresponds to 10 years on the orbit).
- ➔ SiPM annealing at 40 °C has been studied.



```
wf_time : 0 ns
_proton
event_id : 3590000
energy : 76753 GeV
xcore : -632 m
ycore : 180 m
ev_time : 543 ns
nphotons : 57735
n_pe : 12419
n_pixels : 2434
```

Backup

