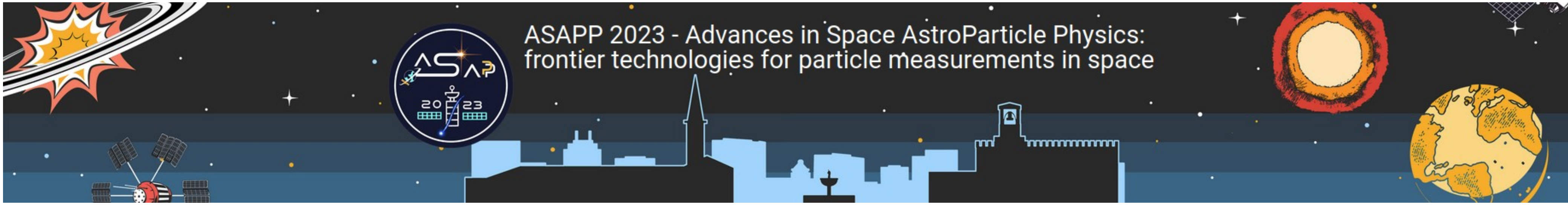
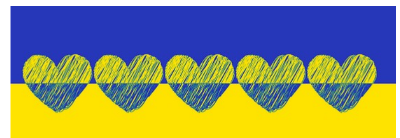


A SiPM based camera for the Terzina telescope on board the NUSES space mission

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

IFJ PAN

EURO-LABS European Laboratories for Accelerator Based Sciences

FBK Fondazione Bruno Kessler — Future built on knowledge

GSSI Gran Sasso Science Institute — School of Advanced Studies — Scuola Universitaria Superiore

The NUSES Collaboration

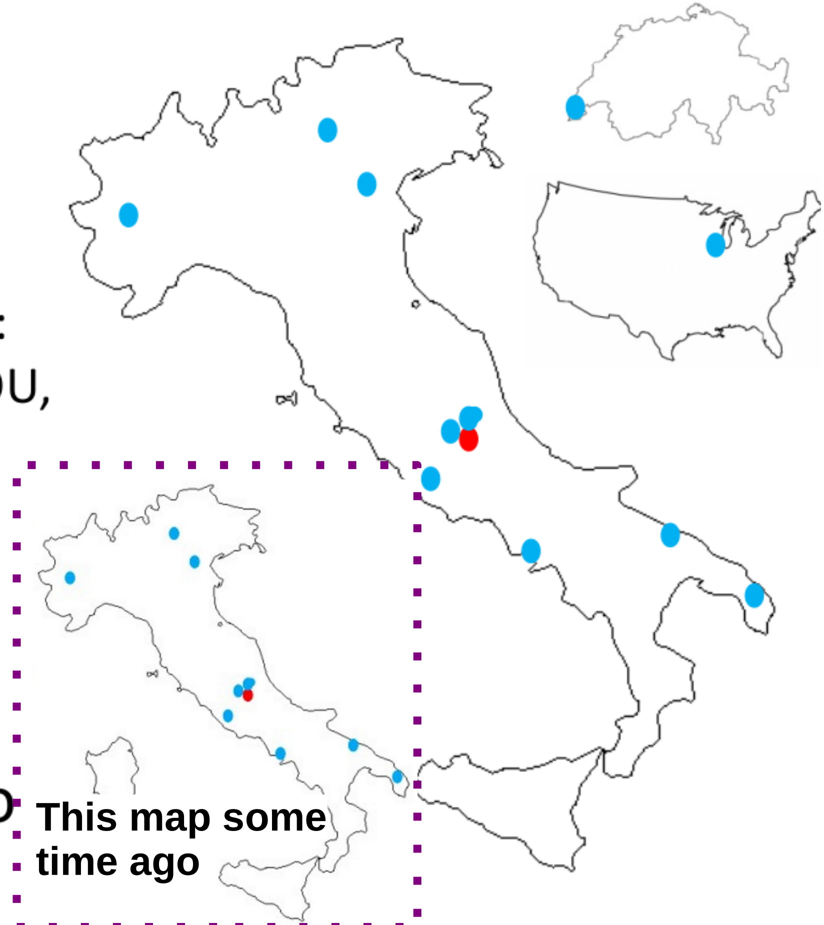
60+ persons from many institutions.

Large expertise (and sinergies) 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



This map some time ago

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** throught 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

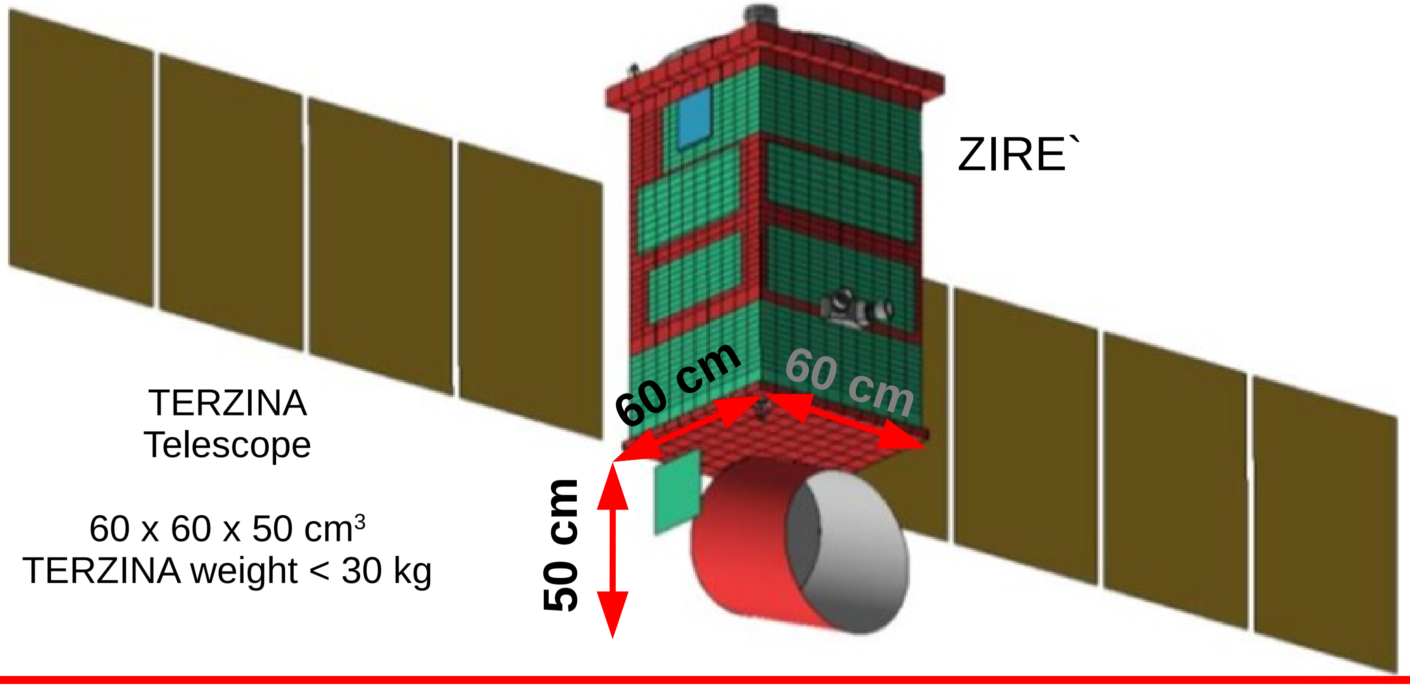
New technologies and approaches

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.



TERZINA
Telescope

60 x 60 x 50 cm^3
TERZINA weight < 30 kg

Two main components :

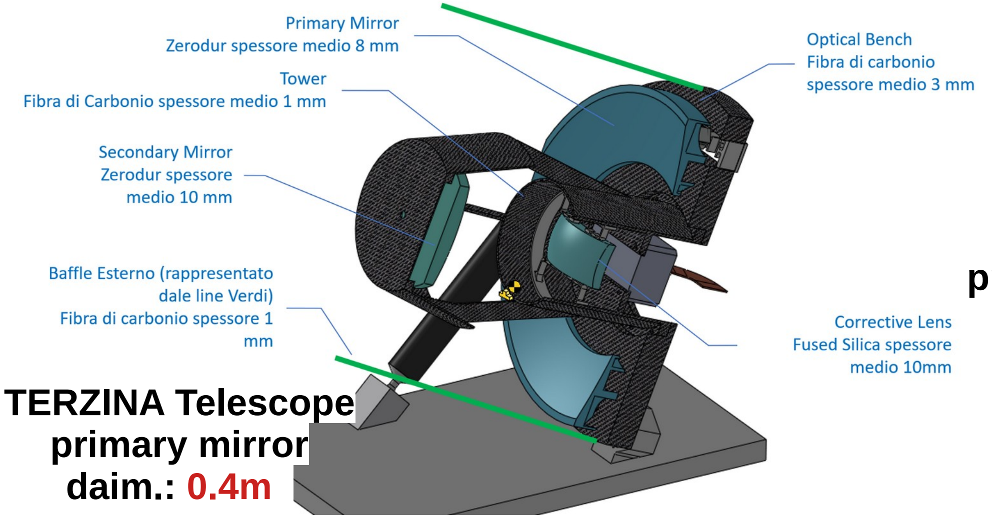
ZIRE

TERZINA

TERZINA Demonstrator of Cherenkov light detection produced by Extensive Air Showers
- First measurement of showers with Cherenkov light from space (E>100PeV)
- 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 MeV),
- Electrons and protons to study Van Allen radiation belts
- Space weather and the magnetosphere-ionosphere-litosphere couplings
- And much more ….

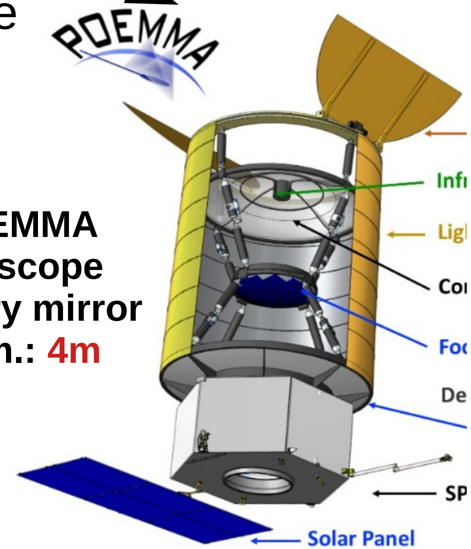
Camera vs POEMMA



TERZINA Telescope primary mirror daim.: 0.4m

Probe

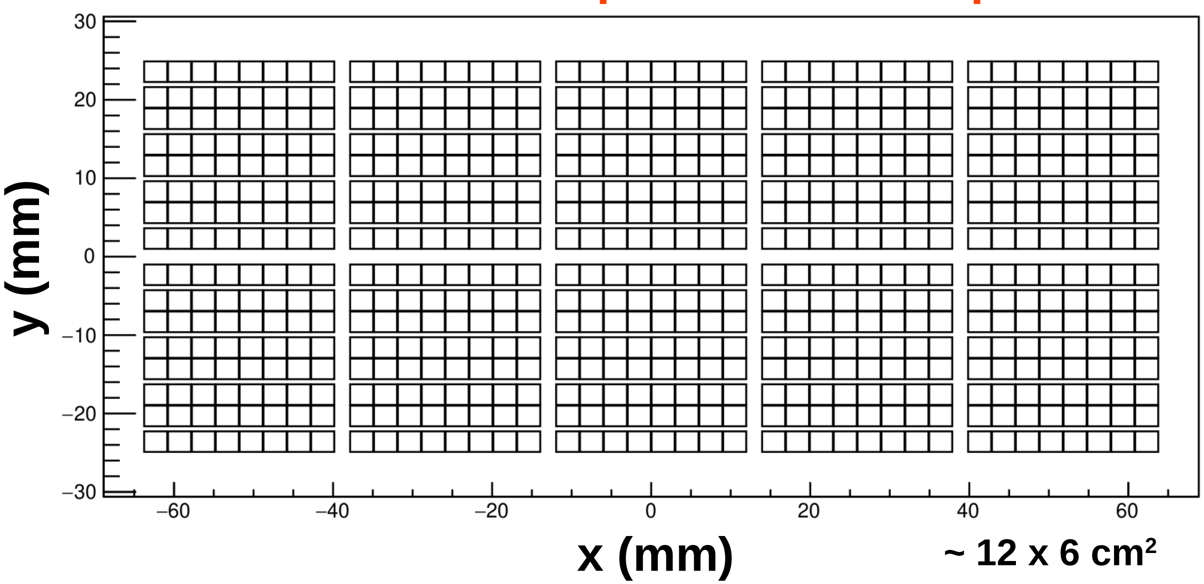
POEMMA Telescope primary mirror daim.: 4m



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

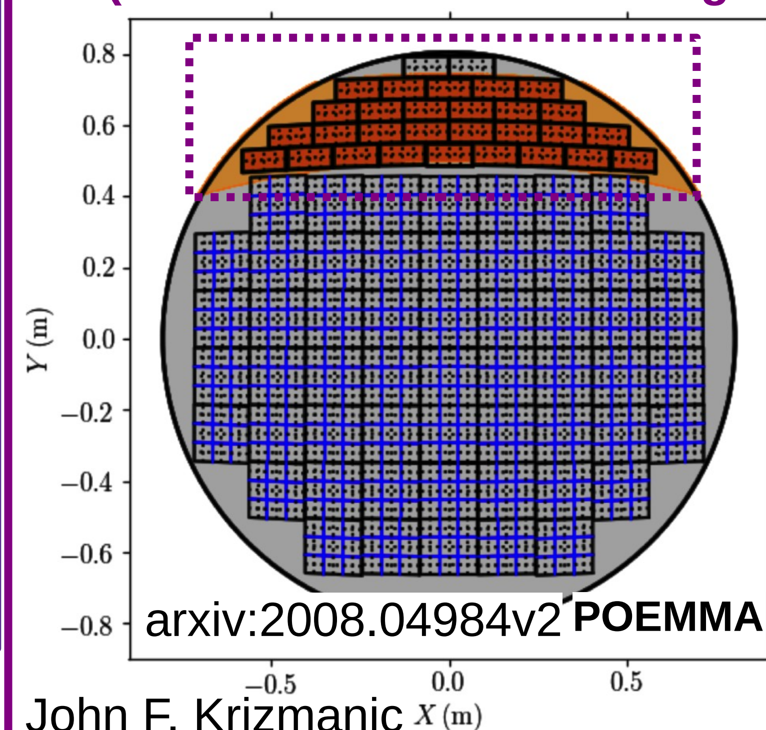
Mission	(2 Telescopes)
Lifetime	3 year (5 year goal)
Orbit	525 km, 28.5° Inc
Orbit Period	95 min

TERZINA SiPM photo detection plane



~ 12 x 6 cm^2

SiPM part (Detection of Cherenkov light)



arxiv:2008.04984v2 **POEMMA**

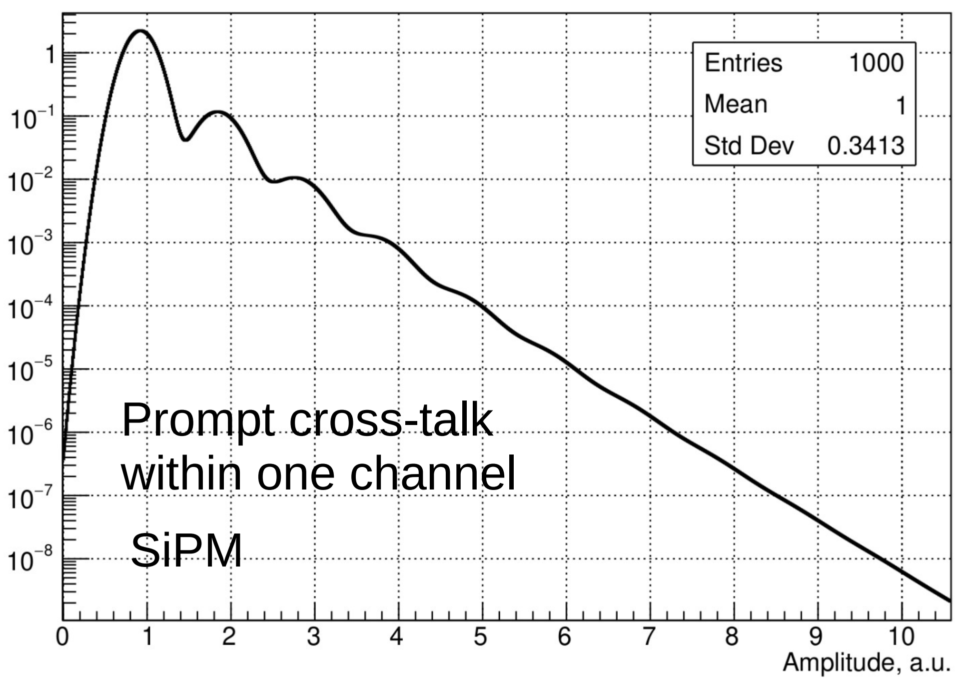
John F. Krizmanic

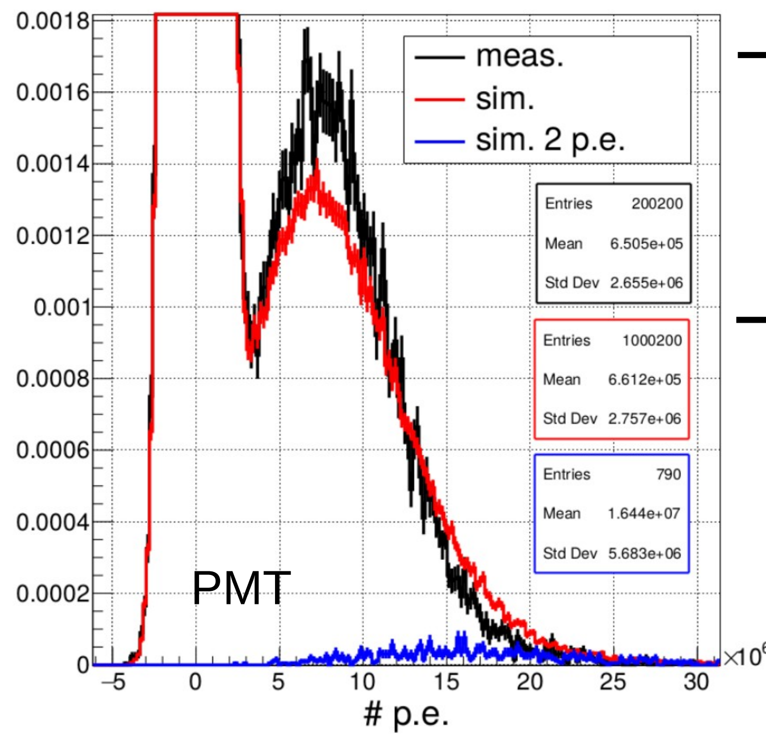
SiPM vs ma-PMT (PMT)

Operation voltage	<100 V	~1000V
Currents	~1 muA	~100 muA
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



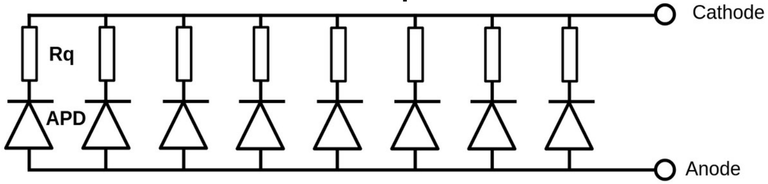


→ Change sharing between anodes.

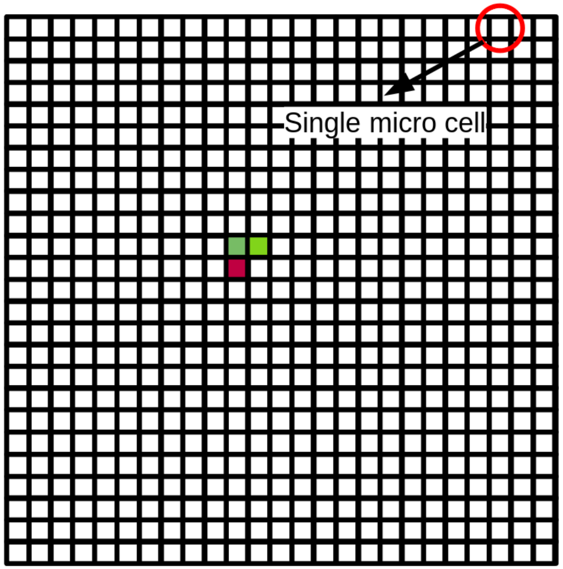
→ Large variation of the response defined by secondary emission

Parametric SiPM simulation

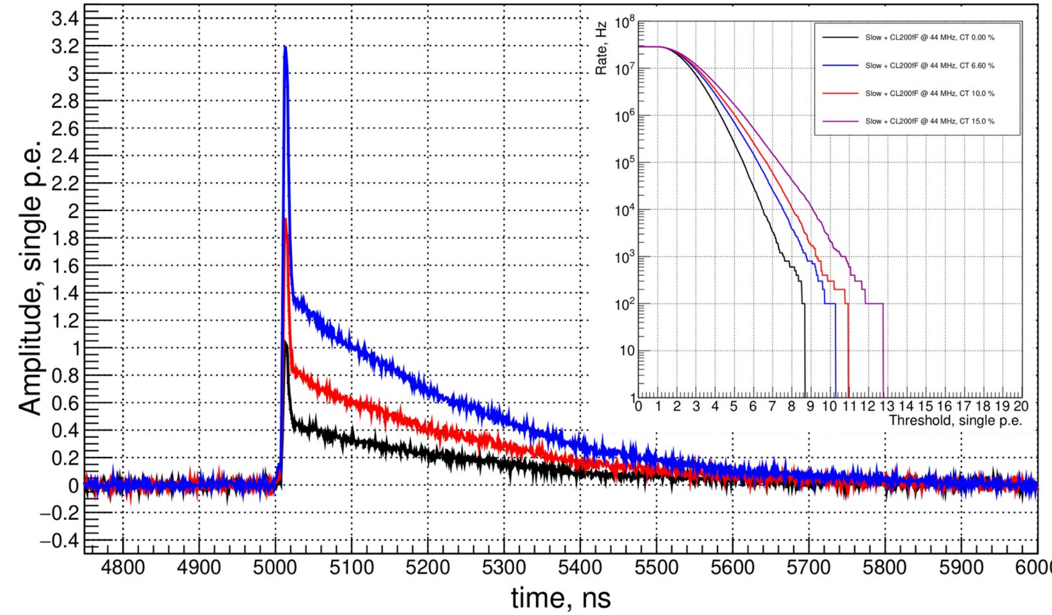
SiPM all the cells are connected in parallel



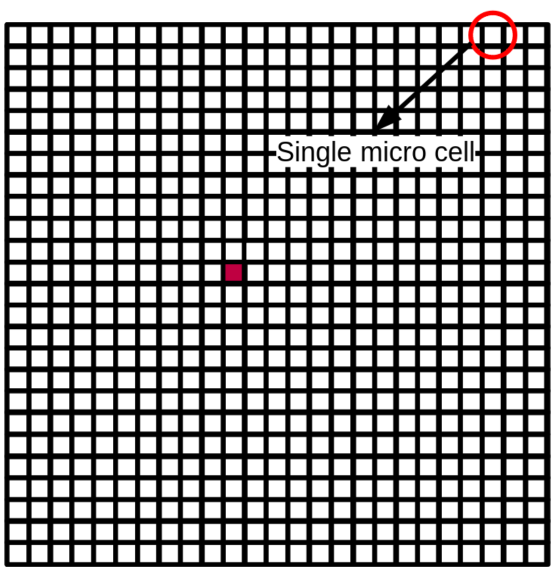
Prompt cross talk.

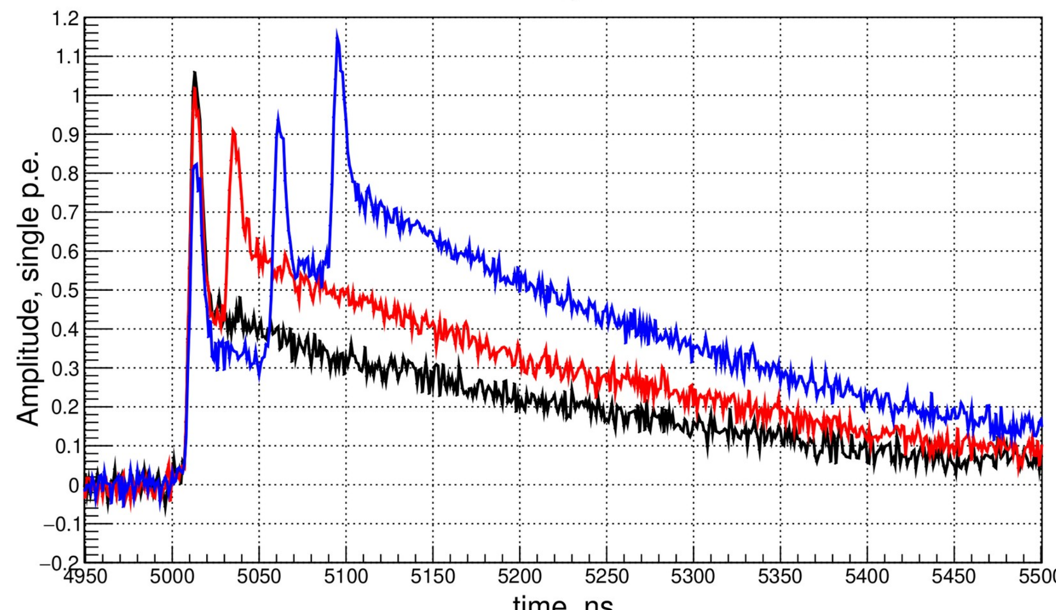


In simulation we include as well :
Gain variation, electronic noise, pre-amplifier, ADC.



After pulsing





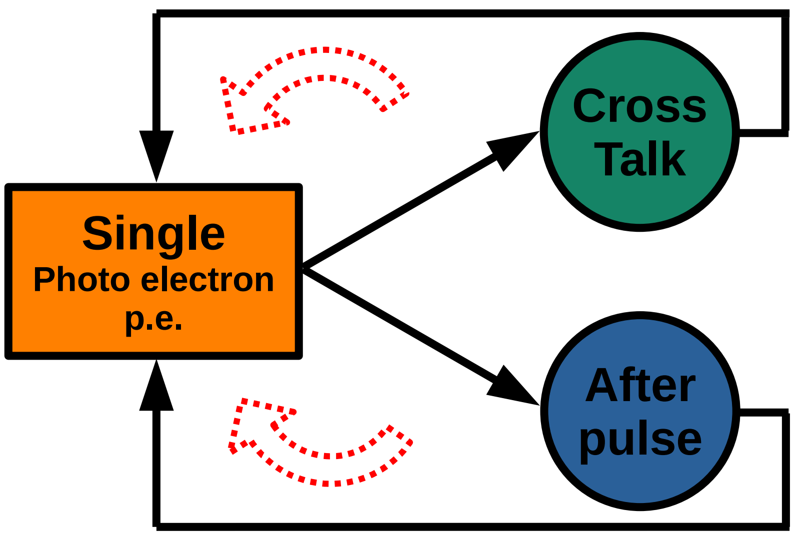
L. Burmistrov Delayed crosstalk imposed in other pixels is not simulated.

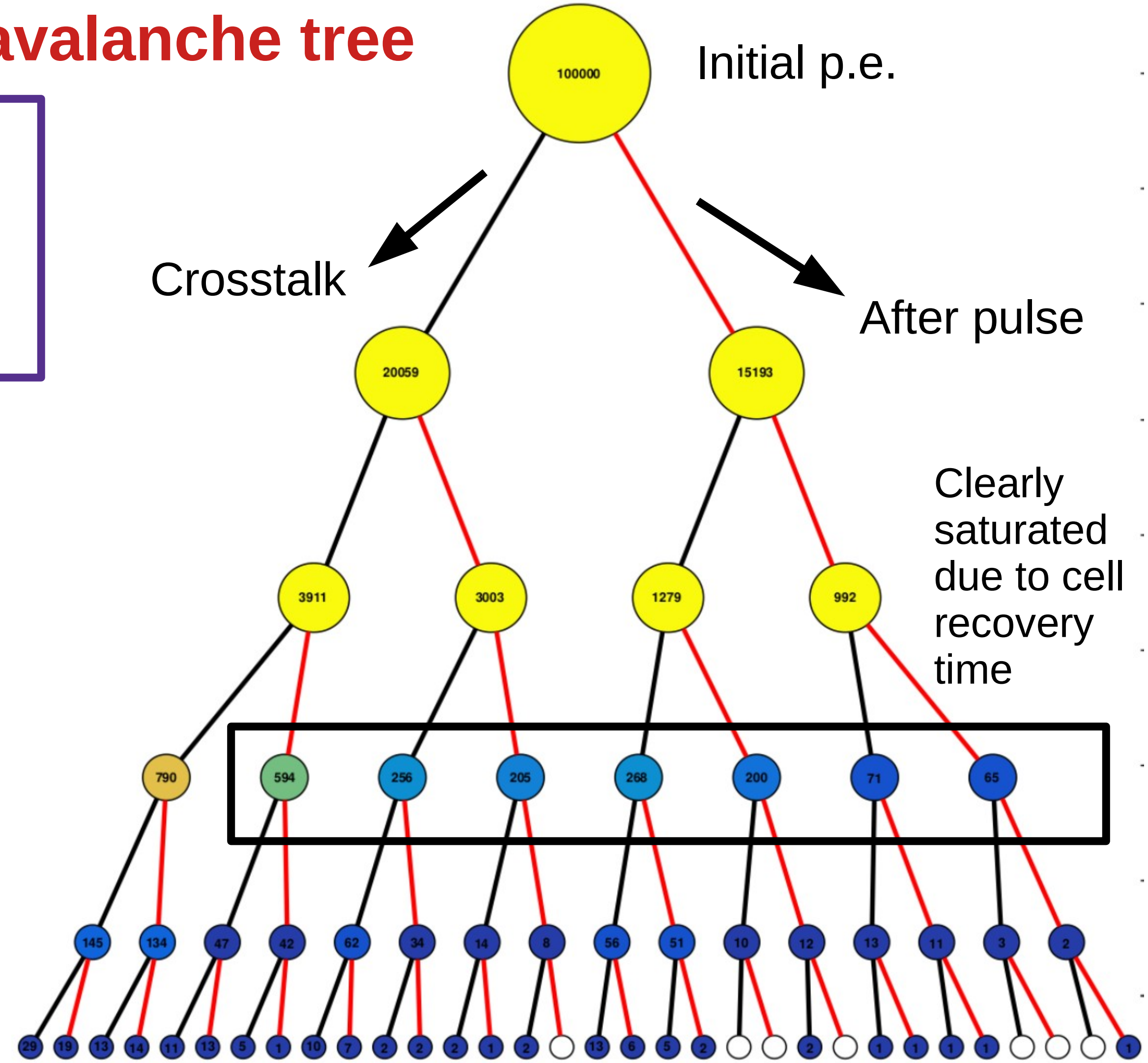
Single p.e. avalanche tree

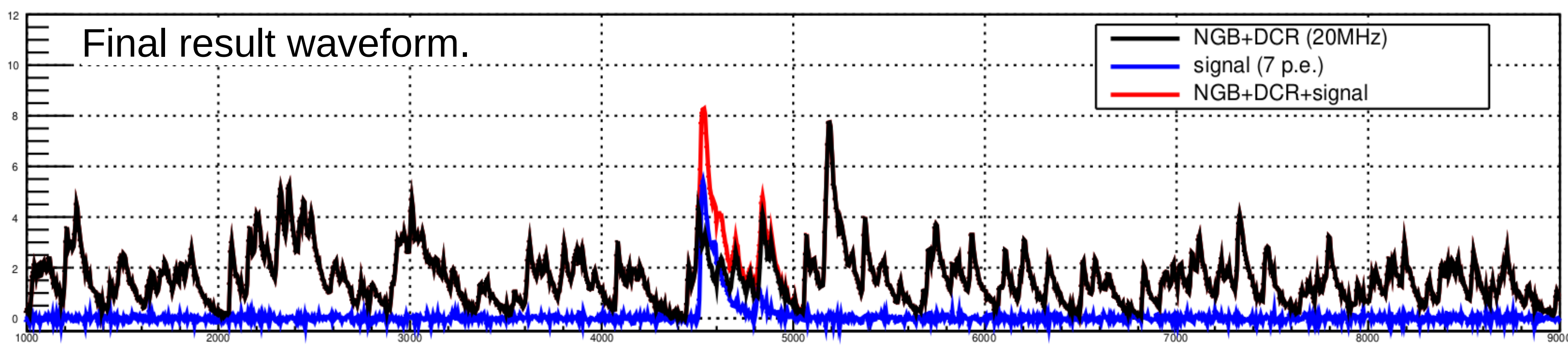
Trial parameters for generator testing:

Probability of the cross talk is set to 0.2
Probability of the after-pulse is set to 0.15
And after pulse decay time 15 ns.

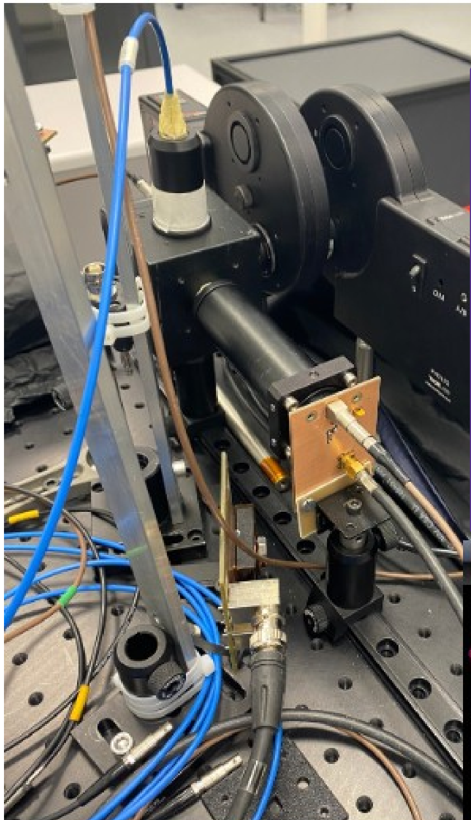
Recurrent process

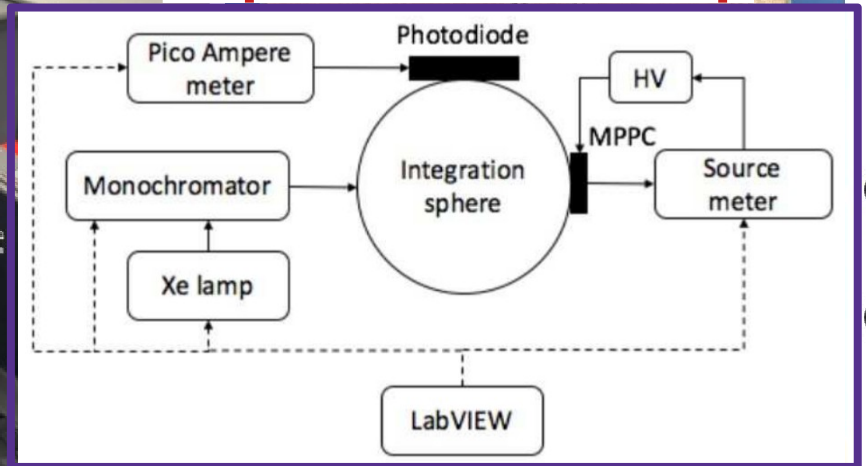




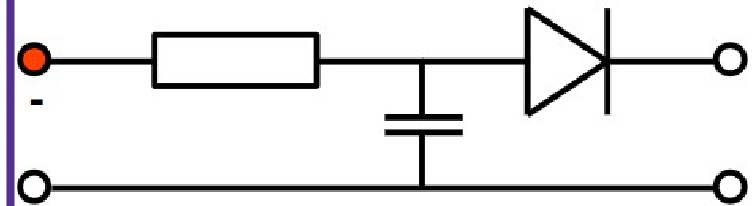


Experimental setup

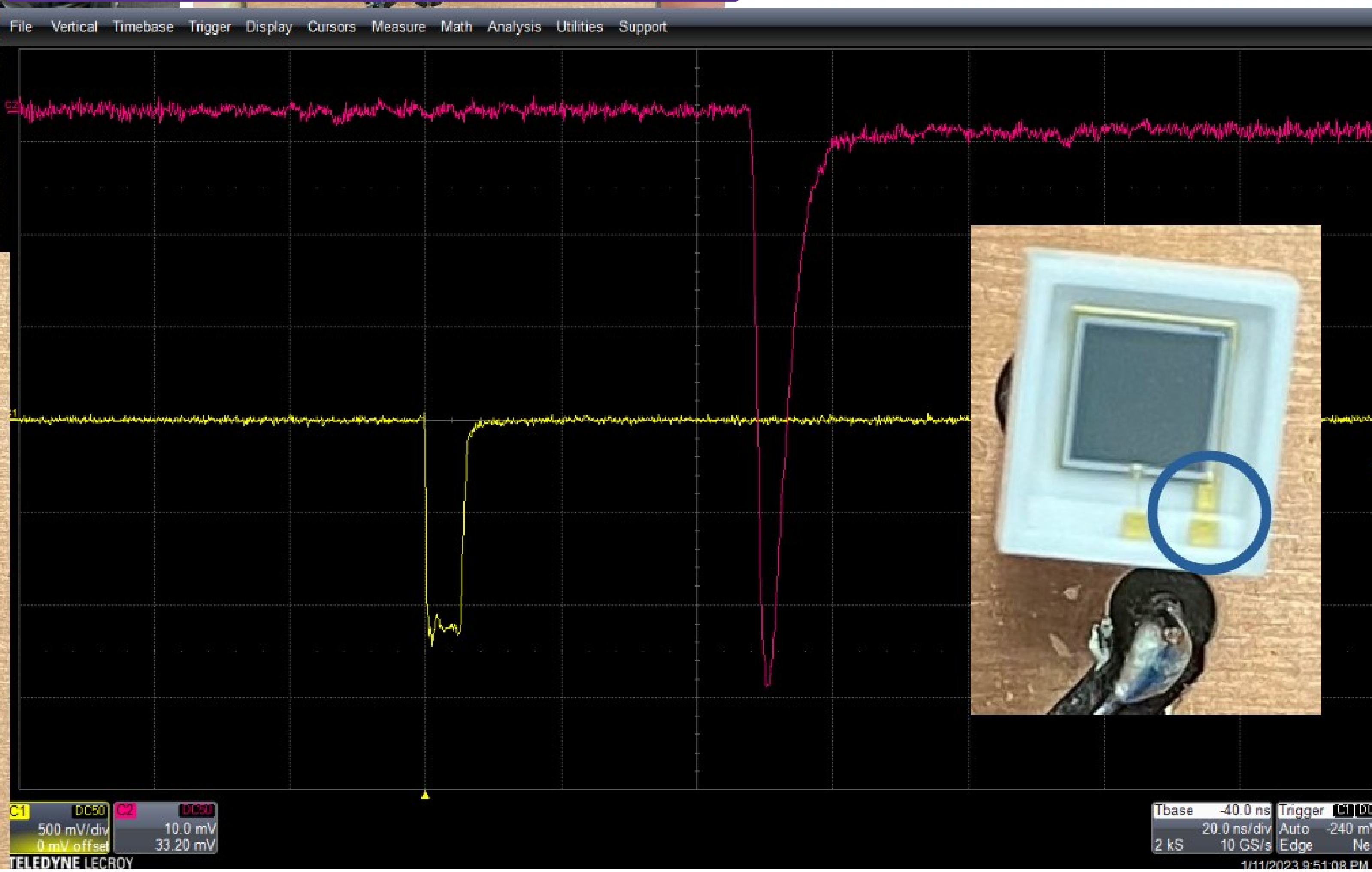


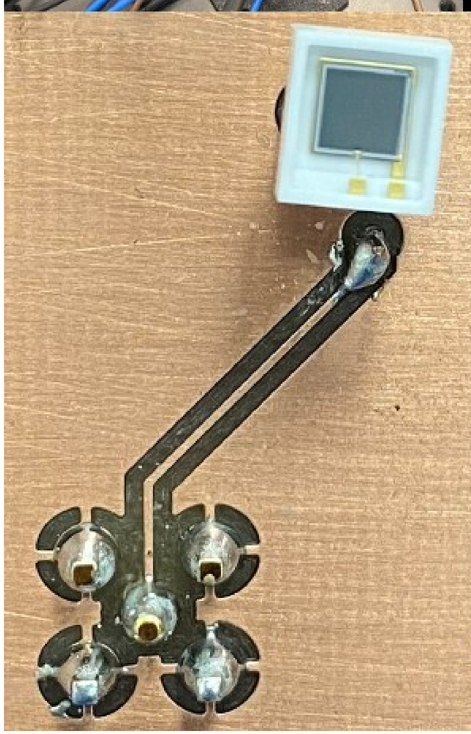


Hamamatsu 2021 (Vbias -54 V)



Read cathode

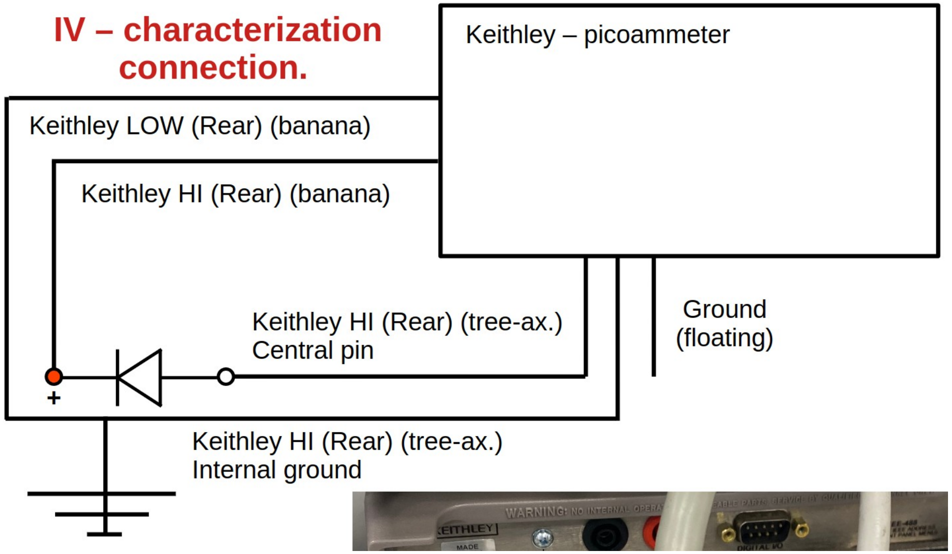


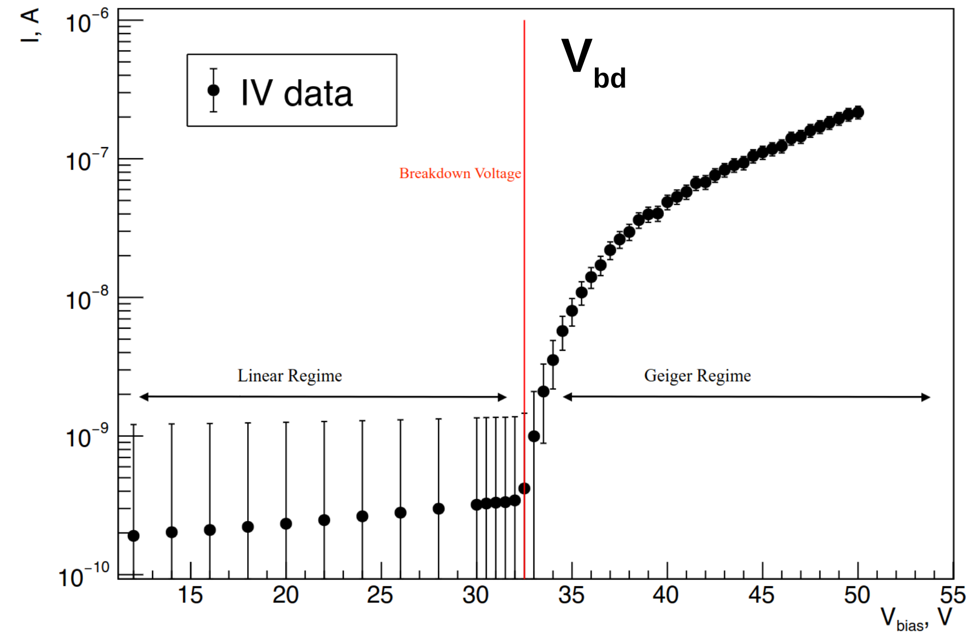


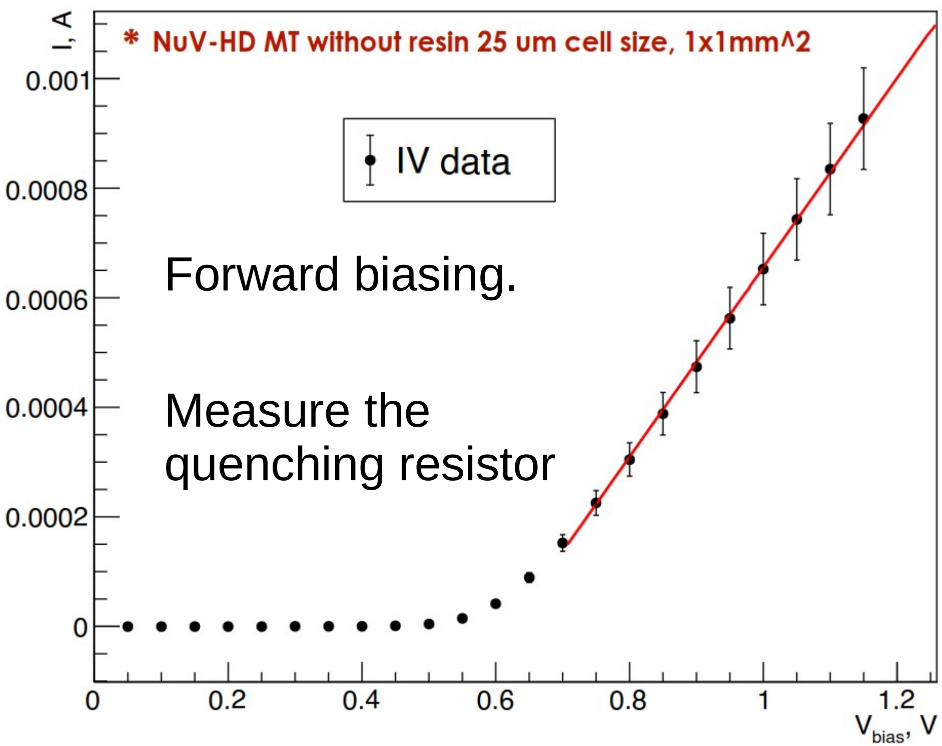
SiPM characterization : $V_{break\ down}$ (V_{bd})

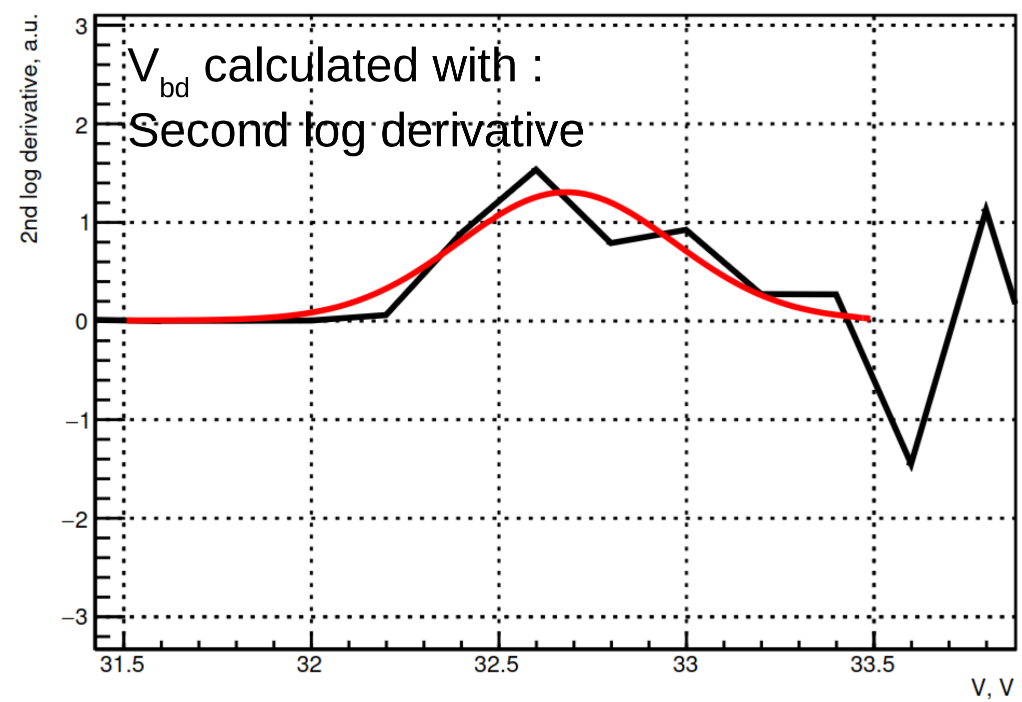
Break down voltage – defines when SiPM start to detect light. It is a function of a temperature.

IV – characterization connection.

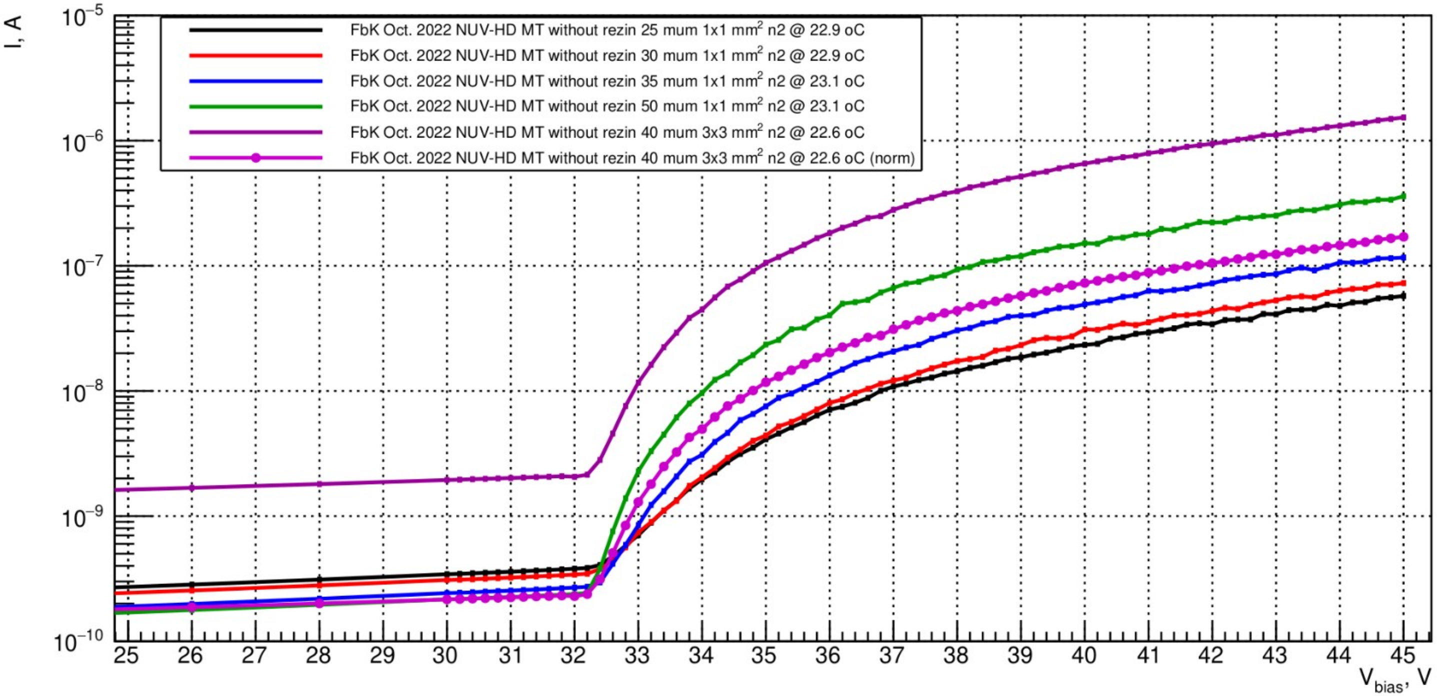






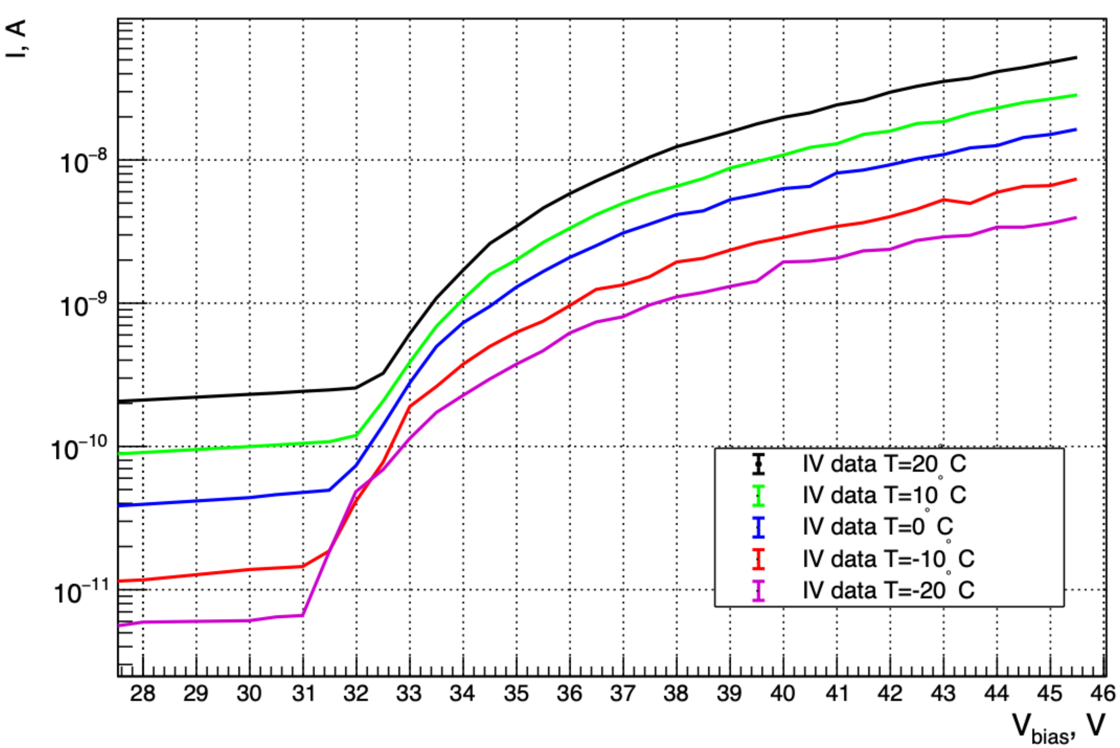


SiPM characterization : IV curves for different mu-cell sizes.



Cell size ↑

Current at same V ↑



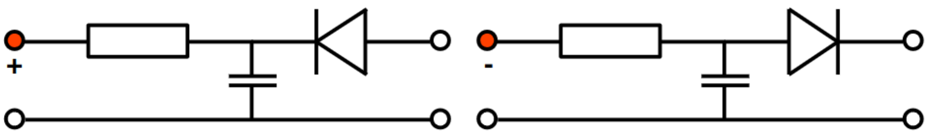
V_{bd} as a function temperature

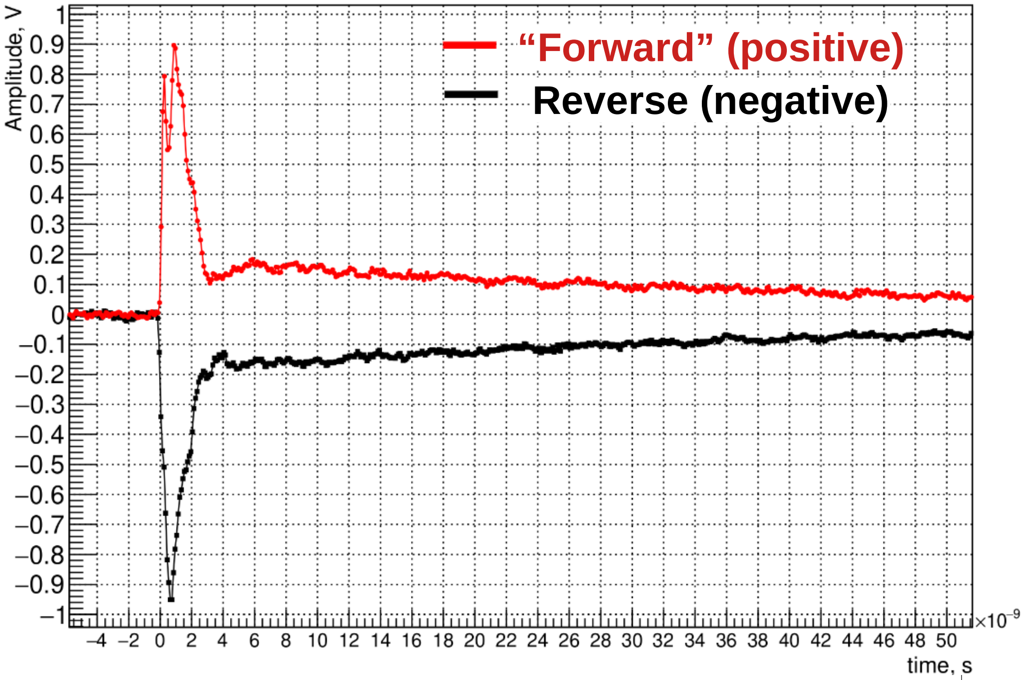
Temperature ↑

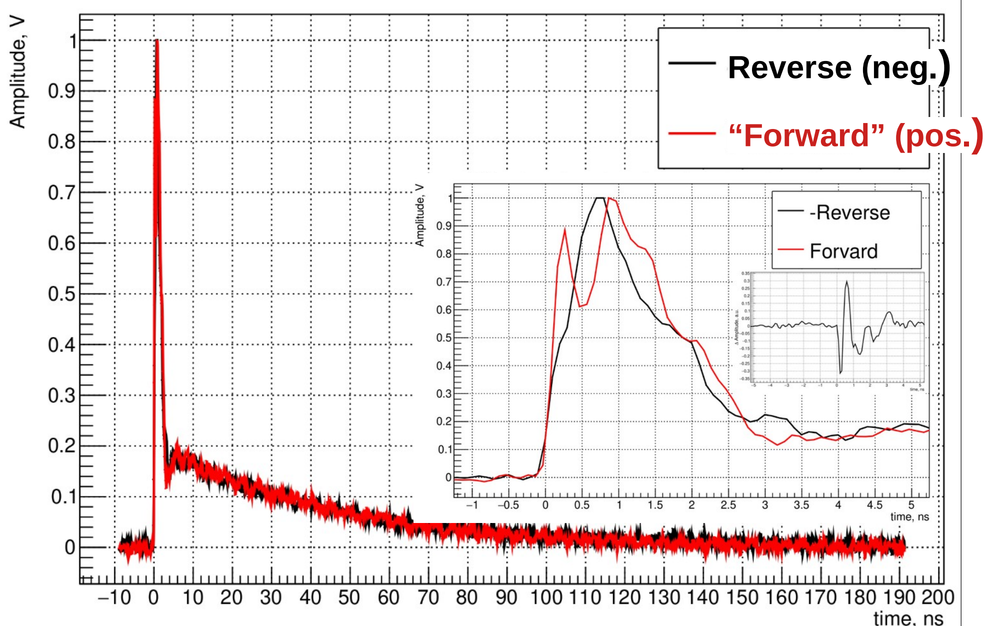
V_{bd} ↑

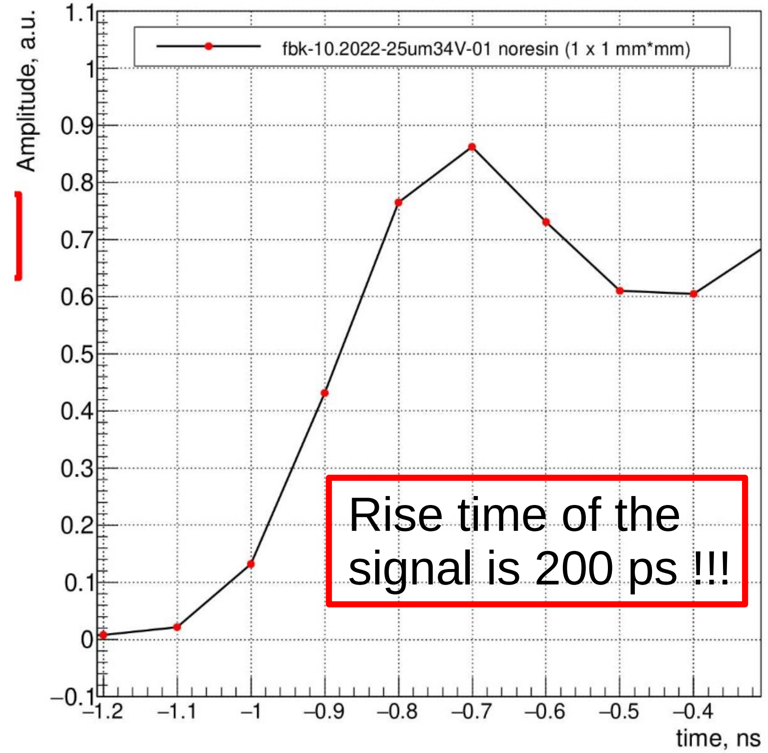
~32.6 V (20°C)
~31.2 V (-20°C)
Temperature coefficient is 33mV/°C

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

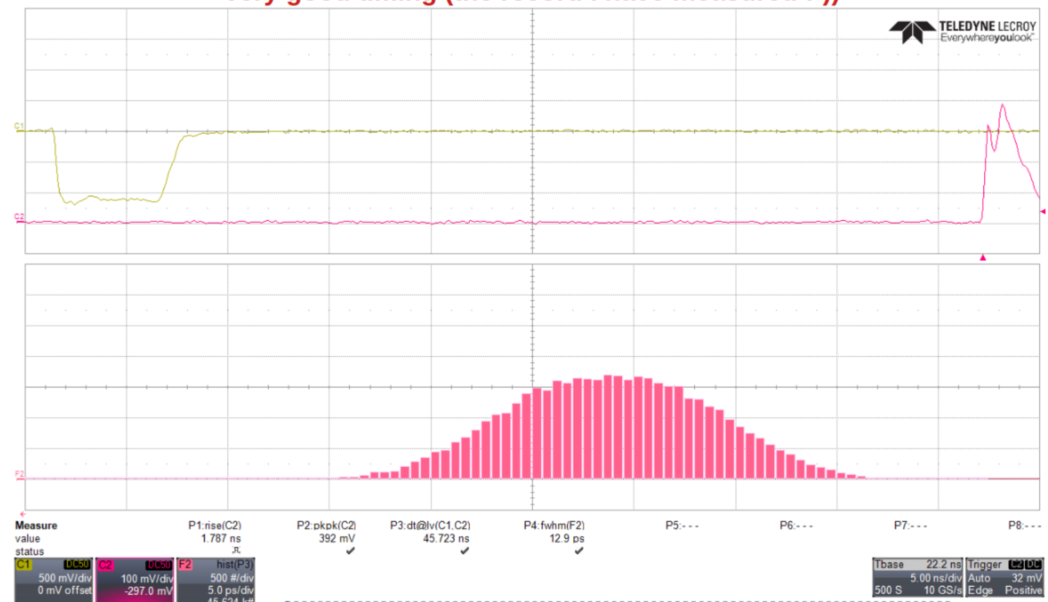








Very good timing (the record I have measured :-))

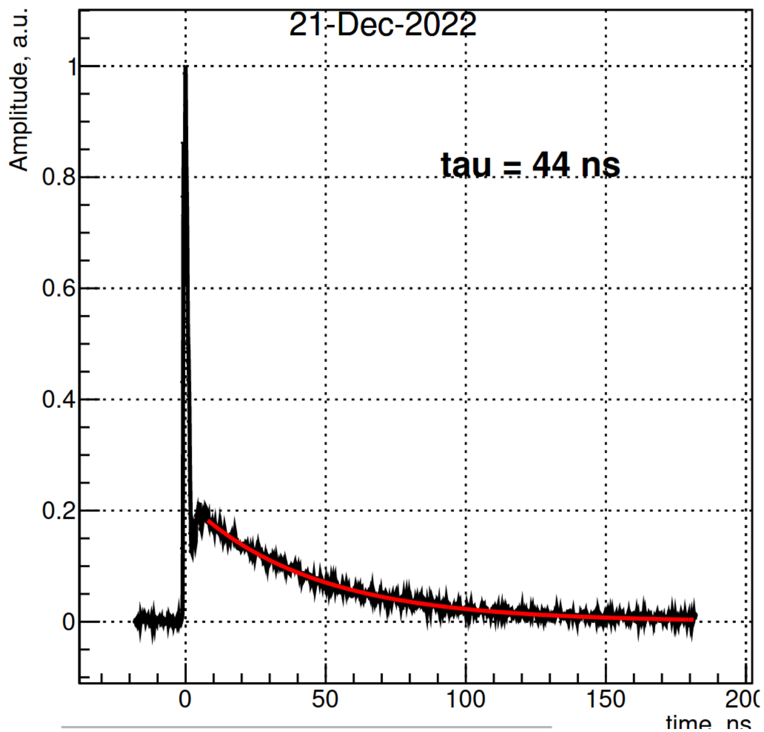


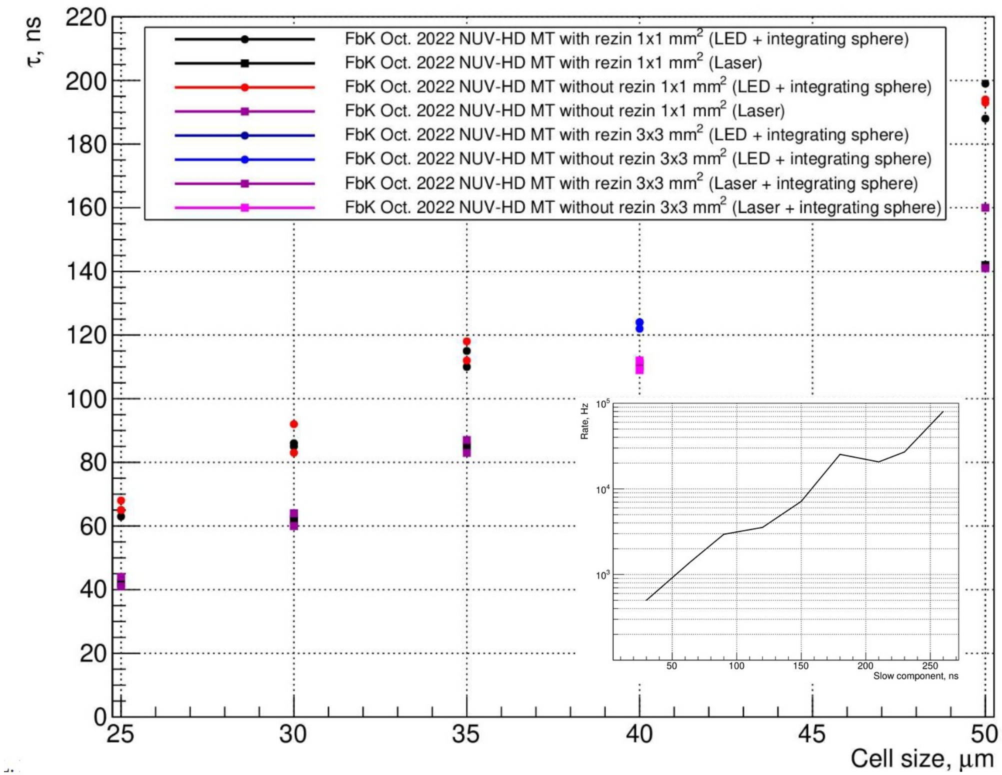
Large amount of light

Time resolution (sigma) = 12.9/2.35/sqrt(2) ~ 4 ps

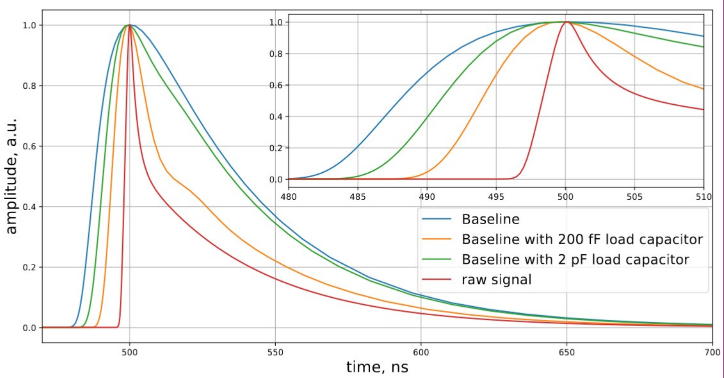
This time resolution with a very good amplifier can be potentially obtain for single p.e. (for a given peak).

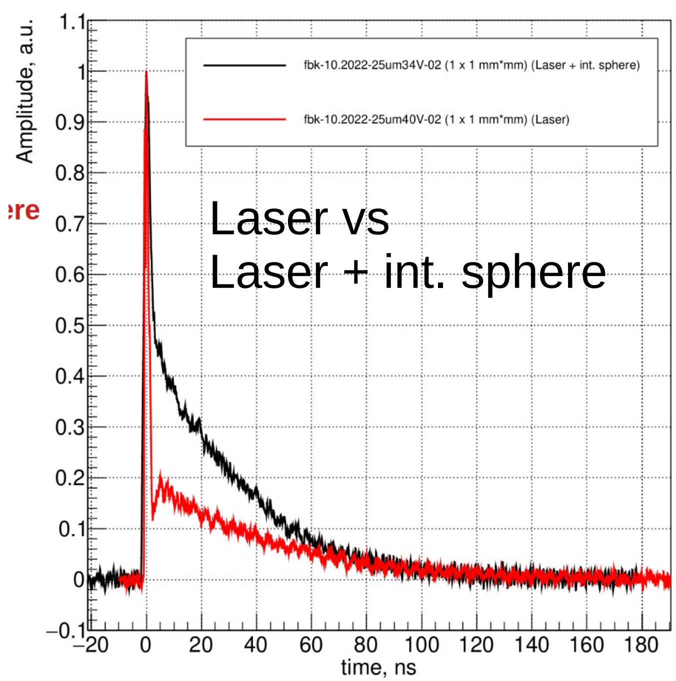
SiPM characterization : decay time of the slow component. Preamplifier optimization.

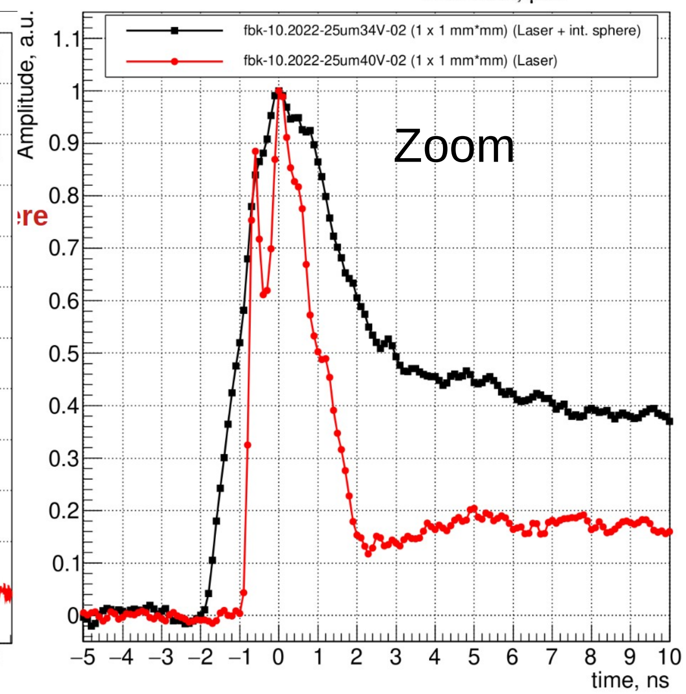




Normalized single p.e. shape after amplification.

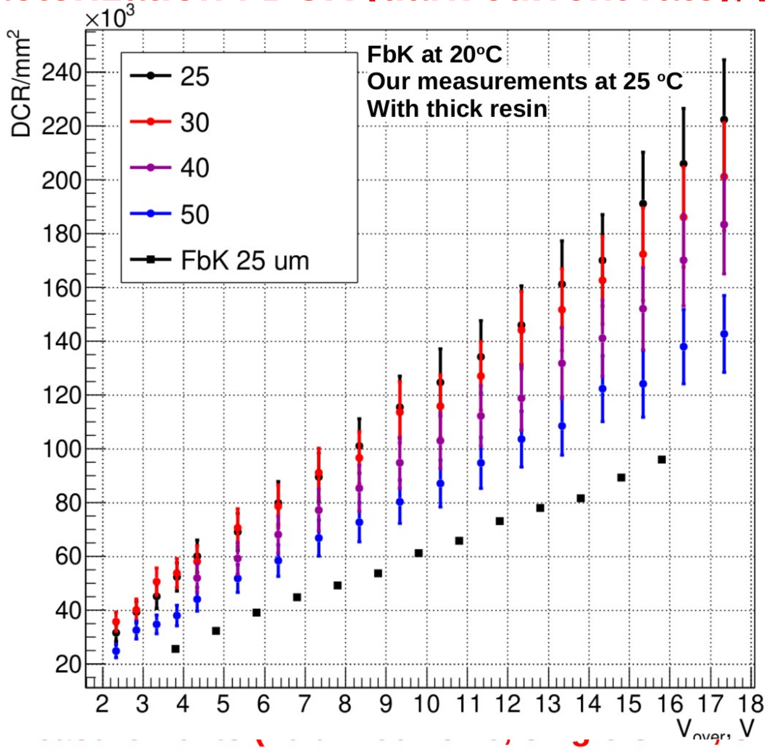


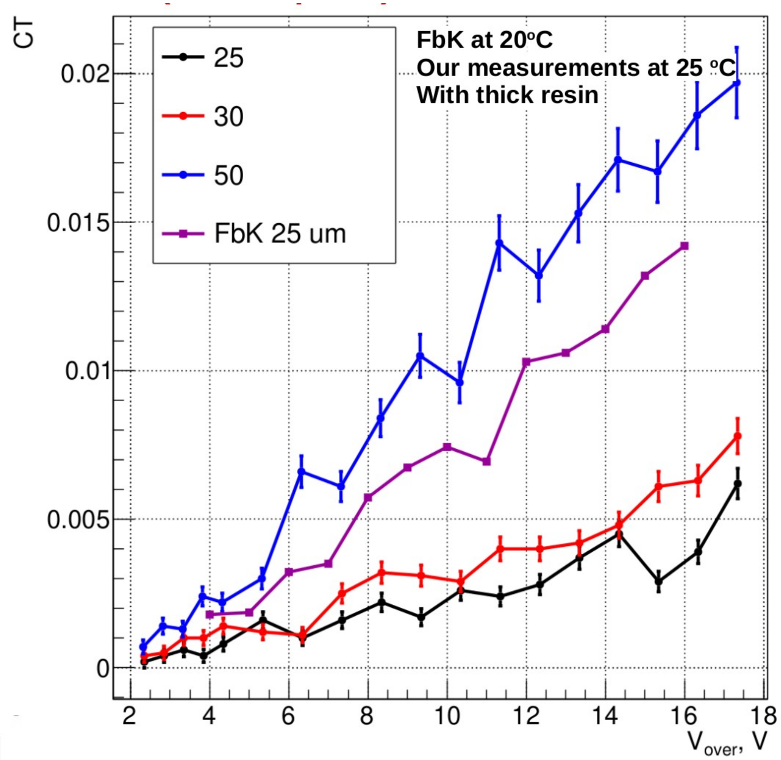


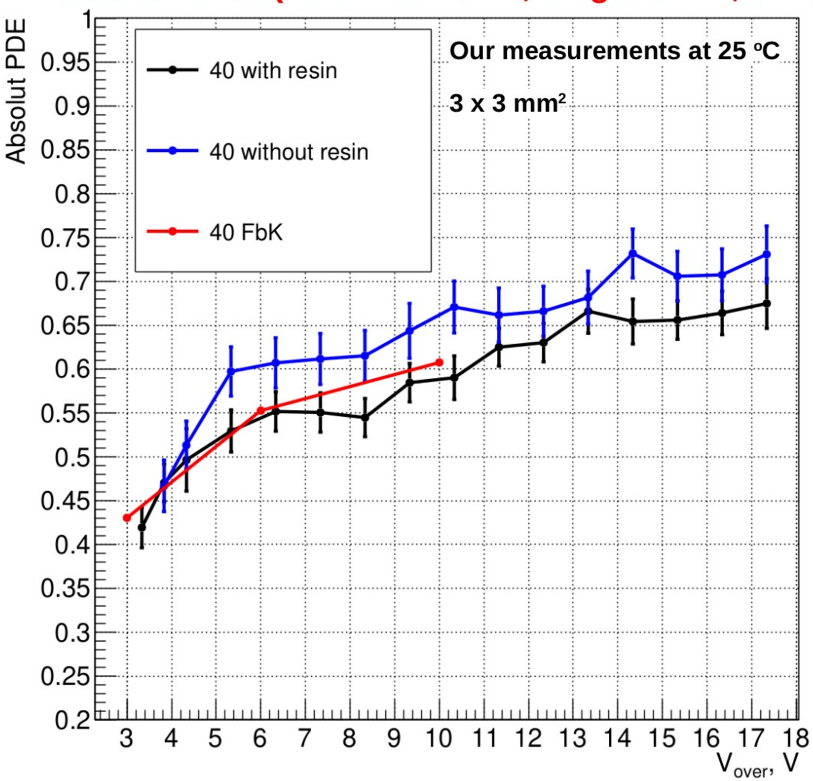


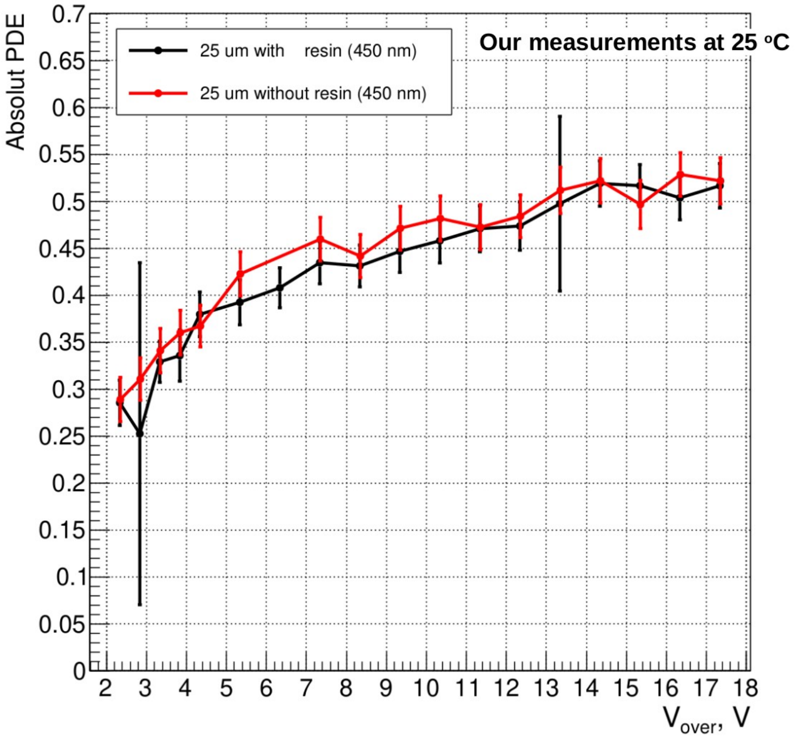
L. Burmistrov

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









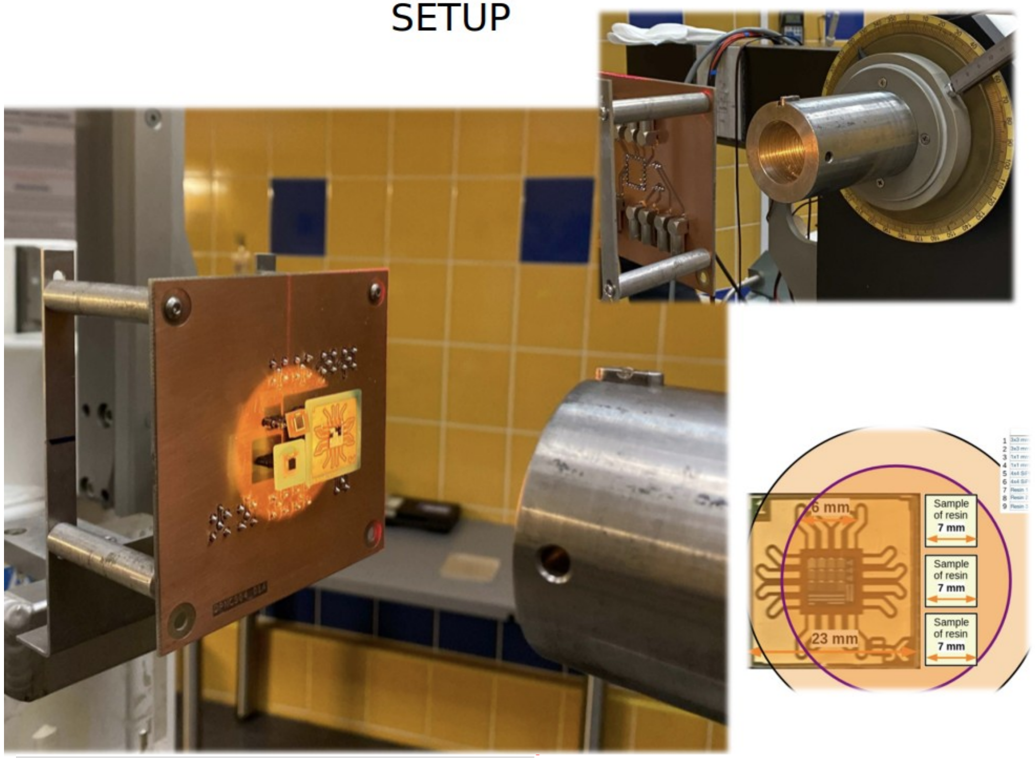
Irradiation facility with horizontal beam line (AIC-144 cyclotron)

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

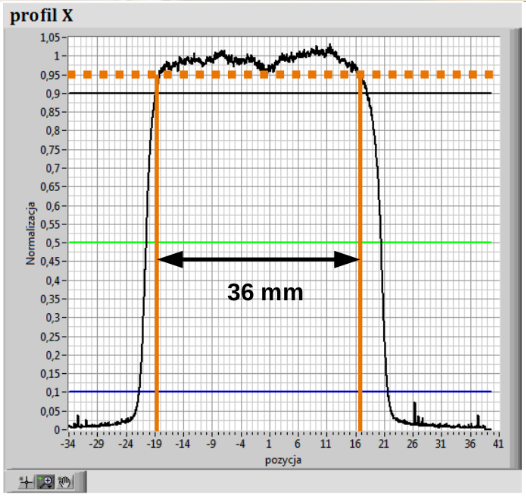
https://www.ifj.edu.pl/

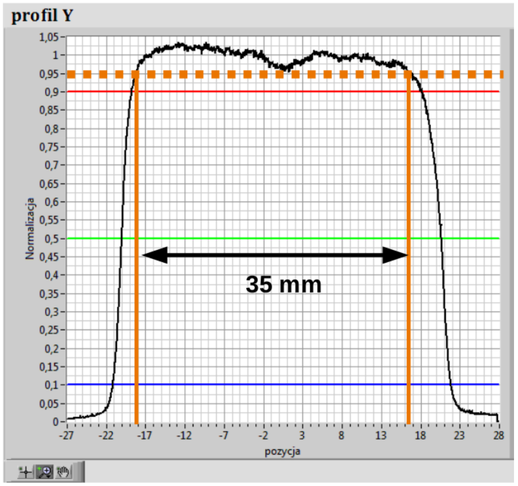
Acknowledgments: IFJ-PAN and Jan Swakon (responsible for proton irradiation campaign).

EXPERIMENTAL SETUP



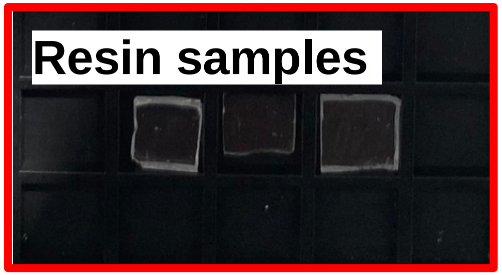
Energy: 0-58 MeV;
Dose rate: 0.001 – 1 Gy/s (measured in water);
Single scattering;
Beam field size: ≤ 40 mm;
Field homogeneity ≥ 5%;
Min flux of protons: 5e5 p/cm2·s (50MeV);
Typical flux: 10e8 – 10e9 p/cm2·s;
Irradiation in SOBP available;
Sample positioning precision (> 0.1 mm);
It is not possible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



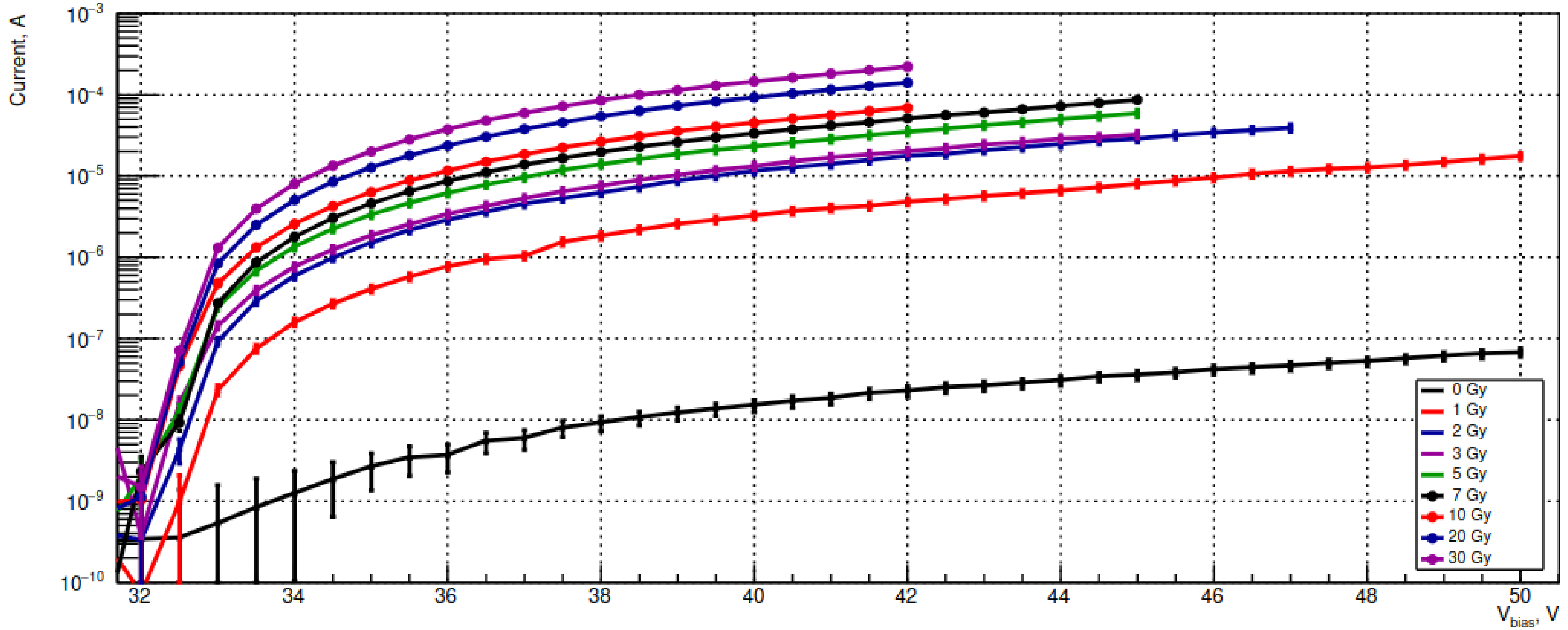


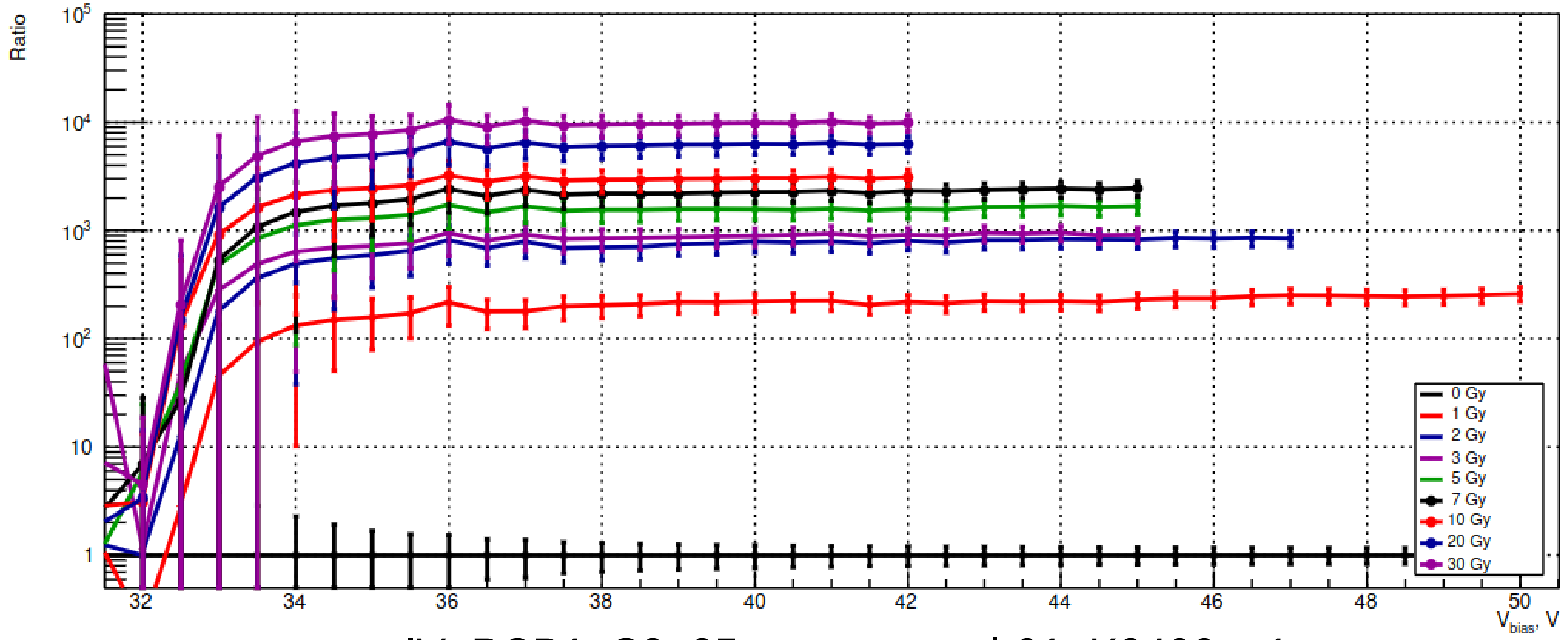
IFJ PAN

Resin samples



IV measurements after each irradiation step



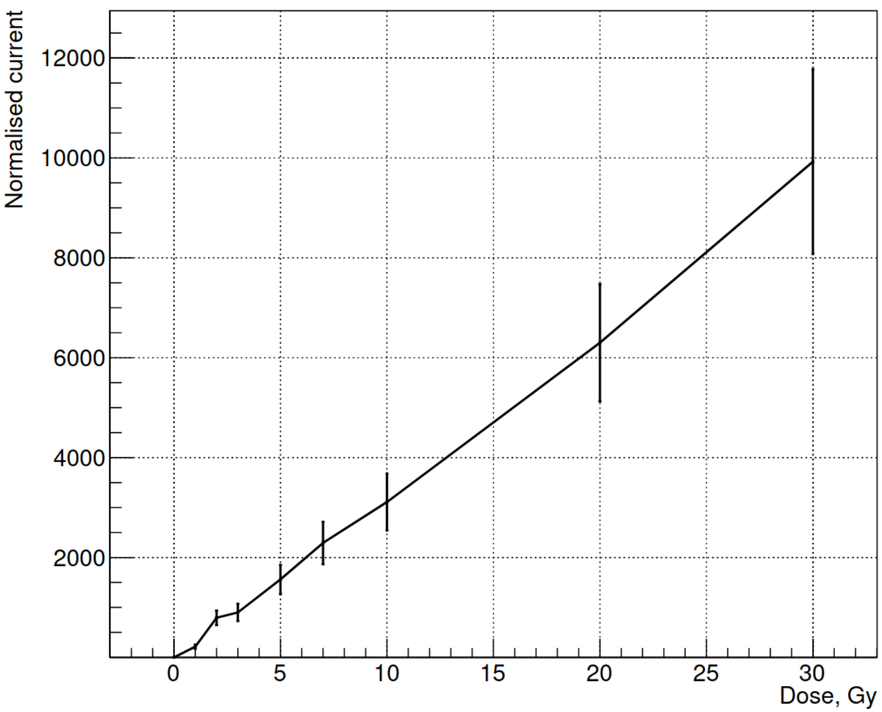


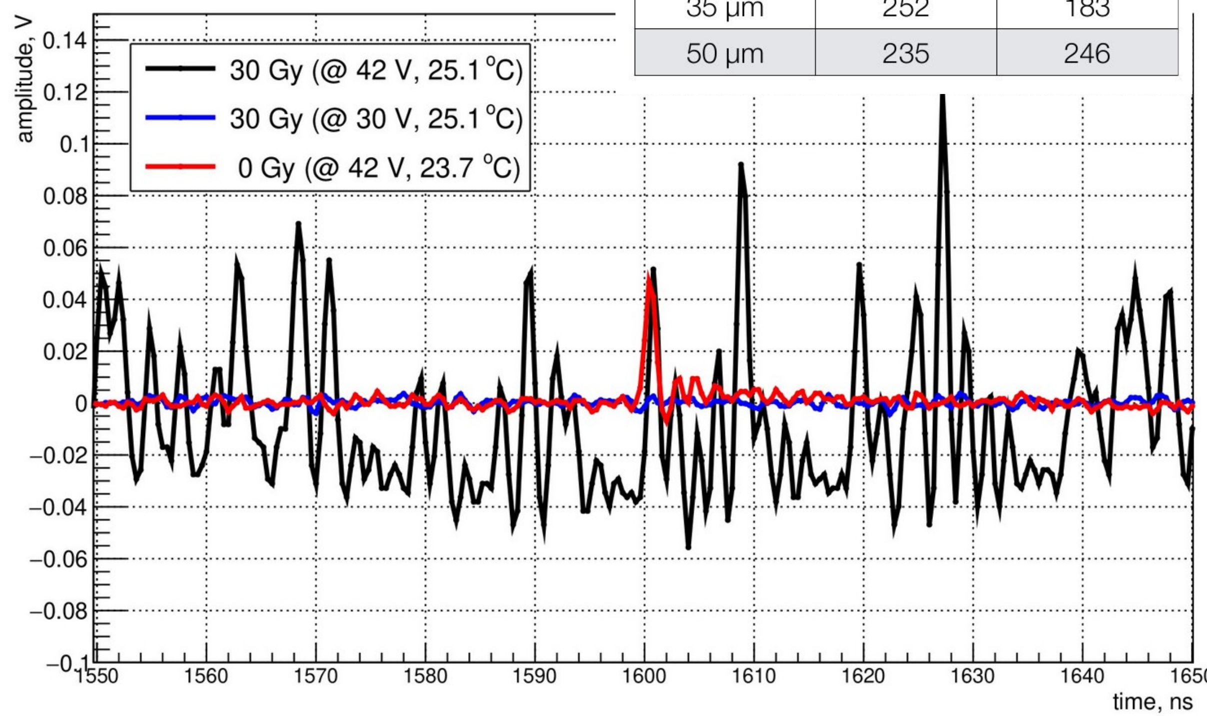
IV_PCB1_S3_25um_wores_ch01_K2400_n1

Results after irradiation test

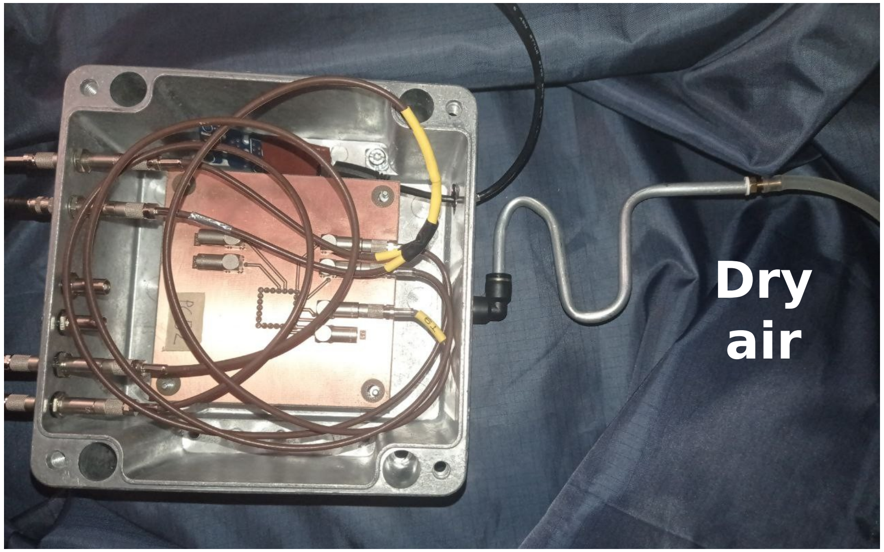
- We observe linear increase of the DCR with irradiation dose.
- Standard characterization of the SiPM is impossible after irradiation.
- The PDE measurements can be done only with large number of photons, as a consequence large systematical are expected for this measurements.
- 30 % of the expected dose are coming from protons.
- We “simulate” 10 years on the orbit (planed 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



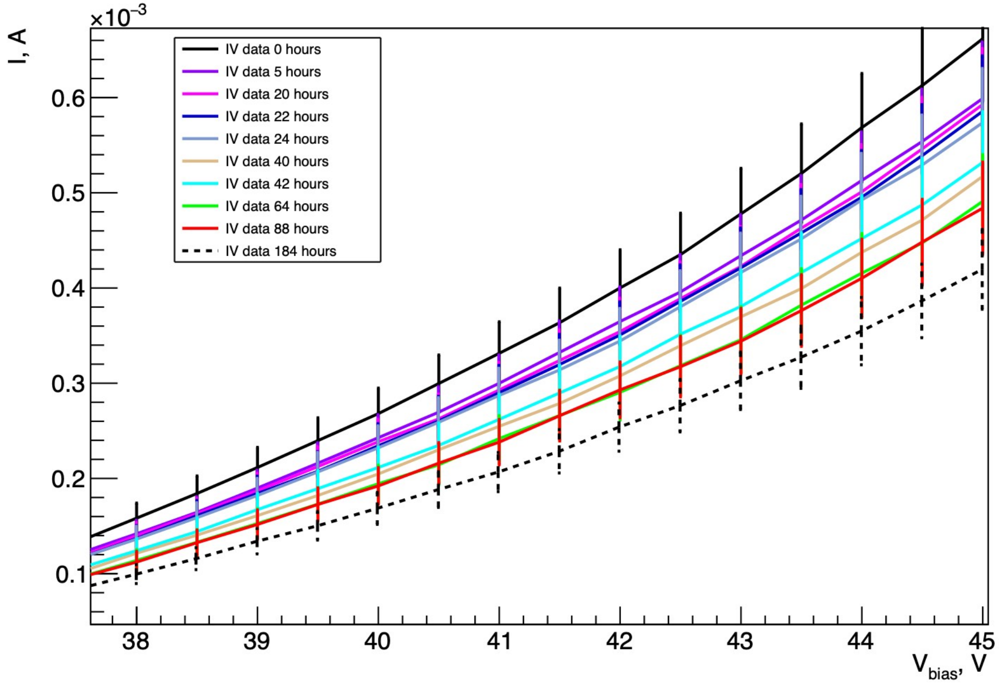


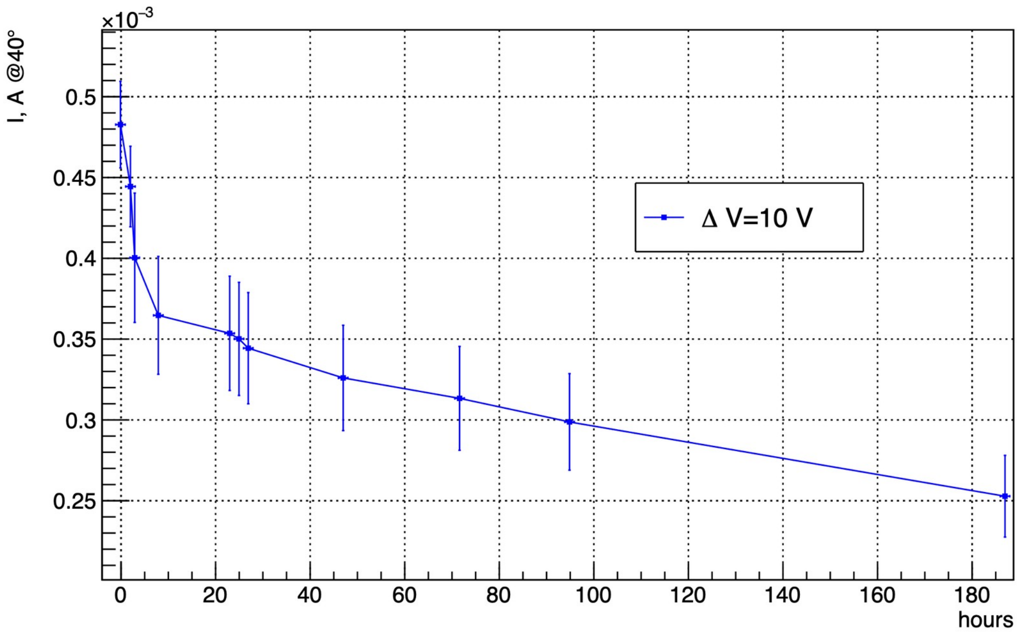
Annealing at 40 ^oC



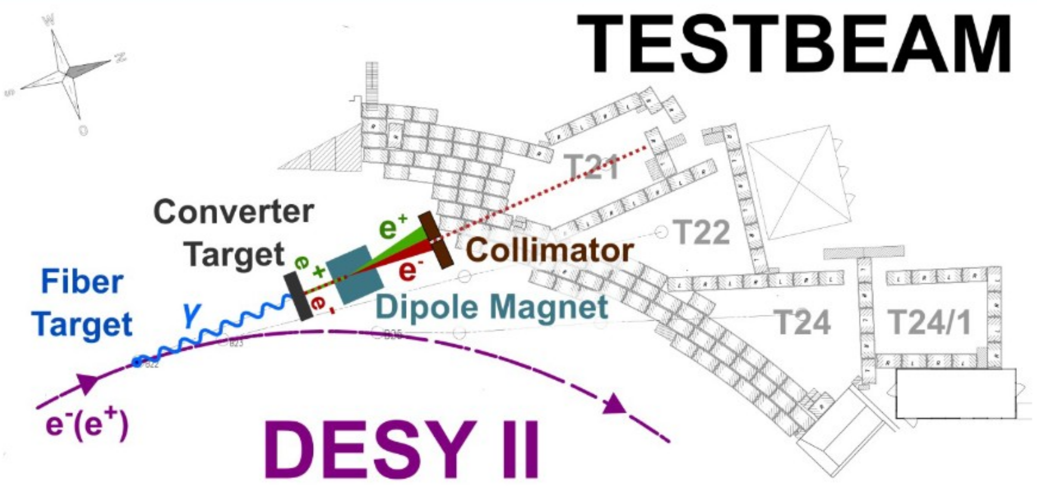
Climatic box, where we can vary the temperature from -20 to 80 ^oC

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

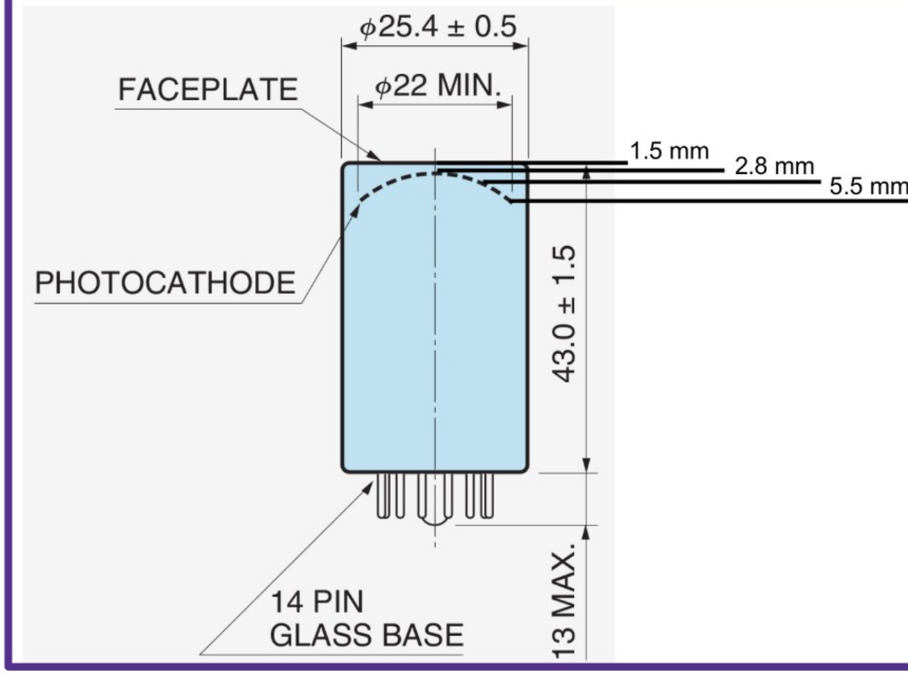




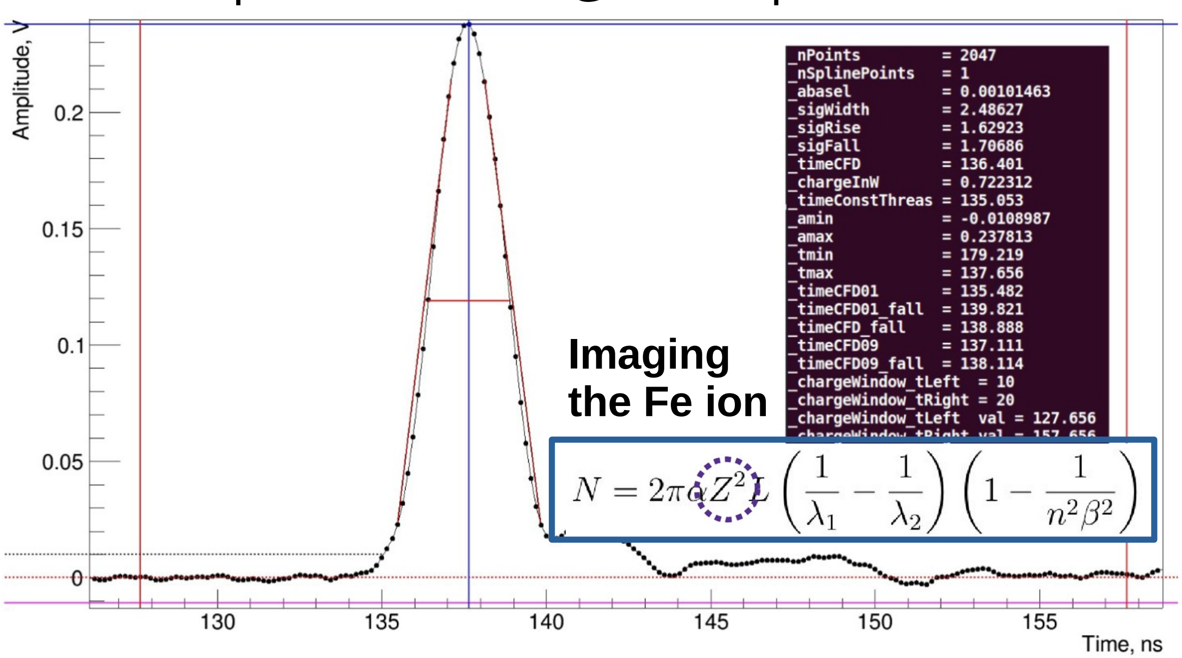
How much light do we produce in the photo sensor window



Beam parameters : 5.6 GeV/c, 15 x 10 mm^2,
~ 2 kHz (single electrons)

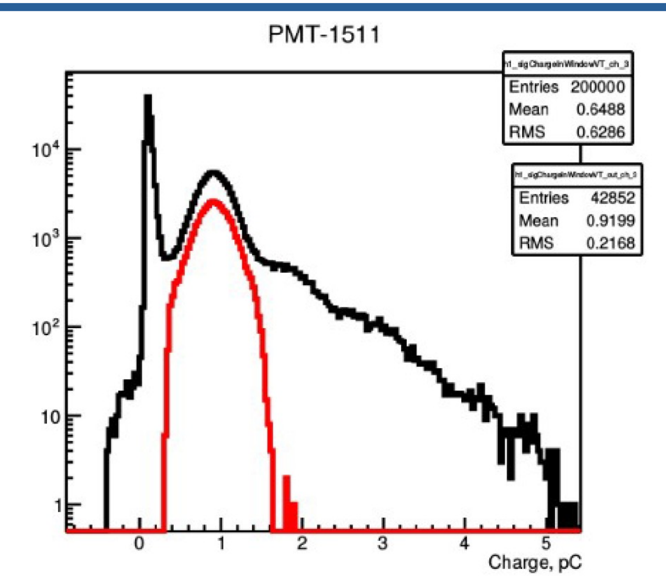


Amplitude 237 mV @ 10^6 amplification



Imaging the Fe ion

$$N = 2\pi\alpha Z^2 L \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\left(1 - \frac{1}{n^2\beta^2}\right)$$



24 p.e./per electron

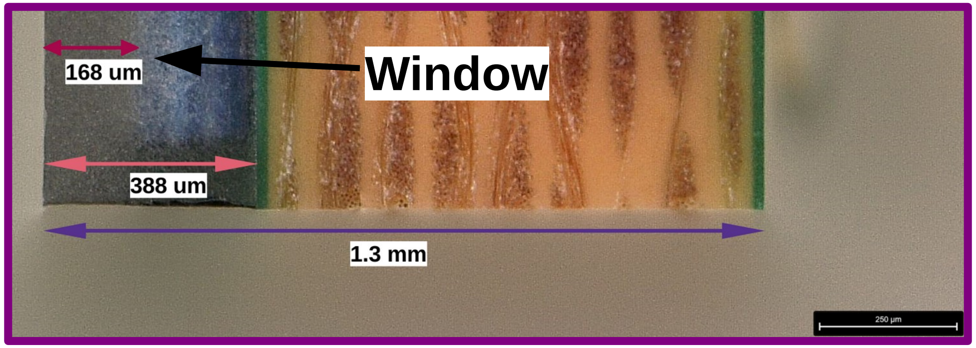
8 p.e./mm/per electron

Bare SiPM or SiPM with thin window ?

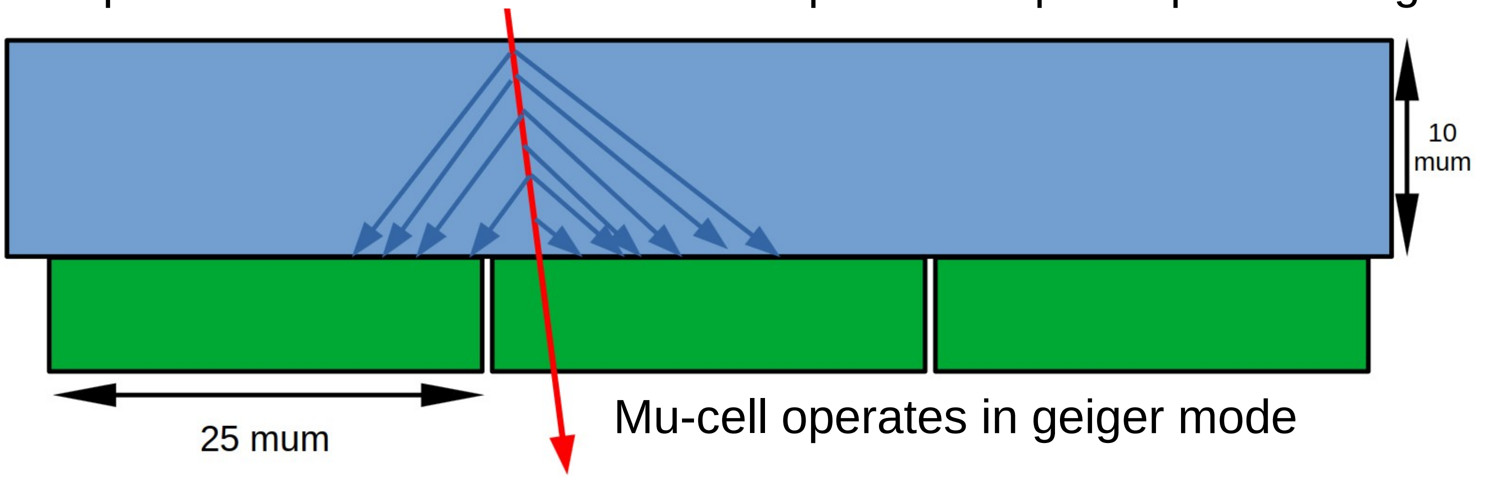
Thikness of the protective window 400 – 40 mum

Can we make it thinner ?   10 mum ?

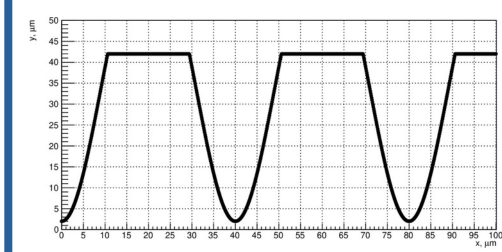
Can we completely remove it ?

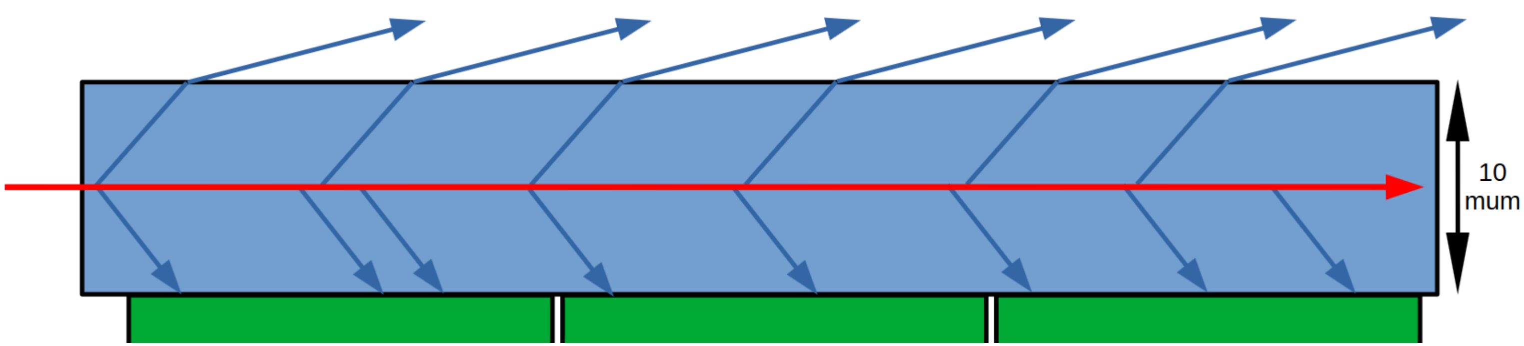


Perpendicular track at maximum will produce 4 p.e. equivalent signal



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

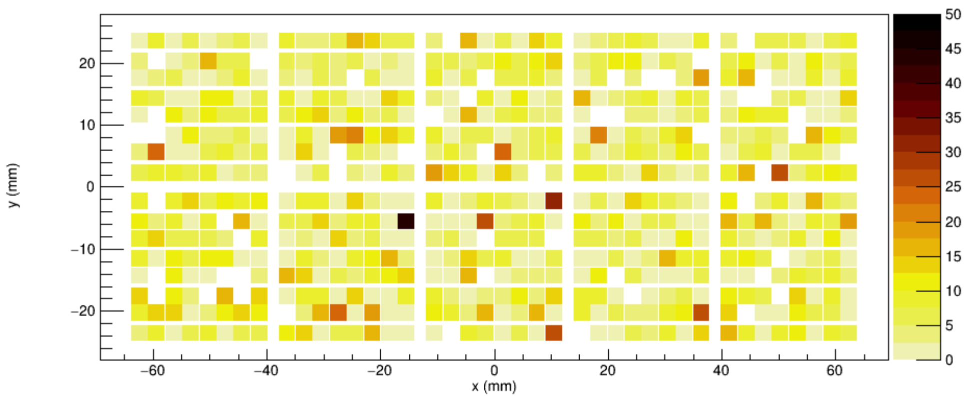


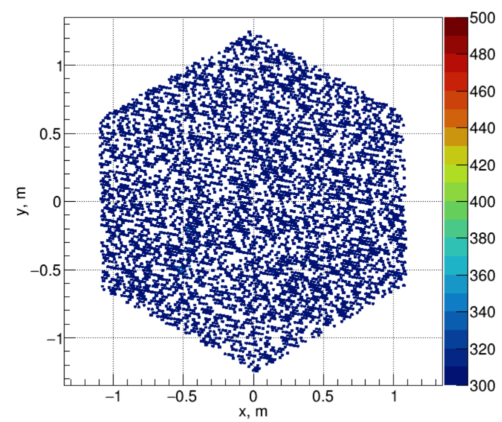


This effect can be vanished by removing the window :-) ...

Conclusions

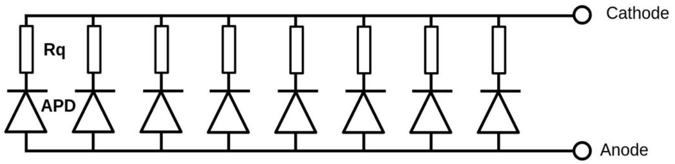
- SiPM are promising photo sensors to be used for space base experiments.
- We present full chain of different activities for Terzina telescope on board the NUSES space mission.
- We present the parametric simulation of the SiPM used in the full simulation chain.
- We characterize SiPM with different 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 ^{o}C has been studied.

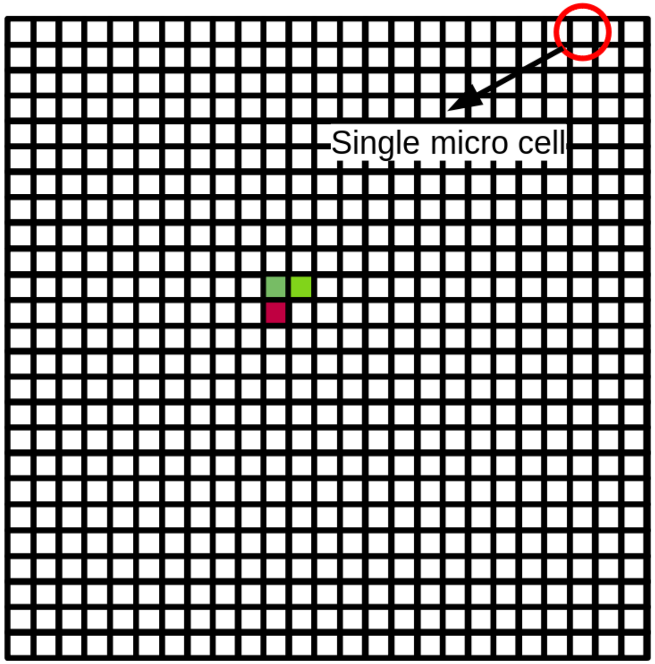


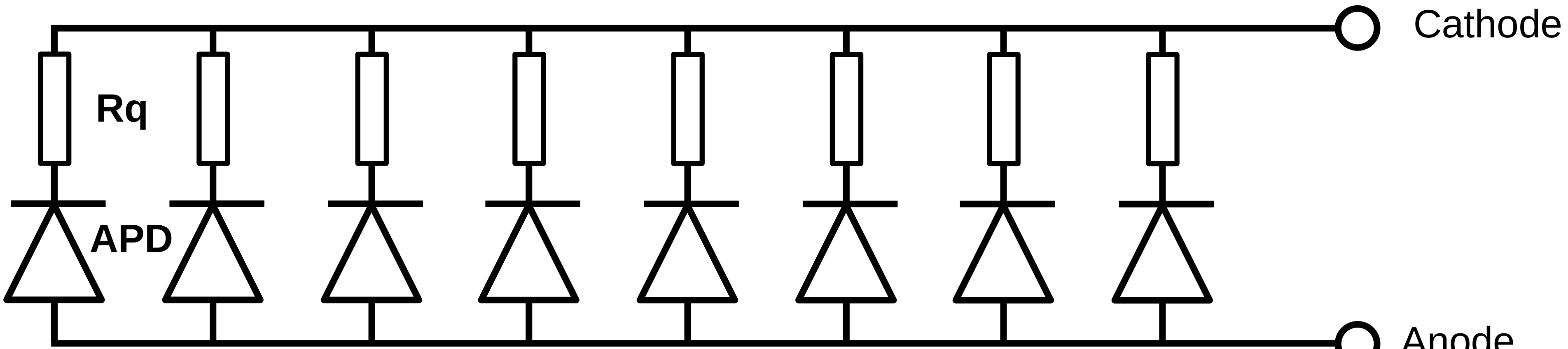


wf_time : 0 ns
proton
event_id : 3590000
energy : 76753 GeV
xcore : -632 m
ycore : 180 m
ev_time : 543 ns
nphotons : 57735
n_pe : 12419
n_pixels : 2434

Backup


Cathode
Rq
APD
Anode


Single micro cell


Cathode
Rq
APD
Anode