SiPM neutron hardening with Cf-252 for space environments

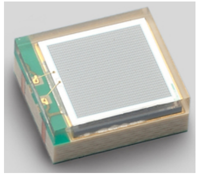
Federico Suarez, Shannon Hoogerheide, Daniel Hussey, Agustín Lucero, Johannes Hulsman

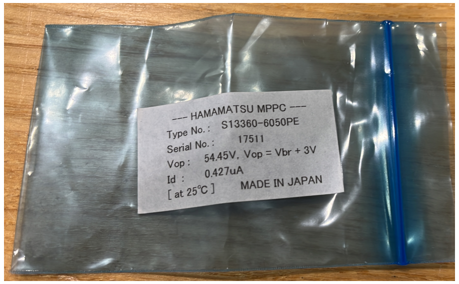
SiPM radiation workshop @ CERN

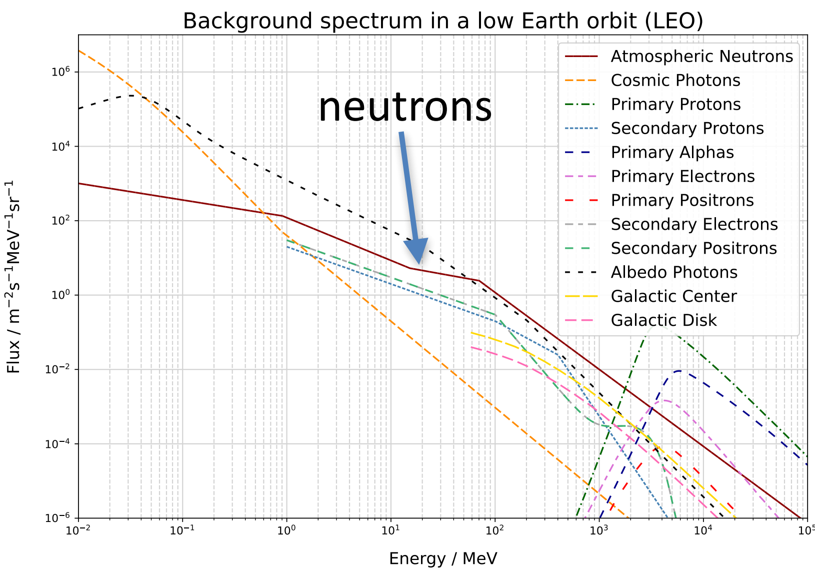
Geneva, April 26th

Motivation

- Spaceborne instruments are prone to fail with background radiation
- Irradiate with n single SiPM to be used in POLAR-2 polarimeter
    - Hamamatsu S13360-6050PE (6mm x 6mm)
    - Provided by University of Geneva
-







Background Spectrum at 300km and at an inclination of 42 deg. (without SAA)

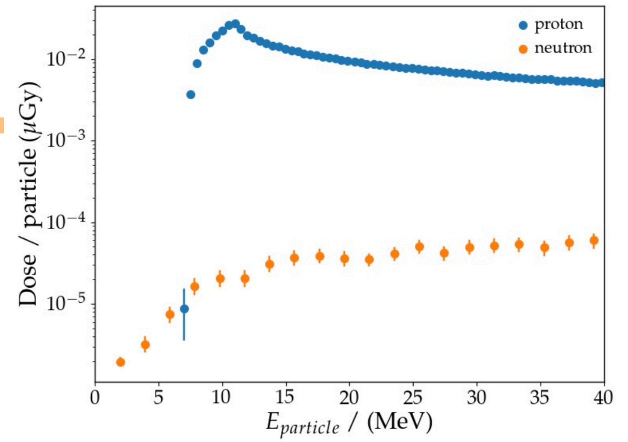
Some estimations

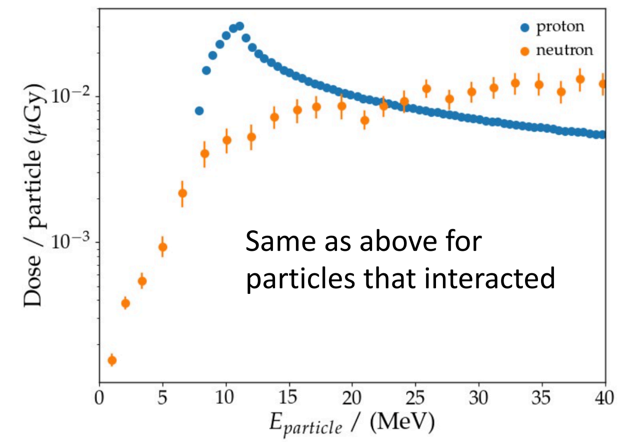
- Different sims scenarios for POLAR-2 with p
  - Dose from p < 2 Gy for 2 yrs. mission (without SAA)
- n flux generally higher than p
- Neutrons easily penetrate shielding for charged particles and photons
  - n well absorbed in materials with Hydrogen
  - not considered in Sims scenarios
- Low n-Si interaction probability but produce additional damage than p (direct+indirect)
- Starting point for irradiation campaign:
  - **< 4.9x10^{11} n on SiPM (2MeV)**
    for 0.984 Gy/yr (extrapolation from p)

- from proton flux
- 100keV to 400MeV
- prediction for 2025
- solar maximum
- AP-8 model

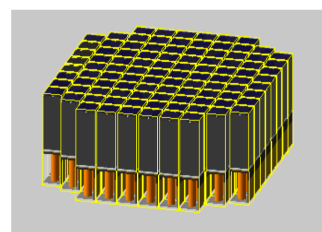
Simulation Setup	POLAR-2 orbit
Bare Instrument	0.984 Gy/yr
Bare Instrument + SpaceLab	0.627 Gy/yr
Full Instrument	0.077 Gy/yr
Full Instrument **+ SpaceLab**	0.064 Gy/yr

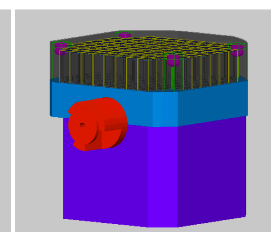
Average p/n dose in Silicone





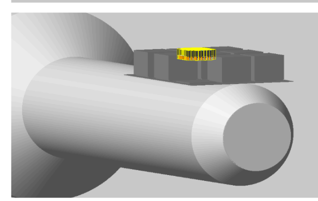
Bare instrument: instrument component suspended in space. No further shielding.

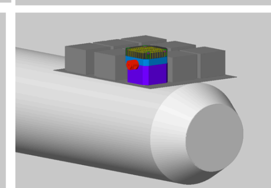




full instrument: all instrument components suspended in space

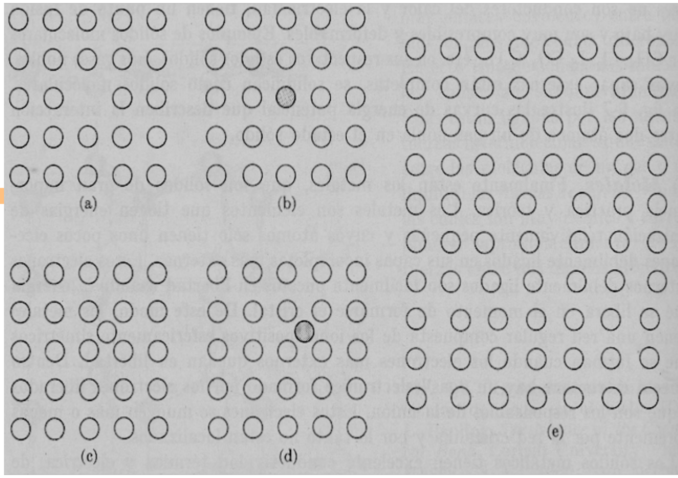
Bare instrument + SpaceLab: same as top (left) figure but with the addition of the SpaceLab





full instrument + SpaceLab: same as top (right) figure but with the addition of the SpaceLab

What do neutrons do to SiPM?



- Bulk damage in the crystalline structure
  - Increases SiPM noise: DarkCurrent, DCR, AP
  - May produce false triggering of detector
  - Bulk damage can also be from low energy n through indirect processes

$^{29}Si(n,\alpha)^{26}Mg$

- Surface damage of SiPM
  - Mostly from photons and low energy charged particles
  - Increases DarkCurrent & Power Consumption (important for space applications)

$^{10}\mathrm{B}(\mathrm{n},\alpha)\mathrm{Li}$

- Change of effective doping density
  - Low energy n produce transmutation doping in Si
  - Fast n produce Al/Mg (but 2 orders of magnitude less likely)
  - Removal of some dopants

$^{30}\mathrm{Si} + \mathrm{n} \rightarrow {}^{31}\mathrm{Si} \rightarrow (\beta^-)\ {}^{31}\mathrm{P}$

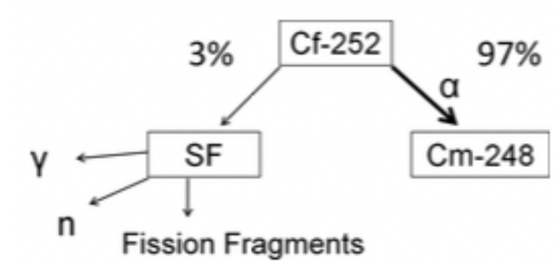
- Other problems
  - Very difficult to shield
  - Activation
  - Additional impurities through other processes

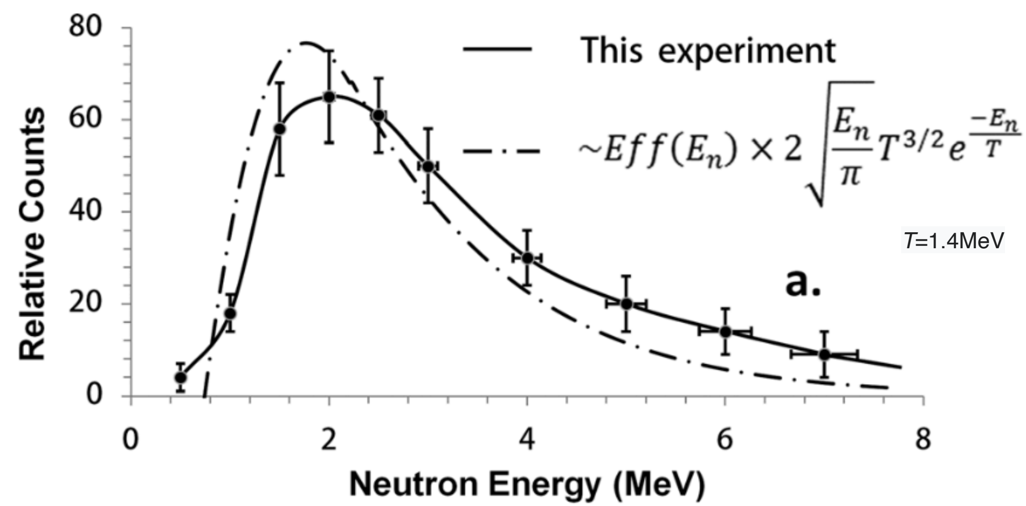
NIST Californium Neutron Irradiation Facility (CNIF)

- Located at NIST, Gaithersburg (Maryland, USA)
- Double room underground facility
  - Room with source in sub-room with n absorbers
  - Room for experiment preparation and remote control
- Cf-252 source intensity: 1.688×10^{7} ns^{-1} (4π)
  - At the moment of irradiation
  - Diameter ~7.7mm

Californium-252

- Neutrons and gammas from spontaneous fissions
  - Neutrons in the MeV order of magnitude
    - Expected bulk damage in Si lattice of the SiPM
  - Gammas rate ~ 2n:1γ with E<155 KeV
    - Expected some surface damage in the SiPM
- Alpha decay
  - Alphas stopped in ^{252}Cf source cladding (Pt-Ir capsule)

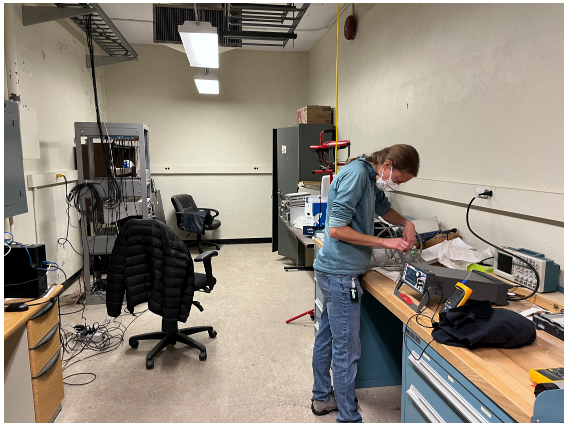


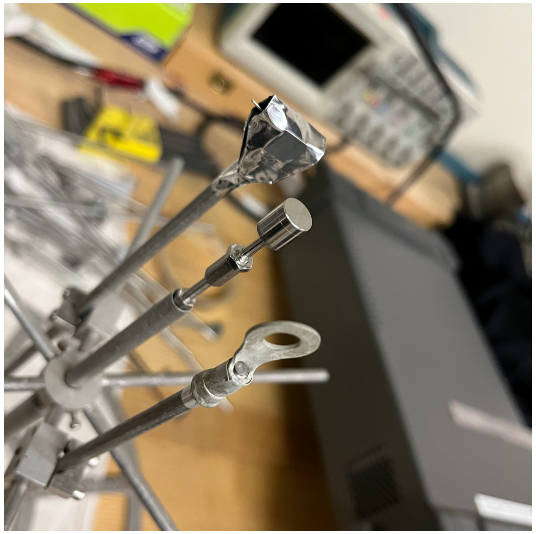


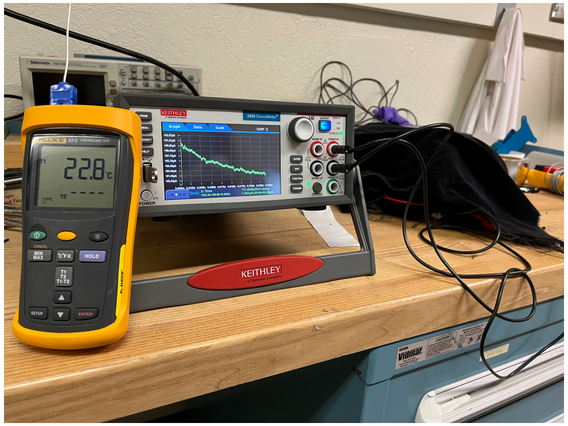
Src: Bechetti et al. doi: 10.1119/1.4769032

Experiment setup and strategy

- 1 hr exposition @ 2.3 cm away from ^{252}Cf source center giving ~3×10^8 n in the SiPM
  - ~1000x lower dose from sims compared to p but still much damage expected
  - Several exposures with different exposition time (check *T*)
- Measurements of dark-current after each exposure
  - In dark-box
  - Directly powered with a SMU Keithley 2450



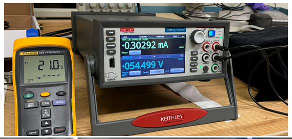


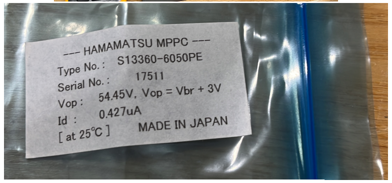


Exposures and Dark-current

Date of 3 exposure 29/Oct/2021
DR measurements taken 20s after polarization
SiPM surface 0.36cm^2

	Duration & Temp. of irradiation [h:m @ °C]	Fluence [ncm^{-2}]	n on SiPM [n]	Estim. ratio n:γ	Dark current @ Temp. @ Voltage [µA @ V @ T]
Before	-	-	-	-	0.3168 @54.5 @22.4
Exposure 1	1:00 @20.9	9.04E+08	3.25E+08	2:1	85.9 @54.5 @22.9
Exposure 2	1:13 @19.8	1.1E+09	3.96E+08	2:1	184.3 @54.5 @22.4
Exposure 3	1:32 @19.9	1.39E+09	5E+08	2:1	302.9 @54.5 @21.0

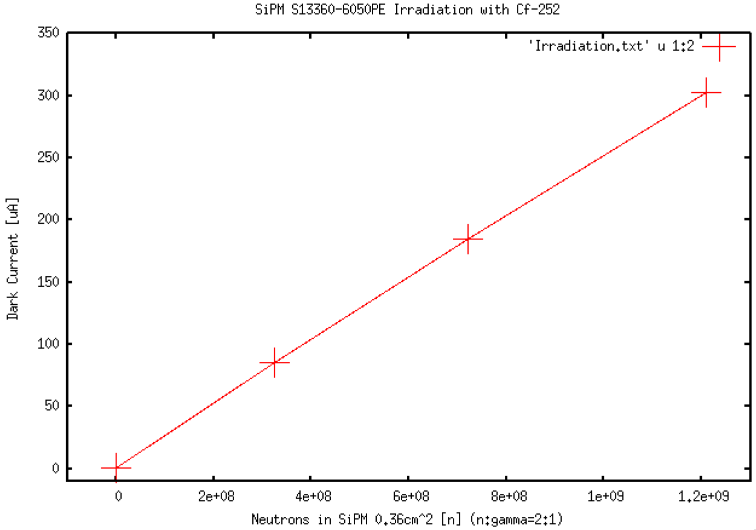




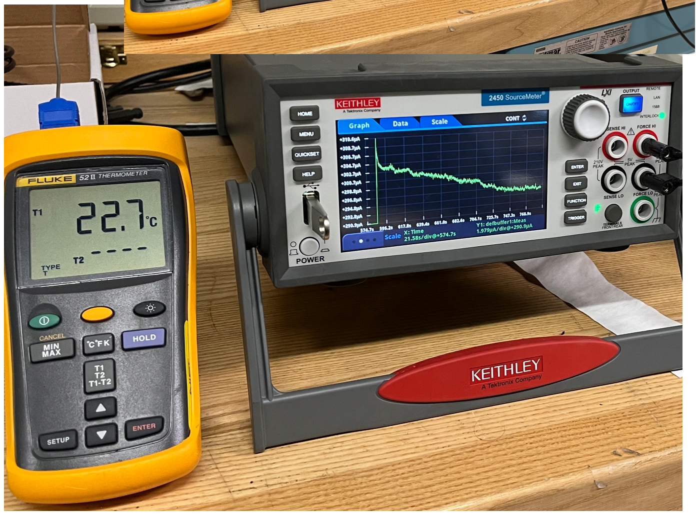
Dark-current before irradiation consistent with Hamamatsu

Almost 1000x Dark-current after 3 exposures

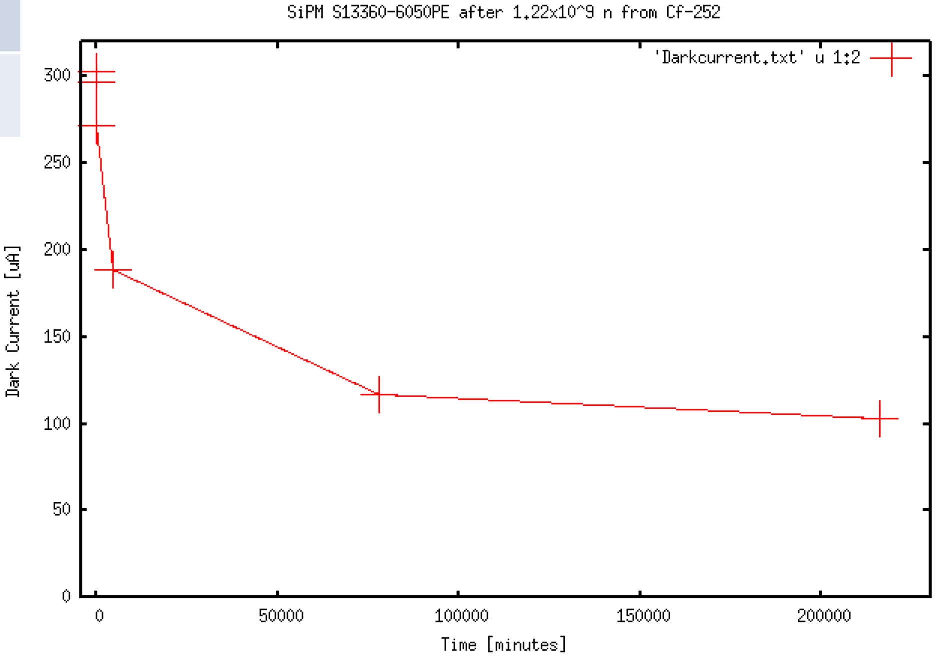
- x271 after 3.25x10^8 n in the SiPM
- x581 after 7.21x10^8 n
- x956 after 1.22x10^9 n



Dark-current settling



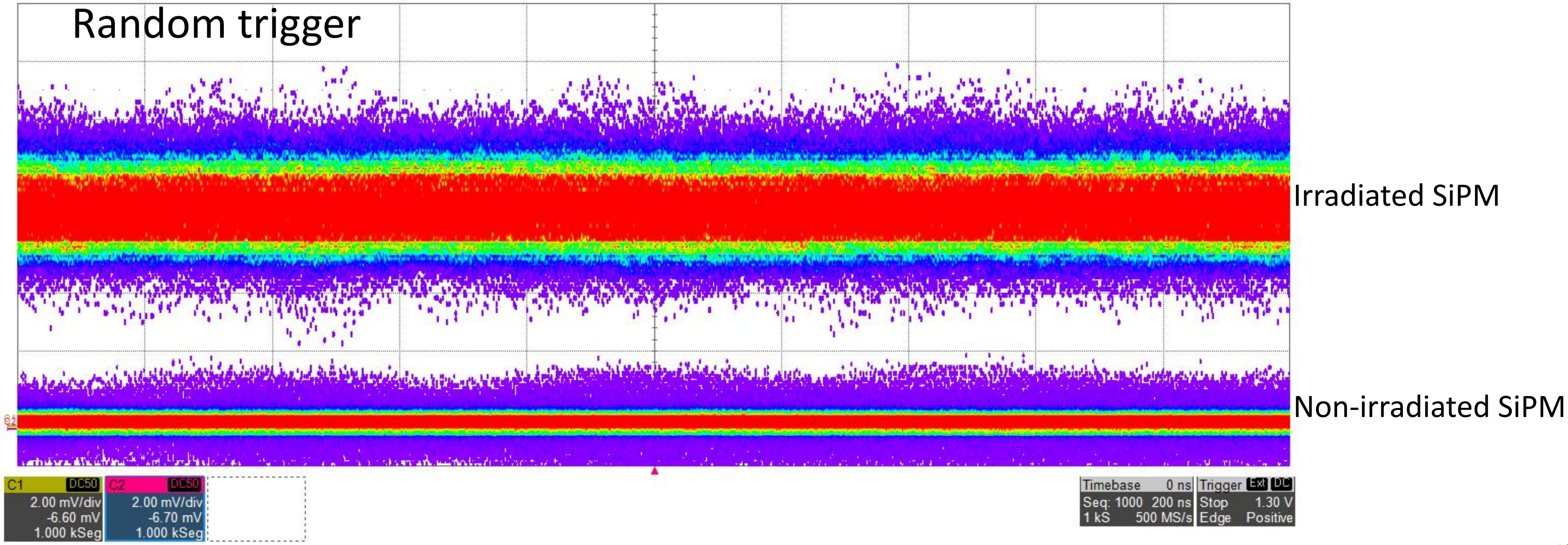
	Time after last irrad. [d h:m]	Dark current @ Temp. @ Voltage [μA @ V @ T]
Meas. 1	0d 00:00	302.9 @54.5 @22.4
Meas. 2	0d 00:03	297 @54.5 @22.7
Meas. 3	0d 00:36	272 @54.5 @23.3
Meas. 4	3d	189 @54.5 @20.6
Meas. 5	54d	117 @54.5 @24.0
Meas. 6	150d	103 @54.5 @24.0



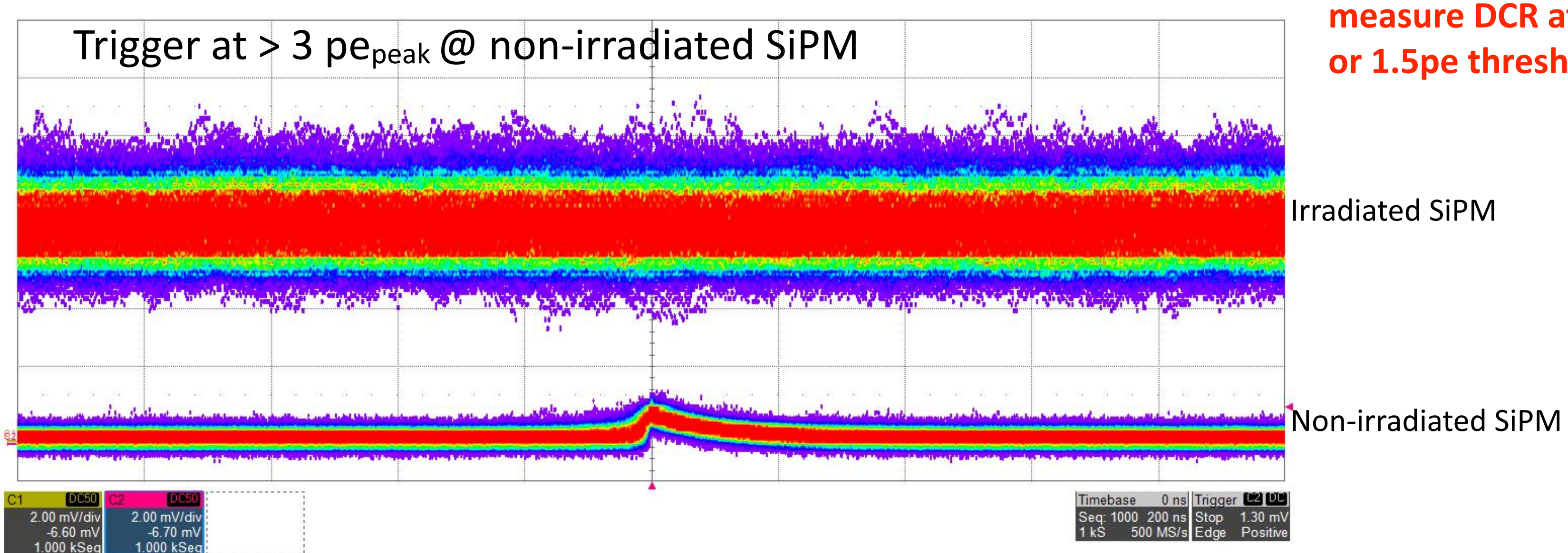
Result after slow annealing at room temperature

- **150 days storage @** $T \leq 25°C$
- **Total of 335x more than before irradiation**

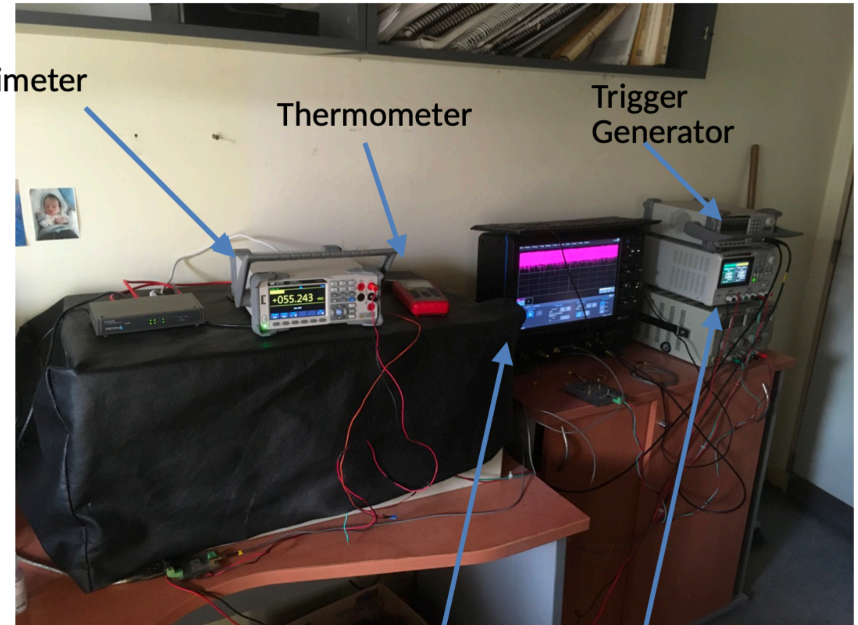
Baseline and Dark-pulses (@ 25°C)



Not even possible to measure DCR at 0.5pe or 1.5pe threshold

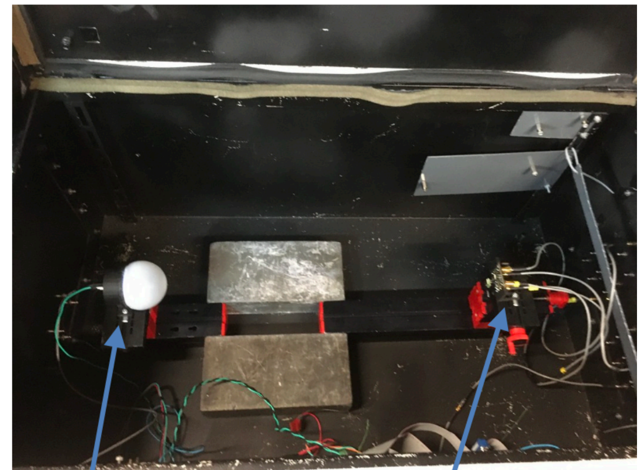


Measurements with pulsed light



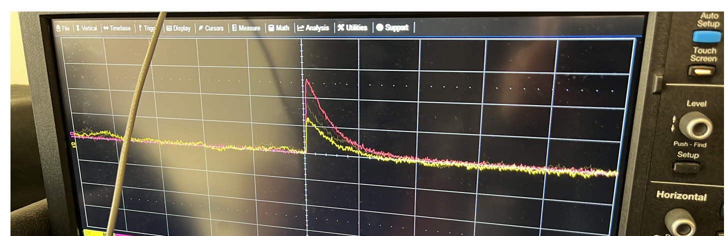
Multimeter
Thermometer
Trigger Generator
Digital Oscilloscope (DAQ) Lecroy Waverunner 9404 10Gs/s
Power Supply

SiPM testing Setup at CNEA



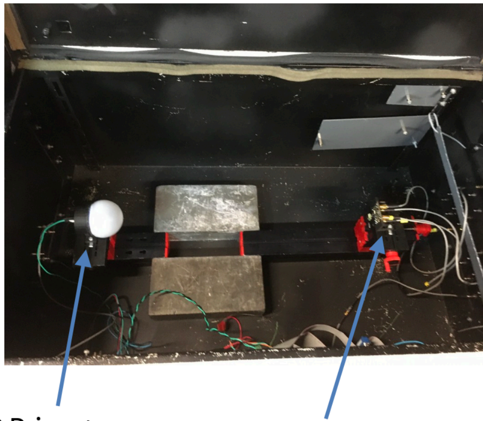
LED Driver + Diffuser
2 X S13360-6050PE (Irradiated & Non Irradiated)

- And it still works!!!!
  - at least with many pe
- But how well does it work?



SiPM testing Setup at CNEA

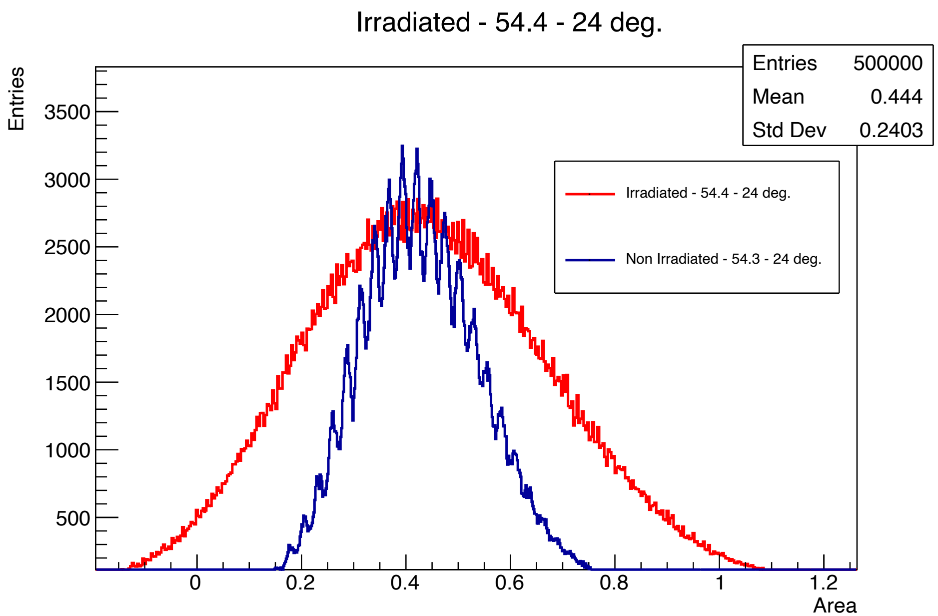
Spectrums

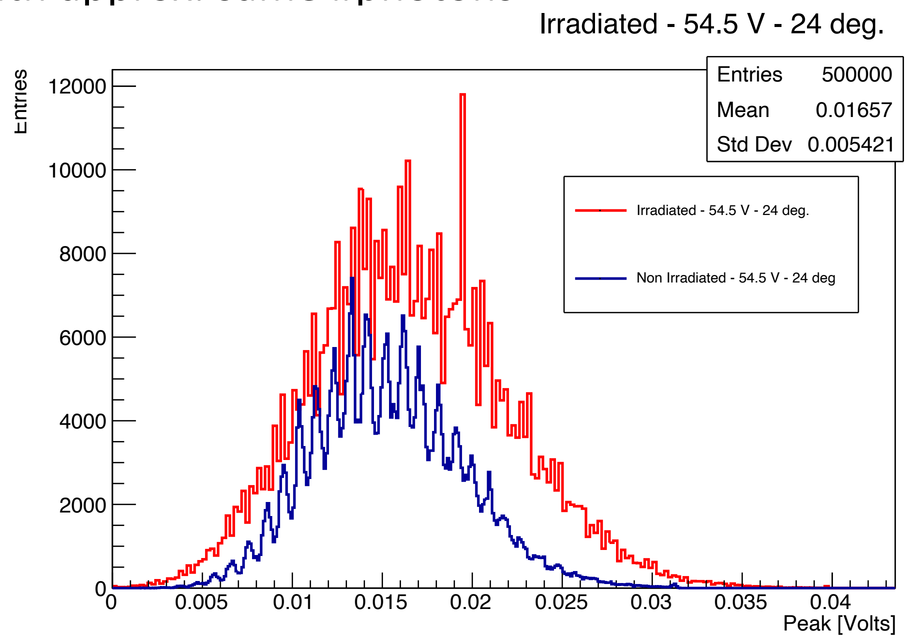


LED Driver + Diffuser

2 X S13360-6050PE (Irradiated Non Irradiated)

- Absolute calibration of Irradiated SiPM not possible with spectrums
  - Not even with 500000 million shots neither amplification
  - ENC too high
  - Artifacts in data analysis too high due to high DCR (poor S/N ratio) but it can be improved
- Cross-calibrated with non-irradiated SiPM with approx. same #photons



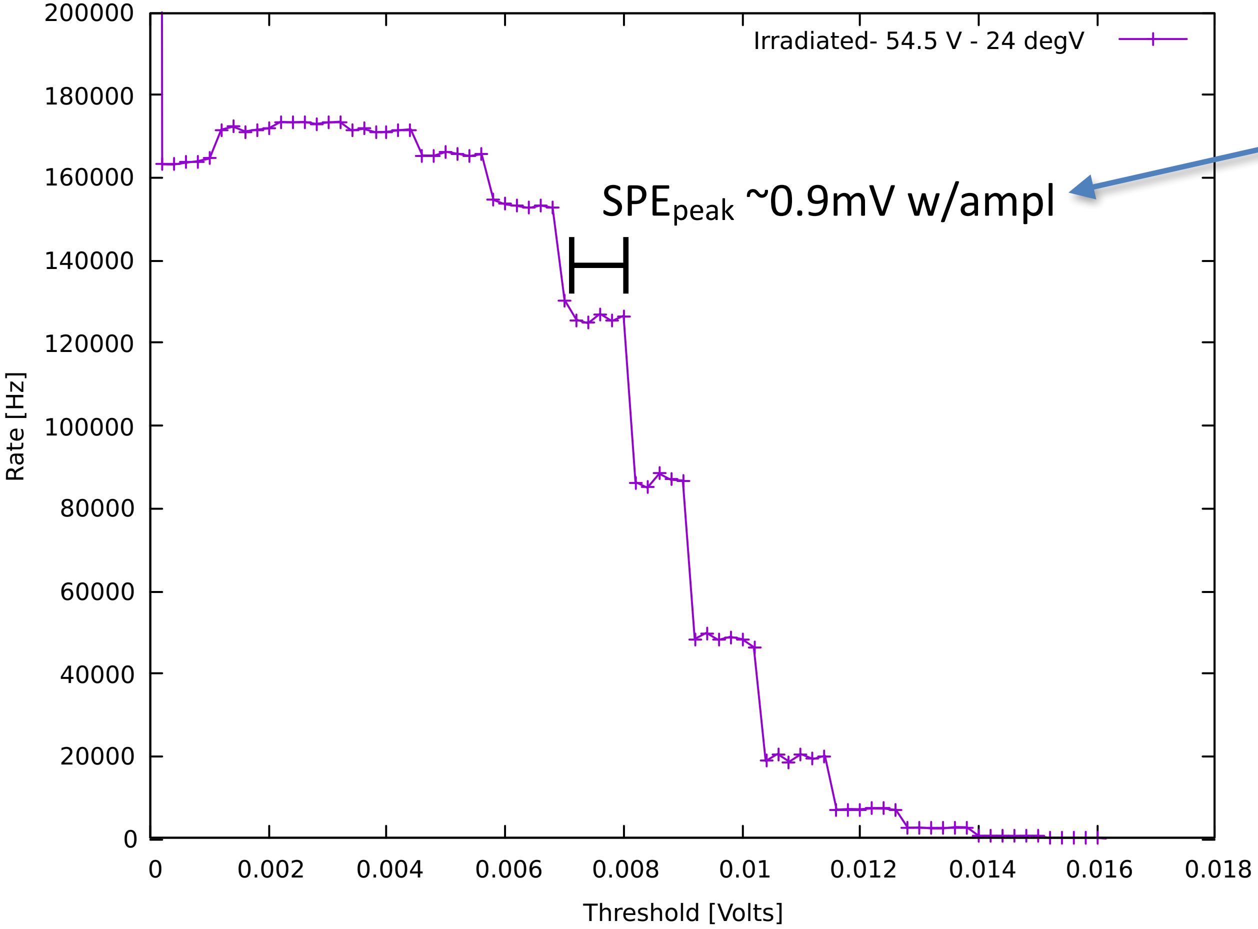


Charge and Peak spectrums for ~16pe @24°C with 5x amplifier calibrated with VNA

Peak spectrum for irradiated SiPM biased because artifacts in analysis due to big baseline fluctuations

Is it still useful to produce data & science?

- Still possible to roughly calibrate it through DCR vs. Threshold!?!



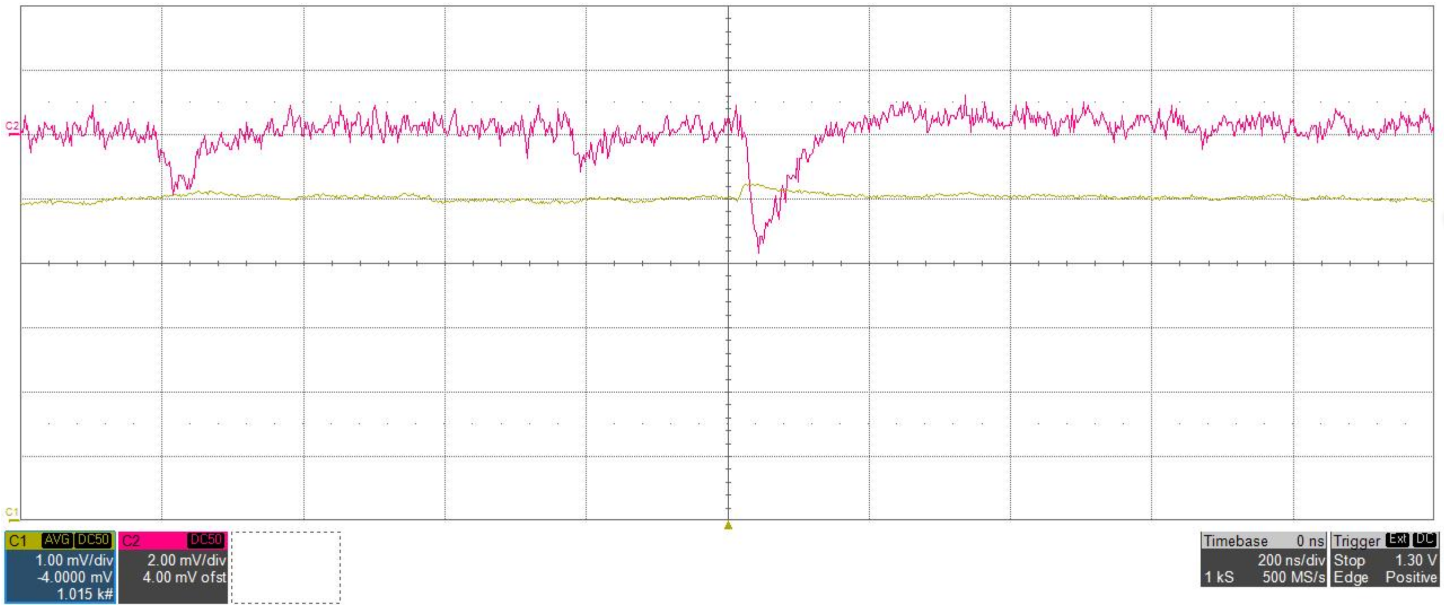
Consistent with spectrum from non-irradiated SiPM?!

Still to be debugged

- Absolutely useful for signals over 14pe
- Also shows accidental T1 self-trigger rate for lower thresholds

Is it still useful to produce data & science?

- Low #photos and T2s or External triggering
  - Possible through less damaged SiPMs and/or Event analysis



Non-irradiated amplified

Non-irradiated not amplified averaged

- Useful above ###photons with external triggering???
  - but much lower than self-trigger

Conclusions:

- Results for Dark-current
  - ~1000x increase in Dark-current after 3.394×10^9 n cm^{-2} on SiPM area (from ^{252}Cf and its γ)
  - Dark-current increases linearly with fluence in our exposition
  - Dark-current settles to ~330x after 3 months at room temp.
- SiPM still works and detect pulsed light!!! but S/N ratio degrades at room temp.
  - Still useful for science by increasing threshold or advanced triggering
  - It can still be calibrated?!
  - May reduce acceptance of detector
- Next steps?
  - Measure other parameters: AP, CT, others???
  - Specification of SiPM "damage" for application?
  - Testing at application temperature?
  - Quantification of "damage" per Gy or Fluence for n vs. p at same *E*?
  - Study effect of thermal neutrons in the SiPM?
    - thermal neutrons are very abundant in space

Muchas Gracias