Characterization of SiPM radiation hardness for application in hadron calorimeters at FAIR, CERN and NICA

Vasily Mikhaylov

Nuclear Physics Institute of the Czech Academy of Sciences

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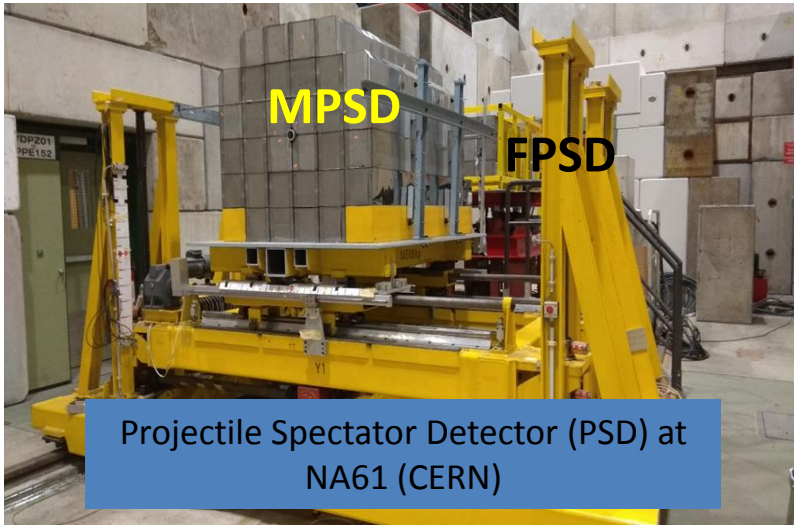
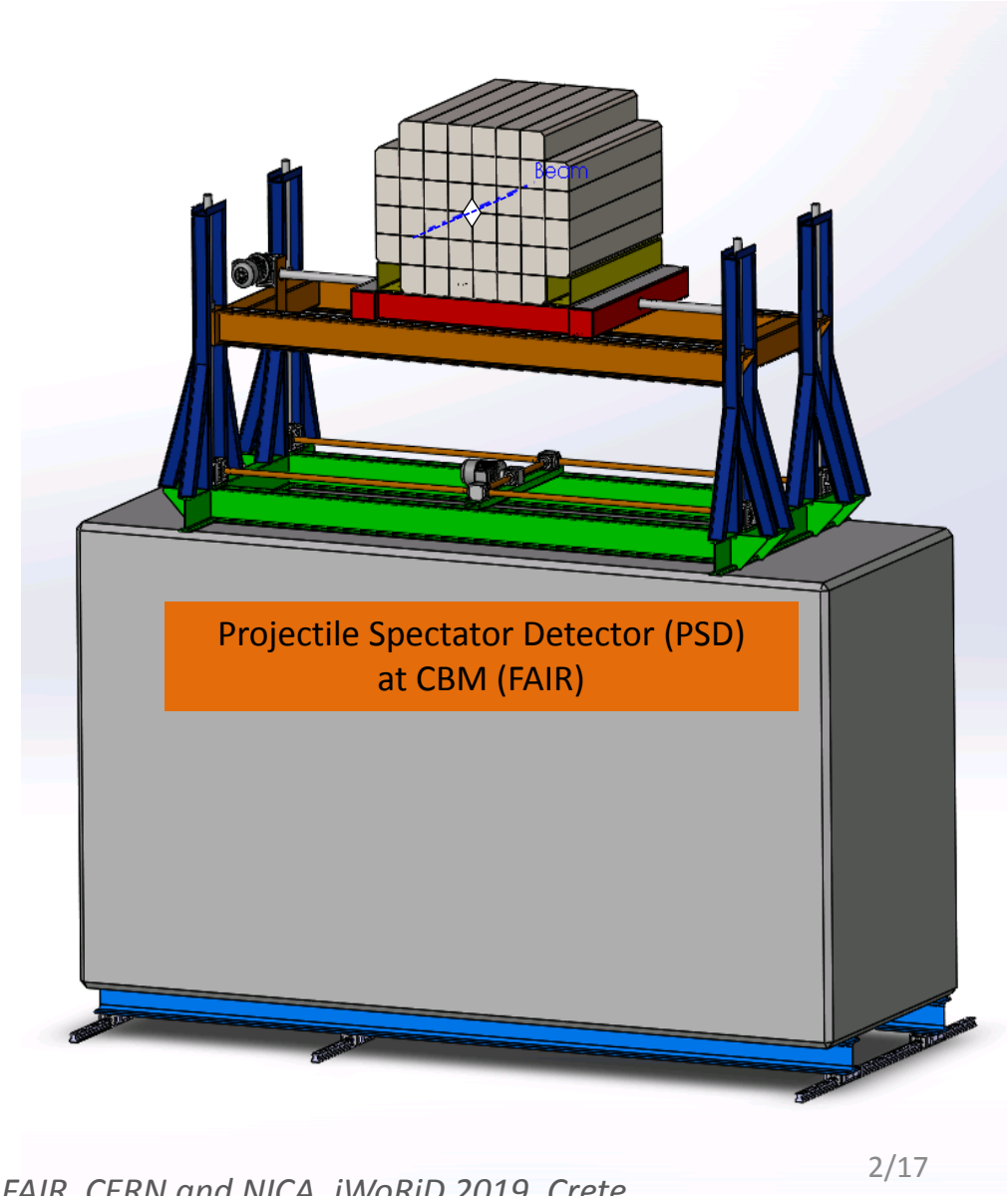
Hadron calorimeters



Projectile Spectator Detector (PSD) at NA61 (CERN)

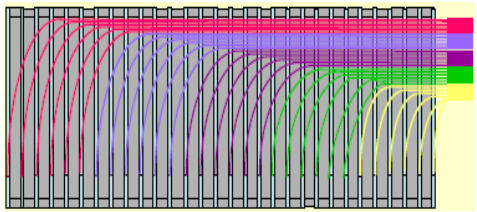
Forward Hadron CALorimeter (FHCAL) at BM@N (NICA)



Projectile Spectator Detector (PSD) at CBM (FAIR)

Hadron calorimeter module

Design: compensating lead-scintillator calorimeters which measure the energy distribution of forward going projectile nucleons and nuclei fragments (spectators) produced close to the beam rapidity



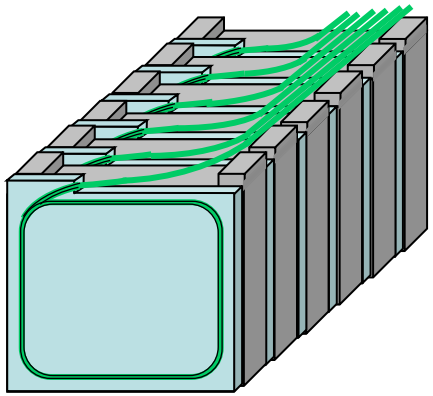
Top view

Features:

- transverse granularity by 44+ modules,
- longitudinal segmentation of 10 sections per module
- light from each consecutive 6 layers collected via WLS-fibers and read-out by SiPM
- ability to operate at high collision rates up to 1MHz

Module properties:

- 60 lead+scintillator plates in one module
- 1 section = 6 scintillator plates
- size = 20 x 20 x 120 cm^3
- depth ~ 5.6 hadron interaction lengths λ_{int}
- optimized for beam energy range of 2 – 35 GeV



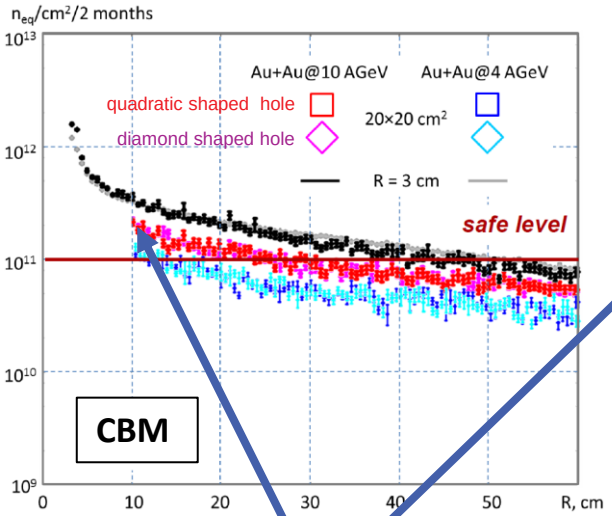
Front view

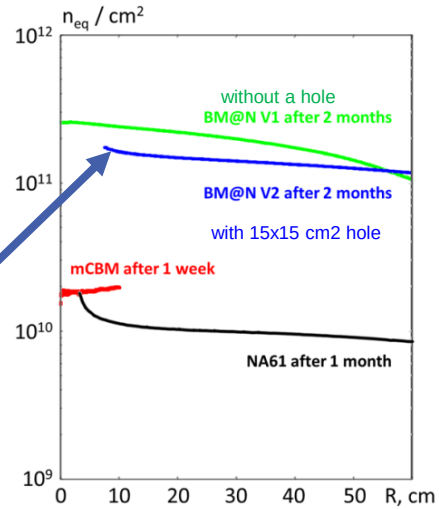
Requirements for Silicon Photomultipliers (SiPMs):

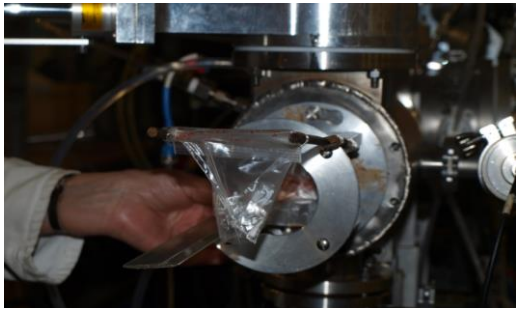
- wide dynamic range ~ 1000 to measure signals from few MeV up to several GeV
- good recovery time ~ tens ns to operate at reaction rates up to 1 MHz
- radiation hardness to neutrons ~ $2x10^{11}$ n_{eq}/cm^2 for CBM and BM@N (lower for other experiments)

Radiation conditions

Simulation of neutron fluence at the SiPM plane



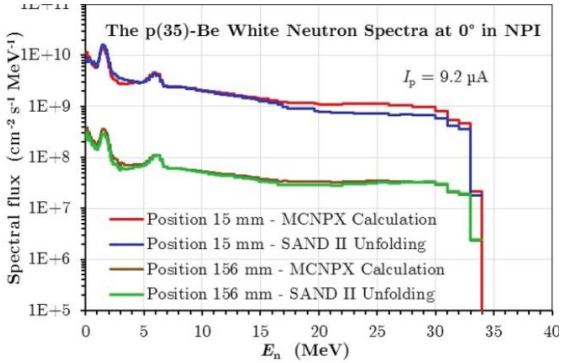




SiPMs placed at cyclotron beam line

Up to 2×10^{11} neutrons$_{eq}$/cm^2 for SiPMs located 10 cm close to the beam center

Beam hole in the center significantly reduces the radiation damage

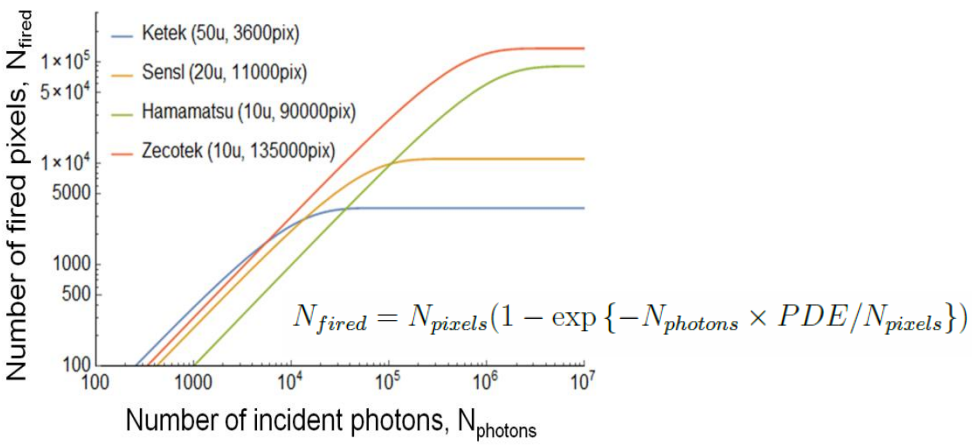


Courtesy of M. Majerle and M. Štefánik

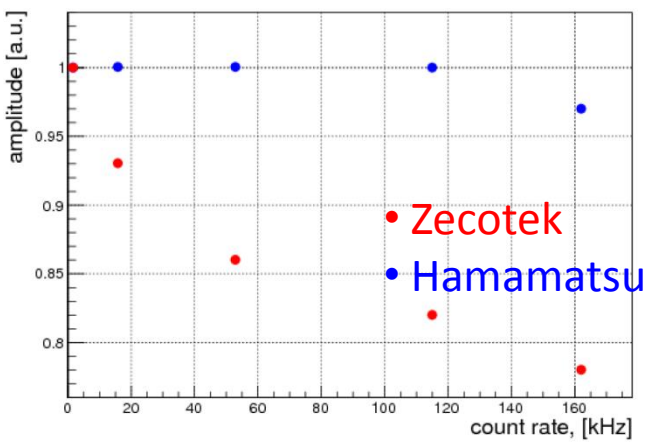
- ✓ SiPMs were irradiated by neutrons at cyclotron of NPI Řež with fluence in a wide range from 6×10^{10} up to 9×10^{12} n_{eq}/cm^2.
- ✓ All SiPMs were systematically studied in our lab before and after irradiation.

SiPM dynamic range and recovery time

	Zecotek MAPD-3A	Zecotek MAPD-3N	Hamamatsu S12572-010P	Sensl uF-C30020	Sensl uF-B30020	Ketek PM-3350
Operating voltage	~ 65 V	~ 90 V	~ 70 V	~ 25 V	~ 25 V	~ 25 V
Number of pixels	135000	135000	90000	11000	11000	3600
Real pixel size	8 µm	8 µm	10 µm	29 µm	29 µm	50 µm
Gain	~ 6×10^4	~ 1×10^5	~ 1×10^5	~ 1×10^6	~ 1×10^6	~ 6×10^6
PDE	~ 20%	~ 30%	~ 10%	~ 25%	~ 25%	~ 40%
Pixel recovery time	~ 2 us	~ 10 us	**~ 10 ns**	~ 100 ns	~ 100 ns	~ 2 us



Dynamic range of different SiPMs



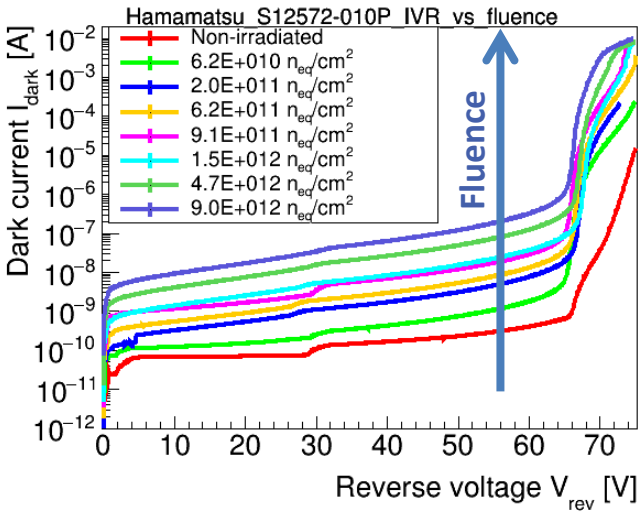
Normalized response vs proton beam rate measured at NA61 PSD calorimeter

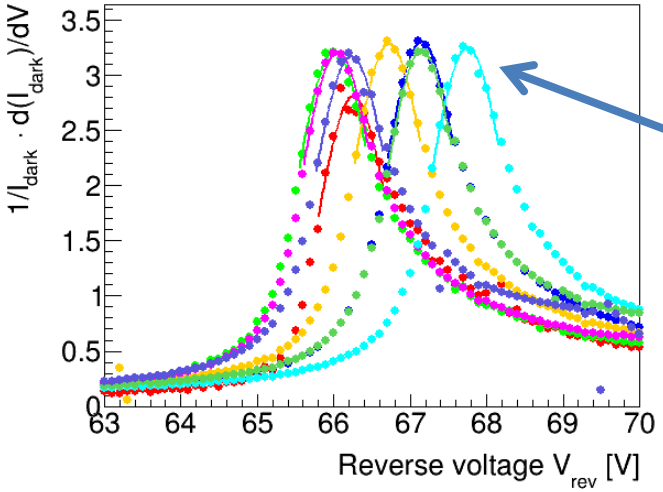
Hamamatsu SiPM was chosen for the further investigation because it has best recovery time and:

- Zecotek SiPMs have too slow pixel recovery time and can not operate at rates > 10 kHz
- Sensl and Ketek SiPMs have significantly lower radiation hardness and dynamic range

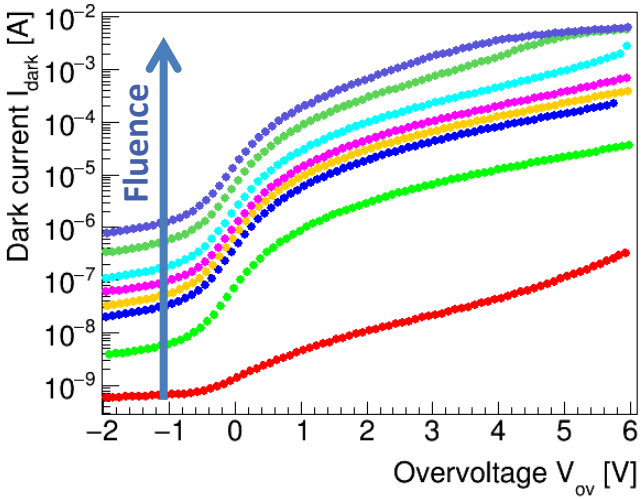
V. Mikhaylov, SiPM radiation hardness for FAIR, CERN and NICA, iWoRiD 2019, Crete

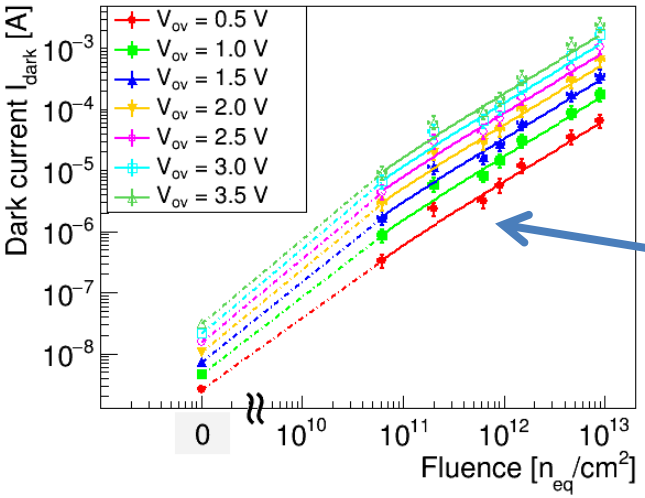
Dark current after irradiation





Breakdown voltage V_{bd} determination

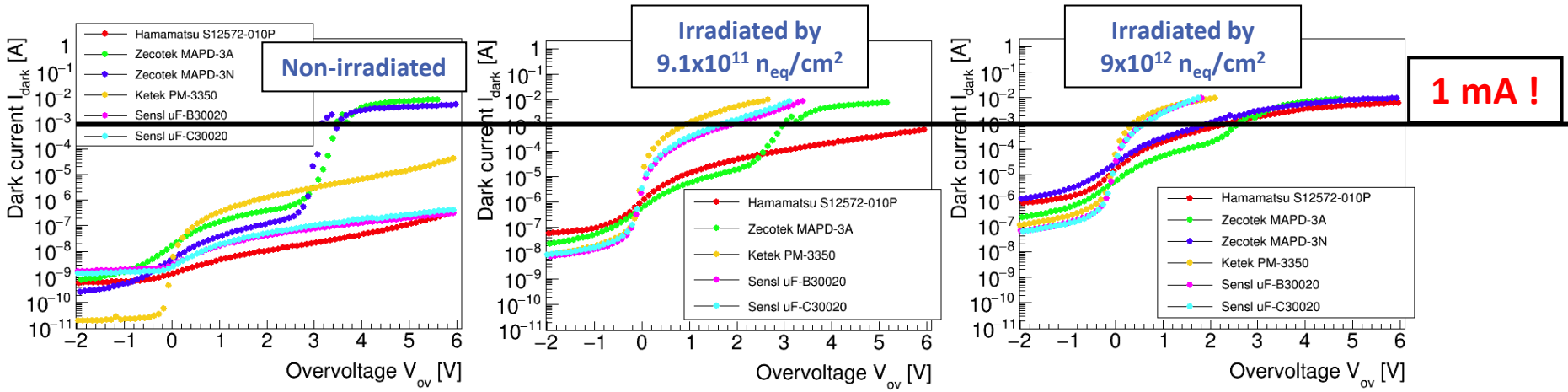


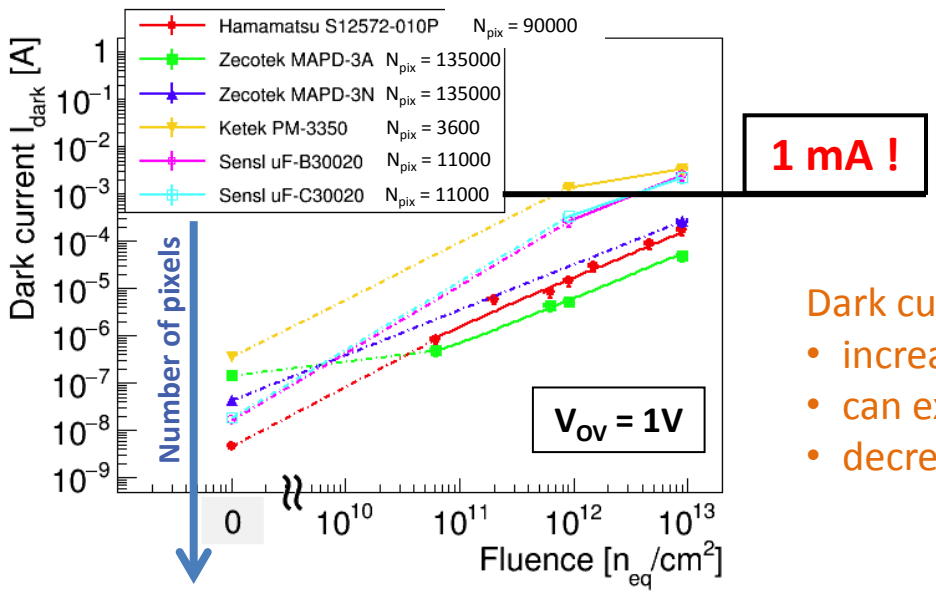


Linear dependence on fluence

V. Mikhaylov, SiPM radiation hardness for FAIR, CERN and NICA, iWoRiD 2019, Crete

Dark current after irradiation

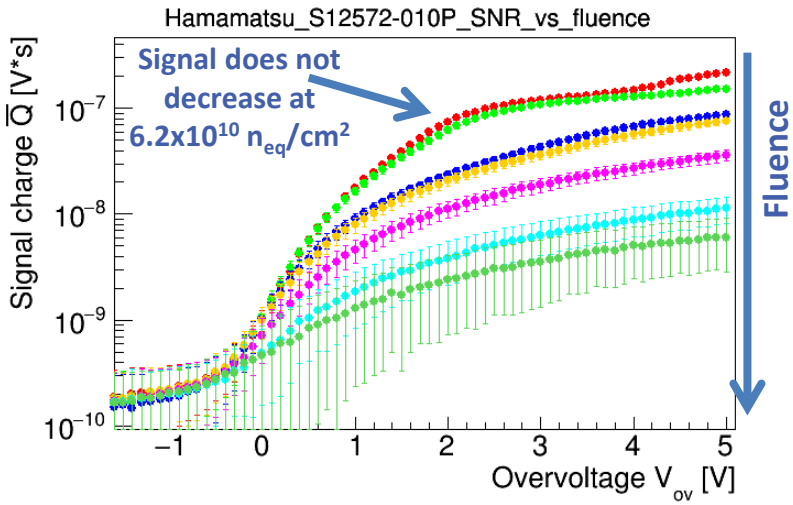


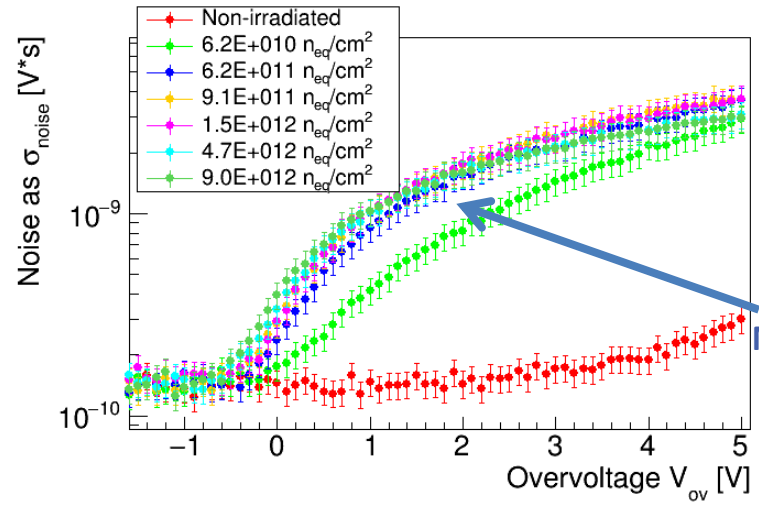


Dark current

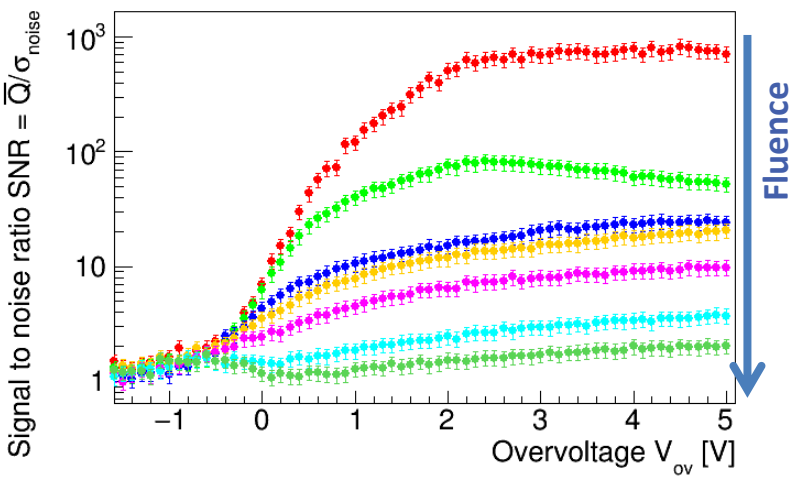
- increases linearly with neutron fluence
- can exceed 1 mA
- decreases with number of pixels

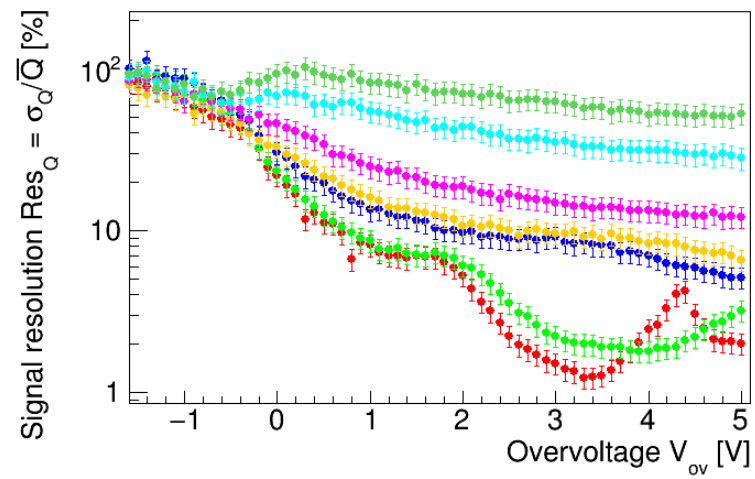
Response to LED after irradiation





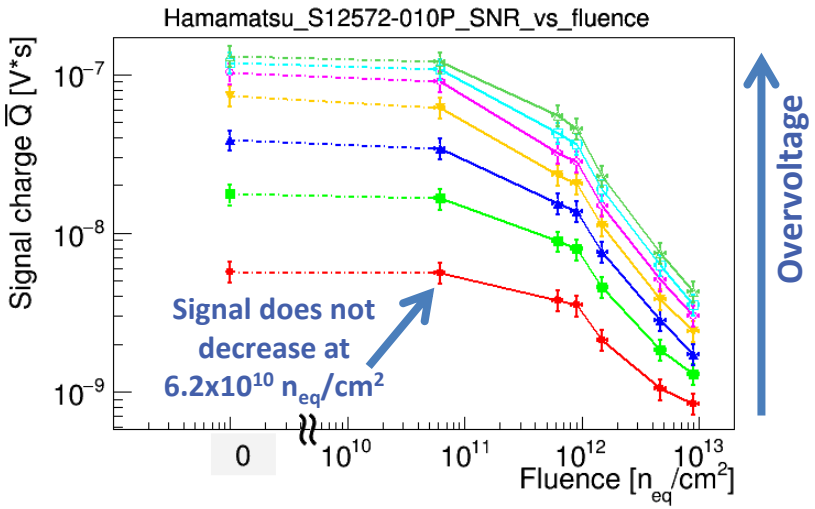
Noise does not increase after ~10^{12} n_{eq}/cm^2

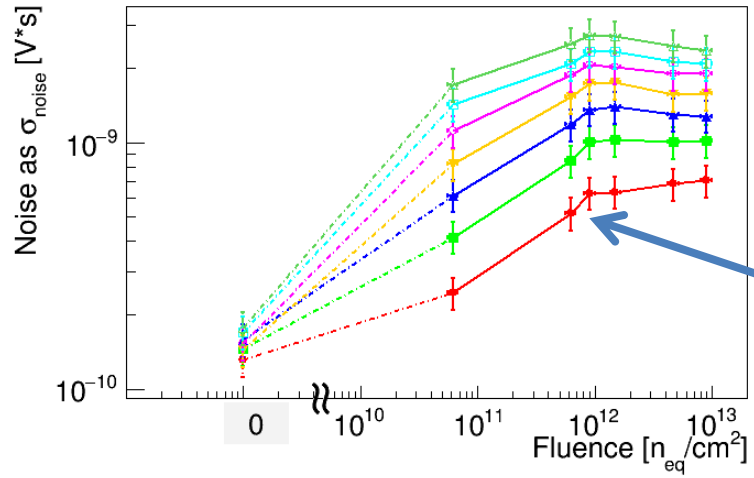




SNR and resolution improve with overvoltage

Response to LED after irradiation





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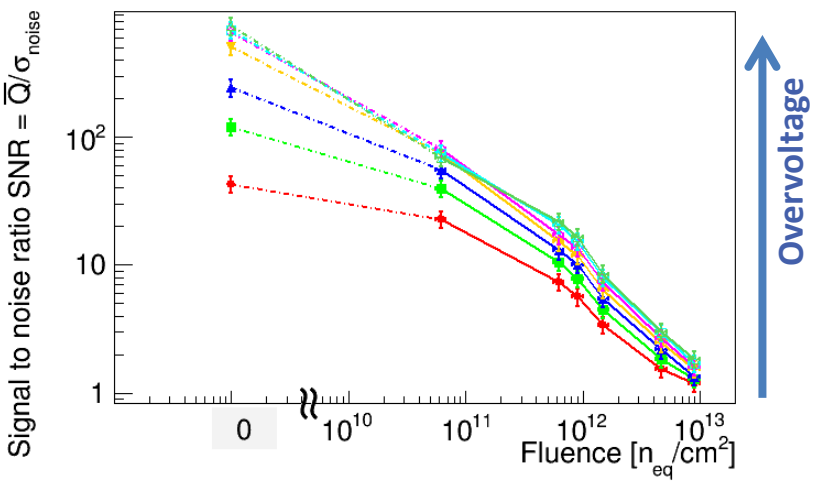

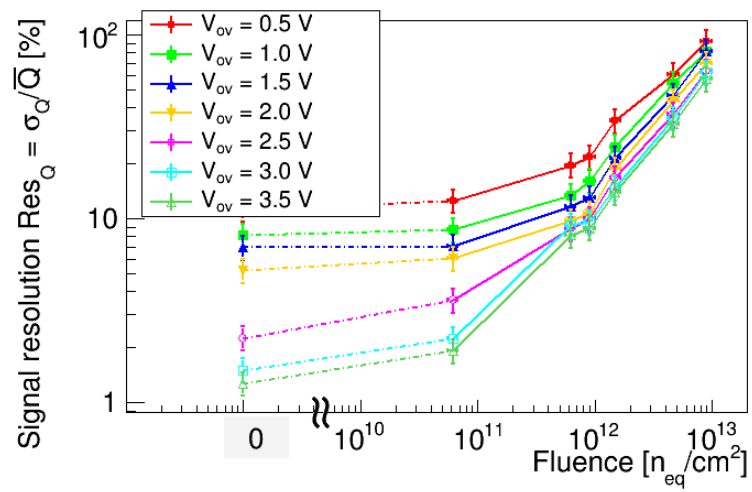

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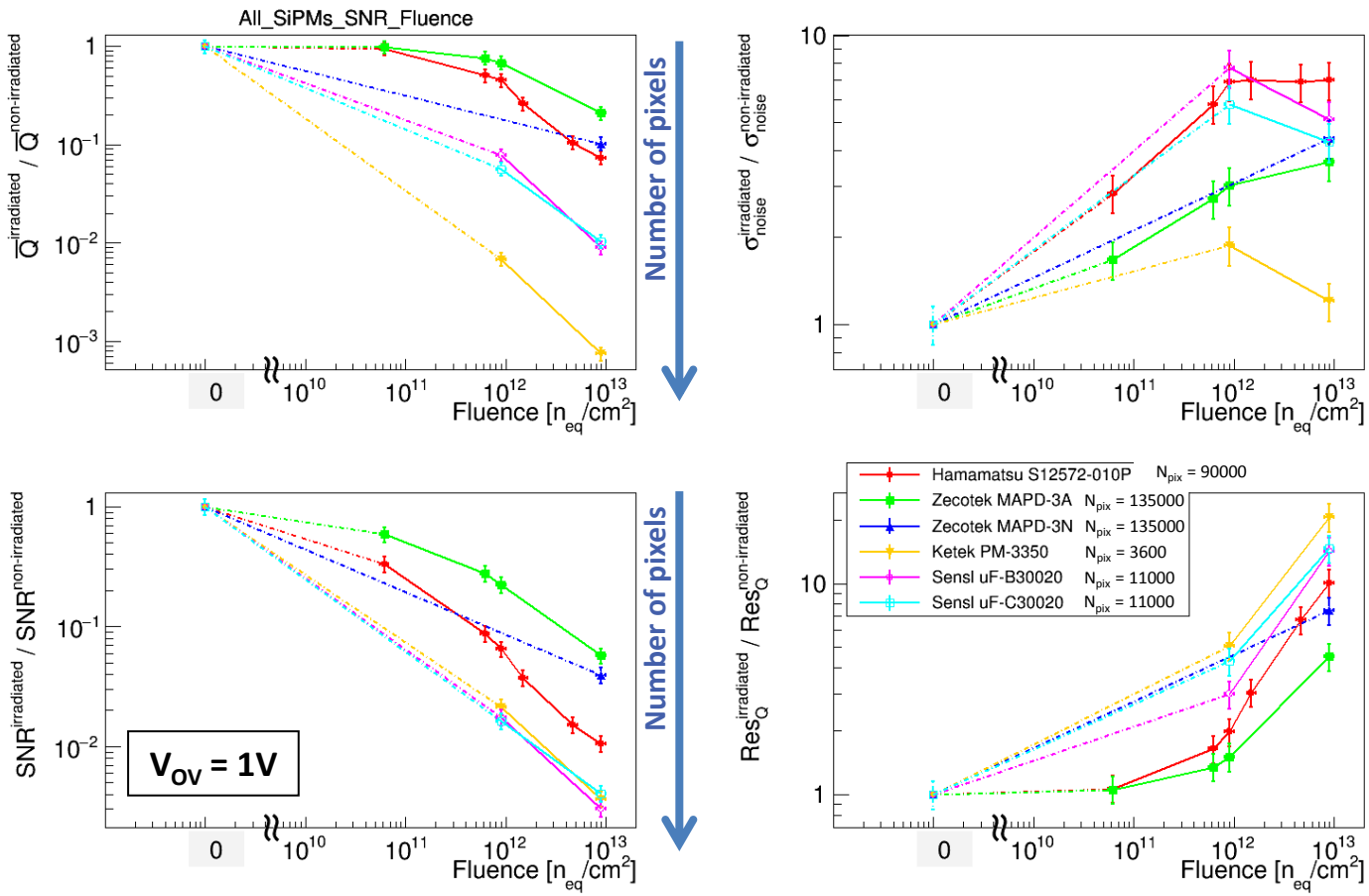
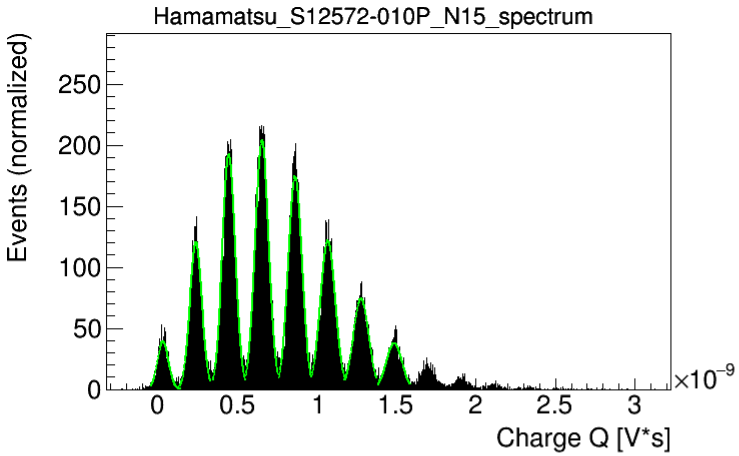
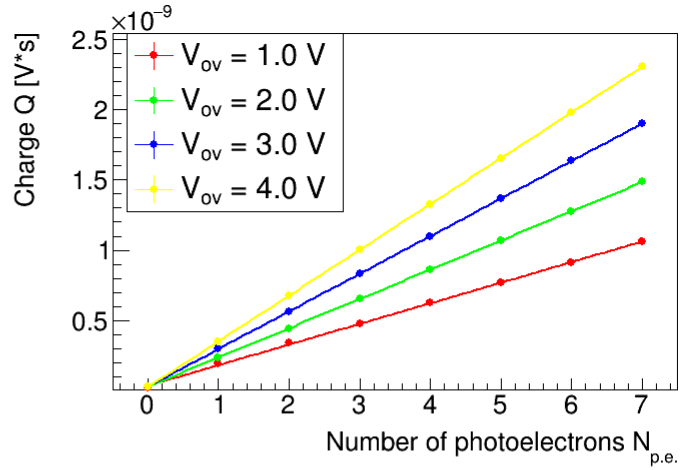
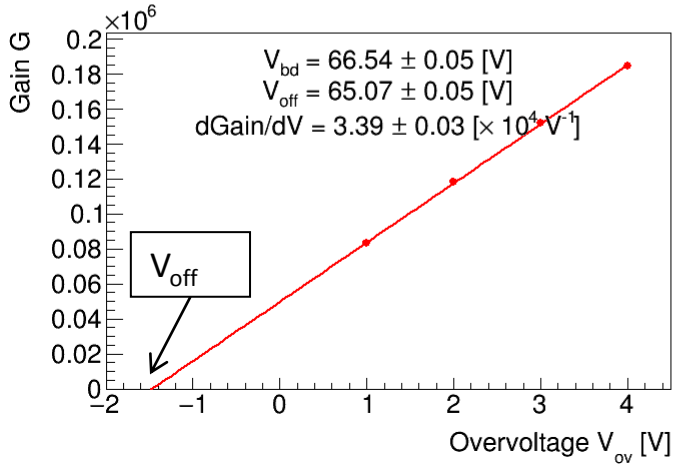


- Response to LED and SNR decrease by 1-3 orders of magnitude with fluence
- Noise increases up to an order of magnitude and then saturates or even decreases (gain drop?)
- Signal parameters degrade slower for SiPMs with high number of pixels

Single photon spectrum







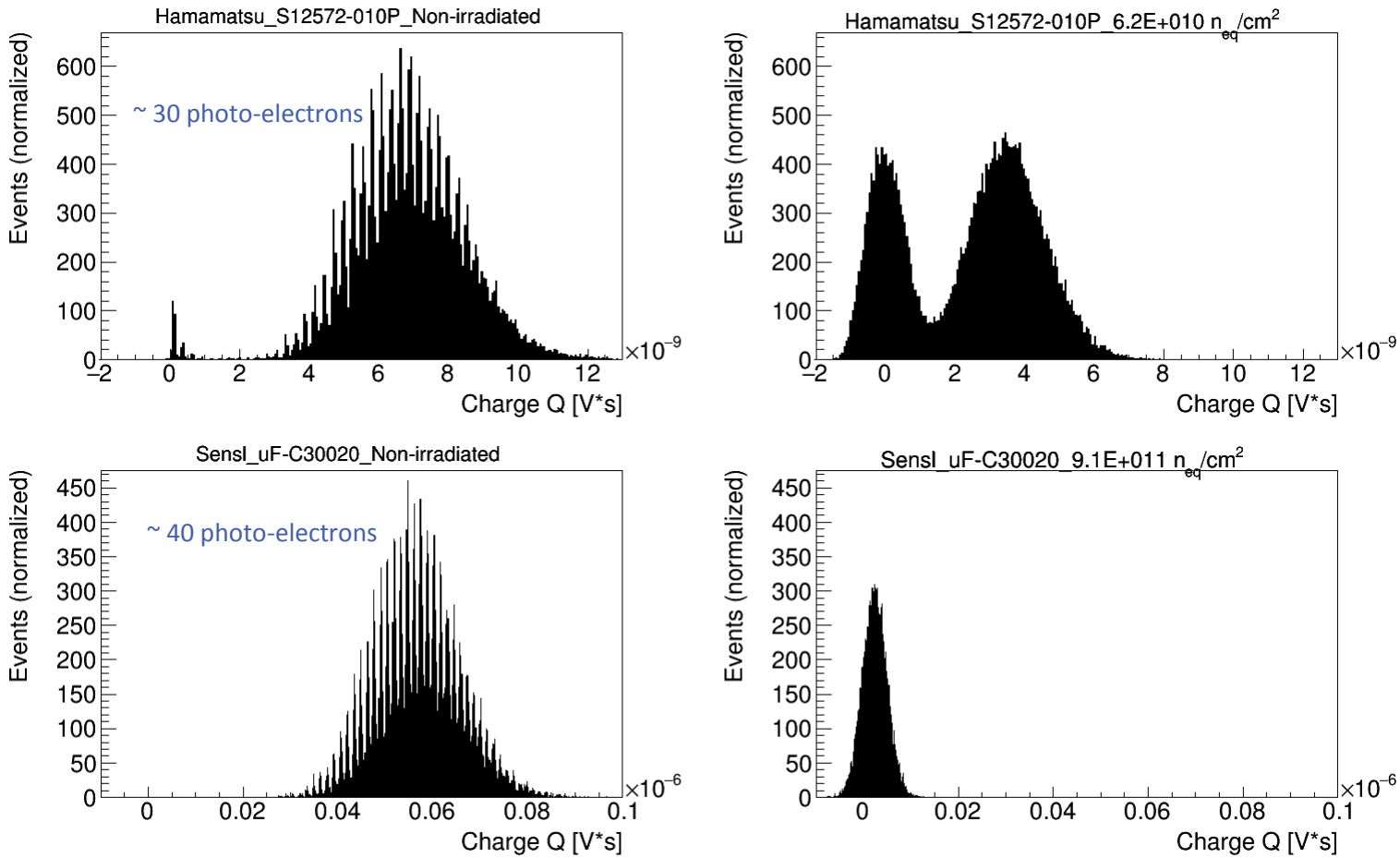
$$\mathrm{Gain}_{\mathrm{SiPM}} = \frac{2\,\mathrm{peaks\ distance}[C]}{q_e[C]} = \frac{2\,\mathrm{peaks\ distance}[pV \cdot s]}{q_e[C]} \cdot \frac{10^{-12}}{R_{in} \cdot \mathrm{Gain}_{\mathrm{Amplifier}}}$$

V_{off} = Voltage at Gain=1.

V_{off} is typically below the breakdown voltage V_{bd} by 0 – 2 V (more pixels – lower V_{off})

Gain and voltage of Geiger discharge turn-off V_{off} can be calculated

Single photon spectra after irradiation

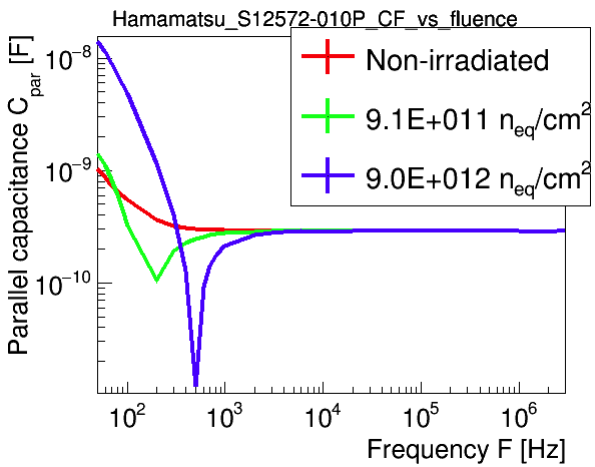


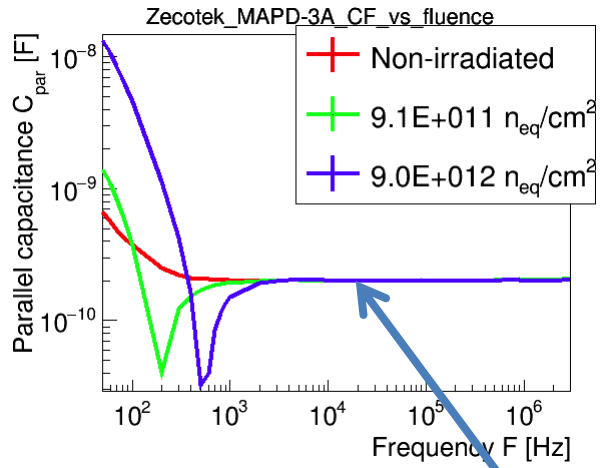
Single photon peaks are not distinguishable after irradiation with 6.2×10^{10} n_{eq}/cm^2

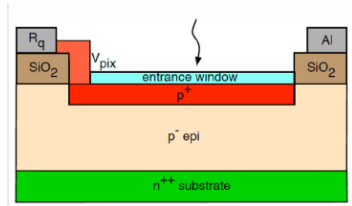
Low photon signals are not visible anymore after irradiation with 9.1×10^{11} n_{eq}/cm^2

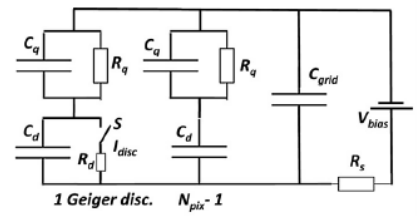
V. Mikhaylov, SiPM radiation hardness for FAIR, CERN and NICA, iWoRiD 2019, Crete

Capacitance after irradiation

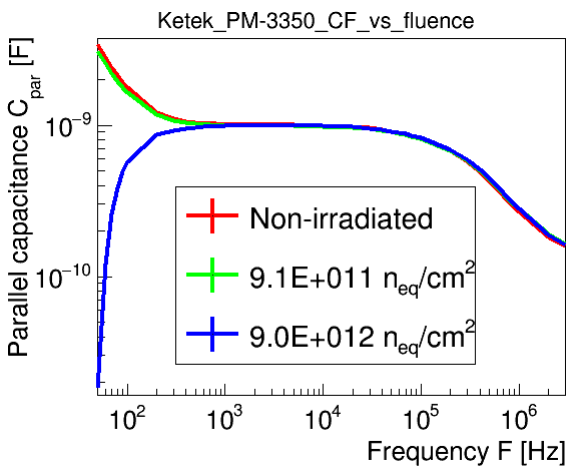


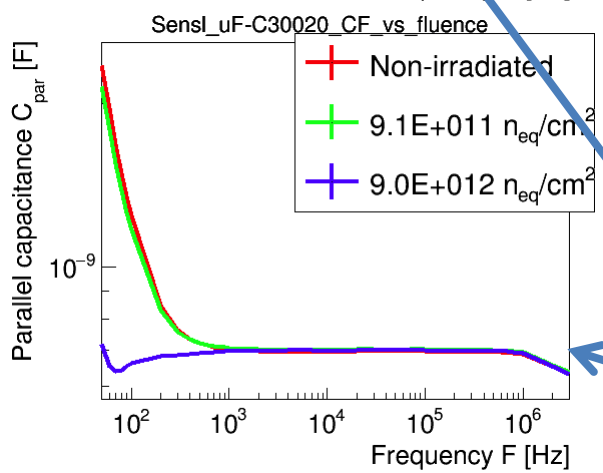






SiPM structure and schematics





SiPM complex impedance Z:

$$Z = \left(\frac{1}{R_{par}} + j\omega C_{par} + N_{pix} \cdot \left(R_{pix} + \frac{1}{j\omega C_{pix}} + \frac{R_q}{1 + j\omega C_q R_q}\right)^{-1}\right)^{-1}$$

Intermediate frequency

$C_{par} \approx C_d \times N_{pix}$

High frequency

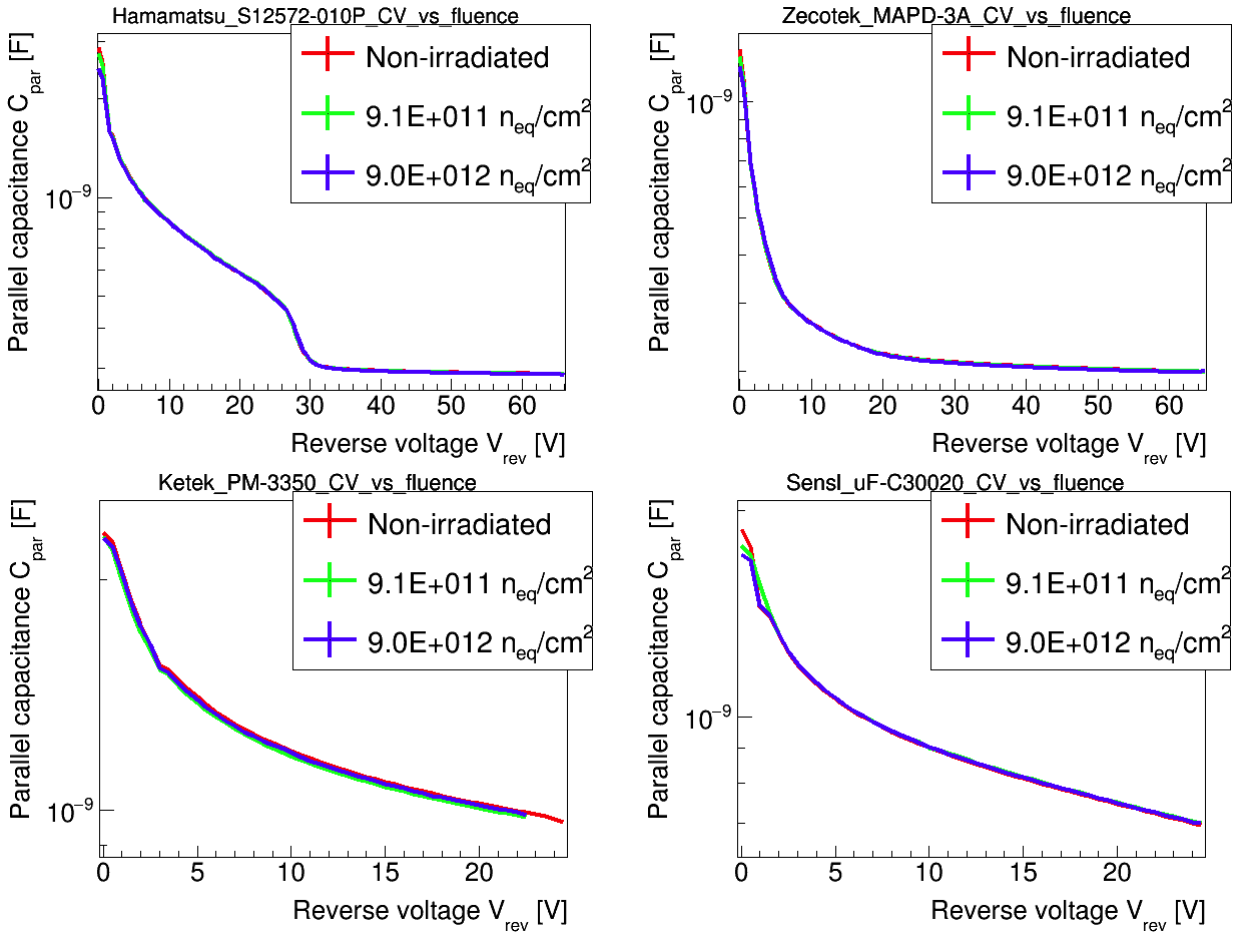
$C_{par} \approx C_q \times N_{pix}$

Strange behavior below 1kHz, but no sizeable change of capacitance after

Stable frequency = 10kHz was chosen for further investigation

Formulas and schemas are from
* R. Klanner, Characterisation of SiPMs
https://doi.org/10.1016/j.nima.2018.11.083

Capacitance after irradiation



$$\text{Gain} = (V_{rev} - V_{off}) \times (C_d + C_q) / q_e$$

$$V_{off} \approx V_{bd}\,,\ C_d >> C_q\,,\ C_d = C_{par} / N_{pix}$$

$\Rightarrow$ **Gain ≈ $V_{ov} \times C_{par} / (N_{pix} \times q_e)$**

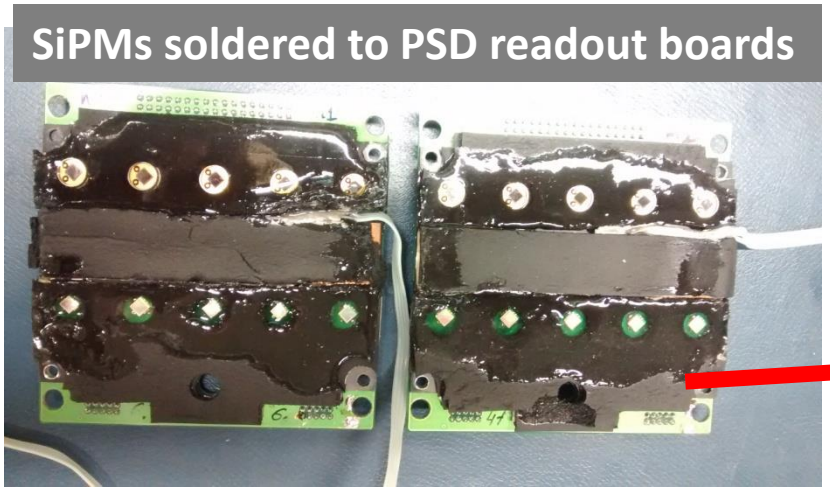
$\Rightarrow$ **C_d = const => Gain = const**

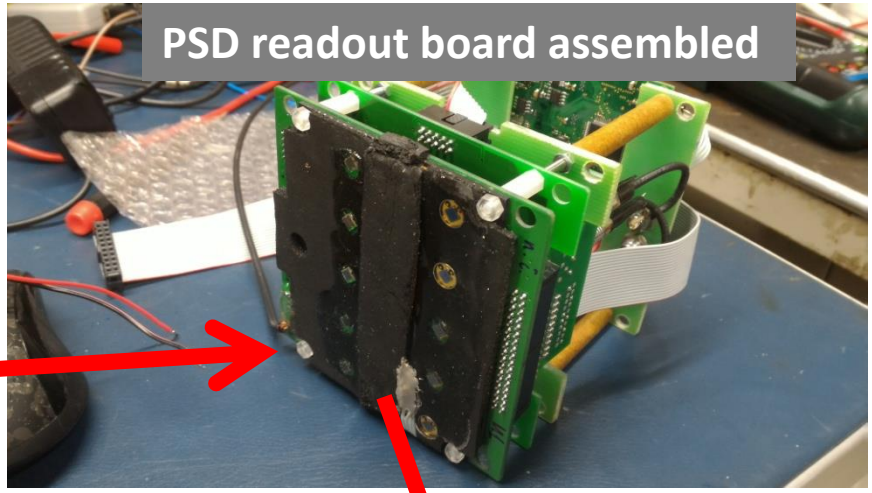
No sizeable change of capacitance after irradiation, therefore no change in gain

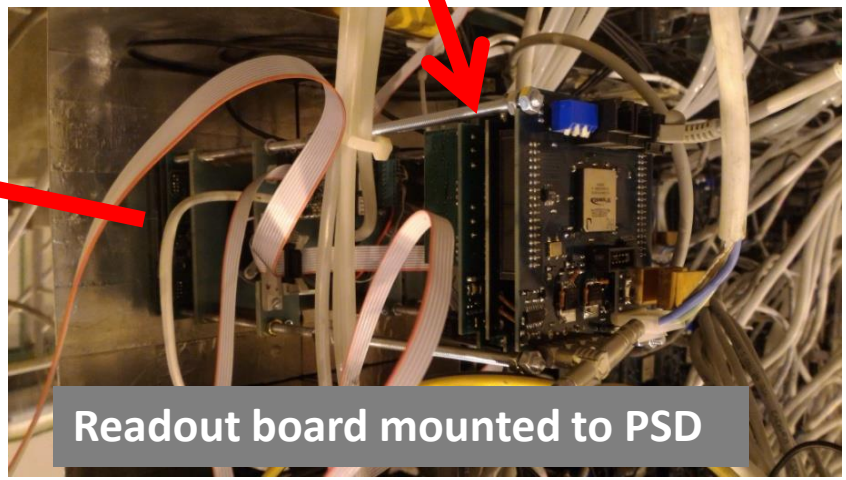
Decrease of SiPM response to LED is solely due to decrease of PDE?

Formulas are from
* R. Klanner, Characterisation of SiPMs
https://doi.org/10.1016/j.nima.2018.11.083

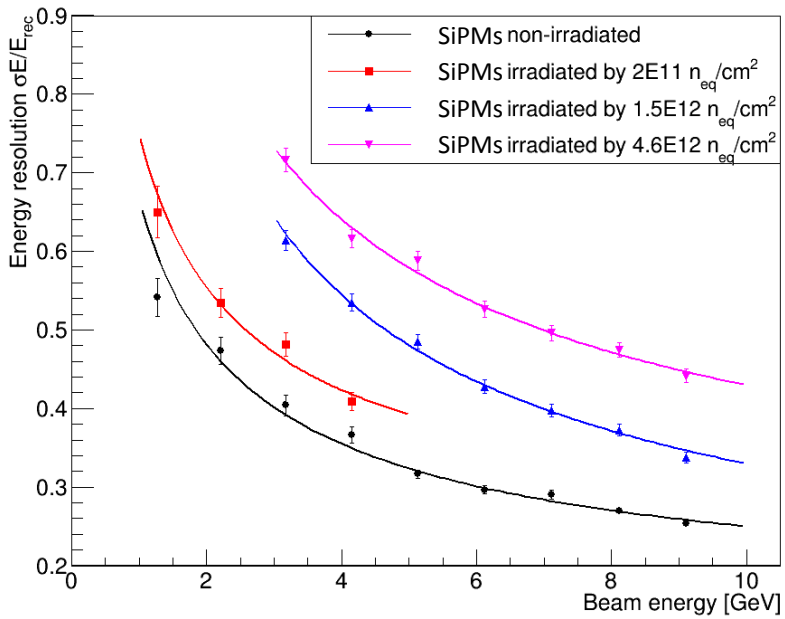
Experiments at PSD in CERN





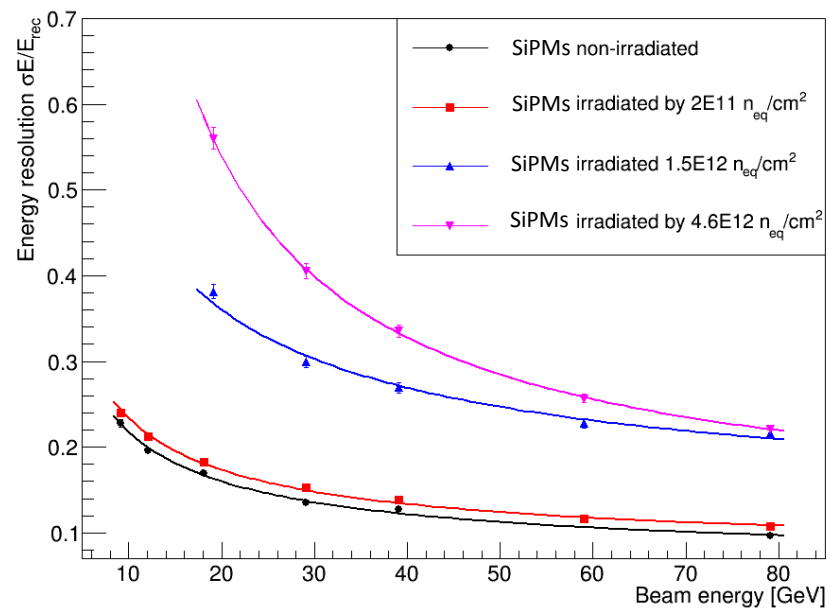


Performance of SiPMs in CERN



Single module energy resolution (CBM supermodule)

Fluence



Single module energy resolution (NA61)

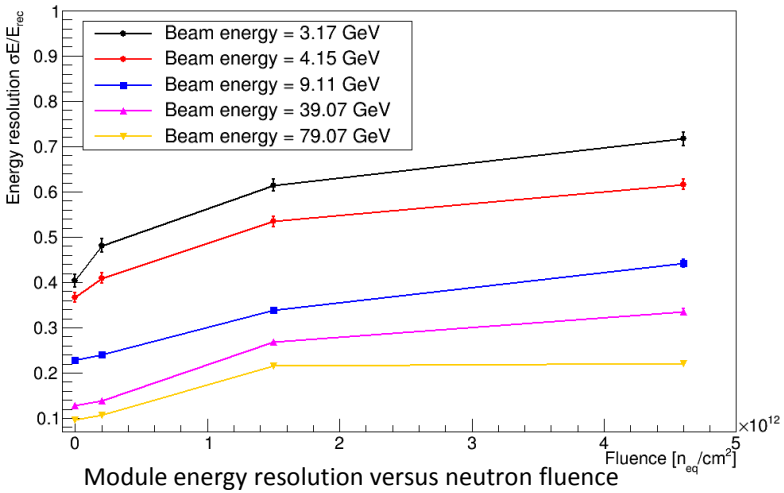
- Energy resolution dropped slightly for SiPMs irradiated by $2x10^{11}$ n_{eq}/cm^2
- Energy resolution dropped in ~1.5 – 2 times for SiPMs irradiated by ~10^{12} n_{eq}/cm^2 but SiPMs were proven to operate even after such a high neutron irradiation

** Reconstruction was performed with the noise cut, which was applied individually for each section*

Conclusions and Outlook

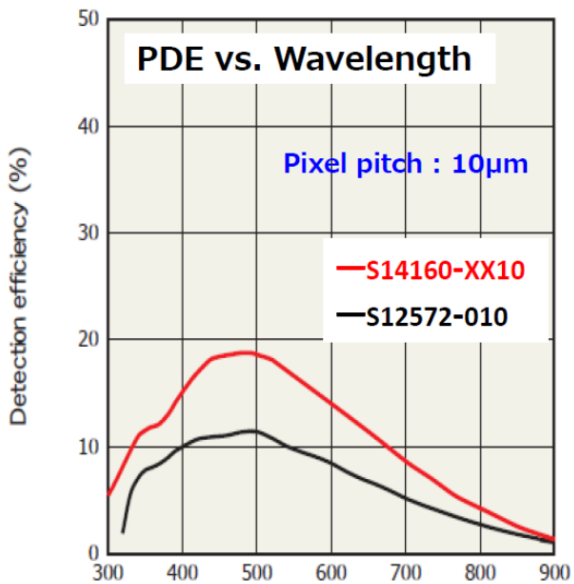
- Investigation of SiPM radiation hardness for calorimeters of CBM (FAIR), NA61 (CERN) and BM@N (NICA) is presented.
- Radiation hardness scales with the pixel number (pixel pitch) like the dynamic range.
- Hamamatsu MPPC S12572-010P was chosen from 6 different studied SiPMs for superior radiation hardness, dynamic range and operation rate.
- Radiation sustainability is sufficient for 1 year of calorimeter operation at maximum reaction rate of 1MHz and for whole experiment lifetime with exchange of SiPMs.

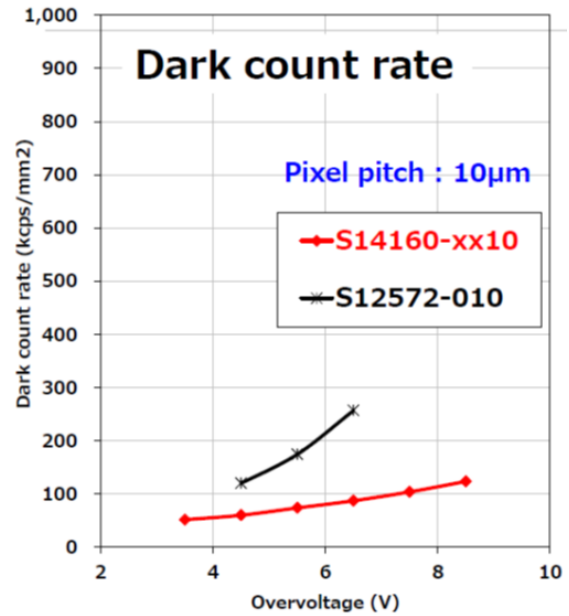
- *Future plans:*
  - *Investigate new SiPMs to increase radiation hardness further*



Module energy resolution versus neutron fluence

Future plans: New Hamamatsu SiPM





Light yield measured with S12572-010 (~45 photoelectrons/section/muon) can be increased by a factor of 1.5

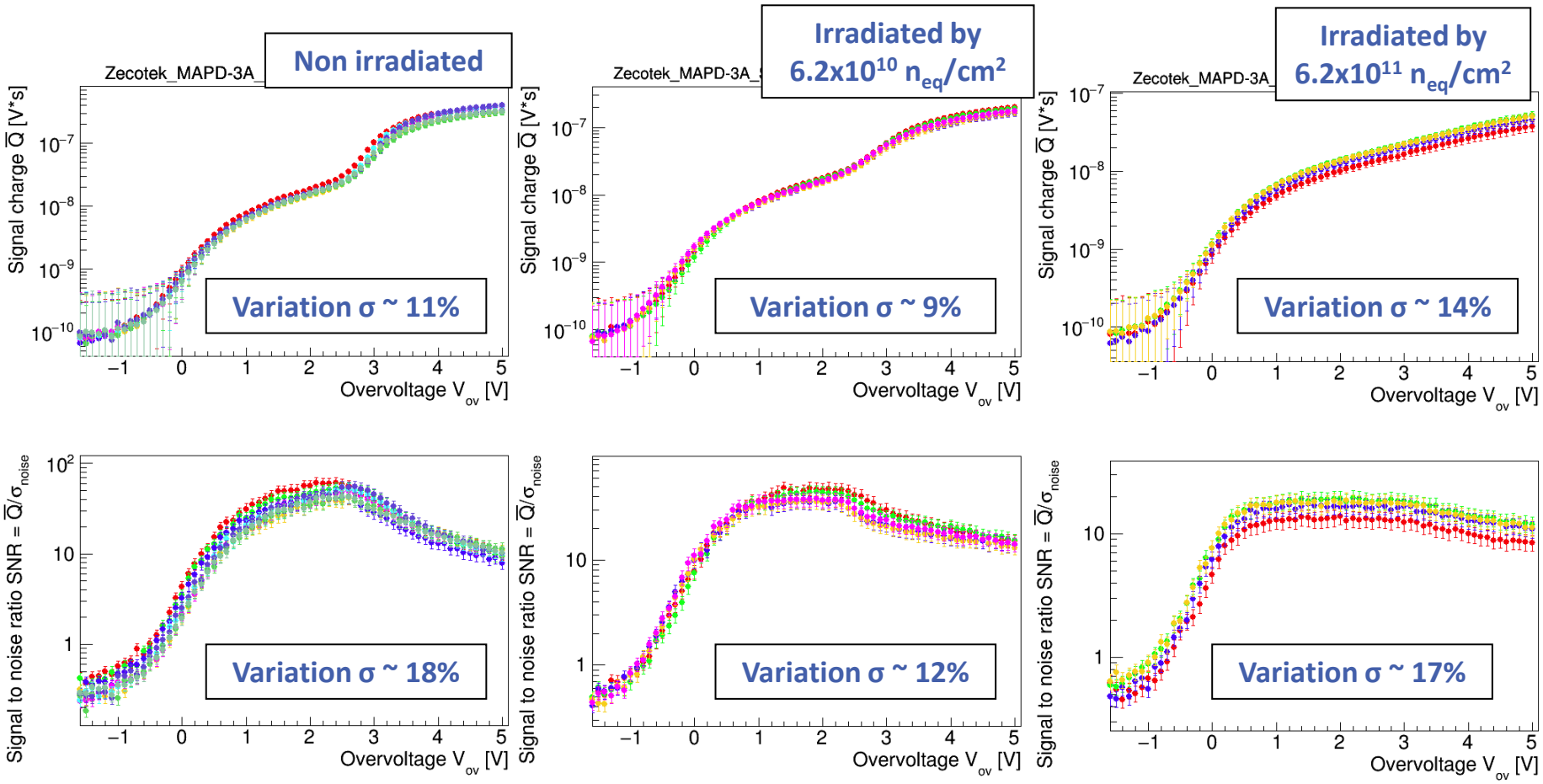
Lower dark current => Better radiation hardness.

Will be irradiated and tested at NPI in the Fall 2019

V. Mikhaylov, SiPM radiation hardness for FAIR, CERN and NICA, iWoRiD 2019, Crete

Backup

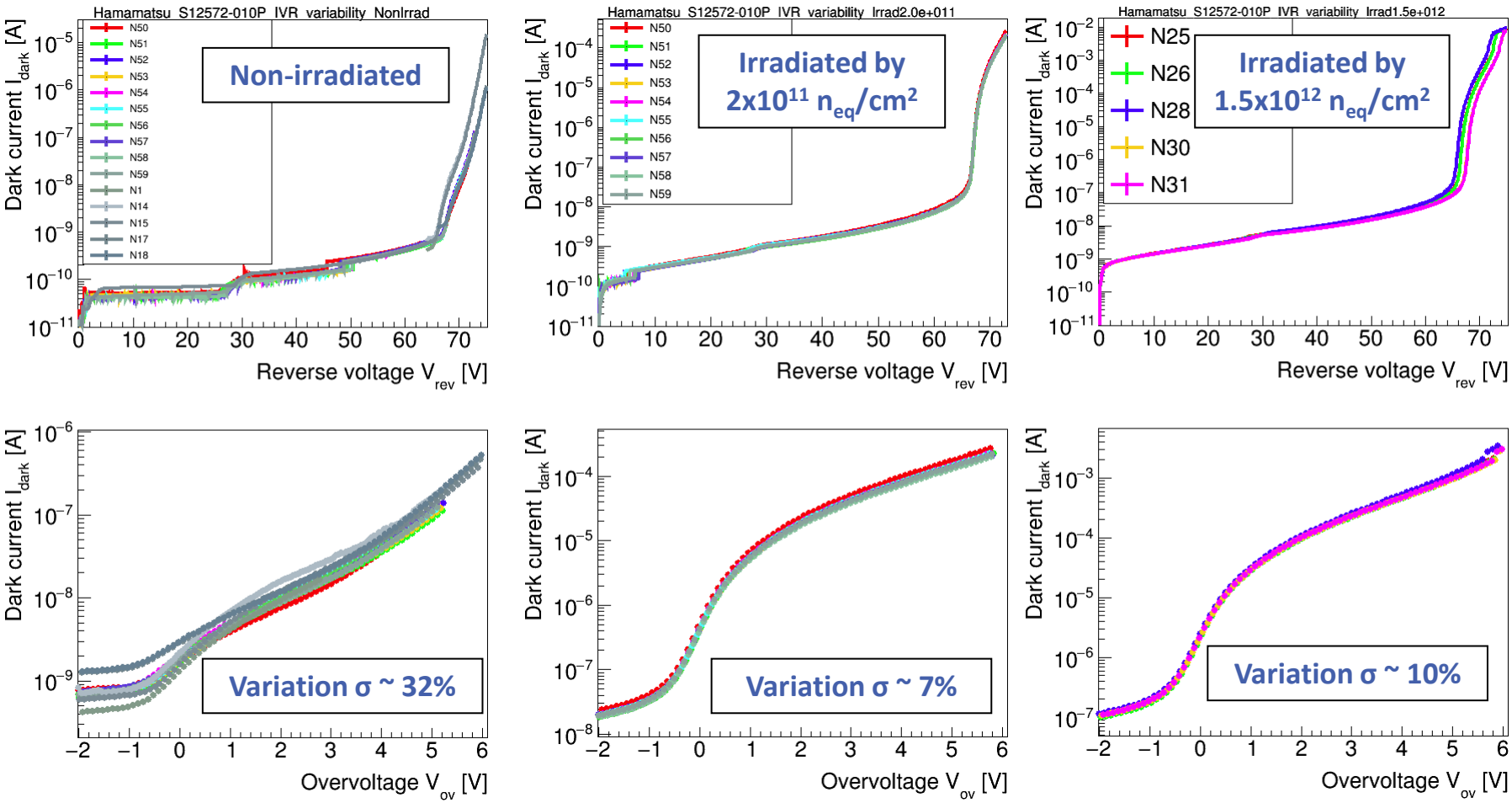
Response to LED: variability



Variation is below 20%

Neutron irradiation was quite uniform

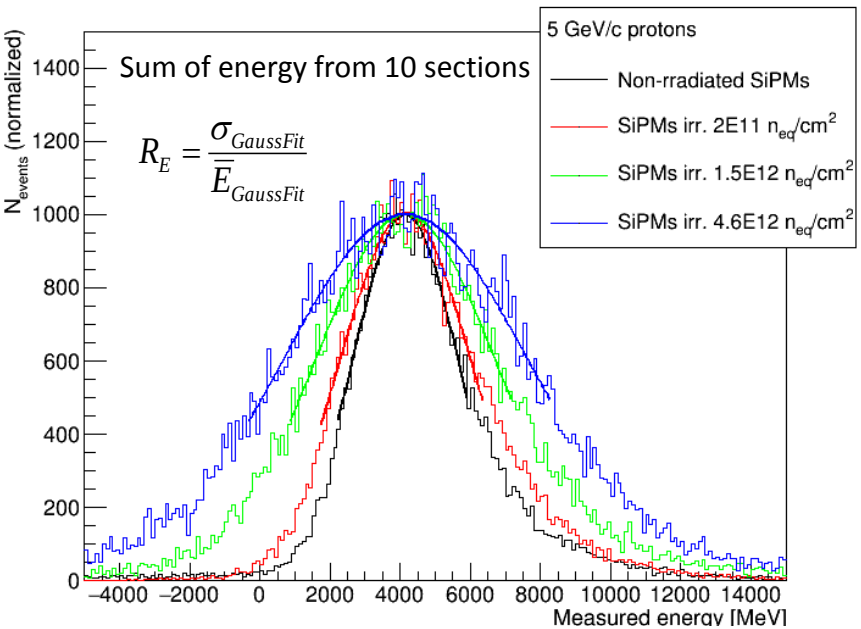
Dark current: variability



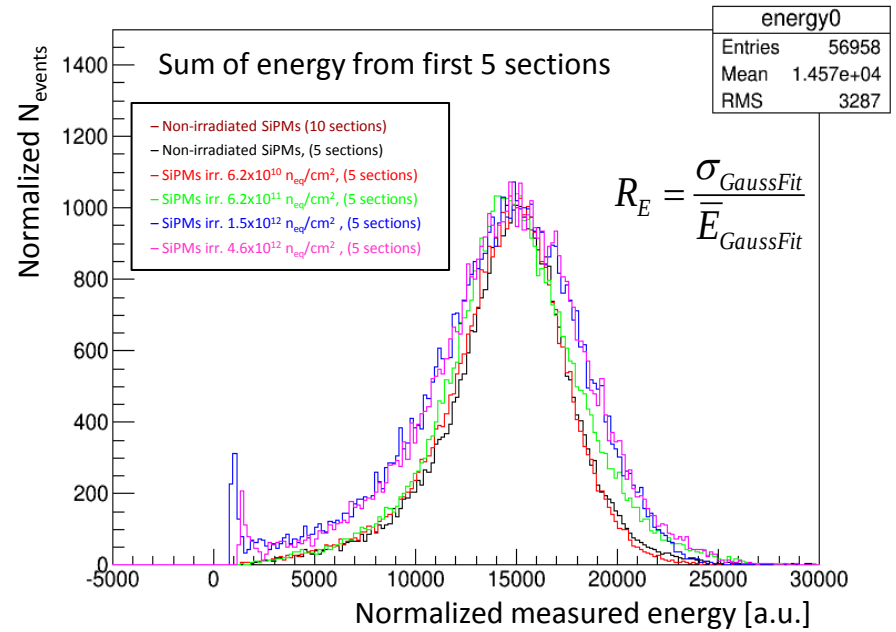
Many different samples,
V_{bd} was not always well defined

Neutron irradiation was quite uniform

Energy deposition in module



Energy deposition for 4.2 GeV proton beam in a single module



Energy deposition for 79 GeV proton beam in a single module

- Energy resolution dropped slightly for SiPMs irradiated by $2x10^{11}$ n_{eq}/cm^2
- Energy resolution dropped in ~1.5 – 2 times for SiPMs irradiated by ~10^{12} n_{eq}/cm^2 but SiPMs were proven to operate even after such a high neutron irradiation

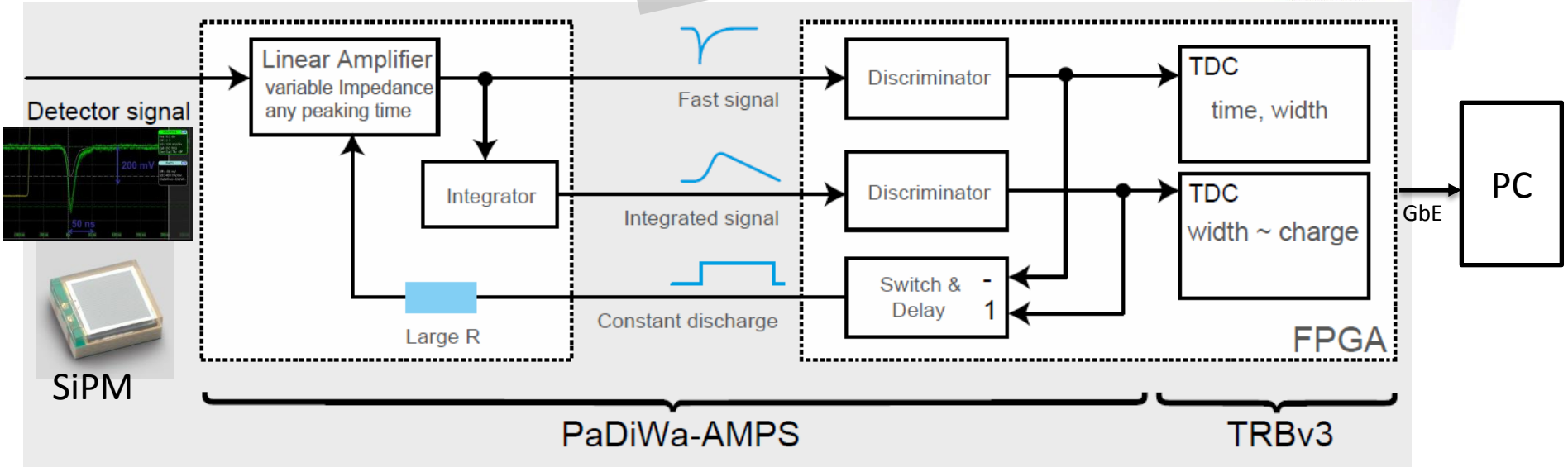
Reconstruction was performed with the noise cut, which was applied individually for each section

CBM PSD readout electronics

Preamplifier
- Attached to photodiode
- Optimized for high capacitance inputs
- Gain ~ 60 V / V
- Good Signal / Noise

PaDiWa-AMPS (GSI)
- Method: Time-Over-Threshold (ToT)
- 8 MMCX input channels
- Time precision: < 50 ps
- Rel. charge resolution: < 0.5 %
- Dynamic range: 250 – 500
- Compact data : max. 50 MB/s

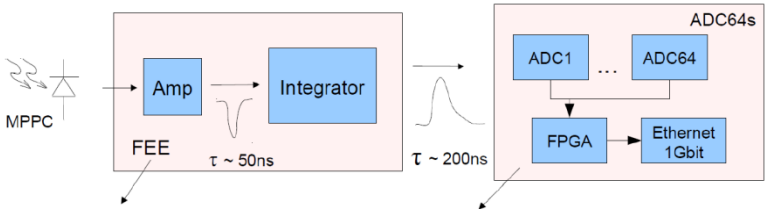
TRBv3 Trigger and Readout Board
- 4 FPGAs, 264 TDC channels
- Single edge & ToT measurement
- Time precision < 20 ps
- 50 MHz hit rate per channel
- Fast data transfer via gigabit Ethernet
- Internal trigger and slow control



CBM PSD: Alternative readouts

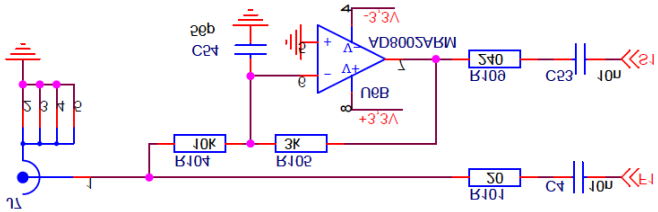
ADC64s/ADC125s electronics (AFI, JINR, Dubna)

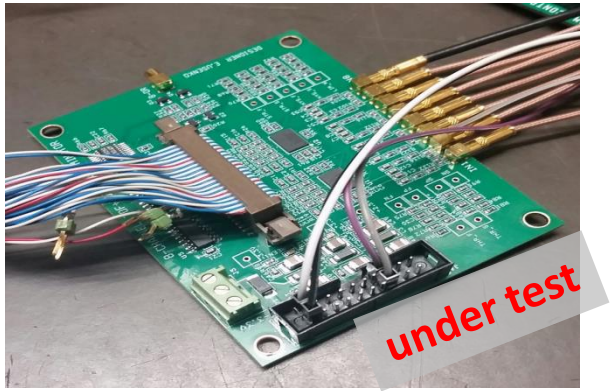
- Method: direct waveform digitization
- 64 channels, 12 bit ADCs
- Speed: 62.5/125 MS/s
- Dynamic range: ~150
- Up to 100 kHz real event rate
- Huge amount of data
- DSP is required on top



Time-Over-Threshold (ToT) board

- Method: Time-Over-Threshold (ToT)
- 8 MMCX input channels
- NINO chip based design
- Dynamic range: ~ 250
- Compact data: max. 50 MB/s
- Coupled to TRB3





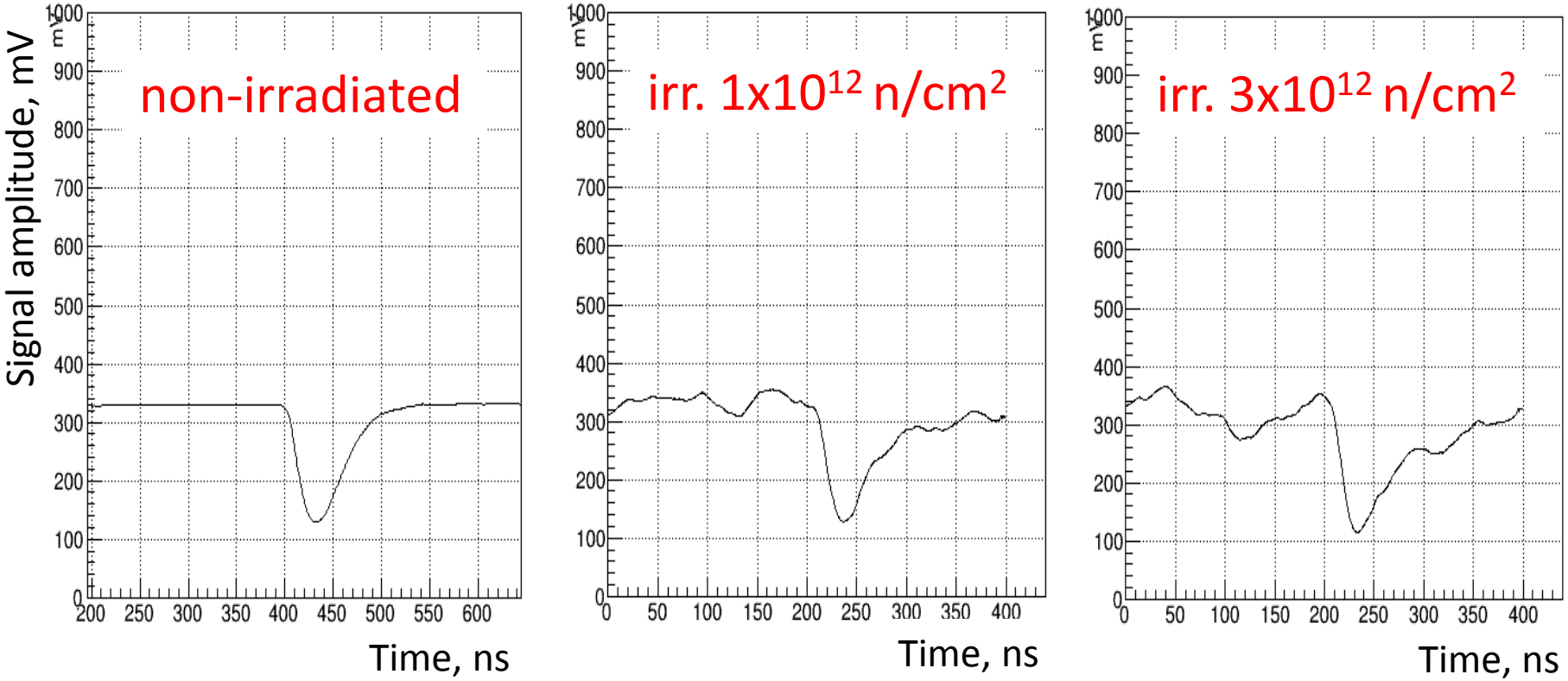
Difference between conducted tests

	Summer 2016 and 2017	September 2017	November 2017
Beamline	NA61	T10	T9
Beam momentum range	20 – 80 GeV/c	2 – 6 GeV/c	2 – 10 GeV/c
Proton selection	Not available	by TOF scintillators	By Cherenkov detector
Proton selection approx. mom. range	Not available	2 – 6 GeV/c	3.5 – 10 GeV/c
SiPMs utilized	Irradiated by 4E10, 4E11, 1E12 and 3E12 n/cm^2	Irradiated by 1E12 and 3E12 n/cm^2	
SiPMs calibration of overvoltages	Calibrated by LED relative to the muon calibration of non-irradiated SiPMs	Previous calibration from NA61 was utilized	Relative to the breakdown voltage measured in lab (seems to be more accurate)
Temperature stabilization	All SiPMs kept at 20 ^{o}C	Not available	
Temperature in the test hall	Not available	~ 26 ^{o}C	~ 18 ^{o}C

V. Mikhaylov, SiPM radiation hardness for FAIR, CERN and NICA, iWoRiD 2019, Crete

How the signals from 6 GeV/c protons look like

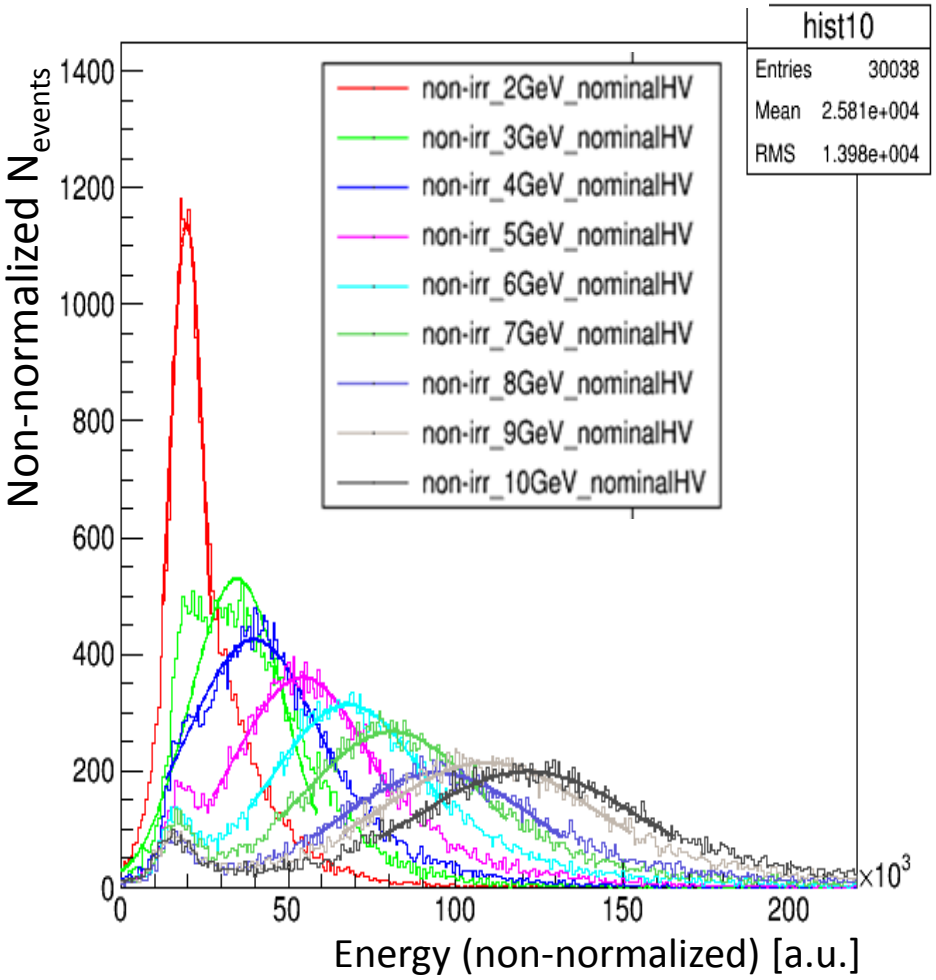
November 2017



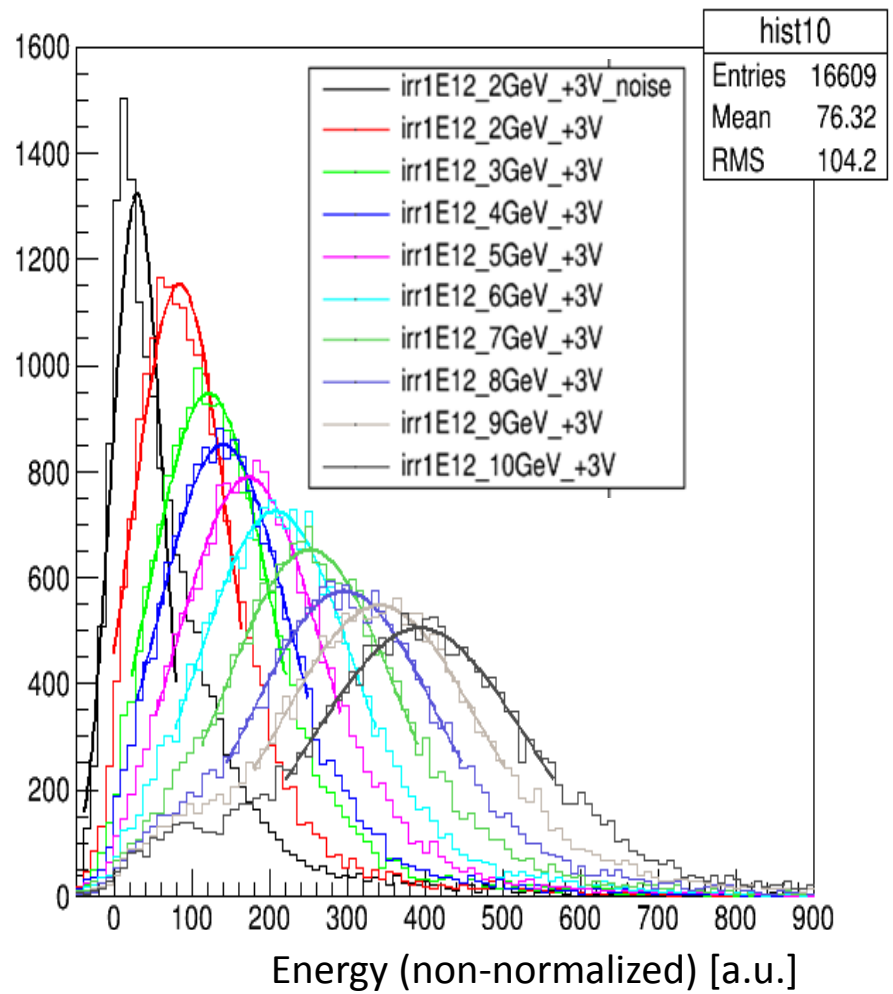
- Very high noise is clearly visible.

Energy scan

Non-irradiated

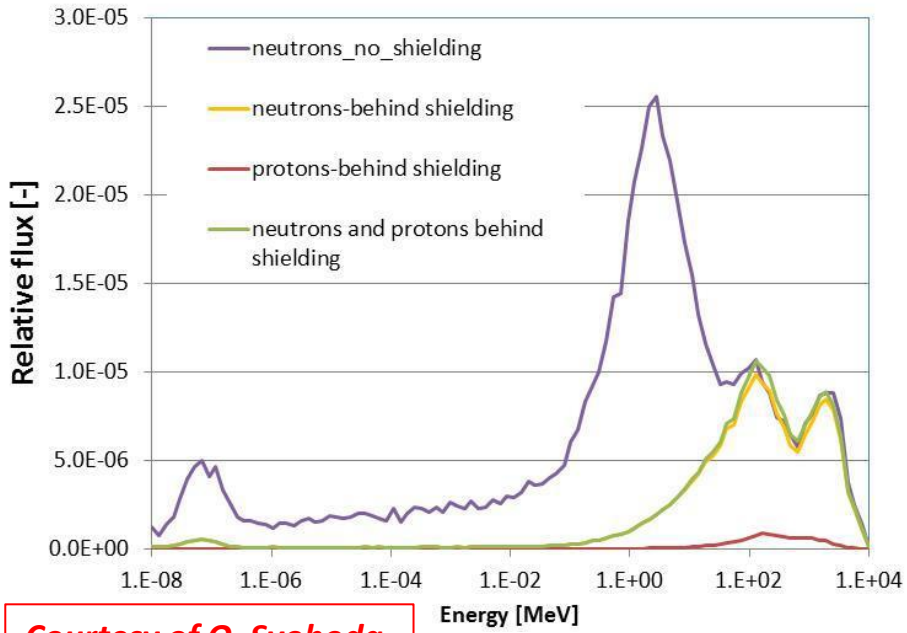


Irradiated 1E12 n/cm2

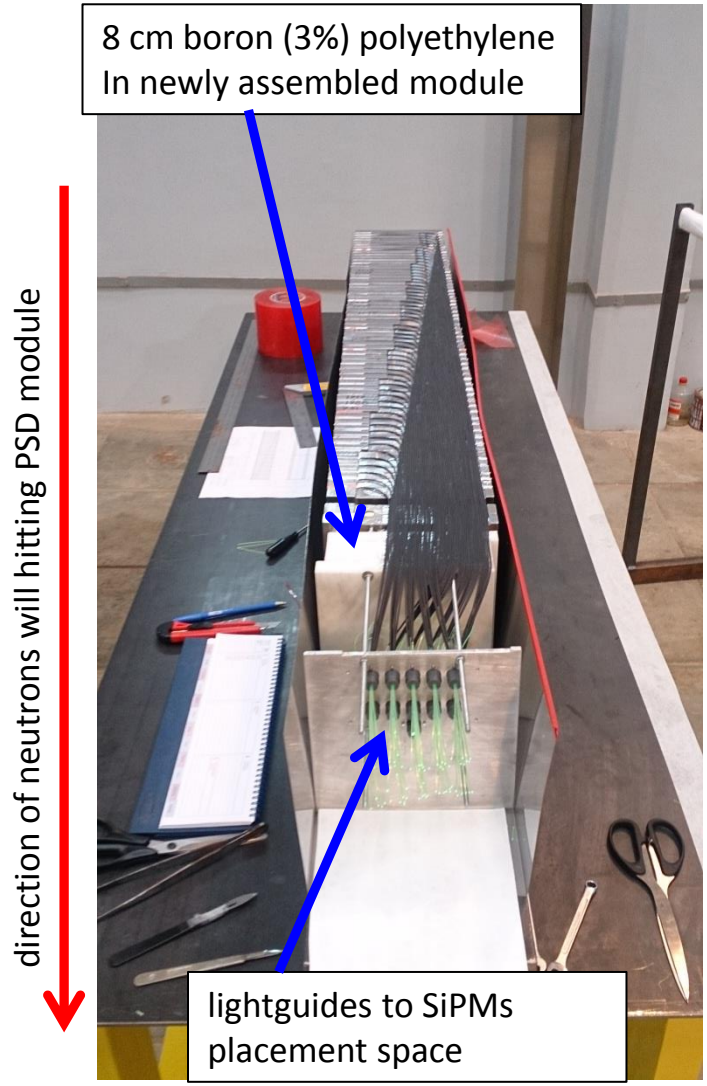


Neutron shielding simulation

- We reduced the neutron flux by 50-70% adding borated polyethylene between the PSD module lead/scintillator blocks and SiPMs.
- Low energetic neutrons are shielded the best, so we reduce the neutrons captured in SiPM by silicon and dopants, especially ^{10}B dopant having huge n cross-section.



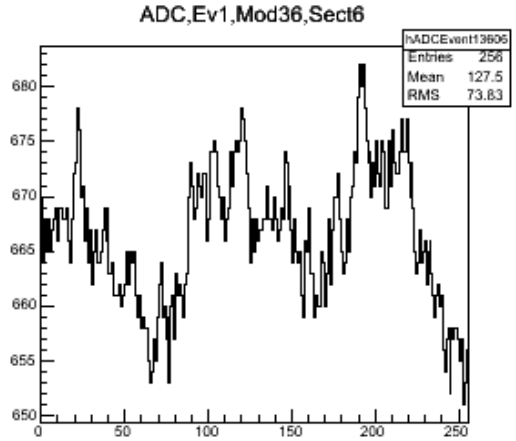
Courtesy of O. Svoboda

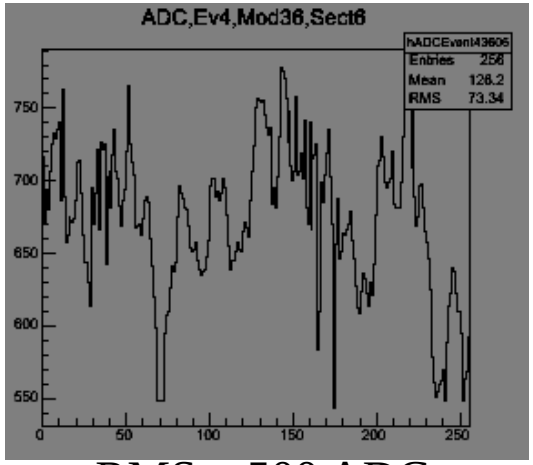


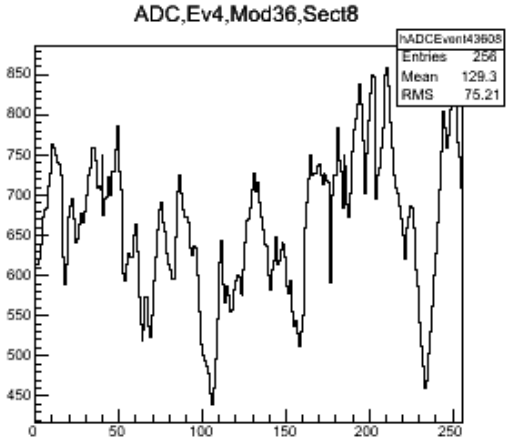
Test of Hamamatsu SiPMs response at NA61 PSD: Waveforms

Non-irradiated | Irradiated 3e11 n/cm2 | Irradiated 3e12 n/cm2

Noise



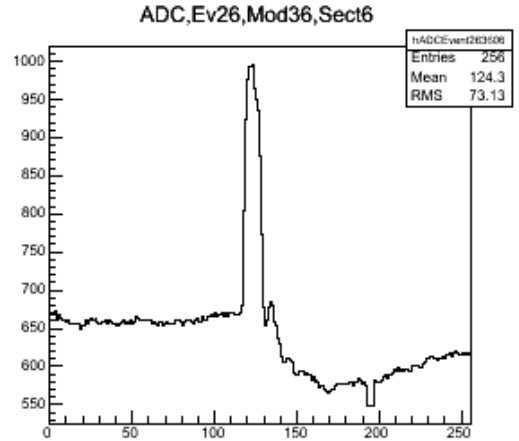


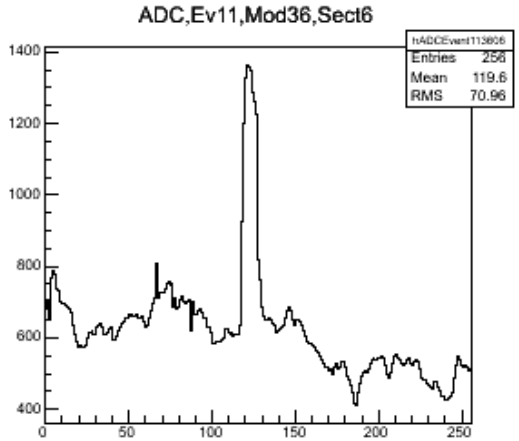


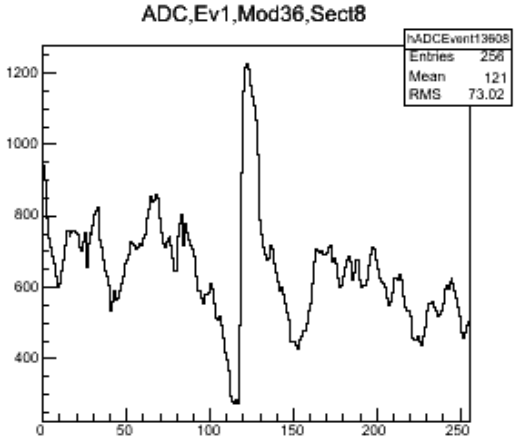
RMS ~ 50 ADC | RMS ~ 500 ADC | RMS ~ 1500 ADC

→ 10 times more noise → 30 times more noise

Proton



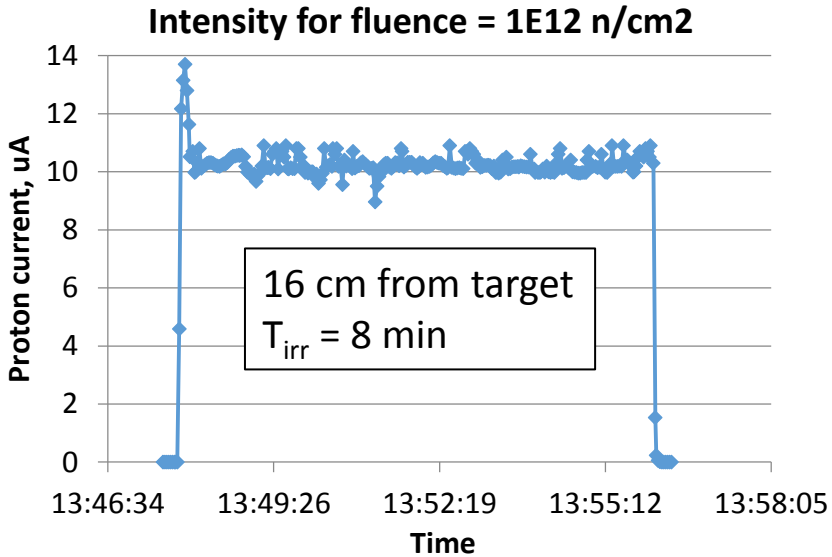


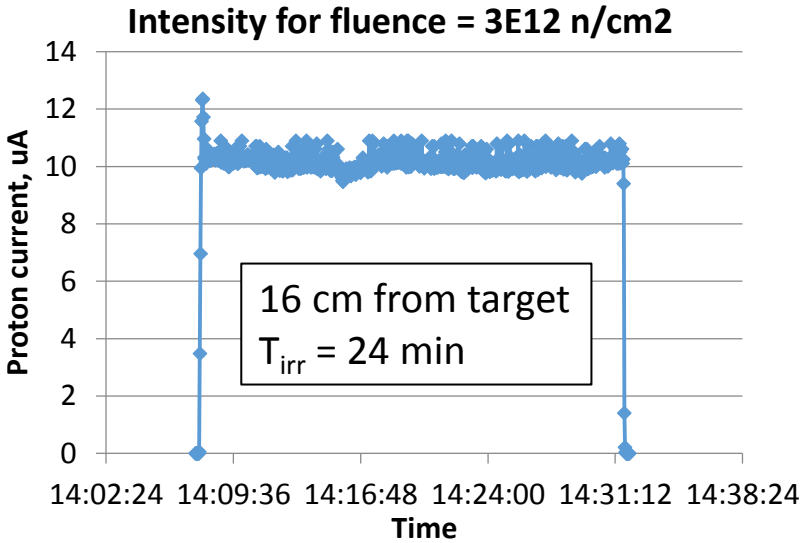


With the noise increased at 10-30 times SiPM cannot detect MIPs (~10-15 photons)!

Details on neutron irradiation experiments

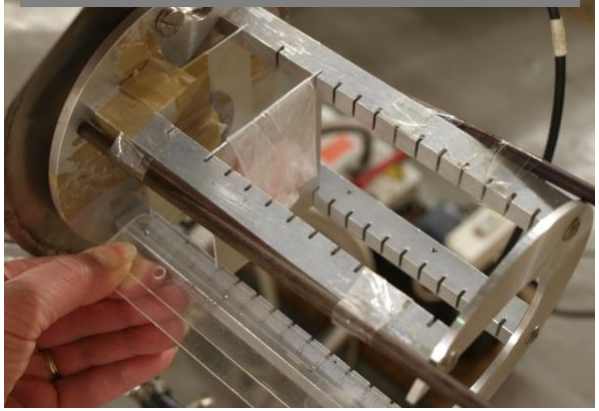
Proton energy = 35 MeV



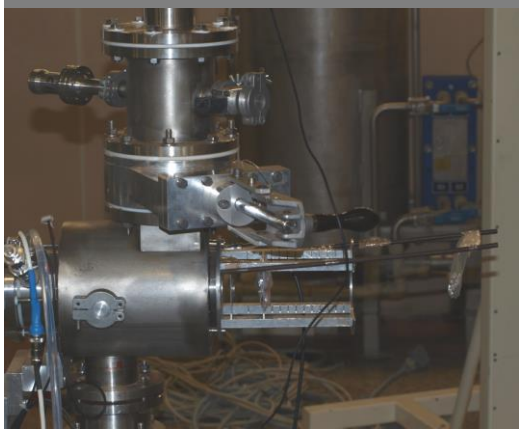


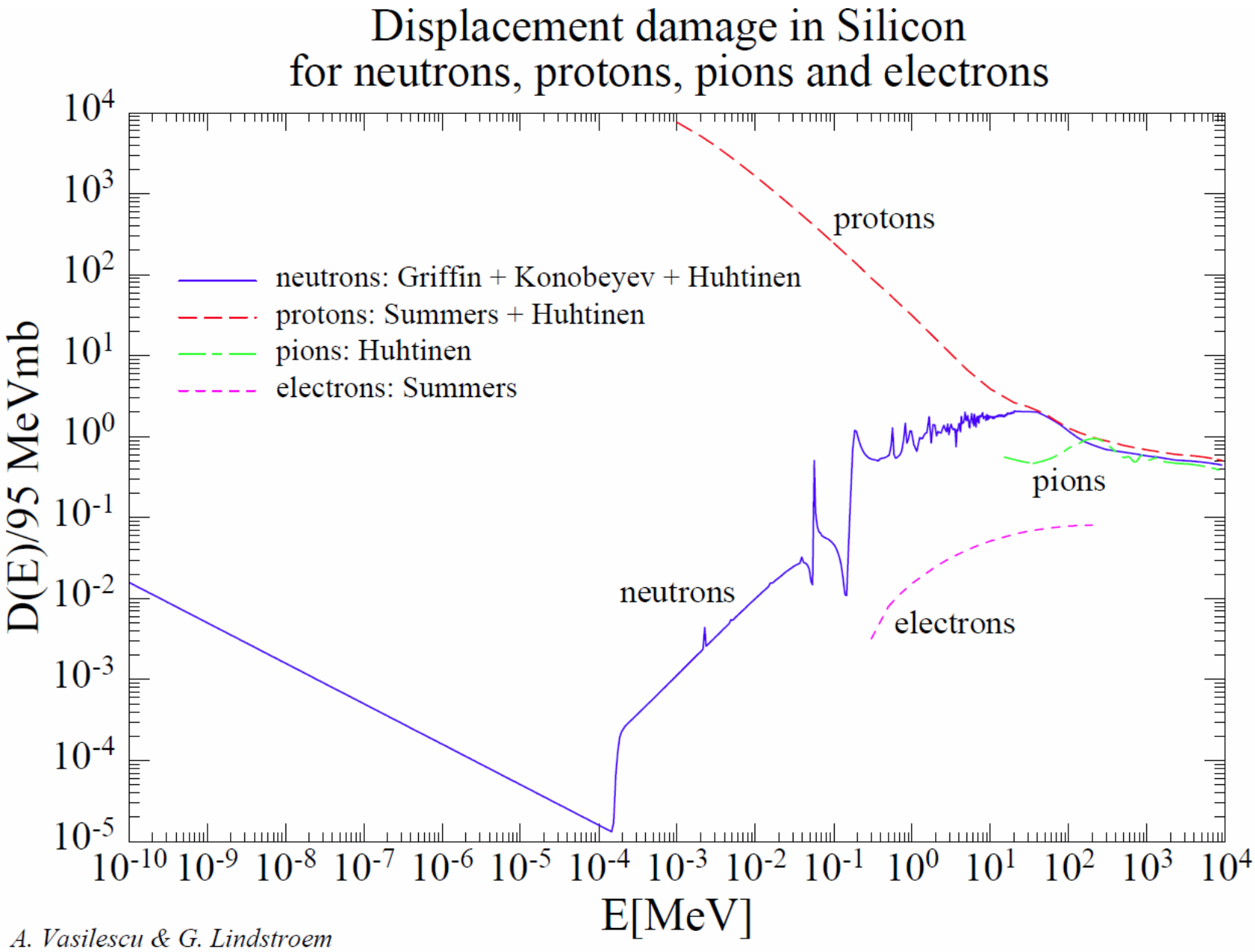
SiPMs prepared for irradiation

SiPMs located at the holder



SiPMs located at cyclotron



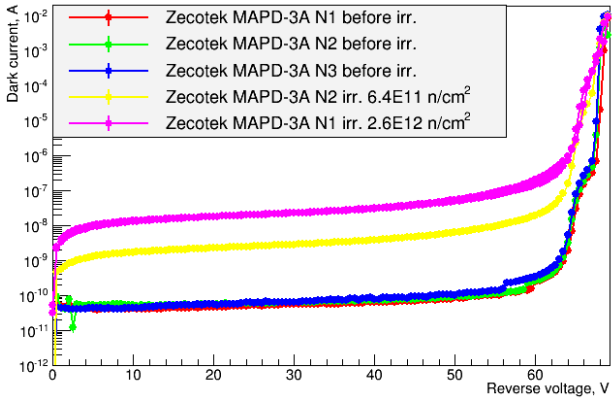

Displacement damage in Silicon
for neutrons, protons, pions and electrons
neutrons: Griffin + Konobeyev + Huhtinen
protons: Summers + Huhtinen
pions: Huhtinen
electrons: Summers
protons
pions
neutrons
electrons
D(E)/95 MeVmb
E[MeV]
A. Vasilescu & G. Lindstroem

SiPM breakdown voltage after irradiation

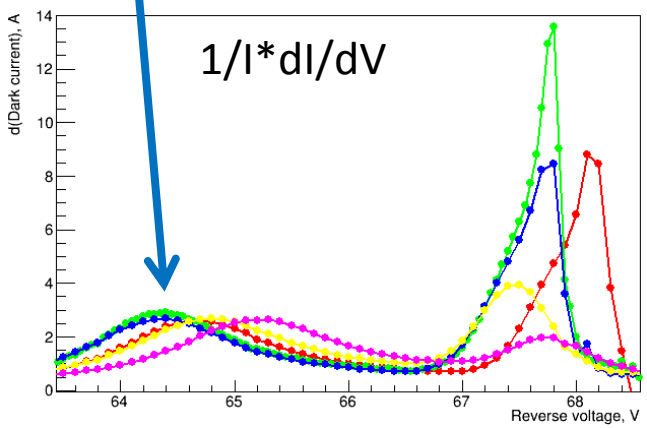
SiPM type->	Zecotek MAPD-3A	Hamamatsu S12572-010P
Sample N	$V_{breakdown}$, V ± 0.2V	$V_{breakdown}$, V ± 0.2V
20	64.4	66.7
21	64.8->65.2	67.6->67.1
22	65	67
23	64.9	67.1
24	64.9	67.4
25	64.7	66.7
26	64.7	66.7
27	64.4	66.1
28	64.4	66
29	64.2->64.3	65.9

2E11 n/cm^2

2E10 n/cm^2



V_{break} = 65 ± 0.2V

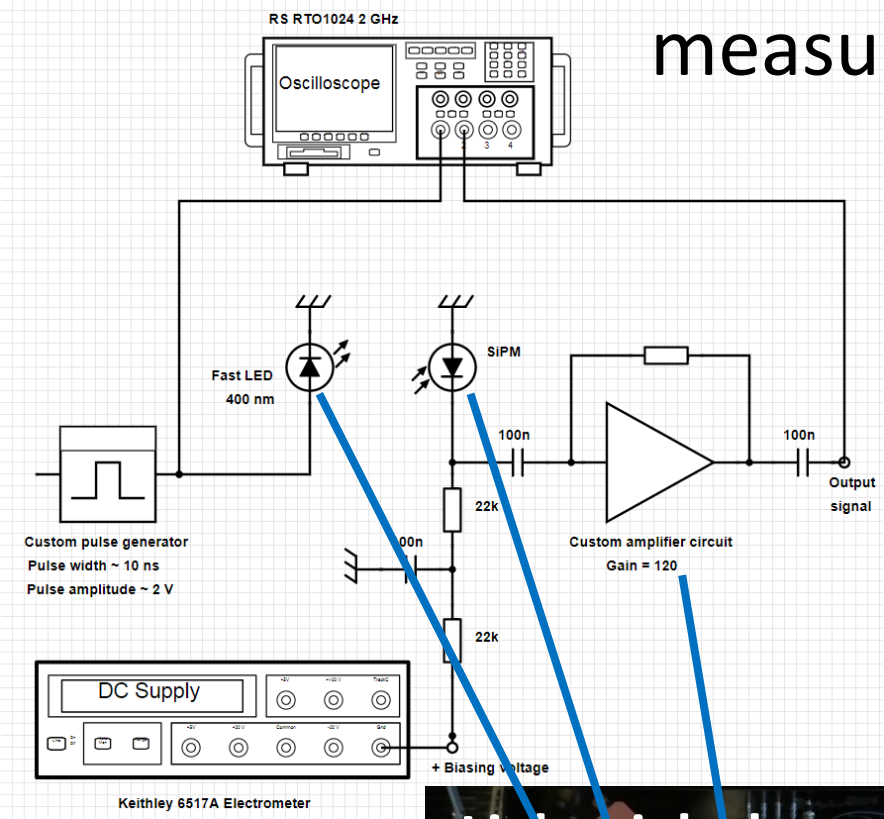


ΔV_{break} (6.4e11 n/cm^2) ~ 0.4V

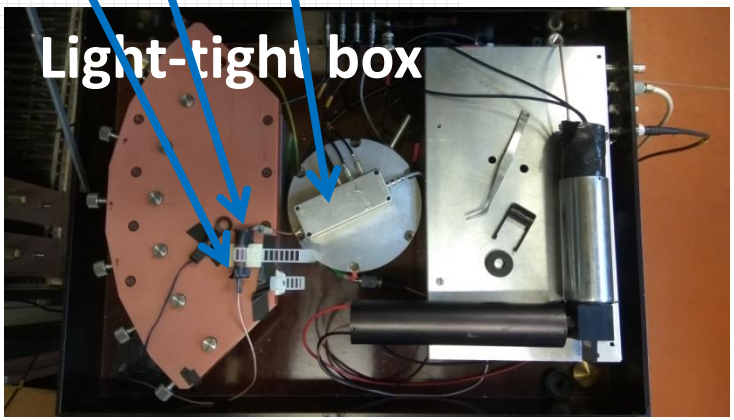
Variation of $V_{breakdown}$ measured for few SiPMs is less than 0.5V.

** SiPMs irradiated by "white" neutron spectrum*

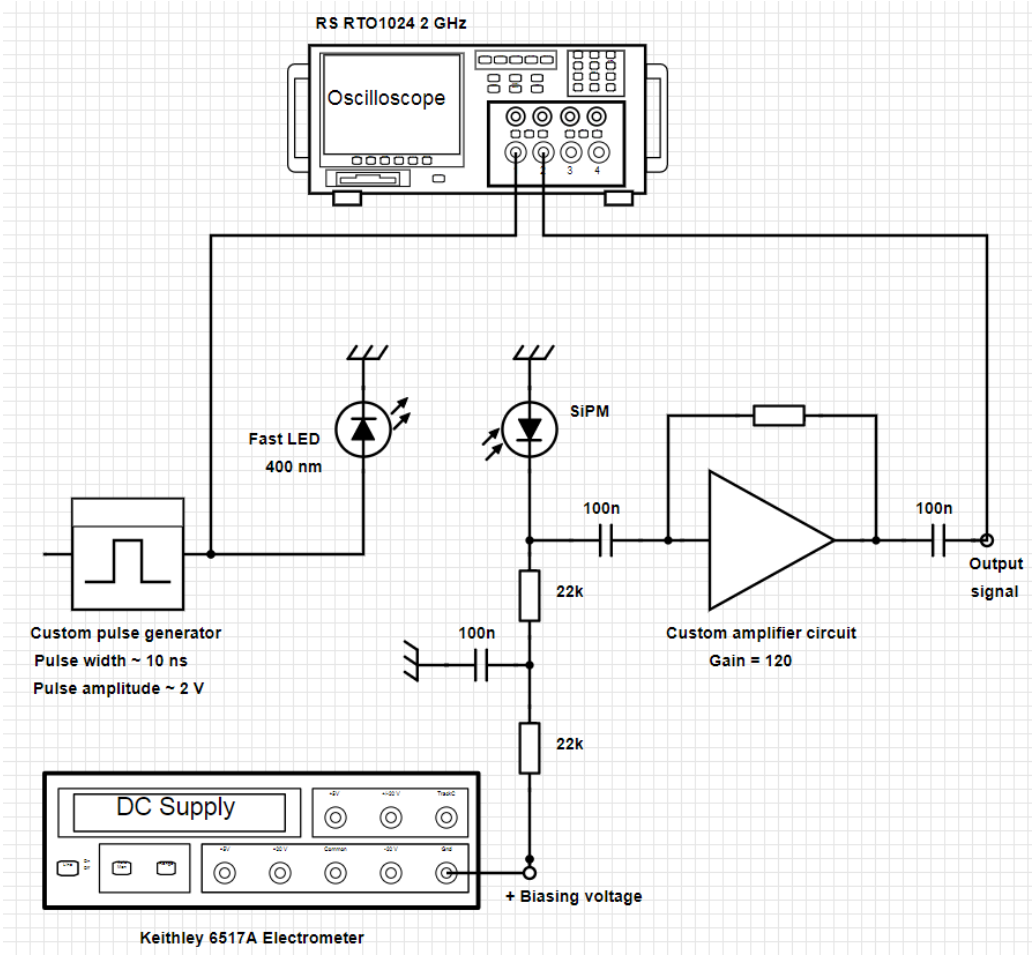
Details on laboratory test setup for SiPM measurements



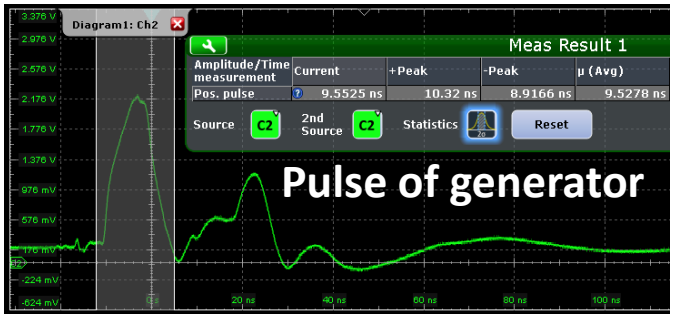
Connection scheme

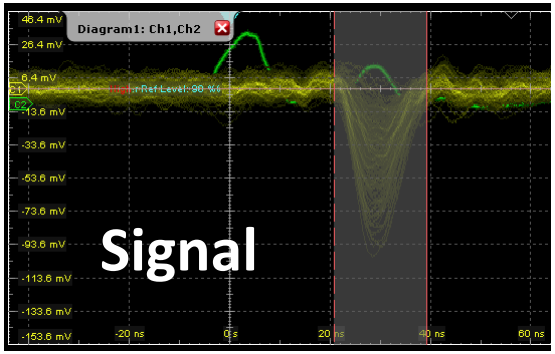


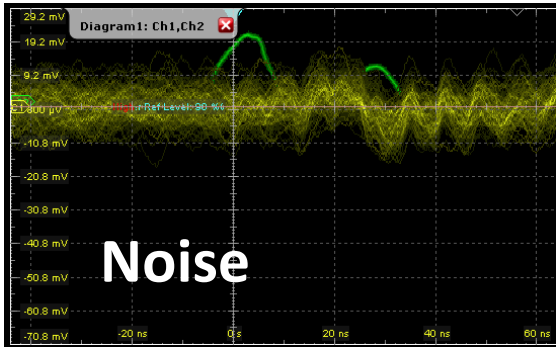
Details on laboratory test setup for SiPM measurements



Connection scheme







Interface of software developed for IV, CV, CF, SNRV measurements