Radiation Damage in SiPMs

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EIC PID Workshop
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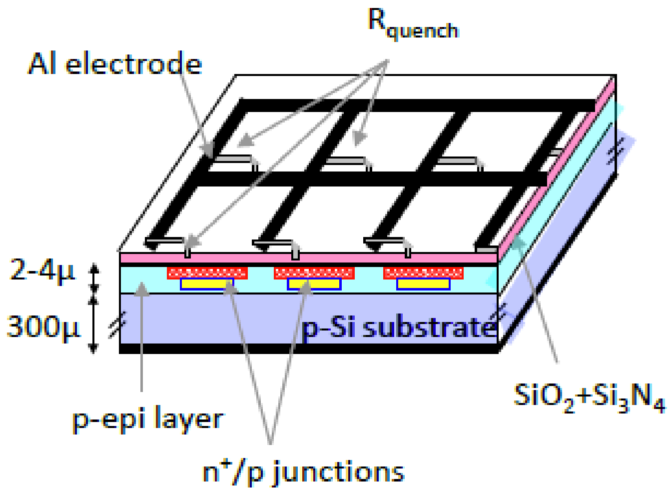
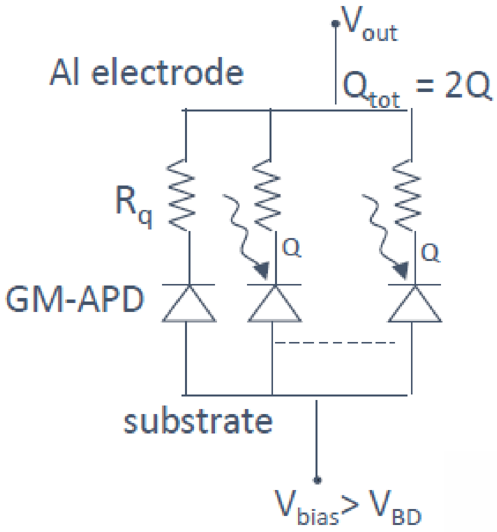
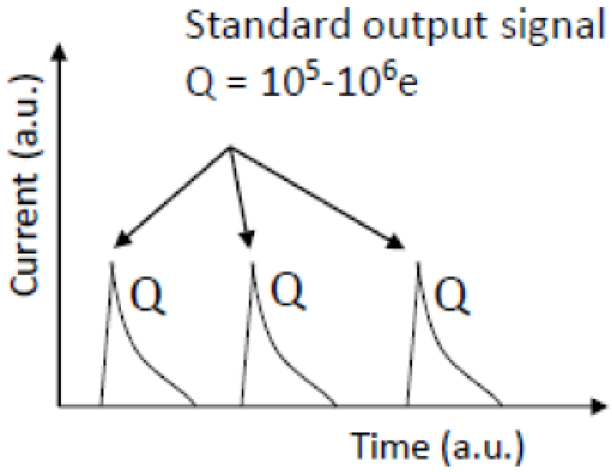
Silicon Photomultipliers (SiPMs)

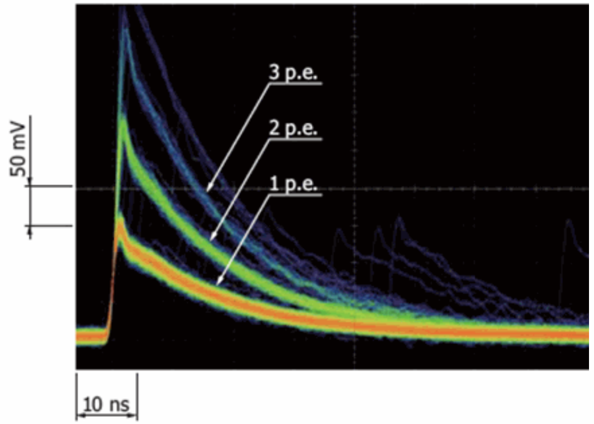
Silicon Photomultipliers are arrays of Single Photon Avalanche Diiodes (SPADs) that are biased slightly above the breakdown voltage such that even a single particle (including a photon) can trigger an avalanche

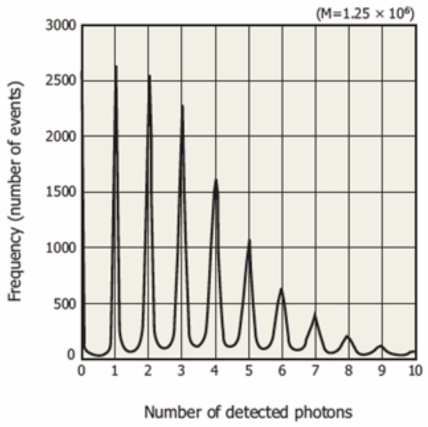






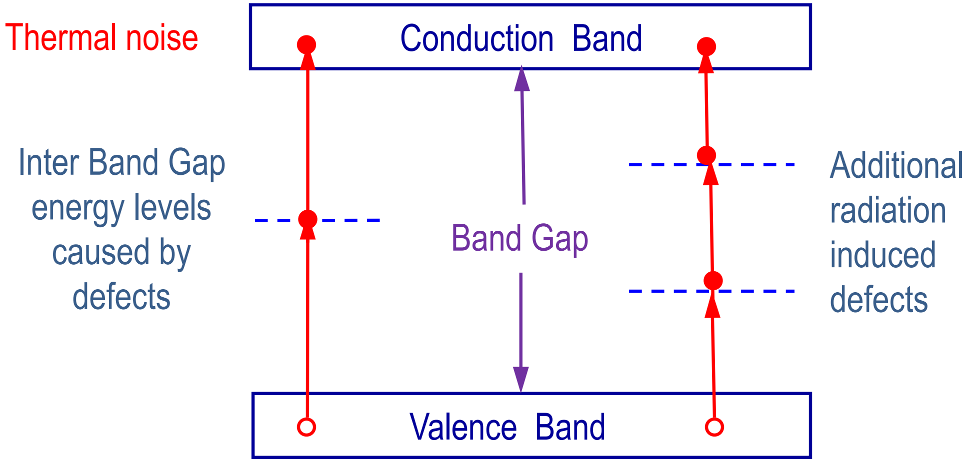
- Provides high gain (similar to PMT)
- Excellent single photon resolution
- Insensitive to magnetic fields
- Non-linear output at high incident flux (saturation of pixels)
- High noise due to thermal carriers (~ 100 kHz/mm^2)
- Large temperature dependence (ΔG/G ~ 2%/°C)
- Very susceptible to neutron damage





Noise in Geiger Avalanche Photodiodes

GAPDs are intrinsically noisy devices due to thermal noise



Band Gaps (eV @ 300 K)

Si	1.12
GaAs	1.42
GaInP	1.90

Larger Band Gap

⇒
- Lower thermal noise
- Better radiation resistance

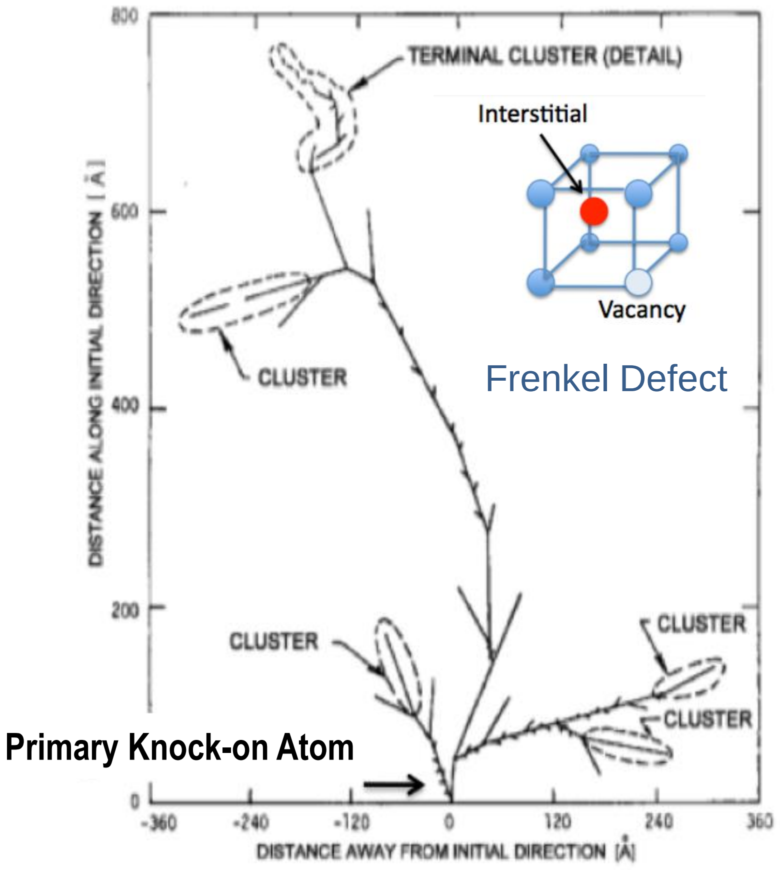
Electrons are promoted from the valence band to the conduction band through Inter Band Gap energy levels caused by defects in the lattice which produce dark current

Radiation can produce additional defects inside the band gap making it easier for electrons to reach the conduction band

⇒ increased noise

Radiation Induced Bulk Damage in Silicon

Damage caused by high energy heavy particles
(e.g., neutrons or protons with E ~ few MeV or higher)



V.A.J. van Lint, Mechanisms of Radiation Effects in Electronic Materials, J.Wiley & Sons (1980)

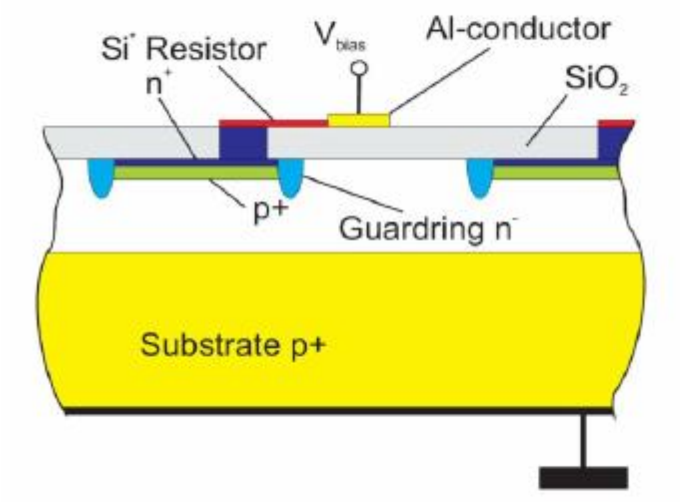
- Bulk damage in silicon is caused displacement of atoms in the lattice
- Incoming particle transfers a certain amount of kinetic energy to the atom
- If the energy transferred is larger than the binding energy of a silicon atom in the lattice (~ 190 eV) then the atom can be displaced, moving it to an interstitial site and leaving a vacancy
- During its path the Primary Knock-on Atom can produce a single point defect or cluster defects
- Defect formation is mainly due to Non Ionizing Energy Loss (NIEL)

Ionization Damage

Ionization damage can be caused by electrons and gammas as well as heavier charged particles and can produce different effects in the SiPMs

- High energy particles (E > 1 MeV) can produce point defects
  Isolated defects, relatively far apart, with low defect density

- Low energy X-rays can cause surface damage affecting the SiO_2 layer



- Ionization can produce charging up effects that can affect the internal electric fields inside the device

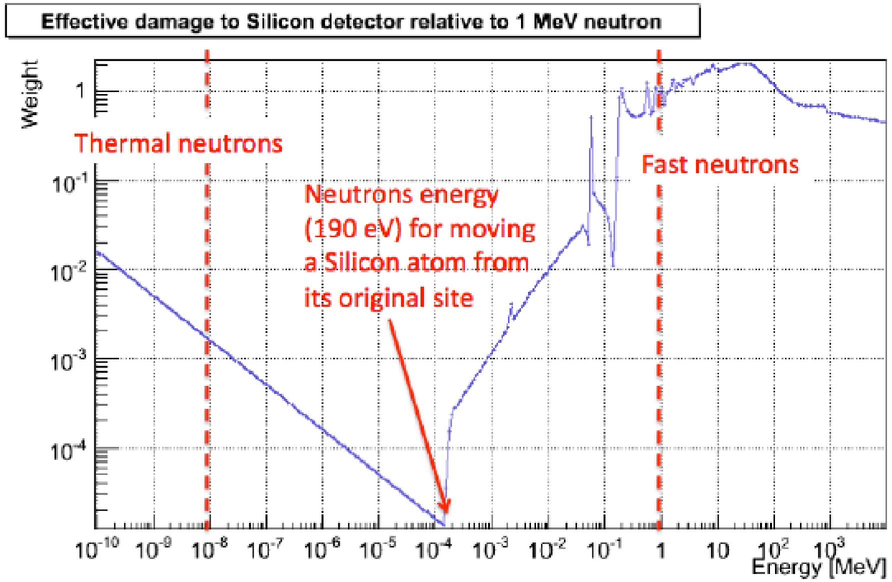
- Ionization can produce optical absorption in the entrance window

Damage from Thermal Neutrons

Thermal neutron capture can cause nuclear transmutations

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

Produces isolated defects with ~ 2-5 defects per absorbed neutron



M.Moll IEEE TNS 65-8 (2018) 1561-1582

Effective damage is energy dependent

Usually scaled and given as 1 MeV energy equivalent (n_{eq} = 1 MeV)

Possible Effects of Radiation Damage

- Increased dark current

  ⇒ increased single photoelectron count rate

- Change in breakdown voltage (I-V curve)
- Loss of PDE (= fill factor × QE × Geiger probability)
  - Efficiency loss due to rate effects of noise if Dark Count Rate per pixel becomes comparable to the recovery time

    ⇒ Loss of pixel efficiency (saturation curve)
    ⇒ Effect reduced by minimizing capacitance
    (e.g. smaller pixel size)

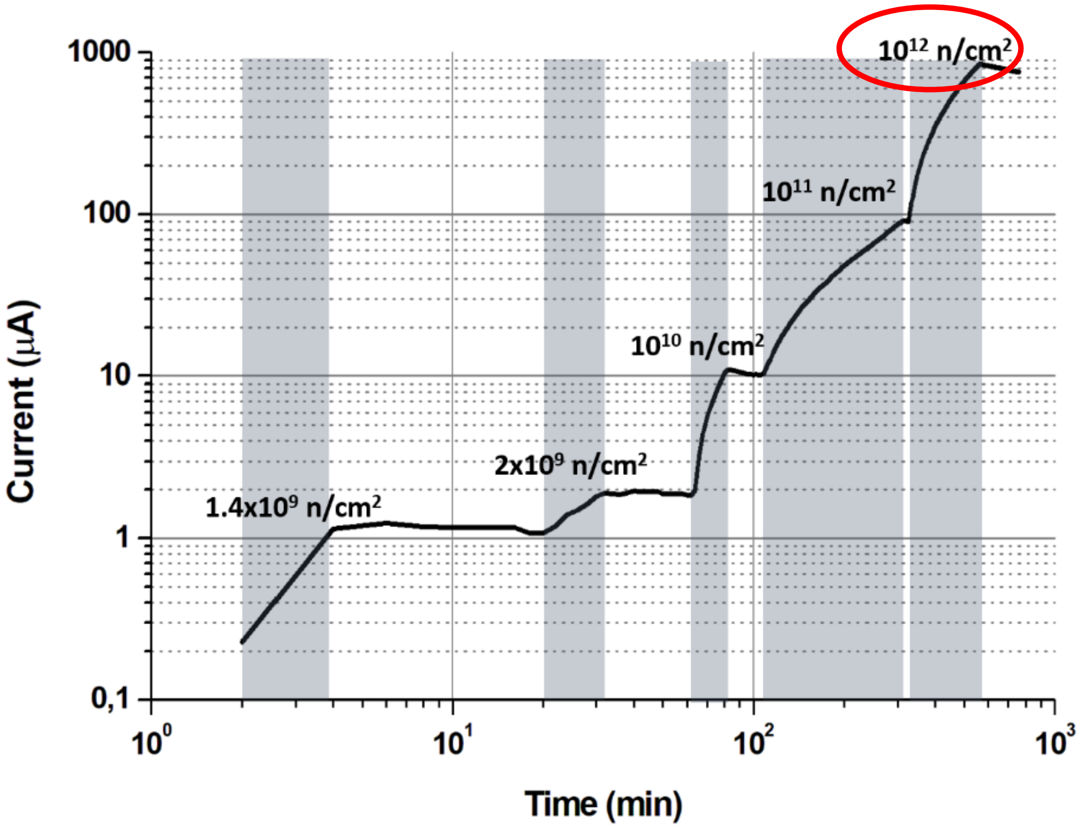
  - Transmission loss in optical window

Neutron Irradiations

SiPMs irradiated with neutrons up to 10^{12} n/cm^2

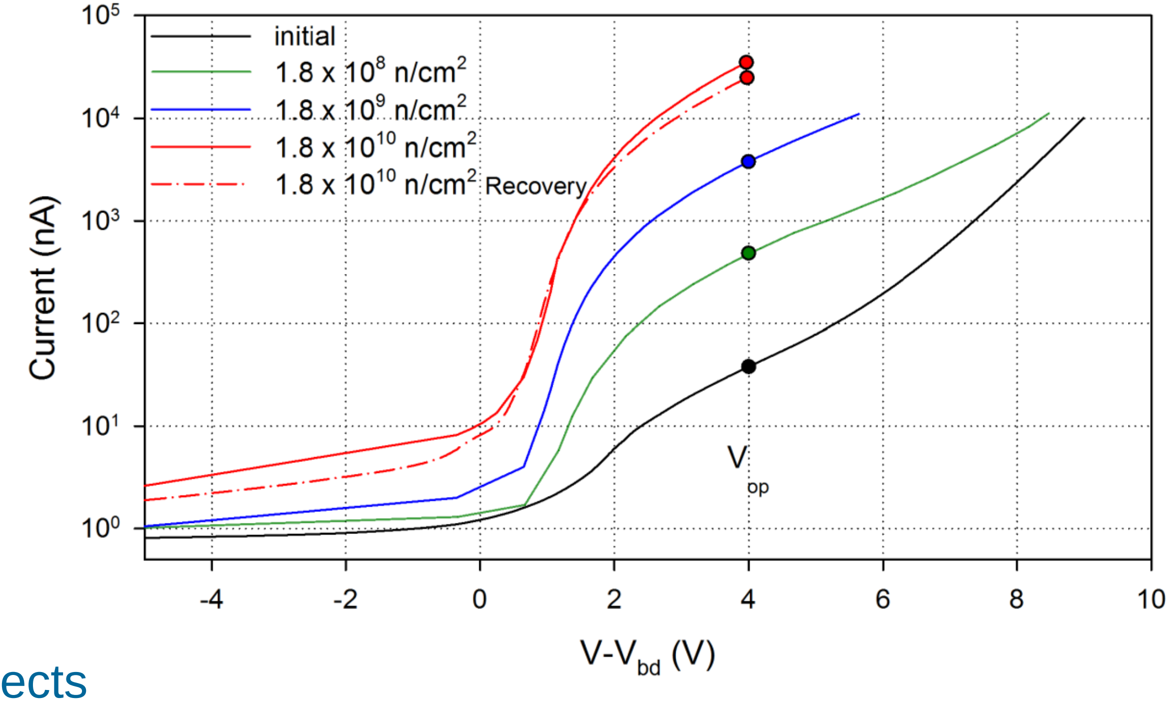
Hamamatsu S12572-015P

1 mA of current in a
3x3 mm^2 device !



Irradiations with neutrons up to ~ 17 MeV at the
Atomki Cyclotron in Debrecen, Hungary

Hamamatsu S12572-015P



Effects

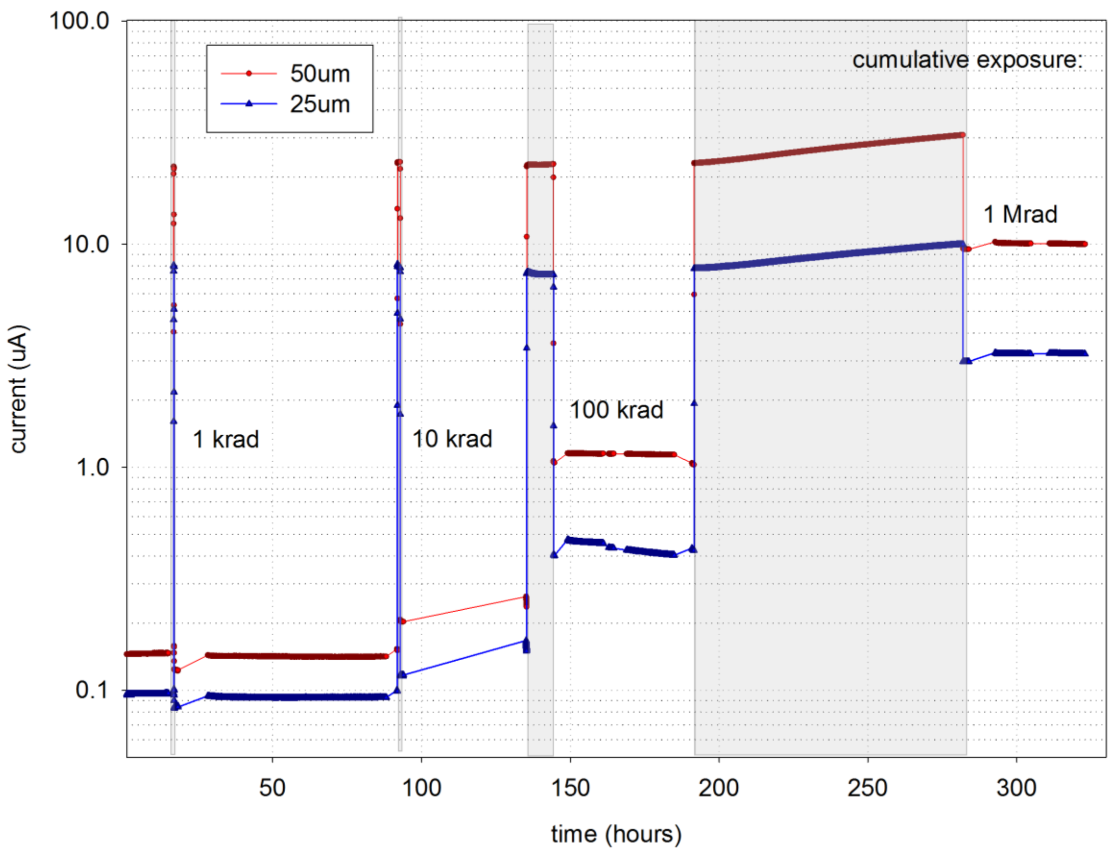
- Steady increase in current with dose
- Small increase in current below V_{op}
- Large increase at V_{op}
- Small, slow long term recovery at RT

arXiv:1809.04594.v4 (2019)
Results soon to appear in IEEE TNS

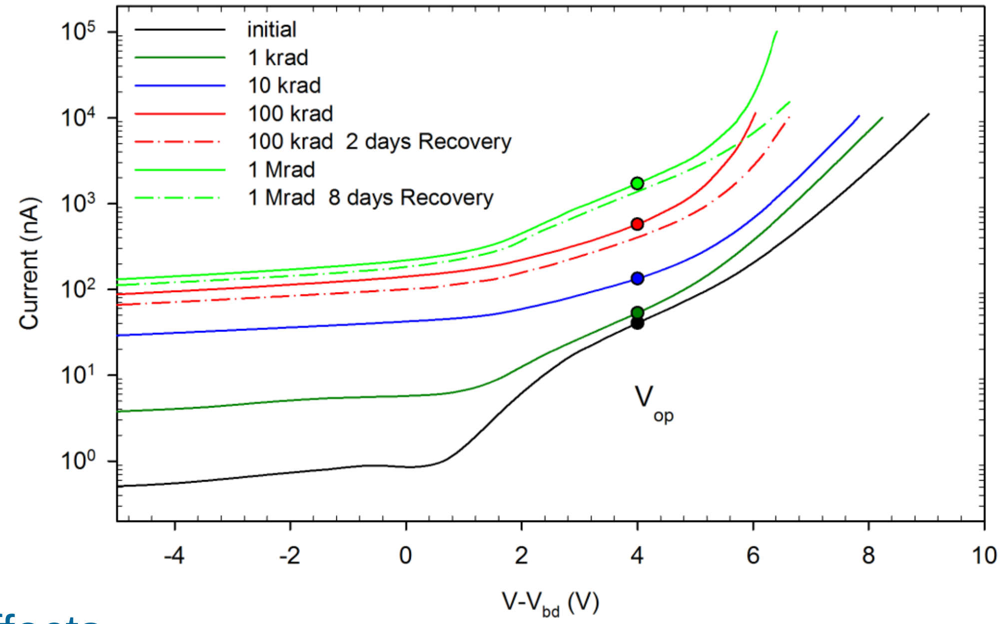
Gamma Ray Irradiations

SiPMs irradiated with ^{60}Co gamma rays to 1 Mrad

Hamamatsu S12572



Hamamatsu S12572-015P



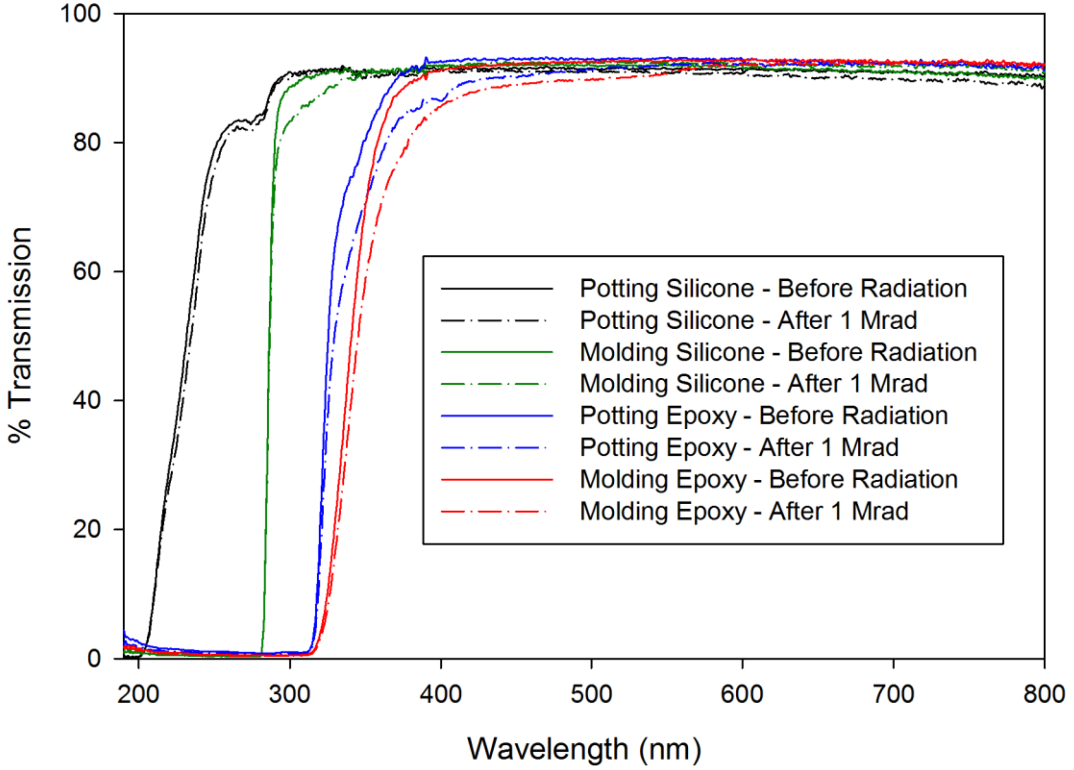
Effects

- Large current during irradiation due to direct ionization which disappears after source is removed
- Significant increase in current below V_{op}
- Moderate increase at V_{op}
- Small, slow long term recovery at RT

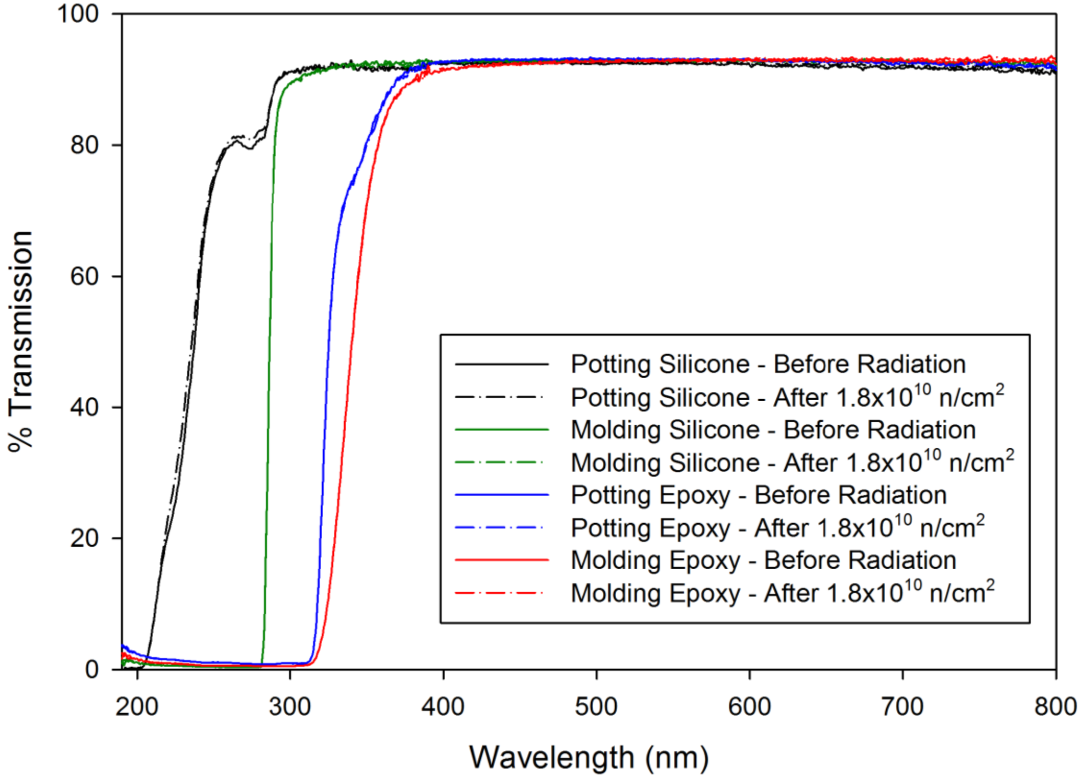
Effects on Entrance Window

No significant damage to entrance window up to fairly high doses of neutrons and gammas

Gammas



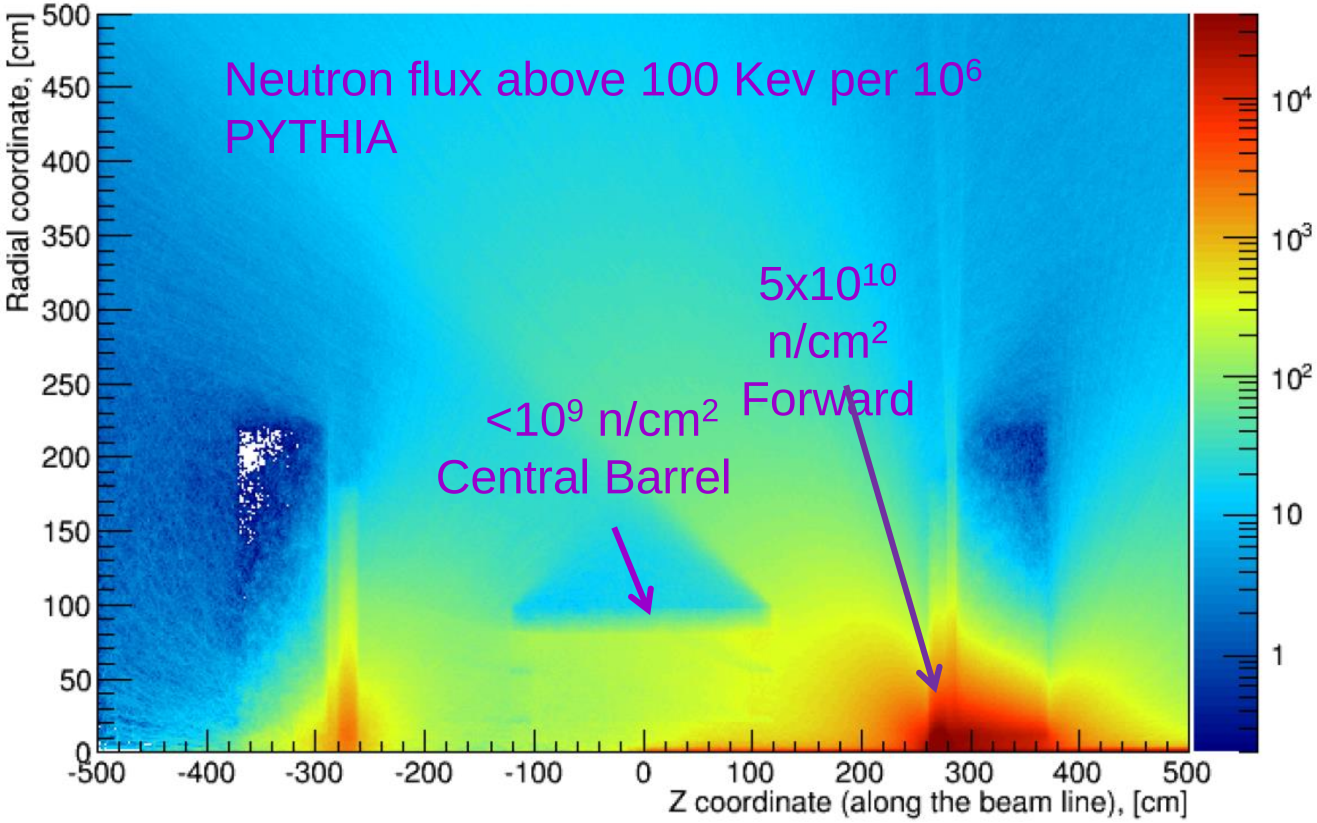
Neutrons



Neutron Fluences at EIC

Neutron Fluxes in BeAST ep 20x250 GeV

Simulation by A. Kiselev



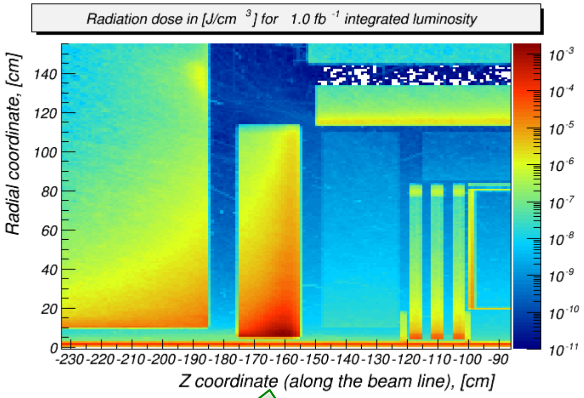
At EIC design luminosity (L ~ 10^{33} cm^{-2}s^{-1}) the fluence in the region of the Forward EMCAL would be ~ 5 x 10^{10} n/cm^2 after 100 days of running

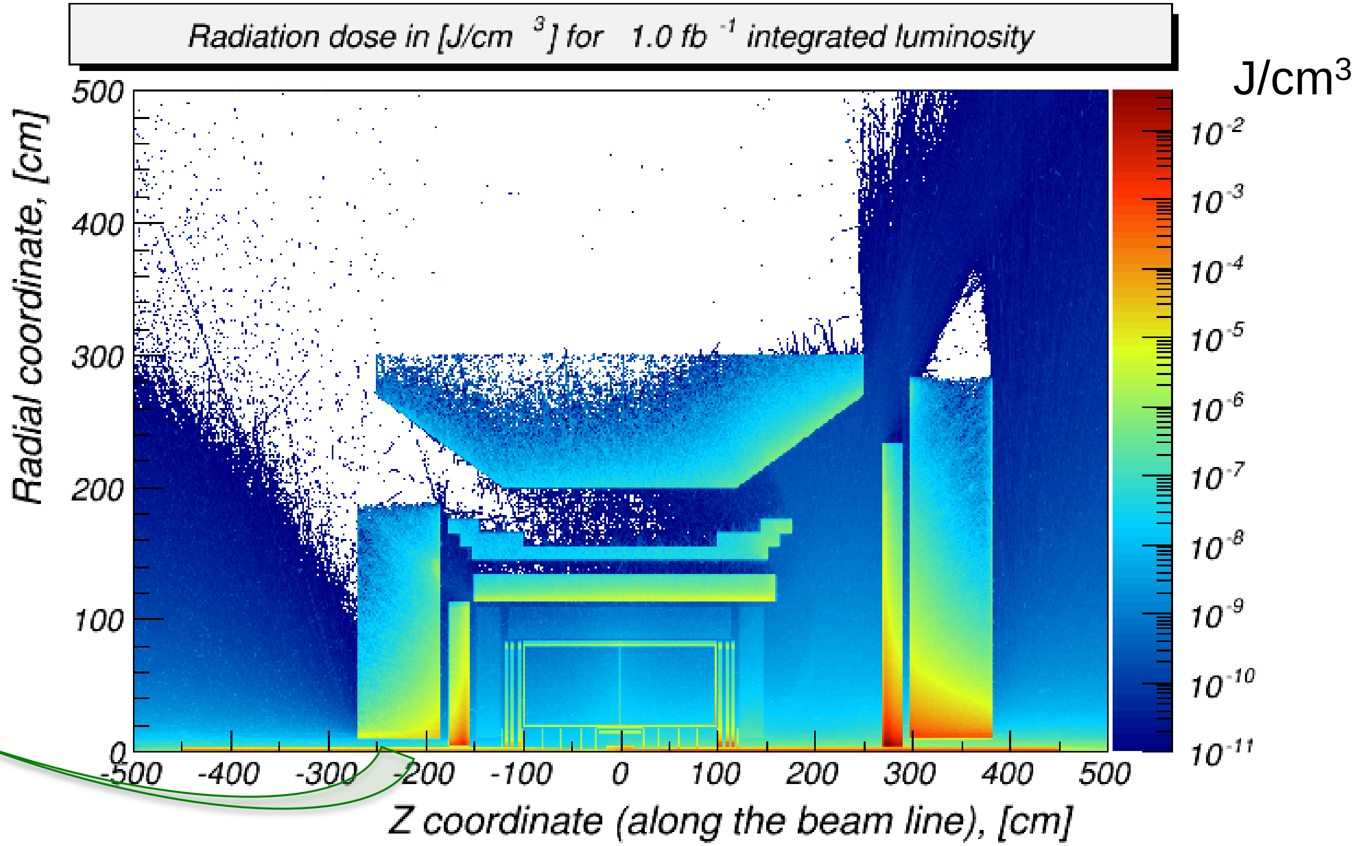
Fluences are 1-2 orders of magnitude lower at the location of the Central EMCAL

Ionizing Radiation Doses at EIC

Radiograph of E_{sum} = “a sum of dE/dx”/”cell volume” (J/cm^3) for N events

Simulation by A. Kiselev





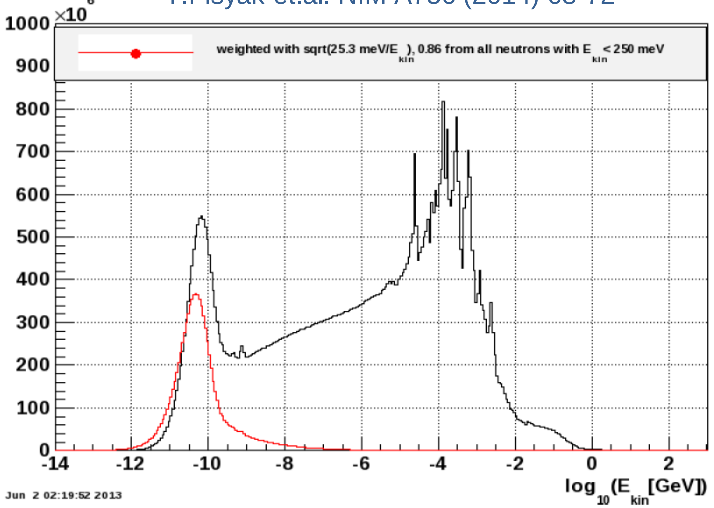
In the very forward region and close to the beam pipe (inner region of the crystal EMCal) dose reaches up to ~2*10^{-3} J/cm^3 per fb^{-1}

Rad = J/kg → J/cm^3 + PWO density (~8g/cm^3) → ~250 rad/year (at “nominal” luminosity ~10^{33} cm^{-2} s^{-1})

Measurements of Thermal Neutrons at RHIC

STAR

Y.Fisyak et.al. NIM A756 (2014) 68-72

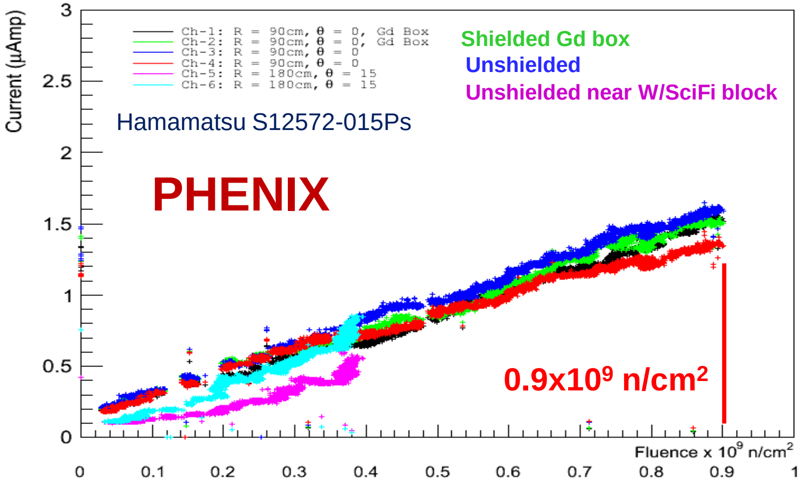


Measure thermal neutrons and use a model to estimate flux of 1 MeV n_{eq}

Estimates for 2013 run ($L=526\ pb^{-1}$):

R= 3-8 cm, |Z| < 10 cm : $\Phi_{eq} \sim 8 \times 10^{10}\ n/cm^2$
R= 100 cm, Z = 675 cm : $\Phi_{eq} \sim 2.2 \times 10^{10}\ n/cm^2$

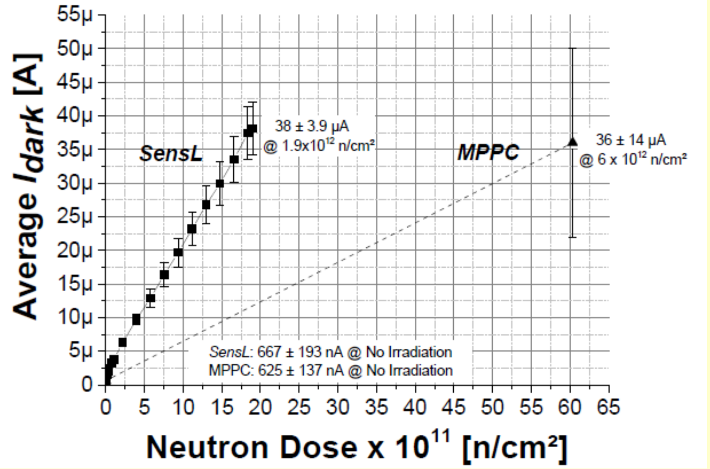
Measurement at PHENIX with Gd shielded SiPMs



Damage caused by thermal neutrons

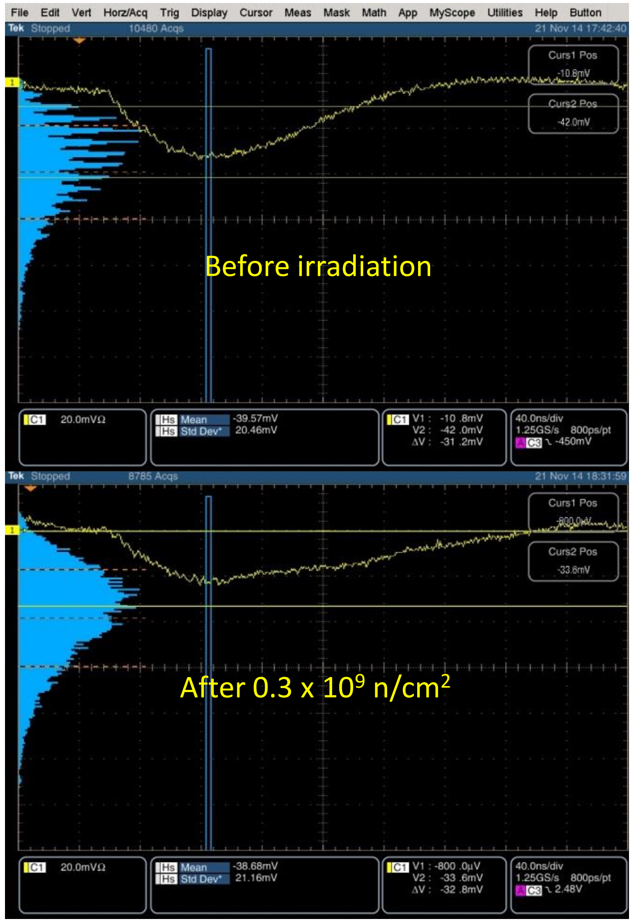
Study at FMR II reactor at Julich ($E_n = 3.27$ meV)

D.Durini et.al., NIM A835, Vol 1 (2016) 99-109

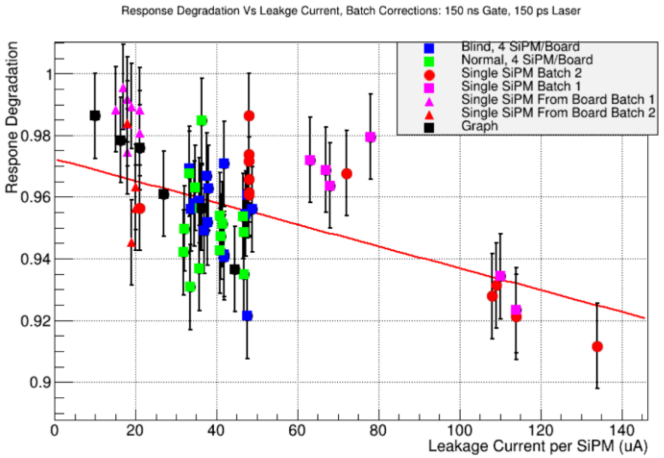


Effects of Radiation Damage in SiPMs

Hamamatsu S12572-025P



3x3 cm^2 SiPMs irradiated in STAR forward direction in Run 17

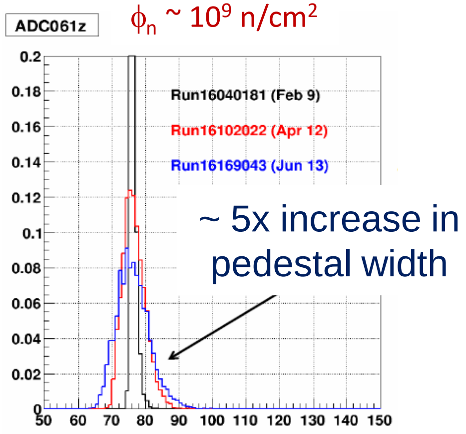


~ Eta 2.5

~ Eta 4

O.Tsai (UCLA)

ϕ_n ~ 10^9 n/cm^2

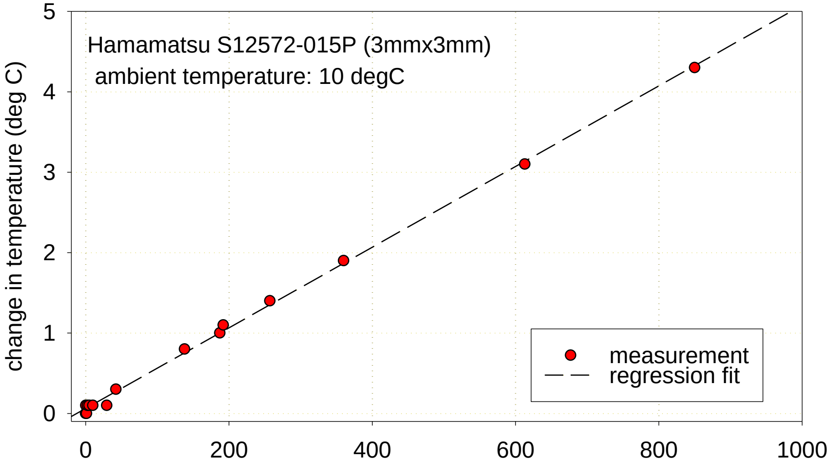


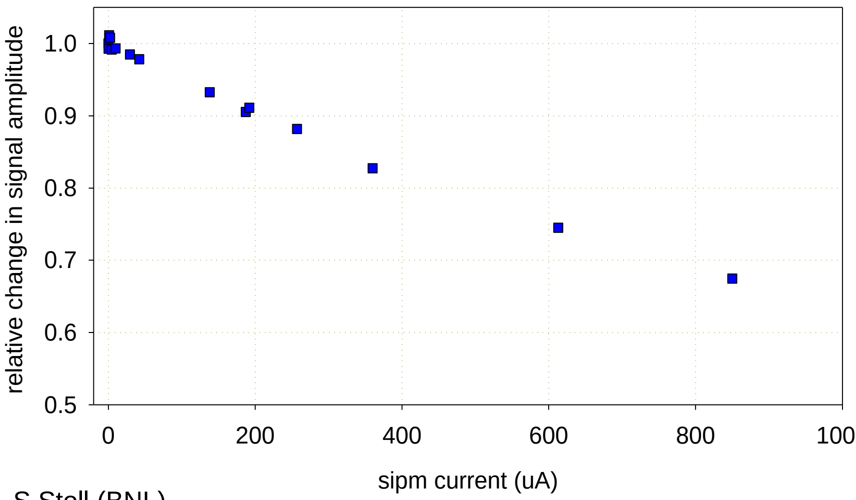
~ 5x increase in pedestal width

STAR Forward Preshower detector during RHIC Run 15

Change in signal response due to increase in dark causing rise in temperature

Vbias (voltage across sipm) is kept constant despite increasing sipm current. sipm current is increased by increasing the ambient (DC) light level.



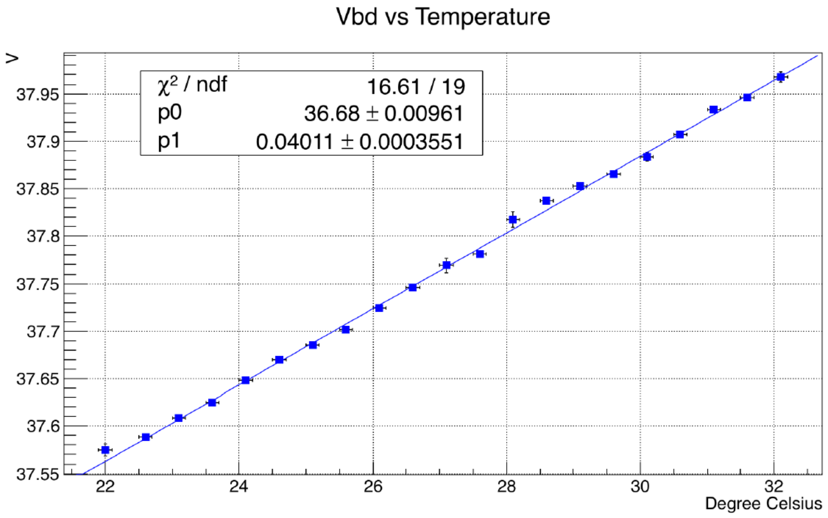


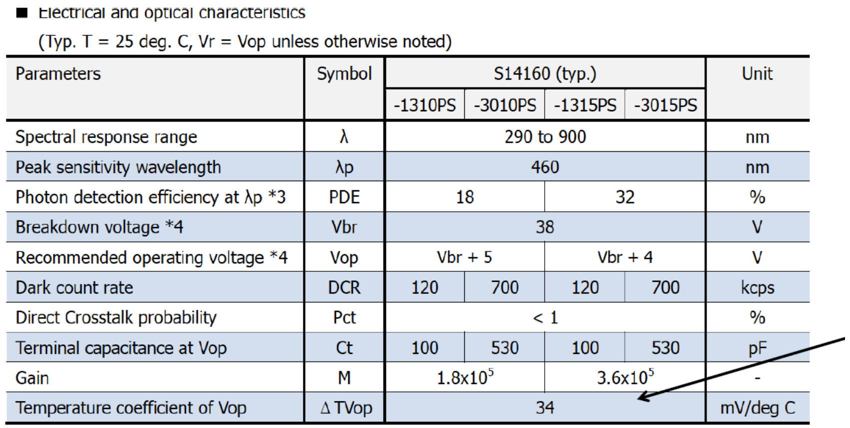
S.Stoll (BNL)

Effect on Breakdown Voltage

Change in breakdown voltage with dose may be due to increase in junction temperature due to increased current

“New” Hamamatsu S14160 MPPCs



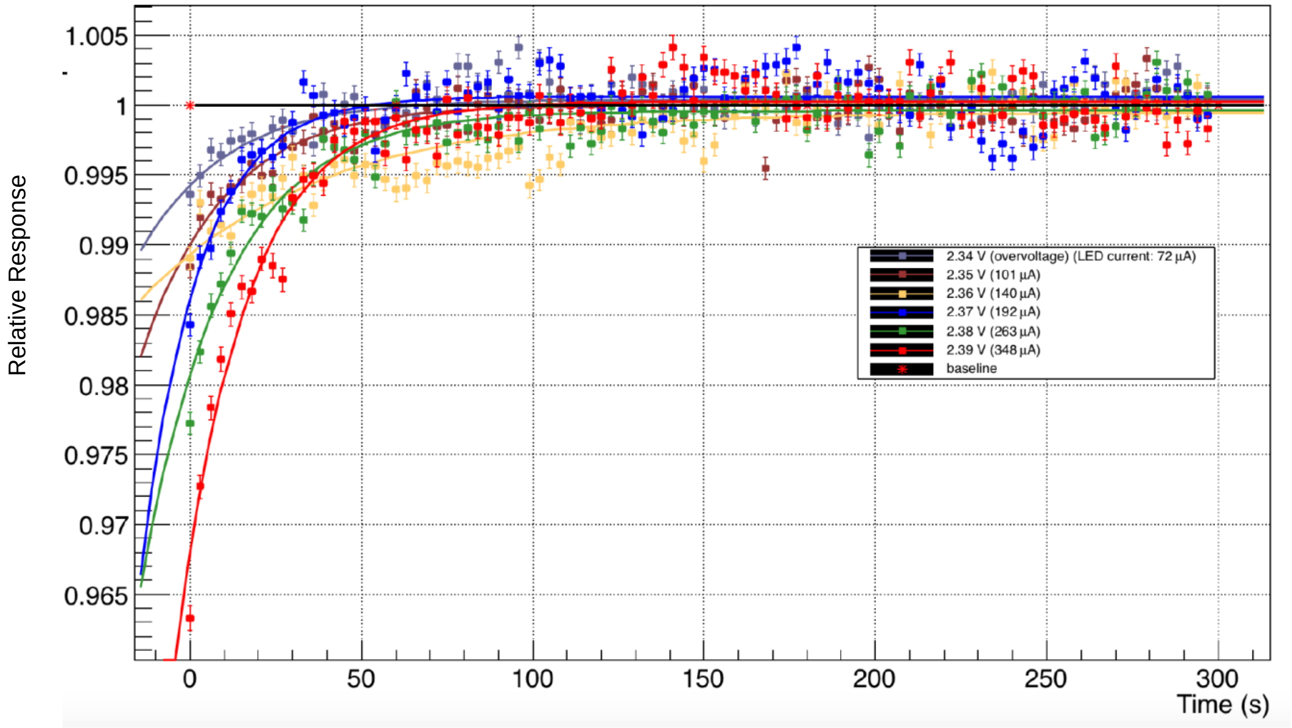


■ Electrical and optical characteristics

(Typ. T = 25 deg. C, Vr = Vop unless otherwise noted)

Parameters	Symbol	S14160 (typ.)				Unit
		-1310PS	-3010PS	-1315PS	-3015PS	
Spectral response range	λ	290 to 900				nm
Peak sensitivity wavelength	λp	460				nm
Photon detection efficiency at λp *3	PDE	18		32		%
Breakdown voltage *4	Vbr	38				V
Recommended operating voltage *4	Vop	Vbr + 5		Vbr + 4		V
Dark count rate	DCR	120	700	120	700	kcps
Direct Crosstalk probability	Pct	< 1				%
Terminal capacitance at Vop	Ct	100	530	100	530	pF
Gain	M	1.8×10^5		3.6×10^5		-
Temperature coefficient of Vop	ΔTVop	34				mV/deg C

34 mV/°C

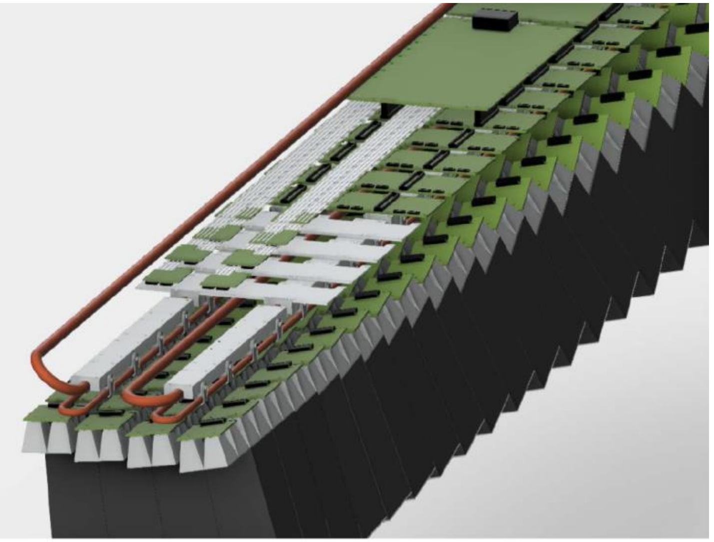


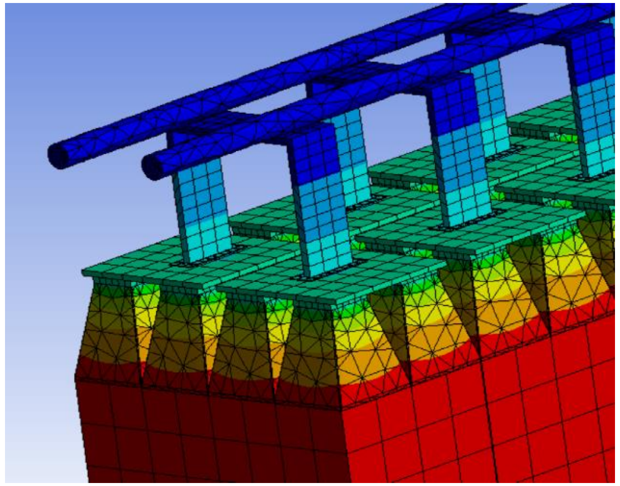
Initial current generated with a high rate LED and then switched off. Response is measured with a separate low rate LED.

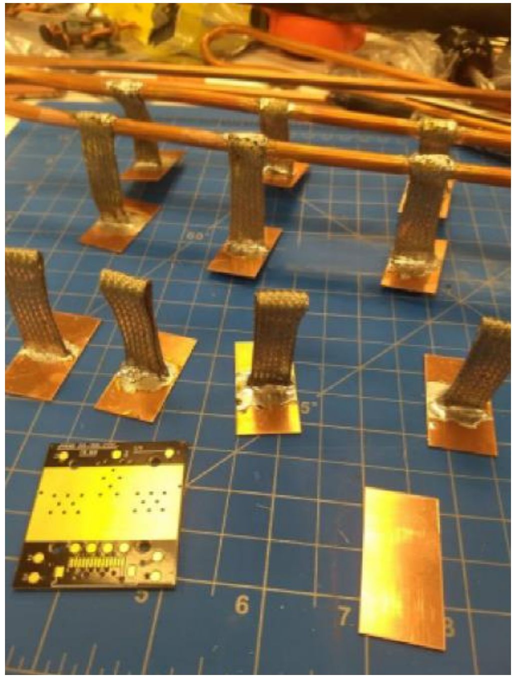
O.Tsai (UCLA)

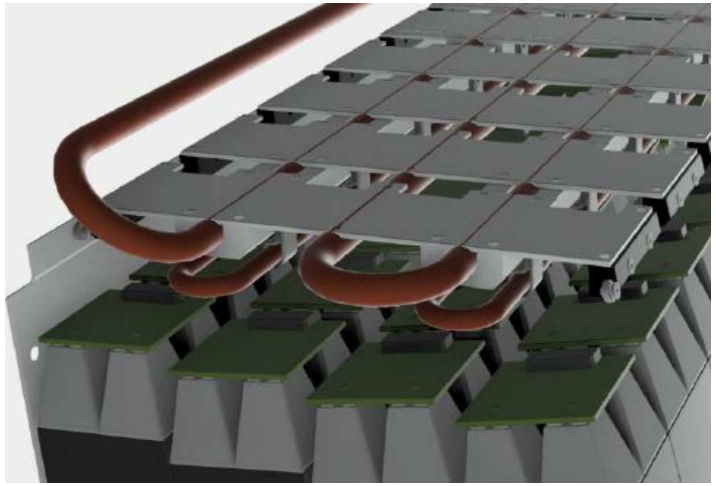
Mitigating the Effects of Radiation by Cooling

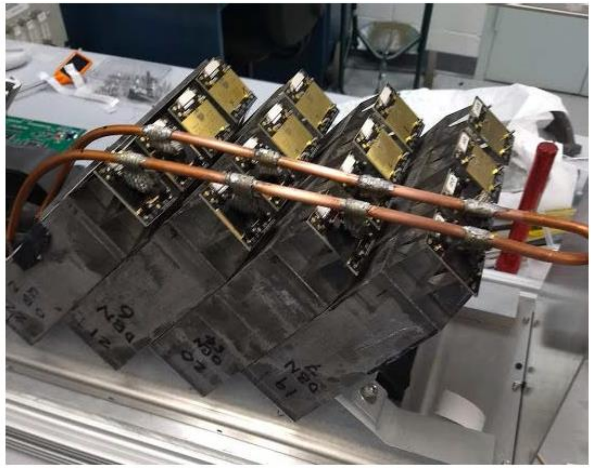
Cooling system for the SiPMs in the sPHENIX EMCAL











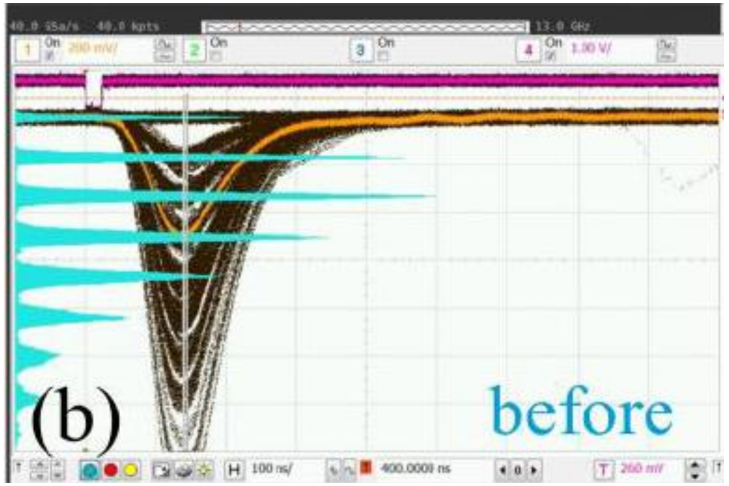
Will initially operate ~20 °C and may go to
~ 5-10 °C as currents increase

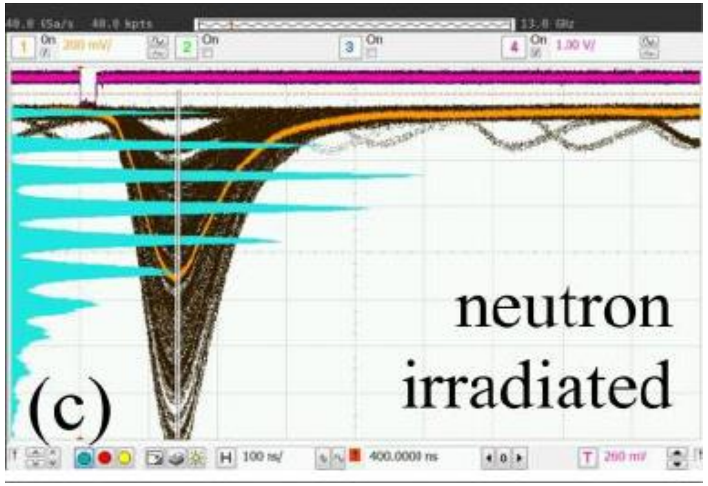
Operation at Low Temperature

Cooling to cryogenic temperatures reduces noise sufficiently to see single photoelectrons even in neutron irradiated devices

85 °K

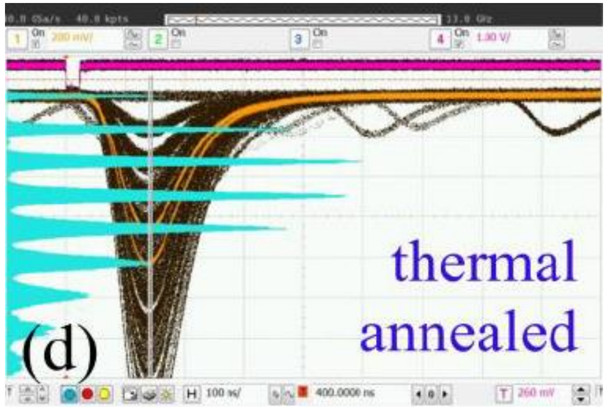
3x3 mm^2 SiPM (Hamamatsu S12572-015P) irradiated to 10^9 n/cm^2

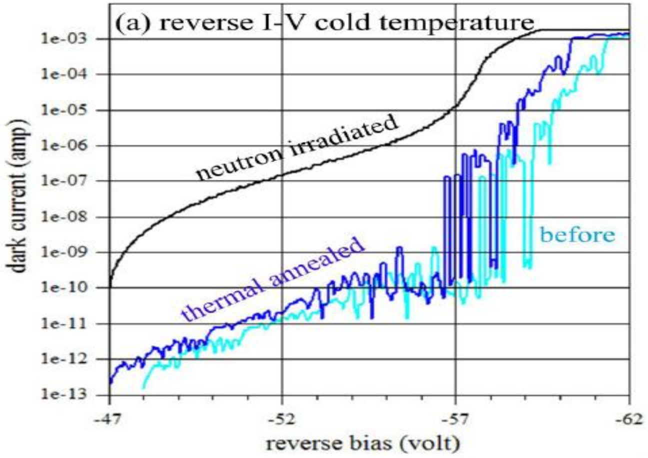




T. Tsang et.al. JINST 11(12) (2016) P12002

Thermally annealed for 3 days at 250 °C
with forward bias applied
(However, the epoxy window turned black !)





Summary

- Different types of radiation produced different types of damage
  - High energy protons and neutrons produce the most damage. This damage is long term and anneals slowly with time at room temperature.
  - Gammas produce comparatively lower damage. No short term recovery at room temperature. Increased current below V_b may be due to surface current.
  - No significant damage in optical window
  - Damage is seen from thermal neutrons but only at high doses.
- Main effects of damage
  - Increased dark current
  - Possible shift in V_b with temperature
  - Possible loss of gain and PDE at high doses
  - Devices generally still remain functional after damage
  - Operation at low (cryogenic) temperature can result in nearly pre-damage operation.