Assessment of photodetection performance of analog and digital SiPMs when exposed to cold neutrons

June 14, 2018 | Daniel Durini[1,2*], Shashank Kumar[1], David Arutinov[1], Carsten Degenhardt[1], Stefan van Waasen[1,3]

[1]Central Institute of Eng., Electronics and Analytics ZEA-2 – Electronic Systems, Forschungszentrum Jülich, Germany

[2]National Institute of Astrophysics, Optics and Electronics (INAOE), Tonantzintla, Puebla, Mexico

[3]Faculty of Engineering, Communication Systems (NTS), University of Duisburg-Essen, Duisburg, Germany

* d.durini@fz-juelich.de

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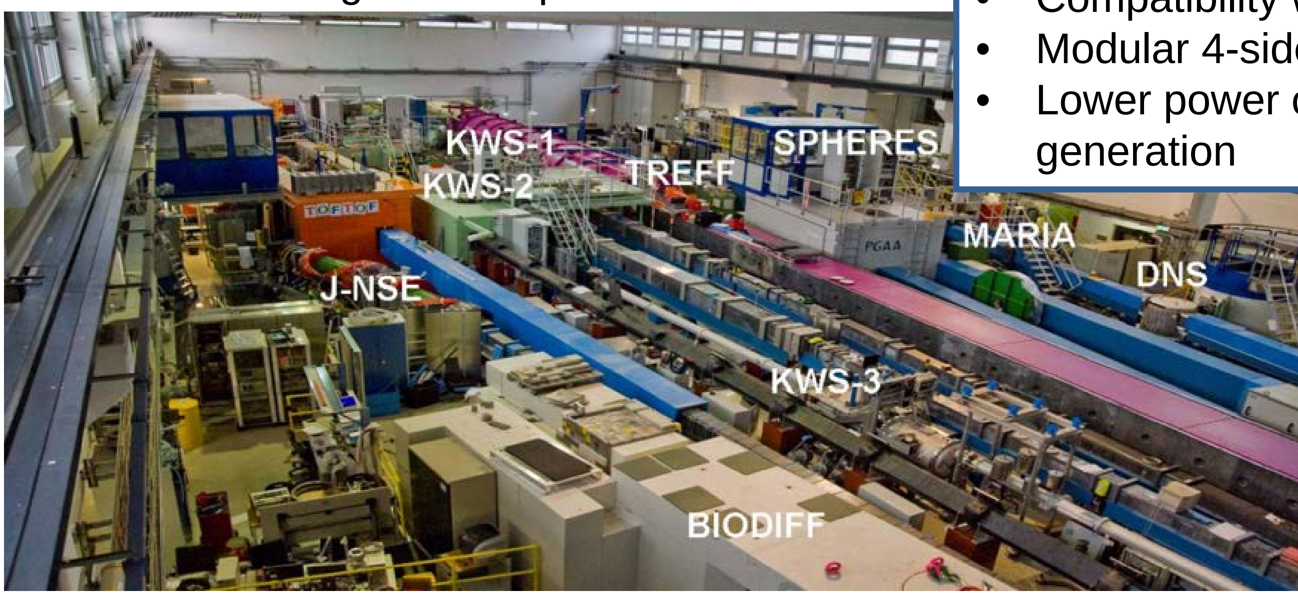
Motivation

Small-angle neutron scattering (SANS):

- Soft matter investigations
- No electric charge → nuclear reactions
- Neutron magnetic moment → investigation of magnetic properties of matter
- Thermal and cold neutrons (1 – 25 meV) deposit only minimum amounts of energy into the investigated sample

We need:

- Higher spatial resolutions (< 1 mm²)
- Higher count rates (to match any future neutron source)
- Compatibility with magnetic fields
- Modular 4-side tileable detectors
- Lower power consumption and heat generation

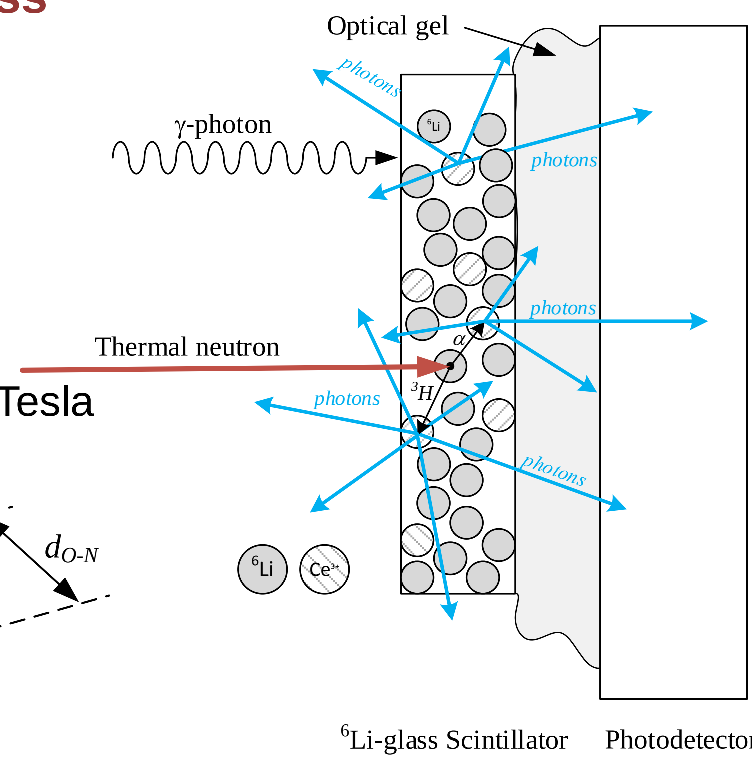


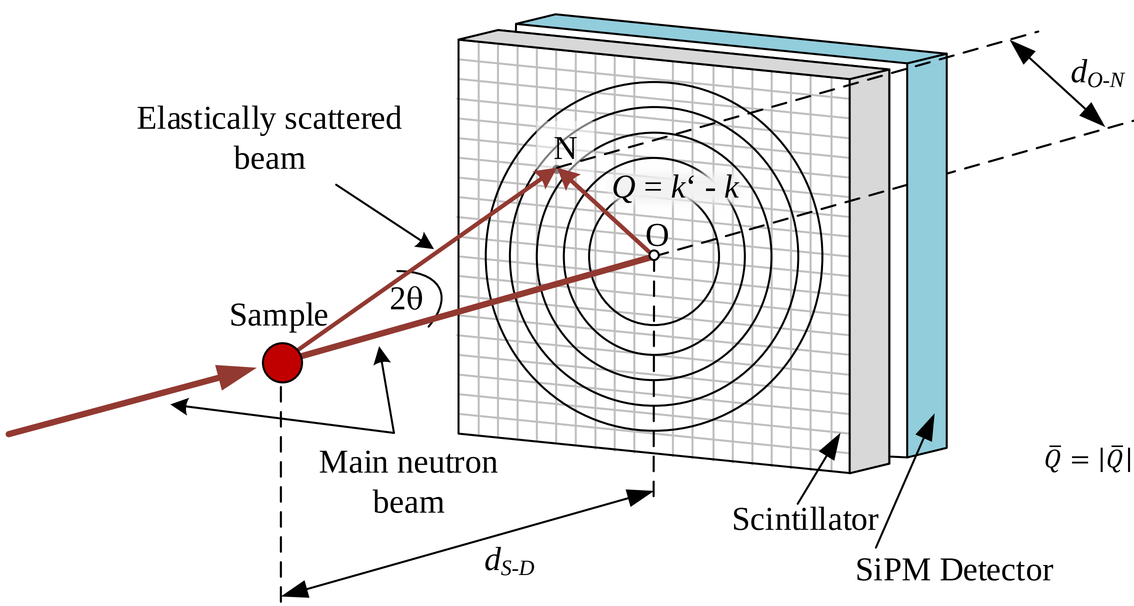
Experimental hall at MLZ (*Heinz Maier Leibnitz Zentrum*) Garching, Munich

We propose…

SANS solid-state pixelated and modular scintillation detectors using Ce-doped ^{6}Li-glass scintillator and an underlying array of SiPM photodetectors:

- Near single photon counting → high η_n
- Low bias voltages (20-70 V)
- Acceptable space resolution (< 1 mm sq.)
- Neutron counting rates ~ 100 Mcps/m²
- Insensitivity to magnetic fields up to several Tesla

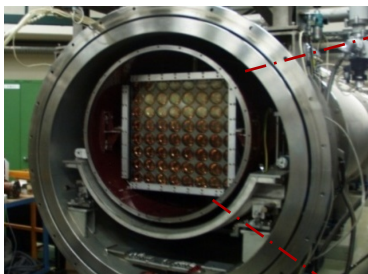




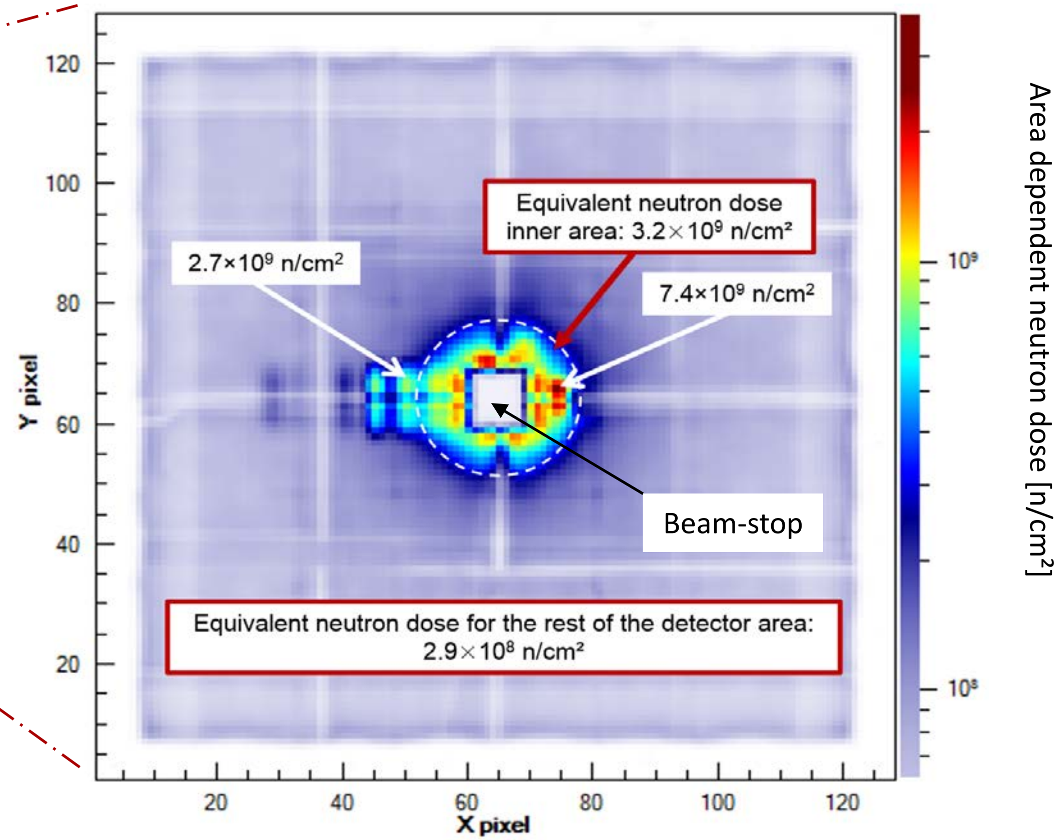
$$\bar{Q} = |\bar{Q}| == \sqrt{k^2 + k'^2 - 2kk'cos2\theta} \xrightarrow{yields} |\bar{Q}| = \frac{4\pi}{\lambda_n} sin\theta$$

Typical operating conditions for SANS experiments

PMT based Anger-camera scintillation detector installed at the KWS-1 instrument of the MLZ in Garching, Germany. The detector has an active area of 60 x 60 cm^2:



Scale-up factor of 7.9 used for the maximum amount of neutrons expected at the instrument in the future.



Graphical presentation of the amount of neutrons detected during 240 days (between August 2014 and October 2015) across all kinds of experiments and setups available at the instrument.

Technical data of the KWS-1 instrument:

- $Q = 0.0007 – 0.5$ Å^{-1}
- Maximal neutron flux: 1.5×10^8 n·cm^{-2}·s^{-1}
- Neutron velocity selector (chopper, FWHM 10%): λ_n = 4.5 Å – 12 Å; typically

λ_n = 5 Å → E_n = 3.27 meV

Source: Durini et al., NIMA 835 (2016) 99–109

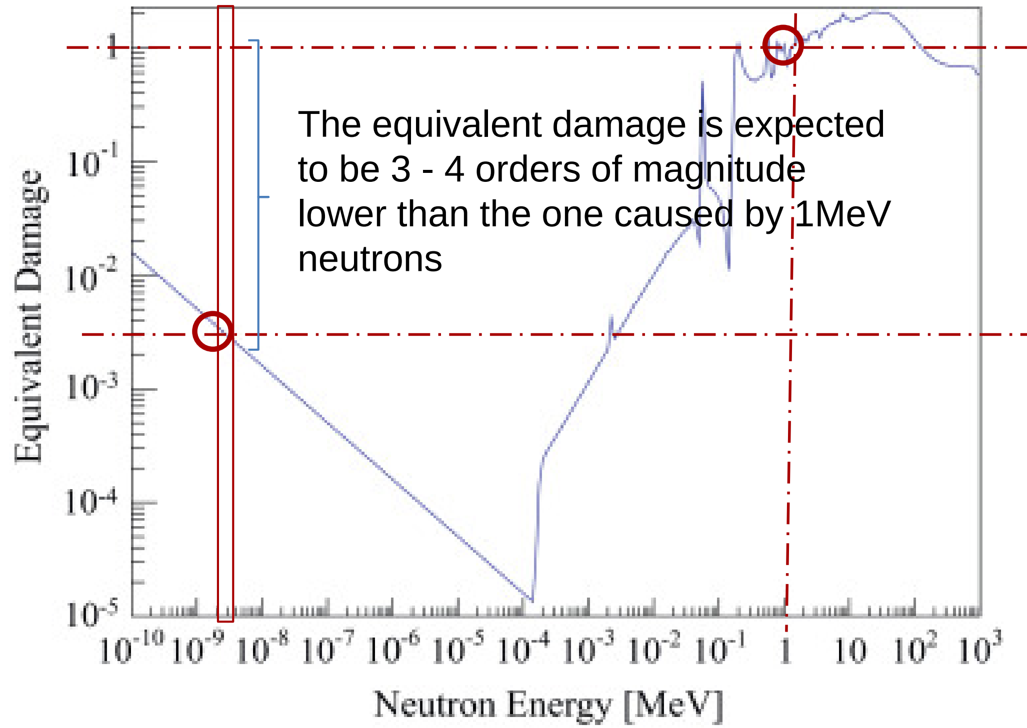
Main concern:

Radiation Hardness of SiPMs

Radiation damage for SiPMs:

- Ionizing damage (mainly due to high-energy gamma photons)
- Displacement damage (DD): 25 eV for a Si atom to be displaced → 175 keV neutrons for generation of *Frenkel* pairs (silicon interstitial and vacancy) to be produced
- Single event effects (SEE): range of effects caused by ionization from a single, high energy particle

Effective damage to Silicon detectors relative to 1 MeV neutron (irradiated with white neutrons):



Source: Qiang et al. "Radiation hardness tests of SiPMs for the JLab Hall D Barrel calorimeter", NIMA 698 (2013) 234–241

Main concern:

Radiation Hardness of SiPMs

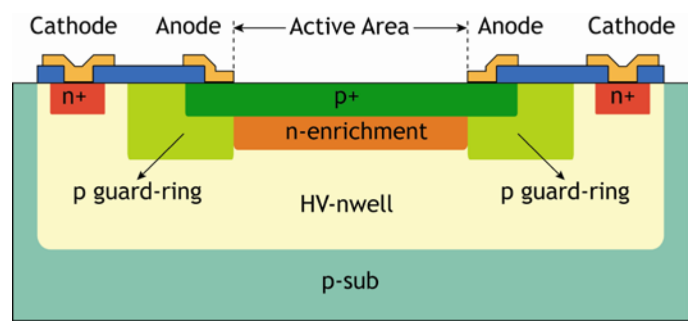
Nuclear transmutation processes initiated by **thermal neutron (*n*) capture**:

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

Damage introduced into silicon by thermal/cold neutrons is primarily **in form of point defects**, approximately **2-5 defects per absorbed neutron** remaining at room temperature.

$$\left|I_{dark}\right| = \alpha_p \left\{ qA_n \left(\frac{n_i^2}{N_D}\sqrt{\frac{D_p}{\tau_{r\_p}}} + N_{def} W_{SCR} \sigma_n c_n T^2 e^{\left(-\frac{E_c - E_T}{k_B T}\right)} \right) \right\}$$

Increase in the dark signal of the SiPMs!



Typical SPAD structure

Source: Durini et al., "CMOS Technology for SPAD / SiPM. Results from the MiSPiA Project", 7th IMS Workshop, 2014

We investigated the dark signal and PDE performances of 3 SiPM technologies under irradiation with cold neutrons.

For dark signal deterioration assessment, we measured it during irradiation with cold neutrons both, with and without a scintillator material covering the photodetector arrays.

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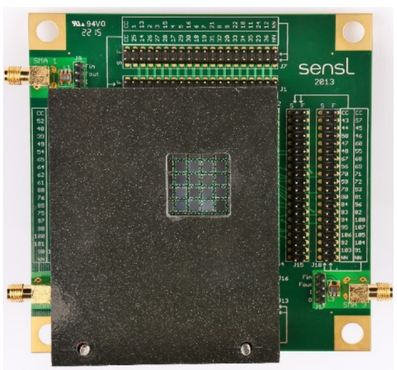
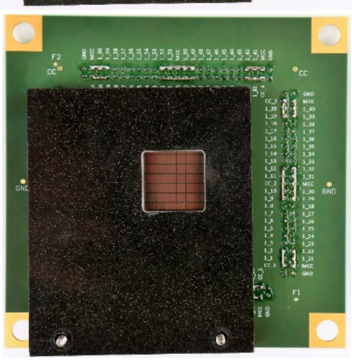
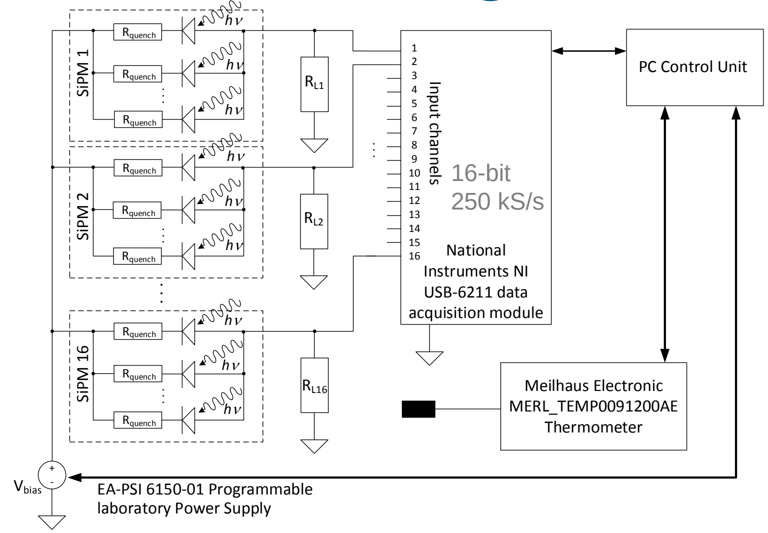
Radiation Hardness of SiPMs: Dark Signal

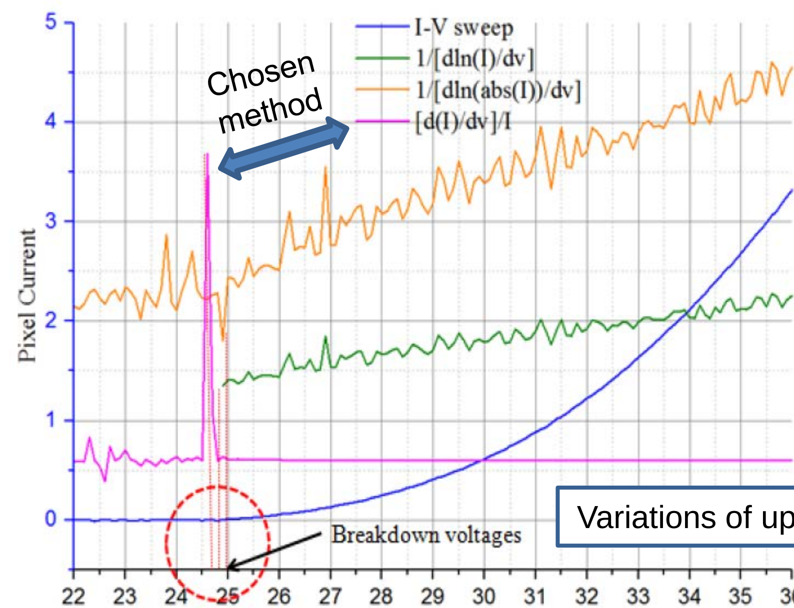
Investigated SIPM technologies →	*SensL Series-C* ArrayC-30035-144P-PCB	*Hamamatsu* 8 × 8 MPPC array S12642-0808PB-50
Array format	12 × 12	8 × 8
Pitch of each individual detector, mm	4.2	3.2
Array package size (4-side tileable), mm²	50.2 × 50.2	22.4 × 25.8
Active area of each individual sensor (pixel), mm²	3 × 3	3 × 3
Microcell size, µm	35	50
No. of micro-cells	4774	3584
Micro-cell fill-factor, %	64	62
Detector fill-factor, %	51	87.9





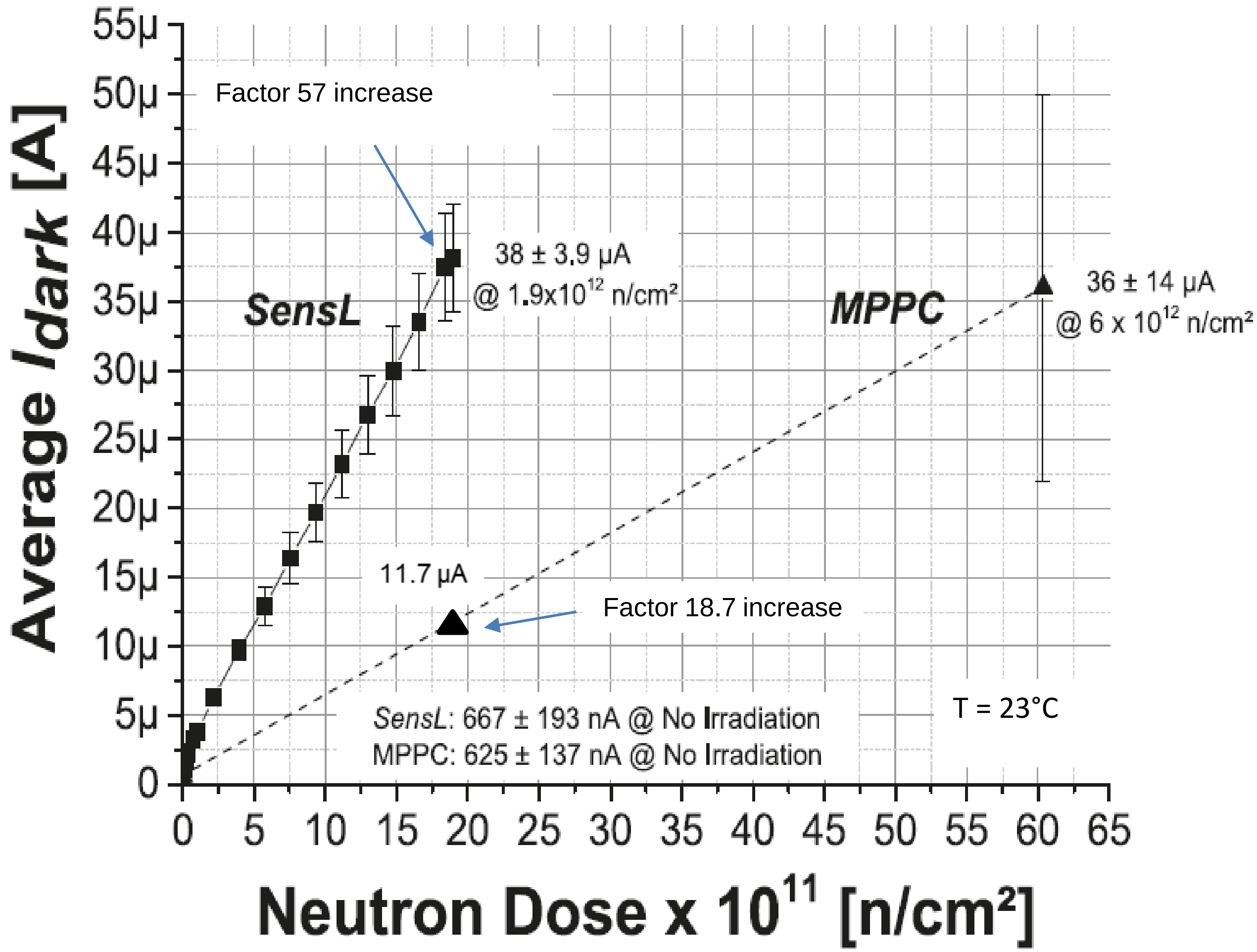


SensL Series-C I-V curve and V_{br} analysis



Variations of up to 0.2 V

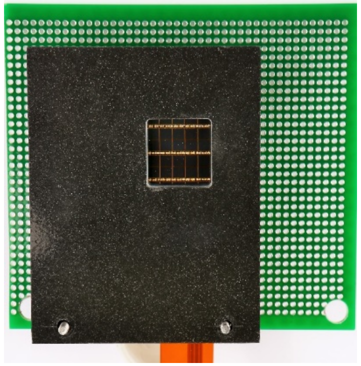
Radiation Hardness of SiPMs: Dark Signal

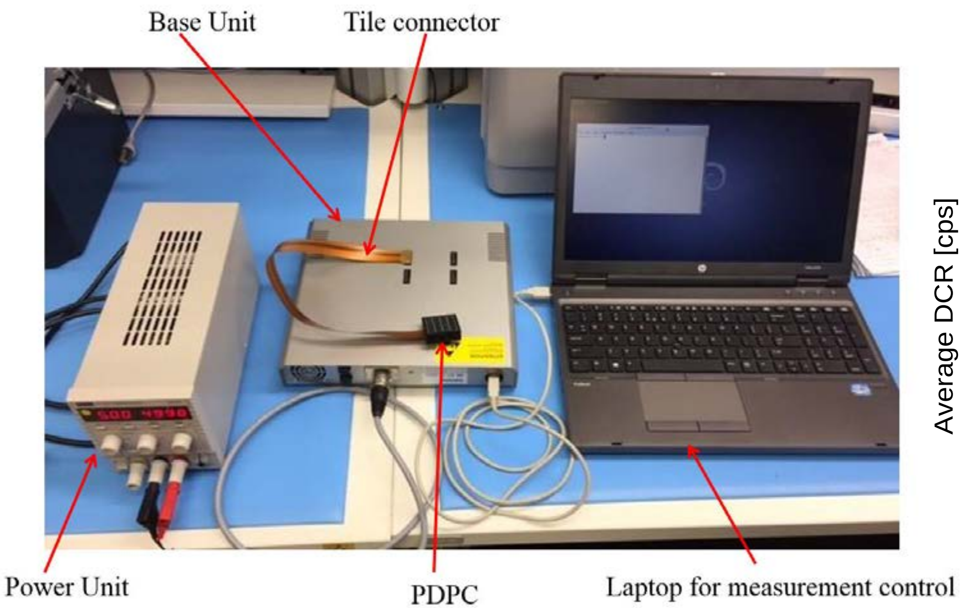


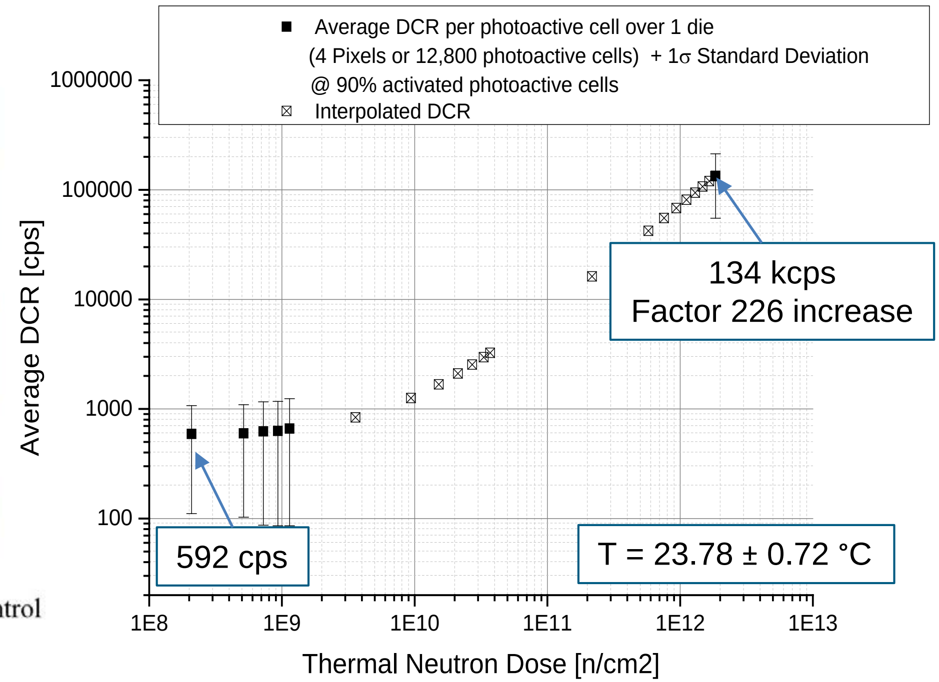
Source: Durini et al., NIMA 835 (2016) 99–109

Radiation Hardness of SiPMs: Dark Signal

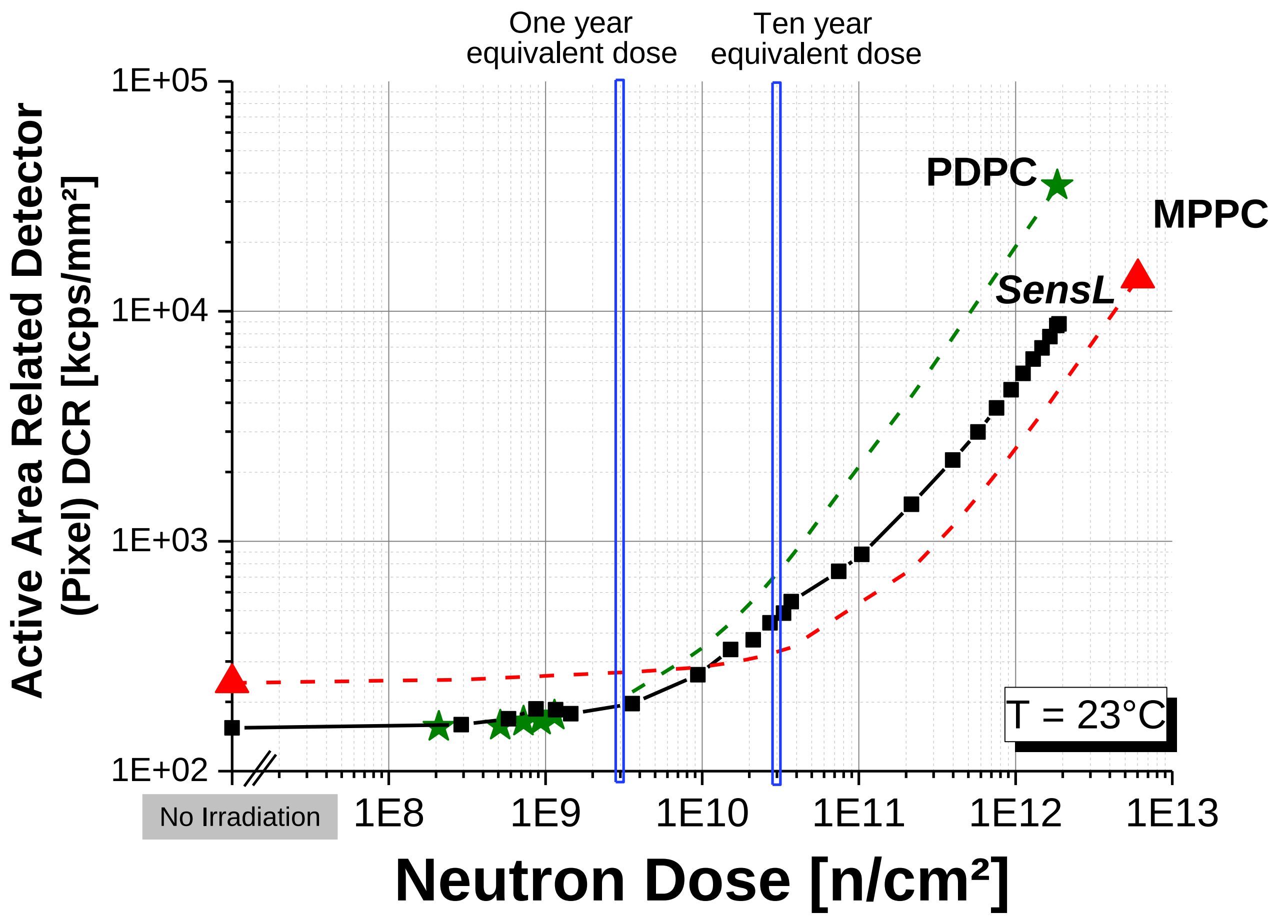
Philips DPC3200-22-44		
Array format	8 × 8	SiPM
Pitch of each individual SiPM detector	4.0	mm
Array package size (4-side tillable)	32.6 × 32.6	mm²
Active area of each individual sensor	3.2 × 3.8	mm²
Microcell size	59.4 × 64	µm²
No. of micro-cells	3200	1
Micro-cell fill-factor	74	%







Radiation Hardness of SiPMs: Dark Signal



Normalizing the aSiPM dark currents:

$$DCR = \frac{I_{dark}}{q \cdot G \cdot A_{active}} \left(\frac{100 - XT - AP}{100} \right)$$

Radiation Hardness of SiPMs: Dark Signal

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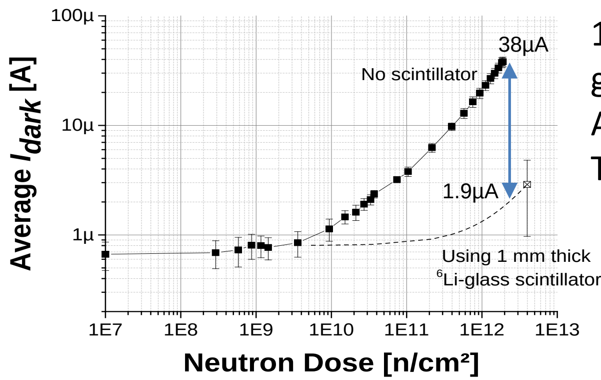
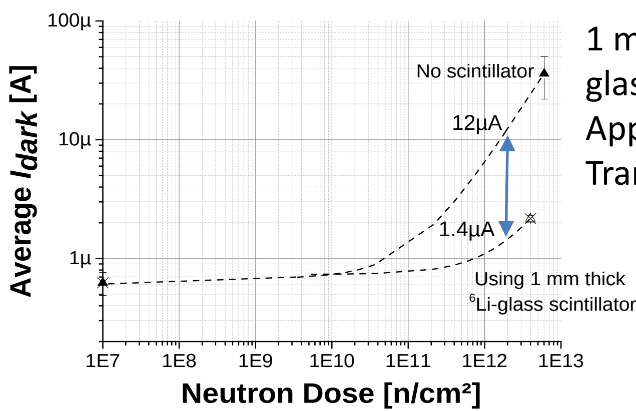
SensL SiPM detectors with 3 × 3 mm² photoactive areas, biased at (V_{br}+2.5) V @ T = 23° C:



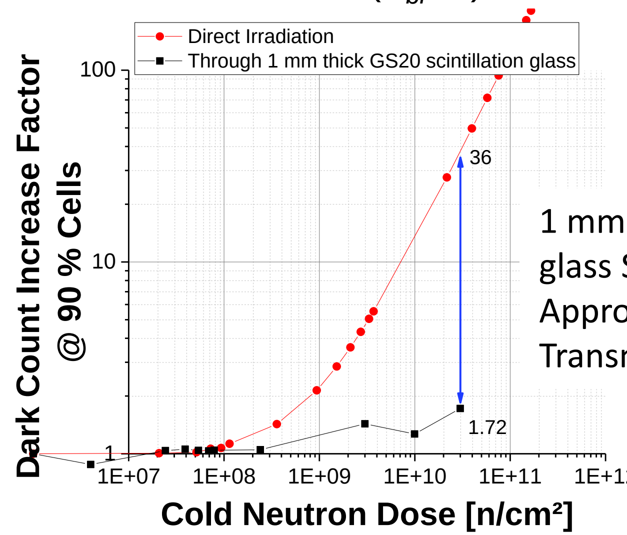
1 mm Ce-doped ^{6}Li-glass Scintillator
Approx. Transmission: ~5 %

Hamamatsu MPPC 3×3 mm² photoactive area detectors, biased at (V_{br}+2.4) V @ T = 23° C



1 mm Ce-doped ^{6}Li-glass Scintillator
Approx. Transmission: ~ 12%

Philips DPC detectors with 4 × 4 mm² photoactive areas, biased at (V_{br}+3) V @ T = 23° C:



1 mm Ce-doped ^{6}Li-glass Scintillator
Approx. Transmission: ~ 5%

Assumption for future work: approx. 10 % of impinging neutrons get absorbed in the scintillator.

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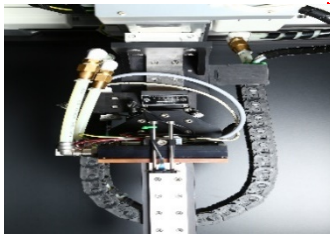
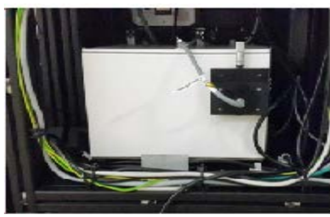
- Radiation Hardness of SiPMs: PDE Issues
- Conclusions and Outlook

Radiation Hardness of SiPMs: PDE issues

Opto Measurement System Setup

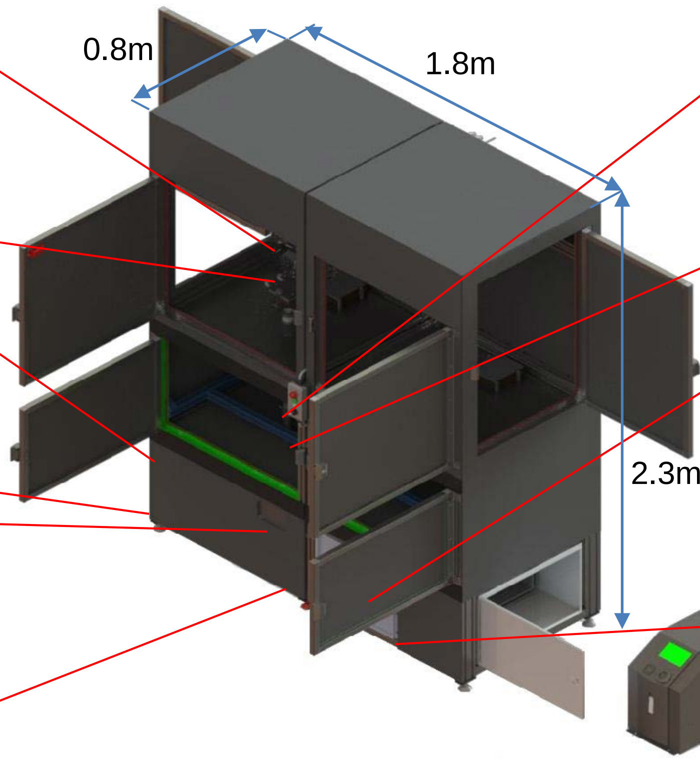


Peltier element & Ref. diode



Monochromator & Optical fibre

Xenon lamp housing & Controller

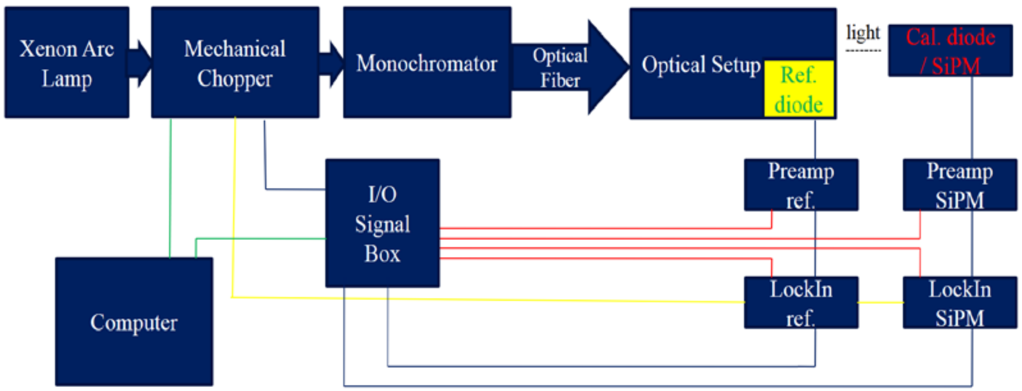


Thermochiller

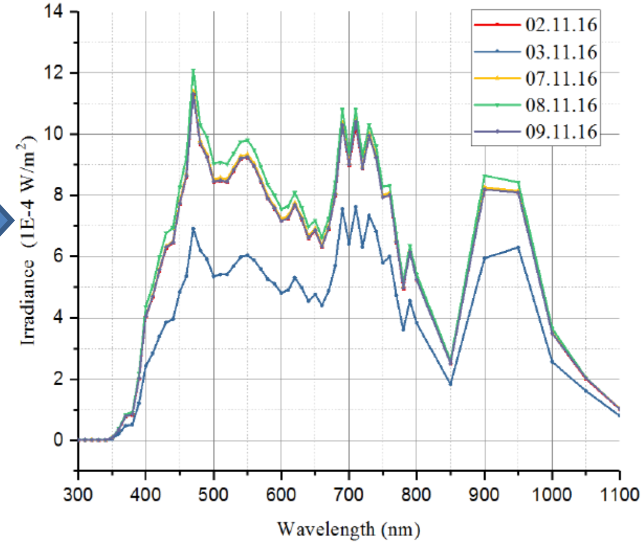
Chopper control & Lock-in Amp.

Cooling system controller & PC

Radiation Hardness of SiPMs: PDE issues

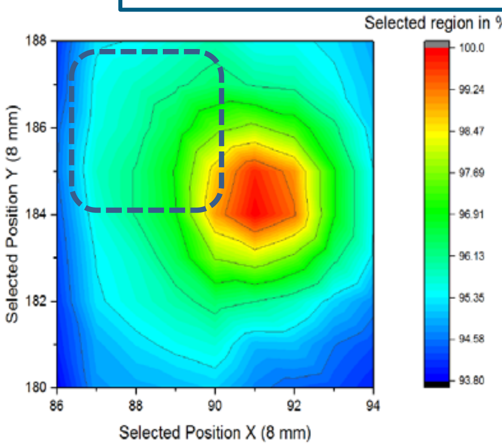


Example of repeated irradiance measurements using a reference photodiode:



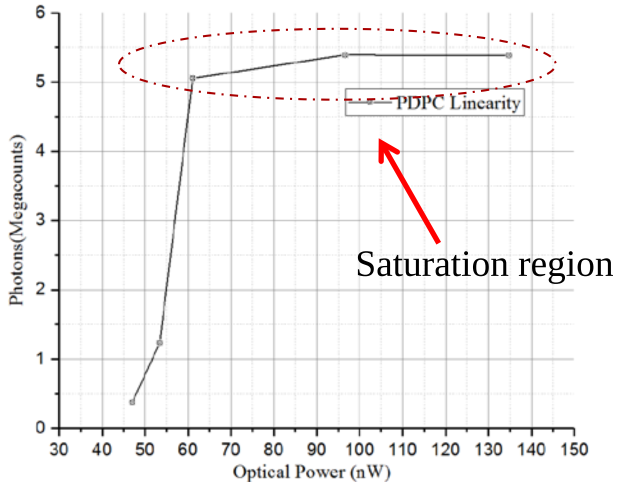
Resulting system uncertainty (including the uncertainty of the ref. PD): 16.6 %

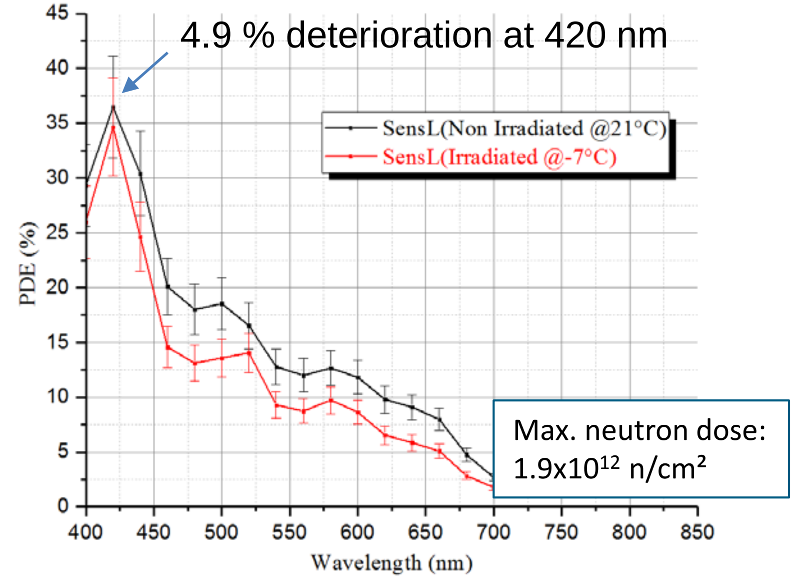
Illumination spot uniformity (8 x 8 mm²):

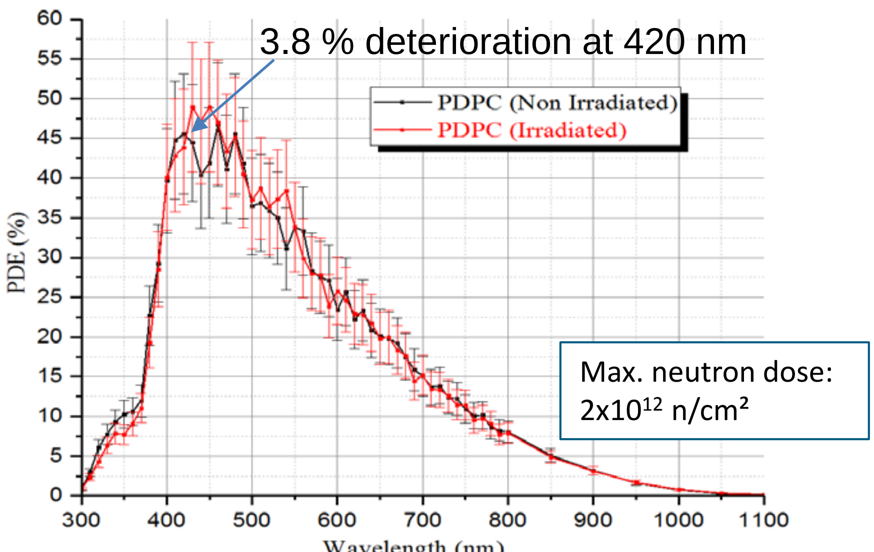


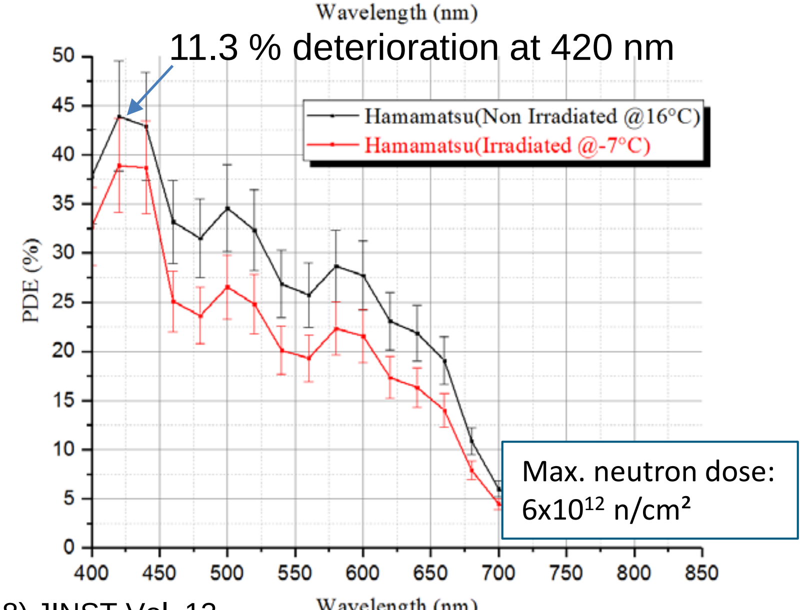
Radiation Hardness of SiPMs: PDE issues

Optimizing the measurement system for “single-photon counting” devices is never easy…









Source: Kumar et al. (2018) JINST Vol. 13

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Conclusions and Outlook:

- **SiPM technology is viable for solid-state pixelated scintillation detectors to be used in SANS applications** having over 10-year life-times
- *Hamamatsu* MPPCs showed higher radiation hardness than *SensL Series-C* and *Philips DPC* → **all three technologies remained within goal specifications**
- An annealing effect at room temperature was observed and will be investigated further (also using active heating or illumination)
- The relative **deterioration in PDE** (λ = 420 nm) after irradiation with 5 Å cold neutrons is proportional to the increase in the DCR → **remained within goal specifications**
- **We chose the *Philips* DPC technology** and developed and characterized the first SANS PDPC based **solid-state scintillation detector demonstrator** yielding:
  - Count-rate (linearity > 90%): **>110 Mcps for 60 x 60 cm²**
  - Neutron Detection Efficiency: 75 ± 5 % @ 5 Å
  - Spatial resolution: **≥ 1x1 mm² for monolithic scintillator glass**
  - A prototype detector of 13 x 13 cm² is currently under development

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Conclusions and Outlook:

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Thank you very much for your attention!

…any questions?