Study of Evolution of MPPC Properties Induced by Neutrons

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The first International Conference on the Advancement of Silicon Photomultipliers
Schwetzingen, 11-15 June 2018

Questions

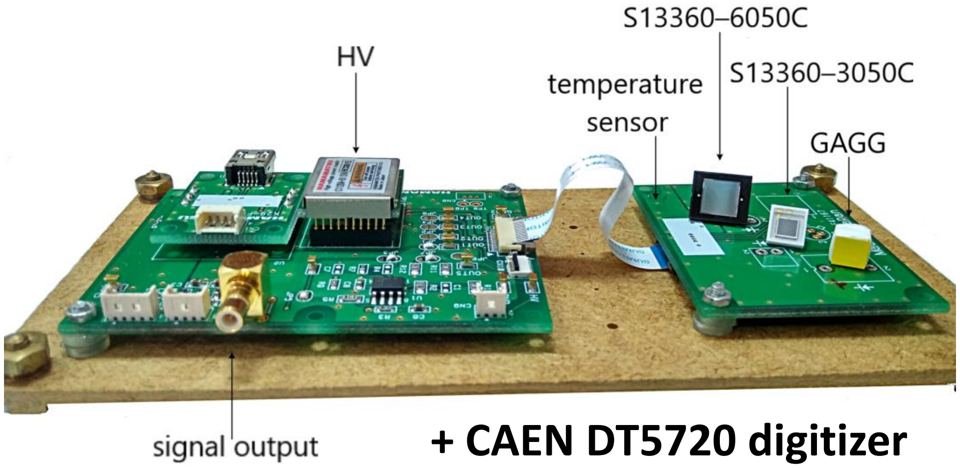
What is a neutron irradiation influence to silicon photomultipliers?

- current – voltage characteristics
- breakdown voltage
- energy resolution
- noise contribution

Why we need this information?

For me: gamma spectroscopy … and many more!

Experimental set-up



+ CAEN DT5720 digitizer

MPPCs:
- **Hamamatsu S13360-3050CS**
  3x3 mm^2, 50 µm cell pitch size
- **Hamamatsu S13360-6050CS**
  6x6 mm^2, 50 µm cell pitch size

Hamamatsu evaluation board C12332-01:
- **precision power supply**
- **temperature sensor**
- **preamplifier (20x)**

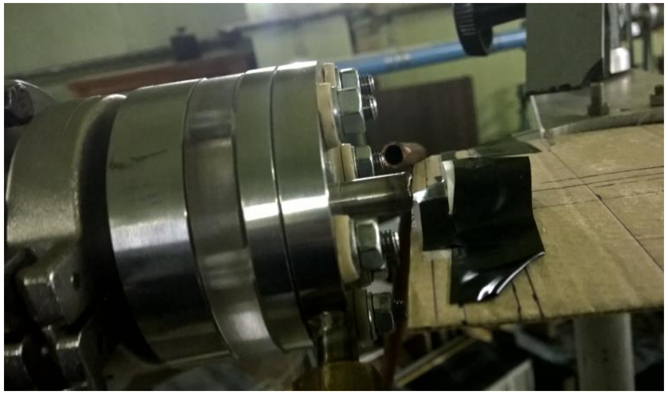
Scintillator GAGG:Ce:
- **size: 5 x 5 x 5 mm^3**
- **light output: (44.6k ± 4.4k) photons/MeV**
- **intrinsic resolution: (2.7 ± 0.3)%@662 keV**

P. Sibczynski et. al, NIM A, 772, 264 (2015) 112-117

Experimental set-up

Keithley SMU 2400 for the I-V charateristics:

- source voltage from 5 µV to 210 V
- measure current from 10 pA to 1.055 A
- upper current limit was set to 100 µA
- controlled by PC



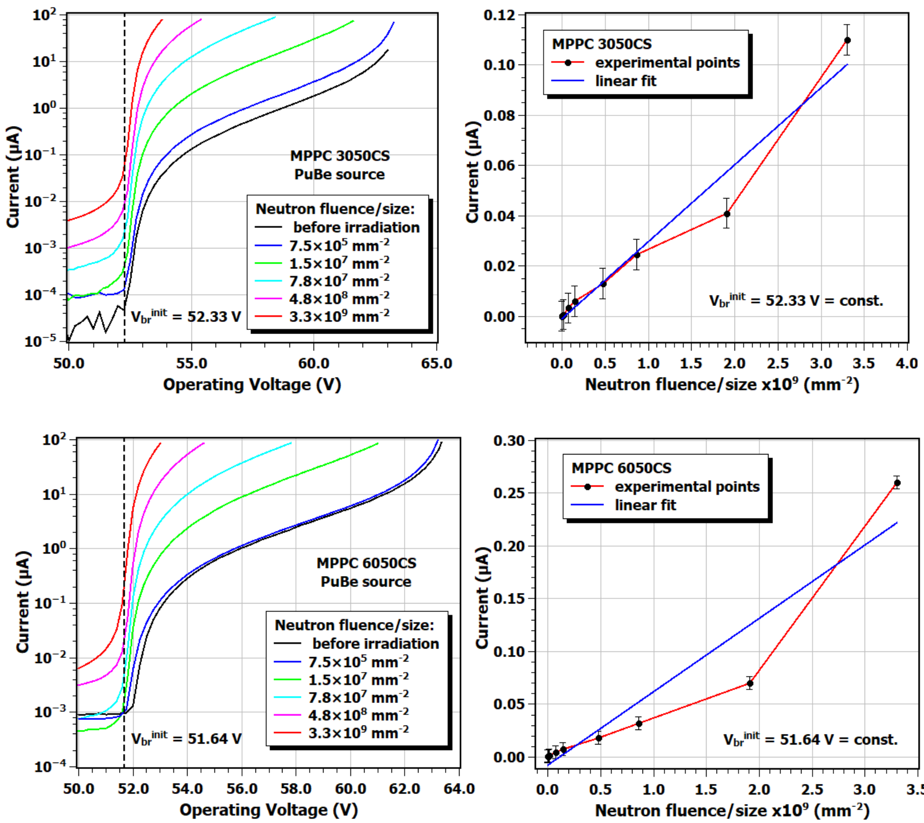
PuBe neutron source at NCBJ

- neutron energy up to 11 MeV
- average neutron energy about 4.6 MeV
- flux: (800k ± 20k) n/s/4π

Van der Graaf accelerator at FLNP (JINR)

- mono-energetic 4.8 MeV neutrons from (d,d) reaction
- average flux: 280k n/s/cm^2

Current – Voltage characteristics



PuBe source

Left hand graphs - dashed vertical lines show the calculated breakdown voltage (V_{BR}^{init}) for the non-irradiated MPPC.

Right hand graphs present the current increase for V_{BR}^{init} compared to linear fit.

Each MPPC had the same neutron fluence

Changes in I-V characteristics with the increase in neutron fluence from a PuBe source for 3x3 mm^2 (upper part) and 6x6 mm^2 (lower part) type of MPPC.

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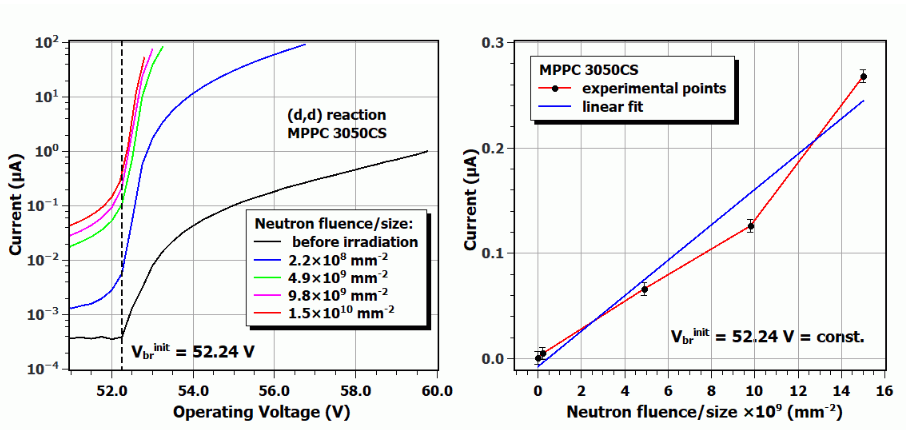
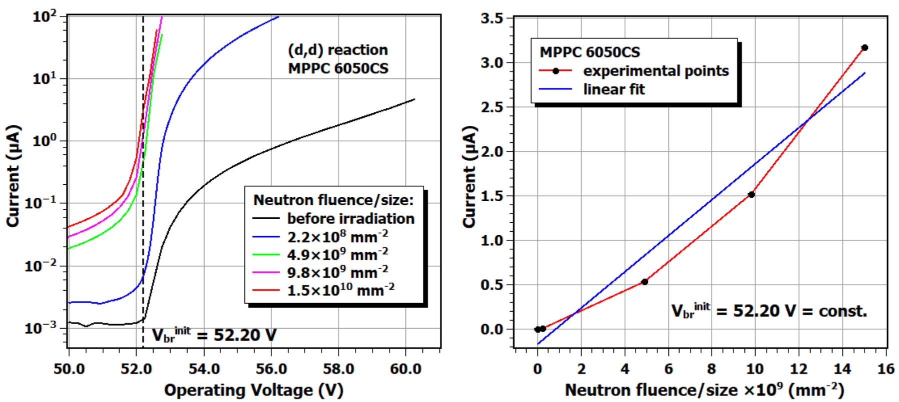
Current – Voltage characteristics





(d,d) reaction

Left hand graphs - dashed vertical lines show the calculated breakdown voltage (V_{BR}^{init}) for the non-irradiated MPPC.

Right hand graphs present the current increase for V_{BR}^{init} compared to linear fit.

Maximum neutron fluence about 4x higher than for PuBe source

Changes in I-V characteristics with the increase in neutron fluence from a (d,d) reaction for 3x3 mm^2 (upper part) and 6x6 mm^2 (lower part) type of MPPC.

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Breakdown voltage determination

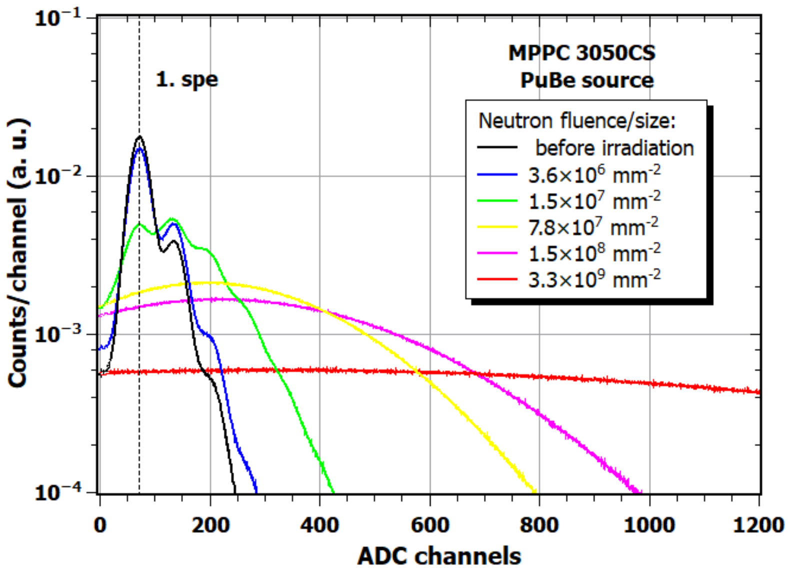
To define the breakdown voltage two methods are usually use:

1. Determination of single photoelectron peak position
(various temperature ranges and different operating voltages)

Disadvantages:
- **time consuming process**
- **the photoelectron peaks become indistinguishable**

↓

Usefulness in this case

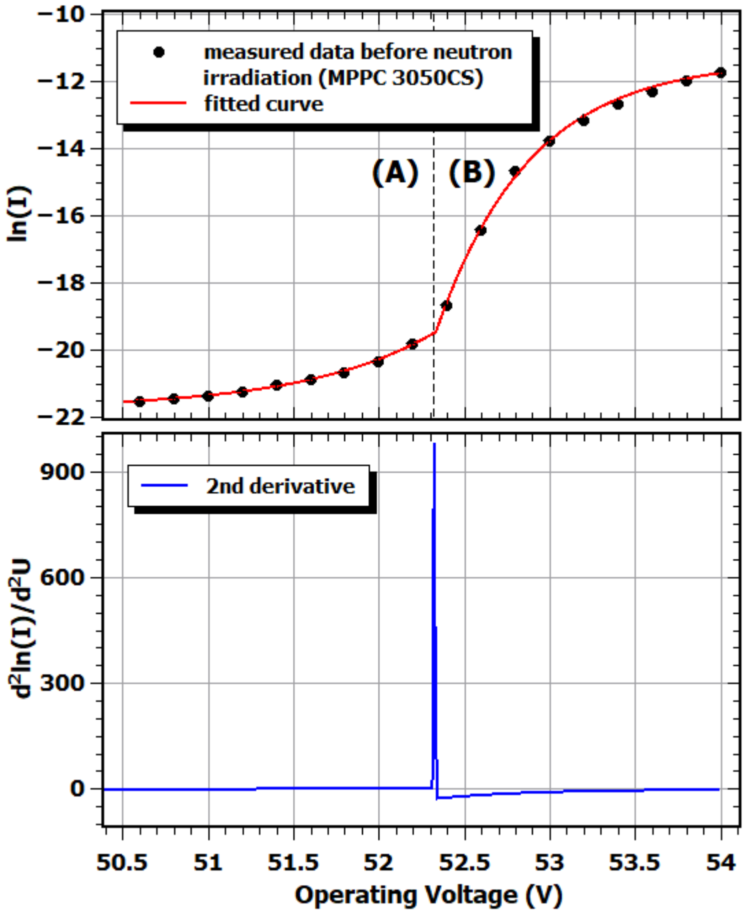


Example of dark count spectra measured for 3050CS for 54.6 V at room temperature for neutrons from a PuBe source. Spectra were normalized to unit area.

2. Current-Voltage dependency analysis

Z.W. Li et. Al., NIM A 242 850 (2017) 35-41 F. Nagy at. al, NIM A 849 (2017) 55-59

Breakdown voltage determination



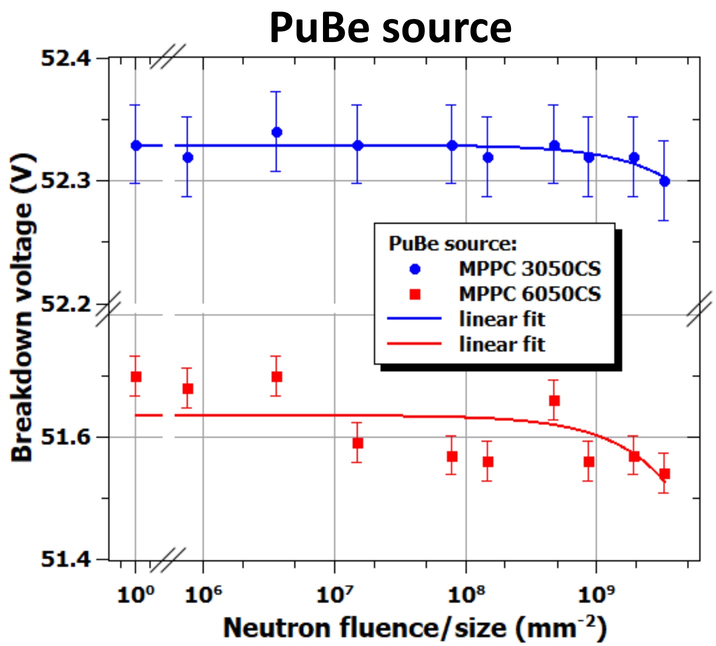
Top - Example of ln(I)-V characteristics in the range of the breakdown voltage with a fitted function. Bottom - the 2nd derivative of the fitted curve.

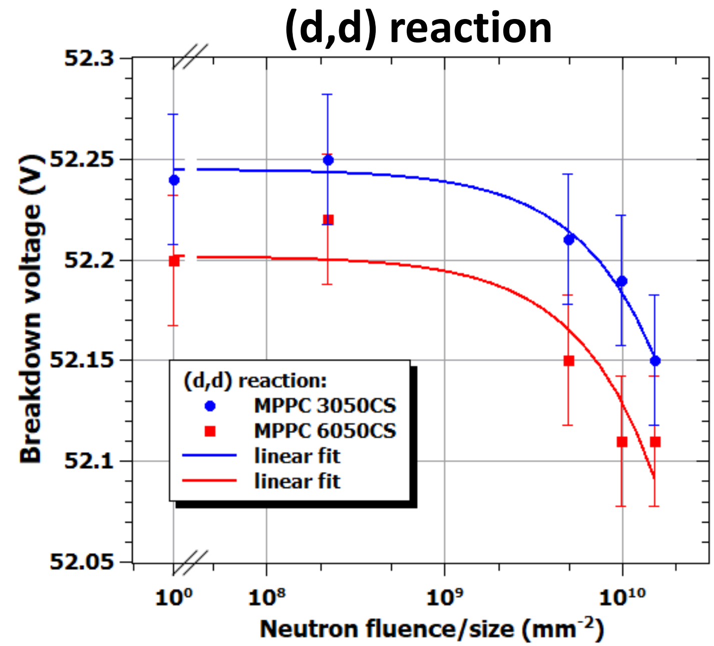
1. V_{init} is chosen as a maximum of the 2nd derivative of the experimental data. This defines two regions (A and B).
2. Function ln(I) is fitted to experimental data.

$$\ln(\mathrm{I}) = \begin{cases} A_1 \cdot \exp\left((V - V_1) \cdot \tau_1\right), & V < V_{init}, \\ A_2 \cdot \left[1 - \exp\left(-(V - V_2) \cdot \tau_2\right)\right], & V > V_{init}, \end{cases}$$

3. The 2nd derivative of the fitted function defines the V_{BR}

Breakdown voltage determination



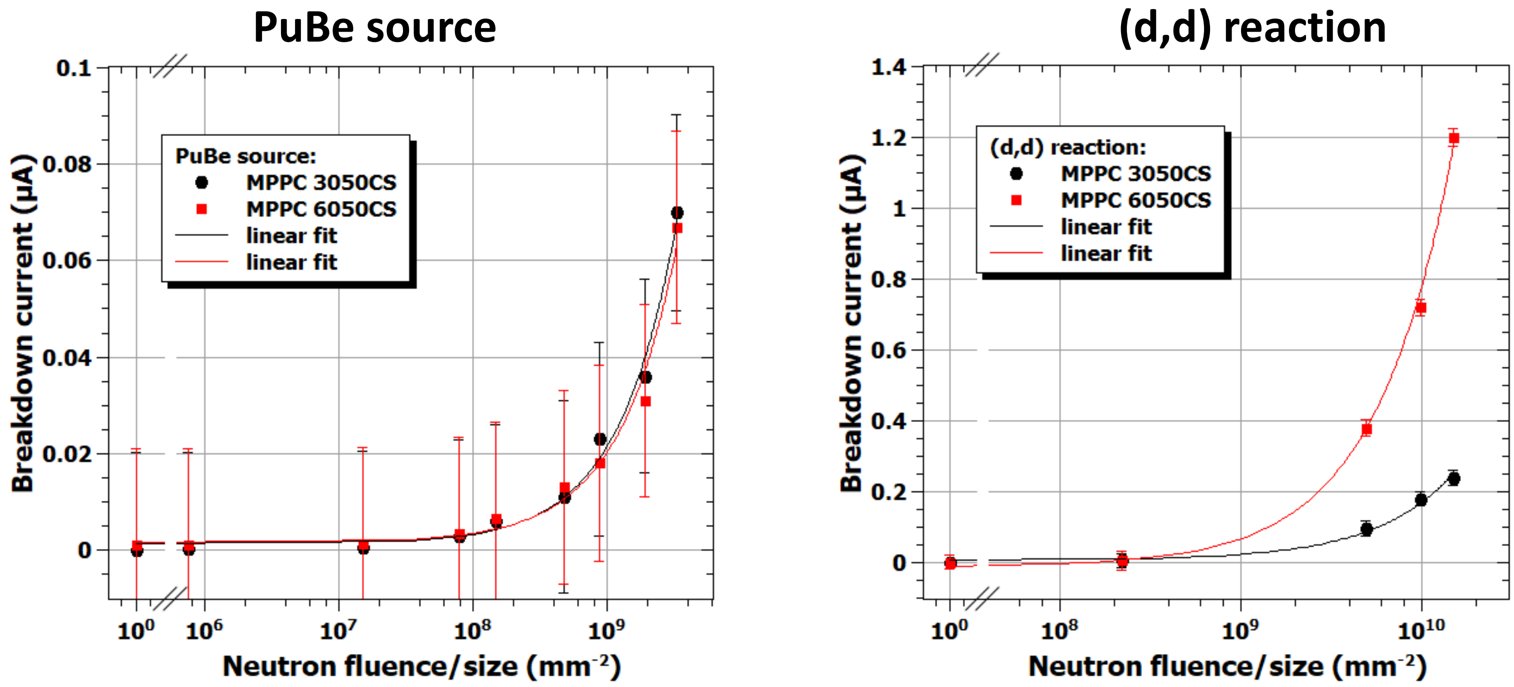


Linear fit in Log-Lin scale!

Breakdown voltage dependency as a function of neutron fluence from a PuBe source (left) and a (d,d) reaction (right).

Neutron source	Rate of change of V_{BR} ($V \cdot mm^2$)	
	3050CS	6050CS
PuBe	$(-8.0 \pm 0.8) \times 10^{-12}$	$(-3.5 \pm 1.7) \times 10^{-11}$
(d,d)	$(-6.2 \pm 0.5) \times 10^{-12}$	$(-7.3 \pm 1.2) \times 10^{-12}$

Breakdown current



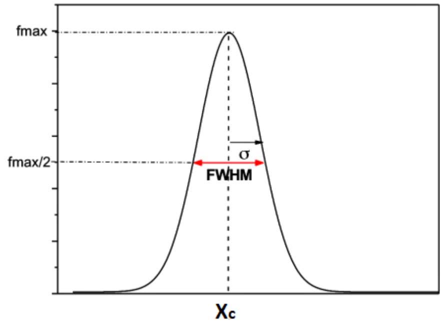
Linear fit in Log-Lin scale!

Breakdown current dependencies determined by fitted breakdown voltage and measured I-V characteristics for neutrons from a PuBe source (left) and neutrons from a (d,d) reaction (right).

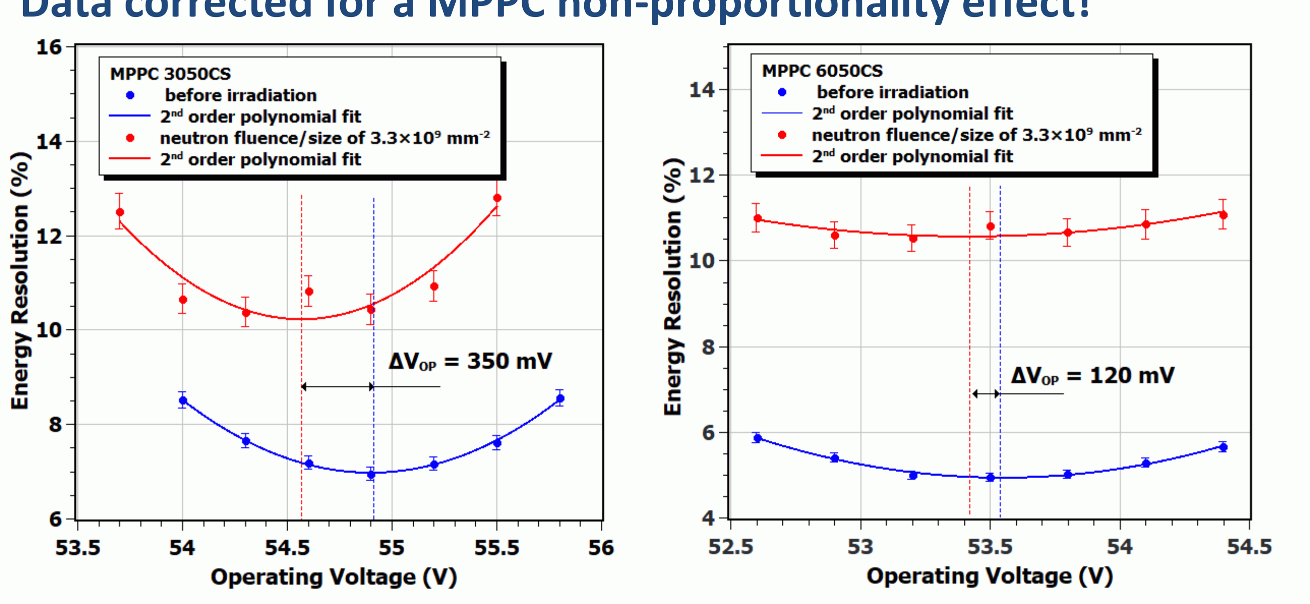
Much better linear dependency!

Energy resolution vs. neutron fluence

$$E_{RES} = \frac{FWHM}{Xc} \times 100\%$$



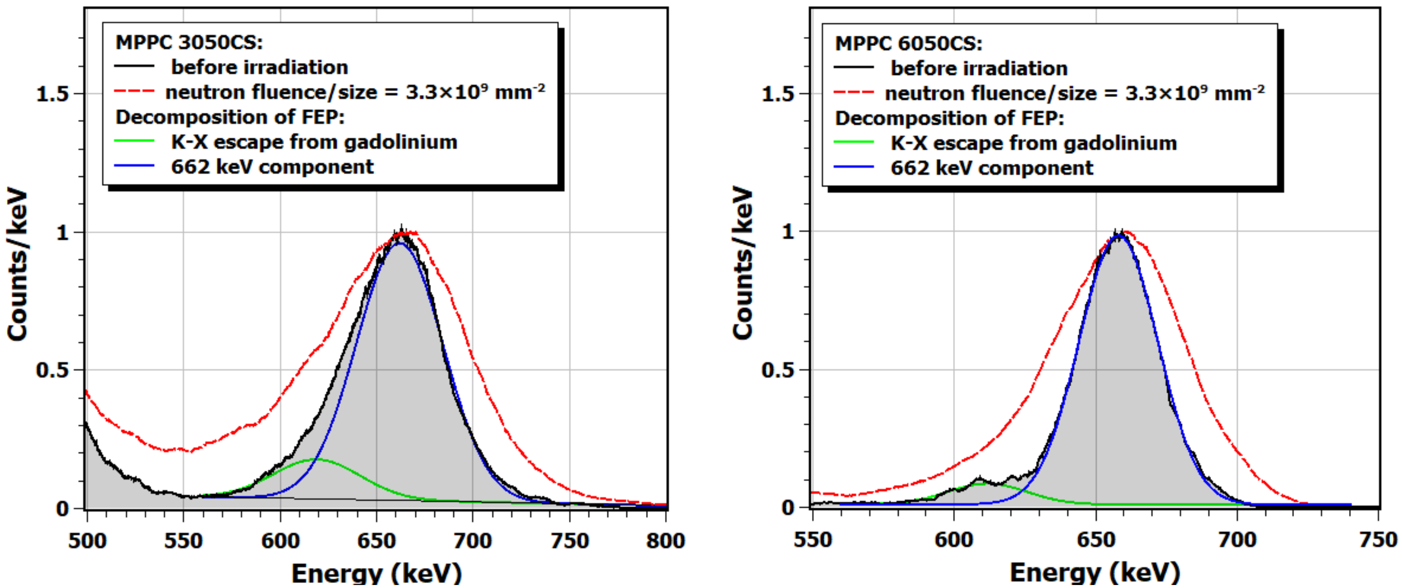
Data corrected for a MPPC non-proportionality effect!



Energy resolution of the 662 keV line from ^{137}Cs for 3050CS (left) and 6050CS (right) coupled to a GAGG scintillator for different operating voltages.

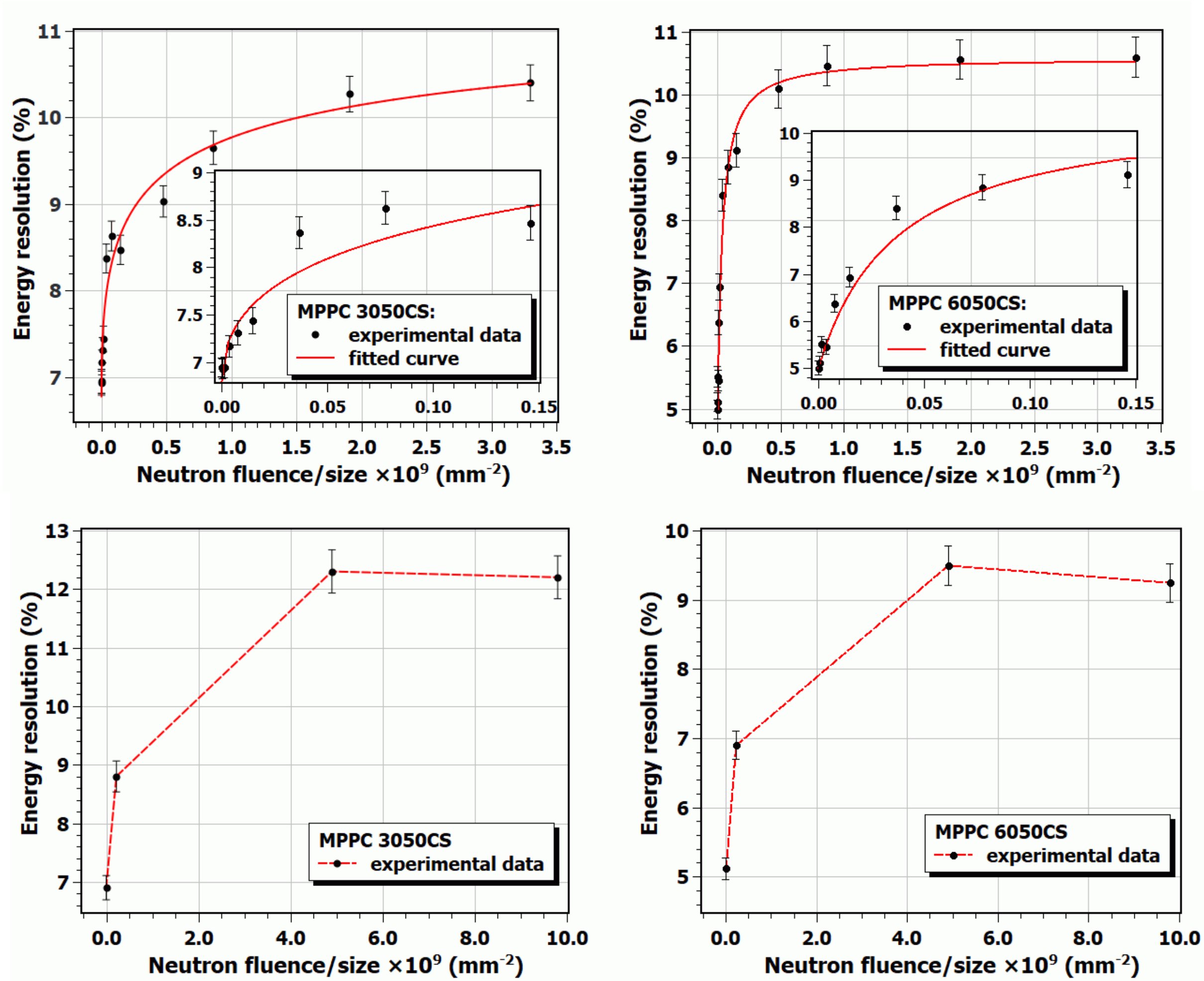
Energy resolution vs. neutron fluence

GAGG:Ce was not irradiated!



The 662 keV gamma line from ^{137}Cs measured with GAGG:Ce scintillator coupled to MPPC before and after neutron irradiation from PuBe source.

Energy resolution vs. neutron fluence



PuBe source

(d,d) reaction

Energy resolution of a 662 keV line from ^{137}Cs for MPPC 3050CS (left) and 6050CS (right) coupled to a GAGG:Ce scintillator as a function of neutron fluence.

Noise contribution to energy resolution

$$E^2_{RES} = \delta^2_{SC} + \delta^2_{STAT} + \delta^2_{NOISE}$$

Scintillator contribution (intrinsic resolution) (2.7 ± 0.3)% @662 keV

Statistical contribution

Noise contribution (?)

Excess noise factor (<=2)

$$\delta^2_{STAT} = 2.355 \times \left(\frac{F}{N_{SPE}}\right)^{1/2}$$

Number of photoelectrons (constant)

Two extreme cases:

- F = 1 – no fluctuation
- $F = F_{MAX}$

$$\delta^2_{NOISE} = E^2_{RES} - \delta^2_{SC} - \delta^2_{STAT} > 0$$

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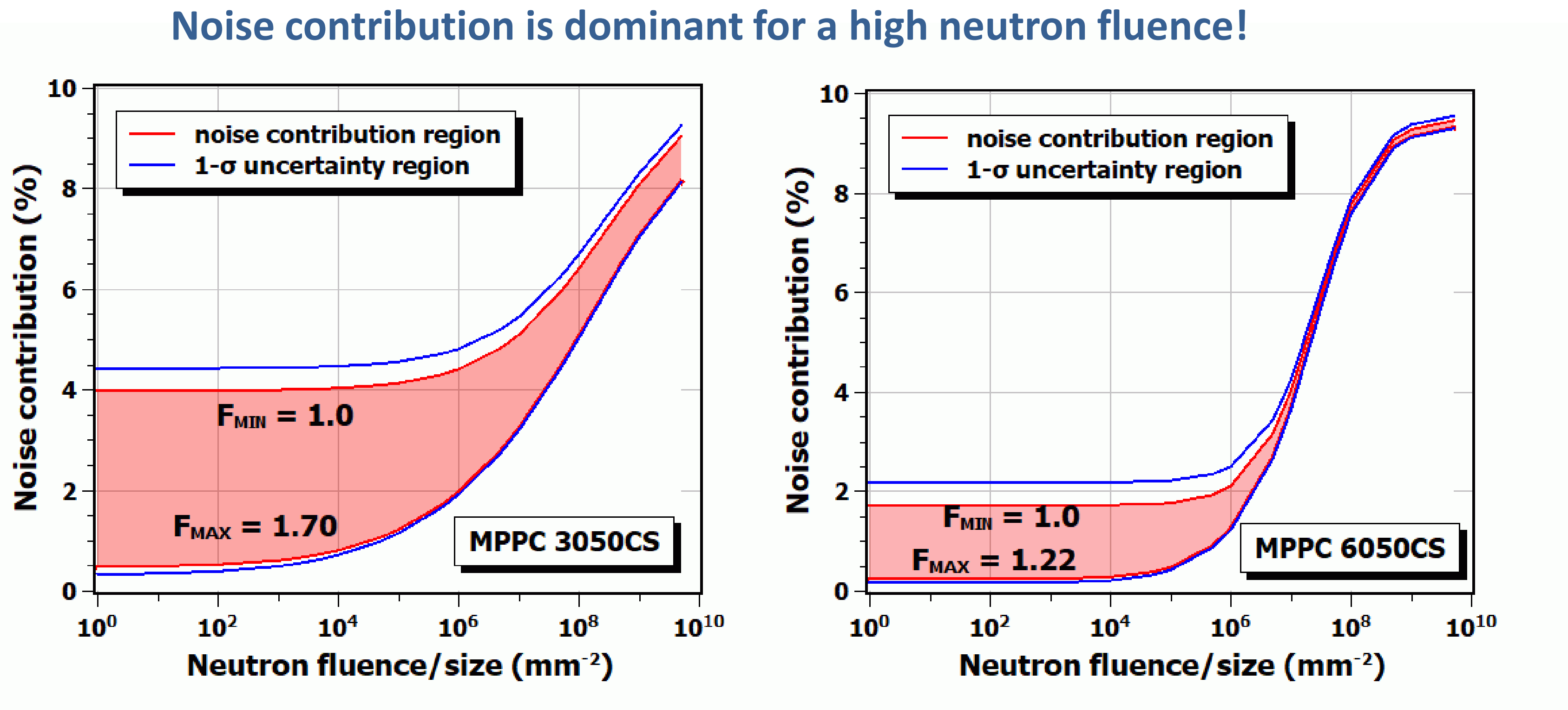
Noise contribution to energy resolution



Noise contribution to energy resolution for 3050CS (left) and 6050CS (right) as a function of neutron fluence from a PuBe source.

Noise contribution to energy resolution

PuBe source and (d,d) reaction - comparison.

Fluence/size (mm^{-2})	3050CS		6050CS	
	Noise (%) (calc.)	Energy res. (%) (exp.)	Noise (%) (calc.)	Energy res. (%) (exp.)
Neutrons from (d,d) reaction				
1	0.3 - 4.2	7.0	0.3 - 2.4	5.0
9.8×10^9	10.0 - 10.9	10.5	7.5 - 7.9	10.6
Neutrons from PuBe source				
1	0.5 - 4.0	7.0	0.3 - 1.8	5.0
3.3×10^9	7.9 - 8.8	12.2	9.2 - 9.5	9.5

Summary and Outlook

1. MPPCs/SiPMs are sensitive to neutron irradiation.
2. The dark current strongly increases with the increase of neutron fluence
3. The breakdown voltage, determined by analysing I-V characteristics, changes slowly (factor of 10^{-12} V mm^{-2}) with the increase in neutron fluence.
4. There is strong energy resolution degradation by a factor of 2.
5. Noise contribution to energy resolution is dominant for a high neutron fluence.

Future plans

1. Study of neutron and proton irradiation influence to MPPCs/SiPMs with a different pitch size

- degradation of energy resolution and timing properties

Our group

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Thank You!