Radiation Damage Effect on Time Resolution of 6 Series-connected SiPMs for MEG II Positron Timing Counter

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Introduction

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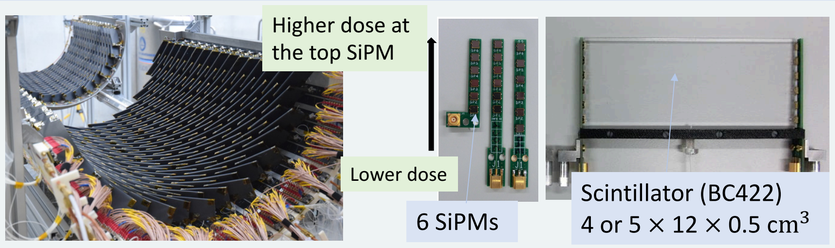
- **MEG II Experiment:** world's most sensitive $\mu^+ \to e^+\gamma$ search [1].
- **Series connection of SiPMs** is effective to get better time resolution [2]. For **MEG II positron timing counter, a series connection with 6 SiPMs** is used to precisely measure positron timing: $\sigma_t \sim$ **35 ps on average** with multi-hit information.
- Expected total dose on counter: $\sim 10^{11}\ [e^+/cm^2]$, and expected current increase of each channel: ~ **100 μA** after 3 years data taking of MEG II.
- Radiation torelance of SiPM has been well studied [3], but effect on series connection for scintillation counter has not been studied in detail.

This is the first detailed study of radiation damage effect on series connected SiPMs, especially on time resolution!

MEG II positron timing counter: composed of 512 small scintillation counters



- Each counter
  - ✓ 6 SiPMs on both side
  - ✓ Ultra-fast scintillator BC422
  - ✓ **70-80 ps** time resolution
  - ✓ **Different dose among 512 counters, among 6 SiPMs**
- Multi-hit of signal e^+
  - ✓ **~ 9 hits/ e^+** on average

Setup for Time Resolution Measurement

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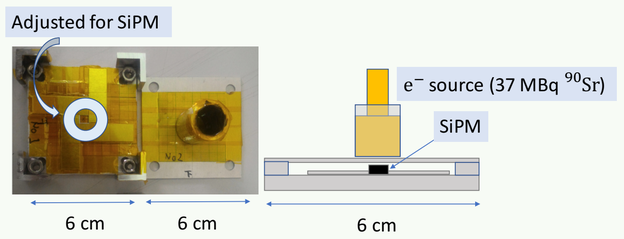
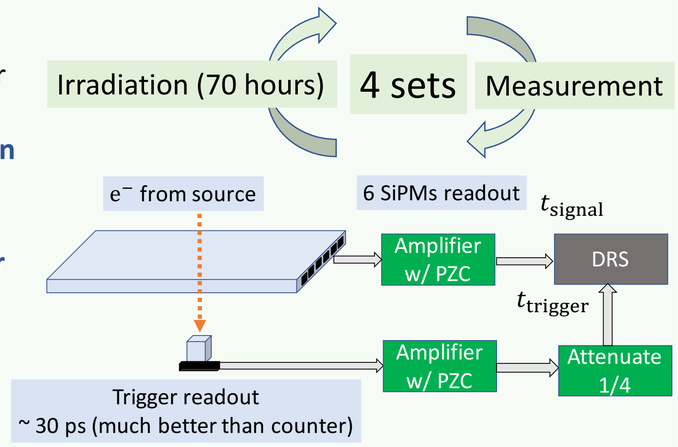
- We repeated **irradiation & measurement**
  - ✓ Irradiated electrons on 6 SiPMs, then measured time resolution with those SiPMs
  - ✓ Test SiPM: SiPM: ASD-NUV3S-P High Gain (MEG)
    - $3 \times 3\ mm^2$ (50 μm pixel pitch), $V_{break\ down}$(Vbr) ~ 24V, from AdvanSiD.

- Irradiation step
  - ✓ e^- irradiation from a 37 MBq ^{90}Sr
  - ✓ 70 hours irradiation × 4 times
  - ✓ 6 SiPMs were equally irradiated
  - ✓ SiPMs were not biased during irradiation



- Measurement step
  - ✓ Measure time resolution w/ scintillator (BC422, $40 \times 120 \times 5\ mm^3$)
  - ✓ Pulse shaping w/ **pole zero cancellation**
  - ✓ Waveform recorded by **DRS (Domino Ring Sampler chip)** [4]
  - ✓ Temperature was controlled **at 30℃ or 10℃**.
  - ✓ $5 \times 5 \times 5\ mm^3$ BC422 + $3 \times 3\ mm^2$ SiPM(HPK S10362-33-050C) compose the trigger counter



I-V Characteristics and Waveforms

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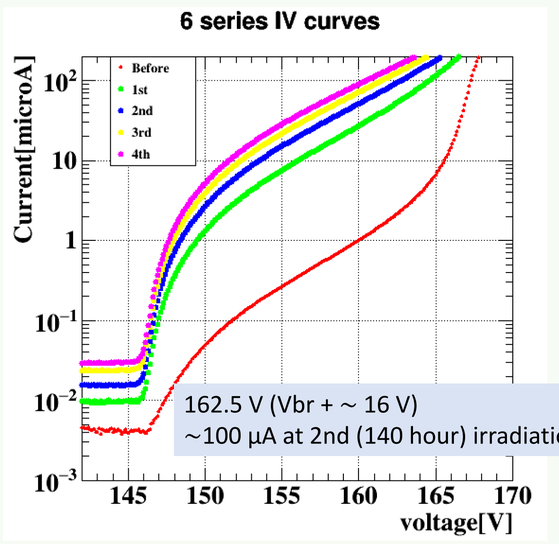
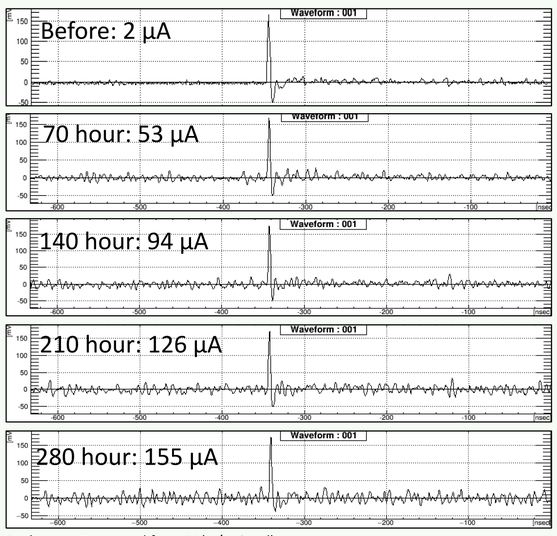
- I-V characteristics (30℃)
  - ✓ 6 SiPMs connected in series
  - ✓ **Current increase** by electron radiation damage
  - ✓ Breakdown voltage (Vbr) has not changed significantly



- Waveforms (30℃)
  - ✓ Large baseline fluctuation by increased dark noise
  - ✓ Time pick up with **constant fraction**
    - Pick up at (V_{height}) × (Fraction)
    - Fraction: optimized in 20, 30, 40 and 50%



Dark current was read from IV (w/o signal).

Reference
[1] A.M. Baldini et al., "The dsign of the MEG II experiment", Eur. Phys. J. C (2018) 78:380
[2] P.W. Cattaneo et al., "Development of High Precision Timing Counter Based on Plastic Scintillator with SiPM Readout", IEEE Trans .Nucl. Sci. 61 No.5 (2014) 2657-2666.
[3] G. Lindström, M. Moll and E. Fretwurst "Radiation hardness of silicon detectors — a challenge from high-energy physics", Nucl. Instrum. Methods A 426 (1999) 1-15
[4] S. Ritt, R. Dinapoli, and U. Hartmann, "Application of the DRS chip f or fast waveform digitiing", Nucl. Instrum. Methods A, 623 (2010) 486–488
[5] P.W. Cattaneo et al., "Radiation Hardness tests with neutron flux on different Silicon photomultiplier devices", 2017 JINST 12 C07012

Time Resolution vs. Dark Current

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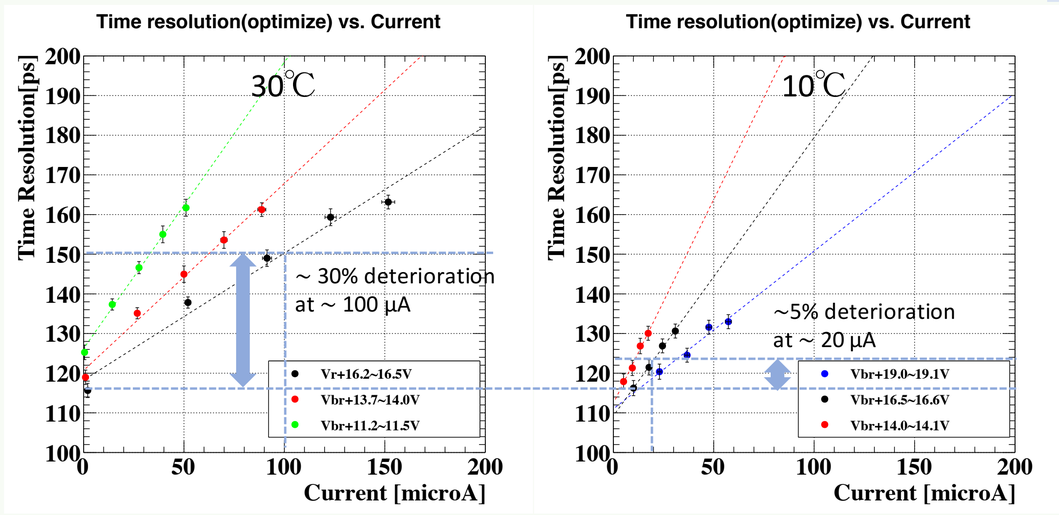

- We evaluated the deterioration at Vbr + ~16 V (black points)
- Time resolution: $\sigma(t_{signal} - t_{trigger})$
- At the expected current level (~ 100 μA), ~ **30% deterioration at 30℃.** At the same condition, ~ **5% deterioration at 10℃** (negligible (< 1%) deterioration for MEG II final sensitivity).

Time resolution deterioration was caused by thermal dark noise increase.

Low temperature operation is effective to suppress the deterioration.

Series Connection of Differently Damaged SiPMs

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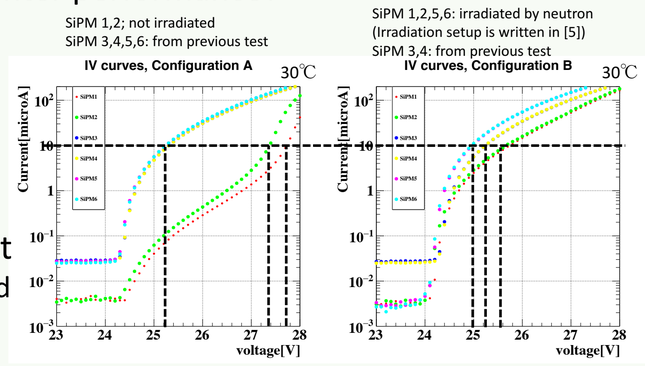
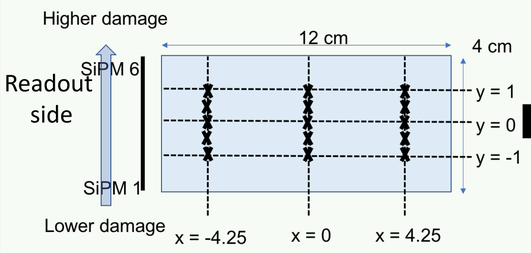
- **Total dose is different among 6 SiPMs** due to the different distance from beam axis. When 6 SiPMs which have different damage level were connected in series, what is the effect on counter performance?

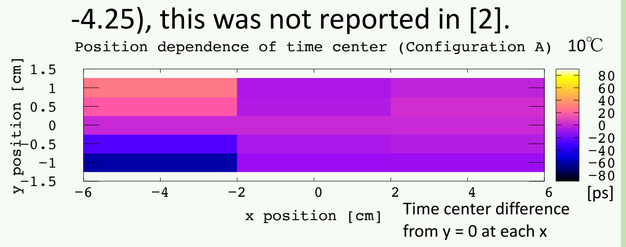
- **Series connection**: **Same current among 6 SiPMs cause different over voltage among 6**
  - ✓ **Highly damaged SiPM have smaller over voltage than not damaged one**
- 2 configurations to check this effect
  - ✓ A. 4 Highly damaged & 2 not damaged
  - ✓ B. Damage level in stage



- Position dependence measurement
  - ✓ Measured at 15 positions w/ previous measurement setup



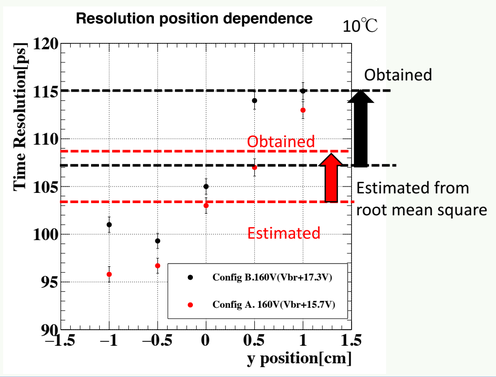
- Position dependence of time center
  - ✓ **Mean value of** $(t_{signal} - t_{trigger})$
  - ✓ Clear dependence at the readout side (x = -4.25), this was not reported in [2].



- Effect on time resolution
  - ✓ **Time center variation will deteriorate the time resolution**
  - ✓ We investigated w/ 5 sampling points at x = -4.25, and ~ **5 – 7% deterioration** observed

Not a serious deterioration

Correction using hit position can be done



Summary & Discussion

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- First detailed study on radiation damage effect of 6 series connected SiPMs, especially on time resolution for MEG II timing counter.
- At the expected damage level, time resolution was deteriorated ~ **30% at 30℃, but ~ 5% at 10℃** by thermal dark noise.
  - ✓ We decided to cool TC to 10℃ with a chiller system.
- When SiPMs connected in series have different current level, **position dependence of time center, pulse height, time resolution** appeared.
  - ✓ Correction for the time center variation using the hit position information provided by external detector (drift chamber in MEG II) will be applied.
- **We understood the radiation damage effect on TC and solutions to suppress the effect. Radiation damage is already not a serious problem for TC.**