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The latest performance and refurbishment of the pixelated Timing Counter (pTC) in the MEG II experiment

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ABSTRACT

We have operated the MEG II pixelated timing counter maintaining its overall timing resolution at high level for precise timing measurement of positrons. Since its construction in 2017, the detector's pixels have shown degradation with high-rate beam irradiation and components (plastic scintillators, SiPMs) aging over time. In 2024, using new 960 SiPMs, we produced and mounted new 80 pixels onto the detector with estimation of the performance improvement.

1. Introduction

The last decade has seen widespread use of silicon photo-multipliers (SiPMs) to detect scintillation photons. With high gain and linear sensitivity, they are comparable to photo-multiplier tubes (PMTs) with several advantages: robustness to magnetic fields, smaller size and lower operating voltages.

The MEG II experiment [1] has been running since 2021 to search for $\mu^+ \rightarrow e^+\gamma$ with the world's most intense DC anti-muon beam up to 5×10^7 μ^+/s at Paul Scherrer Institute (PSI). The pixelated Timing Counter (pTC) for positron timing measurement is composed of 512 fast plastic scintillator tiles with SiPM readout on both ends. The use of SiPMs enables us to utilise the highly-segmented design to suppress the pTC overall uncertainty with $1/\sqrt{N_{\mathrm{hit}}}$ by exploiting multiple-hit events (see Eq. (A.3)) while ensuring a stable performance in the MEG II magnetic field. The individual pixel consists of a small plastic scintillator tile (BC-422, 12 cm-wide × 4 (or 5) cm-height × 5 mm-thick) wrapped in a reflector film (ESR2, 32 μm-thick) and a black sheet (Tedlar®), readout by twin arrays of 6 series-connected SiPMs (3×3 mm^2, ASD-NUV3S-P).

2. Degradation of scintillator pixel

Fig. 1 shows the pTC overall timing resolution under the high rate beam in 2017, 2021 and 2023 deteriorating ∼ 19%. Pixel individual degradation was reported with 2021 data [2]. Dark current increment on the SiPMs with the equivalent radiation damage was also investigated in the past study [3].

3. Refurbishment of scintillator pixel

For a still long-term operation towards 2026, we planned to renovate the pTC. Following the mass-production procedure in the past [4], we produced new 94 pixels with spare scintillators and new 1128 SiPMs with a larger sensitive area 4×4 mm^2 (ASD-NUV4S-P). Fig. 2 shows the new pixel's resolution in laboratory tests. In 2024 maintenance period, we could exchange 80 pixels on the pTC structure.

Considering resolution improvement for each pixel (Figs. 2 and 3) and n-hit rate and event fraction for signal positrons in MC simulation, we calculated the best option of the replacement according to the Eq. (A.5), (A.6).

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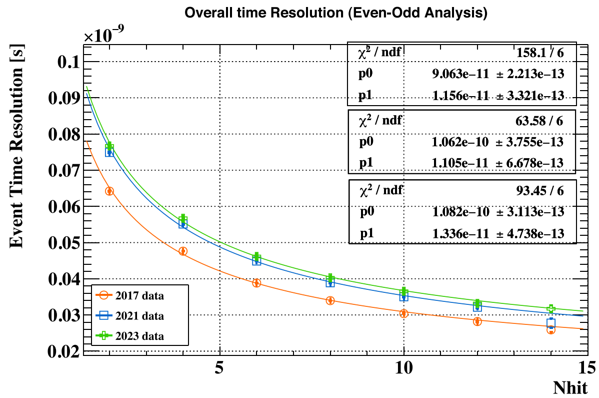

Fig. 1. The pTC timing resolution per hit multiplicity. Evaluated by data in 2017, 2021 and 2023 are shown in the orange, blue and green lines respectively.

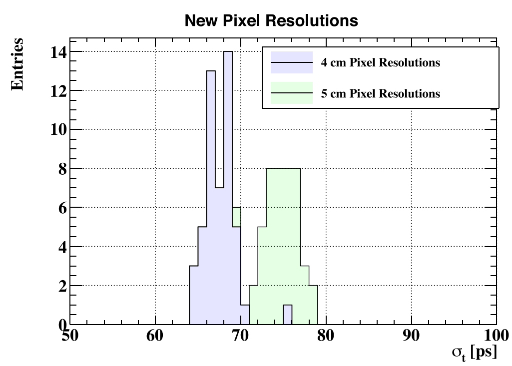

Fig. 2. New pixel time resolution in laboratory tests. Pixels 4 cm-high and 5 cm-high are shown in the blue and green histograms respectively.

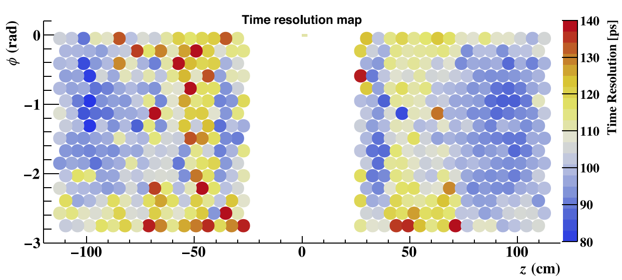

Fig. 3. The pixel timing resolution on the pTC geometry. The z axis is aligned with the beam axis.

4. Conclusion

Taking into account the performance of the MEG II pTC during the physics run, we replaced 80 deteriorated pixels with a new SiPM model having a slightly larger sensitive area which provides better timing resolution than old ones. We will operate and verify their performances for the future MEG II run.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Formalisations

Timing calculation in the pTC is

$$t_{\mathrm{pTC}} = \frac{1}{n}\sum_{i=0}^{n} t_i \tag{A.1}$$

where n is the number of hit pixels in a particle track and t_i is the reconstructed time by the ith hit pixel information. Then its uncertainty can be written in the form

$$\sigma_{t_{\mathrm{pTC}}}(n) = \sqrt{\sum_{i=0}^{n}\left(\frac{\sigma_{t_i}}{n}\right)^2} \tag{A.2}$$

If the individual pixel resolutions are similar, the replacement of σ_{t_i}-s with $\hat{\sigma}_{\mathrm{single}}$ gives a good estimation (see Fig. 1).

$$\hat{\sigma}_{t_{\mathrm{pTC}}}(n) = \sqrt{\sum_{i=0}^{n}\left(\frac{\hat{\sigma}_{\mathrm{single}}}{n}\right)^2} = \frac{\hat{\sigma}_{\mathrm{single}}}{\sqrt{n}} \tag{A.3}$$

Note: another kind of contribution is from adding up the angular spread of multiple scattering between the adjacent hit pixels. Such a term contributes with around 10% for n=9 [5].

Just focussing on the dominant term, when the resolution of one pixel improves by factor $a \in [0,1]$ in a relevant event

$$\frac{\hat{\sigma}_{\mathrm{single}}}{\sqrt{n}} \to \sqrt{\frac{n-1}{n^2}\hat{\sigma}^2_{\mathrm{single}} + \frac{1}{n^2}\left(a\hat{\sigma}_{\mathrm{single}}\right)^2} = \sqrt{1-\frac{1-a^2}{n}}\cdot\frac{\hat{\sigma}_{\mathrm{single}}}{\sqrt{n}} \tag{A.4}$$

Generally, using the rate r_n of how much of all n-hit events the pixel is included in

$$\hat{\sigma}_{t_{\mathrm{pTC}}}(n) \approx \sqrt{\left(1-\frac{1-a^2}{n}\right)\cdot r_n + 1\cdot(1-r_n)}\cdot\frac{\hat{\sigma}_{\mathrm{single}}}{\sqrt{n}} \tag{A.5}$$

The pTC overall timing resolution can be estimated by their convolution

$$\hat{\sigma}_{t_{\mathrm{pTC}}} = \sum_{n}\left(f_n\cdot\hat{\sigma}_{t_{\mathrm{pTC}}}(n)\right) \tag{A.6}$$

where f_n is the fraction of n-hit events of all events.

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