Study on improving the analysis of the pixelated Timing Counter in the MEG II experiment

2019/09/17

日本物理学会 2019年秋季大会

野内 康介 (東京大学)、他 MEG II コラボレーション
Outline

Introduction of MEG II
- MEG II experiment
- pTC design
- pTC performance

Lab test
- Measurement setup
- Pulse height behavior
- Time center behavior

Introduction of this study
- Aim & motivation
- Overview

Effect on MEG II
- MC study
- Correction using data

Summary & prospect
MEG II実験における陽電子の時間再構成法の改善

MEG II experiment

- **Target**
  - Stops muons inside target

- **Liquid Xenon (LXe) calorimeter**
  - Detects signal photons
    - c.f. 17aT12 小林、恩田
    - 19pT14 豊田、小川、家城

- **Radiative decay counter (RDC)**
  - Detects background positrons
    - c.f. 18pT12 大矢

- **Superconducting solenoid magnet (COBRA)**
  - Bends signal positrons with constant radius

- **Cylindrical drift chamber (CDCH)**
  - Single volume wire chamber with He based gas
  - Reconstructs positron track

- **Pixelated timing counter (pTC)**
  - Plastic scintillator + SiPM readout
  - Reconstructs positron time

**Search for $\mu^+ \rightarrow e^+ \gamma$ reaction**
Introduction

pTC design

Pixelated design of pTC allows multiple-hits for signal positron event

- Positron event display
- US (upstream)
- DS (downstream)
- hit pixels
- positron track

Single counter design

- 6 series-connected SiPM chain
- plastic scintillator
- reflector

12 cm 12 cm 4 cm 5 cm
Introduction

- **pTC performance**
  - Pixelated design allows $N_{hit} \sim 8$ for signal event
  - High time resolution can be achieved for multiple-hit events

- \[
\sigma_{event} = \frac{\sigma_{single-counter}}{\sqrt{N_{hit}}}
\]

- pTC time resolution obtained from MC

- Number of hits distribution

\[
\times = \sim 36.6\text{ps}
\]
Outline

➤ Introduction of MEG II
• MEG II experiment
• pTC design
• pTC performance

➤ Lab test
• Measurement setup
• Pulse height behavior
• Time center behavior

➤ Introduction of this study
• Aim & motivation
• Overview

➤ Effect on MEG II
• MC study
• Correction using data

➤ Summary & prospect
Aim & motivation

Aim

- Understand time response of detector & improve analysis algorithm

1. Investigate vertical position dependence of reconstructed hit time
2. Investigate how hit time is affected by (non-uniform) radiation damage to SiPMs
3. Attempt some time correction in offline analysis to improve pTC performance

not considered till now

already considered in analysis
**Aim & motivation**

**Motivation (1)**
- Vertical position dependence is seen for “edge hits” in 2017 data

**Motivation (2)**
- 宇佐見's previous study suggest that radiation damage can affect time center behavior
Overview

- **Lab test**
  - Position scan to check *intrinsic vertical position dependence* of hit time
  - Position scan using SiPMs with different *radiation damage* patterns

- **Effect on MEG II pTC**
  - Reproduction of data with MC simulation
  - Study effect of vertical time offset on *pTC performance*
  - Time *correction* using MC simulation
  - Time *correction* using pTC data
Outline

Introduction of MEG II
• MEG II experiment
• pTC design
• pTC performance

Lab test
• Measurement setup
• Pulse height behavior
• Time center behavior

Introduction of this study
• Aim & motivation
• Overview

Effect on MEG II
• MC study
• Correction using data

Summary & prospect
Measurement setup (1/2)

non-damaged SiPM
electron-irradiated SiPM
neutron-irradiated SiPM

Pattern A
Pattern B
Pattern C

gradation of damage

higher damage
reverse order

normal order

Electron source

Readout
Reference

Amplifier

DRS (1.6GHz)

trigger counter

(Pulse height) = height_{ch1}
(Time center) = cftime_{ch1} - cftime_{ch3}
**IV curves of used SiPMs**

- Damage level of each SiPM is apparent from IV curves
- Damage level of pattern C is comparable to that expected in MEG II ($\sim 5 \times 10^9 n_{1MeV}/cm^2$)
Pulse height behavior (1/2)

Result

- Opposite behavior for normal & reverse order → clear effect of radiation damage
- Pulse height is bigger when hit point is closer to less-damaged SiPM
Pulse height behavior (2/2)

- Interpretation
  - Current flowing through each SiPM is common in series-connection
  - Difference in I-V characteristics causes overvoltage difference between non-damaged & damaged SiPM
  - Non-damaged SiPMs yield higher gain than damaged SiPMs
Time center behavior (1/2)

Result

- Intrinsic time offset from counter $\sim 100 \ [ps]$
- Similar behavior is seen in all patterns $\rightarrow$ clear effect of radiation damage
- Deviations from $\sim 100 \ [ps]$ is additional effect from radiation damage

Non-damaged

Pattern A

Pattern B

Pattern C
Time center behavior (2/2)

Interpretation

- Time response of SiPM (charge collection speed) changes with overvoltage from bias scan result.
- Assumptions (in constant fraction method) to interpret this result:
  - Main pulse is determined dominantly by SiPMs closest to hit point.
  - Rising part of pulse is determined dominantly by SiPMs closest to readout.
  - When SiPMs closest to readout have low gain & slow time response (i.e. radiation damage), effect of following SiPMs also become dominant.

![Bias scan result](image)

Pattern A

- Normal order: $y = -1$
- Reverse order: $y = +1$
Outline

- Introduction of MEG II
  - MEG II experiment
  - pTC design
  - pTC performance

- Lab test
  - Measurement setup
  - Pulse height behavior
  - Time center behavior

- Introduction of this study
  - Aim & motivation
  - Overview

- Effect on MEG II
  - MC study
  - Application on data

- Summary & prospect
Reproducing data

- Vertical position dependence can be reproduced by setting time offset between series-connected SiPMs
- Setting 80 [ps] time offset between each SiPM for 4cm counter best reproduces data

2017 pTC data
Effect of vertical time offset

Condition: set various (0 [ps] - 100 [ps]) time offsets between series-connected SiPMs

Result:

<table>
<thead>
<tr>
<th>Input time offset</th>
<th>pTC resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 [ps]</td>
<td>36.5 [ps]</td>
</tr>
<tr>
<td>20 [ps]</td>
<td>36.6 [ps]</td>
</tr>
<tr>
<td>40 [ps]</td>
<td>37.5 [ps]</td>
</tr>
<tr>
<td>60 [ps]</td>
<td>39.1 [ps]</td>
</tr>
<tr>
<td>80 [ps]</td>
<td>41.4 [ps]</td>
</tr>
<tr>
<td>100 [ps]</td>
<td>44.0 [ps]</td>
</tr>
</tbody>
</table>

Vertical time offset can cause non-negligible pTC performance degradation
Correction

- Vertical position dependence can be corrected from observed position dependence
- Offline time correction can suppress deterioration of pTC performance due to vertical time offset
- Correction becomes more effective when radiation damage to SiPMs accumulate

\[
\begin{align*}
\text{Event time resolution} & \\
\text{with correction} & \sim 41.4 \text{ [ps]} \\
\text{without correction} & \sim 48.6 \text{ [ps]}
\end{align*}
\]

\[
\begin{align*}
\text{80 [ps] (MC)} \\
\text{160 [ps] (MC)}
\end{align*}
\]
pTC performance evaluation

- **Even-odd analysis**
  - Difficulty of pTC performance evaluation: no reference timing
    → Use odd-hits as timing reference of even-hits
  - Effect of vertical time offset cancels out in even-odd analysis

\[
t_{\text{even-odd}}(N_{\text{hit}}) = \frac{1}{N_{\text{hit}}} \sum_{i=1}^{N_{\text{pair}}} (t_{\text{hit}}(2i) - t_{\text{hit}}(2i-1) - ToF_{2i-1\rightarrow2i})
\]

- pTC resolution using even-odd analysis
- Number of hits distribution
- 80 [ps] (Even-odd)
Application on data

**Correction**

- Not as effective as MC
  - Even-odd analysis is used
    - Effect of vertical time offset is canceled out
  - pTC tracking is used
    - Worse position resolution than CDCH tracking
- Correction should improve when we have full CDCH readout

![Event time resolution](image)

- pTC resolution using even-odd analysis on 2017 data
  - w/o correction: \( \sim 38.6 \text{ [ps]} \)
  - w/ correction: \( \sim 38.2 \text{ [ps]} \)
MEG II実験における陽電子の時間再構成法の改善

Outline

- Introduction of MEG II
  - MEG II experiment
  - pTC design
  - pTC performance

- Lab test
  - Measurement setup
  - Pulse height behavior
  - Time center behavior

- Introduction of this study
  - Aim & motivation
  - Overview

- Effect on MEG II
  - MC study
  - Correction using data

- Summary & prospect
Summary & prospect

Summary

- Position dependence of reconstructed hit time for MEG II pTC was found
- Radiation damage to SiPMs can cause additional effect on position-dependent time offset
- MC simulation study suggests this offset could cause non-negligible pTC performance deterioration
- Offline correction seems effective to some extent

Prospect for MEG II pTC

- Correction to compensate time offset effect will be performed in MEG II pTC
- Divide pTC in several sectors according to radiation damage level & monitor time offset
- Update correction values periodically
Backup slides
cLFV (charged Lepton Flavor Violation)

- **Quark mixing**
  - Included in SM
  - Explained by CKM theory

- **Neutrino oscillation**
  - Discovered in Super-Kamiokande
  - Forbidden in SM
  - Firm proof of bSM physics
  → Suggests possibility of flavor violation in charged lepton sector

**Charged lepton flavor violation (cLFV)**
- Forbidden in SM
- Included in many new physics models
- If discovered, certain proof of new physics
- Has been searched in many experiments
**μ → eγ reaction**

**Motivation**
- Considering neutrino oscillation, possible but very rare
- Included in many new physics models at observable rate
- Can search for new physics w/o directly creating new heavy particles

\[ Br(\mu \rightarrow e\gamma) \sim 10^{-54} \] (little background)

\[ Br(\mu \rightarrow e\gamma) \sim 10^{-15} - 10^{-11} \]

**Status of cLFV search**
- Current upper limit is obtained by MEG
  - \( Br(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13} \) (90% C.L.)
  - MEG II aims for one order higher sensitivity
  - \( \sim 6.0 \times 10^{-14} \)

---

SM + neutrino oscillation

SUSY model

SUSY see-saw

SUSY GUT
Signal & background events

Signal

- $e^+$
- $\gamma$
- $\mu^+$
- $52.8 MeV$
- 180°
- back to back

Physics background

- $e^+$
- $\gamma$
- $\nu_\mu$
- $\mu^+$
- $52.8 MeV$
- simultaneous
- RMD (radiative muon decay)

Accidental background

- $e^+$
- $\gamma$
- $\nu_\mu$
- $\mu^+$
- $\nu_e$
- Michel decay
- accidental $\gamma$
MEG II実験における陽電子の時間再構成法の改善

Detectors

SiPM
LXe calorimeter
pTC
RDC
plastic scintillator
LYSO crystal

PMT

photon
positron
Positron spectrometer

- **COBRA (COnstant Bendint RAdius)**
  - Bends positrons at a constant radius independent of emission angles
    → Signal positrons enter pTC region
  - Gradient field to sweep positrons away from detector region
    → Reduce pile-up

- **CDCH (Cylindrical Drift CHamber)**
  - Reconstructs positron track

- **pTC (pixelated Timing Counter)**
  - Reconstructs positron time
### Idea
- Horizontal position can be reconstructed from the time difference of two channels
- Radial coordinate can be reconstructed from hit pattern information

\[
 w_{hit} = v_{eff} \times \frac{t_2 - t_1}{2}
\]
Intra-pixel position correction

- **Positron tracking**
  - Combine discontinuous hit information into single positron track
  - *Kalman Filter* technique is used to extrapolate track and include following hits
  - Segments are fitted with *GENFIT*
  - Two types of tracking (pTC tracking & CDCH tracking) exists
    - CDCH tracking is used for MC study
    - pTC tracking is used for data analysis (due to limited CDCH readout electronics)

**Kalman Filter**
Efficient recursive algorithm to estimate the state vector & its covariance matrix based on previous steps

**GENFIT**
Generic toolkit for track reconstruction for experiments in particle & nuclear physics
**CF scan**

**Pattern A**
- Time center behavior for normal order changes drastically with CF value
  - Longer path components become dominant at higher CF values
- Time center behavior for reverse order is almost same at all CF values
  - Short path component is dominant

---

![Graphs showing time center behavior for different CF values](image-url)
CF scan

Pattern B

- Time center difference for both normal & reverse order changes with CF value
  → Dominant contribution changes from short-path to long-path component with higher CF value (2 non-damaged SiPMs are enough to form pulse rise for CF 20% case but not for CF > 50%)
Pattern C

- Time center difference for both normal & reverse order changes moderately with CF value
- Dominant contribution changes from short-path to long-path component with higher CF value
- CF dependence is relatively small because overvoltage shift is small for pattern C (clear from pulse height behavior)
v resolution

pTC tracking

CDCH tracking
w resolution

- pTC tracking
- CDCH tracking

![Graph of w resolution vs. Hit index for 4cm counters and 5cm counters.](image1)

![Graph of w resolution vs. Hit index for 4cm counters and 5cm counters.](image2)