MEG II実験陽電子タイミングカウンターの
長期運用へ向けた運用・解析パラメータの最適化

-Optimization of the Operation & Analysis Parameters of the MEG II Pixelated Timing Counter for Long-term Operation-

東京大学理学系研究科物理学専攻

野内 康介、他MEG IIコラボレーション
Outline

➢ Introduction
  • $\mu \rightarrow e\gamma$ search
  • MEG II experiment
  • Positron spectrometer
  • pTC design
  • pTC performance
  • pTC status

➢ Bias voltage optimization
  • Upgrade concept
  • New optimization scheme
  • Lab test
  • Application to pTC data

➢ Constant fraction optimization
  • Upgrade concept
  • New optimization scheme
  • Lab test
  • Application to pTC data

➢ Summary & prospect
  • Summary & prospect
**Physics motivation**
- Lepton flavor violation (LFV) is strictly forbidden in standard model (SM)
- Neutrino oscillation
  - LFV in neutral lepton sector
  - Possibility of charged LFV (cLFV)
- SM + neutrino oscillation
  - $Br(\mu \rightarrow e\gamma) \sim \mathcal{O}(10^{-54}) \Rightarrow \text{clean channel}$
  - Predicted in many new physics models
    - $Br(\mu \rightarrow e\gamma) \sim \mathcal{O}(10^{-15} - 10^{-11})$

**Status of $\mu \rightarrow e\gamma$ search**
- Upper limit obtained by MEG experiment
  - $Br(\mu \rightarrow e\gamma) \sim 4.2 \times 10^{-13}$ (90 % C.L.)
- MEG II aims for one order higher sensitivity
  - $Br(\mu \rightarrow e\gamma) \sim 6 \times 10^{-14}$

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**Introduction**
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MEG II experiment

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Use most intense DC $\mu^+$ beam at PSI
**Positron spectrometer**

- **Constant bending radius (COBRA) magnet**
  - Superconducting solenoid with gradient magnetic field
  - Bends signal positrons with constant radius independent of emission angle
  - Sweeps positrons away from central region

- **Cylindrical drift chamber (CDCH)**
  - Single-volume, full-stereo, wire chamber
  - Reconstructs positron track (i.e. $E_{e^+}$, $\theta_{e^+}$)

- **Pixelated timing counter (pTC)**
  - Plastic scintillator + SiPM readout
  - Reconstructs positron time (i.e. $t_{e^+}$)

**Theme of this talk**

- Introduction
  - $\mu \rightarrow e\gamma$ search
  - MEG II experiment
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  - pTC design
  - pTC performance
  - pTC status
pTC design

- Overall design
  512 pixels laid cylindrically upstream & downstream of target

- Single-pixel design
  - 40/50 mm×120 mm×5 mm plastic scintillator + 6 series-connected SiPMs × 2
  - Laser light can be inserted from fiber below

Positron event display
pTC performance

- **Multiple pixel hit scheme**
  - Average number of pixel hits: \(~9\)
  - Single-pixel resolution: \(~80-100\) ps
  - Overall resolution improves with \(1/N_{\text{hit}} \rightarrow \sim 38\) ps

\[
\sigma_{\text{e}^+} (N_{\text{hit}}) = \frac{\text{single hit}}{N_{\text{hit}}}
\]

- **pTC time resolution**

- **Number of pTC hits distribution**

- **Event time resolution**

\[
\text{Mean} = 9.082
\]

\(~38\) ps
Optimization of Operation & Analysis Parameters of MEG II pTC

pTC status

➢ General status
  • pTC has already been operated in past 5 years

➢ What is already achieved
  • Detector construction
  • Basic operation methods
    • Insertion & extraction, cooling system, ...
  • Calibration methods
    • Energy deposit, position, time, ...
  • Analysis
    • Waveform analysis, hit reconstruction, clustering, tracking
  • Performance evaluation

➢ Tasks for pTC
  • Detailed study on effect of radiation damage to SiPMs revealed that pTC resolution can degrade by ~20% in 3 years’ data taking (c.f. backup slide)
  • pTC must be operated at high performance in long term

➢ Motivation of this study
  • Develop methods to bring out maximum performance of pTC in long term
    • Optimize bias voltage to SiPMs
    • Optimize constant fraction (CF) parameter in waveform analysis
Optimization of Operation & Analysis Parameters of MEG II pTC

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  - Lab test
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- **Summary & prospect**
  - Summary & prospect
Upgrade concept

Conventional optimization scheme

1. Perform overvoltage scan w/ laser system (c.f. backup slide)
2. Choose overvoltage (common to all channels) which yields best time resolution

What is known so far

- Time resolution depends strongly on signal-to-noise ratio ($S/N$)
- Radiation damage to SiPMs can moderately increase dark noise
- Dose level depends on global pixel position

Possible improvements for long-term operation

- Channel-by-channel optimization (Dark noise increase rate differs from channel to channel)
- Online optimization using observed $S/N$ (Conventional scheme requires dedicated DAQ)
Optimization of Operation & Analysis Parameters of MEG II pTC

New optimization scheme

➢ General idea
  • Best time resolution should be achieved when $S/N$ is maximized
  • If we can estimate overvoltage dependence of $S$ & $N$ at each time (radiation damage) point, optimal overvoltage can be calculated mathematically
    • This should be possible if $S$ & $N$ are simple functions of overvoltage
Optimization of Operation & Analysis Parameters of MEG II pTC

Lab test

Measurement

- To see effect of radiation damage, SiPMs were irradiated with $^{90}$Sr source in 4 steps
- Bias voltage scan was performed at each damage step

Time resolution & $S/N$

- Time resolution has linear correlation with $N/S$ (inverse of $S/N$)
- Find overvoltage to maximize $S/N$

<table>
<thead>
<tr>
<th>Damage step</th>
<th>Irradiation time</th>
<th>Dose level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0 hours</td>
<td>$0 , n_1 \text{MeV/cm}^2$</td>
</tr>
<tr>
<td>1</td>
<td>70 hours</td>
<td>$7.5 \times 10^8 , n_1 \text{MeV/cm}^2$</td>
</tr>
<tr>
<td>2</td>
<td>140 hours</td>
<td>$1.5 \times 10^9 , n_1 \text{MeV/cm}^2$</td>
</tr>
<tr>
<td>3</td>
<td>210 hours</td>
<td>$2.25 \times 10^9 , n_1 \text{MeV/cm}^2$</td>
</tr>
<tr>
<td>4</td>
<td>280 hours</td>
<td>$3 \times 10^9 , n_1 \text{MeV/cm}^2$</td>
</tr>
</tbody>
</table>
Lab test

- **S dependence**
  - S clearly has linear relation w/ overvoltage
  - Radiation damage does not affect S

- **N dependence**
  - Overvoltage dependence of $N = \sqrt{N_{\text{SiPM}}^2 + N_{\text{elec}}^2}$ can be described well by assuming
    - $N_{\text{SiPM}} = C(V - V_{\text{breakdown}})^3$
    - $N_{\text{elec}} = \text{constant}.$
  - All curves can be fitted solely by changing C

![Pulse height v.s. bias voltage graph](image1)

![Noise RMS v.s. bias voltage graph](image2)
Optimization of Operation & Analysis Parameters of MEG II pTC

Application to pTC data

- **pTC laser data**
  - Linearity of $S$ was verified
  - Overvoltage dependence of $N$ can also be fitted well w/ assumed function

- **Application to beam data**
  1. Obtain $V_{\text{breakdown}}$ from I-V data
  2. Obtain overvoltage dependence of $S$ & $N$ from laser bias voltage scan
  3. Convert overvoltage dependence of $S$ for beam data
  4. Calculate optimal overvoltage

- **Verification of new scheme**
  - We did not have time for beam data
  - Effect of this scheme has not been verified
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Upgrade concept

- **pTC analysis**
  - Constant fraction (CF) method is used to obtain signal time in waveform analysis

- **What is known so far**
  - Optimal CF value strongly depends on noise level
  - Radiation damage to SiPMs can moderately increase dark noise
  - Dose level depends on global pixel position

- **Possible improvements for long-term operation**
  - Channel-by-channel optimization
    (Dark noise increase rate differs from channel to channel)

**Conventional optimization scheme**

1. Perform **CF scan using beam data**
2. Choose **CF value (common to all channels)** which yields **best time resolution**
Optimization of Operation & Analysis Parameters of MEG II pTC

New optimization scheme

- **General idea**
  - Optimal CF should be determined by balance between fluctuation of leading edge & peak time (i.e. $S/N$)
    - Low noise = small baseline fluctuation = small leading edge fluctuation = lower CF preferred
    - High noise = large baseline fluctuation = large leading edge fluctuation = higher CF preferred
  - $S/N$ may be used to determine optimal CF

Low noise case

High noise case
Optimization of Operation & Analysis Parameters of MEG II pTC

Lab test

- **Measurement**
  - To see effect of radiation damage, SiPMs were irradiated with $^{90}$Sr source in 4 steps
  - Bias voltage scan was performed at each damage step

- **Analysis**
  - CF scan was performed in steps of 0.05 from 0.1 to 0.6 for each dataset
  → Optimal CF value (i.e. w/ best time resolution) was obtained for each dataset

- **Optimal CF & $S/N$**
  - Optimal CF has linear correlation w/ $N/S$ (inverse of $S/N$)
  → Optimal CF can be determined simply from observed $S/N$
Application to pTC data

- **pTC laser data**
  - Linear correlation between optimal CF & \( N/S \) was verified for all channels
  - Channel individuality seems pretty large
    \( \rightarrow \) Channel-by-channel optimization should be effective

- **Application to beam data**
  1. Obtain relation between optimal CF v.s. \( N/S \)
  2. Obtain \( N/S \) in beam data
  3. Calculated optimal CF from 1. & 2.

- Optimal CF has wide distribution
Application to pTC data

- **Verification of new scheme**
  - Each pixel time resolution was evaluated (w/ 2-hit analysis) using beam data
  - Pixel time resolution improved for all channels & by ~3 % on average

![Graph showing the effect of new optimization scheme](image-url)
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Summary & prospect
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Summary & prospect

Summary

- MEG II pTC measures positron time with ~38 ps resolution
- Considering the effect of radiation damage to SiPMs, **effective optimization of operation & analysis parameters is needed** to bring out maximum performance of pTC in long term
- A new optimization scheme of bias voltage was developed, which allows **online, channel-by-channel optimization** without dedicated DAQ
- A new optimization scheme of CF was developed, which allows **channel-by-channel optimization**
  → This **improved pTC resolution by ~3 %**, even without radiation damage

Prospect

- Attempt new bias voltage optimization
- **Evaluate its effect on pTC resolution** using beam data
Backup Slides
Signal & background

- **Signal**
  - \( E_{e^+} = E_\gamma = \frac{m_\mu}{2} \approx 52.8 \text{ MeV} \)
  - \( t_{e^+\gamma} = 0 \)
  - \( \theta_{e^+\gamma} = 180^\circ \)

- **Background**
  - **Physics background**
    - Radiative muon decay (RMD)
    - \( E_{\nu_e} \approx 0, E_{\nu_\mu} \approx 0 \)
    - \( \theta_{e^+\gamma} \approx 180^\circ \)
  - **Accidental background**
    - Michel \( e^+ \)
    - RMD or AIF \( \gamma \)
pTC analysis

- **Waveform analysis**
  - Obtain signal time in each channel using CF method

- **Hit reconstruction**
  - Obtain each pixel hit time, x hit position & energy deposit
    - $t_{hit} = \frac{t_{ch1} + t_{ch2}}{2} - \frac{L}{2v_{eff}} - t_{offset}$
    - $x_{hit} = \frac{t_{ch1} - t_{ch2} + \delta t}{2} v_{eff}$
    - $E_{dep} = C_E \sqrt{Q_{ch1} \cdot Q_{ch2}}$

- **Clustering**
  - Group hits from the same positron track

- **Tracking (pTC tracking)**
  - Reconstruct positron track from pTC pixel hits

Channel 1: $t_{ch1}$ [s]  
Channel 2: $t_{ch2}$ [s]  
Hit point: $(t_{hit}, x_{hit}, y_{hit})$
SiPMs in pTC

- **Connection of SiPMs**
  - Parallel connection → large capacitance → blunt waveform → bad time resolution
  - Series connection → small capacitance → sharp waveform → good time resolution
Laser system

- **System**
  - Laser light is divided using optical splitters and can be injected into $432/512$ pixels.
  - Can be used for various DAQ w/o beam.

- **Time calibration**
  - Laser light can be injected into multiple pixels simultaneously.
  - Optical length of laser components are measured beforehand.
  - Time calibration between pixels can be performed.

*432 out of 512 counters have laser light.*
Radiation damage to SiPMs

**Damage type**
- **Bulk damage** can be induced by collision of energetic particles
- Result in **increase of bulk leakage current**
- Dominant damage in MEG II pTC (surface damage is negligible)

**Damage level**
- $\sim 1 \times 10^{11} \text{e}^+/\text{cm}^2$ exposure of $\sim 50 \text{MeV}$ positrons in 3 years
- Absorbed dose: $\sim 25 \text{ Gy}$
- Current increase: from $\mathcal{O}(1) \mu\text{A}$ to $\sim 100 \mu\text{A}$
- Equivalent to $\sim 5 \times 10^9 n_1 \text{MeV}/\text{cm}^2$

**Position dependence of dose level**
- Damage level is different within series-connected SiPMs
- Damage level depends on global pixel position
Effect of radiation damage to SiPMs

- Dark noise increase
  - Radiation damage to SiPMs is known to increase dark noise of SiPMs
  - Time resolution is dependent on S/N
  - Single-pixel resolution can worsen by ~30% at 30 °C
  - pTC is planned to be operated at 10 °C, and resolution deterioration is expected to be suppressed to ~5%

- Hit position dependent time fluctuation
  - Vertical hit position dependence of time center exists due to finite signal propagation time
  - This can be enhanced by a gradient radiation damage to SiPMs, as in MEG II pTC
  → Resolution deterioration is estimated to be ~15% in 3 years