MEG II 実験における陽電子タイミングカウンターの3次元アラインメント

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What is MEG II?

Upgrade of MEG experiment

• The search for $\mu^+ \rightarrow e^+ + \gamma$
  $\mu^+$: most intense beam at PSI
  $\gamma$: detected by LXe
  $e^+$: detected by pTC & CDCH

• expected sensitivity: $6 \times 10^{-14}$
  (higher than ever before searches)

What is MEG II?

- $\mu^+ \rightarrow e^+ + \gamma$ is a rare muon decay which is a charged lepton flavor violation process prohibited in the Standard Model.

\[ \mathcal{B}(\mu^+ \rightarrow e^+ + \gamma) \sim 10^{-54} \] prohibited (unobservable)

- Assuming supersymmetric particles, the decay can be observable.

\[ \mathcal{B}(\mu^+ \rightarrow e^+ + \gamma) \sim 10^{-12} - 10^{-14} \] permitted (observable)
Positron timing counter (pTC)

- a highly segmented (256 tiles × 2) scintillation counter, consists of two semi-cylindrical super-modules mirror symmetric to each other
- expected time resolution is 38 ps
pTC - Pixel counters

- 120mm × 40mm (50mm) × 5mm plastic scintillator (BC422)
- Read by 6 SiPMs on each PCB attached to both side of the scintillator
- Two types (40mm, 50mm) for positrons moving spirally with various radii.
3D alignment - Necessity

• Real value of 3D positions and direction are **critical** to
  • detection efficiency
  • Time-of-Flight among hit pixels for positrons bent by COBRA magnet.
3D alignment - Goal

- Random uncertainty added up every pixel hit and a systematically bias

$$\sigma_{\text{alignment}} = \sigma_{\text{random}} \times \frac{1}{\sqrt{N_{\text{hit}}}} \times N_{\text{hit}} + \sigma_{\text{bias}} \leq 17 \text{ ps (Goal)}$$

(Nhit : number of hitted pixels ~ 9 )

$$\sigma_{\text{random}} \leq (\delta x_{\text{random}} + 60mm \times \sin \delta \theta_{\text{random}})/c$$
$$\sigma_{\text{bias}} \leq (\delta x_{\text{bias}} + 60mm \times \sin \delta \theta_{\text{bias}} )/c$$

( devided by c for positrons moving at light speed)

Propagation of 17 ps error makes pTC time resolution 38ps $\rightarrow$ 42ps added in 4 ps $\sim$10%.
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3D Scan - Scanner

3D Scanner (FARO Edge ScanArm HD)

- Accuracy ± 25μm
- Scan rate: 560,000 points/sec
- Cited from https://www.faro.com/resource/faro-edge-scanarm-hd/
3D Scan - Data

- Scan data are available as an array of (x,y,z) points
- Data is lacking because the light of 3D scanner could not reach
- Only outer 48 counters in upstream are used in this talk
  Their lack of data are less than others.
3D Scan – Fitting

• Each counter position and direction can be described by 6 parameters.
  • center position (x,y,z)
  • rotation angle about each axis (θx,θy,θz)
are adopted here.

• Find a set of 6 parameters which minimize sum of distance between data points and model function.
Analysis

• The coordinate system of scan data is different from that of CAD.

• Only relative values can be compared.

• Each 16 counters on the same backplane are designed to line up at regular intervals and in the same direction.
Analysis

- $d_{cv}$ [mm] : $15 \times 3$ intervals of center position b/w neighborhood
- $\arccos(n \cdot n_0)$ [degree] : $15 \times 3$ angles formed by normal vectors
Analysis

Fitting Results (3D scan + Fit)  CAD data (Design value)

• Fitting error
• 3D scan error
• Deviation from design value

misalignment
Analysis - intervals (\(d_{cv} [\text{mm}] : 15 \times 3\) intervals of center position b/w neighborhood)

<table>
<thead>
<tr>
<th>Intervals [mm] (Fitting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>i1 Entries: 45</td>
</tr>
<tr>
<td>Mean: 55.11</td>
</tr>
<tr>
<td>Std Dev: 1.069</td>
</tr>
</tbody>
</table>

Mean ~ 0.1mm
Standard deviation ~ 1.1mm

\[ dcv - dcv_{CAD} \]
Analysis - angles (Arccos(n•n₀) [degree] : 15 × 3 angles formed by normal vectors)

Mean ~ 0.7°
Standard deviation ~ 0.5°
Discussion

Assuming random error = std dev & alignment bias = mean value

- $\delta x_{\text{random}} = 1.1 \text{ mm}, \delta \theta_{\text{random}} = 0.5^\circ \rightarrow \sigma_{\text{random}} \leq (1.1 + 60 \times \sin 0.5^\circ)/c \approx 5.4 \text{ ps}$
- $\delta x_{\text{bias}} = 0.1 \text{ mm}, \delta \theta_{\text{bias}} = 0.7^\circ \rightarrow \sigma_{\text{bias}} \leq (0.1 + 60 \times \sin 0.7^\circ)/c \approx 2.7 \text{ ps}$

the maximum deviation b/w alignment and real position is

$\sigma_{\text{alignment}} \leq \sigma_{\text{random}} \times 3 + \sigma_{\text{bias}} \approx 19 \text{ ps}$

Propagation of 19 ps error makes time resolution of pTC 38ps $\oplus$ 19ps $\sim$ 42.5ps.
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Summary

• pTC, a highly segmented detector with complicated 3D structure, should be confirmed with each pixel position and direction.

• Preliminary alignment method with 3D scan data showed the error is at most 19 ps which influences the pTC time resolution 38ps by 4.5ps ~ 12%.

• The upper limit 19 ps is slightly over the alignment goal 17 ps, but deterioration of time resolution is ~12%, that is good enough.
Prospects

• Invisible biases of absolute positions & directions, will be eliminated by matching coordinate systems of 3D scan data & design value with reference points from laser tracker.

• An efficient alignment method for inner pixels is developed.

• To complete alignment for all 512 pixels.
Back up
\[ \mu^+ \rightarrow e^+ + \gamma \]

- \((m_\mu, \vec{0}) \rightarrow (p, \vec{p}) + (\sqrt{p^2 + m_e^2}, -\vec{p})\)

\[
\therefore p = \frac{m_\mu^2 - m_e^2}{2m_\mu} \approx 52.8 \text{ MeV/c}
\]

- \(p = \gamma m_e \beta = m_e \sqrt{\gamma^2 - 1} \rightarrow \gamma \approx 10.2 \quad \beta \approx 0.9952\)
3D Fit - Initial value

• To find initial values, data points are manually moved and rotated data before fitting. (they will be replaced by design values)
3D Fit - Data selection

• At least, 3 planes are needed
Data Selection

• A Top plane (5mm*120mm) & a small side plane (5mm*40mm)
• The most depressed points from a large side plane (40mm*120mm)

Green = Data used for fit  Magenta = Model function (3 planes of rectangular)
Inner radius of aluminum frame is smaller than large |z| for docking to COBRA
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Backplane Holes Scan Data

- Hole scan mode of 3D scanner was used
- These are used for intervals b/w counters
Analysis

Fitting Results (3D scan + Fit)

• Fitting error
• Deviation b/w counter & hole

Hole scan data (3D scan)

• 3D scan error
• Deviation from design value of hole

CAD data (Design value)

• Fitting error
• 3D scan error
• Deviation from design value

misalignment
Analysis - intervals

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Analysis - intervals

The bias ~ 0.1 mm
Standard deviation ~ 1.1 mm

$sd_{fit\text{-}Hole} \sim 1.075 \text{ mm}$

$sd_{fit\text{-}CAD} \sim 1.077 \text{ mm}$

$sd_{Hole\text{-}CAD} \sim 0.1102 \text{ mm}$

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Analysis – edge intervals

Distances b/w top side of counters on each end are sharply (sd ~ 0.46mm) distributed but biased from CAD.

The bias (~2mm) contains
- Misalignment
- Deviation from design value

(16 intervals of top side of counters on each end of semi-cylinder)