Development and application of track reconstruction method with MEG II positron timing counter

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MEG II Experiment

- The most sensitive $\mu \to e\gamma$ search with the most intense muon beam
- Upgraded experiment from MEG: Positron spectrometer is newly constructed to achieve $\times \sim 2$ better detector resolution and reconstruction efficiency under $\times \sim 2$ higher beam intensity ($7 \times 10^7 \mu^+/s$)
**μ → eγ Decay**

- **μ → eγ**: charged Lepton Flavor Violation (cLFV)
  - Prohibited in the standard model
  - Predicted in the beyond standard model within experimental reach
  - To discover μ → eγ means to discover the new physics!!

- Signal kinematics of **e and γ**:
  - Timing, position, and momentum is the key
  - High reconstruction efficiency under the intense μ beam is needed

\[ \begin{align*}
\gamma & \quad \mu \\
52.8 \text{ MeV} & \quad \text{52.8 MeV} \\
\text{180° (back to back) at the same timing from the same position} &
\end{align*} \]
• Positron Spectrometer:
  • Pixelated timing counter (pTC): measure a positron crossing timing
  • Cylindrical drift chamber (CDCH): detect a positron track as continuous hits
  • Gradient magnetic field: bend the flight path of positron

• Commissioning with full positron detectors, but partial readout in 2019.
Pixelated Timing Counter (pTC)

- Positron timing is determined by pixelated Timing Counter (pTC)
  - 512 scintillation counter with 6 series connected SiPMs
  - 1 positron crosses multiple counters
  - pTC achieves ~ 35 ps with 8 hits (average # of hits)

\( \sigma(t) \sim 80 \text{ ps at each single counter} \)
Cylindrical Drift Chamber (CDCH)

- Ultra-low mass (90% helium based gas mixture + 10% isobutene) cylindrical drift chamber with stereo wires
- 192 drift cell (~7mm × 7mm) per layer (9 layers)
  - 1.7—0.8 MHz/cell
  - \( <\text{Nhit}> \approx 650 \) in event in 250 ns
- Tracking done based on Kalman Filter technique (with GENFIT)
  - Track seeds are made with outer layer hits

**Image Caption:**
Yellow and purple shows different stereo signal event.
MEG II Positron Analysis Status

<table>
<thead>
<tr>
<th>Positron Resolution</th>
<th>MEG</th>
<th>Design (10 layer)</th>
<th>Updated (9 layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theta (mrad)</td>
<td>9.4</td>
<td>5.3</td>
<td>5.9</td>
</tr>
<tr>
<td>Phi (mrad)</td>
<td>8.7</td>
<td>3.7</td>
<td>5.3 ※A</td>
</tr>
<tr>
<td>Momentum (keV)</td>
<td>380</td>
<td>130</td>
<td>83</td>
</tr>
<tr>
<td>Vertex Z (mm)</td>
<td>2.4</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Vertex Y (mm)</td>
<td>1.2</td>
<td>0.7</td>
<td>0.72</td>
</tr>
<tr>
<td>Positron time (ps)</td>
<td>108</td>
<td>46</td>
<td>49 ※B</td>
</tr>
</tbody>
</table>

※A. Correction based on theta and phi correlation is not applied, though expected value include it.
※B. 1 year radiation damage effect is roughly simulated, w/o cooling condition. \( \sigma_r^{(\text{true})} \sim 10 \text{ ps} \), \( \sigma_{r_{\text{z,0ps}}} \sim 25 \text{ ps} \) is added.

- **Signal only case**
  - Efficiency: \( 80 \pm 1 \% \)
  - 9 layer configuration

- **Signal + BG**
  - Efficiency: \( 60 \pm 1 \% \)
  - 9 layer configuration

• **MC**: We have not yet achieved the target efficiency (70%)
  - Current algorithm is not enough to achieve the target sensitivity
  - Tracking quality is not enough -> becomes inefficiency events (tail)

• **Data**: We do not have enough data to estimate the track quality
  - Limited readout is now available, CDCH tracking is difficult this year

• Analysis breakthrough is now needed to take a step !!!
pTC Self-Tracking

• We have developed new tracking idea: pTC self-tracking
  • Track reconstruction with pTC hits, without CDCH information

• With this algorithm,
  • Improve the positron reconstruction quality and efficiency
    • pTC track gives CDCH for the initial position, momentum, time etc ...
    • Those additional information will help to improve tracking (LR ambiguity, 1st turn & 2nd turn combine, z determination etc ...)

• Detector response study with the commissioning data in 2019
  • We want to reconstruct "track" even with the strictly limited readout
  • This partial track can pick up CDCH hits and combine those as track
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Positron Tracking in pTC

- **Track reconstruction:** estimate the positron's momentum, path-length, and position etc from detector's hits

- We have to estimate the momentum and $y$-position information to make a good track
  - Initial momentum is around the signal value: $\sim 45 \pm 8$ MeV
  - This is determined by our gradient magnetic field's characteristics

- $\sigma (z) \sim 0.25$ cm
- $\sigma (x) \sim 1.1$ cm
- $\sigma (y) \sim ???$

- $x$ from arrival time difference ($\sigma \sim 1.1$ cm)
- $z$ from counter position ($\sigma \sim 0.25$ cm)
- $\times$ $y$ information
- $\times$ momentum information
Parameter Estimation

- y-position from the segmented design of pTC
  - We list up all possible patterns of cluster hits pattern
  - 8 mm resolution on y direction

![Diagram of counter under test](chart)

- Forward counters
- Backward counters

hit pattern: 0000110000

V_hit vs. Nth hit

Entries: 9288
Mean x: 4.866
Mean y: 0.05581
Std Dev x: 3.201
Std Dev y: 0.799

~ 8 mm resolution at each # of hits

No bias for mean value
Track Reconstruction

• Track reconstruction with Kalman Filter technique
  • We use GENFIT package for calculation
  • Outlier can be rejected by using DAF option (extension of kalman filter)

**Kalman Filter**
Efficient recursive algorithm to estimate the state vector and its covariance matrix based on previous states.

**GENFIT**
A generic toolkit for track reconstruction for experiments in particle and nuclear physics.

About GENFIT: http://genfit.sourceforge.net/Main.html
Track Reconstruction (MC)

Blue plane: Detector plane
Blue projection: Forward propagation
Purple projection: Backward propagation
Red projection: Smoothed track

Red: estimated R
Blue: Truth track

Expected Performance (MC)
Efficiency: 90%
R position resolution on each counter: ~5mm
Momentum resolution: 5 MeV
Angle resolution: 100 mrad
TOF b/w adjacent counters: 5 ps
pTC-CDCH Combined Tracking (MC)

- pTC self track gives CDCH for the initial position, momentum, time etc...
  - Current CDCH seeding starts from 2 x 2 hits in 2 layer
  - Especially direction information (momentum) is the key for improvement
- Improve the positron tracking quality by combining two detectors

Work in Progress
pTC-CDCH Combined Tracking (MC)
Intermediate Summary

We established pTC-self tacking algorithm

• This algorithm can give additional information for CDCH tracking
  • Initial momentum (direction), position, timing etc...
  • Momentum (direction), z information is the key to improvement
• CDCH detector study in 2019 commissioning with limited channel

• Application:
  • Track based calibration / performance study in the pTC
  • Resolution improvement study / Outlier rejection with DAF
  • CDCH detector response study in 2019 commissioning with limited channel
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Application for pTC analysis
Application for pTC analysis

Check the all geometrically same combinations

(Notice that counters are used twice or more.)

• Until 2017, we used fixed counter combination to evaluate the pTC’s timing resolution
• With this track, we can use any combination with TOF correction

With any combination

Even-Odd Analysis: $\frac{1}{N} \left( \sum_{i=1}^{N} (T_{2i} - TOF_{2i}) - \sum_{i=1}^{N} (T_{2i+1} - TOF_{2i+1}) \right)$
Application for pTC analysis

Full System of Positron Timing Counter Having Time Resolution under 40 psec with Fast Plastic Scintillator Readout by SiPMs

https://indico.cern.ch/event/716539/contributions/3245920/

Reported by M.Nishimura @ VCI 2019

Pilot Run

Expectation from Pretest with $^{90}\text{Sr}$

2017, fixed combination

2018, any combination
Track Based Calibration

- Calibration with michel positron track by minimizing the chi2
  - Important point is TOF (path length) calculation b/w counters
  - Until 2017, we used the flight pattern classification

Calculation with Millepede II
A software provided by DESY to solve the linear squares problems, such as detector alignment and calibration based on track fits. (www.desy.de/~kleinwrt/MP)
Track Based Calibration (MC)

σ~19.6 ps with 3 tof patterns

σ~13.5 ps with self track
Outlier Rejection

- Sometimes outlier hits in a cluster make a tail event (timing tail or position tail in tracking) and may cause inefficiency
- DAF computes the "weight" in each detector layer, and rejects the outliers
  - Based on "position" (calculated by GENFIT) and "timing" (Added manually)
  - Slight improvement with 2018 commissioning data (36.7 ps -> 36.1 ps on average)

The signal positron does not pass through this counter, but a "hit" is reconstructed (secondary particle entered) -> Strange hits are rejected by the position DAF weight (threshold: 0.5)
Summary

• Positron reconstruction algorithm for MEG II experiment has been developed. And new idea with pTC self-tracking is implemented
  • High efficiency (90%), relatively good resolution on position (~5 mm), and momentum (~ 5 MeV)

• Combined algorithm with pTC self-track reconstruction and CDCH track reconstruction started to be developed
  • To achieve the target efficiency (70%) and target resolution of positron reconstruction
  • Application to 2019 commissioning to try the CDCH detector response study (e.g. hit reconstruction efficiency, z resolution)
Back up
MEG II Positron Analysis Framework

- What we want: **positron timing, momentum, position**
- Analysis framework with pTC and CDCH has been developed

**pTC**
- Waveform Analysis Hit rec.
- pTC counter clustering
- pTC inside tracking
- initial timing

**CDCH**
- Waveform Analysis Hit rec.
- CDCH track finding
- CDCH track fitting (extrapolation)
- initial momentum, position reconstruction

**TOF correction**
- Timing reconstruction
- Extrapolation
- initial momentum
- initial position from CDCH was needed
Outlier Rejection

- DAF computes the "weight" in each detector layer, and rejects the outliers
  - Based on "position" (calculated by GENFIT) and "timing" (Added manually)

This counter has very large waveform (~900mV) compared to normal counters (~200-400mV)
-> Strange reconstruction, rejected in pTC tracking
pTC Tracking with CDCH

- Eff.: 97%
- Resolution
Grouping of r-estimation

※old grouping
TOFの確認

- TOFの精度は全部合わせてstv ≈ 17.6 ps
  - Independent Trackingとさほど変わらない(若干悪い？)
  - gaussianの幅は明らかに細い一方で、外れ値が増加している。
  - 若干ではあるが、Rを小さく見積もりがちな傾向。

### Independent

### with CDCH
TOF の確認

Quality cut

Mom + Quality cut
60%の統計減少
Event Selection

SPX Tracking

Independent Tracking

40 MeV<mom<55 MeV
明らかにtail eventの減少

40 MeV<mom<55 MeV
Propagation to cyl

10%程度の統計減少
改善は小さい