MEG II実験のためのSiPMを用いた
陽電子タイミングカウンターのシミュレーションによる性能評価

Development of the Waveform Simulation for Positron Timing Counter with SiPM for MEG II Experiment

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Topics

- MEG II experiment
- Timing Counter Upgrade
- TC Software
- Waveform simulation
  - Resolution for Single counter with noise
  - Simulation at multi counter setup
- Summary
Search for charged Lepton Flavour violation decay $\mu \rightarrow e \gamma$ predicted in Beyond Standard Model (SUSY-GUT, see-saw model etc...)  
Now upgrading to aim for Branching ratio $4 \times 10^{-14}$  
Accidental background increase by double rate $\mu$ beam $\rightarrow$ Detector performance is improved  
It is necessary to measure the time, direction, energy for $\gamma$ and $e^+$ to identify the signal event

**Signal**

- Same time
- Back to back
- Same energy $E=52.8$MeV

**Background**

- Accidental background

  **Dominant**

- Radiative muon decay

  - Same time
  - $E<52.8$MeV
  - No back to back

- Accidental hit of $e^+$ from Michel decay and $\gamma$ from radiative decay etc.

- Accidental hit of $e^+$ from Michel decay and $\gamma$ from radiative decay etc.
**MEG II Detector**

- **Final result of MEG experiment**
  金子(19aAH-3)
- **Pilot run in 2015 and engineering run for in 2016 for MEG II**
  内山(19aAH-4)

- **Drift chamber**
  e\(^+\) Tracking
  low mass materials and high efficiency

**Timing Counter**

**Timing measurement for the e\(^+\)**

at high precision

- Simulation study: 吉田(19pCA-1)
- Initial result of engineering run: 西村(19pCA-2)
- Analysis method for timing calibration: 中尾(19pCA-3)

**LXe \(\gamma\)-ray detector**

家城(22pAN-3)
小川(22pAN-4)

**Radiative Decay Counter**

岩井(19aAH-10)
中浦(19aAH-11)

**Muon beam**

Stopping rate \(7 \times 10^7 \mu /s\)
Timing Counter Upgrade

- **Pixelated Timing Counter**
  - To measure the time of positron from $\mu^+ \rightarrow e^+ \gamma$
  - One counter consists of fast plastic scintillator and SiPM
  - Total 512 counters at upstream and downstream
  - It has good timing resolution by multiple hits
  - Low pileup effect under high rate $\mu$
  - **Good time resolution ($\sim 30$ps)** is demonstrated at the beam test

$$\sigma_{\text{overall}}^{2}(N_{\text{hit}}) = \frac{\sigma_{\text{single}}^{2}}{N_{\text{hit}}} + \frac{\sigma_{\text{inter-pixel}}^{2}}{N_{\text{hit}}} + \sigma_{\text{MS}}^{2}(N_{\text{hit}})$$

- Improvement by multiple hits (MC)
  - $\sigma_{\text{inter-pixel}} \sim 30$ps
  - $\sigma_{\text{MS}} \sim 5$ps
  - Average $N_{\text{hit}}$: 9 hits
  - $\sigma \sim 30$ps

**Graph:**
- Resolution (psec) vs. Number of hit pixels
- $\sigma \sim 30$ps

**Images:**
- Timing Counter for MEG
- Upgraded Timing Counter for MEG II
- Plastic scintillator bar + PMT
- Fast plastic scintillator+ SiPM
- $250 \times 2$ (up and downstream) counters
Single Counter

- Fast Plastic scintillator BC422
  - Rise time: < 20ps
  - Light output: 55% of Anthracene
  - Peak wavelength: 370 nm
  - Light attenuation: 8 cm
- 120×40×5 mm³, 120×50×5 mm³
- Covered by Mirror type reflector (3M ESR film) and black sheet (Tedlar)
- SiPM (ASD-NUV3S-P High-Gain (MEG))
  - 3×3 mm², 3600 pix made by AdvanSiD
  - SiPM array (6 series) on the PCB
  - 2 ch readout from both side of the counter
- SiPM and Scintillator connected by optical cement
- Optical fiber and support structure for timing calibration

Timing Resolution ~75 ps (for 4 cm counter)
Overall of TC software

**Measurement**
- **DAQ**
  - Data taking by waveform digitizer

**Simulation**
- **Event generation**
  - MC simulation
  - Optical photon tracking
- **Waveform simulation**
  - Digitization of the waveform

**Waveform**
- **Waveform analysis**
  - Waveform timing, charge etc... for each ch
- **Hit reconstruction**
  - Reconstruct hit timing, position for counter
- **Clustering**
  - Make cluster of N hits counters

Get positron timing
Waveform simulation

- To evaluate performance and understand the detector
  - Study the effects of pile up, dark noise, crosstalk, after pulse for timing resolution

- Waveform simulation method
  1. Scintillation photon is generated and tracked by MC
  2. Detected photon timing at SiPM is got
  3. Convoluted the photon pulse and 1p.e. response of SiPM array

1p.e. waveform of SiPM array is necessary
- However, it is difficult to measure 1p.e. signal for 6 series SiPM because of high dark rate
- 1p.e. waveform of SiPM array is simulated from 1p.e. waveform of single SiPM

Flow chart

1. Raw 1p.e. waveform from single SiPM by measurement
2. Simulate SiPM circuit and set the parameters by SPICE to get the 1p.e. waveform for single SiPM
3. Simulate the 1p.e. waveform for SiPM array by SPICE
4. Convoluted the photon pulse and 1p.e. waveform from SiPM

*About making template waveform
日本物理学会2015年秋季大会
吉田(26aSN03)
Waveform Simulation for Single Counter - Previous JPS meeting -

*報告比前回のJPSで良い分解能を報告するが、バグのため*

- **Waveform**
  - Measured
  - Simulated

- **Timing resolution**
  - Measurement
  - Simulation
  - \( \sigma = 77.8 \pm 0.5 \text{ps} \)
  - \( \sigma = 66.8 \pm 0.4 \text{ps} \)

- Event generation by geant4
  - For single counter
  - \( e^- \) from Sr\(^{90} \) source (\( E_{\text{end}} = 2.3 \text{MeV} \))
  - Tracking scintillation photon

- Convoluted 1 p.e. template waveform and photon time distribution

- Light yield is set by matching height with actual signal

- Simulated waveform matches the measured waveform

Noise was not included

*日本物理学会2015年秋季大会 吉田(26aSN03)*
Property Measurement for Single SiPM and implementation in waveform simulation

- Measure the single SiPM property to input to simulation
- Dark signal and Laser signal

- Dark rate $\sim 2.3$ MHz (258kHz/mm$^2$)
  - From poisson distribution: $P(0) = \frac{N_{\text{pede}}}{N_{\text{tot}}} (k=0)$
  - Including the after pulse within 3.5ns from the peak
    → Implementation by adding random at this rate
- Crosstalk $\sim 0.17$ (preliminary)
  - $\frac{N_{2\text{p.e. and over}}}{N_{1\text{p.e. and over}}}$
    → Add 1p.e. signal at neighbor cell in this possibility
- Transit Time Spread (TTS) $\sigma = 71.3$ps
  - Measurement by using laser
    → Fluctuate the photon time at this sigma
- Baseline noise $\sigma = 2.4$ mV
  - RMS of baseline noise
    → White noise following gaussian
Result of Waveform Simulation with Noise

- Timing resolution

Not only waveform but timing resolution for single counter is also reproduced by included noise

Included noise
- White noise (set as reproducing real noise RMS)
- Dark noise (measured value ~14MHz)
- Crosstalk (measured value ~17%)

After pulse of SiPM is not included
Noise scan in waveform simulation

- Dependence of the timing resolution for each noise
- Dependence for crosstalk and dark noise is small around measured value
- Noise RMS effect is most strong
TTS scan in waveform simulation

- Dependence of the timing resolution for TTS
- Estimated $t_{ts}$ is in Plateau region
- Resolution is not depend on TTS around measured value
Simulation at multi counter setup

- Waveform simulation at multi counter setup
  - To estimate multiple hits resolution
  - To study pileup effect

- Setup
  - 9 counters (4cm counter:6, 5cm counter:3)
  - 48MeV $e^+$ beam
  - Trigger event: Selecting the event of hitting reference counter ($5 \times 5 \times 5$ mm)
  - Pileup event: Hit to whole of counter
  - Mix the waveform of trigger event and pileup event to reproduce pileup

- Trigger event
- Pileup event

Side view
Result for multi counter setup

- **Result**
  - Timing resolution: ~30ps (9hits)
  - We observed deterioration of resolution by pileup effect in high rate beam test
  - Pileup effect is not reproduced in waveform simulation in actual pileup rate (70.2kHz from MC)
    - w/o after pulse

*High rate beam test result for michel positron*
Summary and Prospect

- **Summary**
  - Single counter resolution is reproduced in waveform simulation by including some noise (Dark noise, Cross talk, White noise)
  - Estimate noise and TTS effect for resolution
  - Expected resolution (~30ps) is reproduced in multiple counter setup at 9hits
  - Pileup effect is not reproduced in waveform simulation

- **Prospect**
  - Including after pulse effect
  - Simulation at multi counter setup with after pulse
  - Including reflector effect
  - Time difference between SiPMs on the PCB
  - Waveform simulation at actual TC setup
END
MC simulation - Single counter setup -

- A test counter (BC422, 120×40×5 mm³, no wrap, SiPM array on each side)
- A reference counter (BC422, 5×5×5 mm³, wrapped by teflon, 1 SiPM) is set behind test counter
- Irradiating e⁻ from ⁹⁰Sr
- Selecting the event of hitting reference counter

### Scintillator setup

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillation yield</td>
<td>8400 photons/MeV</td>
</tr>
<tr>
<td>Attenuation length</td>
<td>20.6 cm</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.58</td>
</tr>
<tr>
<td>Rise time</td>
<td>0 s *</td>
</tr>
<tr>
<td>Decay time</td>
<td>1.6 ns</td>
</tr>
</tbody>
</table>

Single SiPM After pulse

アフター見積もりと実装法

19
ハイレートビームテスト＠PSI

- PSIのπE5ビームラインのミューオンビームをターゲットに照射し、ミッシェル陽電子を用いたハイレート試験でパイルアップの影響を検証
- MCにより予期されるヒットレートにおいても36.5psの優れた時間分解能

![試作機](image)

## Resolution vs. Number of Hits

- **低ヒットレート**
  - 17.8-64kHz
  - Resolution vs. Number of Hits (lower rate)

- **予期されるヒットレート**
  - 53-166kHz
  - Resolution vs. Number of Hits (expected rate)

- **高ヒットレート**
  - 89-290kHz
  - Resolution vs. Number of Hits (higher rate)

※西村美紀氏より
波形解析

1. ch毎のconstant fraction time (11%) をシグナルの時間とする
2. 2chのシグナル時間の平均 \((t_{ch1} + t_{ch2})/2\) を各カウンターのヒット時間とする
3. カウンターのヒット時間とレファレンス時間 (RC1, RC2のヒット時間の平均) の差の標準偏差から時間分解能を導出

差の標準偏差から時間分解能を導出
Measurement for Single SiPM

- It is necessary to measure these topics for single SiPM to get 1 p.e. response from SiPM array and input property to simulation:
  - 1 p.e. waveform of single SiPM
  - Gain
  - Dark rate
  - Crosstalk probability
  - Single p.e. timing resolution (SPTR)

Setup

- Thermal chamber
- SiPM
- AMP
- HV
- Pocket pulsar
- Waveform digitizer
- LASER
- Controller
- LASER SYNC
- LASER light

SiPM is mounted by conductive epoxy

- SiPM: same to actual TC (ASD-NUV3S-P High-Gain (MEG))
- OV: 3.0V
- 30 degree
- LASER: Picosecond Light Pulsar (Hamamatsu PLP-10) wavelength 401nm
  - For measurement of timing resolution
- Trigger: Random by pocket pulsar for Dark signal
  - LASER SYNC for measurement of timing resolution
- Signal Timing: constant fraction time
ローパス

ハイパス
PDE setting

- New TTS is decided and PDE spectrum is changed for AdvanSiD SiPM → reset pde, noiserms
- PDE scan to decide input PDE in gem4 by matching height with real counter
NoiseRMS setting

- Noise RMS scan to match with noise RMS of real measurement
SiPM timing resolution resolution for $N_{\text{p.e.}}$.

- True resolution $\sigma_{\text{tts}}/\sqrt{N}$
- Laser duration $\sigma_{\text{laser}}/\sqrt{N} \rightarrow \sigma_{\text{laser}}=25.5\text{ps}$ (from catalog)
- Noise effect $\sigma_{\text{noise}}/N \rightarrow$ by fake pulse
- Constant term (from electronics jitter and analysis fluctuation) $\sigma_{\text{const}}$ → by resolution at high p.e.

Timing resolution for $N_{\text{p.e.}}$ by Laser light

![Timing Resolution Graph](image-url)
Fake pulse convoluted 0p.e. event and \( N_{\text{p.e.}} \) template waveform

The template waveform don't have fluctuation

Estimate the resolution of fake pulse for \( N_{\text{p.e.}} \) to estimate the noise effect for \( \sigma_{\text{noise}} / N_{\text{p.e.}} \)

\( \sigma_{\text{noise}} = 99.8\text{ps} \)

Fake pulse of 1p.e.
TTS estimation

- Timing resolution of SiPM at high p.e. (~1000p.e.) by laser light
- $\sigma_{\text{const}} = 33.5\text{ps}$

\[
\frac{\sigma}{\sqrt{N_{\text{p.e.}}}} + \frac{\sigma_{\text{laser}}}{\sqrt{N_{\text{p.e.}}}} + \frac{\sigma_{\text{noise}}}{N_{\text{p.e.}}} + \sigma_{\text{const}}
\]

<table>
<thead>
<tr>
<th>Event</th>
<th>h_highpe'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>20068</td>
</tr>
<tr>
<td>Mean</td>
<td>2.099e–07</td>
</tr>
<tr>
<td>RMS</td>
<td>3.374e–11</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>68.5 / 50</td>
</tr>
<tr>
<td>p0</td>
<td>1190 ± 10.2</td>
</tr>
<tr>
<td>p1</td>
<td>2.095e–07 ± 2.375e–13</td>
</tr>
<tr>
<td>p2</td>
<td>3.354e–11 ± 1.628e–13</td>
</tr>
</tbody>
</table>

At high p.e. Signal – Laser SYNC.
TTS estimation

- Laser duration $\sigma_{\text{laser}} = 25.5\text{ps}$
- Noise effect $\sigma_{\text{noise}} = 99.8\text{ps}$
- Constant term $\sigma_{\text{const}} = 33.5\text{ps}$
  
  $\rightarrow$ Transit time spread $\sigma_{\text{tts}} = 71.3\text{ ps}$

- Red line is fixed at 1 p.e. point but it is not match because of CTAP?
Waveform of pileup event
Waveform for single SiPM

- 1p.e. average waveform for single SiPM from 100 waveforms
- Selecting the waveforms which have no after pulse, flat baseline
- Fitting function: \[0\times\exp\left(-t/\left[\tau_{\text{rise}}\right]\right)-\left[1\right]\times\exp\left(-t/\left[\tau_{\text{spike}}\right]\right)-\left(1-\left[1\right]\right)\times\exp\left(-t/\left[\tau_{\text{tail}}\right]\right)\]
SiPM circuit model

Circuit model of N pixel SiPM

- Rq : Quenching resistance
- Cq : Stray quenching capacitance
- Cd : p-n junction capacitance
- Cg : Stray grid capacitance
- N : Number of pixels

Measurement to decide parameter
- Rq is measured by I-V curve at forward bias
- Cq, Cd, Cg is estimated by SiPM Gain and LCR measurement

\[ Q = V_{OB}(C_D + C_q) \]

- Equivalent circuit for LCR measurement

\[ C_D = \sqrt{\frac{1 + \omega^2 (C_D + C_q)^2 R_q^2}{\omega^2 N_{tot} R_q R_p}} \]

\[ C_g = C_p - N_{tot} C_D + \frac{\omega^2 C_D^2 R_q^2 N_{tot} (C_D + C_q)}{1 + \omega^2 R_q^2 (C_D + C_q)^2} \]

SiPM pixels consist of diode and quenching resistance

- Quenching resistance is measured from I-V curve at forward bias
- \( R_q = 974 \pm 13 \text{ k}\Omega \)
RP and CP is measured by LCR meter (HIOKI LCR HiTESTER 3532-50)

LCR meter input sine wave and measure impedance and phase difference by Four-terminal Method

RP and CP are saturated at high frequency and high bias
- So, we used the value at high frequency and high bias

- From I-V curve
  \[ Rq \sim 973.8 \text{ k}\Omega \]

- From SiPM Gain and LCR measurement
  \[ C_D \sim 97.0 \text{ fF} \]
  \[ C_q \sim 7.04 \text{ fF} \]
  \[ C_g \sim 141.4 \text{ pF} \]
SPICE simulation for single SiPM

- Input the measured circuit parameter and simulate the 1p.e. waveform of single SiPM
- The simulated waveform don’t match measured waveform
- The parameters is adjusted as reproducing measured waveform
- Probably, the uncertainty for Cq is large
SPICE simulation for SiPM array

- Measured waveform for single SiPM
- Simulated waveform for single SiPM
- Simulated waveform for SiPM array (6 series)
- Simulated waveform for SiPM array with the shaping (pole zero cancelation) and the cable

- Simulating 1 p.e. waveform for SiPM array by using the adjusted parameter
- Shaping by pole zero cancelation
- Including the actual long cable effect by measurement
- Convoluting with photon timing pulse from MC