波形シミュレーションを用いたMEG II陽電子タイミングカウンターの性能評価

宇佐見正志、他MEG II コラボレーション
日本物理学会第72回年次大会
2017/03/20＠大阪大学 豊中キャンパス
Overview

• MEG II Overview
• Waveform Simulation
• Afterpulse Measurement
• Application of Waveform Simulation
• Summary and Prospect
MEG II experiment

The most sensitive $\mu^+ \rightarrow e^+ \gamma$ search experiment in the world with the most intense DC muon beam at PSI

✓ In Standard Model

strongly suppressed and cannot be found by experiment

✓ In Beyond Standard Model with SUSY-GUT, SUSY-seesaw model ...

$\text{Br}(\mu^+ \rightarrow e^+ \gamma)$ becomes larger and we can find by experiment!

To discover $\mu^+ \rightarrow e^+ \gamma$ means to discover new physics!
MEG II experiment—detectors—

**Liquid Xe Detector**
Detect gamma-rays with MPPCs and photomultiplier tibe

**Radiative Decay Counter (RDC)**
Detect low-energy positron
Tag BG event

**Drift Chamber**
Track positron

MEG II unprecedented sensitivity:
$\text{Br}(\mu^+ \rightarrow e^+ \gamma) \approx 4.0 \times 10^{-14}$
($\times 10$ better than MEG experiment!)

**positron Timing Counter (pTC)**
Get the timing of positron
Positron Timing Counter

Features:
- Small pixels (512 pixels)
- 6 series SiPM + fast scinti.
- Using multihit information
- Time resolution ~ 30ps

Analysis Flow of Timing Counter

1 pixel counter
- ultra-fast plastic scintillator (BC422) + reflector
  - 120mm x 40mm x 5mm
  - 120mm x 50mm x 5mm

Support structure and laser fiber for calibration

6 series SiPM on PCB
- SiPM: ASD-NUV3S-P High-Gain (MEG)

1 pixel counter and PCB are depicted in the image.
Overview

- MEG II Overview
- **Waveform Simulation**
- Afterpulse Measurement
- Application of Waveform Simulation
- Summary and Prospect
Waveform Simulation

Motivation
☆ Deep understanding on detector
☆ Evaluate the detector performance

1. Set up
   Set detectors
   Event generation

2. Photon Tracking
   Record hit pixel & time

3. Simulate Waveform
   By using hit information & SiPM’s response

4. Waveform Analysis
   Get the time resolution

Application
✓ Physics process in detector
✓ Noise effect on performance
✓ Pile up effect w/ actual MEG II physics run setup
✓ **Radiation damage and current increase effect** etc...

Using *measured* parameters
Ex. Dark count rate, Recovery time, Prompt Cross Talk probability
**Probability of afterpulse & delayed cross talk**
**Time const of afterpulse & delayed cross talk**
Waveform Simulation Status

Already studied & included SiPM noises:
- Cross talk, Dark noise, White noise, etc.

(Ref. JPS Slide {http://meg.icepp.s.u-tokyo.ac.jp/docs/talks/JPS/2016s/yoshida_jps2016s.pdf})

Not studied & included SiPM noises:
- Afterpulse, Delayed cross talk

Including all noises properly must be done to simulate pulse & understand detector

Model of SiPM
- Photons
- Trap & Re-emittance (Afterpulse)
- Diffuse to neighboring pixels (Delayed cross talk)

Source:
- hep-www.px.tsukuba.ac.jp/~hontaku/MPPCSchool/slides/MPPCshibata.pptx
- 23Pの図を引用、一部変更
Afterpulse measurement

• MEG II Overview
• Waveform Simulation
• Afterpulse Measurement
• Application of Waveform Simulation
• Summary and Prospect
There are some previous studies on afterpulse measurement.

**The number of component**

- 2 afterpulse component & 0 delayed cross talk component
- 1 afterpulse component & 1 delayed cross talk component

**Measurement method**

Many of afterpulse measurement uses:

- waveform analysis & deconvolution
  
  ->to suppress the tail of pulse

---

**Measurement set up**

- Random trigger (ch3)
- Pocket pulser (+ divider)
- Thermal chamber @30deg
- HV
- SiPM
- Amp
- DRS
- Dark noise (ch1)
- Waveform analysis

**Waveform acquired by DRS**

- 1st pulse (Random noise)
- 2nd pulse

**Deconvolution**
Measurement Result

Model assumption
✓ Delayed cross talk occurs at only neighboring pixel
✓ Afterpulse occurs at only the same pixel
✓ Only 1 delayed cross talk & afterpulse can occur from 1 avalanche
✓ The time distribution of 2nd pulse obeys to:
\[
\frac{1}{\tau_{DCT}} e^{-\frac{t}{\tau_{DCT}}} \text{ or } \frac{1}{\tau_{AP}} e^{-\frac{t}{\tau_{AP}}}
\]

<table>
<thead>
<tr>
<th>Model case</th>
<th>Delayed Cross Talk</th>
<th>After-pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>( \bigcirc ) ( p_{DCT} )</td>
<td>( \times ) ( (1-p_{AP}) )</td>
</tr>
<tr>
<td>b</td>
<td>( \bigcirc ) ( p_{DCT} )</td>
<td>( \bigcirc ) ( p_{AP} )</td>
</tr>
<tr>
<td>c</td>
<td>( \times ) ( (1-p_{DCT}) )</td>
<td>( \bigcirc ) ( p_{AP} )</td>
</tr>
<tr>
<td>d</td>
<td>( \times ) ( (1-p_{DCT}) )</td>
<td>( \times ) ( (1-p_{AP}) )</td>
</tr>
</tbody>
</table>

2D plot of 2nd pulse distribution

Delayed cross talk + Random noise

Afterpulse

Time difference b/w 1st pulse and 2nd pulse [s]
Model and Fitting

At this model we can get 4 parameters (common to $P_1$ & $P_2$) only by fitting.

\[
P_1(p_{DCT}, p_{AP}, \tau_{AP}, \tau_{DCT}) = P_{1a} + P_{1b} + P_{1c} + P_{1d}
\]

\[
P_2(p_{DCT}, p_{AP}, \tau_{AP}, \tau_{DCT}) = P_{2b} + P_{2c}
\]

Fitting function is:
\[
N_1(p_{DCT}, p_{AP}, \tau_{AP}, \tau_{DCT}) = N_{\text{trigger window width}} P_1/I_{\text{dead time cor.}}
\]
\[
N_2(p_{DCT}, p_{AP}, \tau_{AP}, \tau_{DCT}) = N_{\text{trigger window width}} P_2/I_{\text{dead time cor.}}
\]

<table>
<thead>
<tr>
<th></th>
<th>$p_{DCT}$</th>
<th>$p_{AP}$</th>
<th>$\tau_{DCT}$</th>
<th>$\tau_{AP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>22.3%</td>
<td>31.6%</td>
<td>78.5ns</td>
<td>107ns</td>
</tr>
<tr>
<td>Individual difference</td>
<td>± 1.2%</td>
<td>± 0.6%</td>
<td>± 4.7ns</td>
<td>± 12ns</td>
</tr>
<tr>
<td>Error of each fitting</td>
<td>~3%</td>
<td>~3%</td>
<td>~5%</td>
<td>~10%</td>
</tr>
</tbody>
</table>

1D Plot of Time difference

Afterpulse

Random Noise & Delayed Cross Talk

Average

Individual difference

Error of each fitting

800

3000

200ns

200ns

800

※-1μs is offset for combined fitting

Time difference b/w 1st pulse and 2nd pulse [s]

Average

Individual difference

Error of each fitting

800

3000

200ns

200ns

800

※-1μs is offset for combined fitting

Time difference b/w 1st pulse and 2nd pulse [s]

Average

Individual difference

Error of each fitting

800

3000

200ns

200ns

800

※-1μs is offset for combined fitting

Time difference b/w 1st pulse and 2nd pulse [s]

Average

Individual difference

Error of each fitting

800

3000

200ns

200ns

800

※-1μs is offset for combined fitting

Time difference b/w 1st pulse and 2nd pulse [s]

Average

Individual difference

Error of each fitting

800

3000

200ns

200ns

800

※-1μs is offset for combined fitting

Time difference b/w 1st pulse and 2nd pulse [s]

Average

Individual difference

Error of each fitting

800

3000

200ns

200ns

800

※-1μs is offset for combined fitting

Time difference b/w 1st pulse and 2nd pulse [s]
Waveform Simulation

• MEG II Overview
• Waveform Simulation
• Afterpulse Measurement
• Application of Waveform Simulation
• Summary and Prospect
Radiation damage

✓ Current increase by radiation damage @ past pilot run

✓ Expected current increase: 100~200 μA
  (25 week × 3 year physics run)

At this current level, time resolution may be deteriorated
Check the effect from simulation by changing dark count rate

Pilot run (2015 Dec.) current monitor

2 days @ MEG II expected intensity

~0.5 μA increase each
Simulation Result

The effect on gain: no significant deterioration
The effect on time resolution: ~16%-34%

The deterioration level is not so serious: Estimated ~few % for overall sensitivity
But we have to check operation of Timing Counter @ high current level

Time resolution is defined as:
\[
\sigma \left( \frac{t_{\text{right}} + t_{\text{left}}}{2} \right)
\]

The time when height becomes 20% of peak height

Dark Count Rate vs. Time resolution

---

Pixel

t_{\text{left}}

e^{-}

t_{\text{right}}

Sr90

trigger counter

~75ps

Average

~100-200 μA

Dark Count Rate [MHz]

Time resolution [s]
Summary and prospect

- **Waveform simulation**
  For deep understanding on detector, we are developing the simulation scheme

- **Afterpulse measurement for waveform simulation**
  Calculation of simple & intuitive afterpulse + delayed cross talk model
  Fitting and analysis to get:
  - Probability of afterpulse (31.6%) & delayed cross talk (22.3%)
  - Time const of afterpulse (107 ns) & delayed cross talk (78.5 ns)
  Model comparison w/ previous studies & more systematic study will be done

- **Application of waveform simulation**
  One example of application: Radiation damage effect on time resolution
  - ~16-34% deterioration on time resolution
  It is not so serious but we **have to check the operation** @ high current level
Back up
**AfterPulse + Delayed Cross Talk Model**

- **AP**: AfterPulse
- **DCT**: Delayed Cross Talk
- **RN**: Random Noise

- **Trigger pulse (Dark noise)**
  - **pAP*(1-pDCT)**: Trapped by AP component
  - pAP*(1-p1DCT)
  - pAP*pDCT
  - (1-pAP)*(1-pDCT)
    - **Trapped by DCT + AP component**
    - **AP & DCT did not happen**

- **Afterpulse**
  - **Afterpulse**
  - **Random noise**
  - **Random noise**
  - **Random noise**
    - **DCT**
      - **DCT**
      - **DCT+RN**
      - **AP+RN**
      - **AP+DCT**
    - **Random noise**

Mathematical Equations:

- \( p = \frac{1}{\tau_{AP}} e^{\frac{t}{\tau_{AP}}} \)
- \( p = \frac{1}{\tau_{N}} e^{\frac{t}{\tau_{N}}} \)
- \( p = \frac{1}{\tau_{DCT}} e^{\frac{t}{\tau_{DCT}}} \)
- \( \int_{t}^{\infty} \frac{t}{e^{\frac{t}{\tau_{N}}} dt} = \frac{t}{e^{\frac{t}{\tau_{AP}}}} \)
Calculation of fit function \(-RN + DCT-\)

-1-Detected at DCT+RN region
  
  -1a-Trapped by only DCT component

  \[
P_{1a} = p_{DCT}(1 - p_{AP}) \left(1 - e^{-\frac{t}{\tau_{DCT}}} \times \int_t^\infty e^{-\frac{t}{\tau_{RN}}} dt + \frac{1}{\tau_{RN}} \int_t^\infty e^{-\frac{t}{\tau_{DCT}}} \int_t^\infty e^{-\frac{t}{\tau_{AP}}} dt \right)
  \]

  \[
  = p_{DCT}(1 - p_{AP}) \frac{\tau_{DCT} + \tau_{RN}}{\tau_{DCT}\tau_{RN}} e^{-\frac{t}{\tau_{DCT} + \tau_{RN}}}
  \]

-1b-Trapped by AP and DCT component

  \[
P_{1b} = p_{DCT}p_{AP} \left(1 - e^{-\frac{t}{\tau_{DCT}}} \times \int_t^\infty e^{-\frac{t}{\tau_{RN}}} dt \int_t^\infty e^{-\frac{t}{\tau_{AP}}} dt + \frac{1}{\tau_{AP}} \int_t^\infty e^{-\frac{t}{\tau_{DCT}}} dt \int_t^\infty e^{-\frac{t}{\tau_{AP}}} dt \right)
  \]

  \[
  = \frac{\tau_{RN} + \tau_{DCT}}{\tau_{DCT}\tau_{RN}} e^{-\frac{t}{\tau_{DCT}\tau_{RN} + \tau_{AP}\tau_{DCT} + \tau_{RN}\tau_{AP}}}
  \]

-1c-Trapped by AP component (and RN is detected)

  \[
P_{1c} = p_{AP}(1 - p_{DCT}) \left(1 - e^{-\frac{t}{\tau_{RN}}} \times \int_t^\infty e^{-\frac{t}{\tau_{AP}}} dt \right) = p_{AP}(1 - p_{DCT}) \left(1 - e^{-\frac{t}{\tau_{RN}}} e^{-\frac{t}{\tau_{AP}}} \right)
  \]

-1d-No trap

  \[
P_{1d} = (1 - p_{AP})(1 - p_{DCT}) \frac{1}{\tau_{RN}} e^{-\frac{t}{\tau_{RN}}}
  \]
Calculation of Fit Func. -AP-

-2- Detected in AP region

-1b-Trapped by AP and DCT component

\[ P_{2b} = p_{DCT}p_{AP} \left( \frac{1}{\tau_{AP}} e^{-\frac{t}{\tau_{AP}}} \times \int_{t}^{\infty} \frac{1}{\tau_{RN}} e^{-\frac{t}{\tau_{RN}}} dt \int_{t}^{\infty} \frac{1}{\tau_{DCT}} e^{-\frac{t}{\tau_{DCT}}} dt \right) \]

\[ = p_{DCT}p_{AP} \frac{1}{\tau_{AP}} e^{-\frac{t}{\tau_{AP}}} \frac{1}{\tau_{DCT}\tau_{RN}\tau_{AP}\tau_{RN}} \]

-1c-Trapped by AP component

\[ P_{2c} = p_{AP}(1 - p_{DCT}) \left( \frac{1}{\tau_{AP}} e^{-\frac{t}{\tau_{AP}}} \times \int_{t}^{\infty} \frac{1}{\tau_{RN}} e^{-\frac{t}{\tau_{RN}}} dt \right) \]

\[ = p_{AP}(1 - p_{DCT}) \frac{1}{\tau_{AP}} e^{-\frac{\tau_{AP} + \tau_{RN}t}{\tau_{AP}\tau_{RN}}} \]

So, Fit Func. is

\[ P_1(p_{DCT}, p_{AP}, \tau_{AP}, \tau_{DCT}) = P_{1a} + P_{1b} + P_{1c} + P_{1d} \]

\[ P_2(p_{DCT}, p_{AP}, \tau_{AP}, \tau_{DCT}) = P_{2b} + P_{2c} \]

<table>
<thead>
<tr>
<th>case</th>
<th>DCT</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>trap</td>
<td>-</td>
</tr>
<tr>
<td>b</td>
<td>trap</td>
<td>trap</td>
</tr>
<tr>
<td>c</td>
<td>-</td>
<td>trap</td>
</tr>
<tr>
<td>d</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Analysis

If 1\textsuperscript{st} pulse comes to this region, we do not use that event for analysis to get primary random noise.

First pulse is in VETO -> not used

First pulse is in trigger region -> used

VETO region (300ns)
If 1\textsuperscript{st} pulse comes to this region, we do not use that event for analysis to get primary random noise.

Trigger region (400ns)
If 1\textsuperscript{st} pulse comes in this region, it is efficient event and search for 2\textsuperscript{nd} pulse after 1\textsuperscript{st} pulse.

パルス高が畳み込みの後で分解能が落ちる可能性あり

Deconvolutionのパルス幅や移動平均点数、パルス高については要調査・調整
Example of Deconvolution

Pulse width should be optimized to distinguish the pulse properly.

Parameter optimization & improvement will be studied.

Pulse width should be optimized to distinguish the pulse properly.

Parameter optimization & improvement will be studied.
Delayed Cross Talk and Afterpulse

By fitting, we got the parameters for simulation:
- AP prob.
- AP time const
- DCT prob.
- DCT time const

Also by using the 2D histogram AP region, we can get:
- recovery time
  the result was: \(185 \pm 2\) ns

<table>
<thead>
<tr>
<th>NO.</th>
<th>NAME</th>
<th>VALUE</th>
<th>ERROR</th>
<th>SIZE</th>
<th>DERIVATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Prob_DCT</td>
<td>2.18888e-01</td>
<td>5.07251e-03</td>
<td>5.36147e-06</td>
<td>-4.4471e-04</td>
</tr>
<tr>
<td>2</td>
<td>Prob_AP</td>
<td>3.07108e-01</td>
<td>5.50071e-03</td>
<td>6.57516e-06</td>
<td>2.4753e-04</td>
</tr>
<tr>
<td>3</td>
<td>TimeConst_DCT</td>
<td>7.44914e-08</td>
<td>3.16120e-09</td>
<td>3.24969e-12</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>TimeConst_AP</td>
<td>1.24313e-07</td>
<td>1.10581e-08</td>
<td>1.31117e-11</td>
<td>-9</td>
</tr>
</tbody>
</table>

y: Pulse height

Time difference b/w 1st pulse and 2nd pulse[s]
MEG II Sensitivity vs. Tegamma
Algorithms of simulation

DCT algorithm
DCT occurs at only neighboring pixel

The time difference (t) b/w first pulse and second pulse obeys \( \sim \frac{1}{\tau_{DCT}} e^{\frac{-t}{\tau_{DCT}}} \)

After pulse and DCT time difference is reproduced by MC method:
\[
\xi = \int_0^t \frac{1}{\tau_{DCT}} e^{\frac{-t}{\tau_{DCT}}} \, dt = 1 - e^{\frac{-t}{\tau_{DCT}}}
\]

\( \rightarrow t = -\tau_{DCT} \ln(1 - \xi) \)

where \( 0 < \xi < 1 \) (random number)
Reconstruction from simulation

We could not set 1 μs window, so analysis was not the same to measurement.
Parameter is not optimized yet.

Input:
AP prob. 30%
DCT prob. 26%
AP time const. 110ns
DCT time const. 84ns
recovery time. 185 ns

This is rough analysis
Time resolution measurement set up

\[ \text{time resolution} \quad \sigma \left( \frac{t_{right} + t_{left}}{2} - t_{ref} \right) \]

\( t : \) cftime of each channel

\( ^{90}\text{Sr} : E < 2.2\text{MeV} \quad \beta\text{-ray} \)

Array - left

Array - right

Pixel

TC

Thermal chamber

Amp

Amp

Amp

Light Signal

Light Signal

Trigger Signal

div.

div.

DRS

R

R
参考論文について（Model & Measurement）

P9-12で参考にしたafterpulseやdelayed cross talk のモデル。今後これらのモデルとの比較も検討中。

- 修士論文 半導体光検出器 PPD の基本特性の解明と，実践的開発に向けた研究 (生出 秀行、平成21年1月8日)(http://www.icepp.s.u-tokyo.ac.jp/yamashita/archives/oide/oide_mthesis.pdf)

Afterpulse 2成分でのモデルを組み立てたもの。Fittingから確率を求めるモデルの組み立て方、ランダムノイズの切り分け、測定におけるDeconvolutionの手法等を参考にした。Recovery timeを考慮していない。

- Afterpulse and delayed crosstalk analysis on a STMicroelectronics silicon photomultiplier (Ferenc Nagy et al., Nuclear Instruments and Methods in Physics Research A 759 (2014) 44–49）
(http://www.sciencedirect.com/science/article/pii/S0168900214004501)

Delayed Cross Talk 1成分、Afterpulse1成分のモデル。Delayed Cross Talk 現象についての記述や、時間差が指数関数に従うこと等を参考にした。

(http://www.sciencedirect.com/science/article/pii/S0168900210008156)

Afterpulse2成分の比較的シンプルなモデル。積分から確率を求める。
その他引用など

• P8 Model of SiPMの引用
（hep-www.px.tsukuba.ac.jp/~hontaku/MPPCSchool/slides/MPPCshibata.pptx）
23Pの図を引用、基盤部を厚くし、クロストークの発生機構を省略し、Delayed Cross
Talk, Afterpulseの発生機構を追加するなどの一部追記

• P8のステータス
2015年秋季大会（https://meg.web.psi.ch/docs/talks/JPS/2015a/yoshida_jps2015a.pptx）
第71回年次大会（https://meg.web.psi.ch/docs/talks/JPS/2016s/yoshida_jps2016s.pdf）
K. Yoshida “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”で報告

• P5の写真
1 pixel counterとPCBの写真は2015年秋季大会のスライドより引用