Performance evaluation of the upstream MEG II Radiative Decay Counter

「大強度μ粒子ビーム上で運用するMEG II輻射崩壊同定用カウンターに期待される性能の評価」

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Introduction

- Signal & background in MEG II experiment

**μ → eγ decay**
- Back-to-back
- Coincident in time
- \( E_γ = E_e = 52.8 \text{ MeV} \)

**Dominant BG source (accidental BG)**
- Proportional to square of μ decay rate

- Source of BG γ
  1. Radiative Muon Decay (RMD)
  2. Annihilation in flight (AIF)

**Smaller fraction of AIF thanks to low mass e+ tracker**

- Important to reduce BG γ from RMD

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**MEG**
- RMD
- AIF

**MEG II**
- RMD
- AIF

Background rate per μ decay \((×10^{-6})\)
Radiative Decay Counter (RDC)

- RDC identifies BG $\gamma$ from RMD
  - Low momentum $e^+$ from RMD swept along the beam axis
  - RDC measures time coincidence of low momentum $e^+$ and BG $\gamma$ on $\mu$ beam axis
- Detector requirement: Finely segmented, compact design (diameter ~20 cm)

Accidental BG (Michel decay + RMD)

- $1-5$ MeV
- $>48$ MeV

Only downstream detector was constructed and tested with $\mu$ beam
Upstream detector

- Upstream detector requires R&D concerning operation in high intensity $\mu$ beam ($10^8 \mu$/s)
- Provisional design: Measure timing of $e^+$ with layer of multi-clad scintillating fibers
  - 250 $\mu$m thick square shape fiber
  - 784 fibers are grouped into 18 bundles to reduce number of channels
  - Bundles are bent at right angles
  - Readout bundle ends with SiPM
- 28 MeV/c $\mu$ beam slowed-down by degrader
- Influence on $\mu$ beam is expected to be small (reported in previous JPS meeting)

RDC can be installed by equalizing total amount of substance
Upstream detector

- Sensitivity improvement with RDC (ideal case)

<table>
<thead>
<tr>
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<th>MEGII sensitivity</th>
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<tbody>
<tr>
<td>w/o RDC</td>
<td>$5.0 \times 10^{-14}$</td>
</tr>
<tr>
<td>w/ downstream</td>
<td>$4.3 \times 10^{-14}$</td>
</tr>
<tr>
<td>w/ downstream + upstream</td>
<td>$3.9 \times 10^{-14}$</td>
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</table>

Assuming detection efficiency:
- 100% (downstream)
- 90% (upstream)

Upstream detector has 10% efficiency loss due to fiber cladding

- In real case, detection efficiency of upstream RDC is limited by:
  1. Pile-up beam $\mu$ (large efficiency loss due to SiPM after-pulse in $\mu$ waveform)
  2. Small light yields of thin scintillating fiber

- In this study, total detection efficiency for $e^+$ is evaluated by considering pile-up and light yield
In beam test with prototype, we observed small light yields of e^+

- Scintillating fiber
  - 20 cm length, multi-cladding
  - 250 μm thick square shaped

- Photosensor
  - Double readout
  - 1.3×1.3 mm² SiPM

- Probability to detect no photons ~29% (single side)

- Small light yields is probably due to short attenuation length of the fiber

\[ I(x) = I_0 \left( e^{-\frac{x}{\Lambda_1}} + e^{-\frac{x}{\Lambda_2}} \right) \]

- \( I_0 \) : Light output of fiber core
- \( I \) : Measured light yield at \( x \)
- \( \Lambda_1, \Lambda_2 \) : Attenuation length of core or cladding light

2.7 m in data sheet (fitted region: 1-3 m from fiber end)

Attenuating length is not measured in short region (< 1m)
Light yield study

- Items to be considered in calculation

1. Simulated energy deposit of RMD $e^+$

   ![Energy Deposit Graph]

   - Entries: 60553
   - $\chi^2$/ndf: 473.7 / 372
   - Constant: 1517 ± 11.3
   - MPV: 38.52 ± 0.05
   - Sigma: 4.556 ± 0.035

   ~ 40 keV

2. Light output of fiber core

   8000 photon/MeV

   * from data sheet

3. Reflection angles to cladding wall

4. Attenuation length of fiber

   Further investigation is needed

5. PDE of SiPM

   40%

   * from data sheet

- Calculation reproduces the observed light yield by assuming attenuation length ~7 cm
Light yield study

- Attenuation length was measured for few fiber samples

![Diagram of a setup with Photodiode, LED, fiber, and Support]

Each sample was measured 3 times (0→100 cm)

- Large attenuation in short region was measured
  - Variation between sample needs to be investigated
  - Shorter region (<10 cm) should be measured

<table>
<thead>
<tr>
<th>Attenuation length</th>
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<tbody>
<tr>
<td>short</td>
</tr>
<tr>
<td>fiber A</td>
</tr>
<tr>
<td>fiber B</td>
</tr>
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</table>
Detection efficiency & sensitivity

- Probabilities to detect $e^+$ signal with several light yields

  - $P_{\text{single}}$: detect at single side
  - $P_{\text{OR}}$: detect at either side
  - $P_{\text{AND}}$: detect at both ends

![Graph showing detection probabilities](image)

- Observed detection efficiencies and sensitivities
Detection efficiency & sensitivity

• Detection efficiency was evaluated by considering light yield and pile-up
  • Simulated hit timing, position of $\mu$
  • $|T(e^+) - T(\mu)| < 60$ ns in same bundle $\rightarrow$ pile-up

• Probability to detect signal at either fiber end was calculated for each event

• Hit pattern & event by event efficiency
  • Assuming 18 bundles

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**Standard readout**

- SiPM
- bundle

- $\mu^+ \ast \ast e^+$
  - eff. $= P_{\text{OR}}$
- $e^+ \ast \ast \mu^+$
  - eff. $= 0$

**Staggered readout**

- eff. $= P_{\text{OR}}$
- eff. $= P_{\text{single}}$
- eff. $= 0$
Detection efficiency & sensitivity

- Detection efficiency of $e^+ (E_\gamma > 48\text{MeV})$

- Sensitivity was evaluated with detection efficiency
  - $4.3 \times 10^{-14}$ only with downstream RDC
  - Sensitivity improvement
    - w/ downstream : 16%
    - w/ downstream + upstream : 22%
    *at observed light yield
  - Further improvement is possible by increasing light yield or higher segmentation
Radiation hardness of scintillating fiber

- Another potential issue is radiation damage on scintillating fiber

  * Light yield is expected to largely drop down (~1/4 after 16 days operation)
  
  * Actual irradiation test in high dose environment ($10^5$ Gy) is needed
    
    - Irradiation test at proton irradiation facility at PSI is planned
Radiation hardness of scintillating fiber

- If light yield drop due to radiation damage is correct, upstream RDC based on scintillating fiber is not realistic

- We are also considering detector based on CVD diamond
  - 85 µm thick single-crystal diamond mosaic
  - Radiation tolerance (~MGy)

- Difficulty: Low charge collection of e^+ signal (~3000 e-h pairs)
  - In principle possible with commercial charge sensitive amplifier
Summary

- RDC identifies dominant source of background by detecting low momentum $e^+$
- We are considering further improvement of sensitivity by installing scintillating fiber based detector in $\mu$ beam
- Detection efficiency of $e^+$ was evaluated by considering light yields of fiber and pileup $\mu$
  - $e^+$ detection efficiency $\sim 50\%$ (at observed light yield)
  - MEG II sensitivity improvement with downstream + upstream RDC $\sim 22\%$
- Further study on attenuation length of scintillating fiber is necessary to better understand performance
- Light yield is expected to largely drop due to high radiation dose ($2.2$ kGy/day)
  - Literatures say light yield become $\sim 1/4$ after 16 days
  - Actual irradiation test is planned
  - We are also considering to use diamond mosaic detector
Backup
Optical attenuation length measurements of scintillating fibers

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Particle Detector Group, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Fig. 13. Attenuation length curves for "core," "cladding," and "core + cladding" light.
Total detection efficiency

- Probabilities to detect scintillation photons and pileup were considered

\[
\text{Efficiency} = \frac{\text{Number of detected events by the SiPMs (either side)}}{\text{Number of entered positrons in the upstream RDC}}
\]

- Simulated hit timing, position

- Standard readout scp filename.xxx muegamma@meg.icepp.s.u-tokyo.ac.jp:/html/docs/talks/JPS/2016a/name_jps2017s.xxx
• Staggered readout

\[ \mu \text{ hit in } \Delta T \]

- yes (99.7%)
  \[ \Rightarrow \mu \text{ hit bundle} \]
  \[ \Rightarrow \text{case A (28.7%)} \rightarrow 0 \]
  \[ \Rightarrow \text{case B (26.2%)} \rightarrow P_{\text{Single}} \]
  \[ \Rightarrow \text{case C (5.0%)} \rightarrow 0 \]
  \[ \Rightarrow \text{case D (40.1%)} \rightarrow P_{\text{OR}} \]

- no (0.3%)
  \[ \Rightarrow P_{\text{OR}} \]

\text{case A}

\[ e^+ \times \times \mu^+ \]

\text{case B}

\[ e^+ \times \mu^+ \]

\text{case C}

\[ e^+ \times \mu^+ \]

\text{case D}

\[ e^+ \times \mu^- \]
RDC data in physics analysis

- MEG II uses Maximum likelihood analysis to decide number of signals

\[ \mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) \]

- RDC makes PDF of 3 observables \((t_{\text{ds}}, E_{\text{ds}}, t_{\text{us}})\) and implement in likelihood function

![Graphs](image)

(a) \(T_{\text{us}}\)  
(b) \(T_{\text{ds}}\)  
(c) \(E_{\text{ds}}\)

Figure 27: Projection of RDC PDF. The red and black line shows the accidental background and the signal PDF, respectively.
Dose in fiber

- Fiber at 1 sigma region (~2 cm)

Mass \[= 0.025 \text{[cm]} \times 0.025 \text{[cm]} \times 2.0 \text{[cm]} \times 1.05 \text{[g/cm}^3\text{]}\]

\[= 1.3e-6 \text{[kg]}\]

\[\Delta E/s \, = 0.6 \text{[MeV]} \times 500 \text{[kHz]} \times 0.68\]

\[= 2.04e5 \text{[MeV/s]}\]

\[= 2.04e5 \text{[MeV/s]} \times 1.0e6 \text{[eV/MeV]} \times 1.6e-19 \text{[J/eV]} \rightarrow 2.82e-3 \text{[J/day]}\]

\[= 3.26e-8 \text{[J/s]}\]

Dose \[= 3.26e-3 \text{[J/day]} / 1.3e-6 \text{[kg]}\]

\[= 2.5e-2 \text{[Gy/s]} \rightarrow 2.2e3 \text{[Gy/day]}\]
Radiation effect

- Peter reported degradation of light yield of plastic scintillator

- 48% light yield after 3.4e4 [Gy]

- US-RDC reaches 3.4e4 [Gy] after 16 days
Radiation effect

- Influence on attenuation length of fiber should be also considered


3HF fiber: Scintillating fiber with wavelength shifter for radiation hardness

Shortened attenuation length was observed even with small dose (~100 Gy)

Both optical fiber & scintillating fiber were characterized by:

\[
\frac{\lambda}{\lambda_0} = (0.80 \pm 0.01) - (0.144 \pm 0.007) \log_{10} D
\]

- \(\lambda/\lambda_0\): Ratio of attenuation length
- \(D\): Dose in krad
Radiation effect

- Attenuation length in RDC

**muon hit fraction at central fiber**

1 sigma ~ 2 cm

<table>
<thead>
<tr>
<th>hit rate (kHz)</th>
<th>170</th>
<th>68</th>
<th>12</th>
</tr>
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<tbody>
<tr>
<td>dose (Gy/day)</td>
<td>2200</td>
<td>880</td>
<td>160</td>
</tr>
<tr>
<td>$\lambda/\lambda_0$ (1 day)</td>
<td>0.46</td>
<td>0.52</td>
<td>0.63</td>
</tr>
<tr>
<td>$\lambda/\lambda_0$ (16 day)</td>
<td>0.29</td>
<td>0.35</td>
<td>0.45</td>
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Assuming $\lambda_0 = 20$ cm

Assuming fiber length ~20 cm, total light yield will be ~1/4 after 16 days

Assuming $\lambda_0 = 20$ cm

Light yield attenuation
Radiation effect


- Irradiation test with BCF-12 (planned to be used in RDC)

- 30 cm long fiber was uniformly irradiated with X-ray source (42 Gy/h)

![Graph showing pulse height of particles penetrating the middle of fiber over time](image)

- Current measured short component of attenuation length has large uncertainty (15-60 cm)

- Result is consistent with previous calculations if $\lambda^0$ (attenuation length before irradiation) is 35-40 cm
Alternative plan

- CVD diamond based RDC is considered
  - Discussing about design with E. Griesmayer (TU Wein, Cividec®)
  - 85μm thick, multiple single crystal CVD diamond

- Advantages:
  - Radiation tolerance (~MGy)
  - High detection efficiency (~100%) & Fast signal (~10ns)
  - Space limitation for photosensor can be solved
  - 2D continuous μ beam monitoring

- Difficulty
  - Readout of positron signal (3300 e-h pairs)
  - Manufacturing large area & thin mosaic detector (cost, mechanical stability)
  - Effect on μ beam should be carefully studied

- Possible readout: Charge sensitive amplifier (~5 mV/fC) + broadband amplifier (40dB~)

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Gold : 500 nm

Diamond : 85 μm

Gold : 500 nm

Diamond mosaic detector @CERN n_TOF facility

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