Evaluation of Radiation Damage to VUV–MPPC for MEG II Liquid Xenon Detector

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On behalf of MEG II collaboration
The University of Tokyo
γ Detector of MEG II Experiment

- MEG II experiment searches $\mu \rightarrow e \gamma$ decay, which is one of charged Lepton Flavor Violation.
- Liquid xenon photon detector (LXe) detects energy, position and timing of $\gamma$.
- Scintillation lights from liquid xenon are detected with PMT and MPPC.
Motivation

- We are suspecting degradation of MPPC PDE for VUV light in beam time of 2018. ← Radiation damage??
- Radiation effects on PDE of VUV-MPPC were not evaluated because it is known that there is no effect on PDE of other types at the dose level of MEG II.

Estimated Radiation in 2018

<table>
<thead>
<tr>
<th>Irradiation Source</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (Gy)</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>neutron (n/cm$^2$)</td>
<td>$2.7 \times 10^6$</td>
</tr>
<tr>
<td>photon</td>
<td>$2.5 \times 10^{13}$</td>
</tr>
</tbody>
</table>
Discussion on PDE Degradation

• The issue of the PDE degradation for the VUV-MPPC was discussed with HPK.

• Similar degradation is known for photodiode. QE of photodiode is reduced after strong UV light irradiation.

• Surface damage at Si-SiO$_2$ interface is most suspicious.
  • Ionizing particles such as $\gamma$, charged particle and VUV light can damage it.
  • The electric field near the interface can be reduced by accumulated holes from the ionization.
  • Only PDE in VUV range can be reduced.

• Annealing can be effective to remove the accumulated charge.
Plans

1. PDE measurements for irradiated samples
   - irradiation source: $\gamma$, neutron and VUV light
   - Only PDE of VUV-MPPC irradiated by ionizing particles($\gamma$, VUV light) will be degraded.

2. Annealing
   - Some VUV-MPPCs in LXe were annealed.
   - PDE of the annealed VUV-MPPCs will compared with those measured last year.
   - PDE is supposed to recover after annealing.

3. Taking series data with fixed environments this year
   - The data of beam time 2018 was taken under unstable environments: beam intensity, B-field, firmware update, TRG condition...
   - Calibration data was not taken so frequently.
PDE Measurements

1. γ/neutron irradiated samples
   • We had γ/neutron irradiated samples.
     • $\gamma : ^{60}\text{Co} \rightarrow ^{60}\text{Ni} + e^- + \gamma$ @ Takasaki Advanced Radiation Research Institute in Jan. 2015.
     • neutron: $^9\text{Be} + d^+ \rightarrow ^{10}\text{B} + n$ @ Kobe University tandem accelerator in Jan. 2015.

   • PDE was measured using scintillation light of LXe using α source

<table>
<thead>
<tr>
<th></th>
<th>Dose of Sample</th>
<th>MEG II Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (Gy)</td>
<td>$1.4 \times 10^3, 4.1 \times 10^3$</td>
<td>0.6</td>
</tr>
<tr>
<td>neutron (n/cm$^2$)</td>
<td>$4.8 \times 10^9 - 2.0 \times 10^{12}$</td>
<td>$1.6 \times 10^8$</td>
</tr>
</tbody>
</table>

Dose levels of the samples are much larger than expected values of MEG II

2. VUV light irradiated samples
   • A xenon lamp was used as a irradiation source.
   • PDE was measured using the xenon lamp.
PDE Measurement for $\gamma$/neutron Irradiated Samples
Setups

- MPPCs were installed in a chamber, which is filled with LXe.
  (two non-irradiated and six irradiated samples)
- \( \alpha \) source was fixed in front of MPPCs.
- Signals were amplified with an amplifier and data was taken with a waveform digitizer.
PDE Measurement

- PDE can be evaluated by comparing measured and expected number of photons from α source ($^{241}$Am)

\[
PDE = \frac{N_{phe}}{N_{pho}}
\]

- The expected number of photons can be calculated considering incident angle.

\[
N_{pho} = \frac{E_\alpha}{19.6 \text{eV}} \times \frac{\Omega}{4\pi}
\]

- Parameters:
  - $E_\alpha : 4.78 \text{ MeV}$,
  - $\frac{\Omega}{4\pi} : \sim 0.4\%$

- The measured number of photons can be calculated from a peak of a charge distribution using calibration factors.

\[
N_{pho} = \frac{Q_\alpha}{(\text{Gain}) \times (\text{Excess Charge Factor})}
\]
Calibration

- The number of detected photons is calculated by
  
  \[ N_{\text{ph}} = \frac{Q_\alpha}{(\text{Gain}) \times (\text{Excess Charge Factor})} \]

- The calibration factors can be obtained by photo-electron peaks.
- The data was taken using LED (\( \lambda = 390 \text{ nm} \), OSA Opto Light GmbH, OCU-400, UE390).
Gain

- Gain can be calculated by subtracting the mean of zero photo-electron peak from the mean of single photo-electron peak.
- Clear linear correlations b/w gain and $V_{\text{over}}$ were observed.

![Graph showing gain vs. overvoltage with data points labeled.

- #3093-1 (non-irradiated)
- #0626-0 ($\gamma$: 1.4e3 Gy)
- #0631-2 ($\gamma$: 4.1e3 Gy)
- #0631-3 ($\gamma$: 4.1e3 Gy)
- #0660-0 ($\gamma$: 4.1e3 Gy)
- #3091-1 (non-irradiated)
- #0626-0 ($\gamma$: 1.4e3 Gy)
- #0631-2 ($\gamma$: 4.1e3 Gy)
- #0631-3 ($\gamma$: 4.1e3 Gy)
- #0660-0 ($\gamma$: 4.1e3 Gy)

Mean: 0.0188
RMS: 0.02606
Excess Charge Factor

- Charge of MPPC is enhanced because of correlated noise: crosstalk and afterpulse.
- The excess factor is calculated by comparing the expected and measured mean number of photo-electrons.

\[
\text{(Excess Charge Factor)} = \frac{\mu}{\lambda}
\]

\( \mu \) : mean of measured distribution

- The expected mean number of photo-electrons can be estimated from the number of zero photo-electrons by assuming Poisson distribution:

\[
P(0) = e^{-\lambda}
\]

- Excess charge factors increase as \( V_{\text{over}} \) get larger as expected.
- Clear difference b/w proto-type and final version was observed.
• PDE degradation was not observed for all irradiated samples.
• Overall PDE were lower than those of the previous measurements (14-20%) \( \rightarrow \) purity of LXe??
• Only PDE of #0660-0 was lower though other samples with the same dose level were not the case.
  • PDE of #0660-0 for visible light was similar to others.
  \( \rightarrow \) there might be a certain damage in the surface except for radiation damage.

※Errors include statistic errors and a systematic error of W value (10%)
PDE Measurement for VUV Light Irradiated Samples
• A xenon lamp was used for irradiation.
• Stability of light was monitored by measuring current of SiPD, which is tolerant to UV light (S12698-02, Hamamatsu).
• VUV-MPPC and SiPM which is not sensitive to VUV light (S13350-3050PE) were irradiated.
• Charges of irradiated and non-irradiated samples were measured using the xenon lamp.
• Only PDE of VUV-MPPC is supposed to be deteriorated.
Setups

Irradiation/PDE measurement for VUV light

Light from the xenon lamp enters after passing through filters.

- **bandpass filter**: to select VUV light
  - $\lambda_1 = 193.0$ nm, $T_1 = 26\%$, FWHM$_1 = 20.0$ nm
  - $\lambda_2 = 181.0$ nm, $T_2 = 28.2\%$, FWHM$_2 = 38.5$ nm
- **ND filter**: to reduce light

![Diagram of setups](image)
Setups

- All photo sensors were mounted on a support structure.
- ND filters or plastic plates were placed in front of them during irradiation and measurement.
  - Non-irradiated samples were masked during irradiation.
  - Charges were measured ND filters w/ lower transmission to suppress radiation effects.

![w/o filters](image1.png)

![w/ filters](image2.png)
Radiation Effects

- Total dose was $\sim 2.7 \times 10^{13}$ photons. $\leftarrow \sim 2.5 \times 10^{13}$ photons @ beam time 2018
- Radiation effects were estimated by comparing charge measured by irradiated and non-irradiated samples at the same positions.
- Charge fraction, (irradiated)/(non-irradiated) was
  - VUV-MPPC : $1.09 \pm 0.13$
  - SiPM : $0.99 \pm 0.14$
- Expected PDE deterioration was $\sim 10\%$.
  $\rightarrow$ **Uncertainties of the measurements are too large to conclude the effects.**
- The large uncertainties result from position dependence of light of the xenon lamp. $\leftarrow$ The xenon lamp seemed to be deteriorated.
- Improvement of setups is planned:
  - using a new xenon lamp, using scintillation light from Xenon
Summary

• PDE of γ/neutron irradiated samples were measured using scintillation light from α source.
  • Dose levels were much higher than expectation of MEG II experiment.
  • No radiation effect on PDE for VUV light was observed. ⇒ The result does not support the hypothesis.

• PDE measurements for VUV light samples were performed using a xenon lamp.
  • Total dose was 2.7e13 photons, which is equivalent to the dose level of beam time 2018.
  • PDE deterioration could not be concluded from the results due to a large position dependence of light distribution.
  ⇒ Setups will be improved for precise measurements.
    ex. using a new xenon lamp, using scintillation light from Xenon

• Effects of annealing will be checked using VUV-MPPC in LXe.
• Series data will be taken with fixed environments this year.
Backup Slides
• Normal SiPM is insensitive to VUV light because its protection layer and thick p+ layer absorb VUV light before reaching p- layer.
• VUV-MPPC has quartz window to protect its surface instead of the protection layer and thinner p+ layer.
Energy from α source was measured with a Silicon Surface Barrier (SSB) detector. Energy can be lost in a protection layer at the surface of the source.

• SSB detector was calibrated by measuring another calibration source ($^{241}$Am).
• The energy peak was measured to be 4.78 MeV.
IV Measurement ($\gamma$)

- All MPPCs work fine.
- From the results of IV measurements, correspondence of serial number and dose was reconstructed.

### Dose (Gy) vs. Serial Number

<table>
<thead>
<tr>
<th>Dose (Gy)</th>
<th>Serial Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.4 \times 10^3$</td>
<td>617</td>
</tr>
<tr>
<td>$1.4 \times 10^3$</td>
<td>626</td>
</tr>
<tr>
<td>$4.1 \times 10^3$</td>
<td>631</td>
</tr>
<tr>
<td>$4.1 \times 10^3$</td>
<td>660</td>
</tr>
</tbody>
</table>
**IV Measurement (Neutron)**

- All MPPCs work fine.
- From the results of IV measurements, correspondence of serial number and dose was reconstructed.

**Dose (n/cm²)** | **Serial Number**
--- | ---
4.8 × 10^9 | 627
4.4 × 10^{10} | 629
7.9 × 10^{10} | 639
2.6 × 10^{11} | 645
2.0 × 10^{12} | 661
Response to Visible Light

- Responses to visible light at low temperature were also checked by comparing charges of strong LED light.
- There is no apparent difference.
- Even the sample whose PDE for VUV light is lower has the similar PDE for visible light. There might be a certain damage in the surface?

※no correction was applied.
VUV Light (Xenon Flash Lamp)

L4633-01 (Hamamatsu)

光源

放射スペクトル

発光パルス波形

1.5 μs

放射強度 (μW/cm²) at 50 cm

波長 (nm)

<table>
<thead>
<tr>
<th>型名</th>
<th>アーチサイズ (mm)</th>
<th>外形寸法</th>
<th>出射光</th>
<th>面材</th>
<th>放射波長 (nm)</th>
<th>推奨主電圧電圧 (V dc)</th>
<th>トリガ電圧 (PP) (kV)</th>
<th>最大平均出力 (W)</th>
<th>最大出力エネルギー (μJ)</th>
<th>発光脈波高周波数 Max. (Hz)</th>
<th>光出力安定性 Max. (%)</th>
<th>A 動作寿命 (次)</th>
<th>冷却方法</th>
<th>他社相当品</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4633</td>
<td>1.5</td>
<td></td>
<td></td>
<td>硅酸ガラス</td>
<td>240 ～ 2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4633-01*</td>
<td></td>
<td></td>
<td></td>
<td>UVガラス</td>
<td>185 ～ 2000</td>
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<td></td>
<td></td>
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<tr>
<td>L4634</td>
<td></td>
<td></td>
<td></td>
<td>硅酸ガラス</td>
<td>240 ～ 2000</td>
<td>700 ～ 1000</td>
<td>5 ～ 7</td>
<td>15</td>
<td>0.15</td>
<td>100</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4634-01*</td>
<td></td>
<td></td>
<td></td>
<td>UVガラス</td>
<td>185 ～ 2000</td>
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</tbody>
</table>
Spec of ND Filters
Spec of Bandpass Filters
Waveform of Xenon Lamp

Example of Waveform

<table>
<thead>
<tr>
<th></th>
<th>VUV-MPPC</th>
<th>SiPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge (a.u.)</td>
<td>8.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Transmission</td>
<td>0.41%</td>
<td>24%</td>
</tr>
<tr>
<td>Size</td>
<td>6 × 6 mm²</td>
<td>3 × 3 mm²</td>
</tr>
</tbody>
</table>

※Two bandpass filter was mounted.

- Irradiation level was estimated by charge.
- About 1.6e6 photons per pulse enter in a chip.
- Irradiation time should be ~42 h to reach an irradiation level of beam time 2018, ~ 2800 h for MEG II (3 years)
- Effects from visible light was estimated using the SiPM, which is insensitive to VUV light.
  ➔ VUV : visible = 96% : 4% (if PDE is constant)
Position Dependence: Xenon Lamp

- Fraction of VUV light was checked before starting irradiation.
- There found to be a large position dependence.
- It was 0.65-0.98 depending on position.
  ⇐ Not a problem as long as it is stable.
Stability of Xenon Lamp

- A decrease of SiPD current was observed during irradiation (~50h).
- Radiation damage to SiPD is negligible at this dose level; 4.5e13 photons
- Output light from the xenon lamp greatly decreased.
• Total dose of irradiated VUV-MPPC was \( \sim 2.7 \times 10^{13} \) photons.
• A decrease of charge were also observed for irradiated and even non-irradiated VUV-MPPC.
• However, charge of non-irradiated SiPM also decreased while that of irradiated SiPM was stable.

Position dependence of the xenon lamp deterioration is suspicious.
Charge Before and After Irradiation

- Light distribution changed during irradiation.
  - VUV light at the position of VUV-MPPCs decreased.
  - Visible light at the position of non-irradiated SiPM had a large drop.
- The charge decrease was greatly affected by the decrease of light.
IV Curve (SiPD)

- No apparent difference

※with LED
IV Curve (VUV–MPPC)

- No apparent difference
IV Curve (SiPM)

- No apparent difference?

JPS Autumn(17aT12-5)
Radiation Effects

- The charges were measured at 18 positions.
- The fractions were calculated using charges at three points in the same hole.
VUV–MPPC

- a

Diagram:

LXe

α source

VUV-MPPC

LED