Annealing of MPPCs for MEG II liquid xenon detector

Kei Ieki
on behalf of MEG II collaboration
\( \mu \to e\gamma \) search

MEG II experiment searches for cLFV decay, \( \mu \to e\gamma \).

- Sensitivity goal: \( 6 \times 10^{-14} \)  
  (10 times better than MEG)
- BSM prediction: \( 0(10^{-14}) \)  
  (e.g. SUSY-seesaw)

If \( \mu \to e\gamma \) is found, Discovery new physics!
MEG II experiment

Key concepts:
- **High rate** continuous $\mu^+$ beam at PSI ($7 \times 10^7 \mu$/sec)
- **High resolution** detectors to distinguish $\mu \rightarrow e\gamma$ from accidental BG

- Both $x2$ improve from MEG

- $\mu \rightarrow e\nu\nu\gamma$ or $e^+e^- \rightarrow 2\gamma$

**Signal**
- Back-to-back same timing $E_\gamma = E_e = 52.8$ MeV

**BG** (Accidental)

- Commissioning is ongoing with all detectors (w/ partial readout electronics)
Liquid Xe detector

900L liquid Xe (LXe) scintillator to detect energy, position and timing of $\gamma$

In MEG II, $\gamma$ entrance face is replaced from 216 PMTs (2 inches) to 4092 MPPCs (12x12 mm$^2$)

Light collection uniformity and granularity improved! $\rightarrow$ x2 energy and position resolution improvement expected

$\gamma$ energy distribution (MC)

MEG II
$\sim$1% resolution at 52.8MeV

MEG
$\sim$2%
PDE degradation problem

Decrease of MPPC PDE was observed while commissioning with $\gamma$ from $\mu \rightarrow e\nu\nu\gamma$.

$\rightarrow$ surface damage by VUV light from LXe scintillation?

$\rightarrow$ Accumulation of holes near SiO$_2$-Si interface $\rightarrow$ reduction of carrier collection efficiency

Similar phenomena is known for UV photo diode.

Mean PDE vs. time

VUV photons ($\lambda \sim 175$ nm)

SiO$_2$

Si

~$1.3 \times 10^{12}$ photons / day / MPPC

Irradiation time @ 7e7 muon/s [days]
Possible solution: annealing

Accumulated charges can be removed by annealing (heating).

→ Generate Joule heat by applying reverse bias on MPPC under light
   (We need special HV source to apply high current.)

We should not exceed temperature limits:

- MPPC 100 deg.
- PCB 120 deg.
- CFRP 45 deg.
- Glue 65 deg.
Lab. tests
How much voltage can we apply?

PCB temperature should not exceed 45 deg. \( \rightarrow \) How much V,I can we apply?

- Temperature and V*I have roughly linear relationship. \( \rightarrow \) V should be below \( \sim 70\text{V} \) to keep backside of PCB below 45 deg. \( T_{MPPC} \) is around 70 deg.
- Adjacent channels are also heated to \( T_{MPPC} \sim 45 \text{ deg.} \)
Does heating cause any damage?

We applied reverse voltage $V_{\text{over}} = 12\text{-}22\text{V}$ under room light with three spare MPPCs

- 20\text{-}100\text{deg} (several hours)
- 70\text{deg}, 63 hours
- 62\text{deg}, 60 hours

Then we tested the performance:

- I-V curve measurement (all samples)  
  → Current reduced for 62 and 70\text{deg}., samples, while it increased for 100\text{deg}.
- Gain, crosstalk + afterpulsing, dark rate measurement (62\text{deg} sample)  
  → Gain, crosstalk + afterpulsing did not change. Dark rate reduced by 15%.

**No performance degradation except for 100\text{deg} sample**
Annealing of installed MPPCs
Annealing test for installed MPPCs

In 2019, we **annealed 7 MPPCs in cryostat** before filling LXe. LEDs inside the cryostat were used as light source.

- In LXe, PDE was measured with VUV light from $\alpha$ source.
- **Increase of PDE was observed (up to 80%)!**
  - Large current applied $\rightarrow$ large PDE increase
- **Response to blue LED also increased (up to 13%).**
  - $\rightarrow$ VUV PDE can be monitored with LED w/o filling LXe

<table>
<thead>
<tr>
<th>MPPC</th>
<th>Current [mA]</th>
<th>Time [hr]</th>
<th>PDE [%] 2018</th>
<th>PDE [%] 2019</th>
<th>Recovery</th>
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<tbody>
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<tr>
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<td>8.37</td>
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<td>9.18</td>
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<tr>
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<td>21-24</td>
<td>38</td>
<td>7.21</td>
<td>13.4</td>
<td>1.86</td>
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</tbody>
</table>
Annealing speed measurement

In 2020, we measured annealing speed at different voltages.

→ Investigate optimal condition for annealing.

- Response to blue LED was monitored instead of measuring VUV PDE.
- Annealing speed is found to depend on voltage and production lot.
- MPPC at 0V, heated to ~40 deg. by neighbor channel, was also annealed.

It might be safer and efficient to do annealing with warm (<45 deg.) gas.
Summary

- MPPC PDE decrease was observed in MEG LXe detector. We suspect surface damage by VUV light.

- PDE can be recovered by annealing (heating). We can heat the MPPC by applying reverse bias under LED light.

- In lab. test, no damage on the MPPC performance was observed up to ~70 deg. Reduction of dark current was observed.

- Some of installed MPPCs are annealed, and we observed increase of VUV PDE up to ~80%. Speed of increase seems to depend on voltage and production lot. It might be safer and more efficient to heat by warm gas.
Related talks

- 16pG22-11 (S. Kobayashi)
  More detail of measurement of PDE decrease under muon beam

- 16pG22-13 (S. Ogawa)
  Effect of PDE decrease on detector performance

- 17aG22-7 (R. Onda), 17aG22-8 (K. Shimada)
  Reproduce PDE decrease with Xe flash lamp, with room and low temperature
Backup slides
So far

- PDE degradation is confirmed in 2019 beam data. \(\rightarrow 0.08\% / \text{hour} \) with MEG II intensity

- It might be explained by accumulation of holes near Si interface due to VUV irradiation.

- Annealing was tested for few channels, and we observed increase of PDE.
Further annealing test

- **Goal:** Find optimal condition of annealing
  - How much current?
  - How much time do we need?

- **Method is same as before.**
  - *Use MPPCs installed in XEC or spare MPPCs in lab.*
  - *Operate MPPCs under strong LED light and high voltage to heat them up*

- **Effect of annealing will be seen in increase of charge in LED run because there was a correlation between VUV PDE and visible PDE.**
PDE degradation tests in lab

- Room temperature (Rina)
  - PDE degradation is already observed with Xe flash lamp irradiation
  - Degradation seems to stop at some level
  - VUV signal size after irradiation was 30% of non-irradiated MPPC
    → More precise measurement to be done soon
PDE degradation tests in lab

- Low temperature (Kohei)
  - Irradiation in LXe with light from $\alpha$ source close to MPPC to reproduce the problem in low temperature
  - Expected PDE degradation: $\sim$5% in $\sim$2 weeks measurement.
  - Measurement is just started.
PDE degradation tests in lab

- Low temperature 2 (Kohei)
  - Faster irradiation with Xe flash lamp
  - Expect more (faster?) PDE degradation than in room temperature
  - Maybe we can make irradiated samples quickly and use it for annealing tests.
  - Setup is under preparation
Annealing test

- Previous results
  - 100 deg, 85V, several hours → dark current increased
  - 70 deg, 70V, 61 hours → dark current decreased
    Back side of PCB was 53 deg.

- Updates
  - 62 deg, 65V, 60 hours
  - Measurement of gain, CTAP, dark noise, relative PDE (visible light)
Measurements with LED

Measurements were done before/after annealing. In light tight box (not in thermal chamber), clean room.

- Weak light $\rightarrow$ gain, CTAP
- Strong light $\rightarrow$ relative PDE
- No light $\rightarrow$ Dark noise
Example of raw data

Weak light

Strong light

charge

charge
Weak light results

No difference observed.
Strong light result

I compared gaussian fitted mean of charge distributions.

<table>
<thead>
<tr>
<th></th>
<th>Charge (annealed)</th>
<th>Charge (reference)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before annealing</td>
<td>2.869</td>
<td>2.674</td>
<td>1.073</td>
</tr>
<tr>
<td>After 60 hours</td>
<td>2.724</td>
<td>2.622</td>
<td>1.039</td>
</tr>
</tbody>
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V = 56 V (V_{over} \sim 3.5V)

3.4% decrease by annealing
(Maybe within systematic fluctuation)