Core-to-Core Program

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

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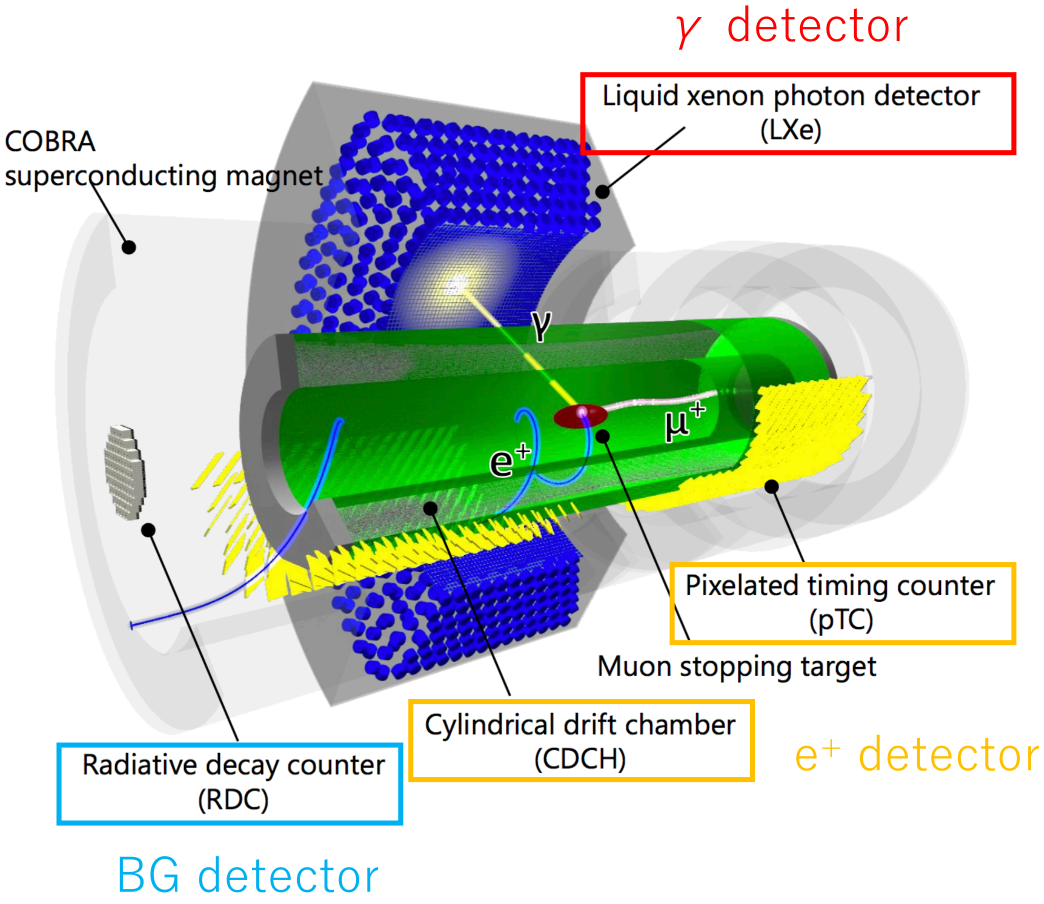
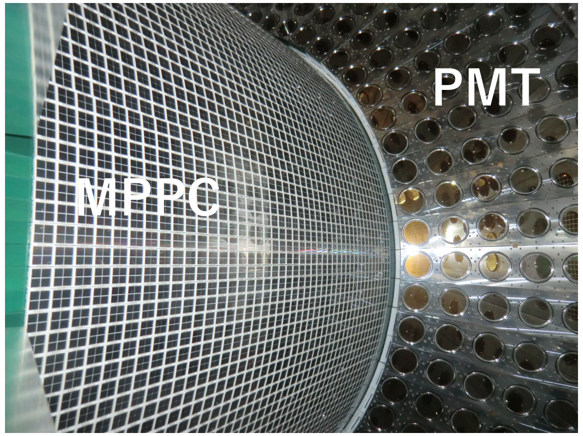
On behalf of MEG II collaboration
The University of Tokyo

γ Detector of MEG II Experiment



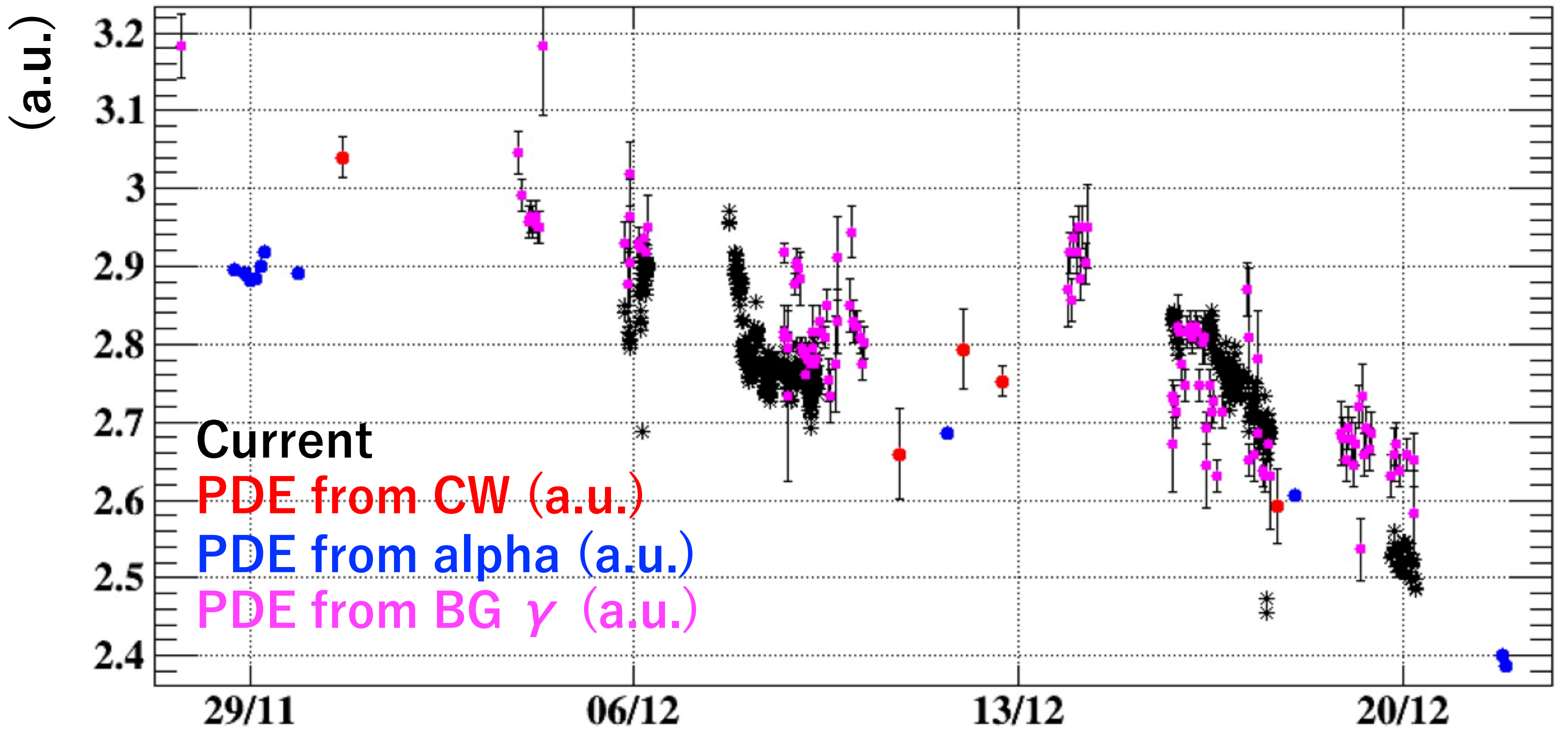
Inside LXe



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

Motivation

MPPC PDE history in 2018



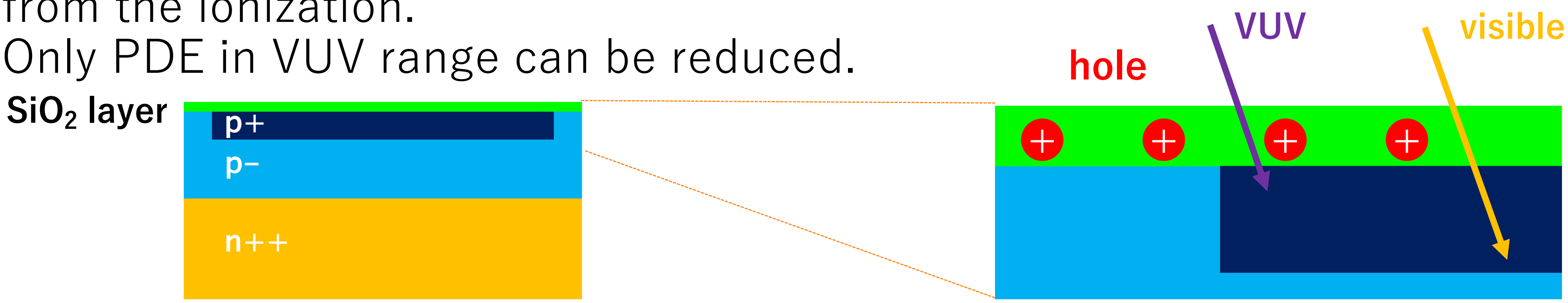
Estimated Radiation in 2018

Irradiation Source	Dose
γ (Gy)	1×10^{-2}
neutron (n/cm^2)	2.7×10^{6}
photon	2.5×10^{13}

- 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.

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 γ, 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 : γ, neutron and VUV light
   - Only PDE of VUV-MPPC irradiated by ionizing particles(γ, 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.
     - γ : ${}^{60}_{27}\mathrm{Co} \longrightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \gamma$ @ Takasaki Advanced Radiation Research Institute in Jan. 2015.
     - neutron: ${}^{9}\mathrm{Be} + d^{+} \rightarrow {}^{10}\mathrm{B} + n$ @ Kobe University tandem accelerator in Jan. 2015.

	Dose of Sample	MEG II Expected
γ (Gy)	1.4×10^{3} , 4.1×10^{3}	0.6
neutron (n/cm^2)	$4.8 \times 10^{9} - 2.0 \times 10^{12}$	1.6×10^{8}

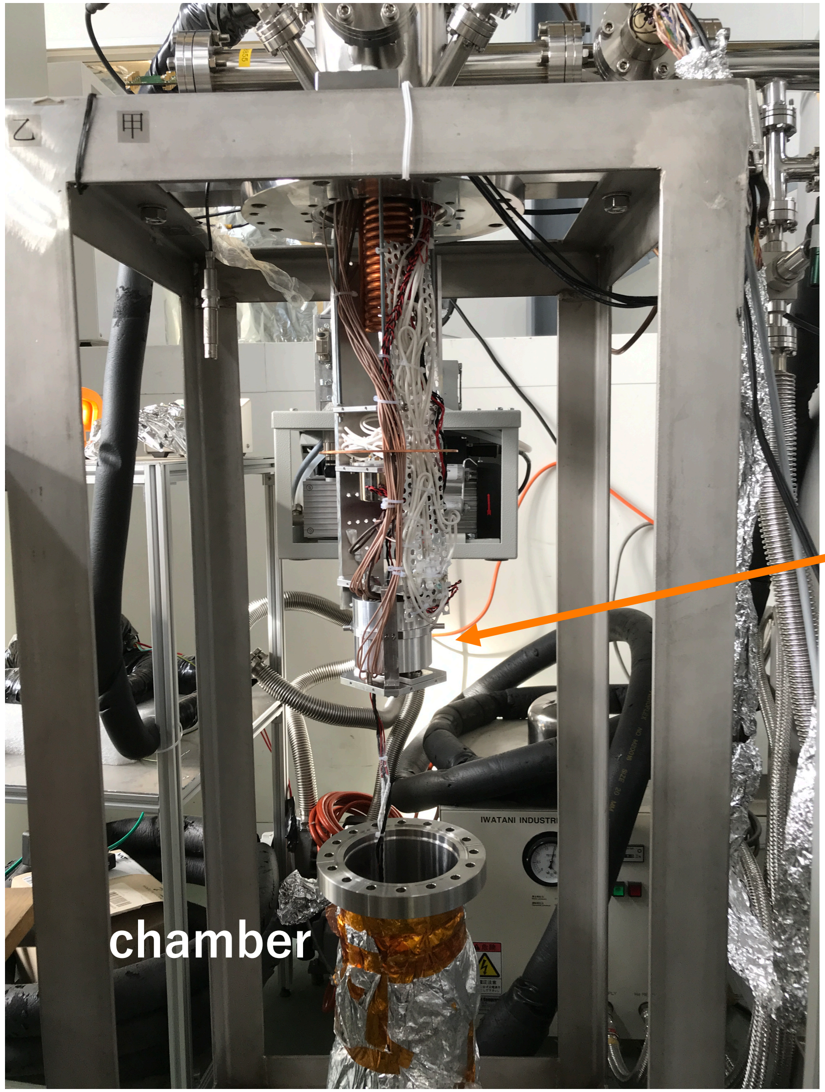
Dose levels of the samples are much larger than expected values of MEG II

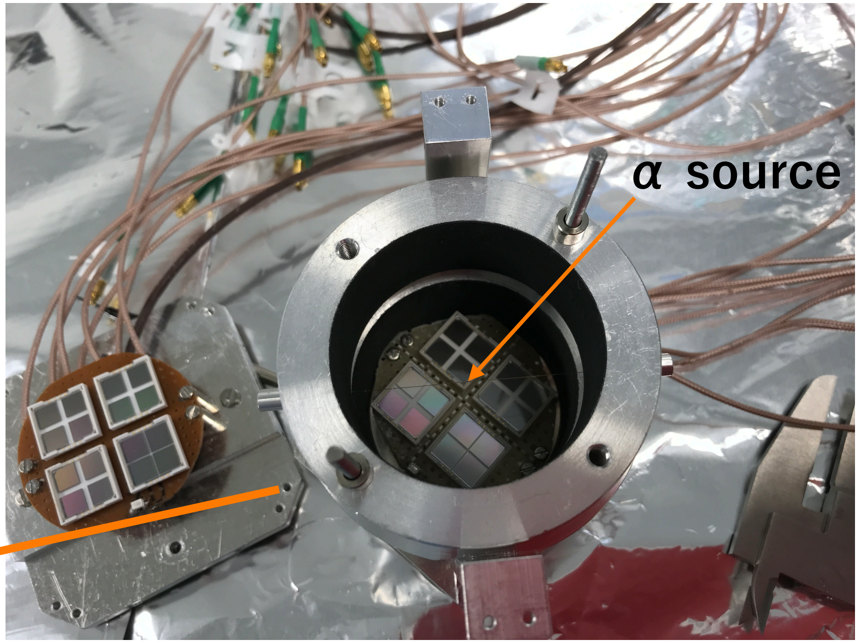
   - PDE was measured using scintillation light of LXe using α source

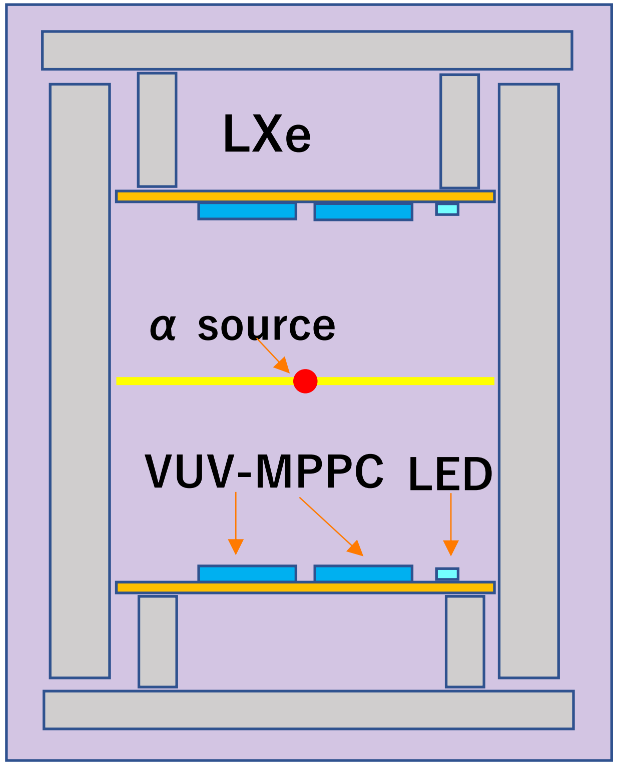
2. VUV light irradiated samples
   - A xenon lamp was used as a irradiation source.
   - PDE was measured using the xenon lamp.

PDE Measurement for γ/neutron Irradiated Samples

Setups



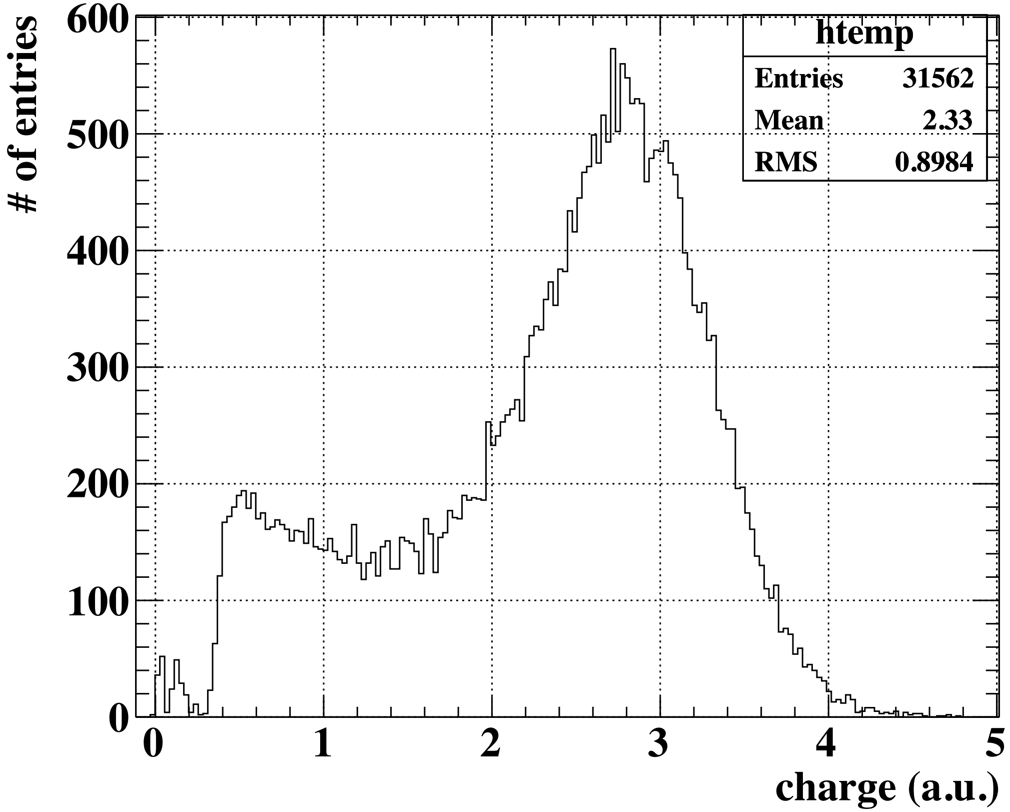




- MPPCs were installed in a chamber, which is filled with LXe.
  (two non-irradiated and six irradiated samples)
- α source was fixed in front of MPPCs.
- Signals were amplified with a amplifier and data was taken with a waveform digitizer.

PDE Measurement

Example of Charge Distribution



- 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.

$$N_{npho} = \frac{E_\alpha}{19.6\,\mathrm{eV}} \times \frac{\Omega}{4\pi}$$

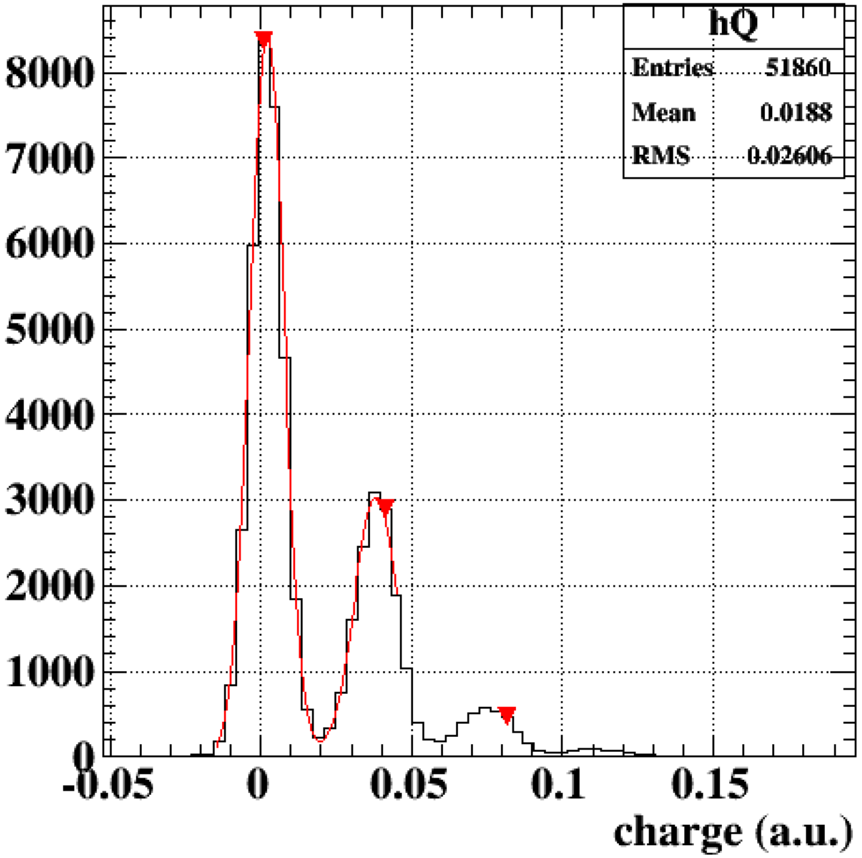
E_α : 4.78 MeV, $\frac{\Omega}{4\pi}$: ~0.4%

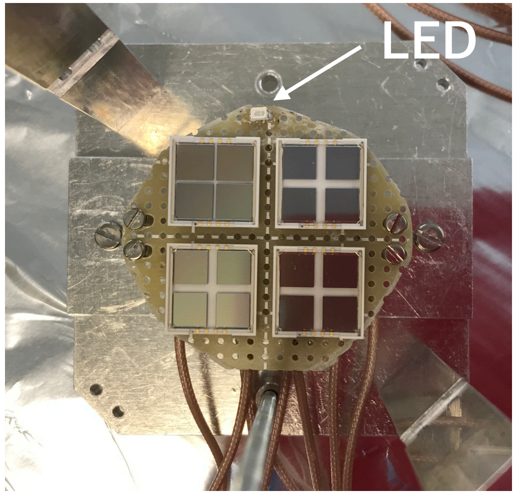
- The measured number of photons can be calculated from a peak of a charge distribution using calibration factors.

$$N_{\mathrm{pho}} = \frac{Q_\alpha}{(\mathrm{Gain}) \times (\mathrm{Excess\ Charge\ Factor})}$$

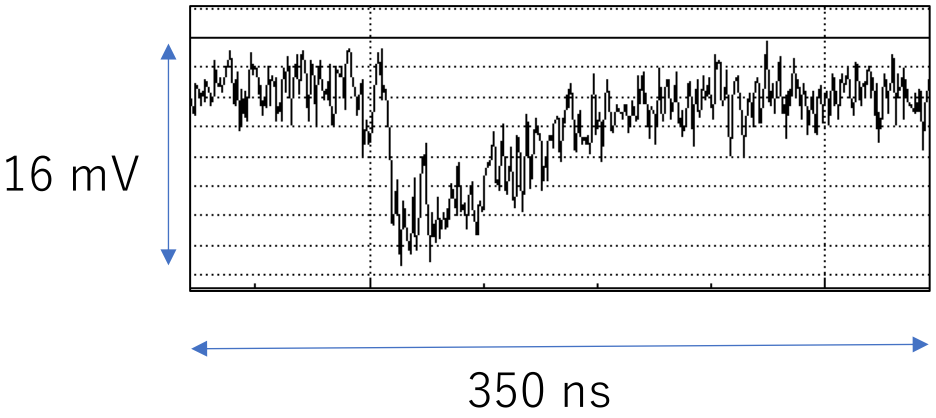
Calibration

Example of Charge Distribution





Example of Waveform

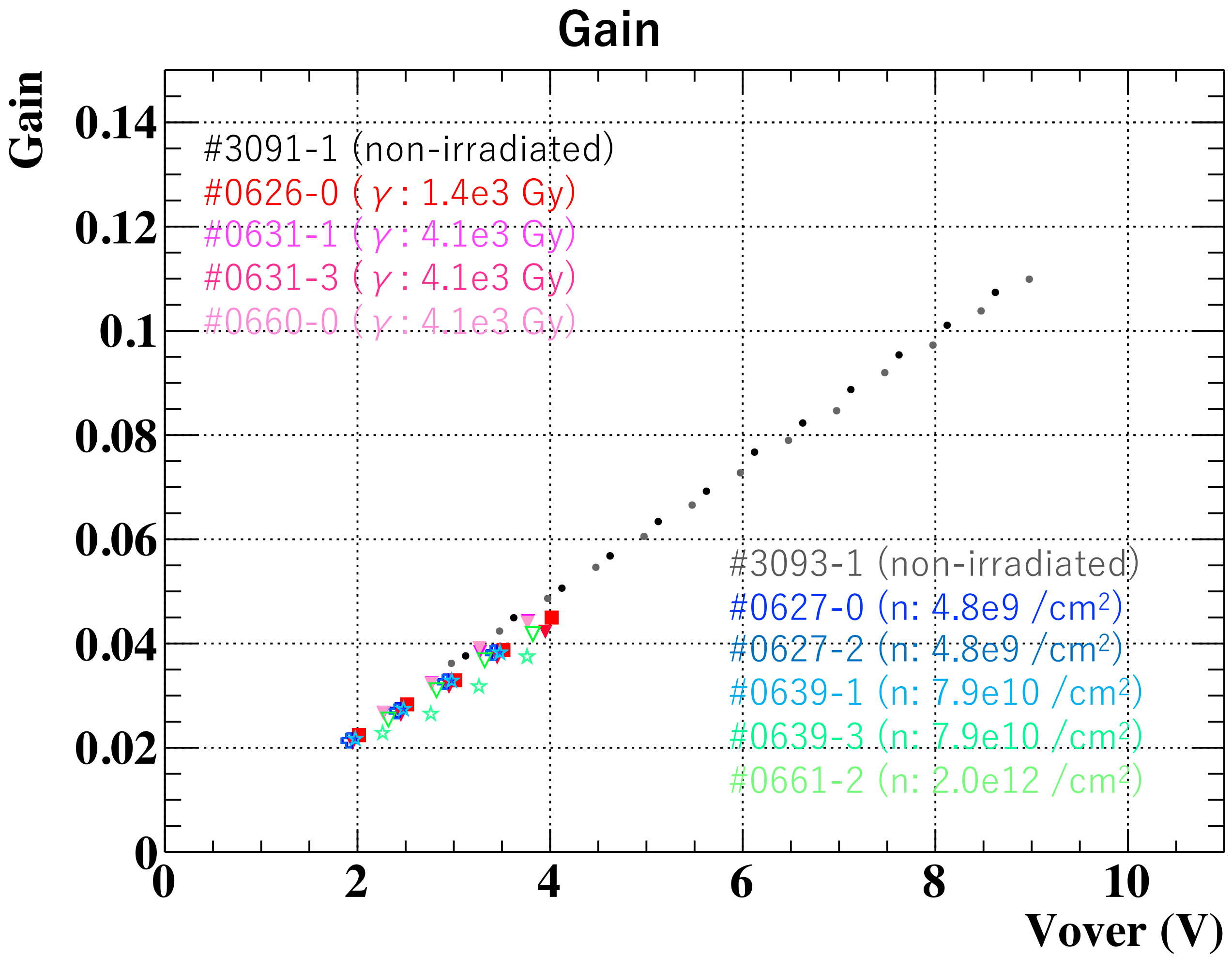


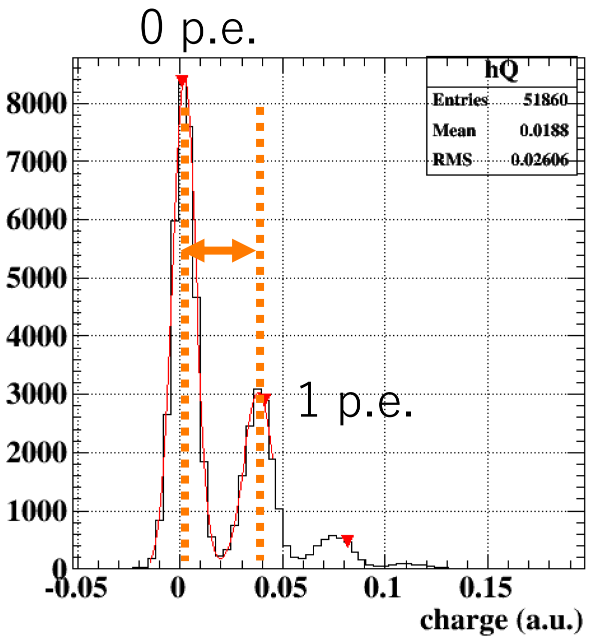
- The number of detected photons is calculated by

$$N_{\mathrm{pho}} = \frac{Q_{\alpha}}{(\mathrm{Gain}) \times (\mathrm{Excess\ Charge\ Factor})}$$

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

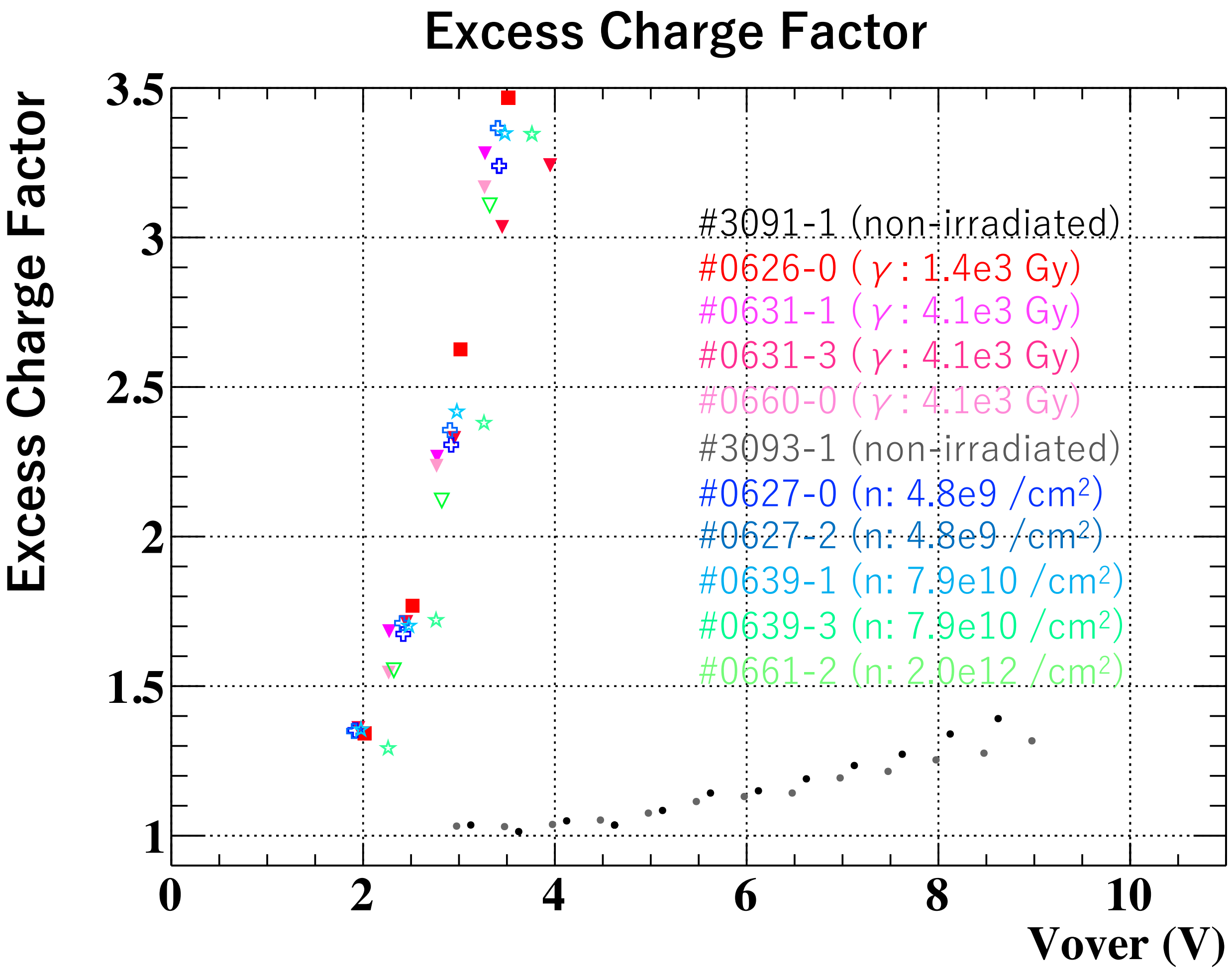
Gain





- 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_{over} were observed.

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.

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

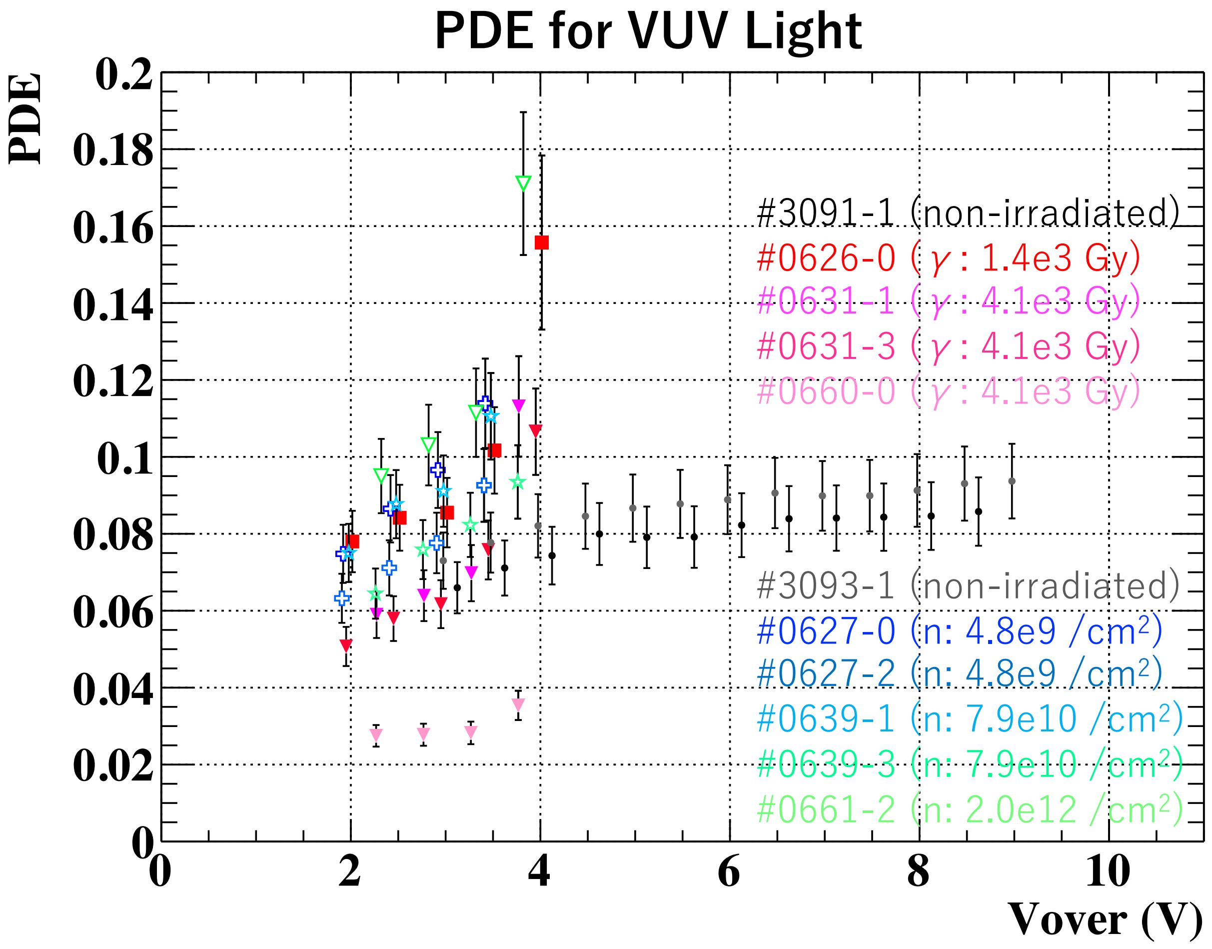
μ : mean of measured distribution

- 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_{over} get larger as expected.
- Clear difference b/w proto-type and final version was observed.

PDE for VUV Light



※Errors include statistic errors and a systematic error of W value (10%)

- **PDE degradation was not observed for all irradiated samples.**
- Overall PDE were lower than those of the previous measurements (14-20%)
  ← 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.
    ← there might be a certain damage in the surface except for radiation damage.

PDE Measurement for VUV Light Irradiated Samples

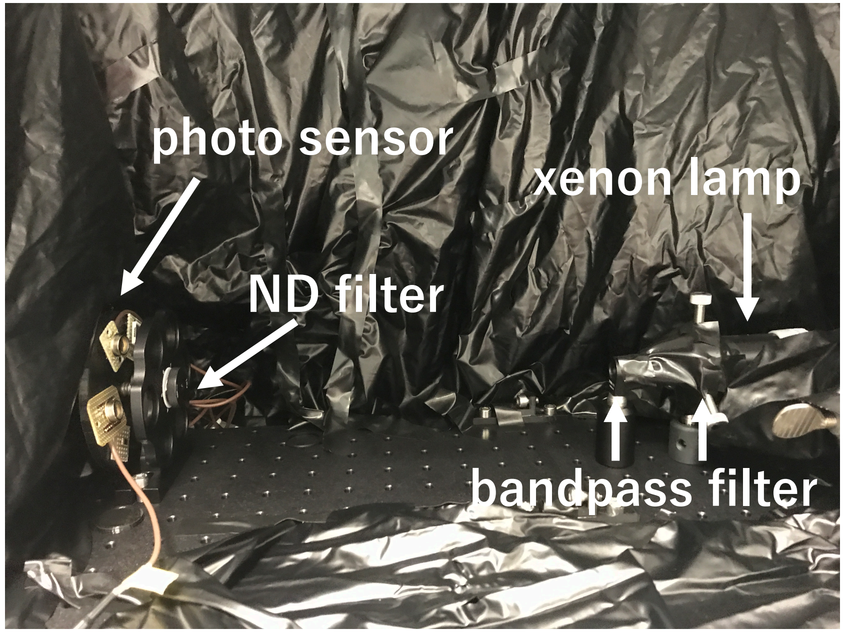
VUV Light Irradiation

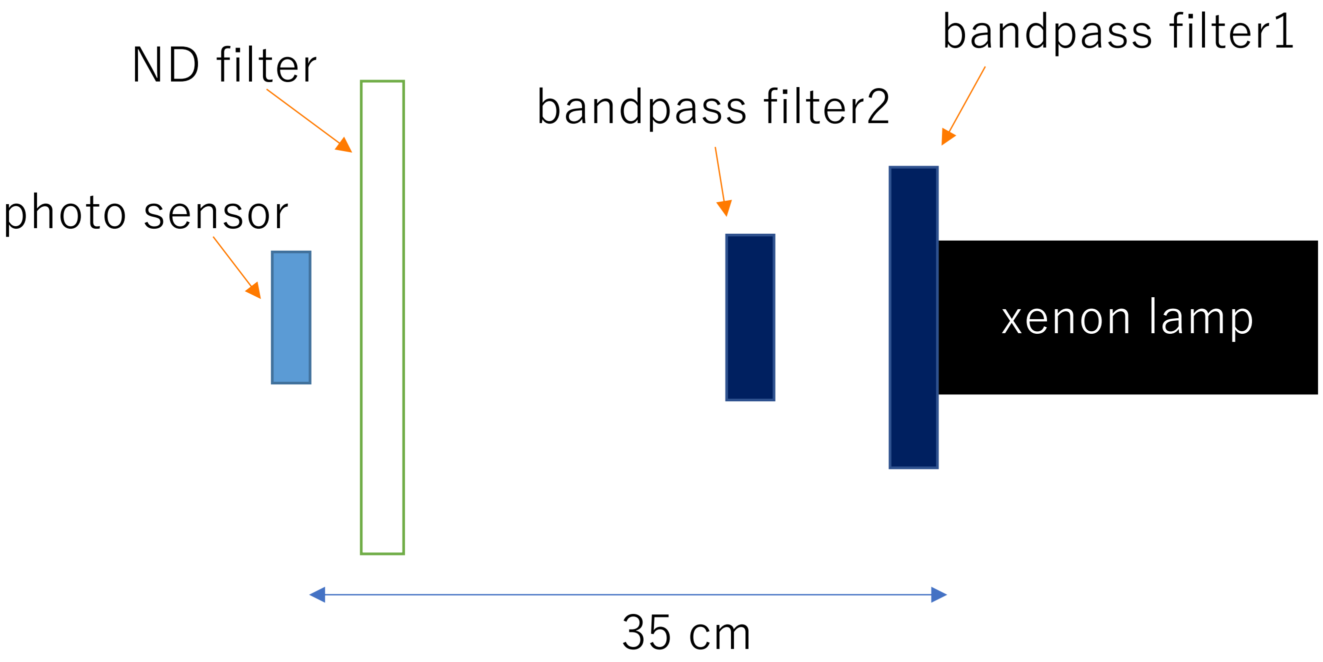
- A xenon lamp was used for irradiation.
- Stability of light was monitored by measuring current of SiPD, which is tolerant to UV light (S12698-02, Hamamatsu).
- VUV-MPPC and SiPM which is not sensitive to VUV light (S13350-3050PE) were irradiated.
- Charges of irradiated and non-irradiated samples were measured using the xenon lamp.
- Only PDE of VUV-MPPC is supposed to be deteriorated.

Xenon Flash Lamp:
L4633-01(Hamamatsu)

Setups

Irradiation/PDE measurement for VUV light



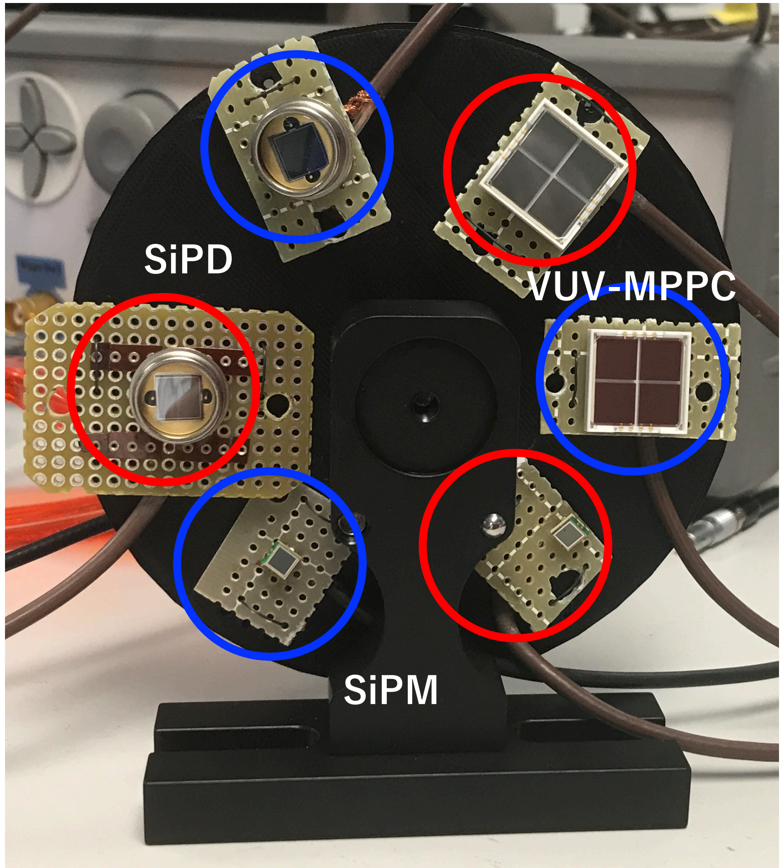


Light from the xenon lamp enters after passing through filters.

- bandpass filter : to select VUV light
  λ_1= 193.0 nm, T_1= 26%, $FWHM_1$= 20.0 nm
  λ_2= 181.0 nm, T_2= 28.2%, $FWHM_2$= 38.5 nm
- ND filter : to reduce light

Setups

w/o filters



w/ filters

irradiated

non-irradiated

- 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.

Radiation Effects

- Total dose was ~2.7e13 photons.
  ← ~2.5e13 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 ± 0.13
  - SiPM : 0.99 ± 0.14
- Expected PDE deterioration was ~10%.
  → **Uncertainties of the measurements are too large to conclude the effects.**
- The large uncertainties result from position dependence of light of the xenon lamp.
  ← The xenon lamp seemed to be deteriorated.
- Improvement of setups is planned:
  using a new xenon lamp, using scintillation light from Xenon

Summary

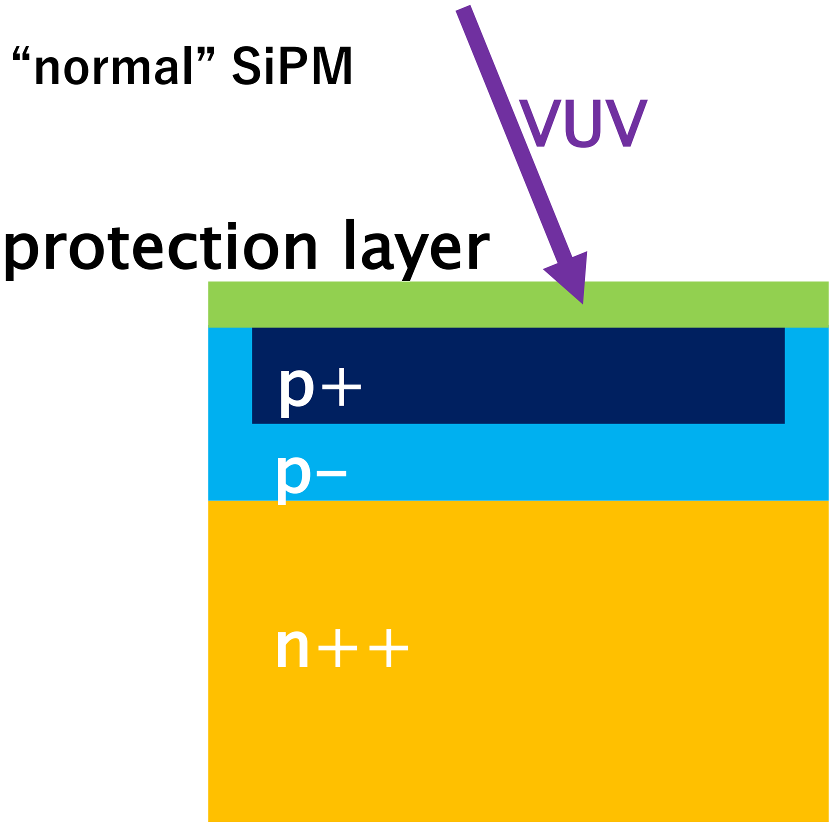
- PDE of γ/neutron irradiated samples were measured using scintillation light from α source.
  - Dose levels were much higher than expectation of MEG II experiment.
  - **No radiation effect on PDE for VUV light was observed**.
    ← The result does not support the hypothesis.

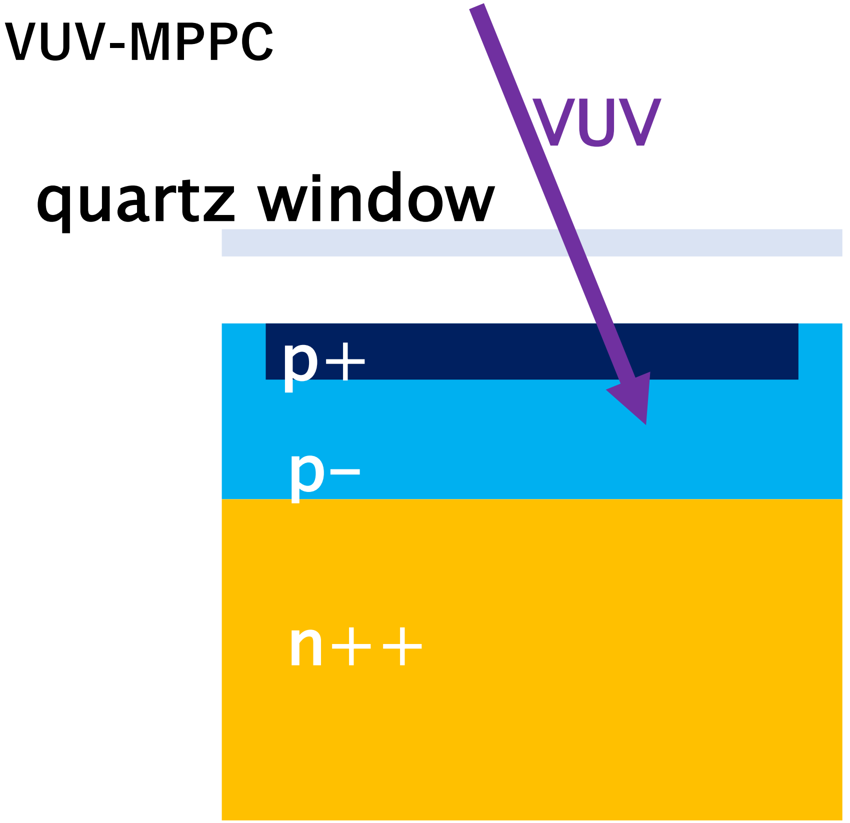
- PDE measurements for VUV light samples were performed using a xenon lamp.
  - Total dose was 2.7e13 photons, which is equivalent to the dose level of beam time 2018.
  - **PDE deterioration could not be concluded from the results** due to a large position dependence of light distribution.
    ← Setups 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

VUV–MPPC



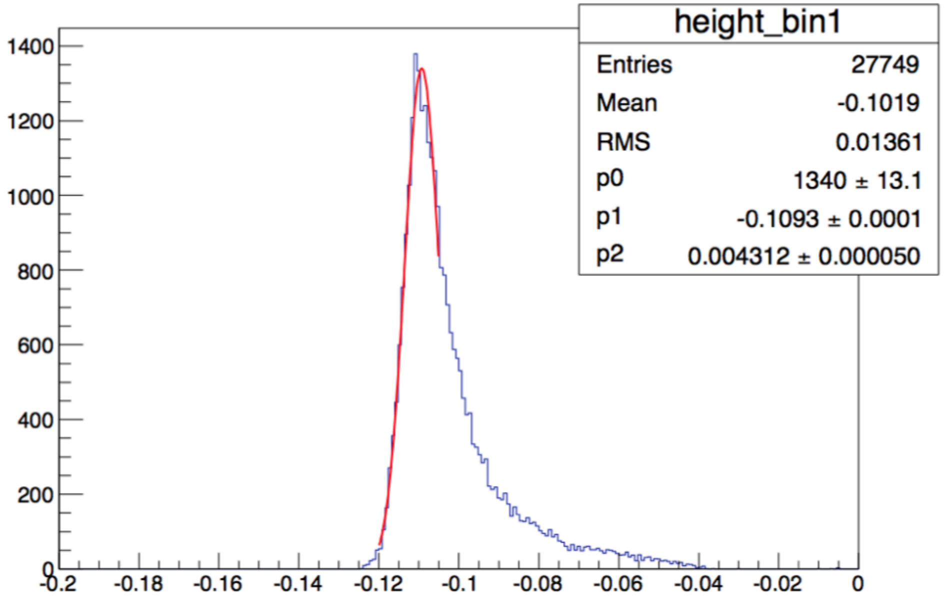


- Normal SiPM is insensitive to VUV light because its protection layer and thick p+ layer absorb VUV light before reaching p- layer.
- VUV-MPPC has quartz window to protect its surface instead of the protection layer and thinner p+ layer.

α Source

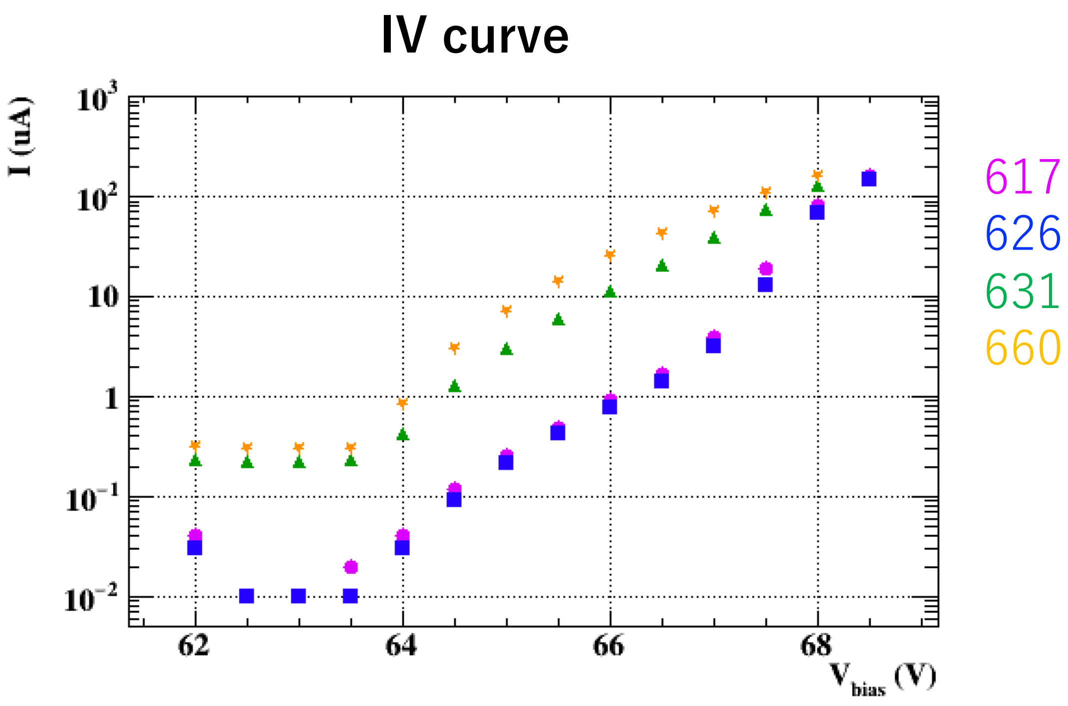
SSB Detector

Energy Distribution



- 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.

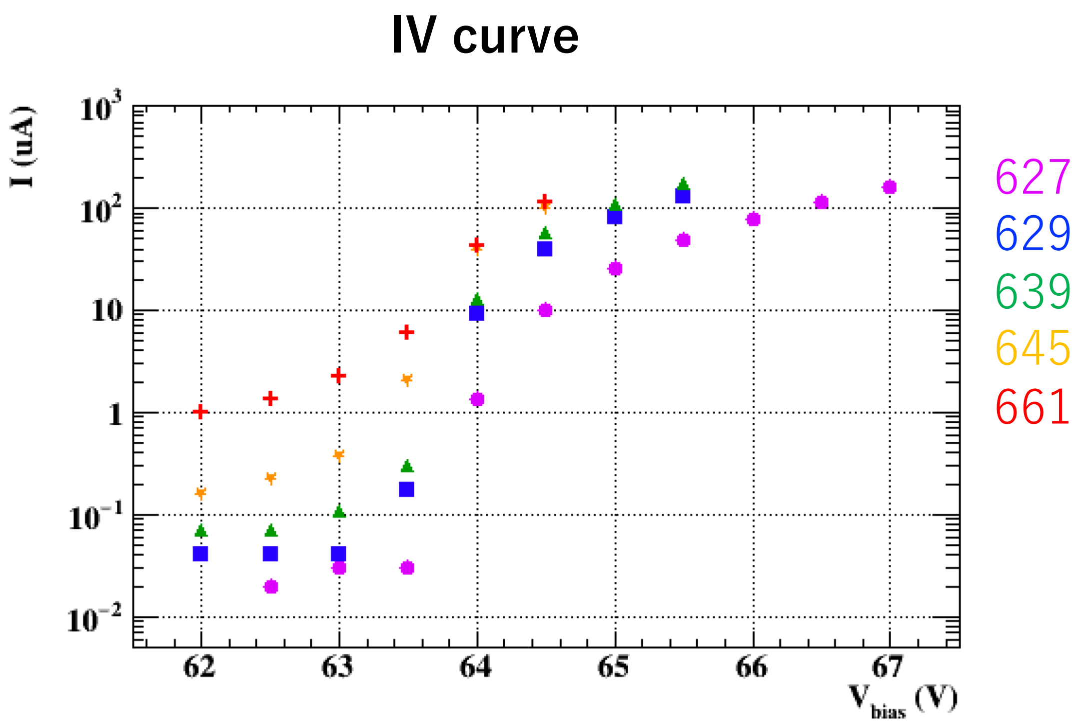
IV Measurement (γ)



Dose (Gy)	Serial Number
1.4×10^3	617
1.4×10^3	626
4.1×10^3	631
4.1×10^3	660

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

IV Measurement (Neutron)

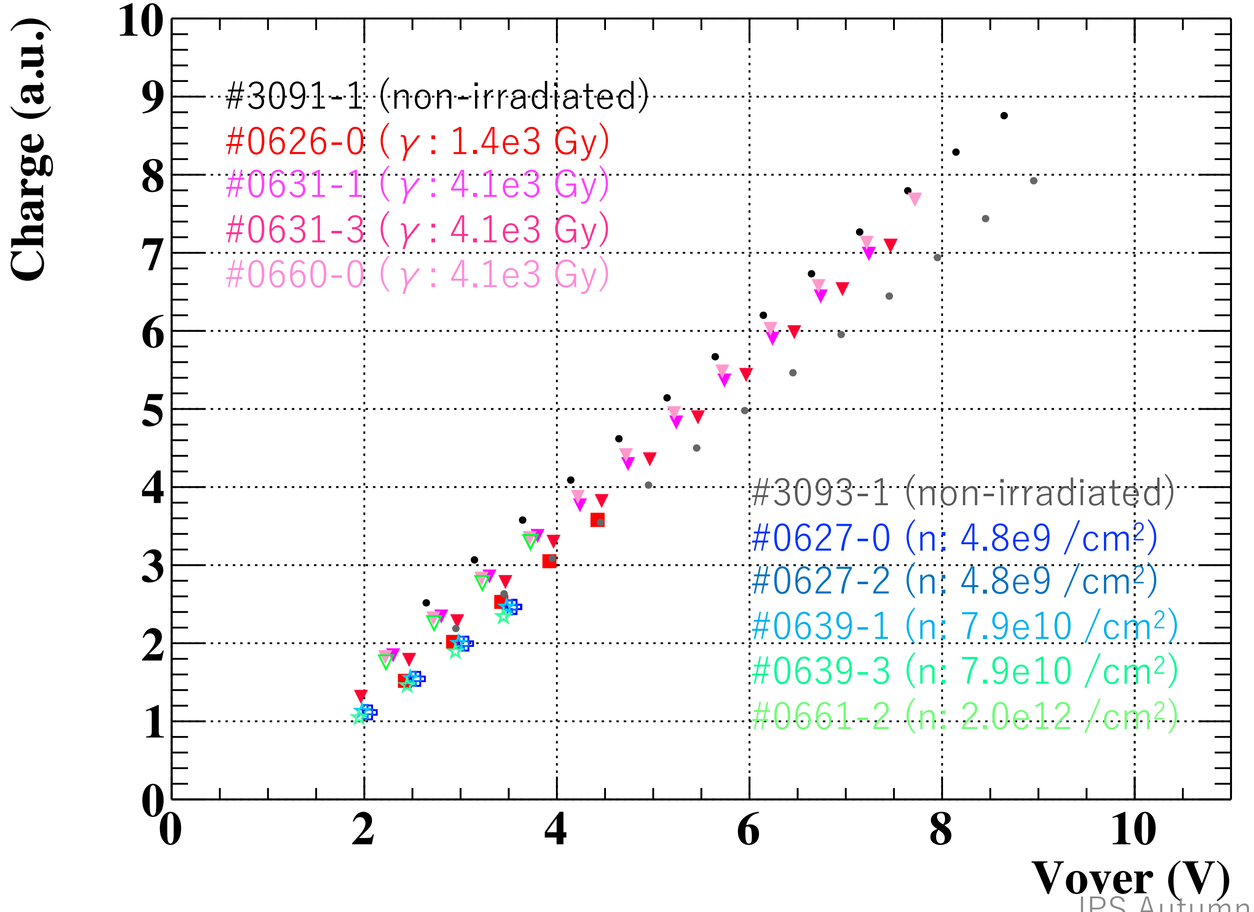


Dose (n/cm²)	Serial Number
4.8×10^9	627
4.4×10^{10}	629
7.9×10^{10}	639
2.6×10^{11}	645
2.0×10^{12}	661

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

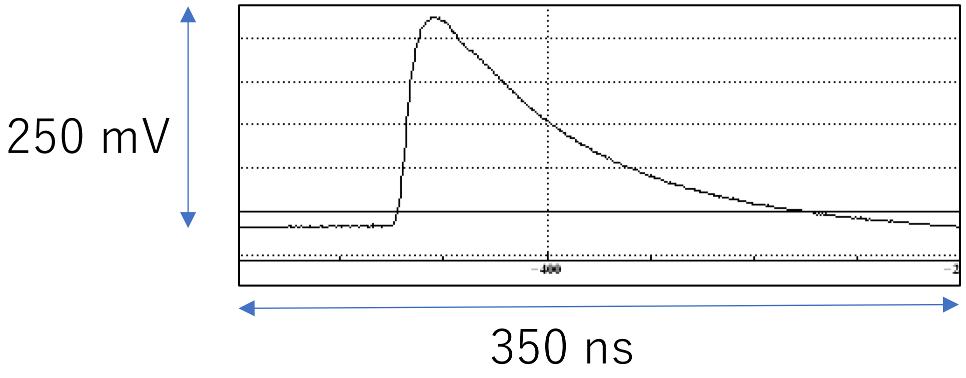
Response to Visible Light

Measured Charge of LED



※no correction was applied.

Example of Waveform

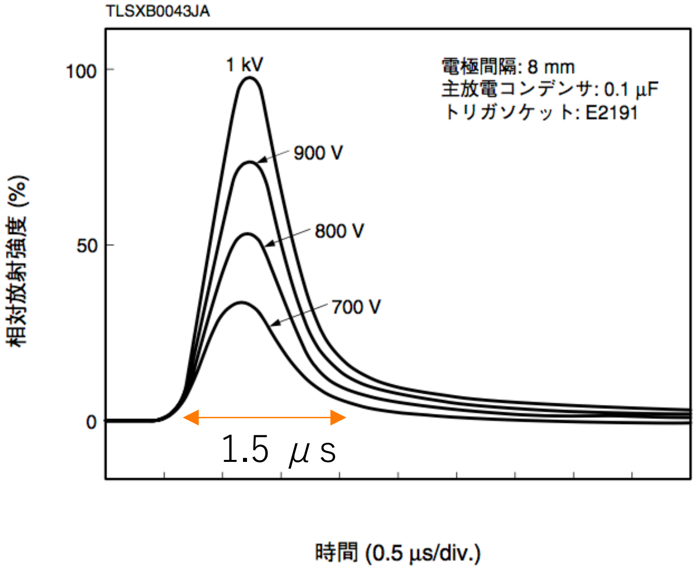


- Responses to visible light at low temperature were also checked by comparing charges of strong LED light.
- There is no apparent difference.
- Even the sample whose PDE for VUV light is lower has the similar PDE for visible light. ←there might be a certain damage in the surface?

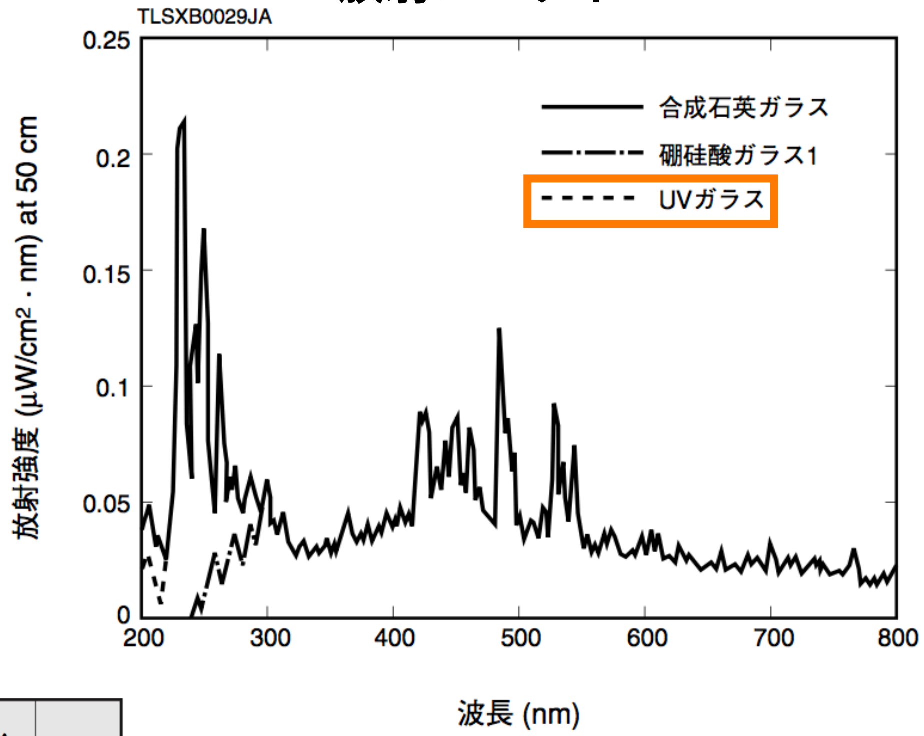
VUV Light (Xenon Flash Lamp)

L4633-01(Hamamatsu)

発光パルス波形

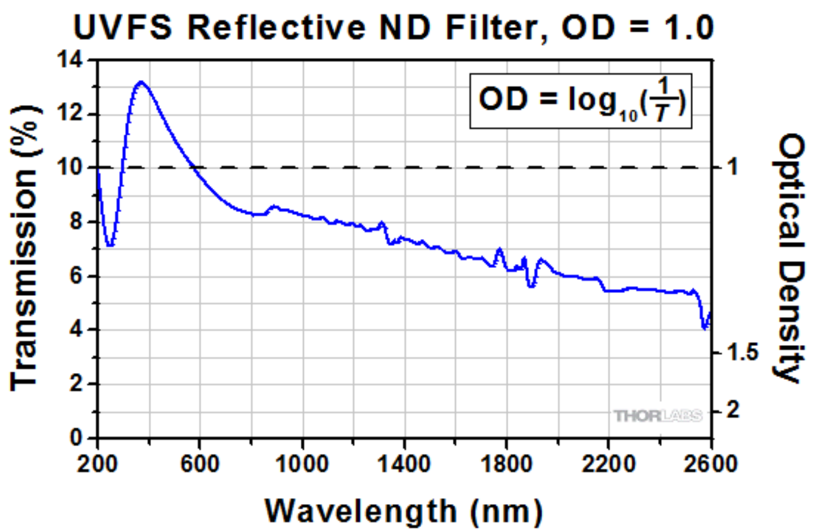


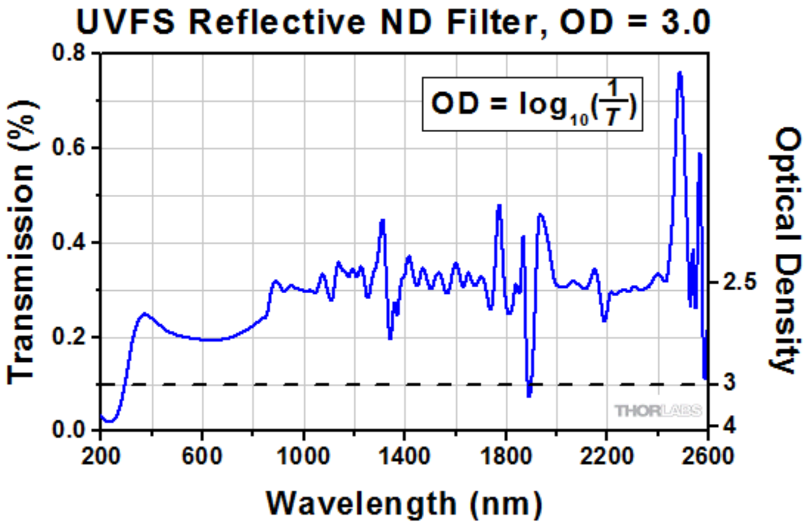
放射スペクトル

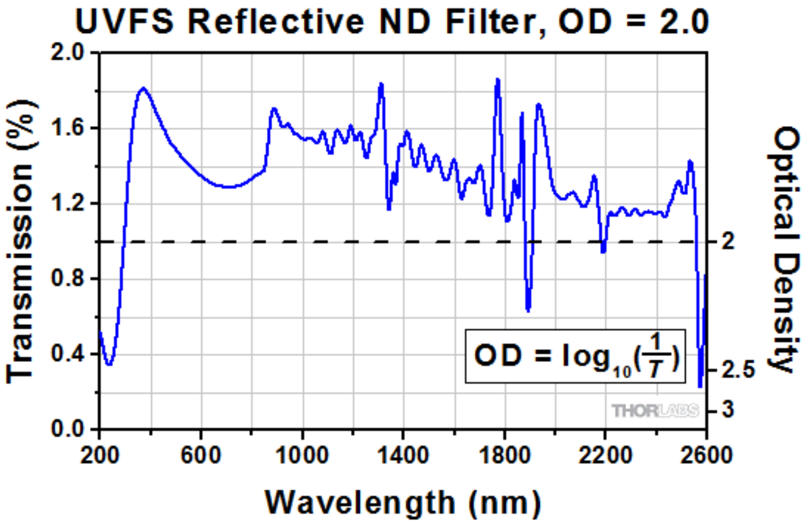


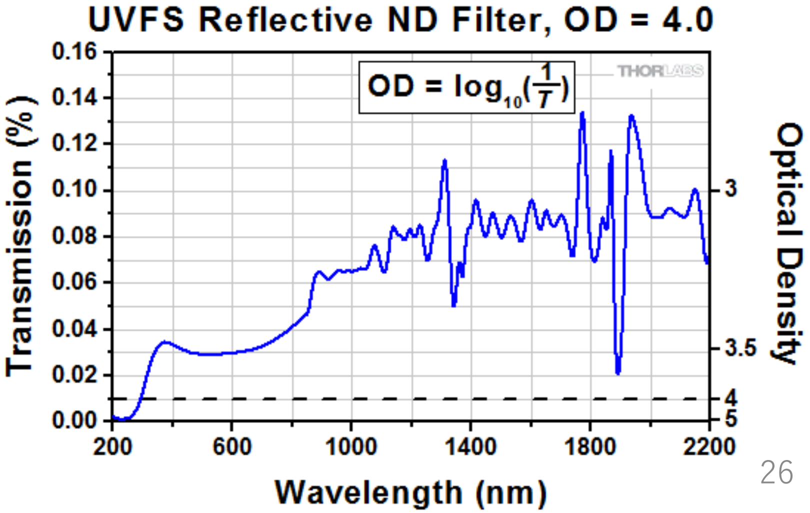
型名	アークサイズ (mm)	外形寸法図	出射光	窓材	放射波長 (nm)	推奨主放電電圧 (V dc)	トリガ電圧 p-p (kV)	最大平均入力 [連続] (W)	最大平均入力エネルギー [1フラッシュ] (J)	発光繰り返し周波数 Max. (Hz)	光出力安定性 Ⓐ Max. (%)	動作寿命 ⒶⒷ Min. (フラッシュ)	冷却方法	適合トリガソケット	他社相当品
L4633	1.5	❶	集光	硼硅酸ガラス	240 ～ 2000	700 ～ 1000	5 ～ 7	15	0.15	100	5	5 × 10^8	自然空冷	E4370-01	—
L4633-01*				UVガラス	185 ～ 2000										
L4634		❷	平行光	硼硅酸ガラス	240 ～ 2000										
L4634-01*				UVガラス	185 ～ 2000										

Spec of ND Filters

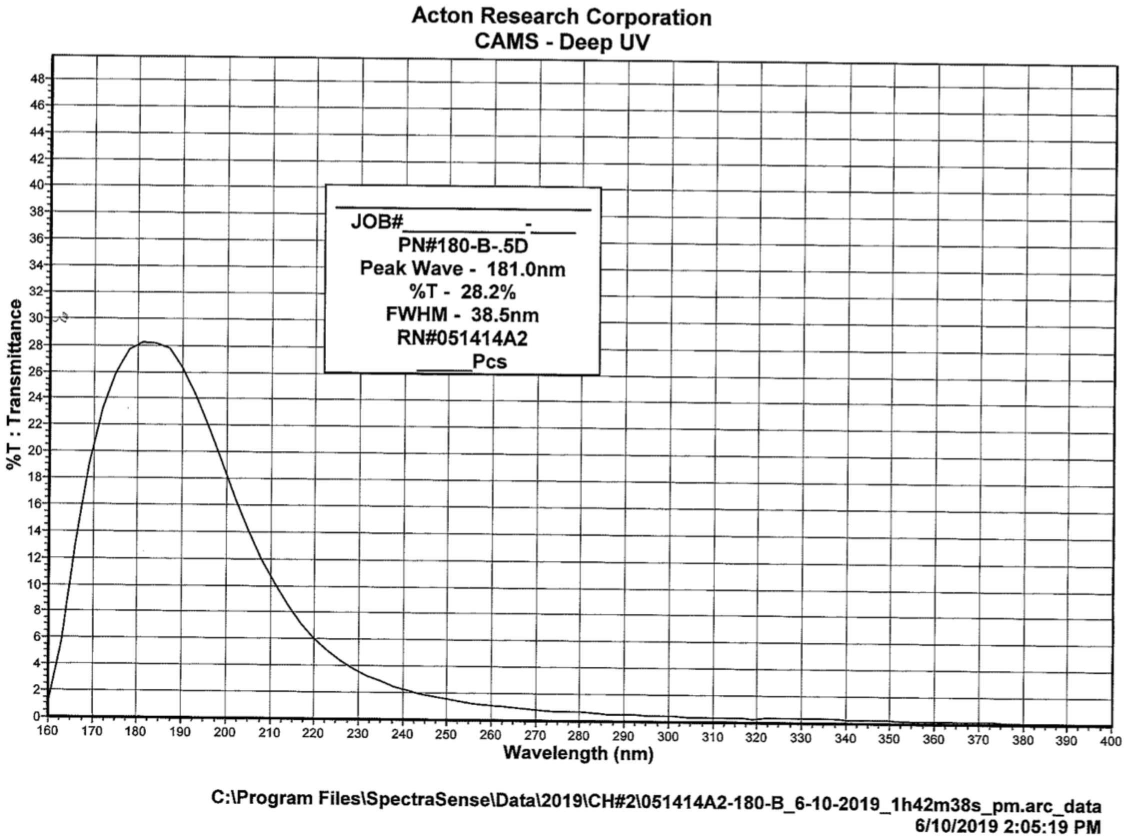


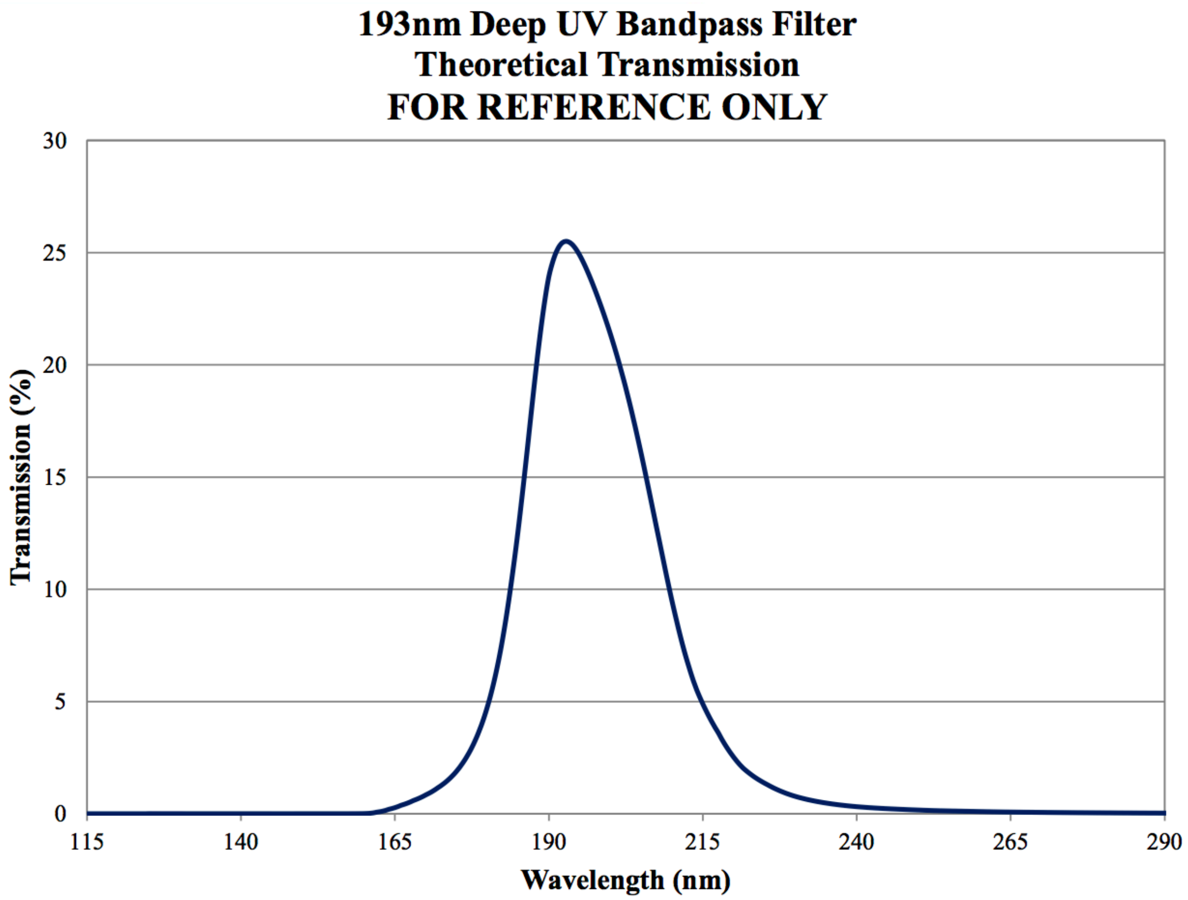






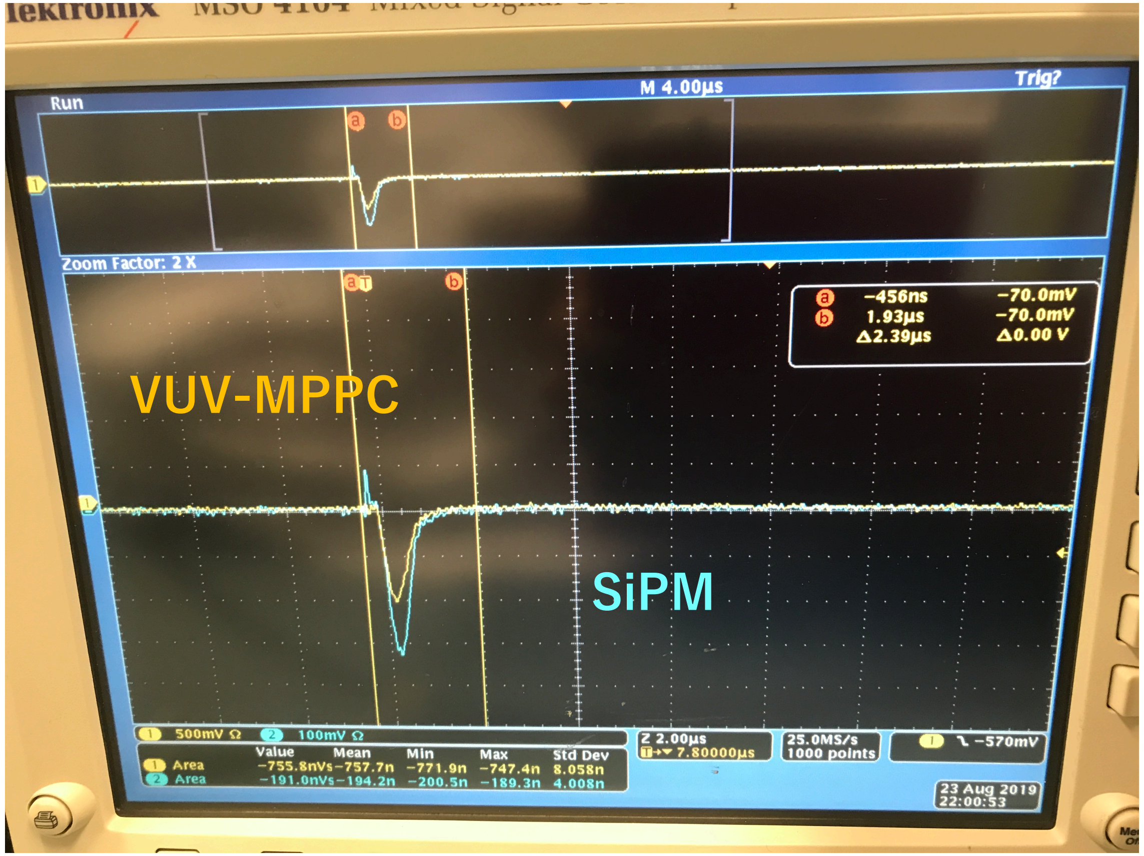
Spec of Bandpass Filters





Waveform of Xenon Lamp

Example of Waveform

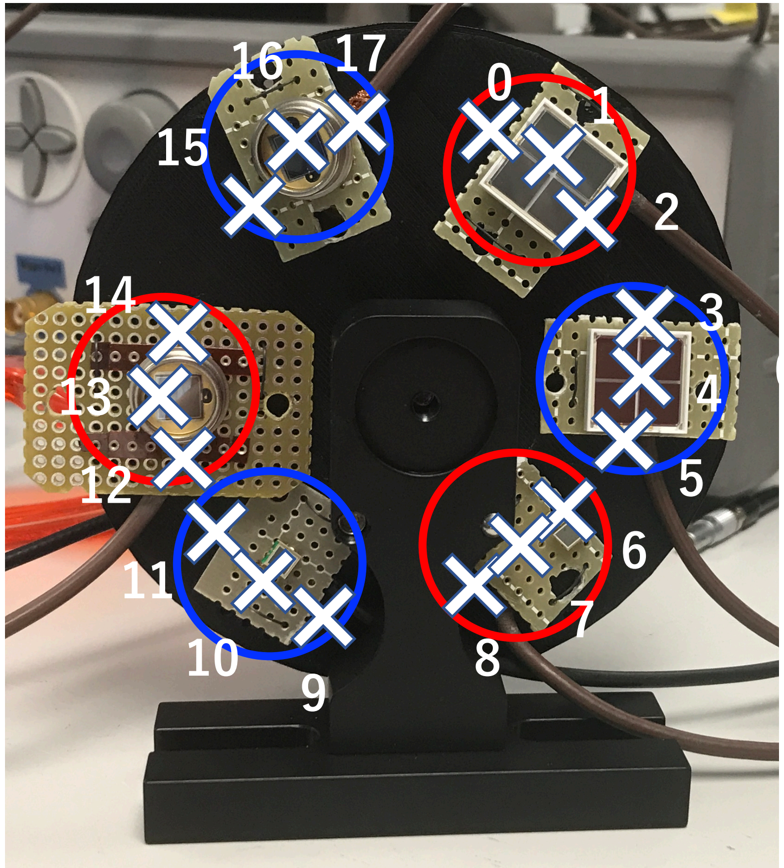


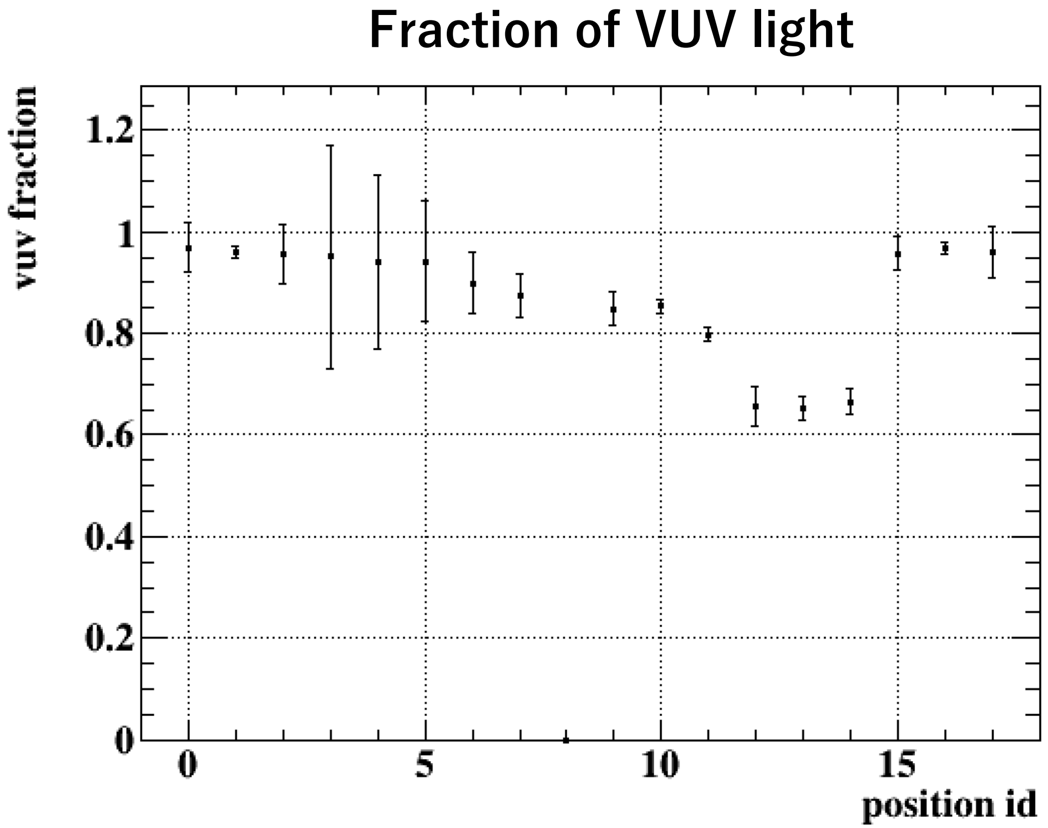
	VUV-MPPC	SiPM
Charge (a.u.)	8.8	5.0
Transmission	0.41%	24%
Size	6 × 6 mm^2	3 × 3 mm^2

※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

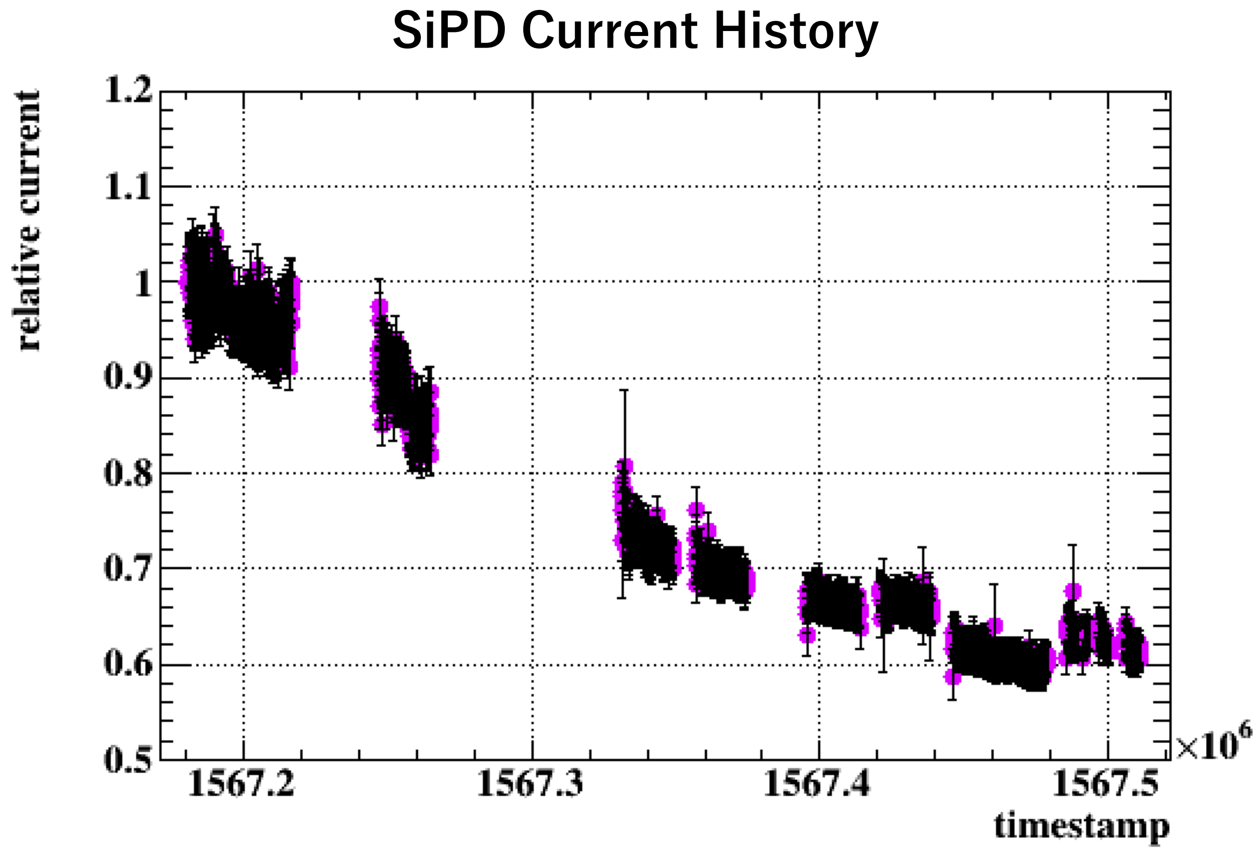


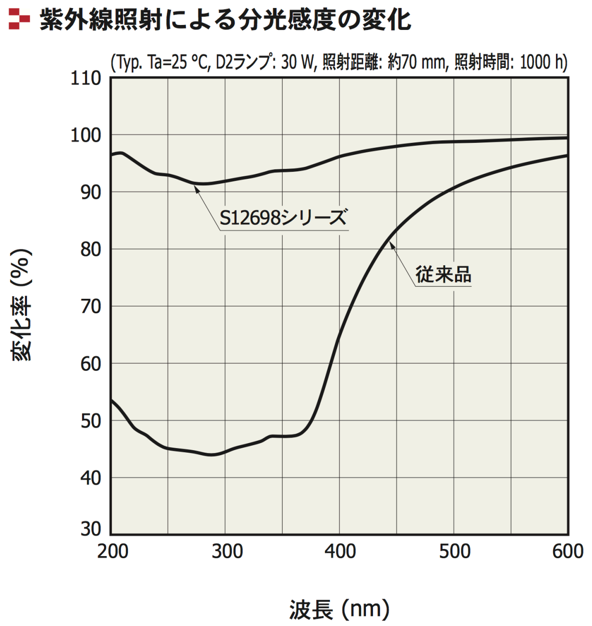


- Fraction of VUV light was checked before starting irradiation.
- There found to be a large position dependence.
- It was 0.65-0.98 depending on position.

← Not a problem as long as it is stable.

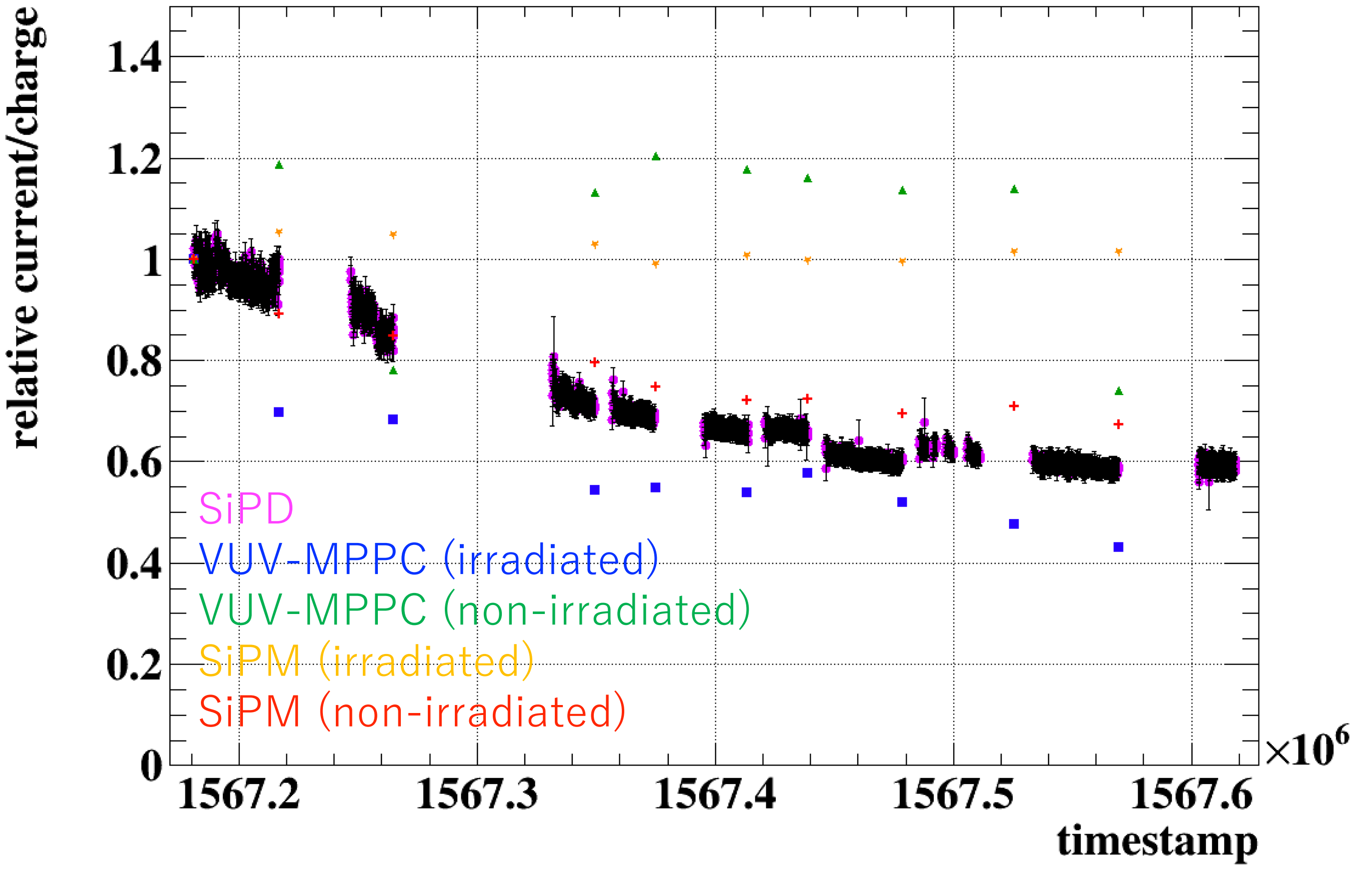
Stability of Xenon Lamp





- 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.

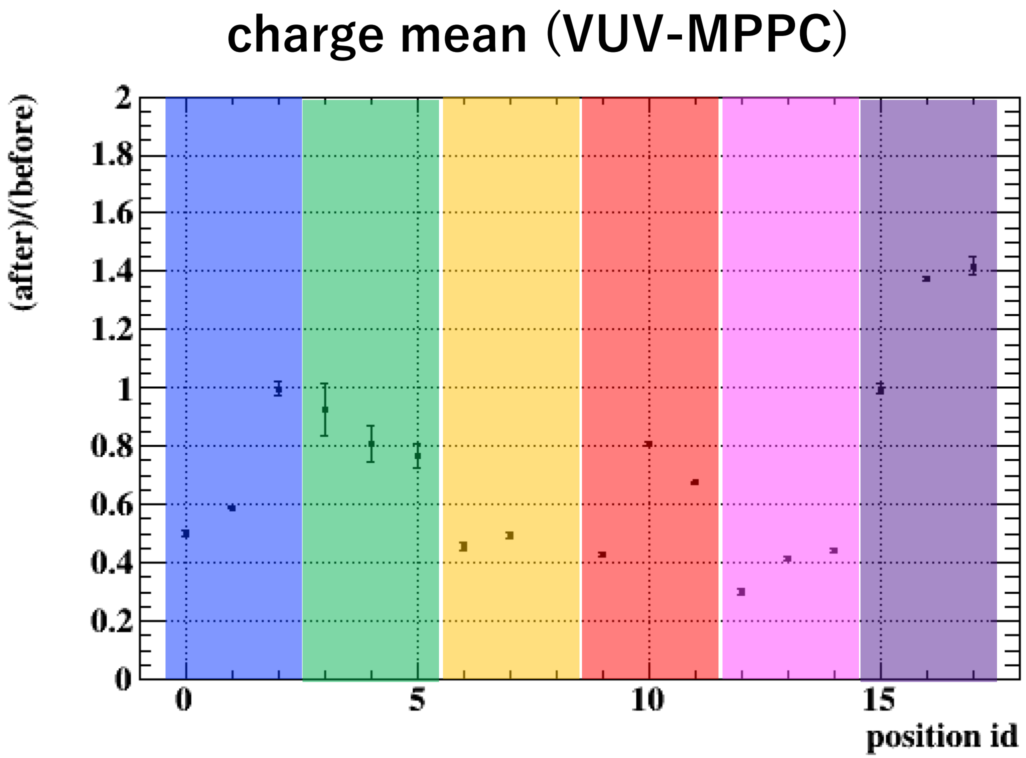
Charge History

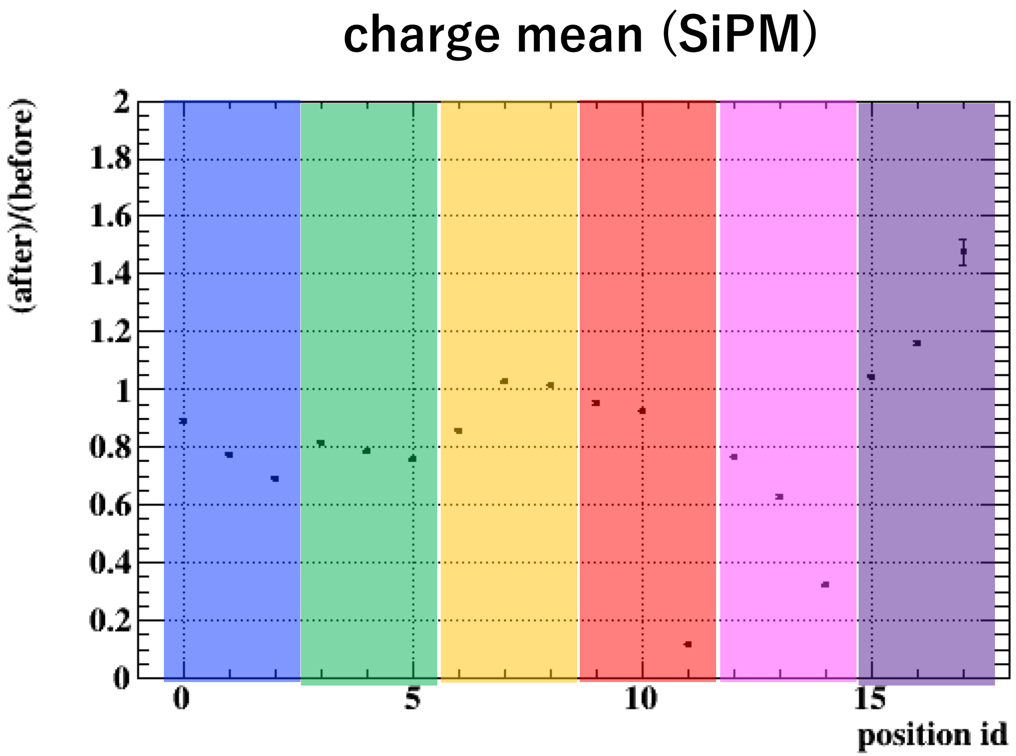


- Total dose of irradiated VUV-MPPC was ~2.7e13 photons.
- A decrease of charge were also observed for irradiated and even non-irradiated VUV-MPPC.
- However, charge of non-irradiated SiPM also decreased while that of irradiated SiPM was stable.

Position dependence of the xenon lamp deterioration is suspicious.

Charge Before and After Irradiation





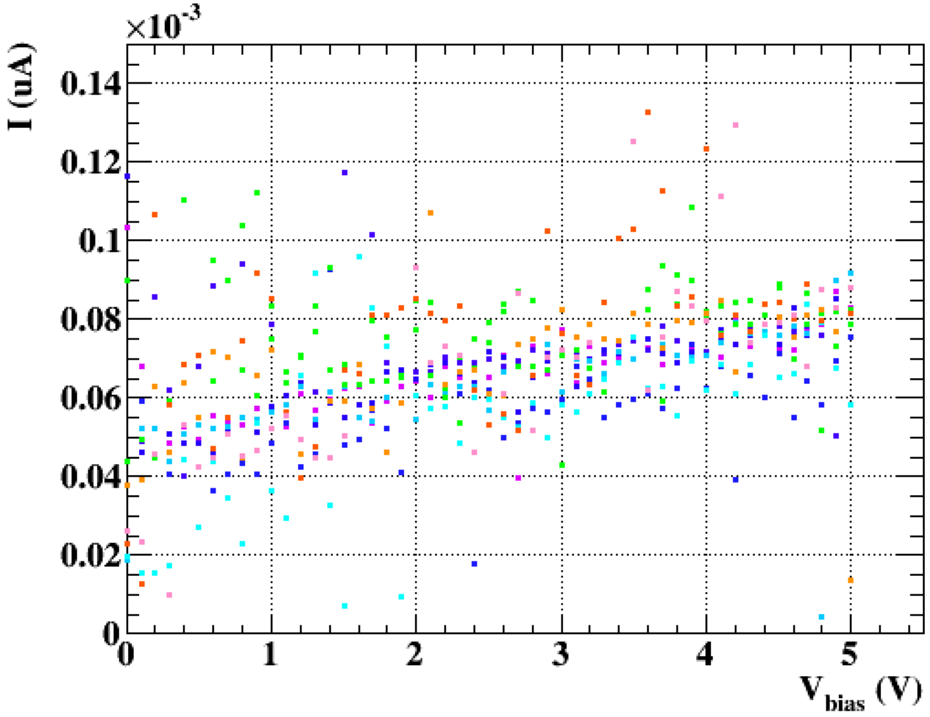
- Light distribution changed during irradiation.
  - VUV light at the position of VUV-MPPCs decreased.
  - Visible light at the position of non-irradiated SiPM had a large drop.
- The charge decrease was greatly affected by the decrease of light.

Sensor at the positions
- VUV-MPPC (irradiated)
- VUV-MPPC (non-irradiated)
- SiPM (irradiated)
- SiPM (non-irradiated)
- SiPD (irradiated)
- SiPD (non-irradiated)

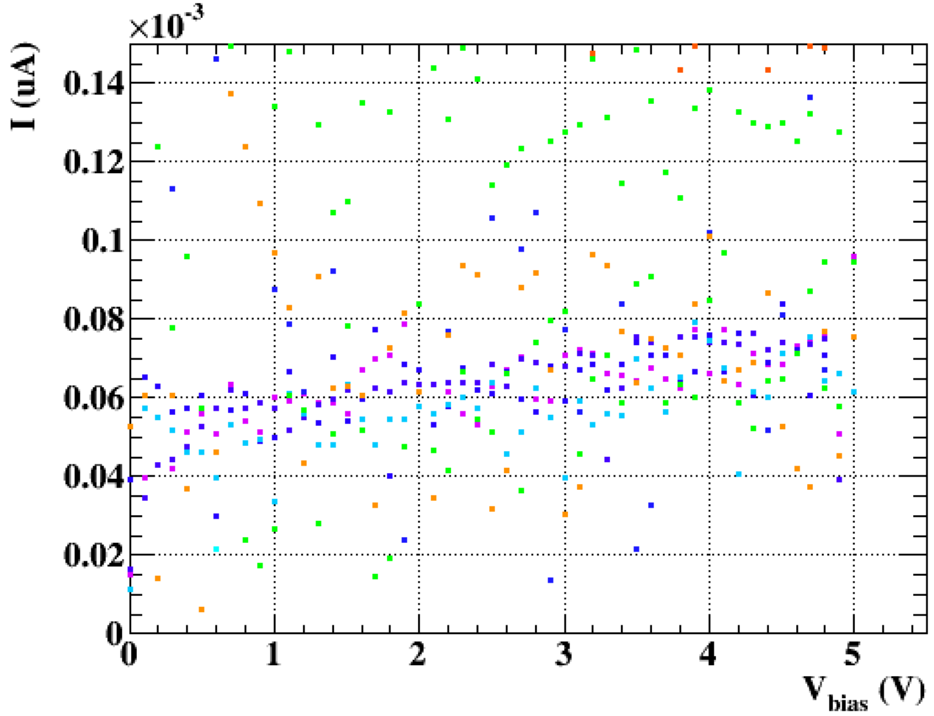
IV Curve (SiPD)

※with LED

IV (irradiated)



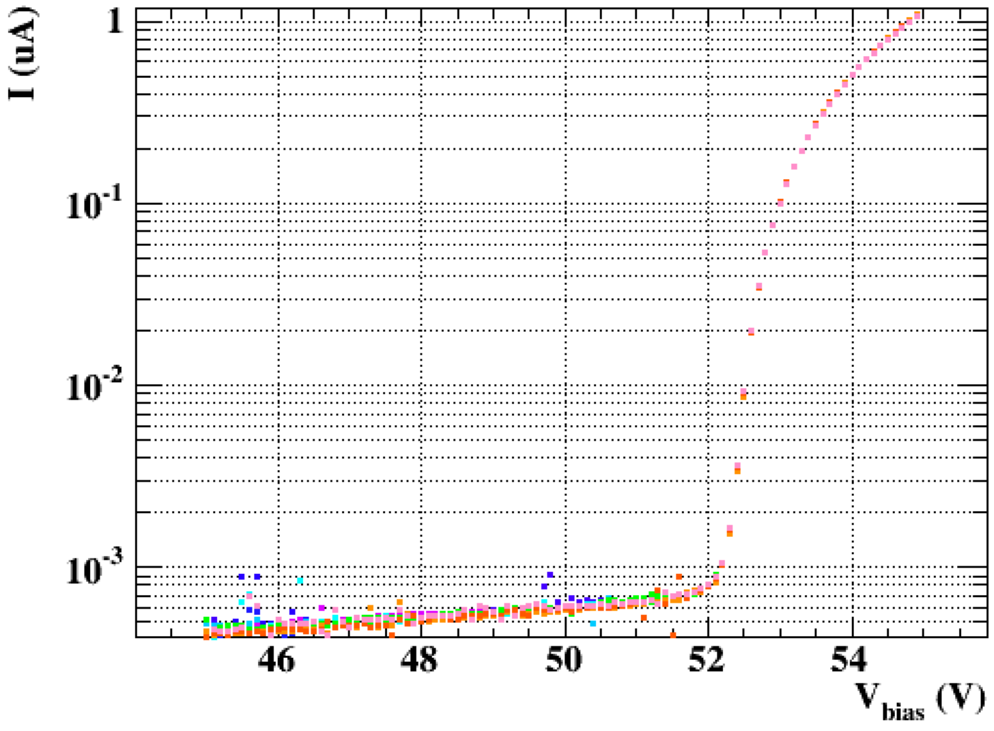
IV (non-irradiated)



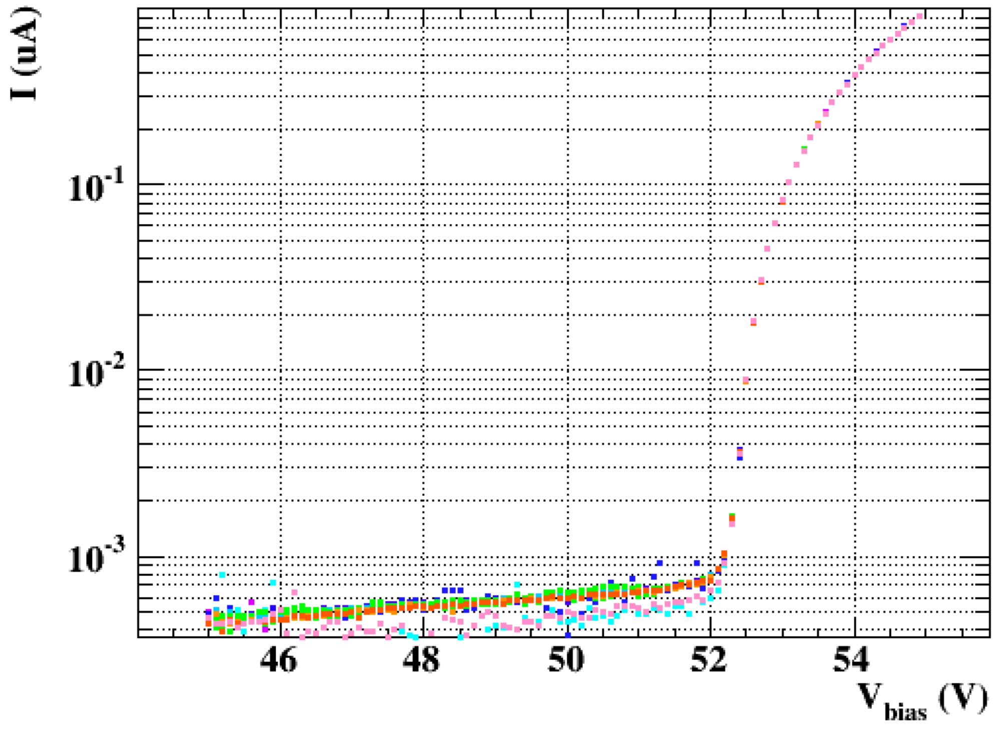
- No apparent difference

IV Curve (VUV-MPPC)

IV (irradiated)



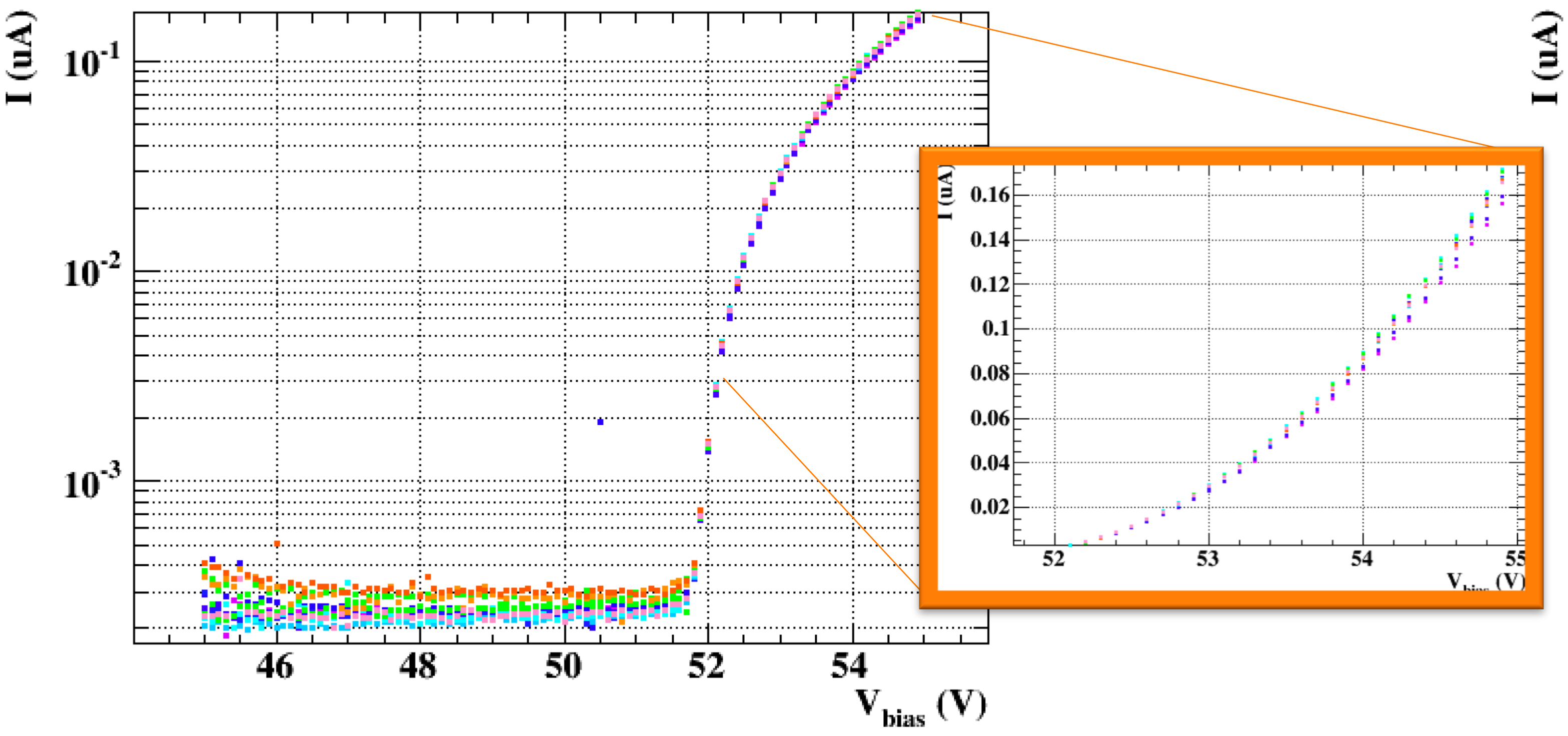
IV (non-irradiated)



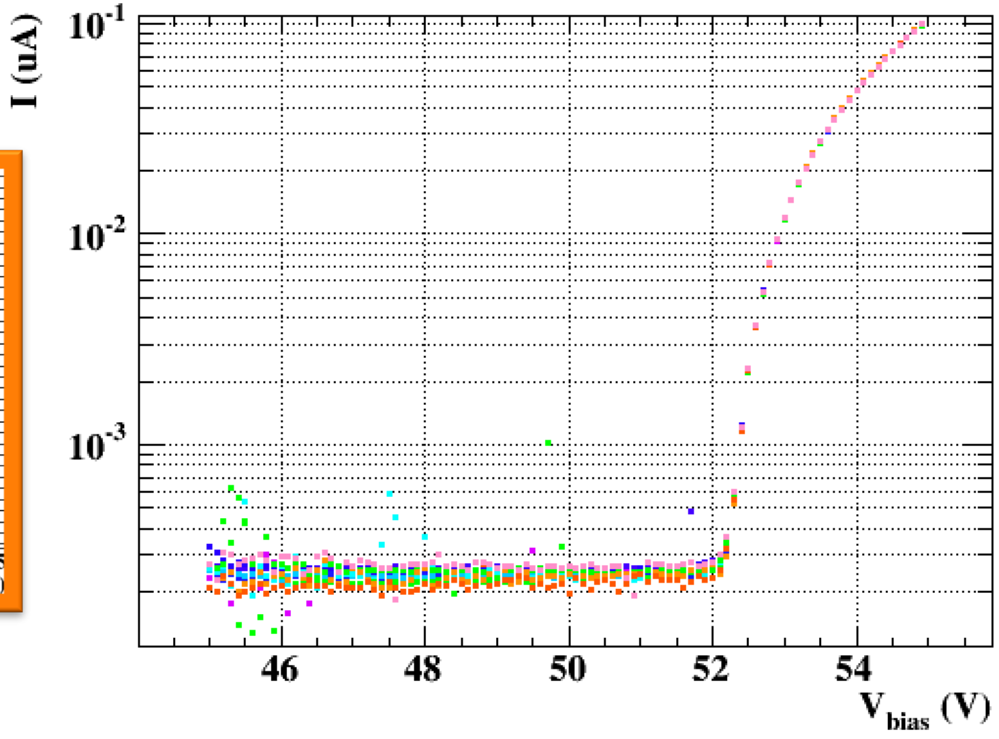
- No apparent difference

IV Curve (SiPM)

IV (irradiated)

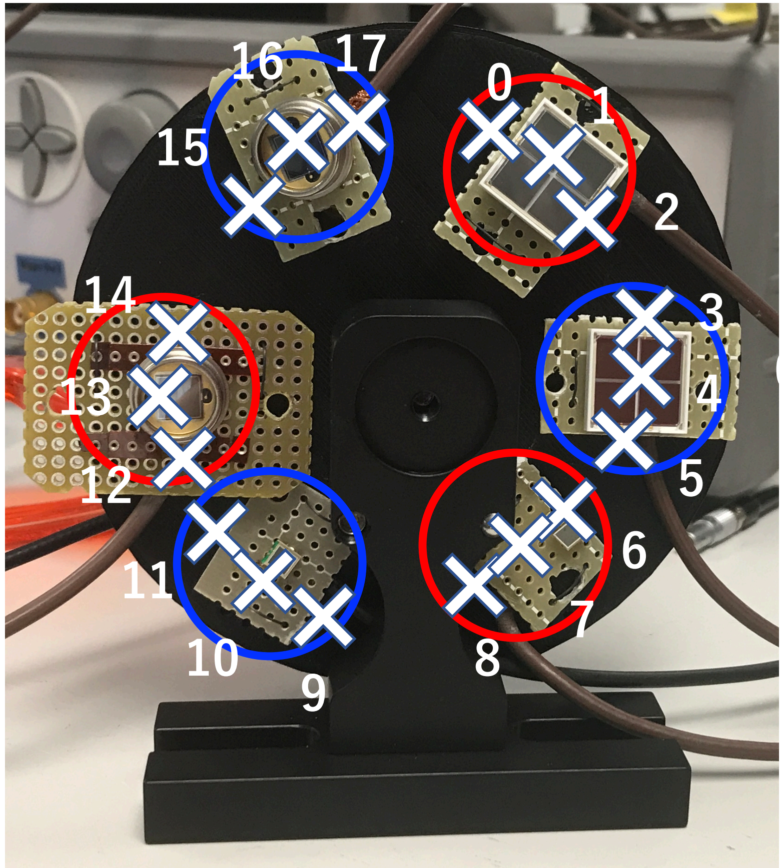


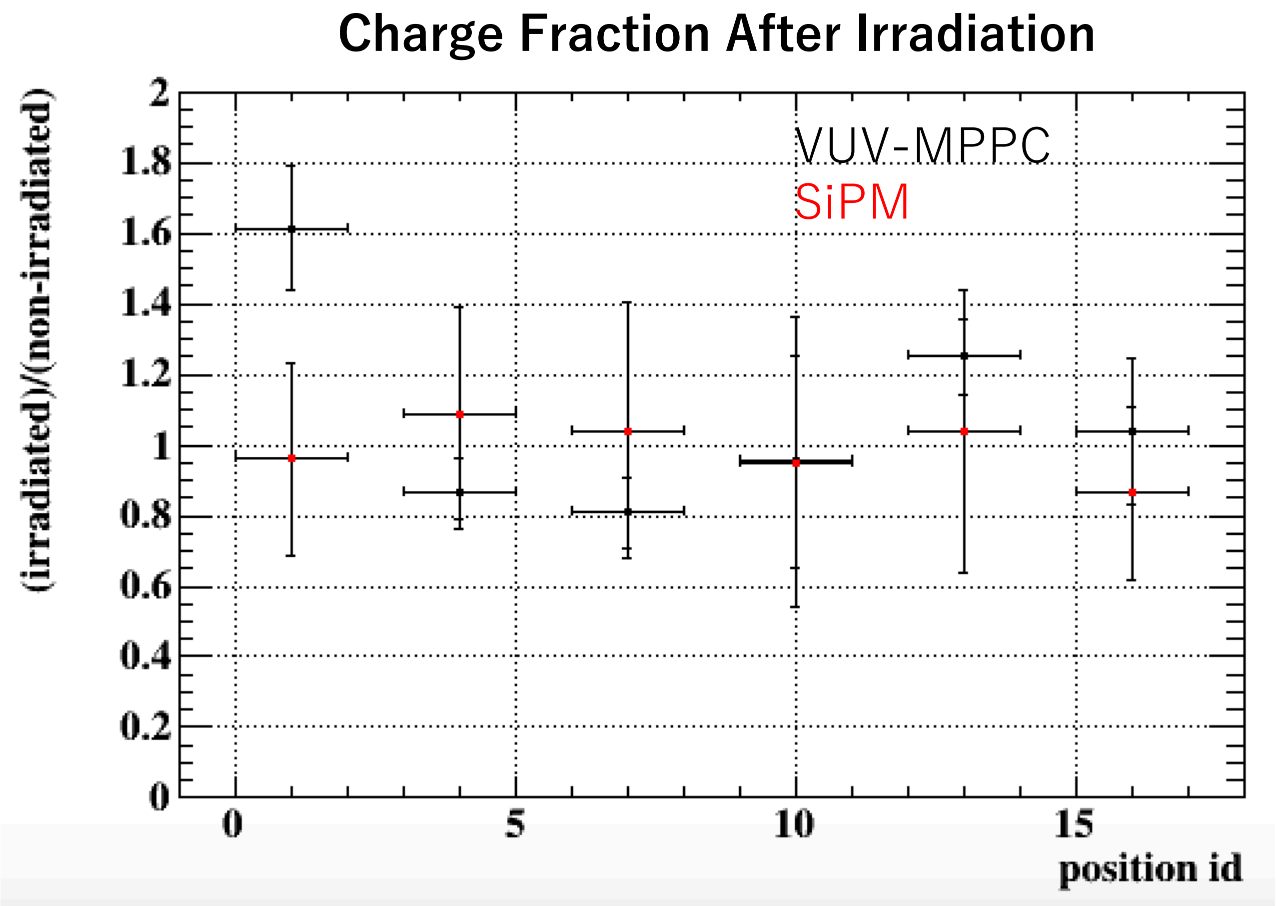
IV (non-irradiated)



- No apparent difference?

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