Core-to-Core Program

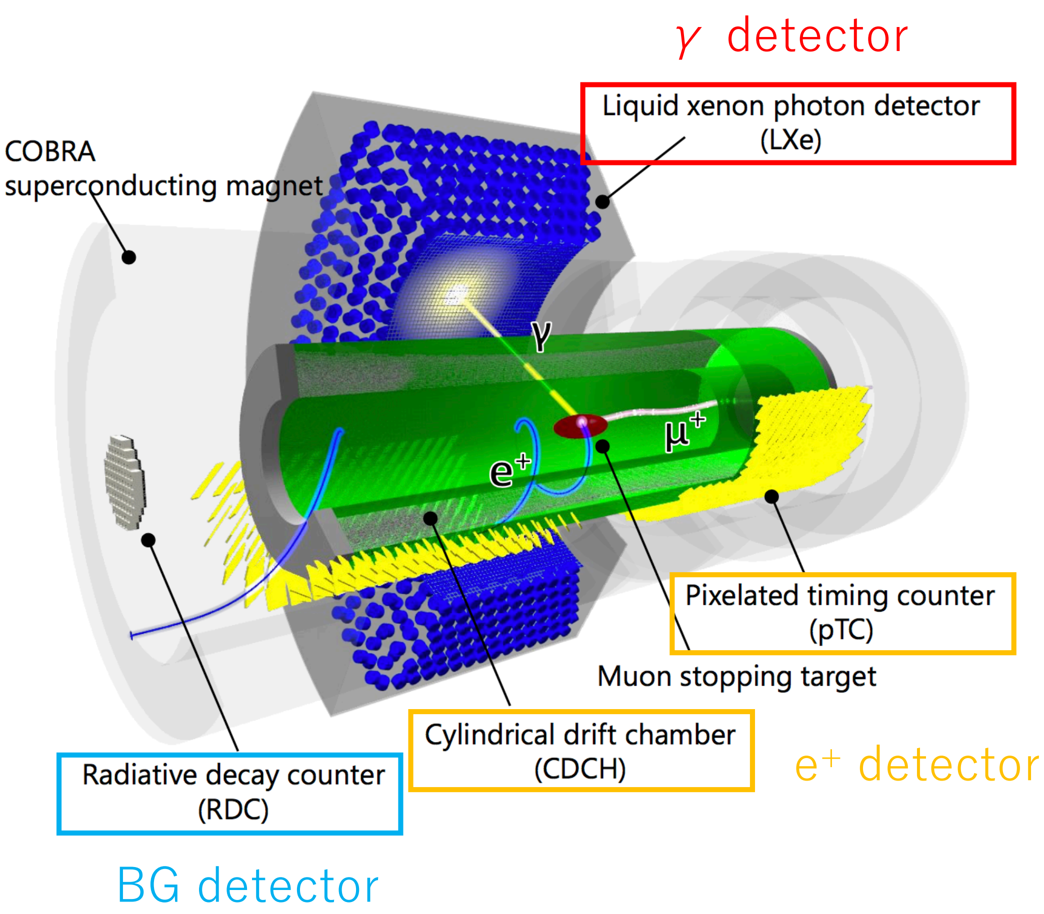
Evaluation of Radiation Damage to VUV-MPPC for MEG II Liquid Xenon Detector

Rina Onda

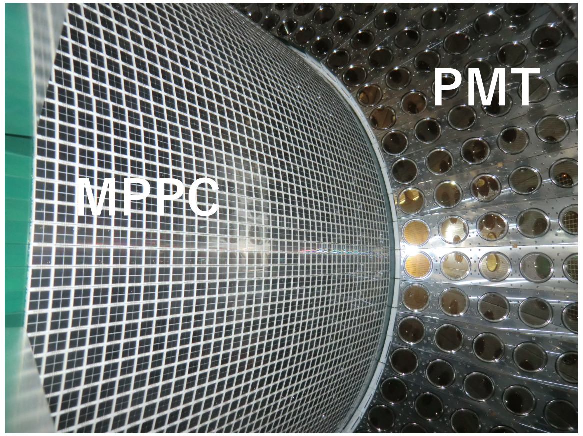
On behalf of MEG II collaboration

The University of Tokyo

γ Detector of MEG II Experiment

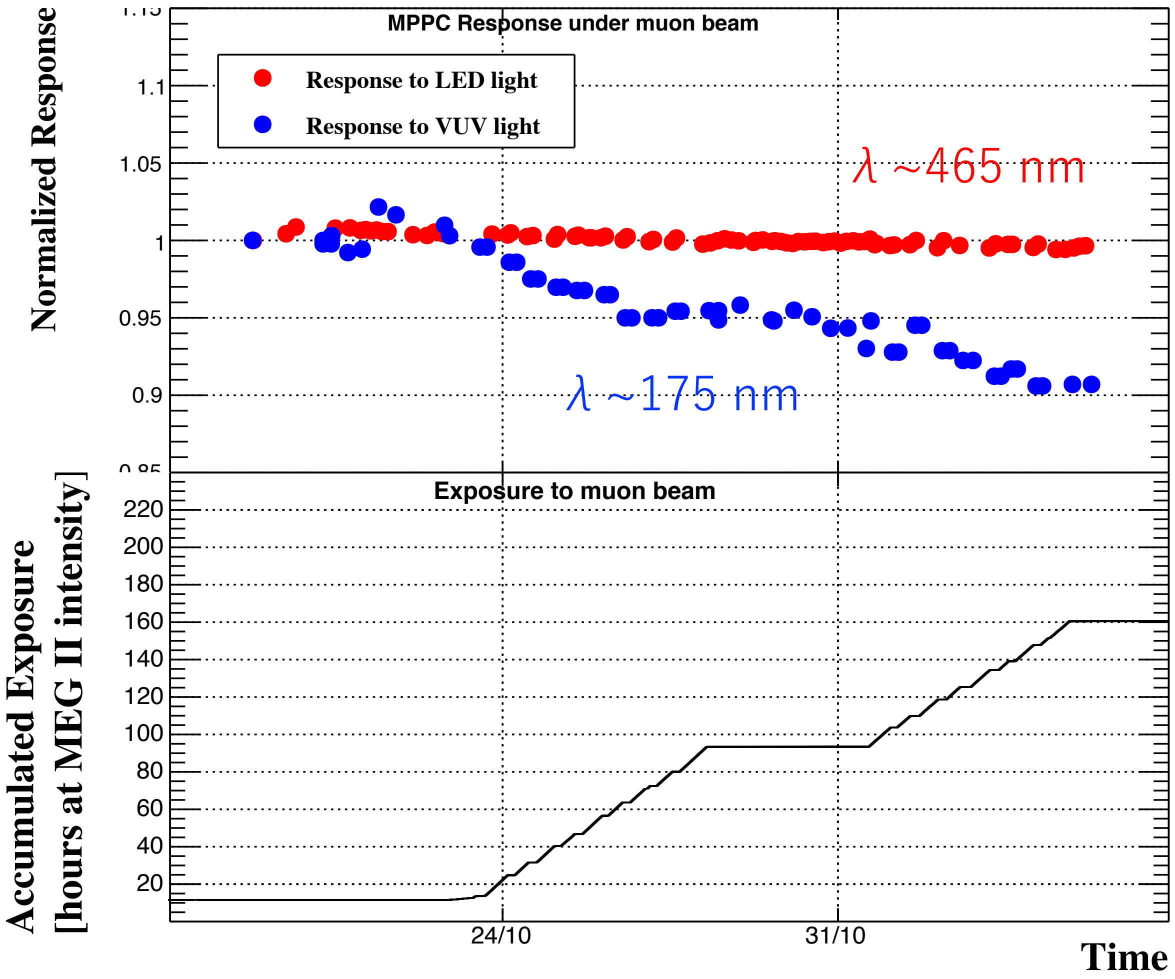


Inside LXe



- 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 PMTs and MPPCs.

PDE Degradation of VUV-MPPC in LXe



Estimated Radiation in 2019

Irradiation Source	Dose
γ (Gy)	1×10^{-2}
neutron (n/cm^2)	2.7×10^{6}
Photon (/mm^2)	5.6×10^{10}

- PDE for VUV light of the VUV-MPPCs in LXe was observed under μ beam.
  ← Radiation damage??
- It is known that there is **no effect on PDE of other types** at the dose level of MEG II.

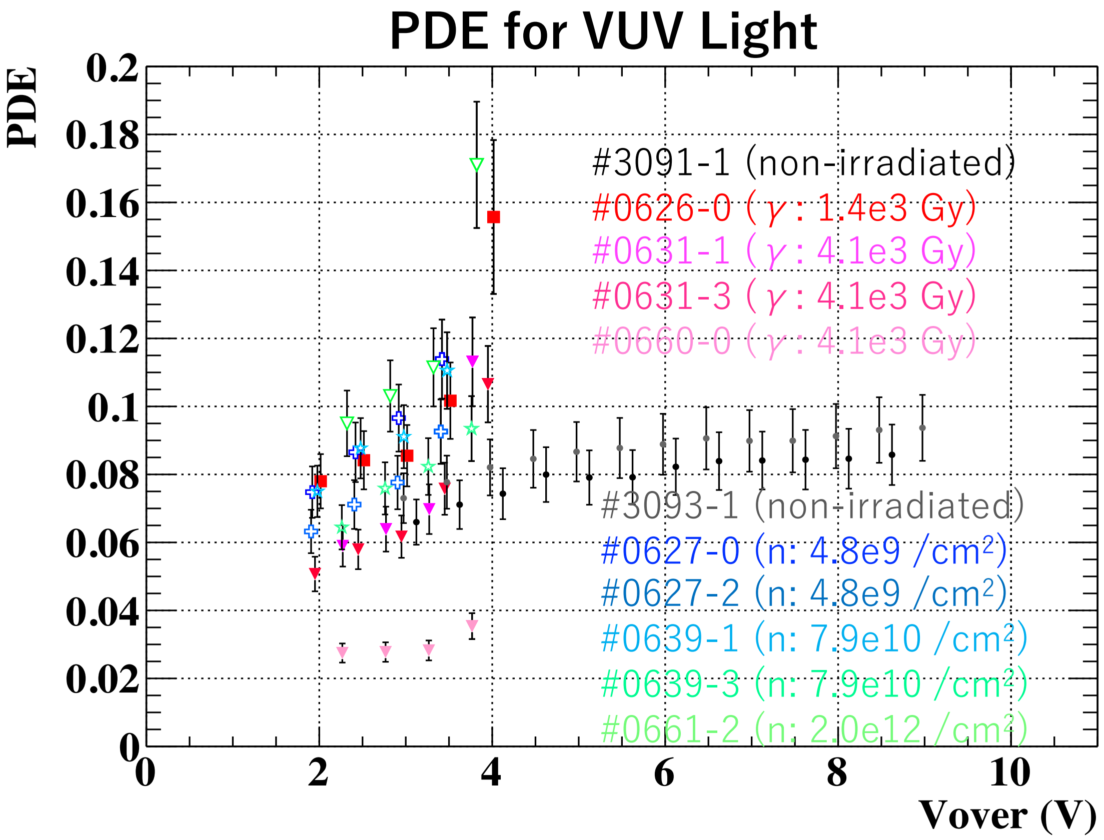
PDE for VUV Light (γ/neutron irradiated samples)

Reported in JPS (2019/09/17)

We measured PDE of γ/neutron irradiated samples using scintillation light of LXe from α source.

- γ: Co → Ni + e^- + γ @ Takasaki Advanced Radiation Research Institute in Jan. 2015.
- neutron: $^9Be + d^+ \rightarrow {}^{10}B + n$ @ Kobe University tandem accelerator in Jan. 2015.

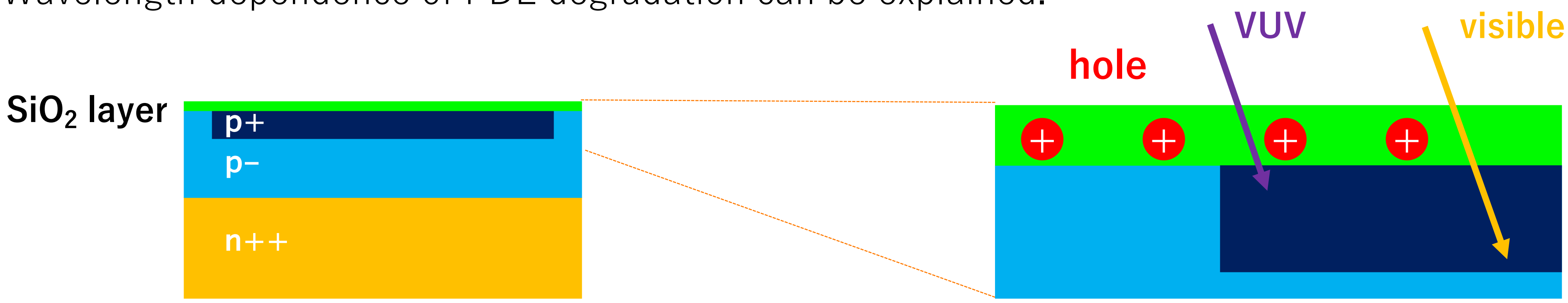
	Dose of Sample	MEG II Expected
γ (Gy)	1.4×10^3, 4.1×10^3	0.6
neutron (n/cm^2)	4.8×10^9 – 2.0×10^{12}	1.6×10^8



PDE degradation was not observed for γ/neutron irradiated samples.

Possible Cause of 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.
  - Wavelength dependence of PDE degradation can be explained.



- **Annealing can be effective** to remove the accumulated charge.

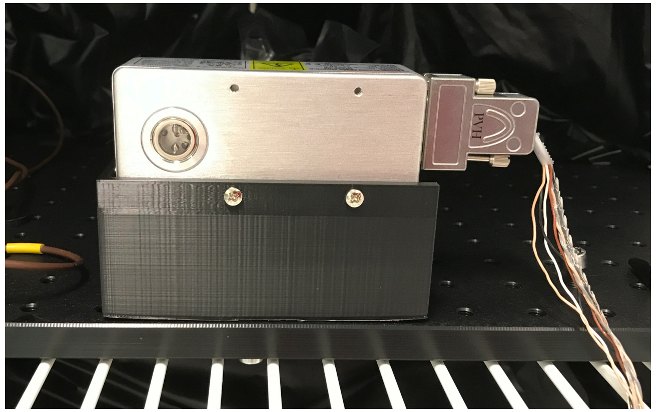
VUV Light Irradiation

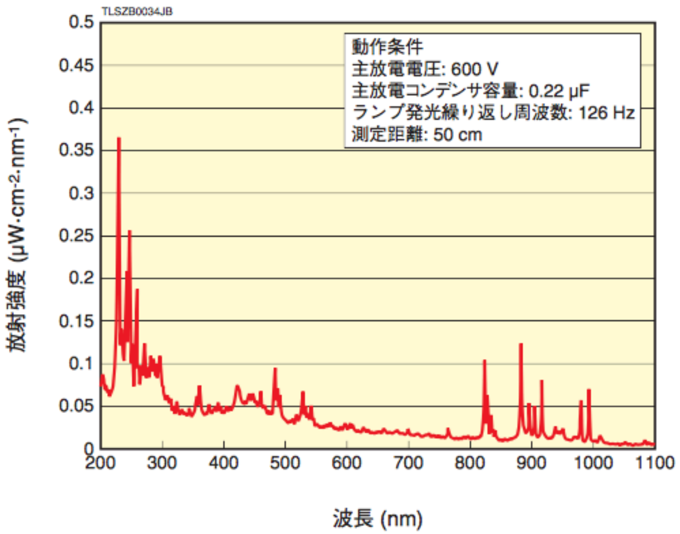
- Light source
  - For irradiation : xenon lamp
  - For measurement : xenon lamp (with filters) borrowed by Dr. Nakamura (YNU)
    LED (λ ~380 nm)
- Irradiated photo sensor
  - VUV-MPPC
  - standard MPPC (S13350-3050PE)
- Reference photo sensor
  - SiPD (S12698-02, Hamamatsu), which is tolerant to UV light
  - VUV-MPPC
  - standard MPPC (S13350-3050PE)

Expectation :

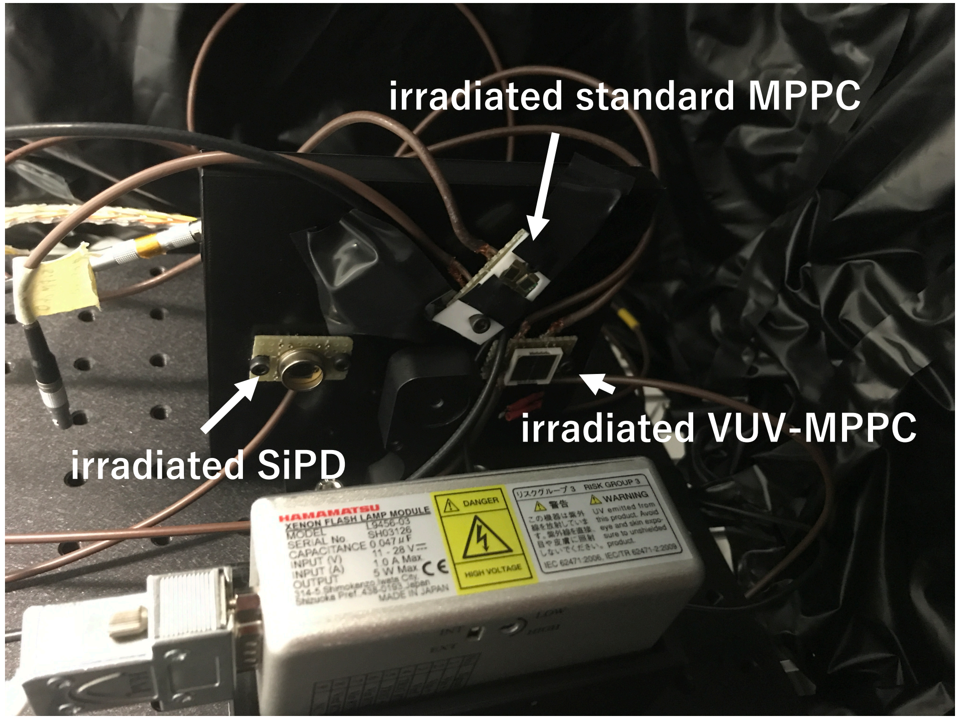
- PDE degradation
- Saturation of PDE degradation
- Dependence of the level of PDE degradation on wavelength

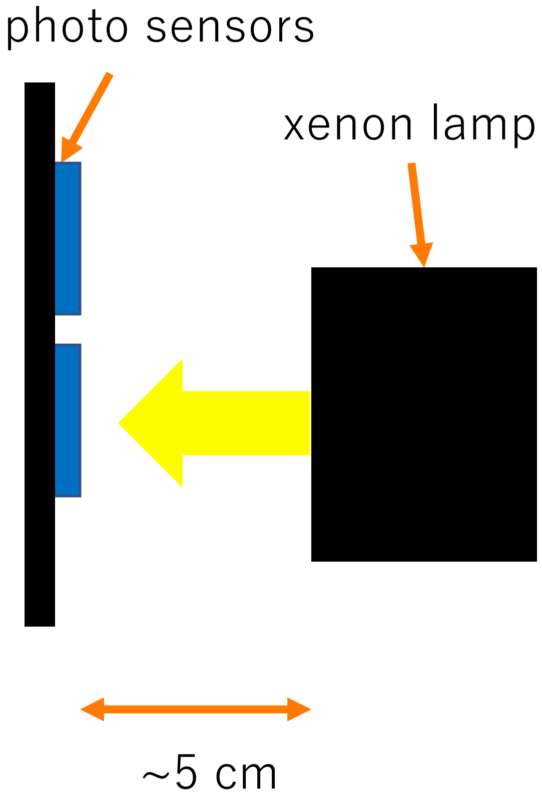
Xenon Flash Lamp:
L9455-13 (Hamamatsu)





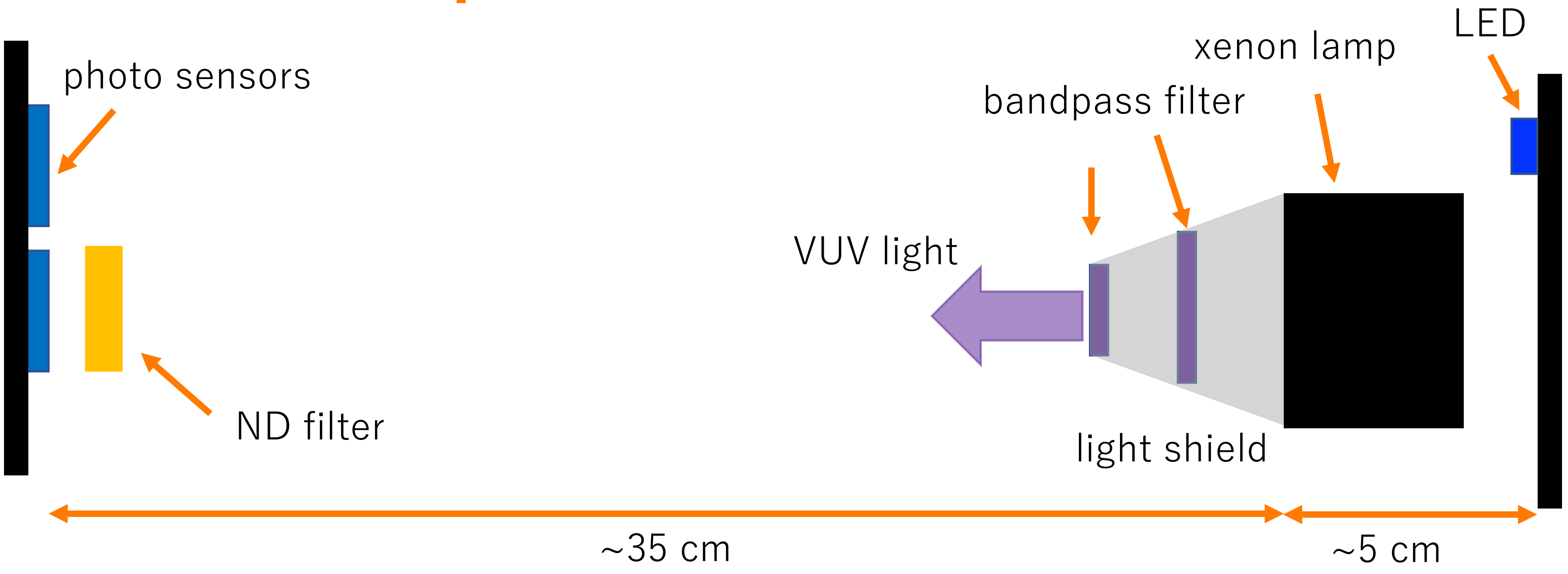
Setups for Irradiation





- The setups were placed in a thermal chamber and the temperature was kept at 25°C.
- Photo sensors were mounted on a support structure.
- They were irradiated directly with the xenon lamp.

Setups for Measurement



- For the measurements, light from a xenon lamp was reduced with some filters.
  - bandpass filters 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
    T = 3.3% @ λ ~190 nm
- Charge was measured by recording waveforms with an oscilloscope or a waveform digitizer.

Flow of VUV Light Irradiation

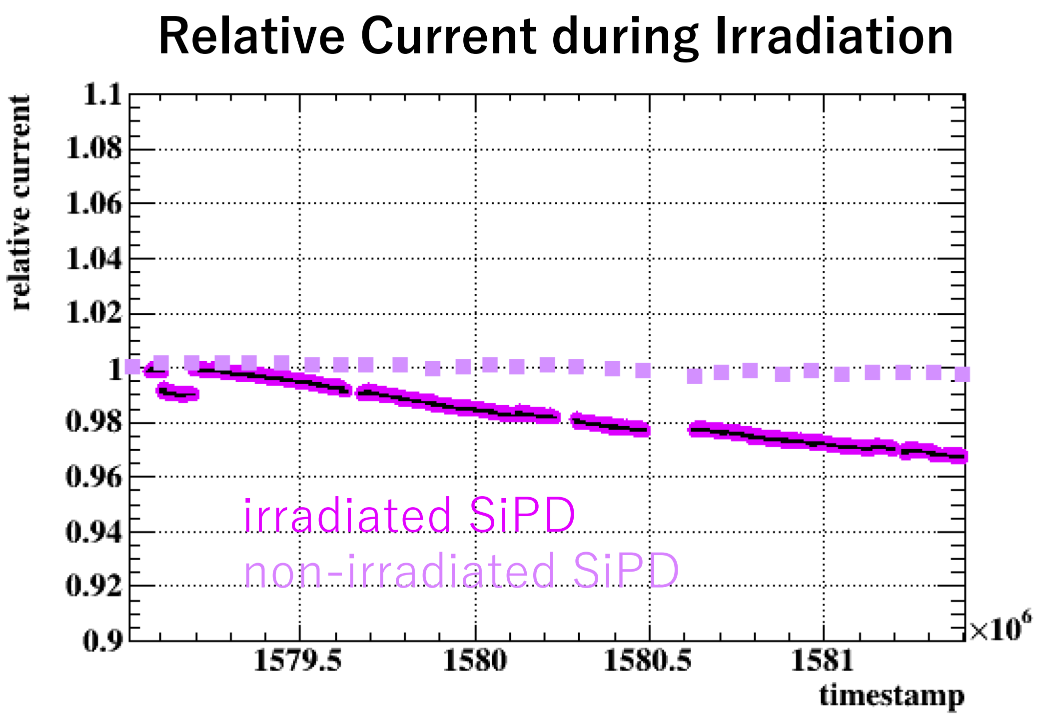
The experiment was done in the three steps.

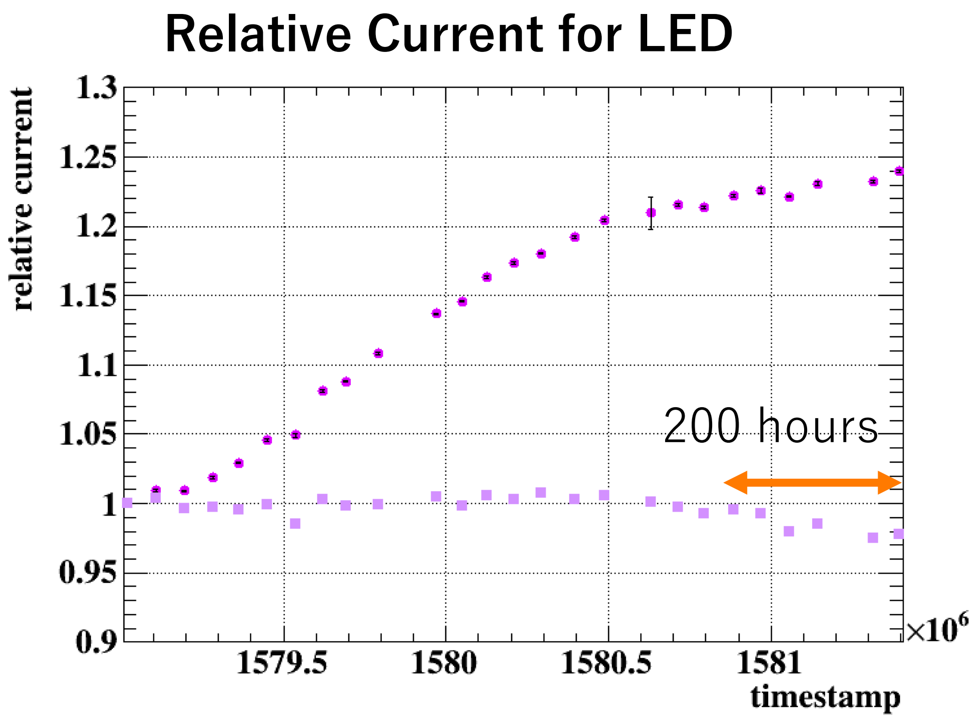
Irradiation
- Stability of Light
- PDE for VUV light
- PDE for visible light

Annealing
- PDE for VUV light
- PDE for visible light
- I-V curve

Reirradiation
- PDE for VUV light
- PDE for visible light

Stability of Light

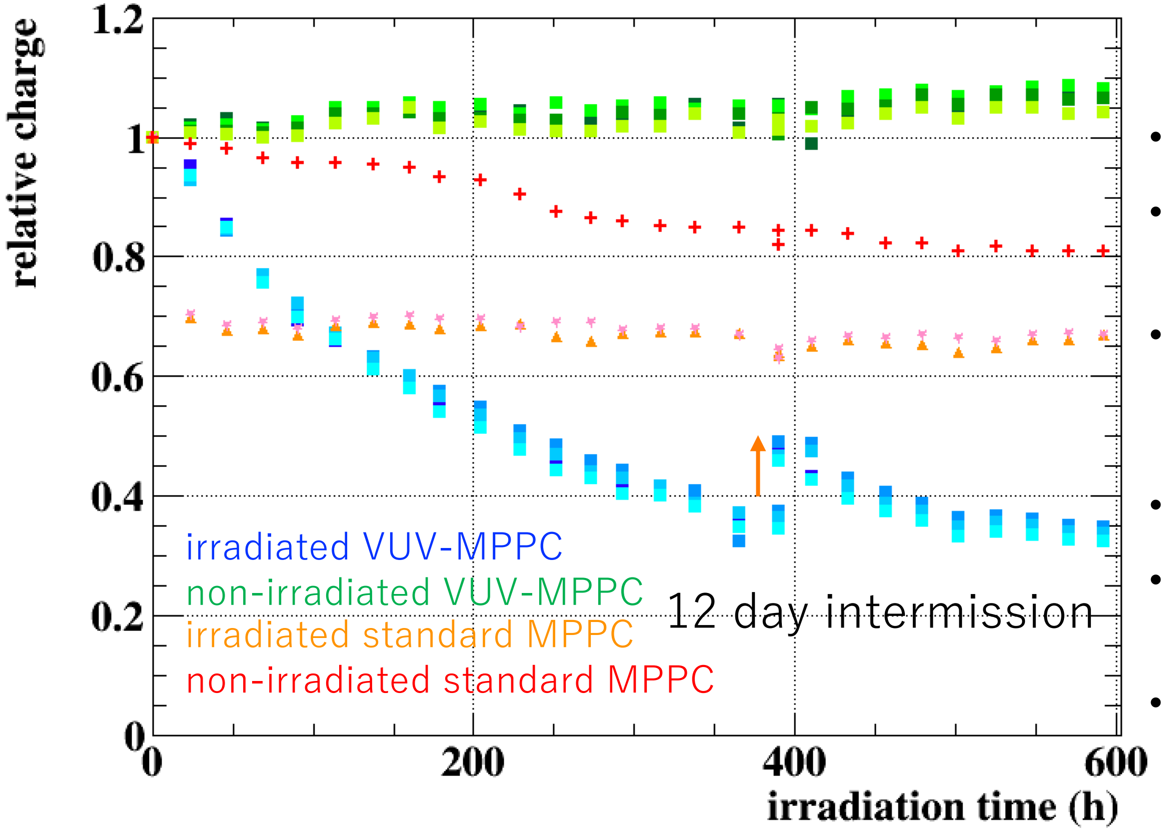




- Current of irradiate SiPD for a xenon lamp started to decrease though **that of non-irradiated SiPD was stable.**
  → QE of the irradiated SiPD decreased.
- . Current of irradiate SiPD for LED is increasing though **that of non-irradiated SiPD was almost stable**.
  → Effect of UV cleaning? (ref:https://www.ushio.co.jp/jp/technology/glossary/glossary_ha/vuvcleaning.html)
- Current of non-irradiated SiPD for LED **slightly decreased in the last 200 hours**.
  → Light yields of LED may have decreased.

PDE for VUV Light

Relative Charge during Irradiation

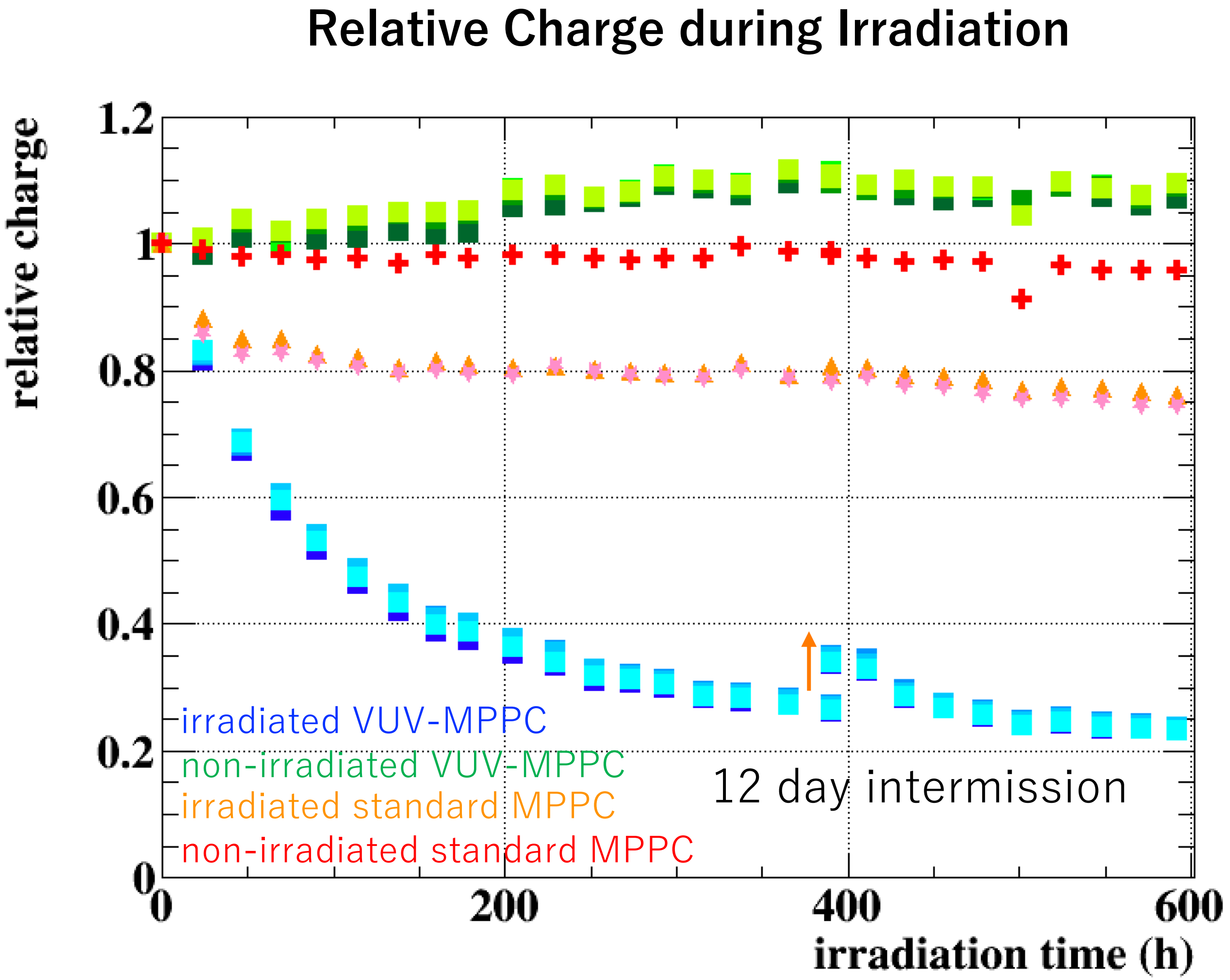


Intensity: 5.2e13 photons/mm^2/h @ λ ~190 nm
Total dose: 3.1e16 photons/mm^2 @ λ ~190 nm

- Charge of irradiated VUV-MPPCs decreased and was **saturated at 35%.**
- **The degradation was >10^3 times slower than that observed by LXe.**
  ← Lower temperature accelerate it?
- Charge of non-irradiated sample was stable though there was a slight increase.
  ← Effect of UV cleaning?
- Charge of irradiated standard MPPCs also was **saturated at 70%.**
- Charge of a non-irradiated standard MPPC decreased gradually.
  ← probably because of light leakage from the irradiation source.
- The irradiated samples seemed to be annealed in room temperature during 12 day intermission.
  → 11% recovery

*makers of similar colors correspond to different chips on the same VUV-MPPC or different standard MPPCs

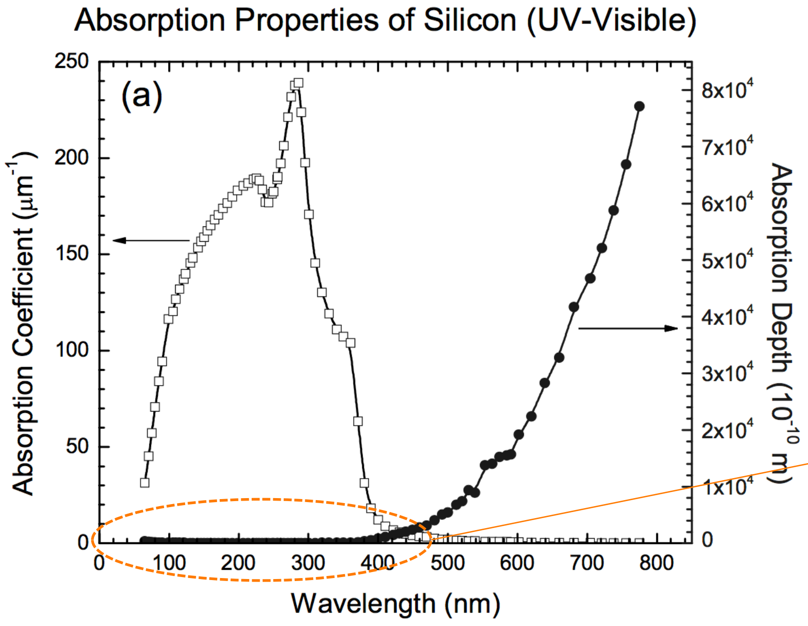
PDE for NUV Light

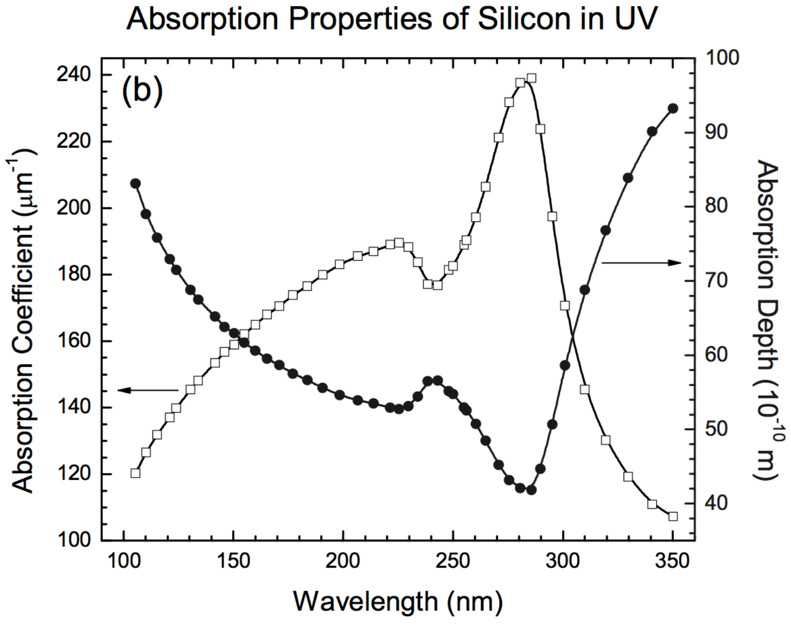


*makers of similar colors correspond to different chips on the same VUV-MPPC or different standard MPPC

- Charge decrease of irradiated samples also observed for visible light.
- Charge of irradiated VUV-MPPCs decreased and was **saturated at 25%.**
- Charge of irradiated standard MPPCs also decreased and was **saturated at 80%.**
- The annealing effect was also observed.
  → 8% recovery

Wavelength Dependence of PDE Degradation

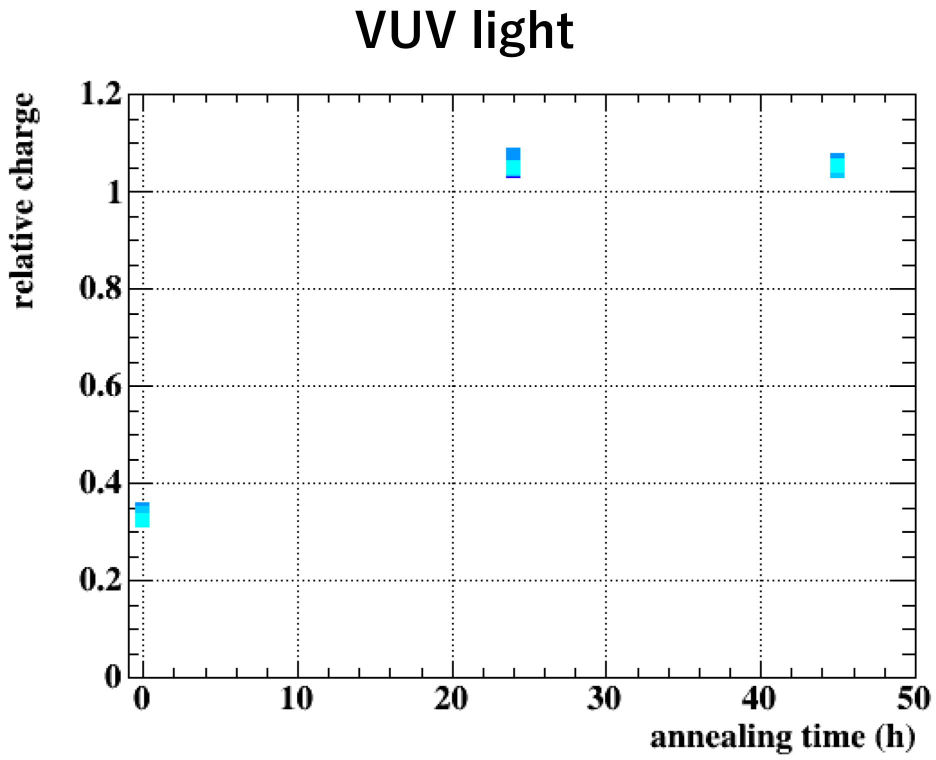


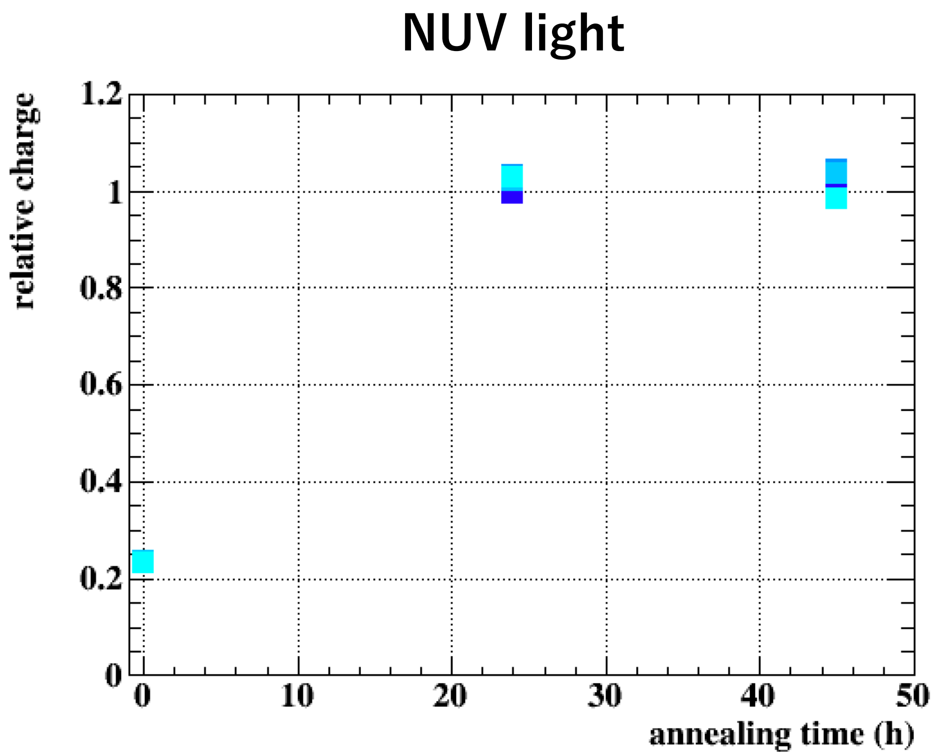


CCD Image Sensors in Deep-Ultraviolet

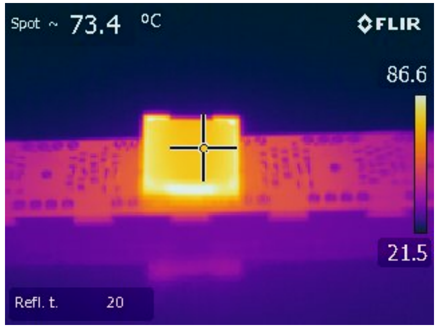
- PDE degradation of VUV-MPPC for NUV light was greater than that for VUV light.
  ← Can be explained by **wavelength dependence of absorption**:
  - Absorption depth in Si is the minimum at λ ~280 nm.
  - Other components such as absorption in SiO_2 can also affect the dependence.
- Inconsistency b/w VUV-MPPC and standard MPPC can be caused by structure differences.

Annealing



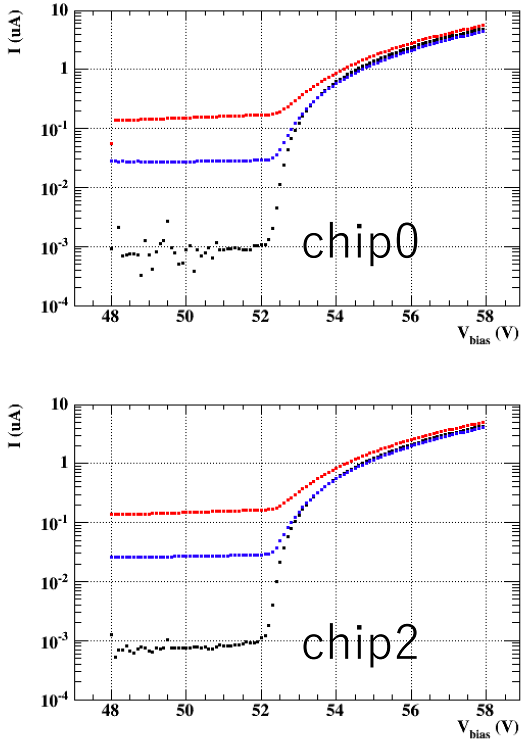


- The irradiated VUV-MPPC was annealed for 45 hours.
- It was exposed to room light with the reverse bias voltage of 70 V.
- Current was ~30 mA and surface temperature reached ~70°C.
- **PDE for both light source was recovered completely**.

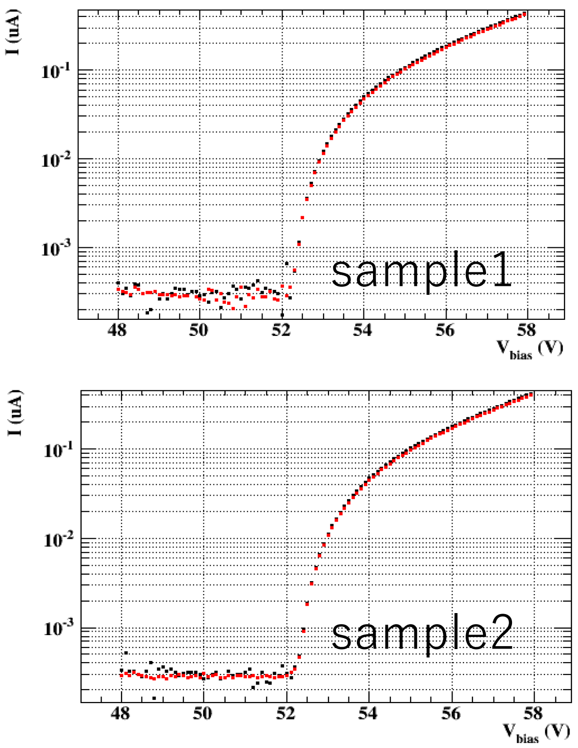


I–V Curve

Irradiated VUV-MPPC



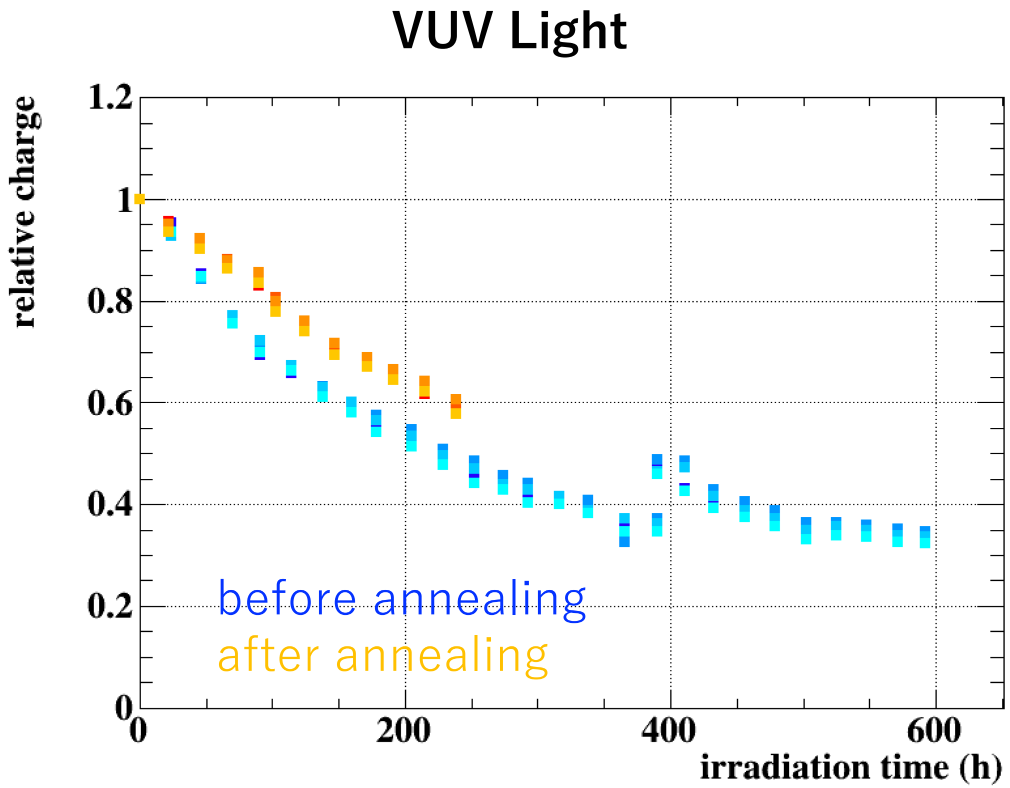
Irradiated standard MPPC

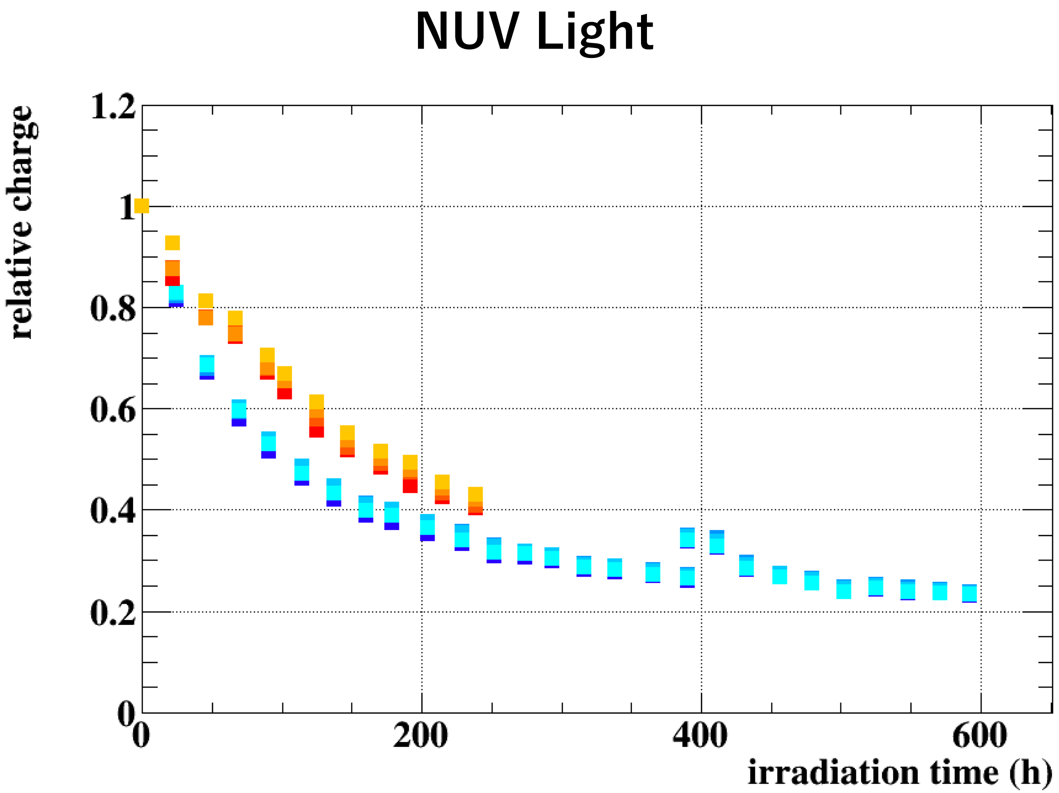


before irradiation
after irradiation
after annealing

- Dark current of the VUV-MPPC increased by irradiation.
  - Increase of current below the break down voltage was significant. ←Increase of surface current
- Annealing reduced it to some extent, but not completely.
- There was no difference in the standard MPPCs. ←Difference of structures or the damage level?

Reirradiation after Annealing





- Reirradiation was performed after annealing.
- The speed of PDE degradation seems to become slower than that before annealing.
- It was reduced gradually.
  → supposed to be saturated again.

Summary

- Irradiation using a xenon lamp was performed at room temperature.
- Total dose was 3.1e16 photons/mm^2 @ λ ~190 nm.
  (though there was a PDE recovery during intermission)
- **PDE degradation was observed**.
  - **The degradation saturated** as expected.
  - The speed is much slower than that observed by LXe.
    → Accelerated by lower temperature? (see 17aG22-8)
  - **Wavelength dependence was inconsistent to the expectation**.
  - The dependence was not the same b/w the VUV-MPPC and the standard MPPC.

PDE_{after} / PDE_{before}	VUV light	NUV light
VUV-MPPC	35%	25%
Standard MPPC	70%	80%

- **PDE recovered completely thanks to annealing**.

Prospects

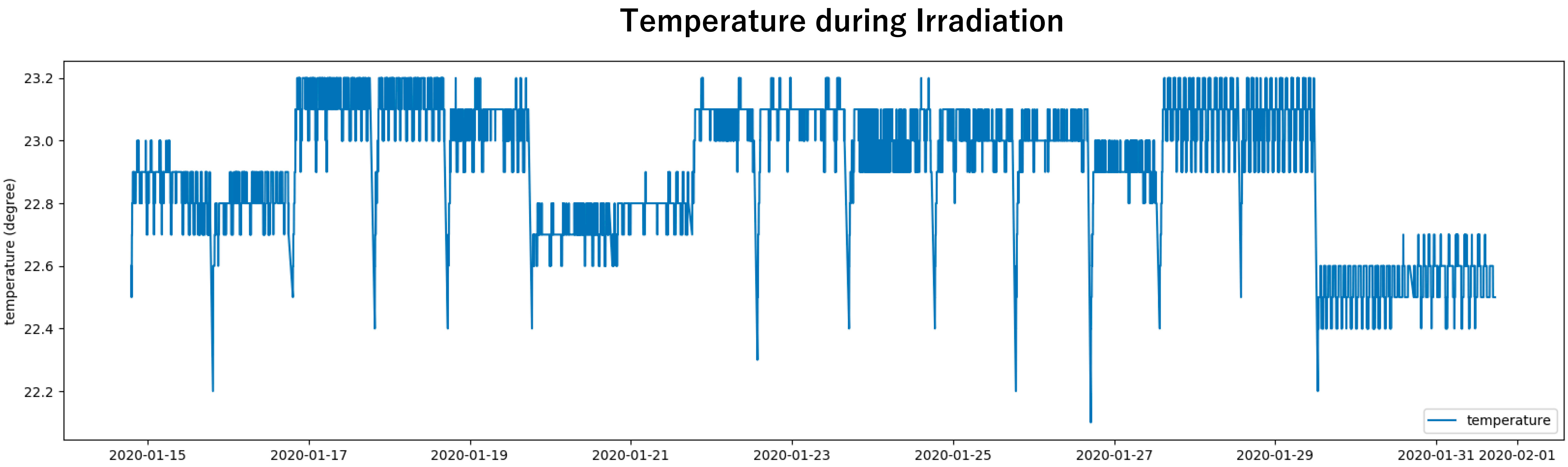
- **Precise estimation of the dose level**
  - Irradiation light included all wavelengths from a xenon lamp.
    → It was difficult to estimate the dose level with the current setups.
  - We will use a 20W module (×4 powerful!!).
    → Irradiation can finish in reasonable time (~1 month) even with a bandpass filter.
- **Study on wavelength dependence**
  - We observed differences of PDE degradation depending on wavelength.

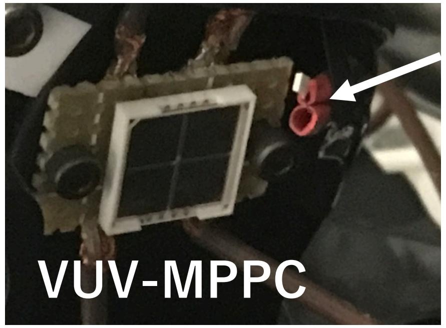
PDE_{after} / PDE_{before}	VUV light	NUV light
VUV-MPPC	35%	25%
Standard MPPC	70%	80%

  - We can monitor PDE for several wavelengths using LEDs and a xenon lamp:
    - 181 or 193 nm from a xenon lamp
    - 280, 380, 465, 569, 645 nm from LEDs

Backup Slides

Temperature

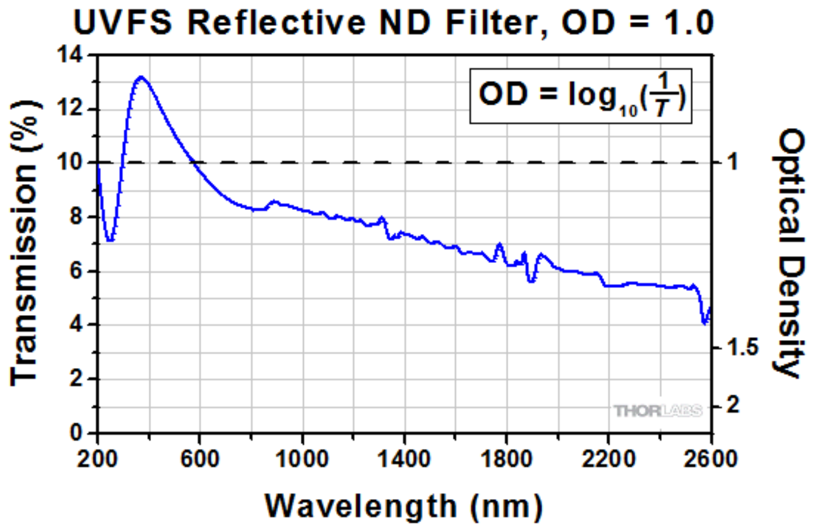


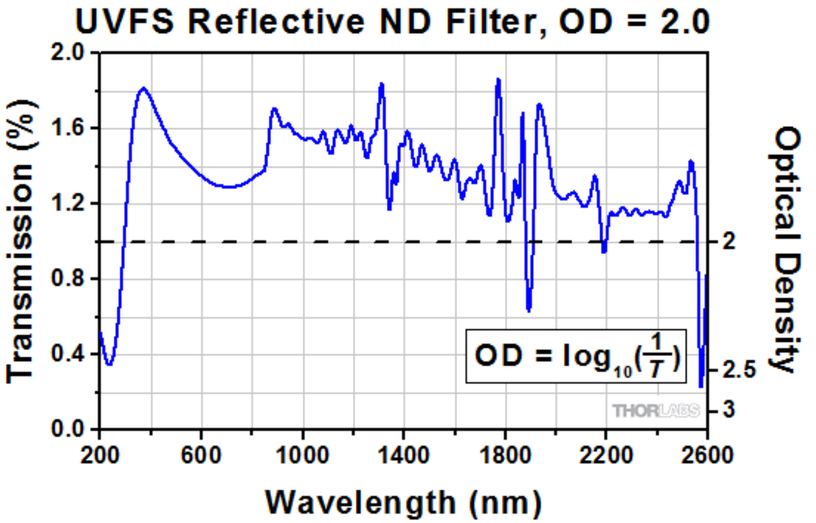


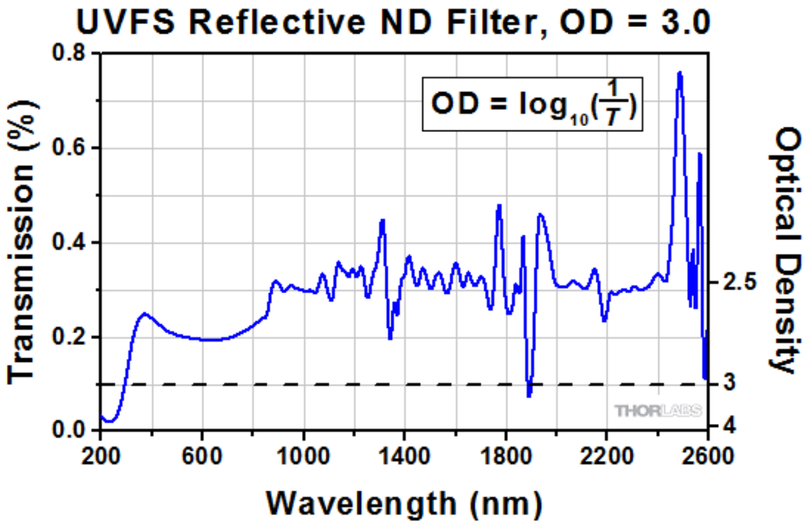
thermometer

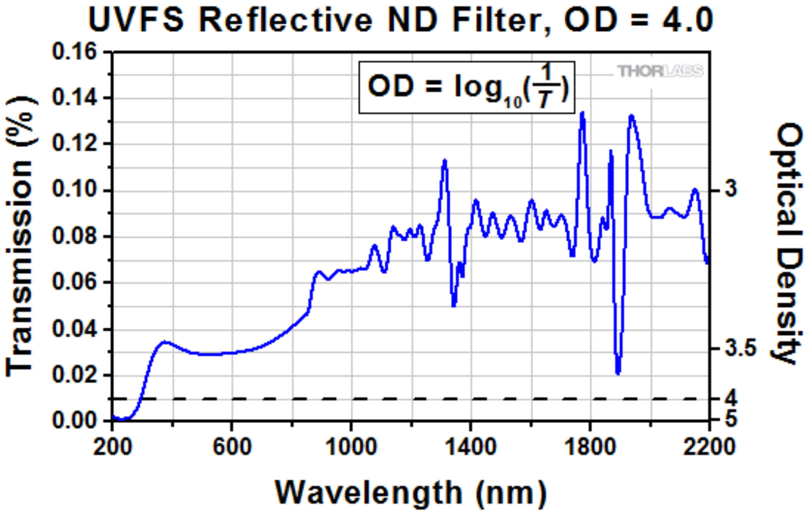
- Temperature around the VUV-MPPC was monitored.
- There is a increase at the beginning of each irradiation.
- It was stable within 1°C.

Spec of ND Filters

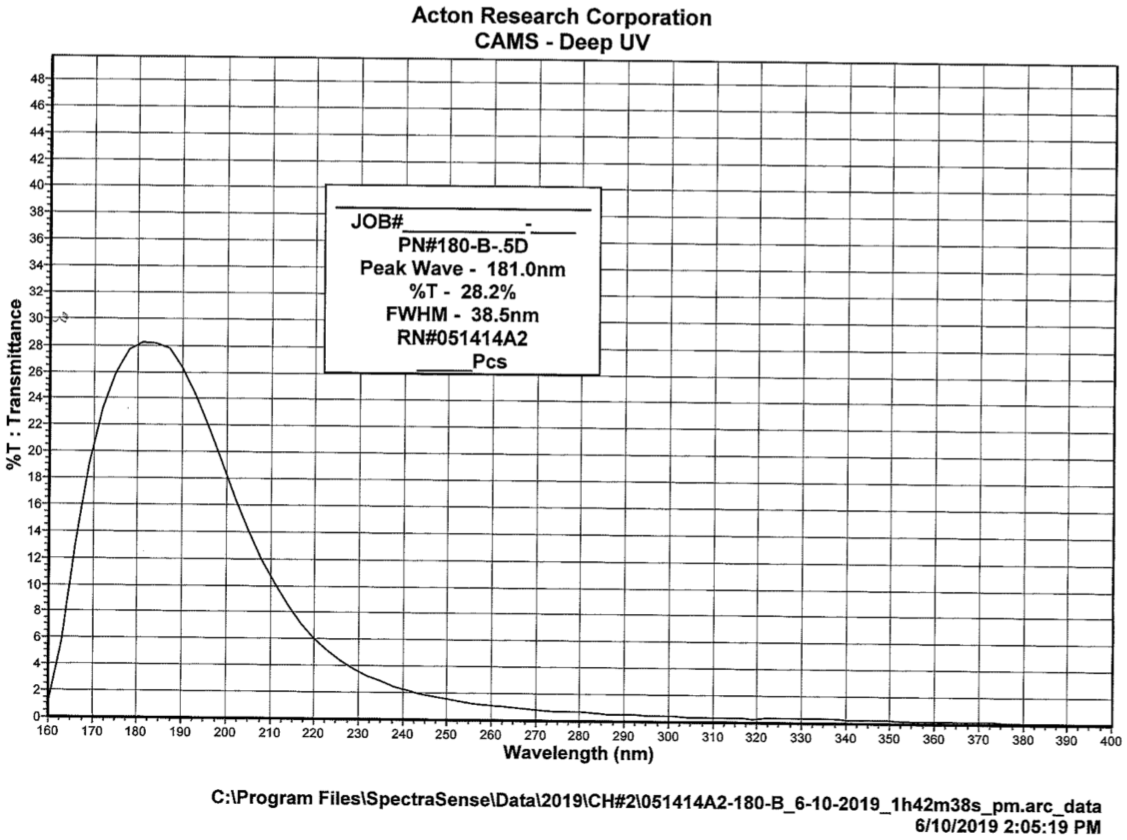


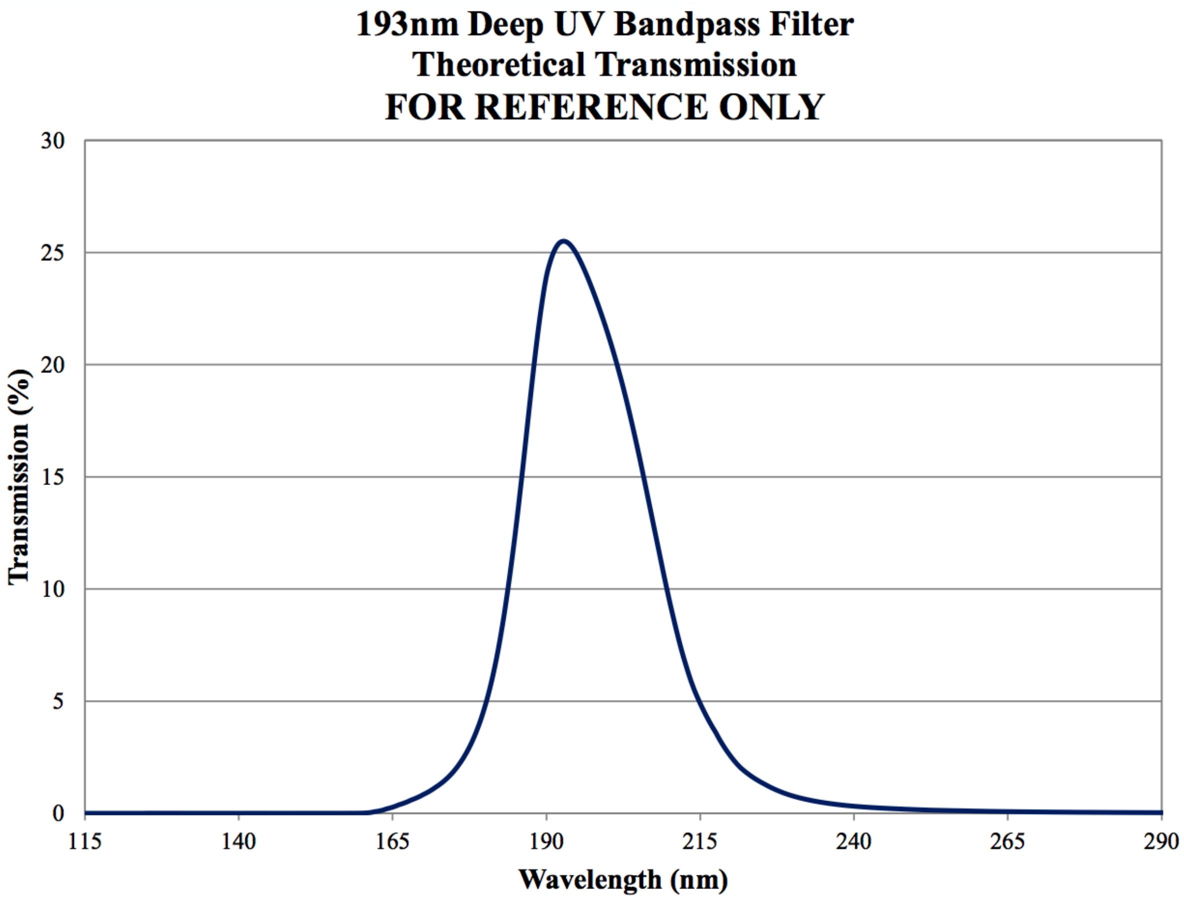






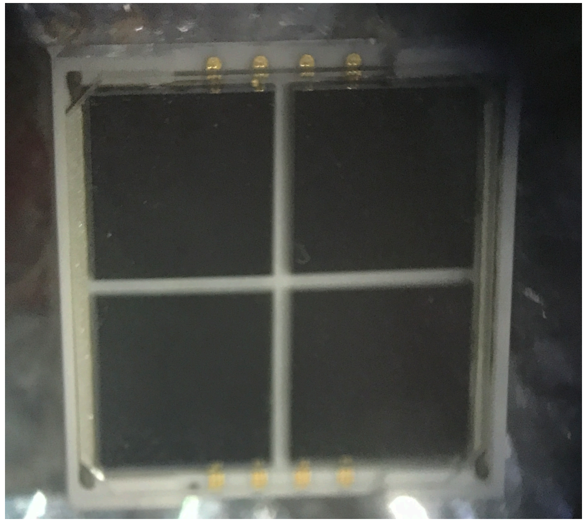
Spec of Bandpass Filters



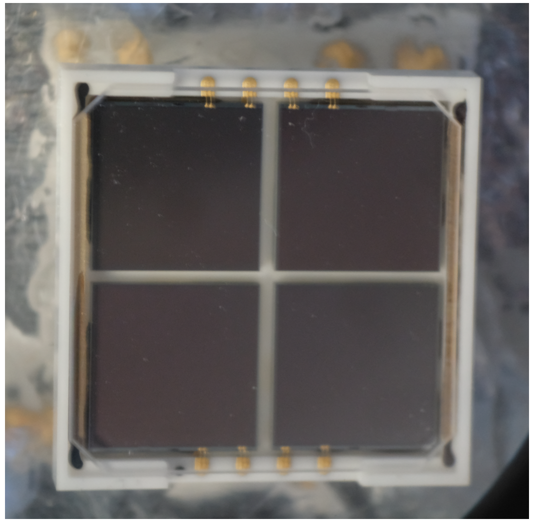


Radiation Damage to Glue(?)

Before Irradiation

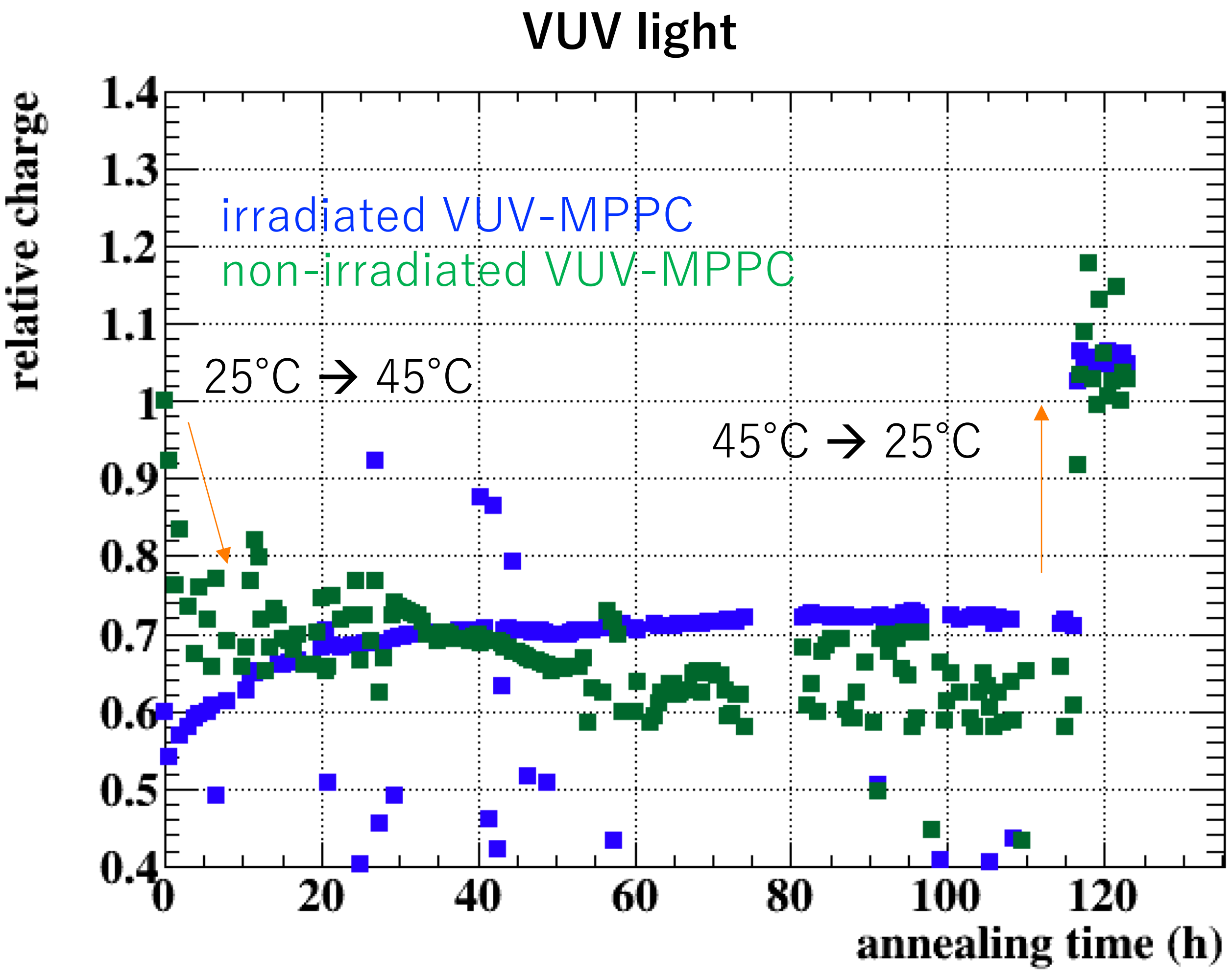


After Irradiation



After the irradiation, color of glue(?) which fixes the quartz window to the VUV-MPPC was changed.
↔ The window peeled off during the previous irradiation.

Gas Annealing

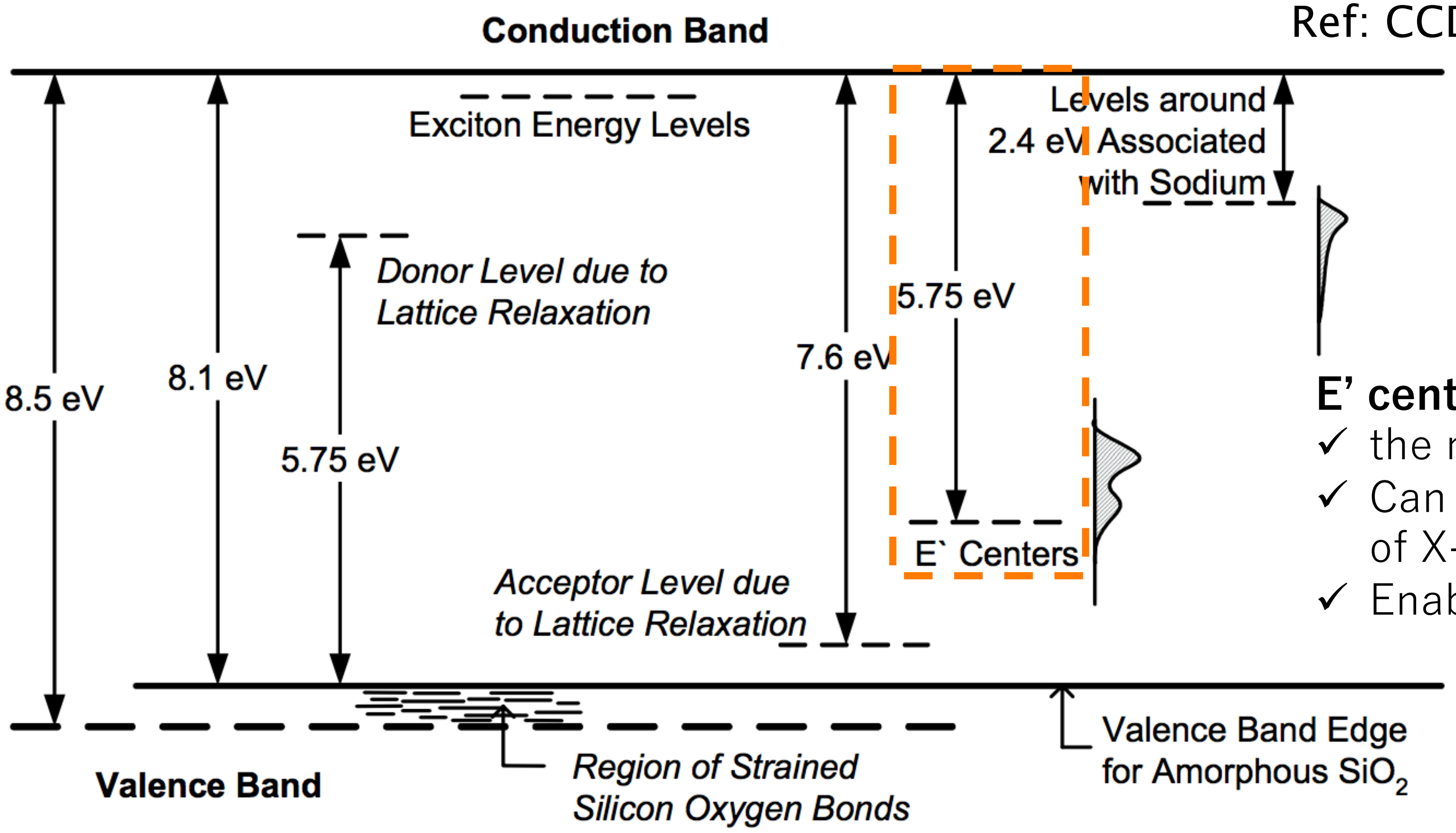


- Irradiated VUV-MPPC was annealed @ 45°C in a thermal chamber.
- Non-irradiated VUV-MPPC was annealed @ 70°C beforehand.
- Temperature dependence is included.
  - The first drops : increase
  - The last jumps : decrease
- PDE of the irradiated sample was completely recovered.

*The first point is normalized to be 0.6 as for the irradiated sample.

Defects in SiO_2

Ref: CCD Image Sensors in Deep-Ultraviolet



E' centers defect

- ✓ the most commonly observed defect
- ✓ Can be generated in SiO_2 by the irradiation of X-rays, γ-rays, electrons, and UV light
- ✓ Enable VUV light to generate e-h pairs:

5.75 eV ~ 210 nm

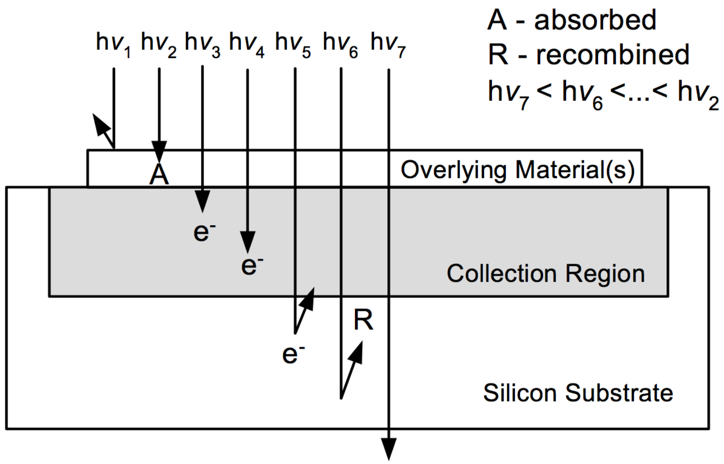
The energy levels introduced in the band-gap of SiO_2 due to presence of some defects

Photoelectric Effect on Si

- Typically, a photon with an energy of 1.1 eV to 3.1 eV generates a single e-h pair in the Si.
- More energetic photons with energies greater than 3.1 eV can produce multiple e-h pairs.
- For a photon with an energy greater than 10 eV, the average number of electrons generated is

$$\eta_{\mathrm{i}} = \frac{E_{\mathrm{ph}}(\mathrm{eV})}{E_{\mathrm{e\text{-}h}}}$$

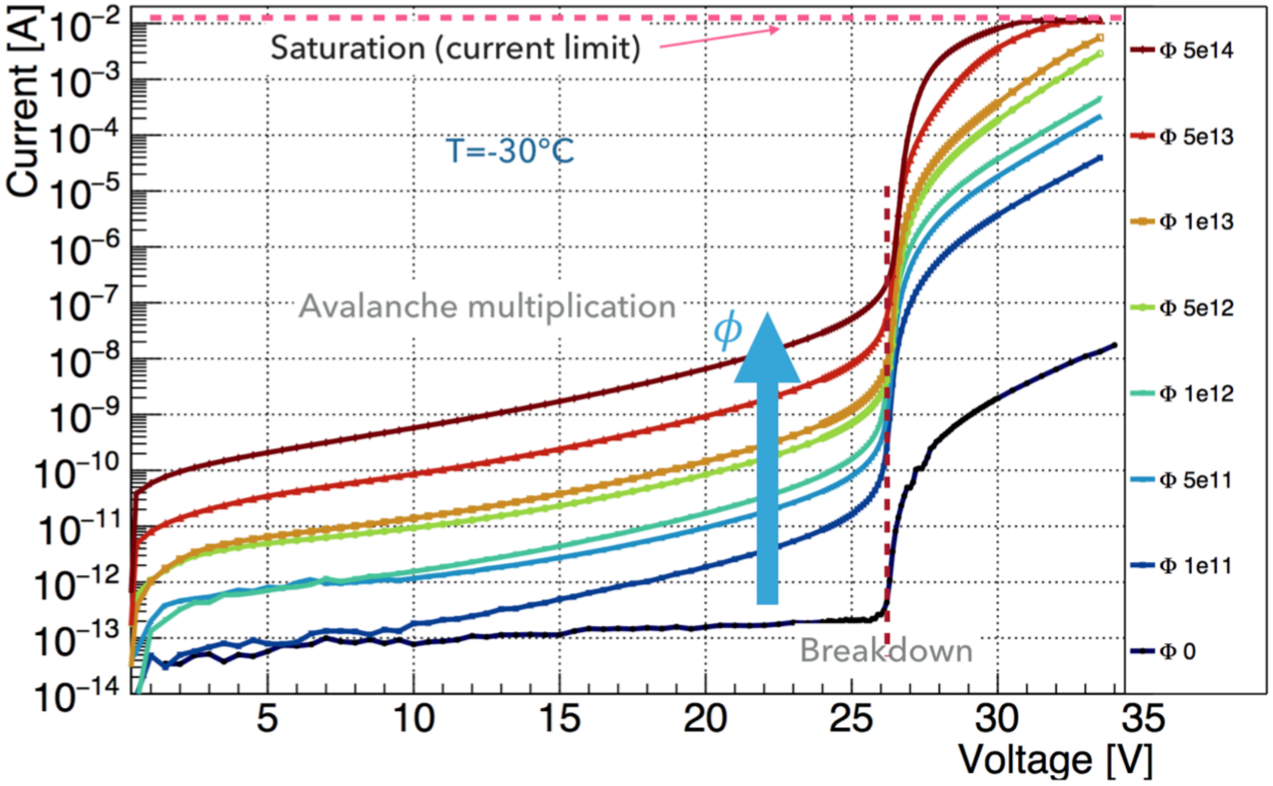
where, $E_{e\text{-}h}$ is the energy required to generate an e-h pair, which for Si is 3.65eV/electron at room temperature.



Therefore, photons with different energies interact with Si in a slightly different manner.

Interaction of photons at different energies with silicon

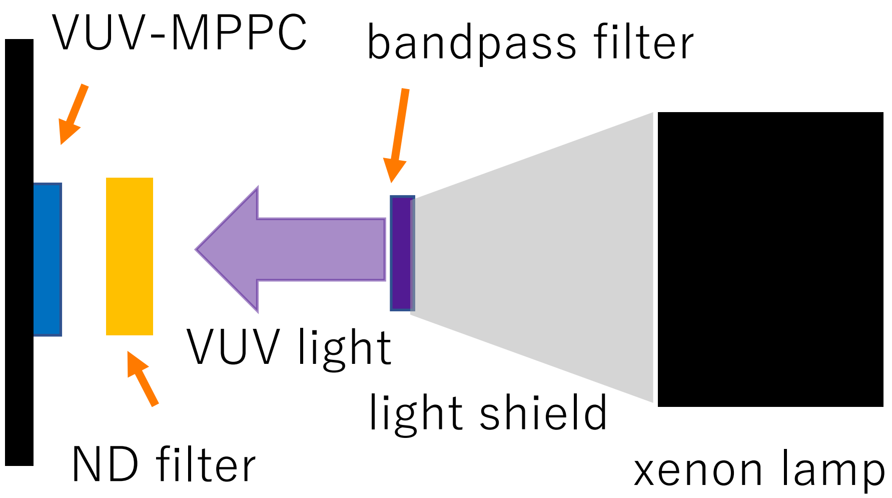
I–V Curve with Bulk Damage

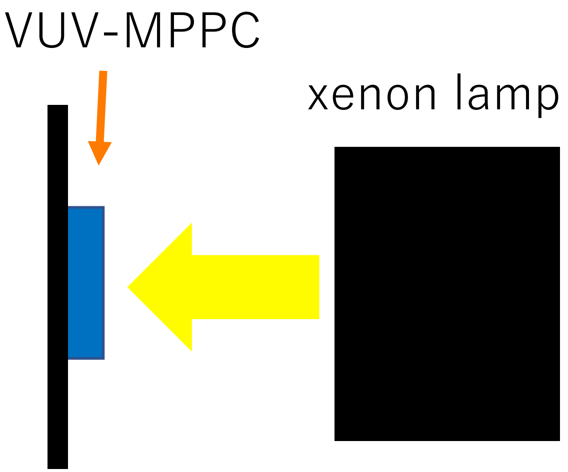


Exemplar current-voltage curves for a KETEK SiPM (15 μm pixel size) irradiated with neutrons up to $\Phi_{eq} = 5 \cdot 10^{14}$ cm^{-2} and operated at -30 C.

In the region of unit gain (V ~ 5 V) the dark current increases by about three orders of magnitude after $\Phi_{eq} = 5 \cdot 10^{14}$ cm^{-2}, whereas above breakdown voltage the increase is more than six orders of magnitude.

E. Garutti, R. Klanner, D. Lomidze, J. Schwandt, M. Zvolsky, Characterisation of highly radiation-damaged SiPMs using current measurements,arXiv:1709.05226.


VUV-MPPC
bandpass filter
VUV light
light shield
ND filter
xenon lamp


VUV-MPPC
xenon lamp