Study on SiPM readout method for scintillator-based electromagnetic calorimeter

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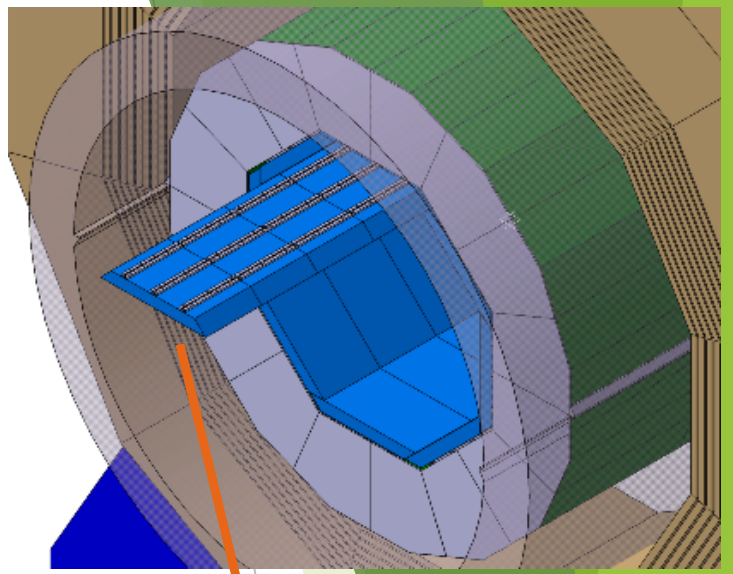
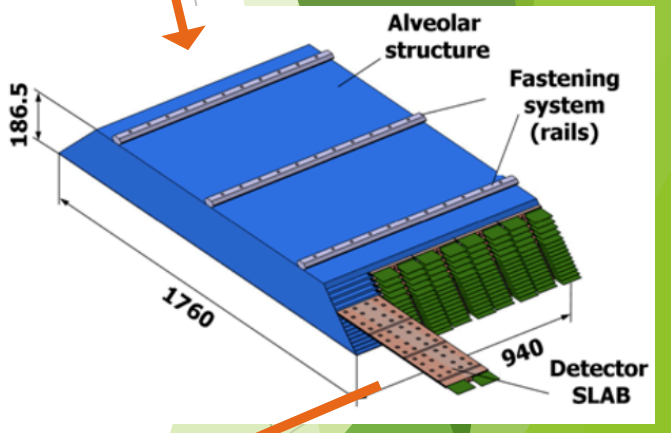
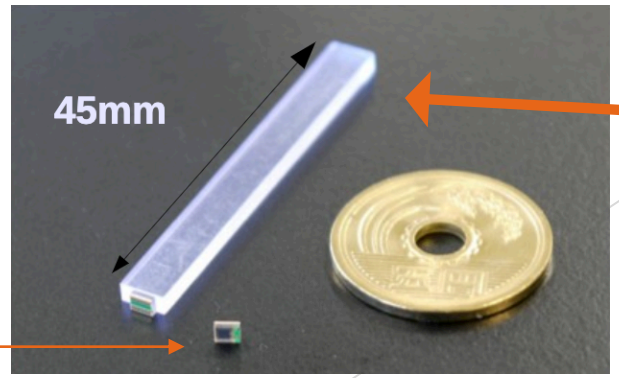
Scintillator Electromagnetic Calorimeter (Sc-ECAL)

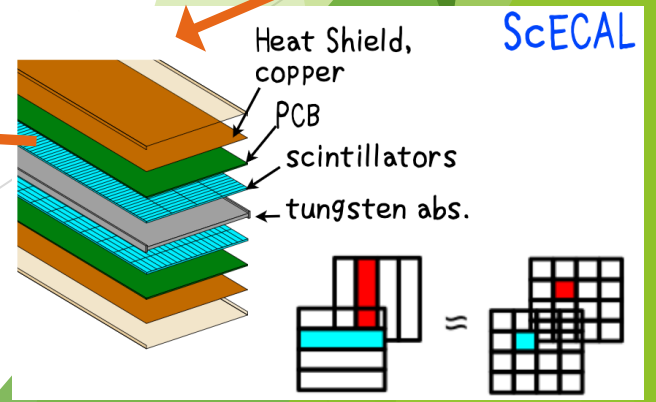
- Sc-ECAL (Scintillator Electromagnetic Calorimeter)
  - Technology option for ECAL of ILD
  - Based on scintillator strip with SiPM readout
    - $5 \times 45 \times 2\ \mathrm{mm}^3$ scintillation strip (EJ-212)
  - Virtual segmentation : 5mm × 5mm with strips in x-y configuration

- Silicon Photomultiplier (SiPM)
  - Made up of multiple APD pixels operated in Geiger mode
  - Excellent photon-counting capability







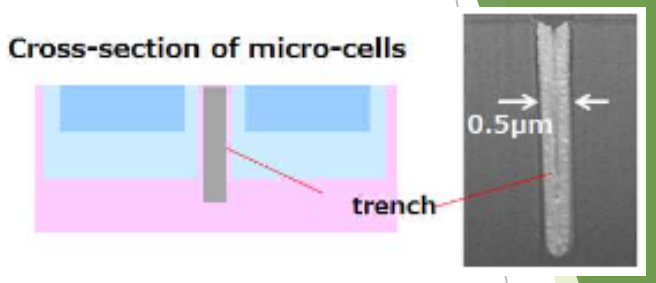


SiPM for Sc-ECAL

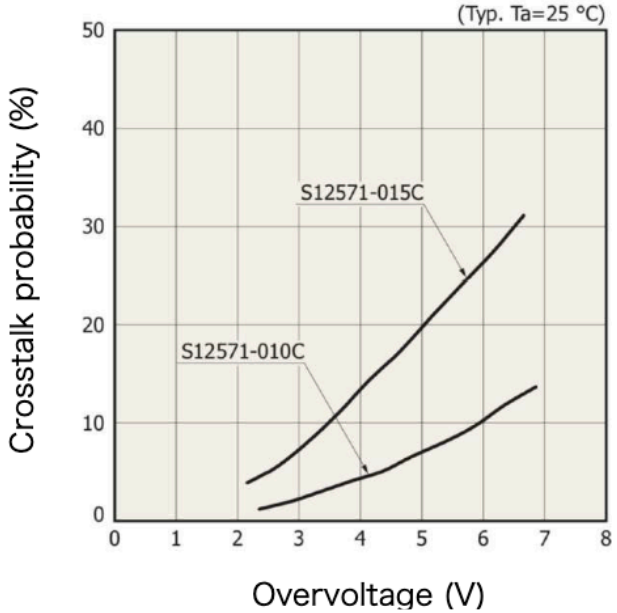
- Hamamatsu MPPC S12571-015P
  - Small pixel size : 15 μm
  - Active area : $1\times1\mathrm{mm}^2$
  - Breakdown voltage : 65 V
  - No trench isolation
- Hamamatsu MPPC S14160-1315PS
  - Small pixel size : 15 μm
  - Active area : $1.3\times1.3\mathrm{mm}^2$
  - Breakdown voltage : 38 V
  - 0.5 μm trench isolation

Crosstalk : carriers from avalanche in fired pixel firing adjacent pixels

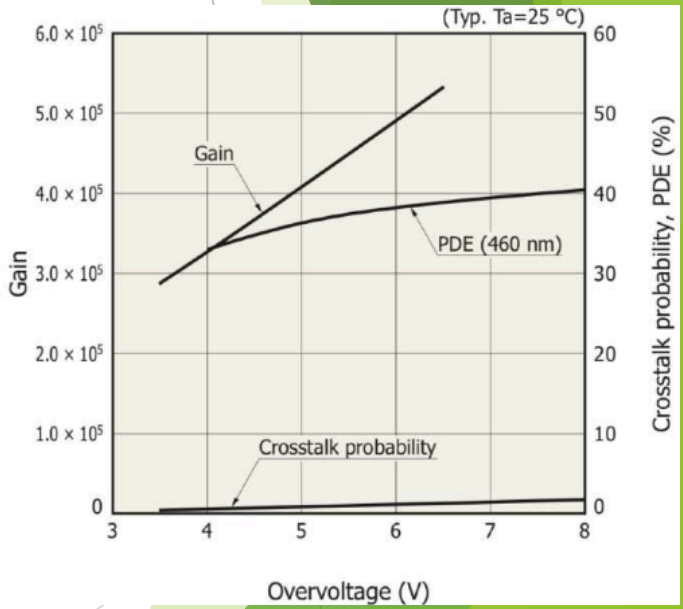
Trench : separation between pixels



S12571-015P



S14160-1315PS



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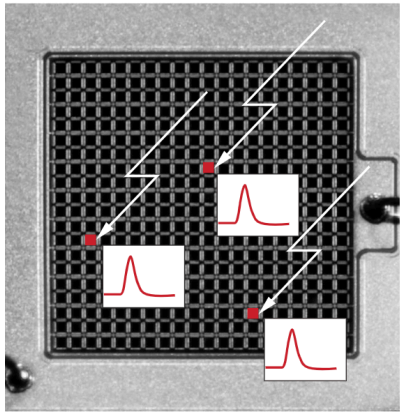
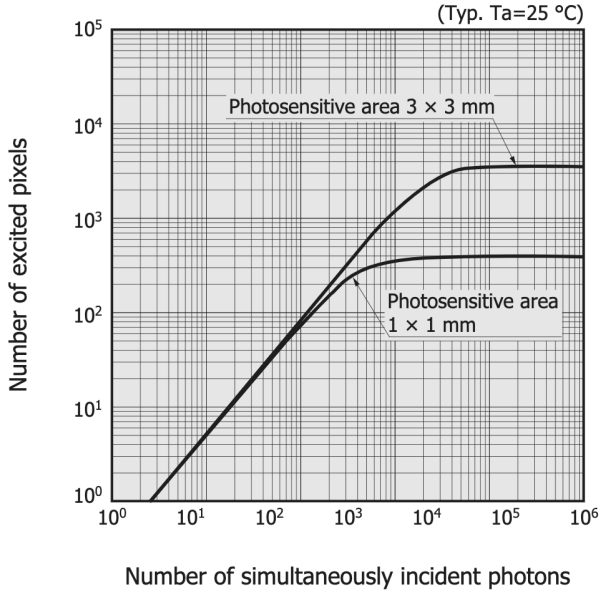
SiPM Saturation

- SiPM signal saturates for many photons due to limited number of pixels.
  - Proper correction for SiPM saturation is crucial for Sc-ECAL for ILC.
- This saturation curve is affected by scintillation emission time constant and SiPM recovery time.
  - Time constant of scintillation light (2.4ns) is not negligible compared to the SiPM recovery time (few ns)
  - Over-saturation, detecting more photons than number of pixels, can occur
- We propose to measure SiPM saturation curve with scintillator light excited by injecting UV-laser.

[Figure 2-2] Image of MPPC's photon counting





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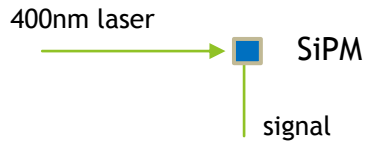
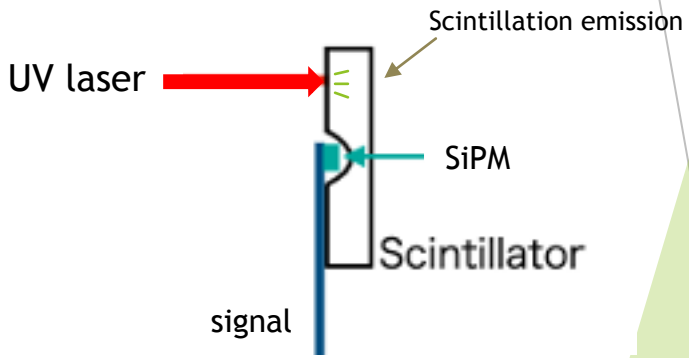
Experimental principle

- Saturation is usually studied by injecting 400nm pulse laser directly to SiPM.

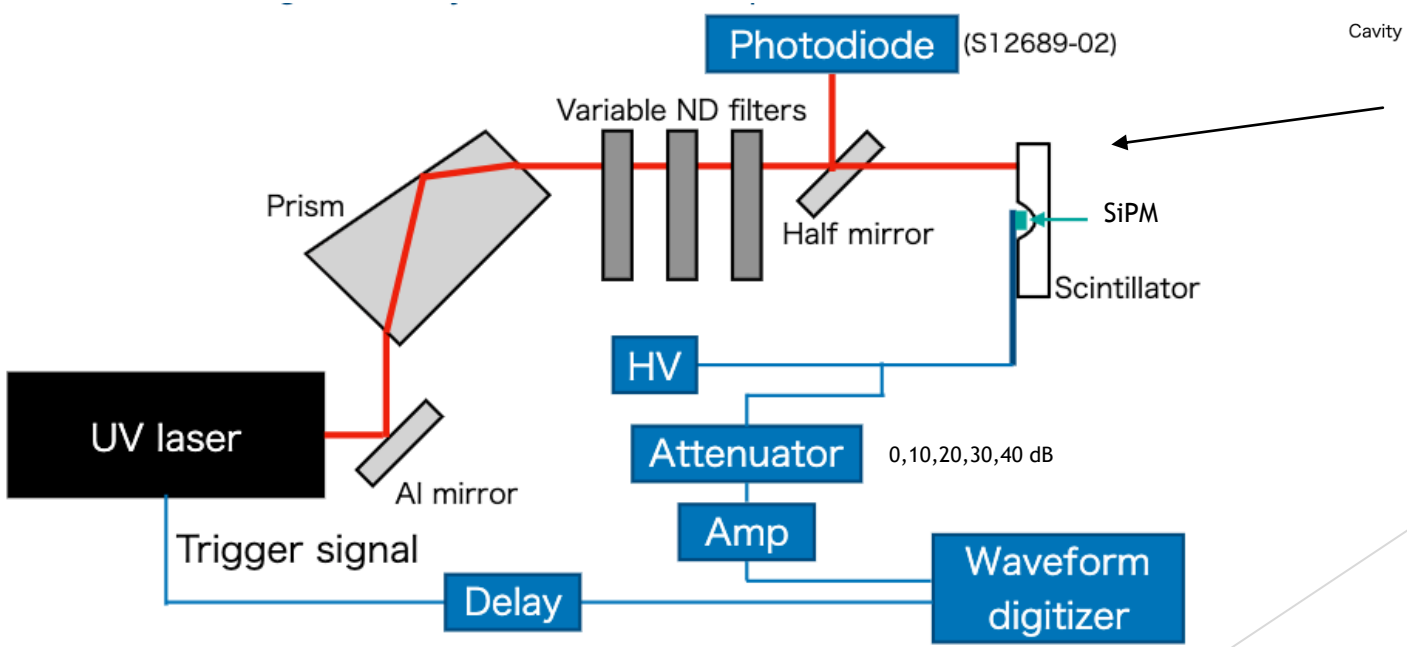


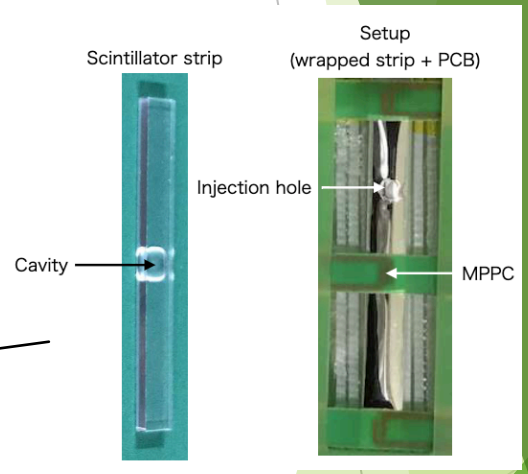
- Saturation can be measured by injecting UV-laser to the same **scintillator-SiPM system** as the detector
  - Excite scintillator by UV laser
  - Scintillation light intensity is controlled by the laser intensity
  - Effect of scintillation emission time constant is included.
  - Measured saturation curve can be used directly for the saturation correction.



Experimental setup

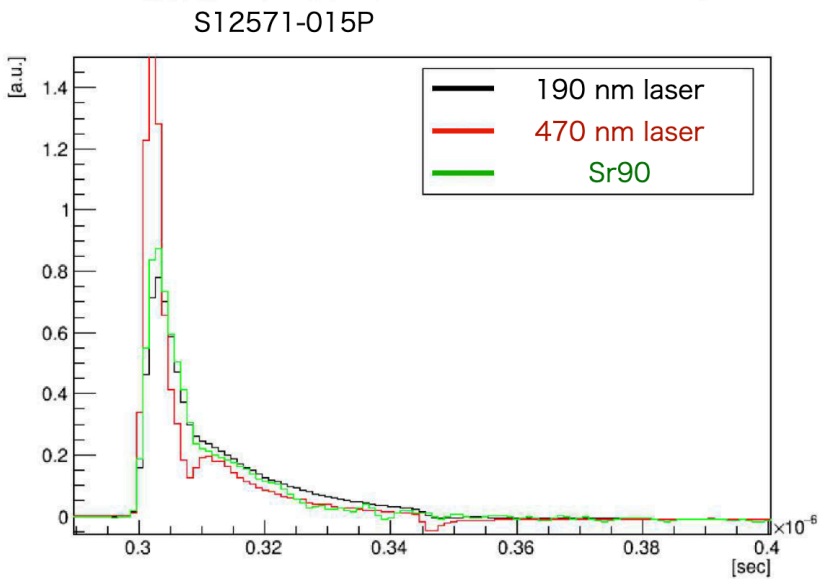
- Excite scintillation light with fsec UV pulse laser
  - 5×45×2 mm^3 scintillation strip (EJ-212) (same strip and SiPM as Sc-ECAL)
  - MPPC S12571-015P/S14160-1315PS with over voltage of +5V (Recommended voltage by Hamamatsu Photonics)
  - 190 nm wavelength → invisible to MPPC
  - Incident UV light intensity is monitored with photodiode
  - Signal attenuators are used to avoid electronics saturations.

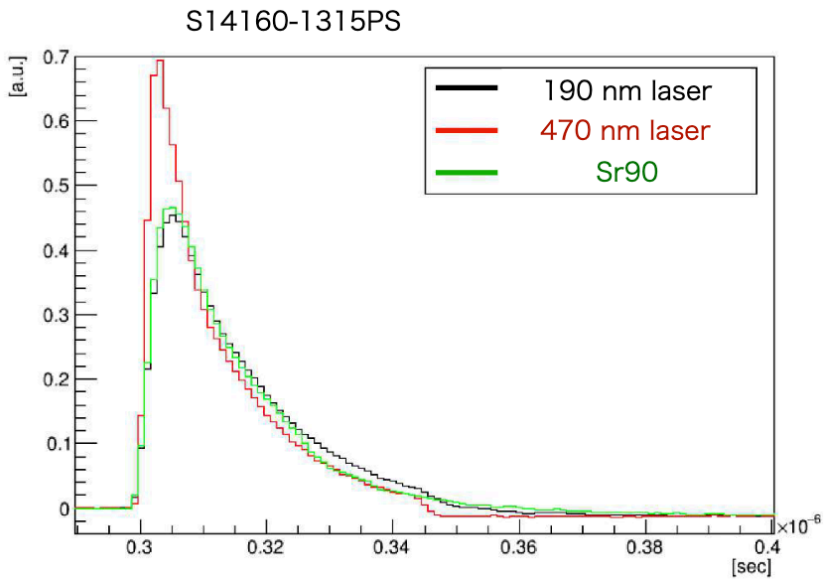




Signal Waveform

- Similar experiment is conducted with fast fsec 470 nm laser for comparison.
- Comparison of signal waveform
  - 190 nm laser injection to scintillator
  - 470 nm laser injection to SiPM
  - Beta-ray from Sr-90 injection to scintillator
- Faster signal for 470 nm laser.
- Almost the same waveform between 190 nm laser and Sr90.
  - 190 nm laser really excites scintillation light.





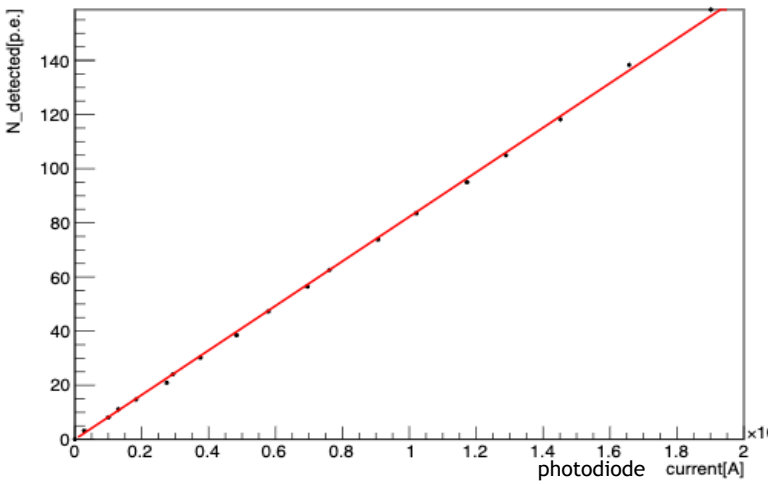
Saturation curve with 190nm

N_{seed} : number of photoelectrons when assuming no saturation

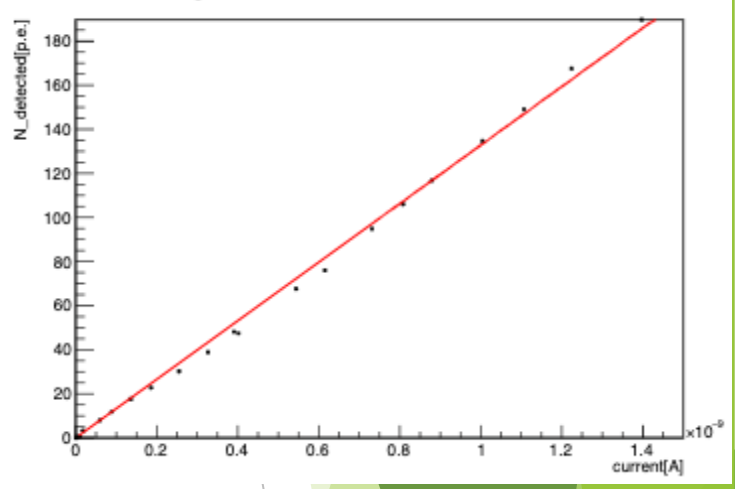
$N_{detected}$: number of photons MPPC detected

- Laser intensity is monitored with photodiode.
  - Photodiode current is converted to $N_{detected}$ [p.e.] at low laser intensity where SiPM do not saturate.
  - This calibration is used to estimate scintillation emission at high laser intensity where SiPM saturate.
  - We assumed UV laser intensity is proportional to scintillation emission.
- Measured saturation curve.
  - Over-saturation is observed.

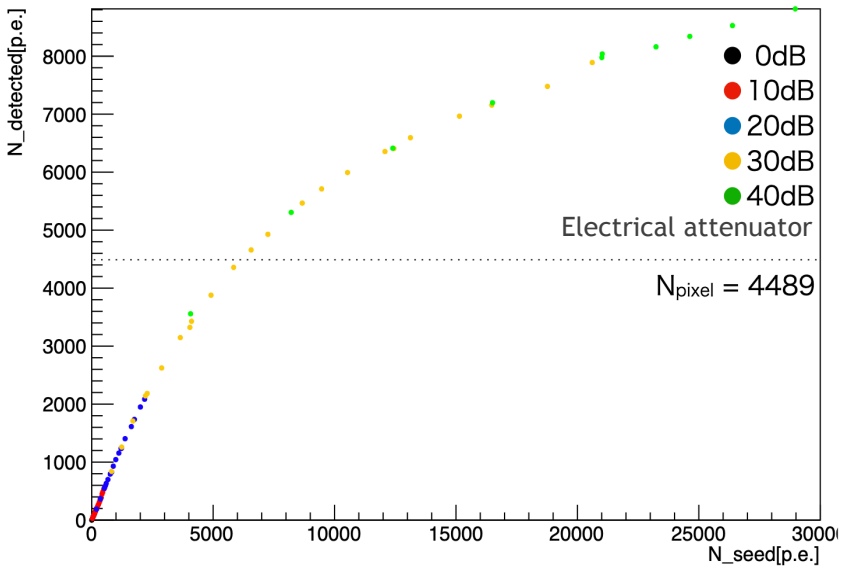
Linear region of S12571-015P



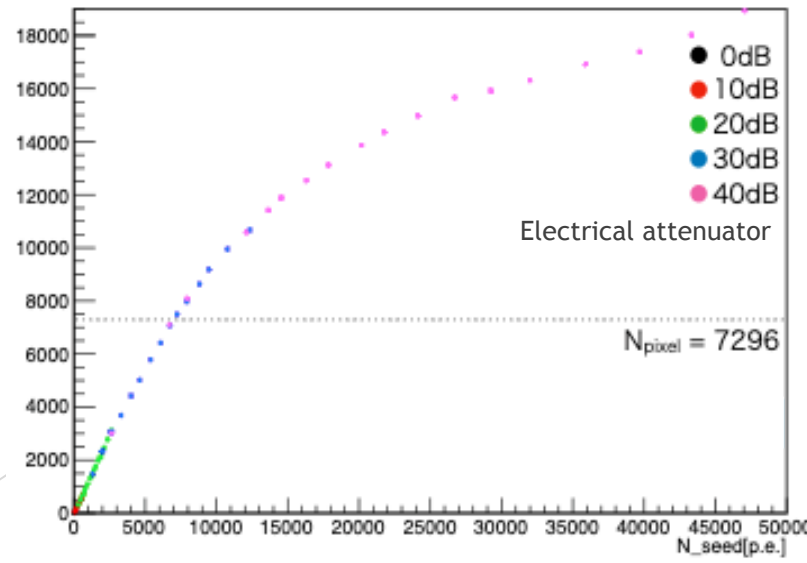
Linear region of S14160-1315PS (MPPC w/ trench)



S12571-015P saturation curve

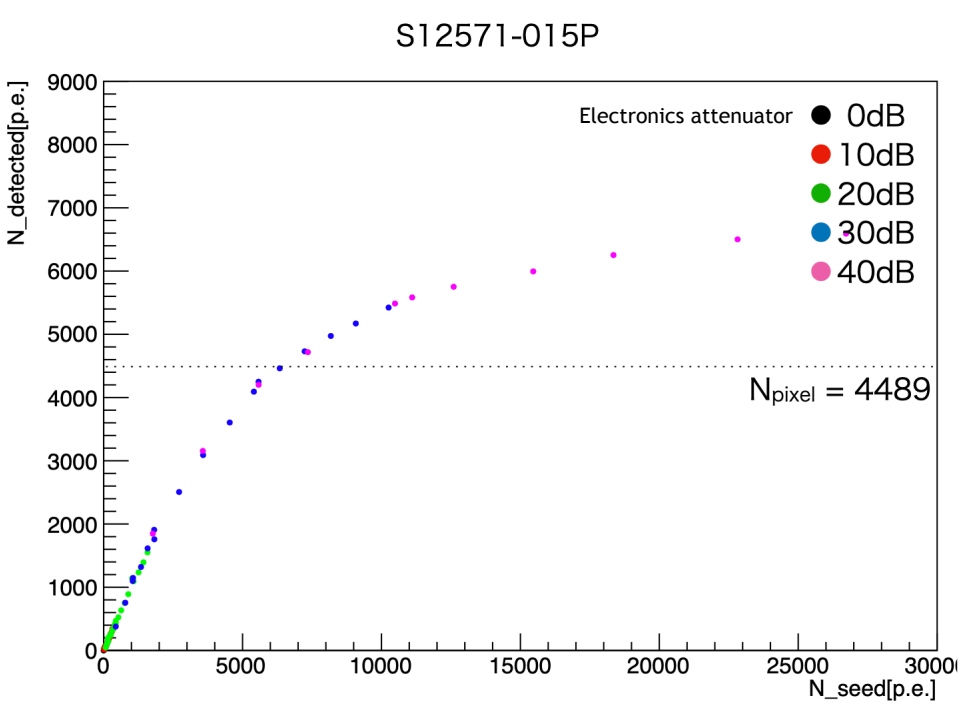


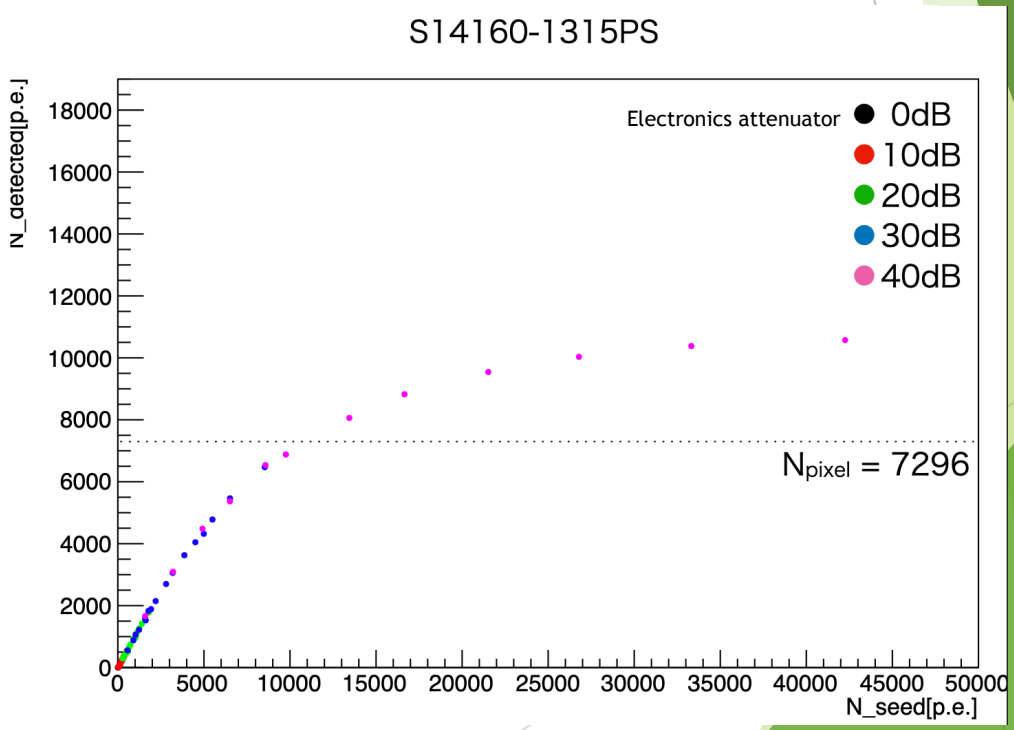
S14160-1315PS saturation curve



Saturation curve with 470 nm

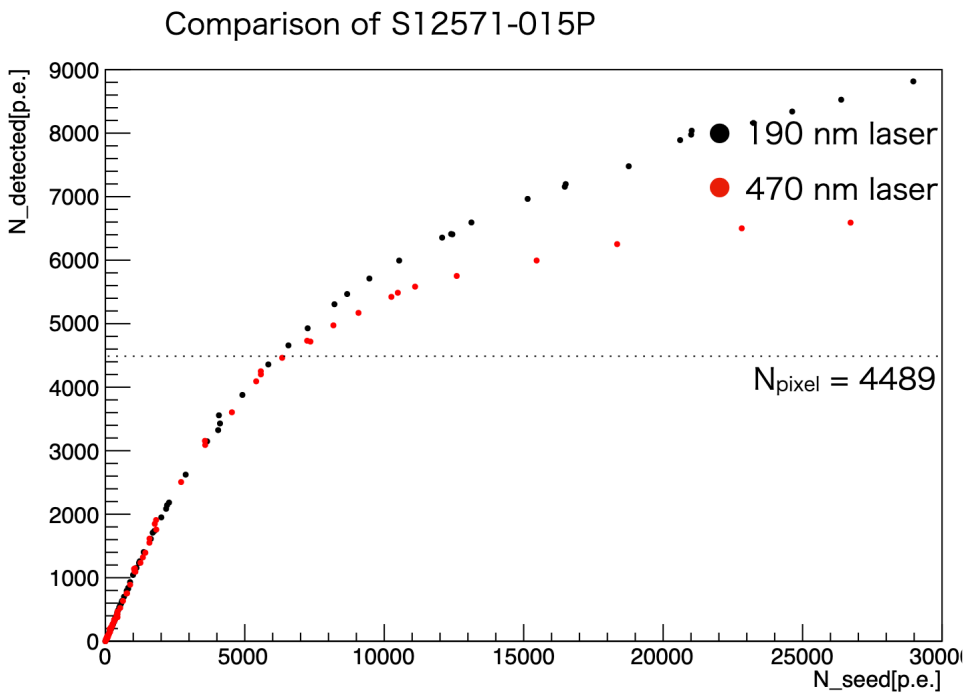
- Saturation curve with 470 nm is also measured to compare with 190 nm.
- Over-saturation is considered to be caused by after-pulsing

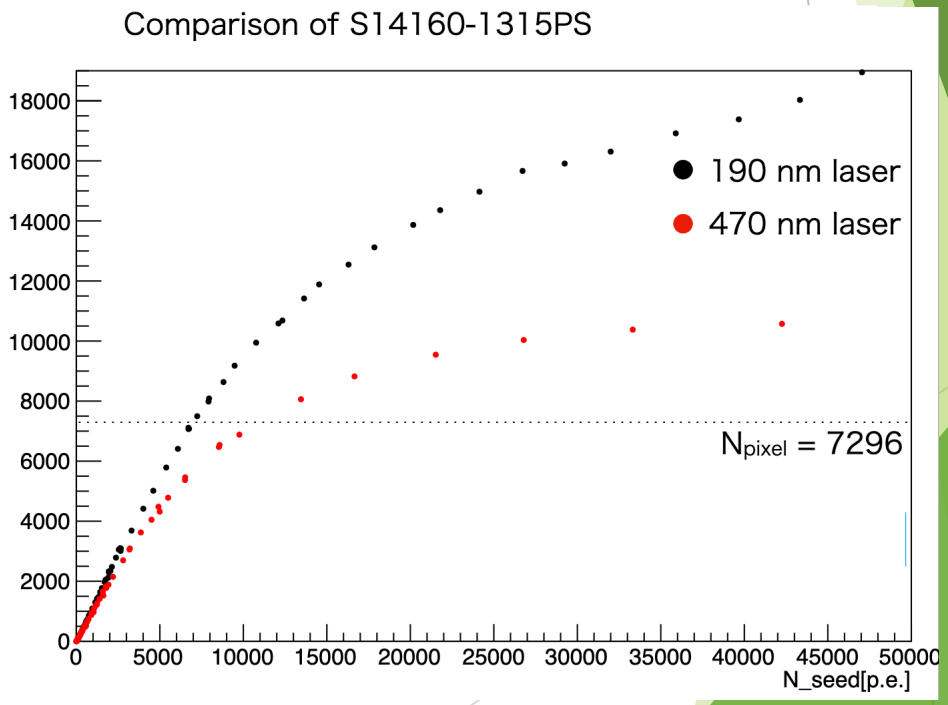




Comparison of saturation curves

- Saturation is relieved with UV laser
  - The effect of time constant of scintillation light emission is observed.





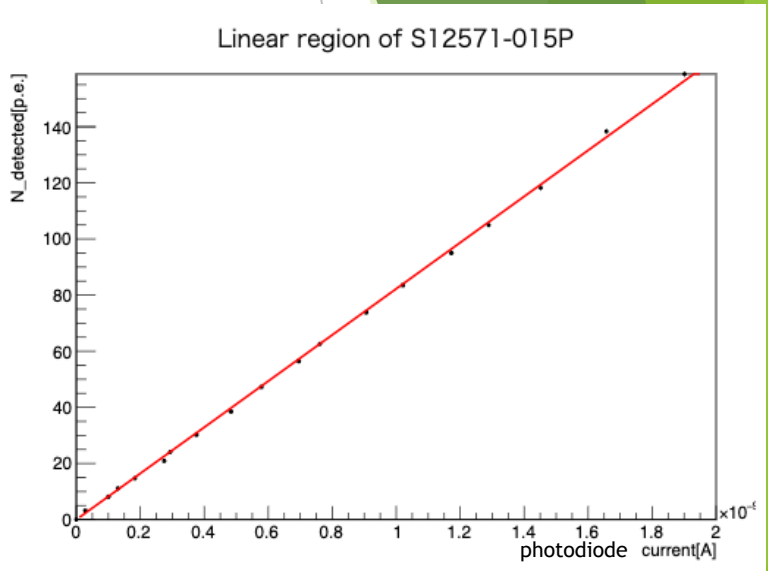
Possible issues

- The assumption in this measurement :

  Scintillation emission is proportional to the intensity of the injected UV-laser in whole range

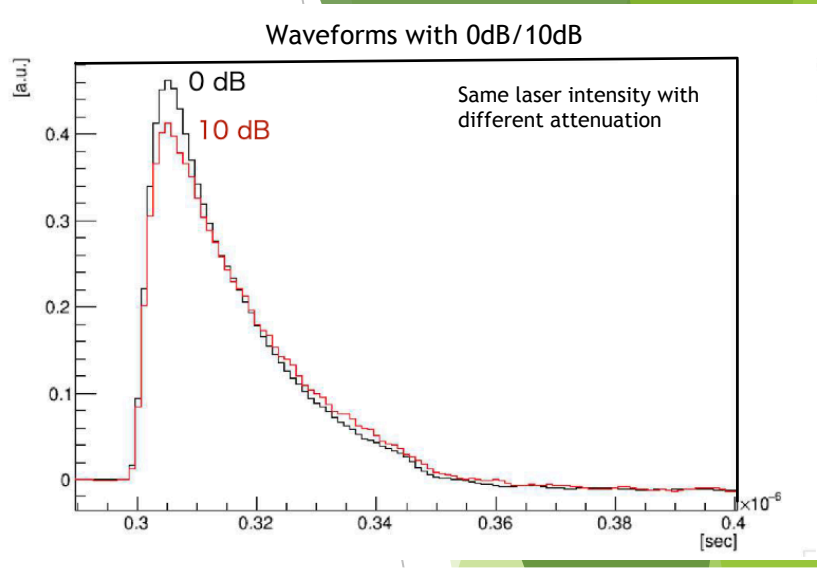
  - Used this relation in whole range to estimate scintillation emission.
  - This proportionality must be experimentally confirmed.

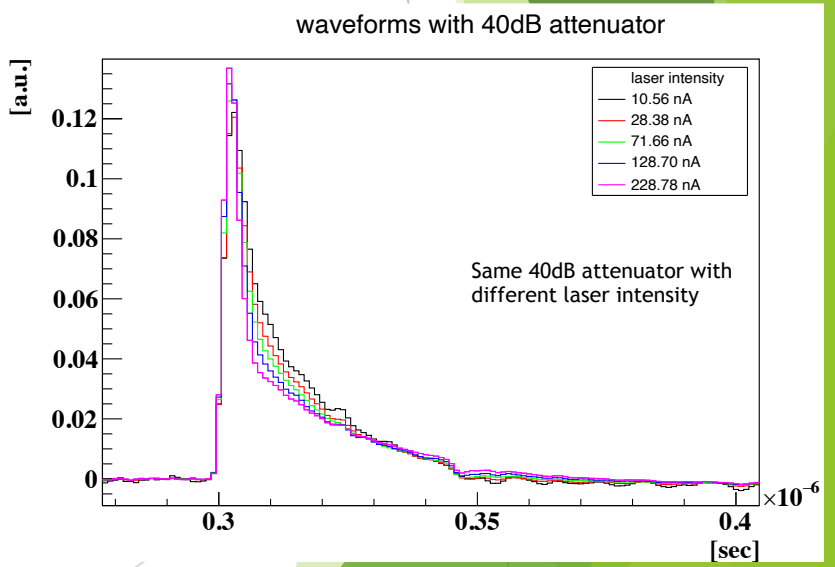
- We plan to measure the relation between the scintillation emission and the intensity of the UV laser over the whole range.



Possible issues

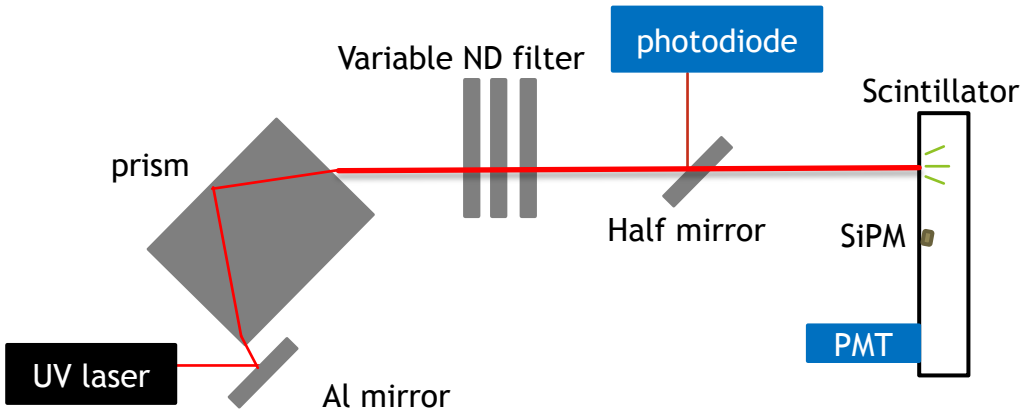
- Inserting and removing attenuators during the measurement.
  - To avoid saturation of electronics, signal attenuator is inserted.
  - High frequency region is more attenuated than low region.
- Signal waveform will change as UV laser intensity increases.
  - This shape change affects estimation of photoelectrons.
- To avoid the effect of the limited bandwidth of the signal attenuator, it is planned to study SiPM saturation by measuring SiPM current without using the attenuator.





New set up for saturation measurement

- Measuring relation between scintillation emission and UV laser intensity by PMT.
  - PMT has a much wider dynamic range.
  - Non-linearity is corrected if observed.
- Changes from the last measurement
  - **Photomultiplier tube** H6152-70
    - No signal attenuation for PMT to avoid distortion of signal, which can affect linearity.
  - Measuring current by Picoammeter



Summary and Prospects

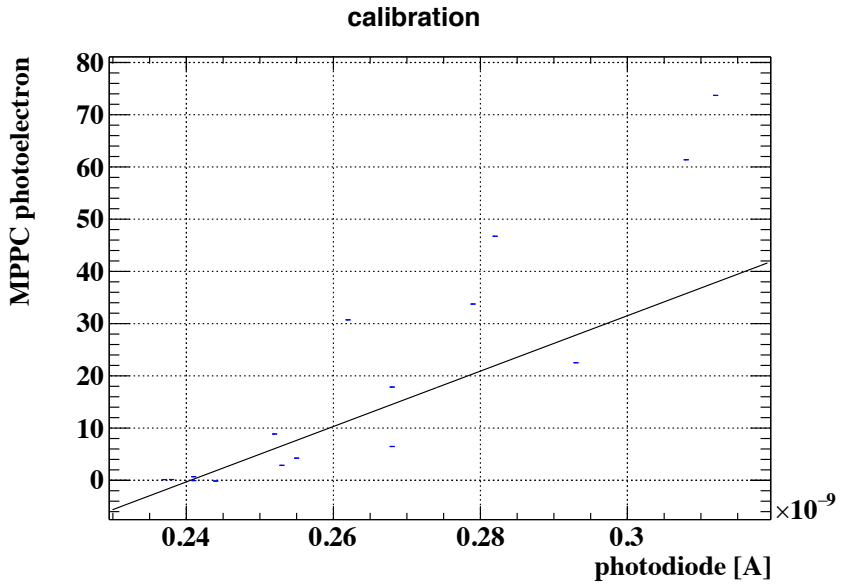
- Measuring SiPM saturation curve with scintillator is important for energy reconstruction of particles in ScECAL.
  - We measured and compared saturation curve of SiPM with 190 nm laser and 470 nm laser.
  - Saturation curve with 190nm seems reasonable.

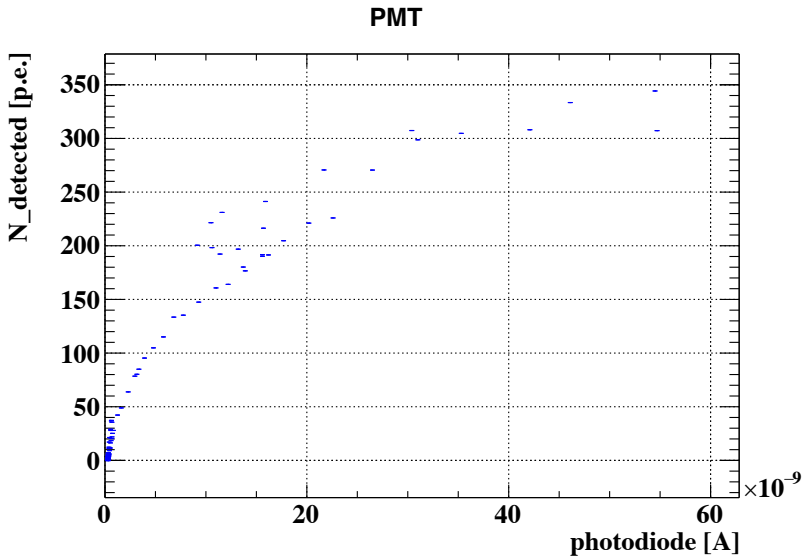
- Improved new set up is in preparation
  - To check the linearity of excitation caused by UV laser, measure scintillation light with PMT
  - To avoid waveform variation, measure SiPM output in current

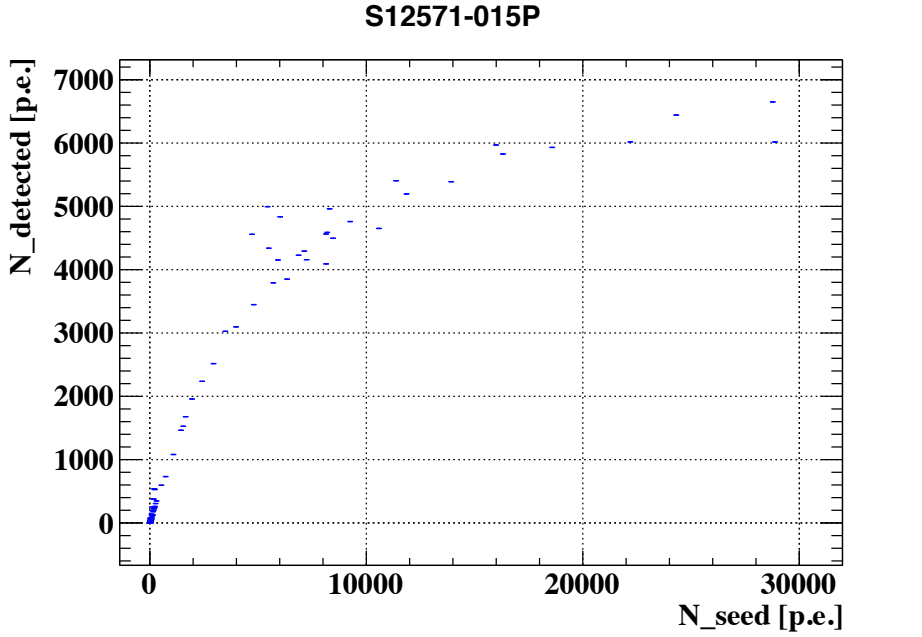
Back up

Result of new setup (S12571-015P)

- Laser intensity was not stable
  - Calibration of incident photons is bad
- Path of laser may be modified during measurement
- PMT H3165-11PX also saturated
  - H3165-11PX has narrow dynamic range.

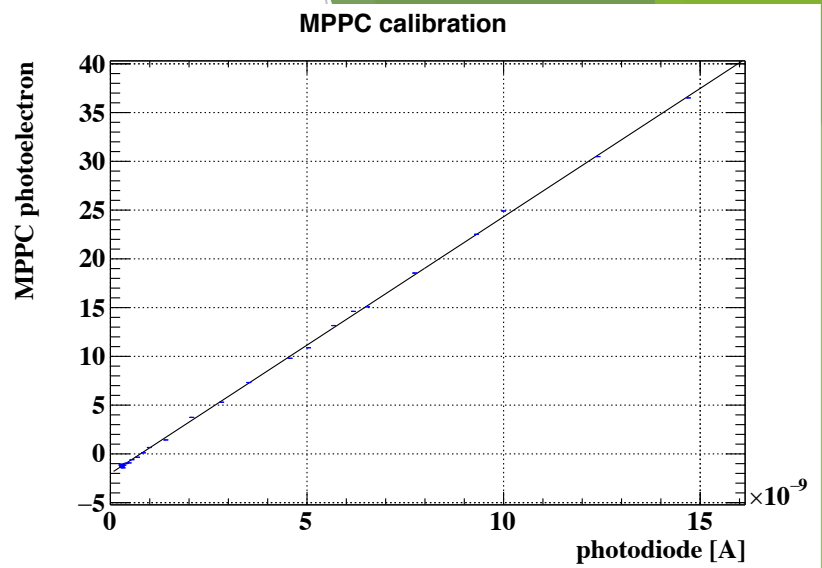


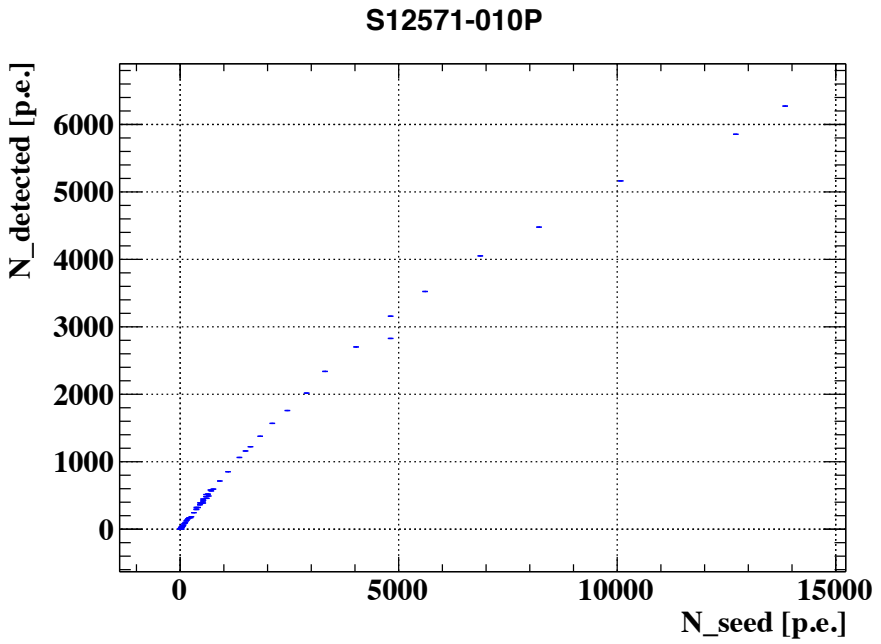




Result of new setup (S12571-010P)

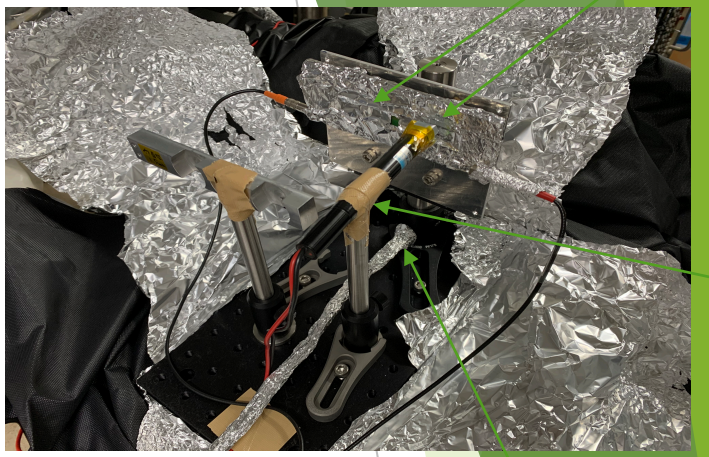
- Saturation was not sufficient.
  - S12571-010P has a greater number of pixels
    - S12571-015P : 4489
    - S12571-010P : 10000
- Laser intensity was low
  - Inadequate to measure saturation

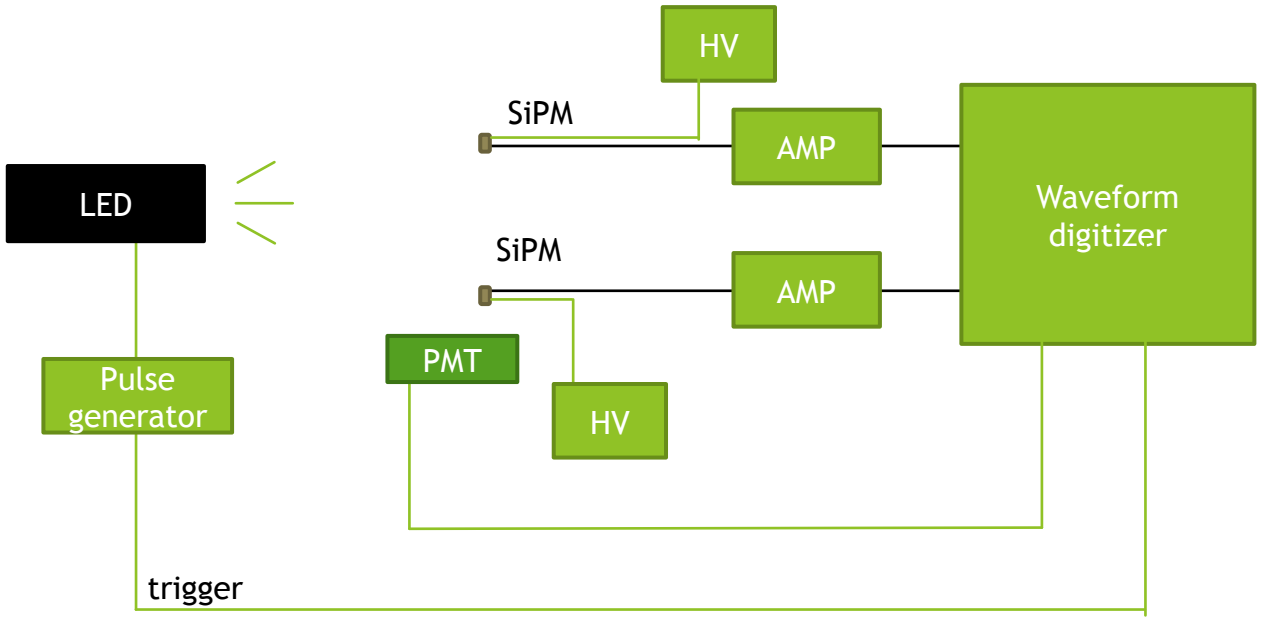




Calibration of Photo-sensors

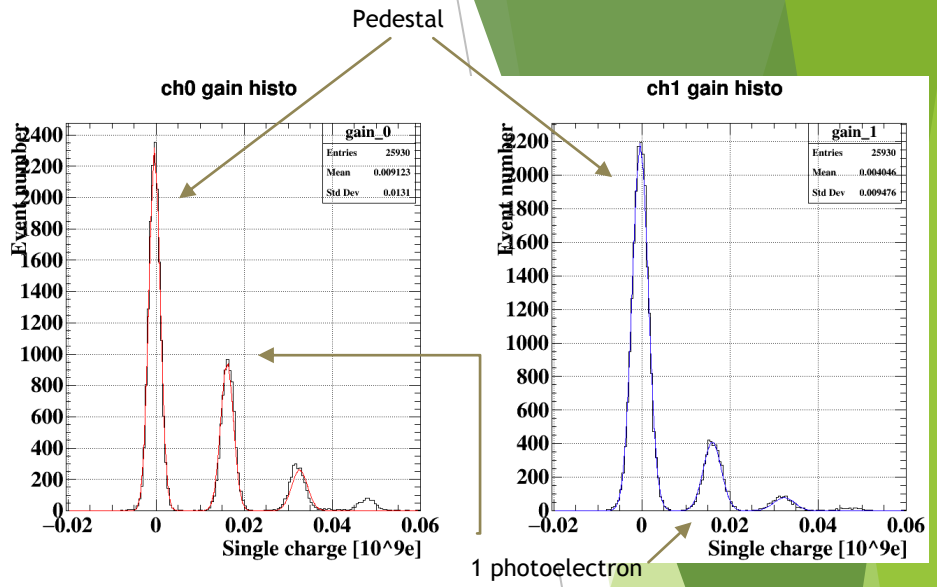
- The SiPMs and the PMT are calibrated by LED light.
  - Gain and probability of cross-talk and after-pulsing for SiPM
  - Gain for PMT





SiPM characteristics

- SiPM has a capability of separating photoelectrons.
- SiPM gain is calculated from one photoelectron charge.



	MPPC 1	MPPC 2
Operation voltage	68.15 V	68.16 V
Gain*	1.60×10^{7}	1.60×10^{7}
Cross-talk and after-pulsing probability	0.14	0.15

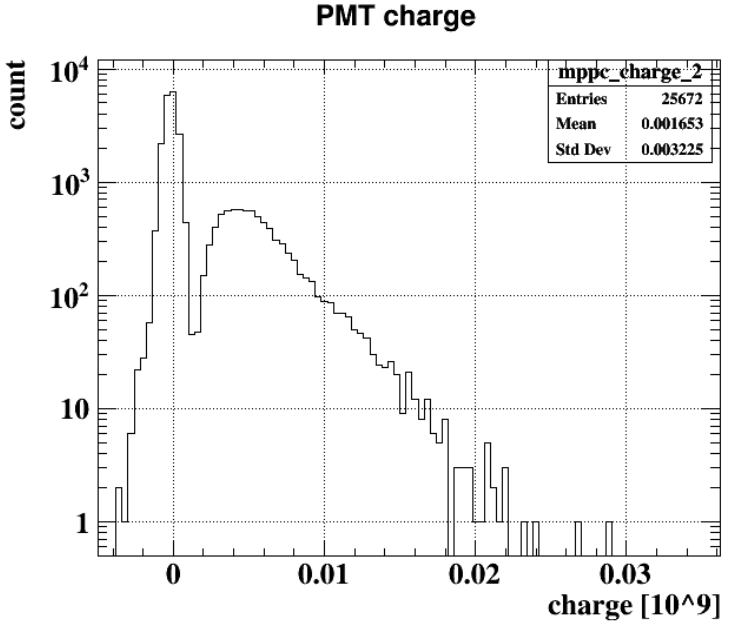
* including amp gain

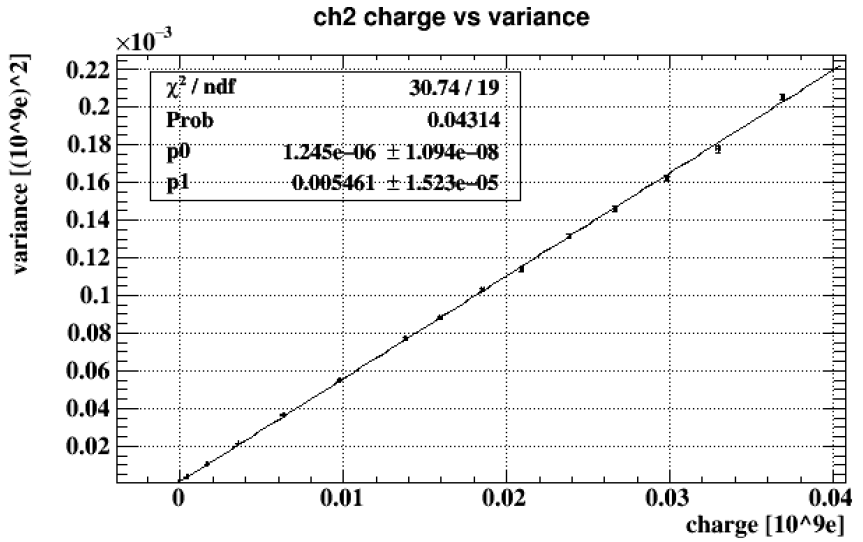
PMT gain

- Since it is difficult to resolve photoelectron peaks, the PMT gain is measured by statistical method.
- Using white noise mean(Q_0) and variance (σ_0^2), the mean($\bar{Q}$) and the variance(σ_Q^2) of the charge distribution can be written as

$$\sigma_Q^2 = \sigma_0^2 + \bar{G}e(\bar{Q} - Q_0)$$

- Measured gain at V_{op}=1000V :
  $(5.46 \pm 0.02)\times 10^6$





Readout electric linearity

- DRS linearity range : ~1 V
- PMT output : 100 mV to 15 V

- By using fixed attenuator, signal is within the linear range of the PMT and the readout electronics.

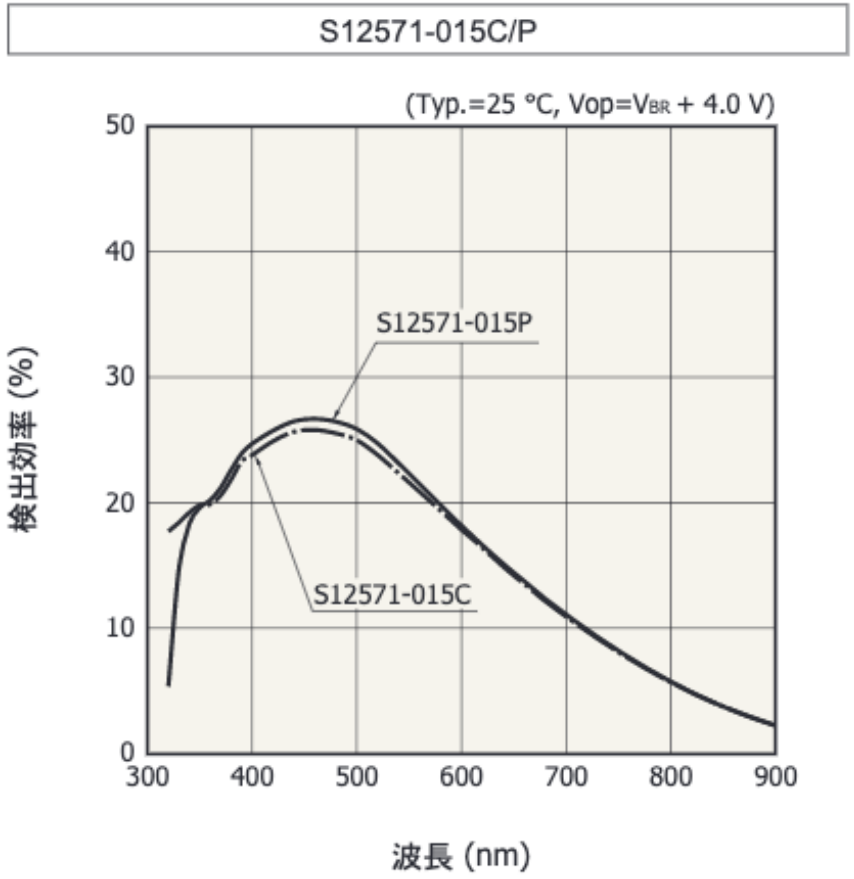
PMT pulse linearity

- Scintillation light has to be monitored in the linear range of the PMT and the readout electronics.
- The acceptance of the PMT to the scintillation light is adjusted to be in the linear region

- Maximum number of photoelectron observed at SiPM : 3×10^{4}
  - 10^{3} photoelectrons at PMT
  - 6.6×10^{-4} mA/kHz

- PMT pulse linearity : 2% at 3mA, 5% at 7mA
- PMT pulse linearity is guaranteed.

MPPC S12571-015P，PMT H3165-11PX の検出効率の波長依存



PMT H3165-11PX

感度波長 (Short)	300 nm
感度波長 (Long)	650 nm
感度波長 (Peak)	420 nm

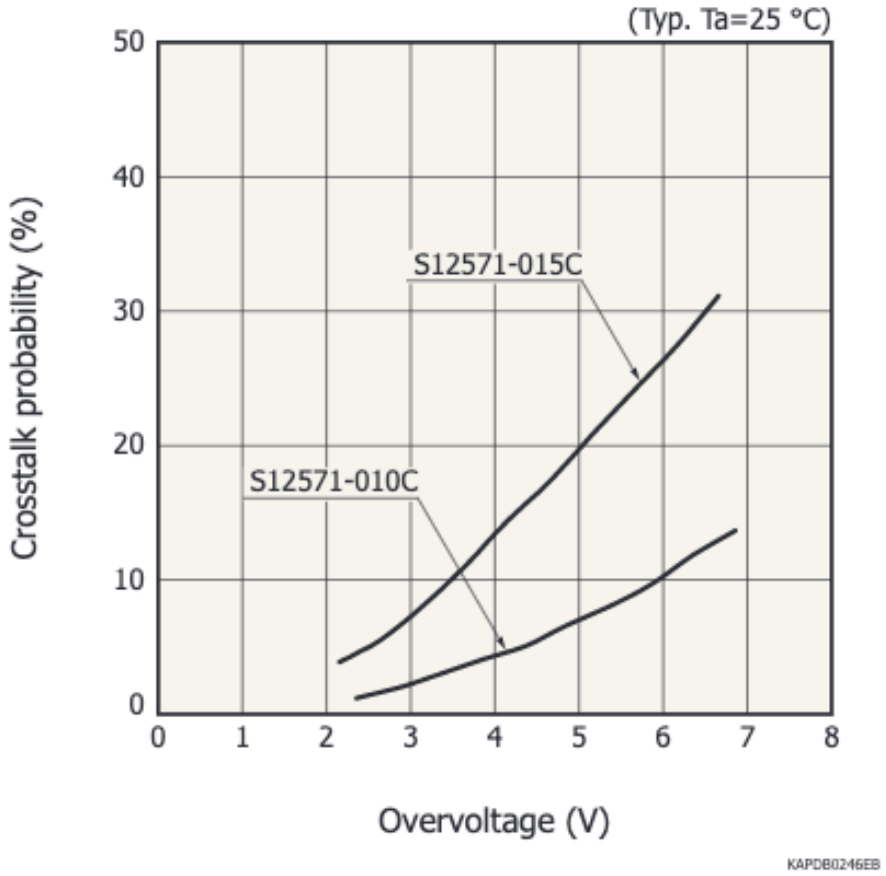
MPPCのPDEのグラフ

CT+AP Measurement

- Assume the signal distribution of LED calibration is Poisson
- Ideal probability for 0 photon and 1 photon is
  - $P(0) = e^{-\mu}$
  - $P(1) = \mu e^{-\mu}$
- CT and AP do not affect $P(0)$ but only decrease $P(1)$
  - $P'(1) = (1 - \chi)\mu e^{-\mu}$
- The CT+AP probability χ is calculated as
  - $\chi = 1 - \frac{P(1)}{P(0)\log P(0)}$

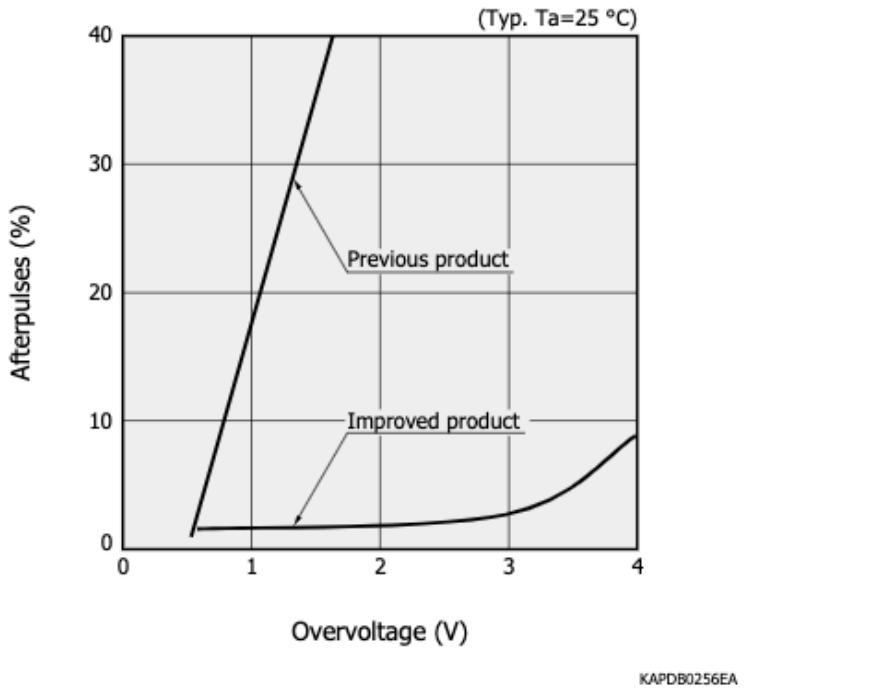
MPPC S12571-015P

Crosstalk probability vs. overvoltage

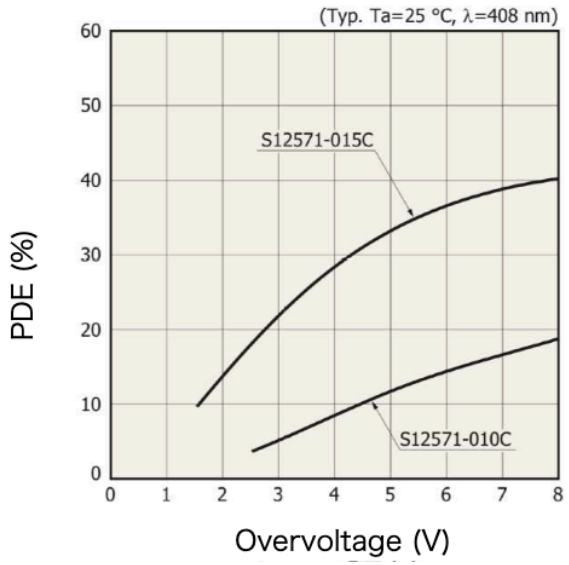


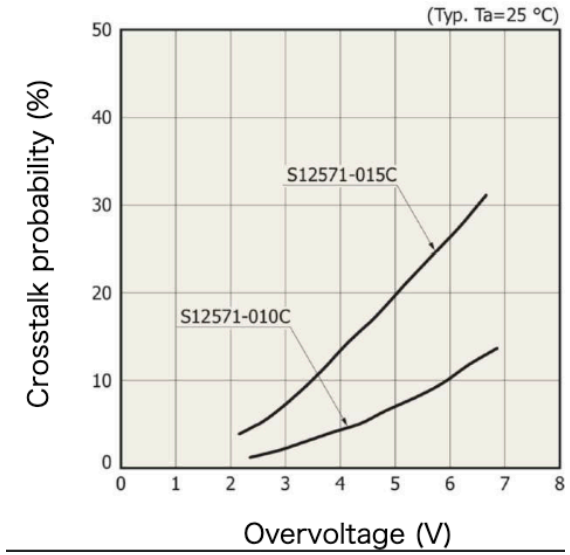
After pulse

[Figuer 1-26] Much reduced afterpulsing of Hamamatsu MPPC

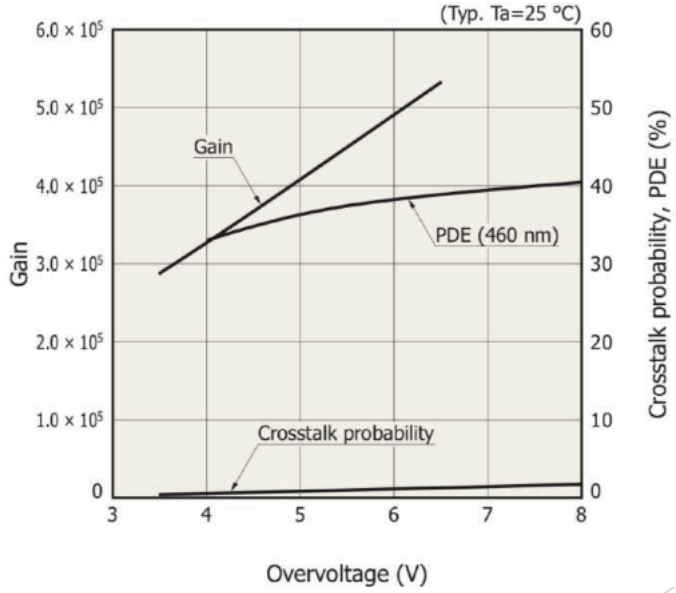


S12571-015P





S14160-1315PS



MPPC

S12571-015P

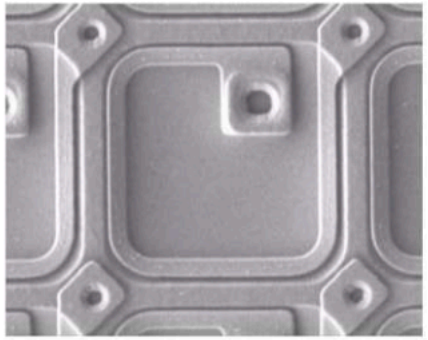
S14160-1315PS

Hamamatsu Photonics K. K., PD18

Old design (w/o trench)

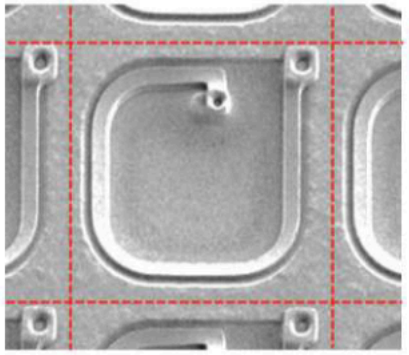
- **Fill factor: 53%**

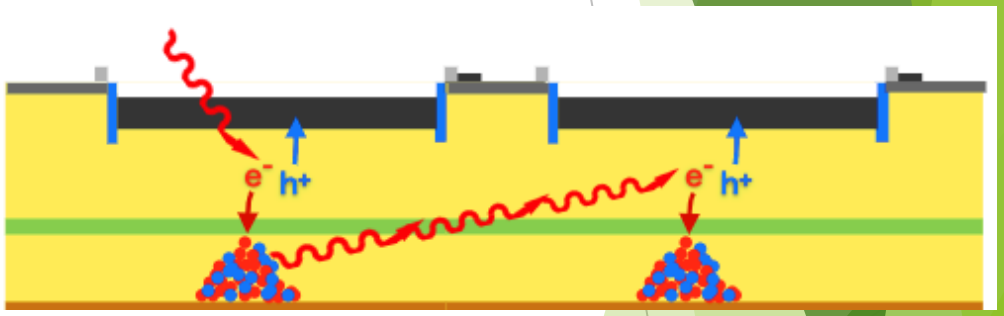
15 μm



New design (w/ trench)

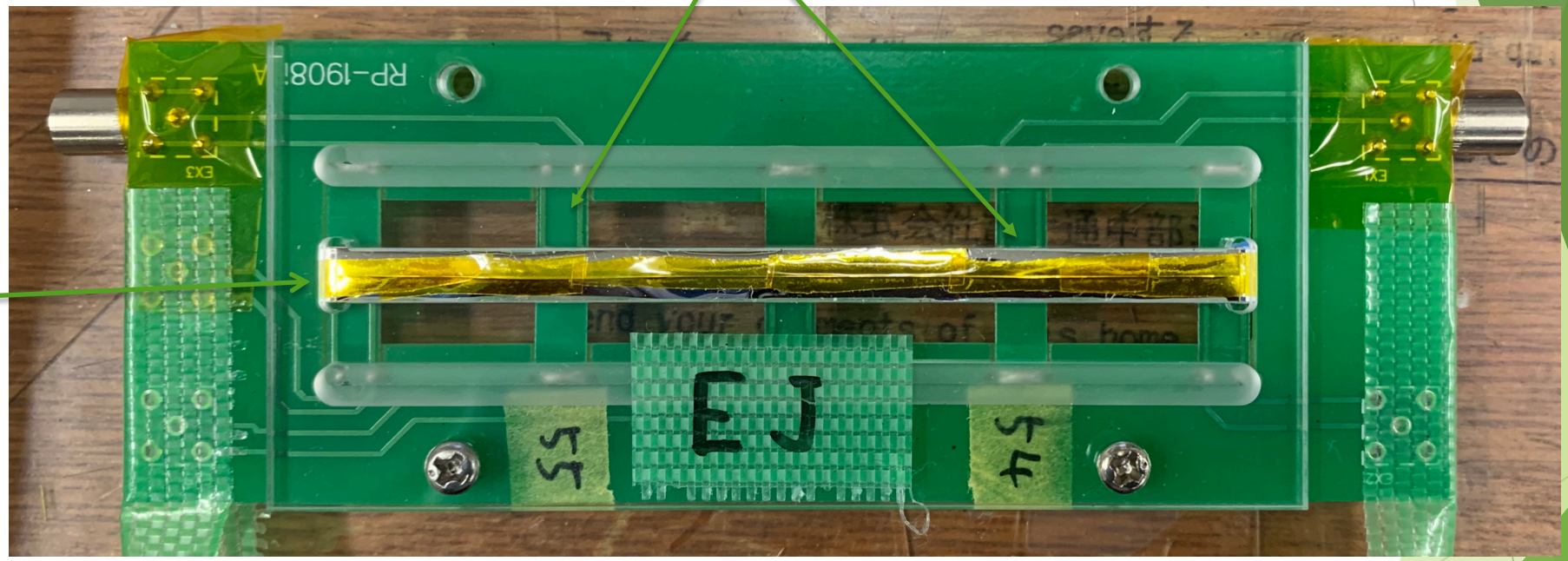
- **Fill factor: 49%**





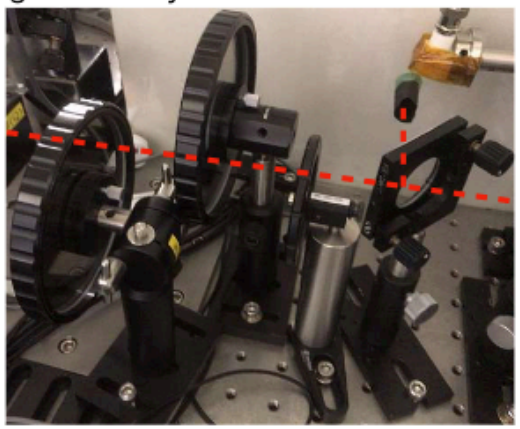
MPPC

Scintillator



Experiment setup

Incident light intensity controlled with three ND filters

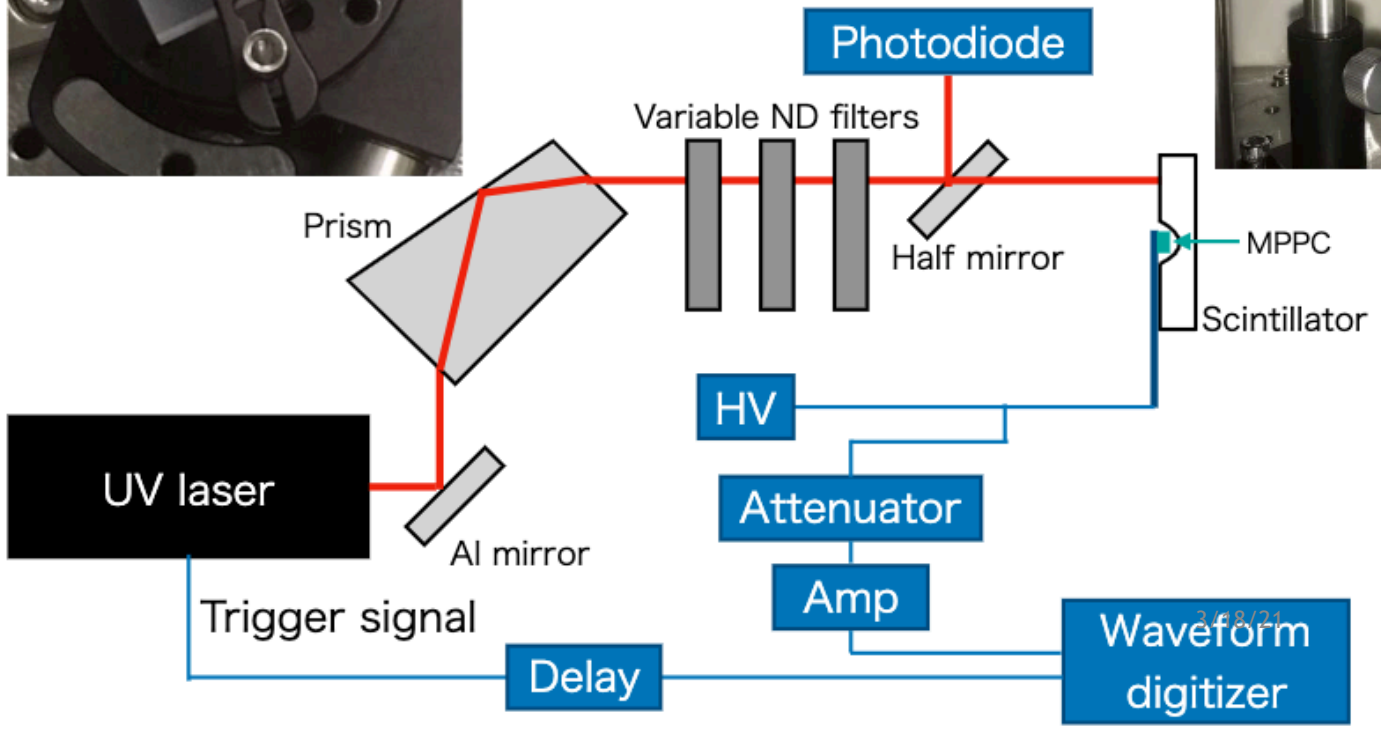


Cut off contamination of other wavelength light

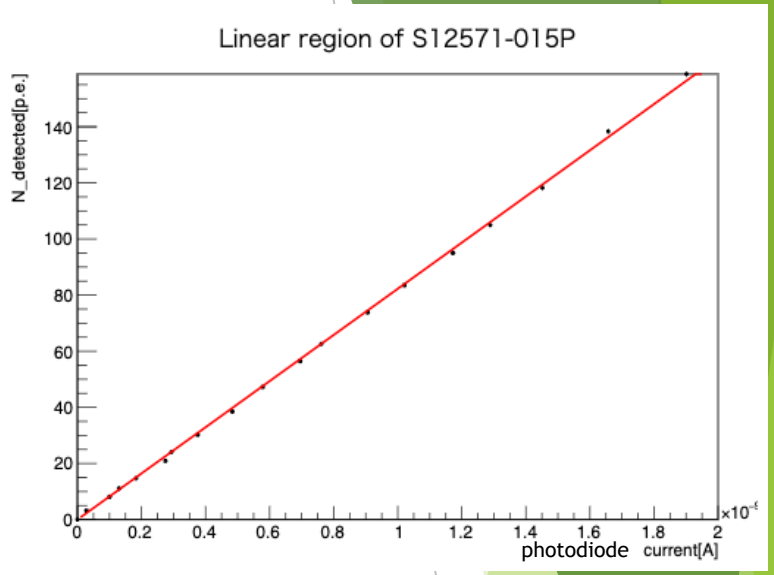
Laser Light is split using half mirror

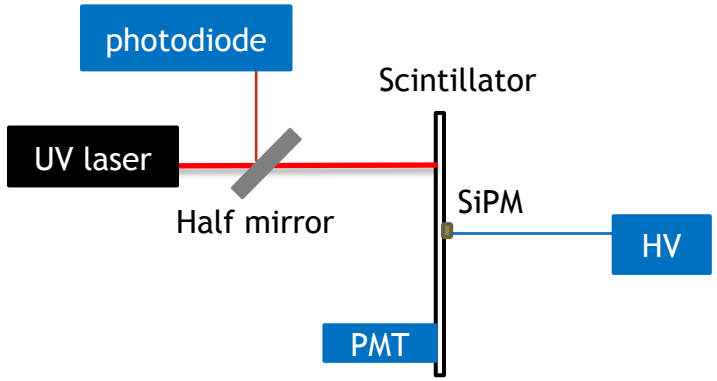
Photodiode

Scintillator & PCB



Possible issues

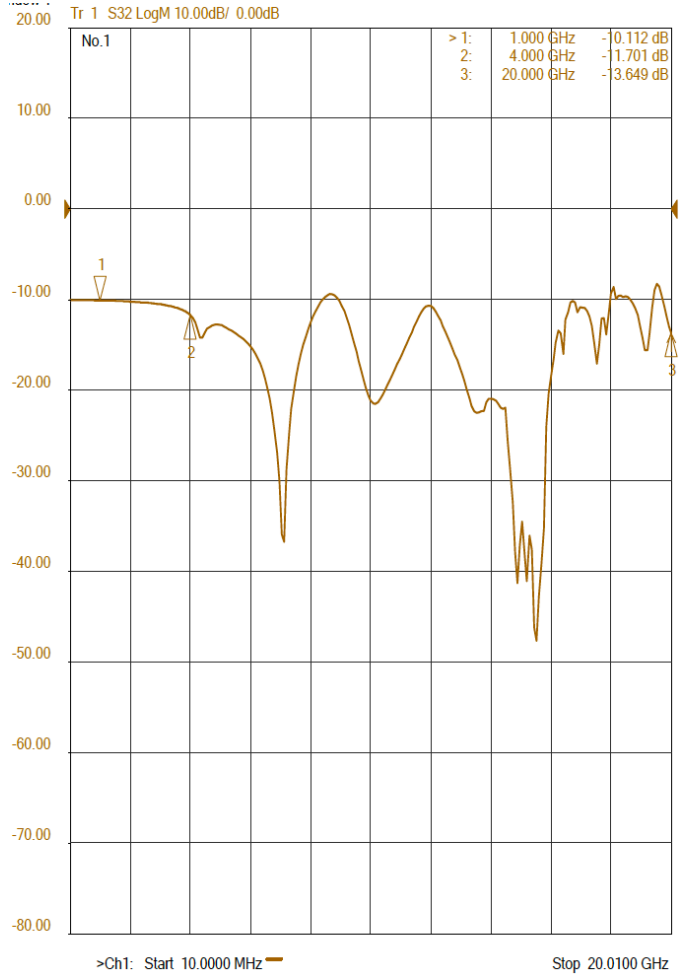




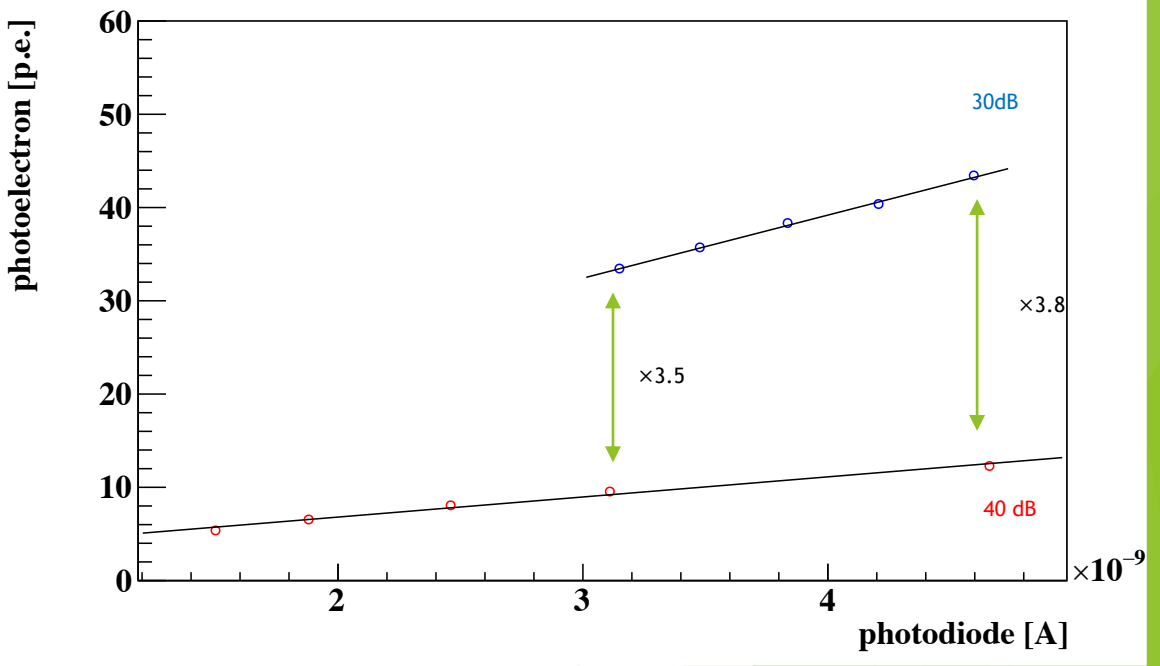
Current measurement

- Measuring relation between scintillation emission and UV-laser intensity by PMT.
  - PMT has a much wider dynamic range.
  - Non-linearity is corrected if observed.
- Changes from the last measurement
  - **Photomultiplier tube** H6152-70
    - No signal attenuation for PMT to avoid distortion of signal, which can affect linearity.
  - Two SiPMs to check individual difference in saturation curve
  - 5×90×2 mm^3 scintillation strip (EJ-212) (same strip as ScECAL)
  - Measuring current at Picoanmeter

Frequency dependence of attenuator



Attenuation



picoanmeter