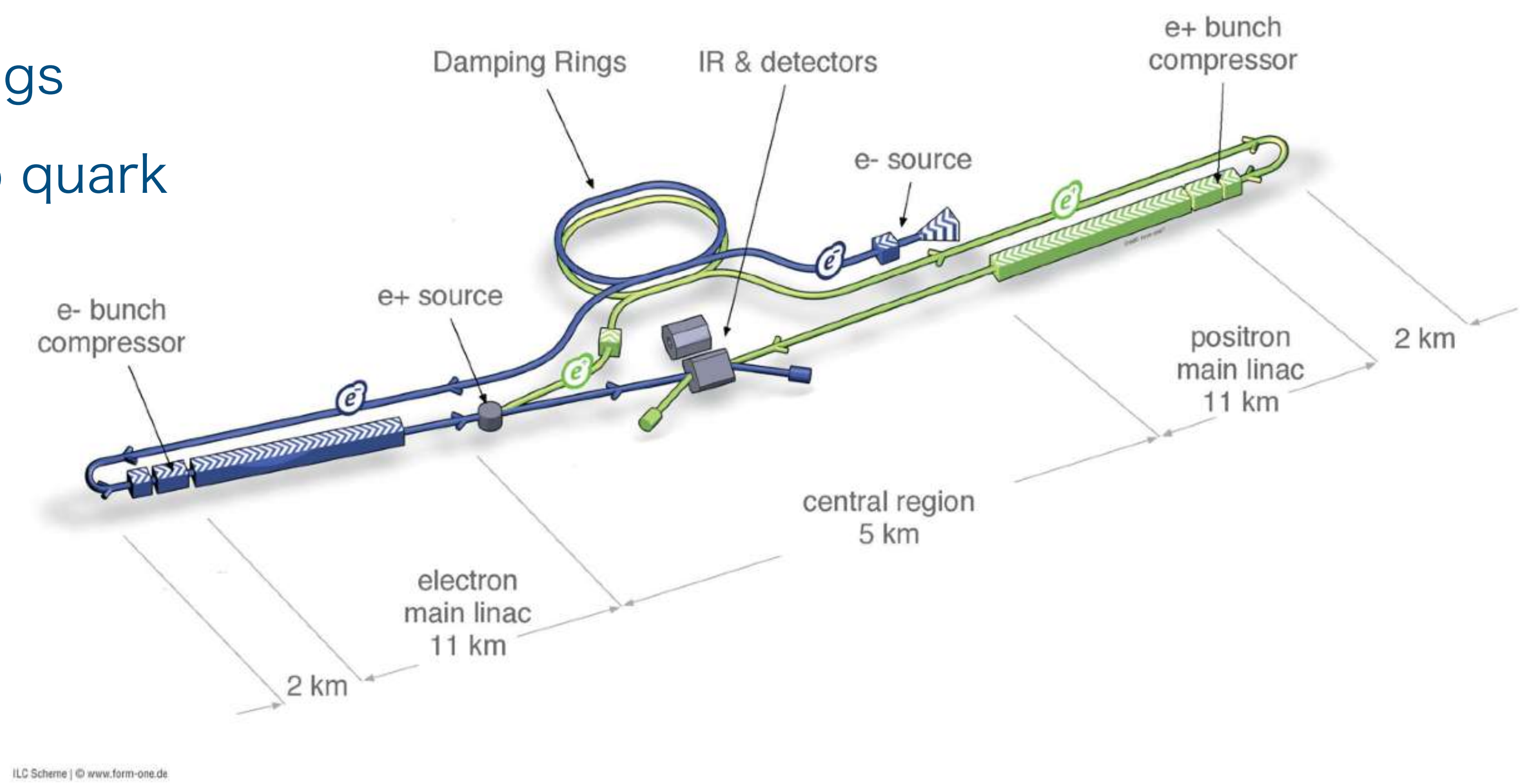
Study on Saturation of SiPM for scintillator calorimeter using UV laser

Naoki Tsuji, The University of Tokyo
Linghui Liu, Wataru Ootani, Kosuke Yoshioka, Makoto Gonokami, Yusuke Morita
CHEF2019 at Fukuoka, 25-29 November 2019

International linear Collider (ILC)

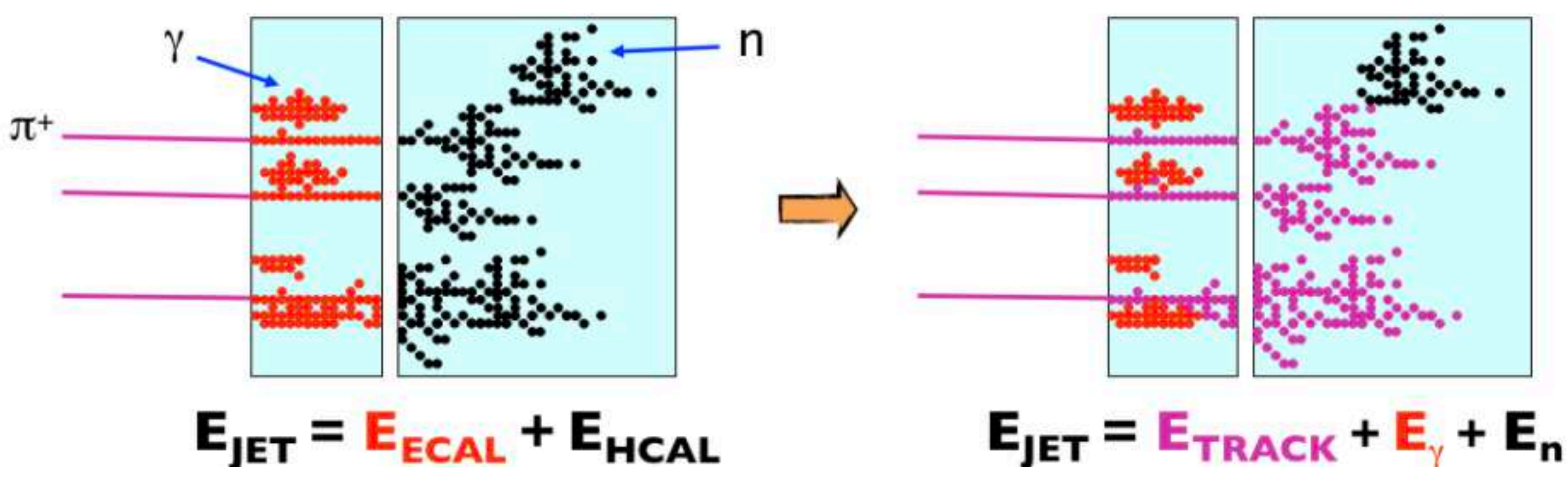
- Future high energy frontier machine
  - Electron-positron collider
    - Lepton, elementary particle
    - Low background → precise measurement
  - E_{cm} : 250 - 500 GeV
    - Initial plan : 250 GeV
    - Extendable to 1 TeV
- Search for new physics
  - Precise measurement of Higgs
  - Precise measurement of top quark
  - Search for dark matter

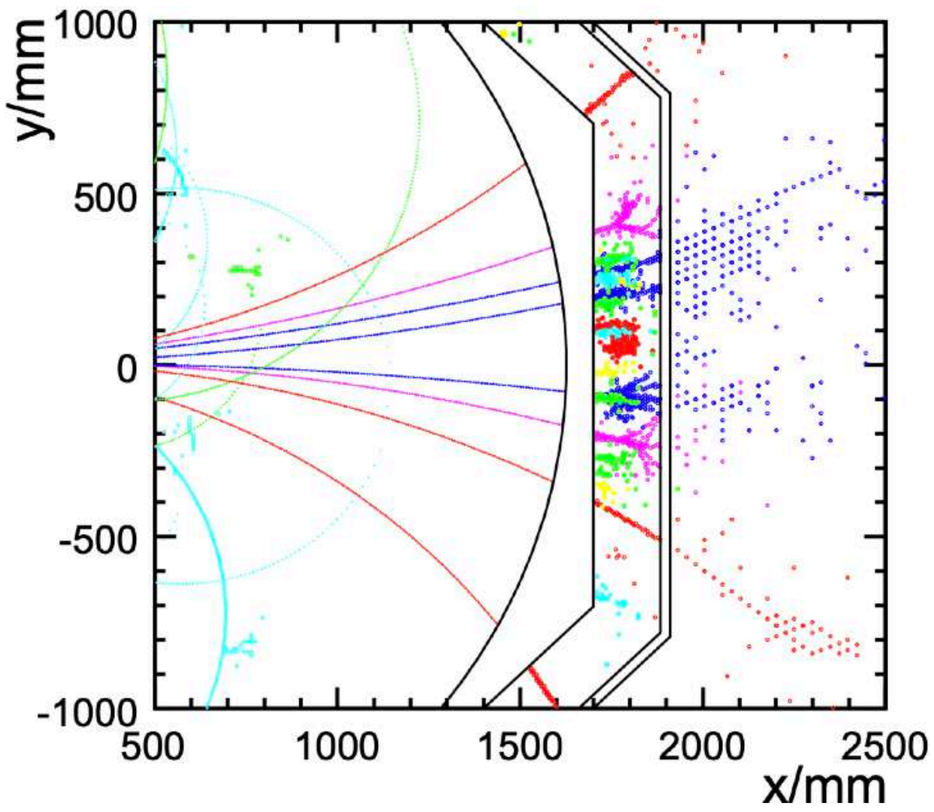


International Large Detector (ILD)

- ILD consists of vertex detector, central tracker, EM calorimeter, hadron calorimeter, and muon tracker
- Particle Flow Algorithm (PFA)
  - Each particle is detected by the best suited detectors
  - Improved jet energy resolution
- It is necessary to classify charged particle and neutral particle precisely

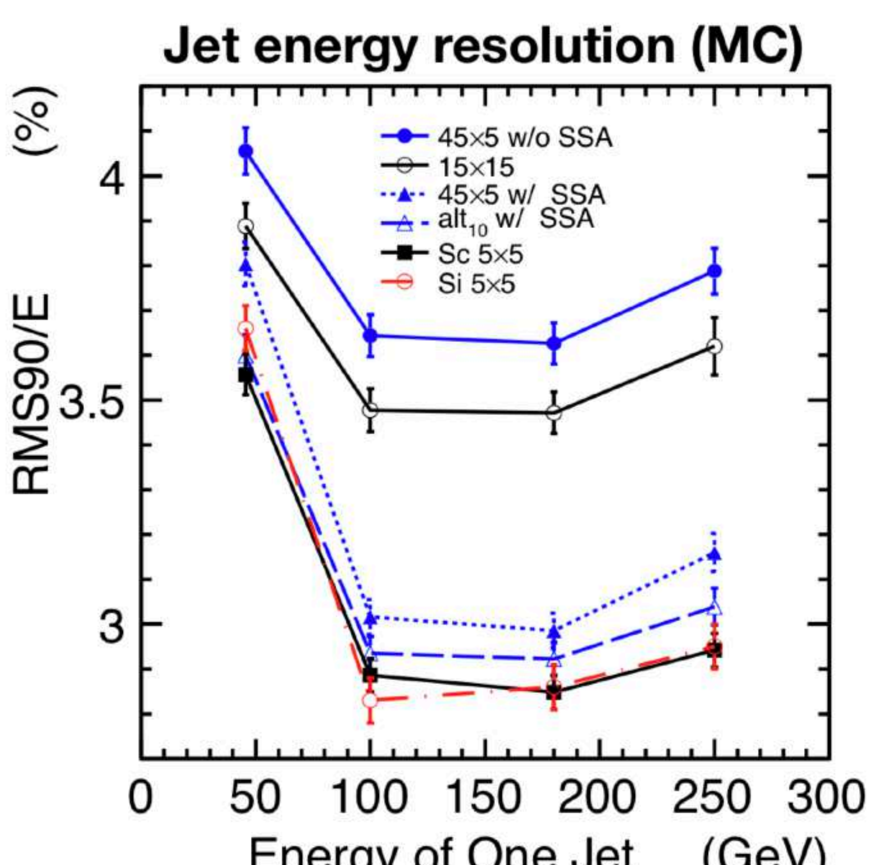
➡High granularity calorimeter is required.

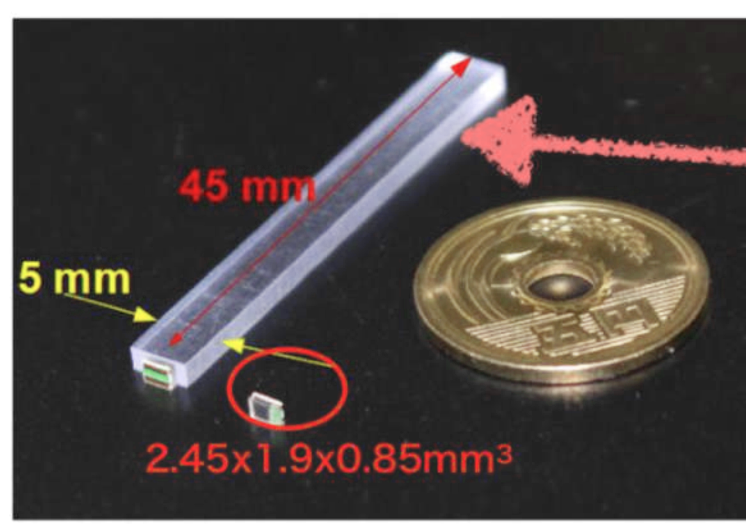


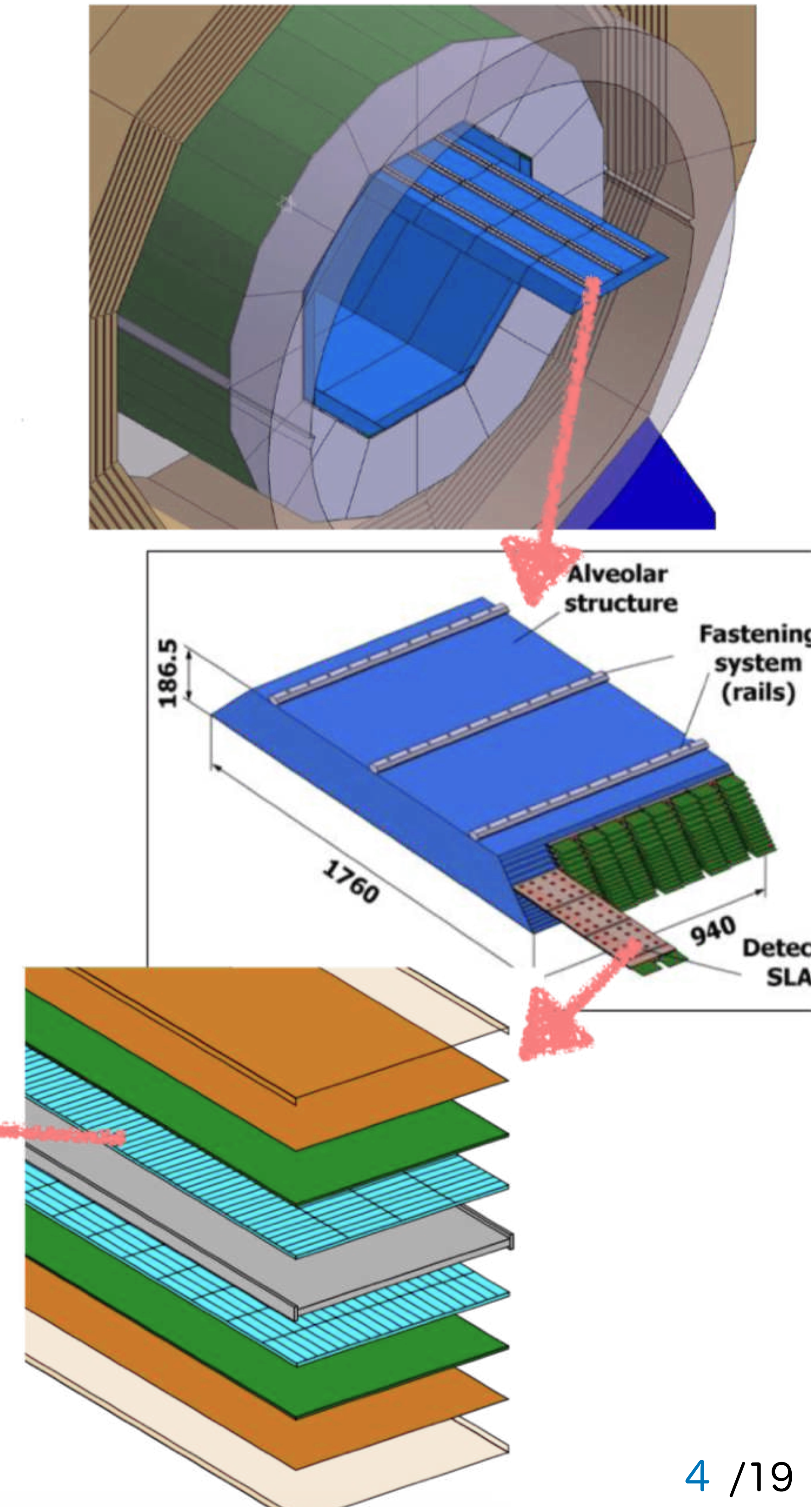


Sc-ECAL

- Scintillator Electromagnetic CALorimeter (Sc-ECAL)
  - Technology option of EM calorimeter for ILD
- Based on scintillator strips readout by SiPM
  - 5 × 45 × 2 mm^3 scintillator strip
- Virtual segmentation : 5mm × 5mm with strips in x-y configuration
- Timing resolution < 1 ns
- Low cost

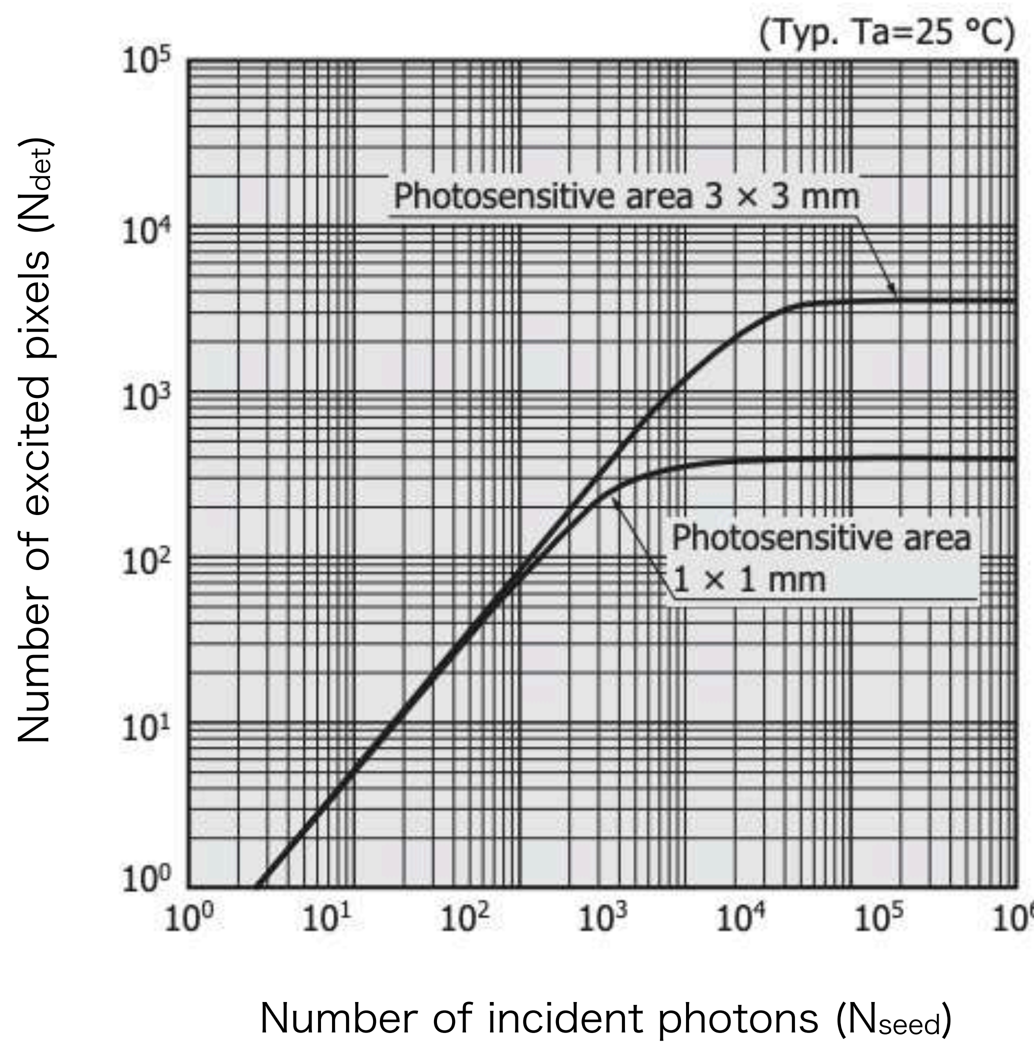






Saturation of SiPMs

- SiPM saturation can be an issue for Sc-ECAL
  - To measure small and dense EM shower
  - Pile-up hits in small and dense EM shower
  - When a large number of photons are injected to SiPM, output of SiPM can be saturated due to limited number of pixels
- Saturation curve is usually measured by direct injecting fast laser pulse (~400 nm) to SiPM
  - Time constant of emission of scintillation light (few ns) is not negligible compared to recovery time of SiPM cell (dozens ns)
- **Our idea is to measure the SiPM saturation with scintillation light excited by UV pulse laser**
  - **The measured saturation curve can directly be used for saturation correction in Sc-ECAL**



Hamamatsu Photonics K.K., Opto-semiconductor Handbook

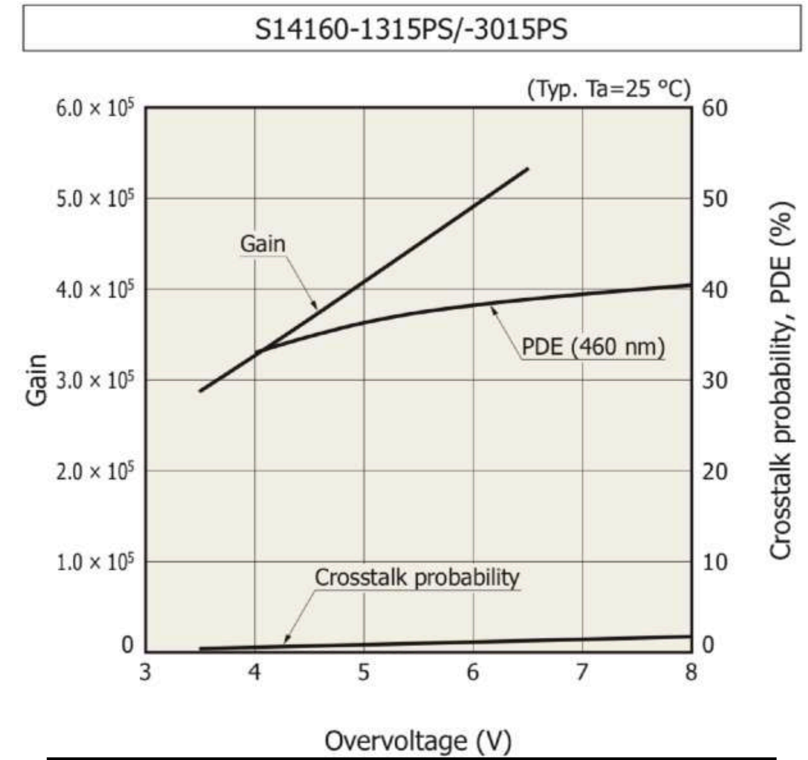
SiPMs for Sc-ECAL

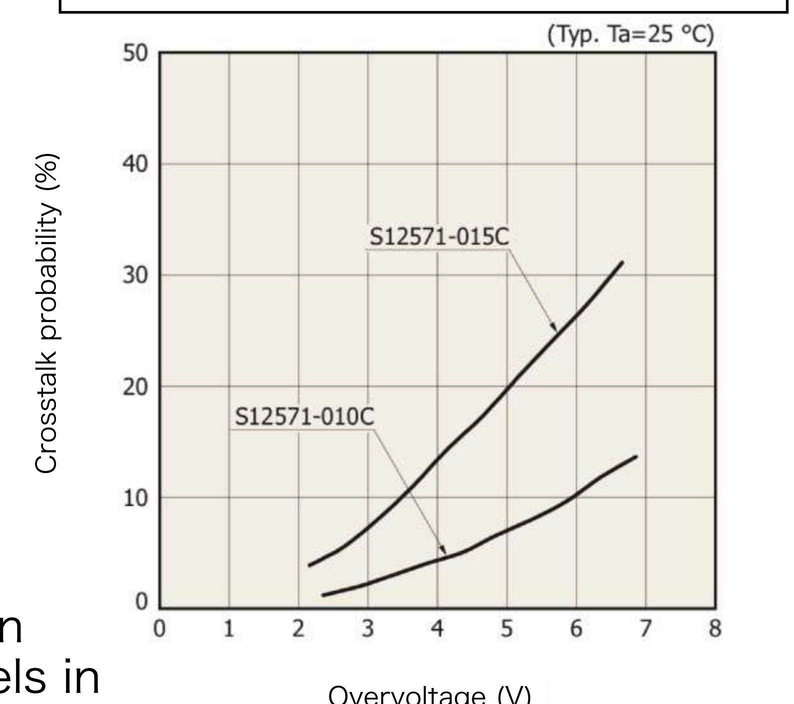
- Hamamatsu MPPC S12571 series
  - Small pixel size : 10 / 15 μm
  - Active area : 1 × 1 mm^2
  - Breakdown voltage : 65 V
  - No Trench isolation
- Hamamatsu MPPC S14160 series
  - Small pixel size : 10 / 15 μm
  - Active area : 1.3 × 1.3 / 3 × 3 mm^2
  - Breakdown voltage : 38 V
  - 0.5 μm trench isolation → low crosstalk

MPPC : Product name of Hamamatsu SiPM

Crosstalk : IR photons from avalanche in fired pixel can trigger adjacent pixels

	S12571	S14160 (Latest)
Breakdown voltage	**65 V**	**38 V**
Trench isolation	**none**	**Yes**
Trench width	**-**	**~ 0.5 μm**
Fill factor	**10μm: 33%** **15μm: 53%**	**10μm: 31%** **15μm: 49%**

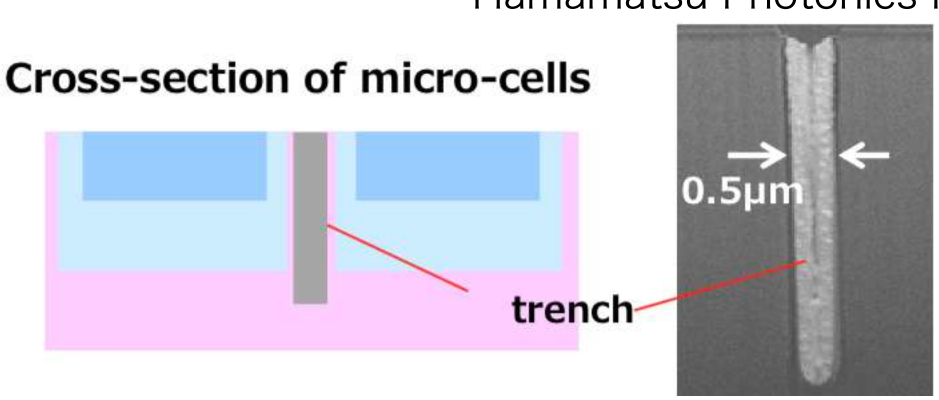




Hamamatsu Photonics K. K., PD18

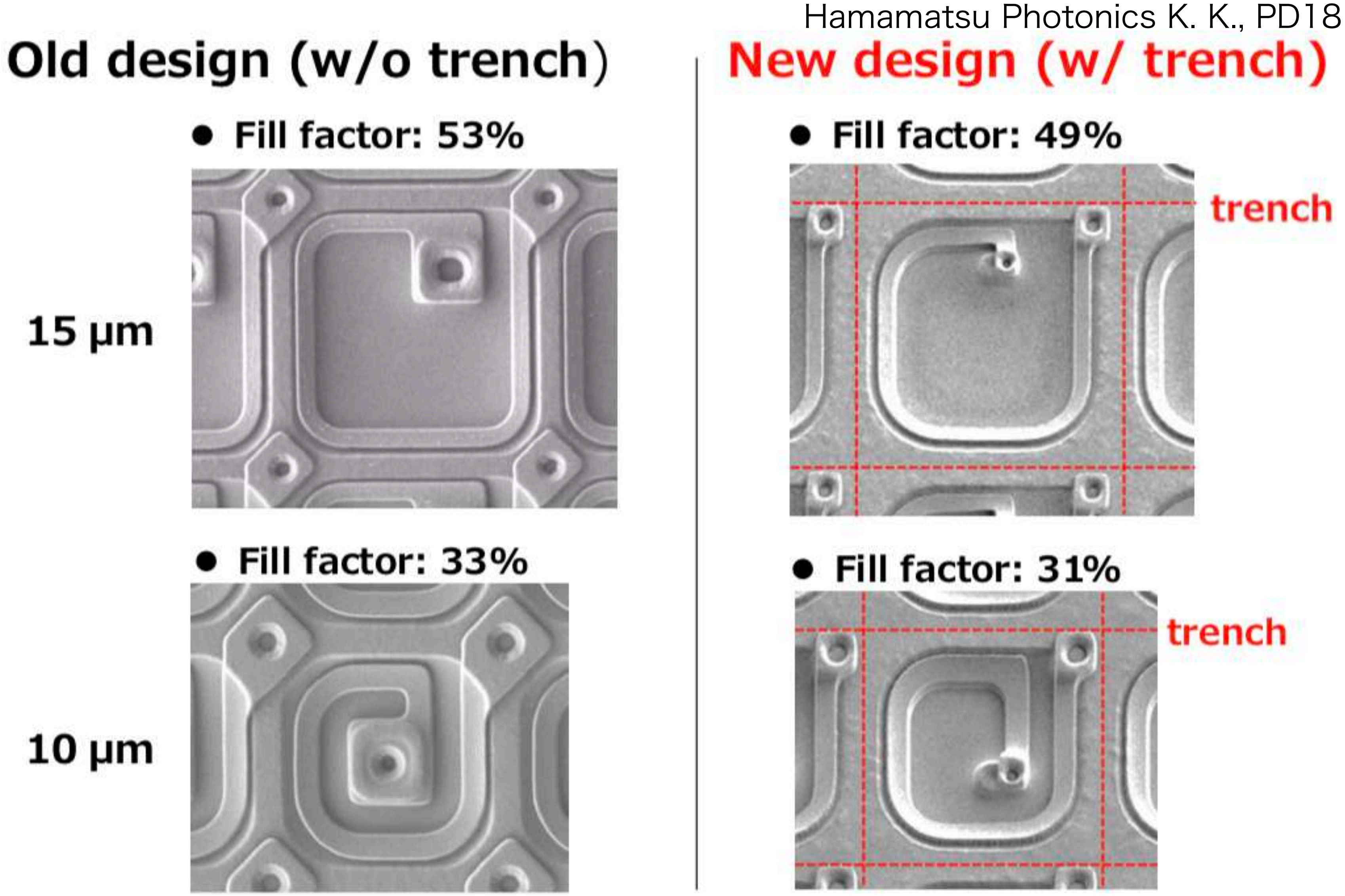
Trench : Separation between adjacent pixels in order to reduce crosstalk

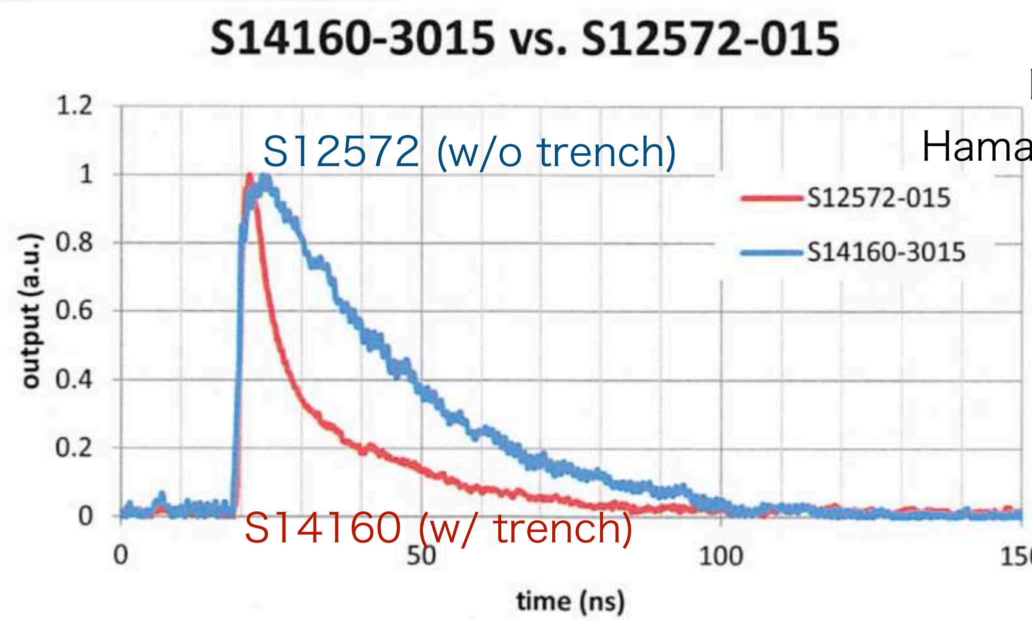
Cross-section of micro-cells



Trench technique of new MPPC

- MPPC S14160 series employ trench technique
  - Low crosstalk
  - Low operation voltage
  - No reduction of fill factor
- Longer tail due to larger cell capacitance
  - Longer recovery time
- Saturation is improved for new MPPC?
  - Low crosstalk → saturation ↓
  - Longer recovery → saturation ↑



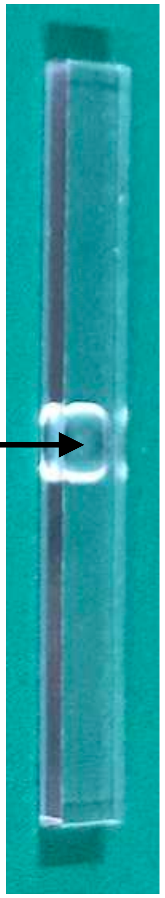


Provided by Hamamatsu Photonics

Experimental setup

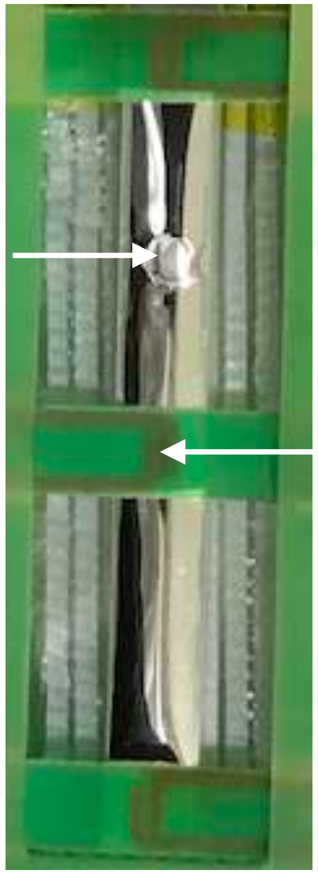
- Laser
  - **190 nm laser : Scintillation excitation, invisible to MPPC**
  - 470 nm laser : No scintillation excitation, directly detected by MPPC
- Setup for Sc-ECAL
  - 5 × 45 × 2 mm^3 scintillator strip (EJ-212) with center dimple
  - MPPC w/o trench : S12571-015P
    - Active area : 1.0 × 1.0 mm^2
    - Pixel pitch : 15 μm
    - 4489 pixels
  - MPPC w/ trench : S14160-1315PS
    - Active area : 1.3 × 1.3 mm^2
    - Pixel pitch : 15 μm
    - 7296 pixels

Scintillator strip



Cavity

Setup (wrapped strip + PCB)

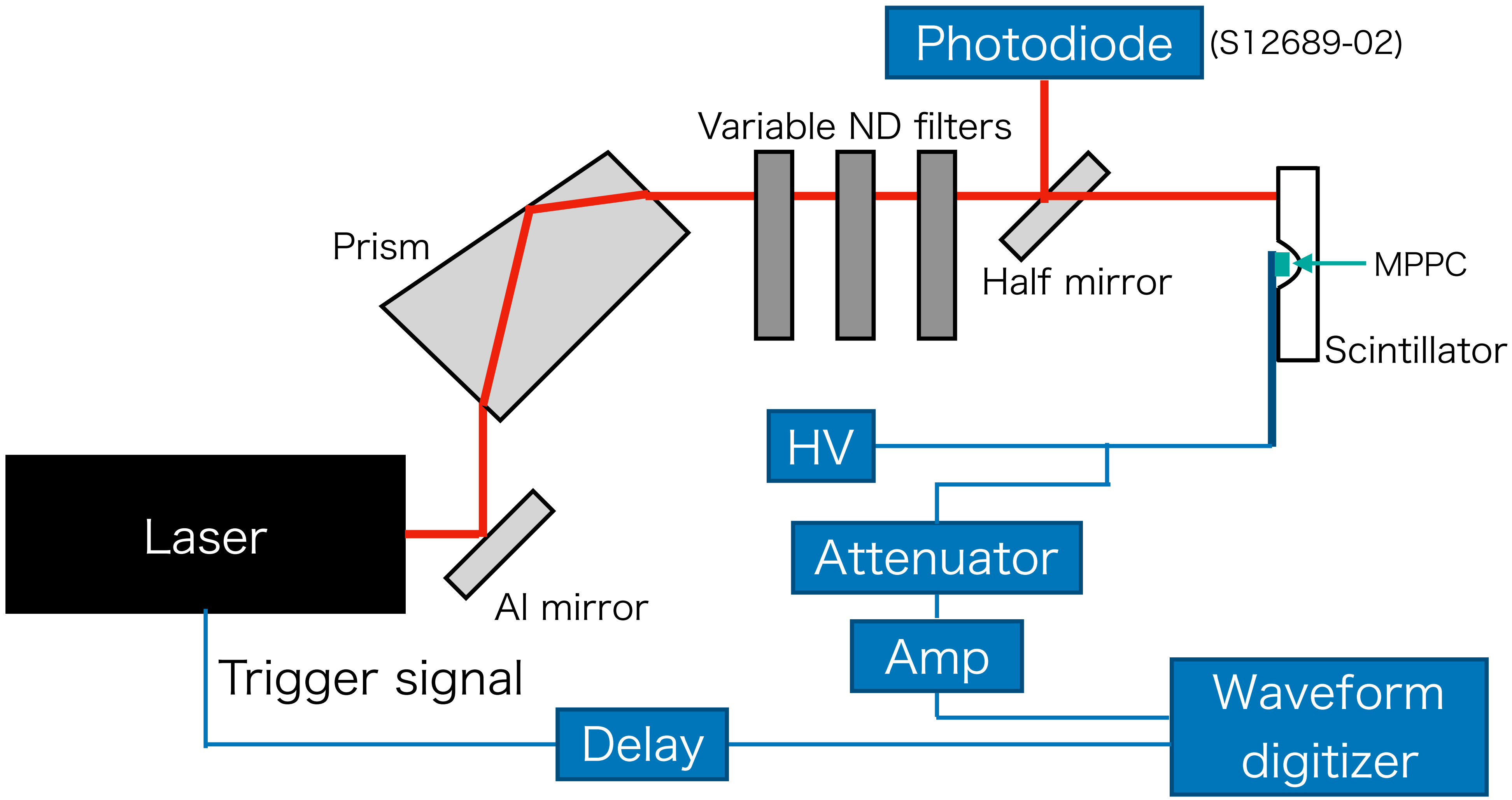


Injection hole

MPPC

Experimental setup

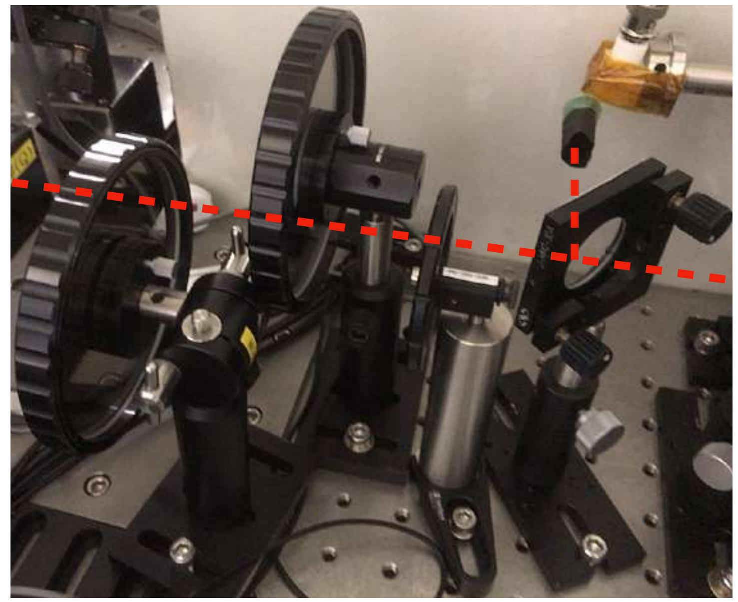
- Excite scintillation light with fast fsec UV pulse laser
  - Laser light is split using half mirror (to scintillator, to photodiode)
  - Incident light intensity is monitored with photodiode
  - MPPC S12571-015P with over voltage of +4 V (Recommended voltage by Hamamatsu)
  - MPPC S14160-1315PS with over voltage of +4 V (〃)
  - Signal attenuations (10 - 40 dB) used to avoid saturation of electronics



Experiment setup

Cut off contamination of other wavelength light

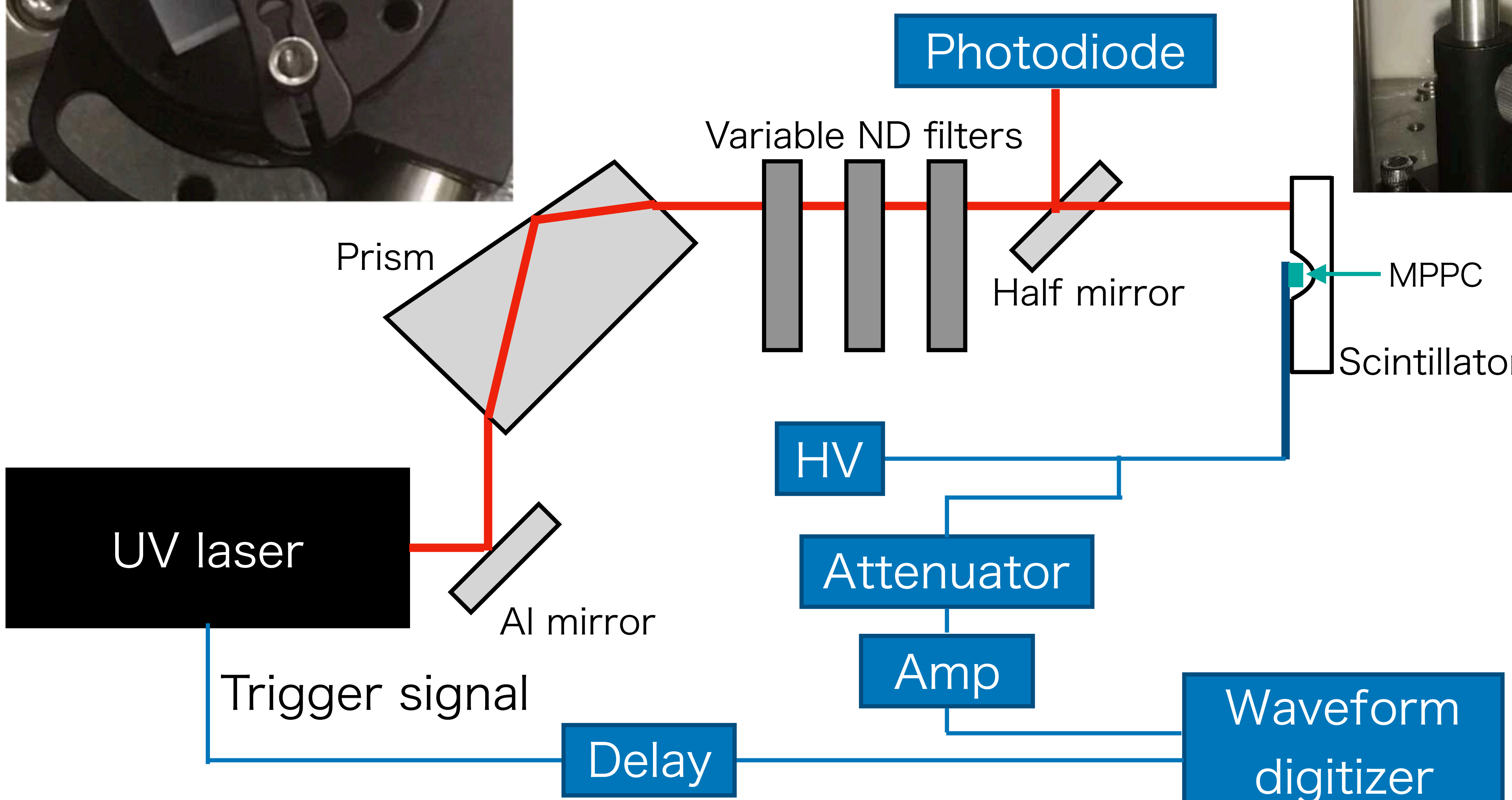
Incident light intensity controlled with three ND filters



Laser Light is split using half mirror

Photodiode

Scintillator & PCB

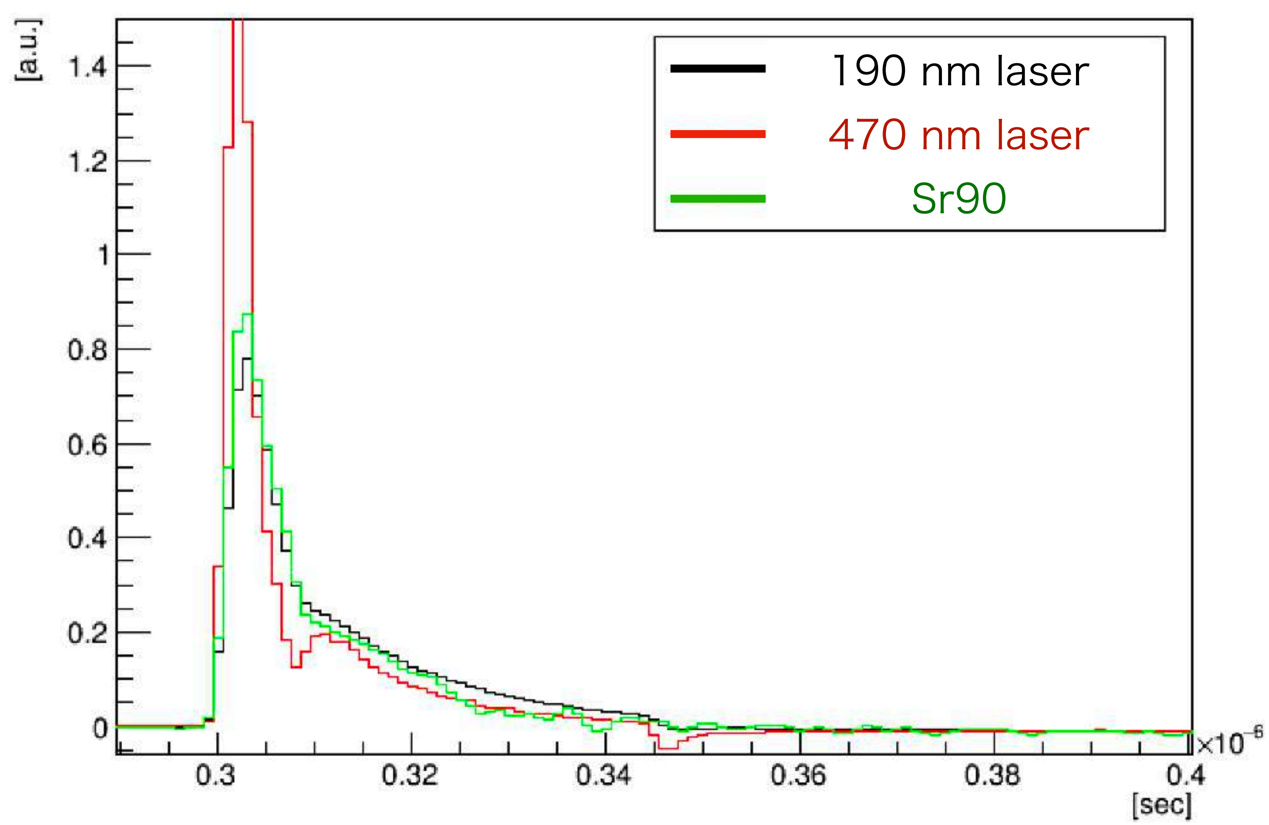


Signal waveform

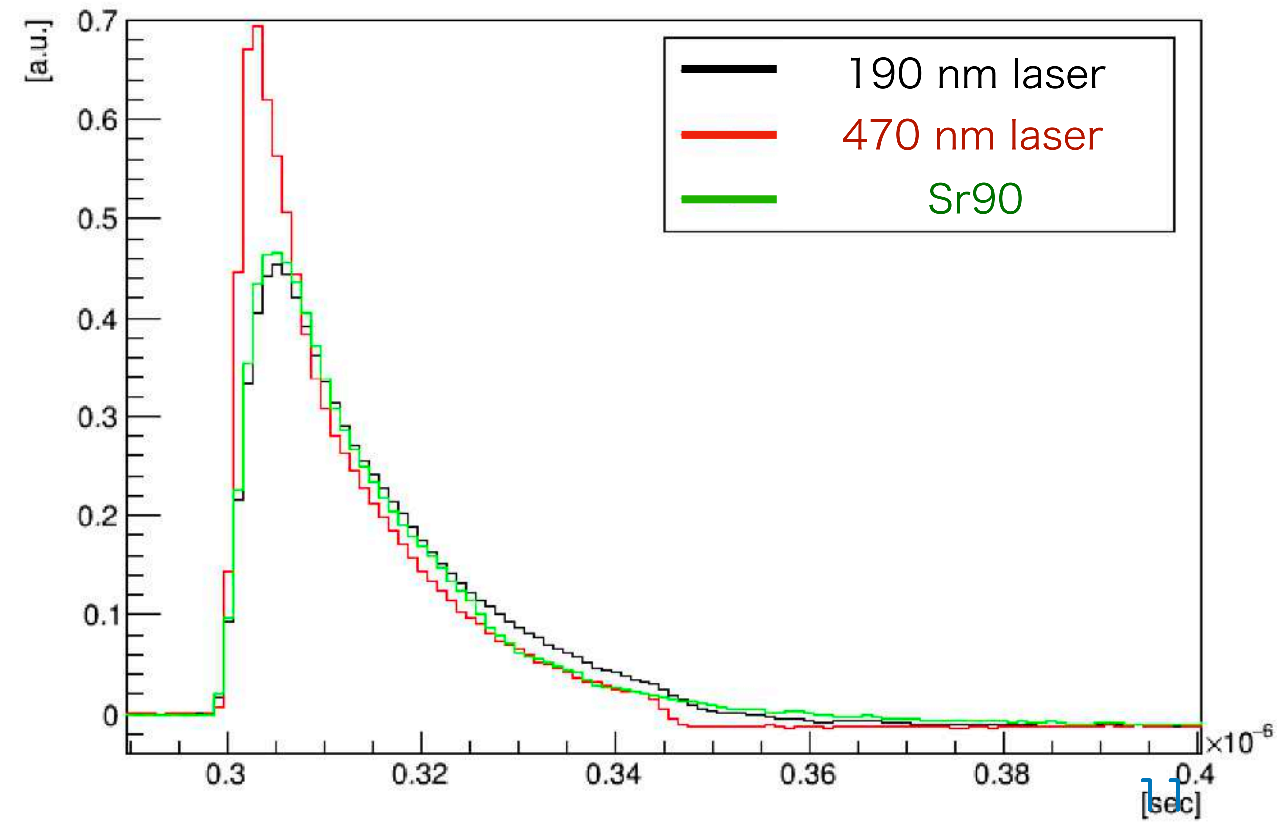
- Waveform is compared among 190 nm laser, 470 nm laser, and Sr90
  - 190 nm laser, Sr90 → MPPC detects scintillation light
  - 470 nm laser → MPPC detects laser light directly
- Almost the same waveform b/w 190 nm and Sr90
- Faster signal for direct injection of 470 nm laser

➡Suggesting that injected UV laser really excites scintillation light !

S12571-015P (MPPC w/o trench)



S14160-1315PS (MPPC w/ trench)

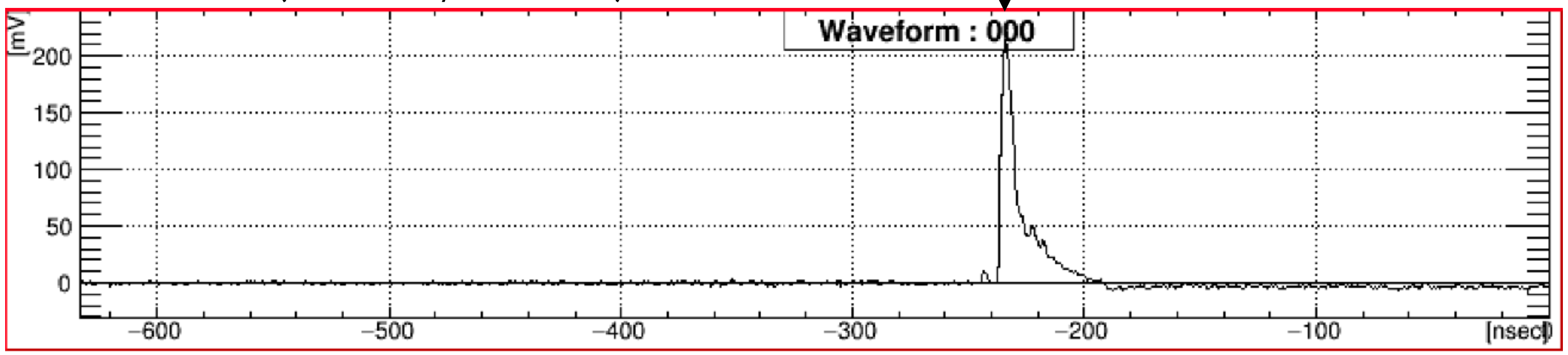


Analysis

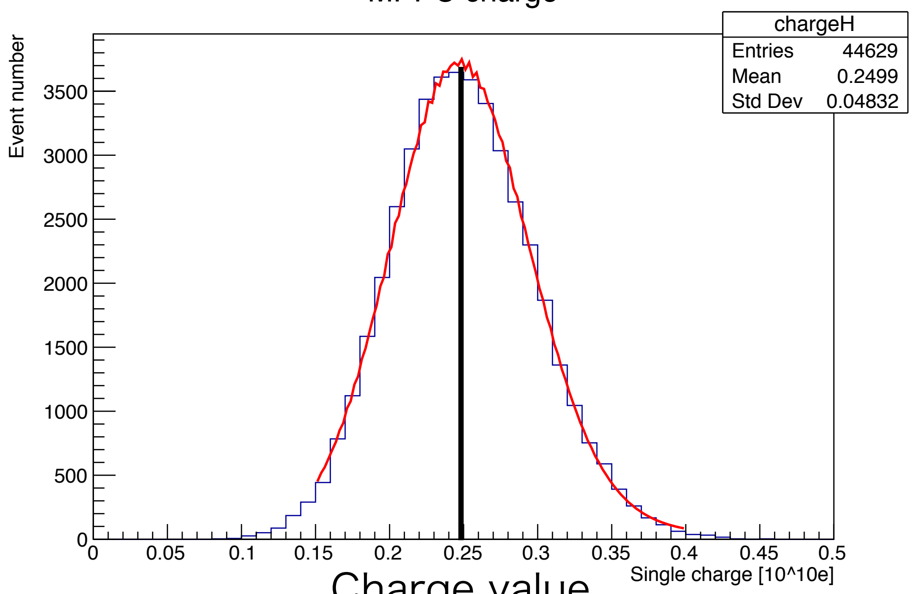
- Digitized waveform is integrated to estimate charge.
- The charge is then converted into number of photoelectrons being divided by single photoelectron charge.
  - Single photoelectron charge is obtained from dark noise signal found in off-time region

Signal of scintillation light

S12571-015P(MPPC w/o trench)

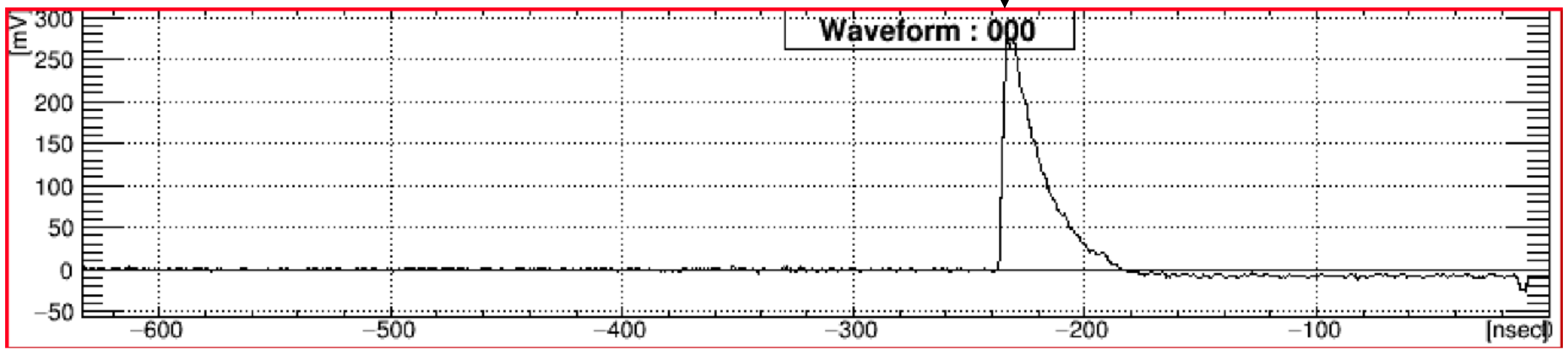


Integration range (100 ns)

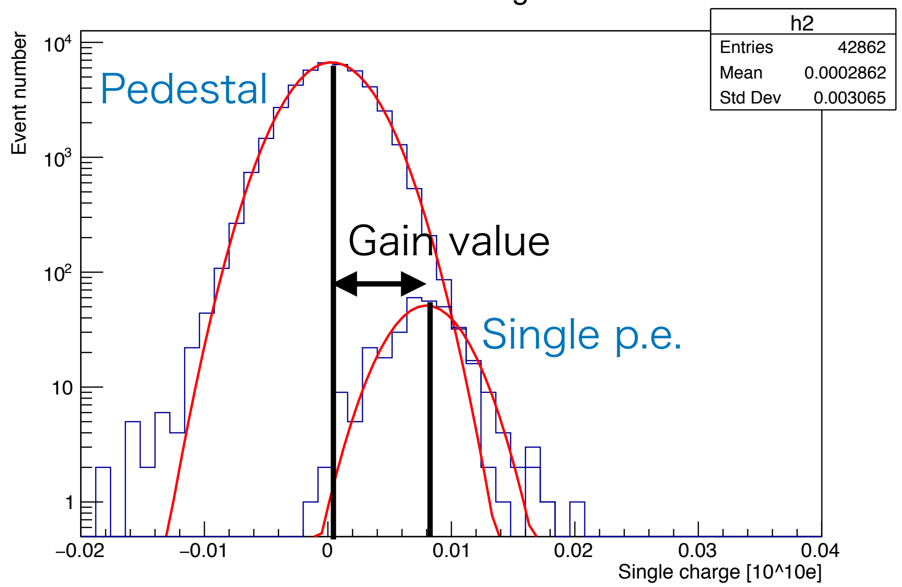


Signal of scintillation light

S14160-1315PS (MPPC w/ trench)



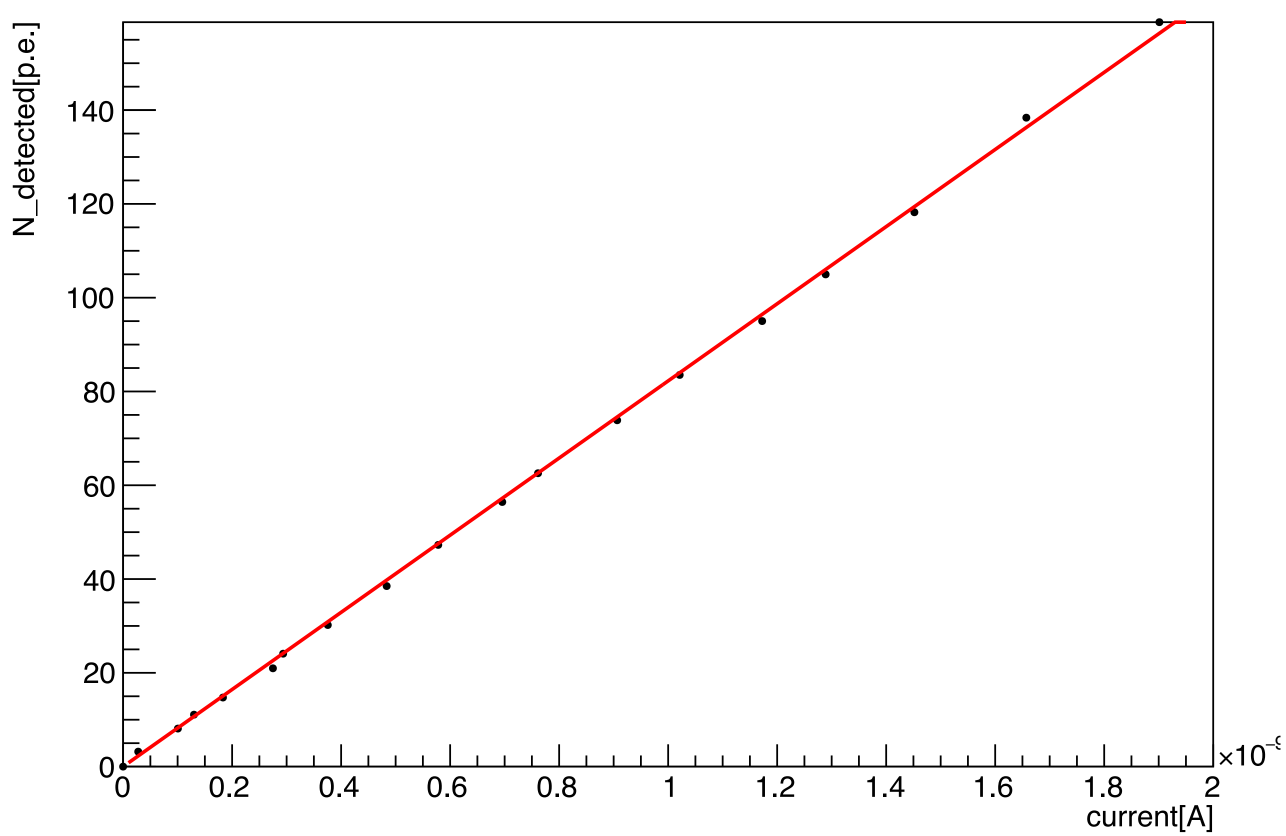
Integration range (100 ns)



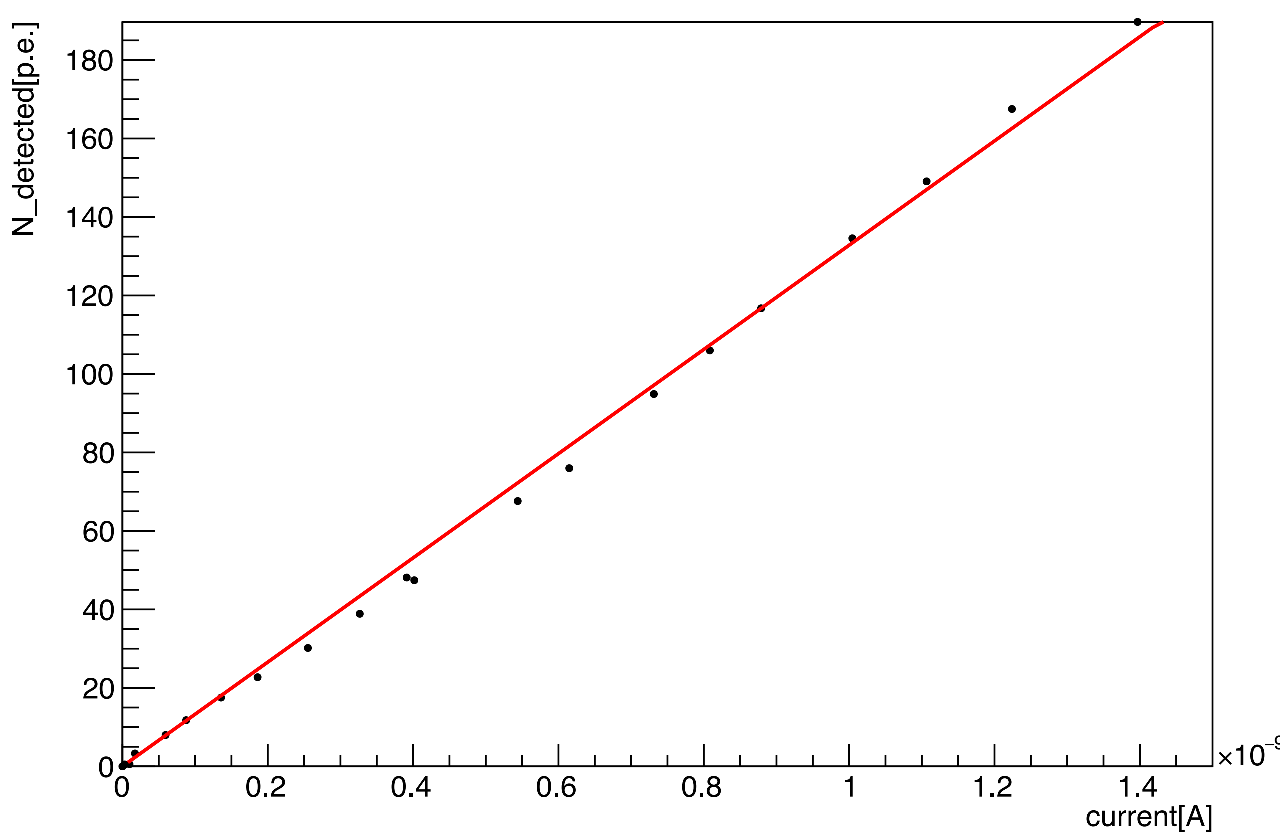
Laser intensity

- Incident light intensity is monitored with photodiode
  - Laser light is split using half mirror
- Photodiode current is converted to N_{seed} using calibration constant obtained at low light intensity where no saturation is anticipated
  - (N_{seed} : number of photoelectrons when assuming no saturation)
- Effect of crosstalk and after-pulse is not corrected yet

Linear region of S12571-015P (MPPC w/o trench)



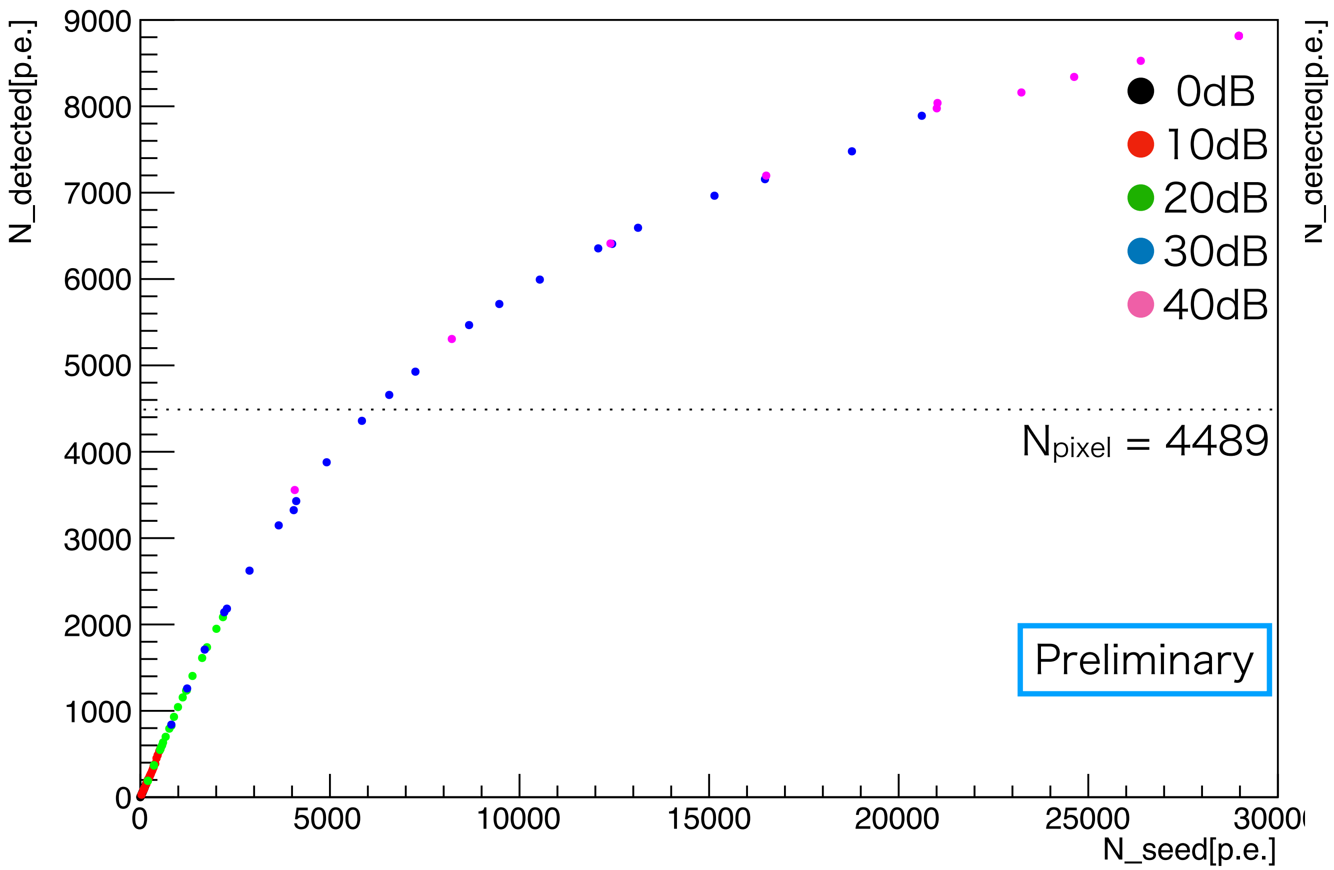
Linear region of S14160-1315PS (MPPC w/ trench)



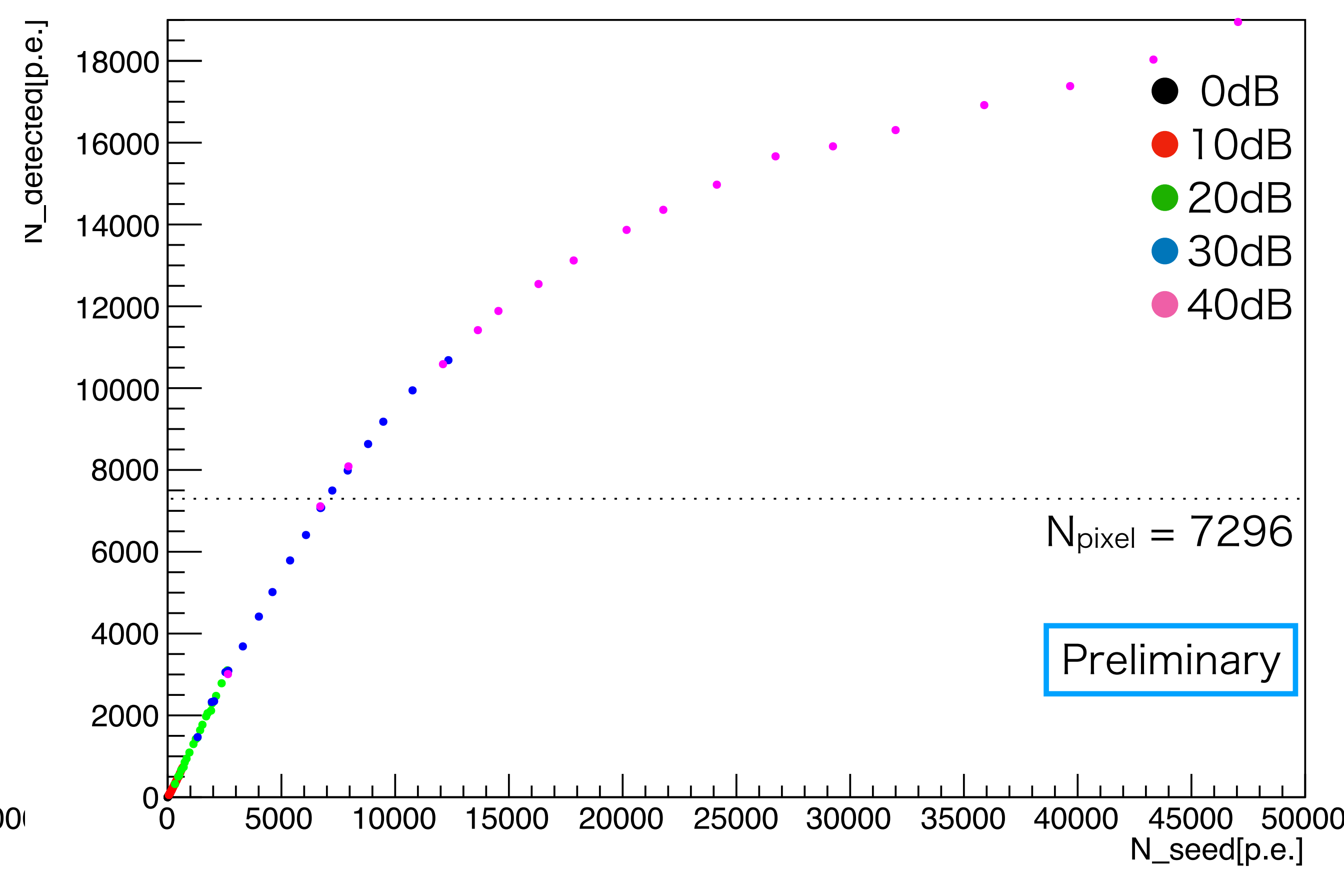
Saturation curve with 190 nm laser

- Over-saturation is observed for both MPPCs
- N.B. still some uncertainties in estimation for signal attenuation factors
  - We observed that the attenuation factor depends on light intensity
  - Probably due to change in signal shape caused by MPPC saturation

UV scan of S12571-015P (MPPC w/o trench)



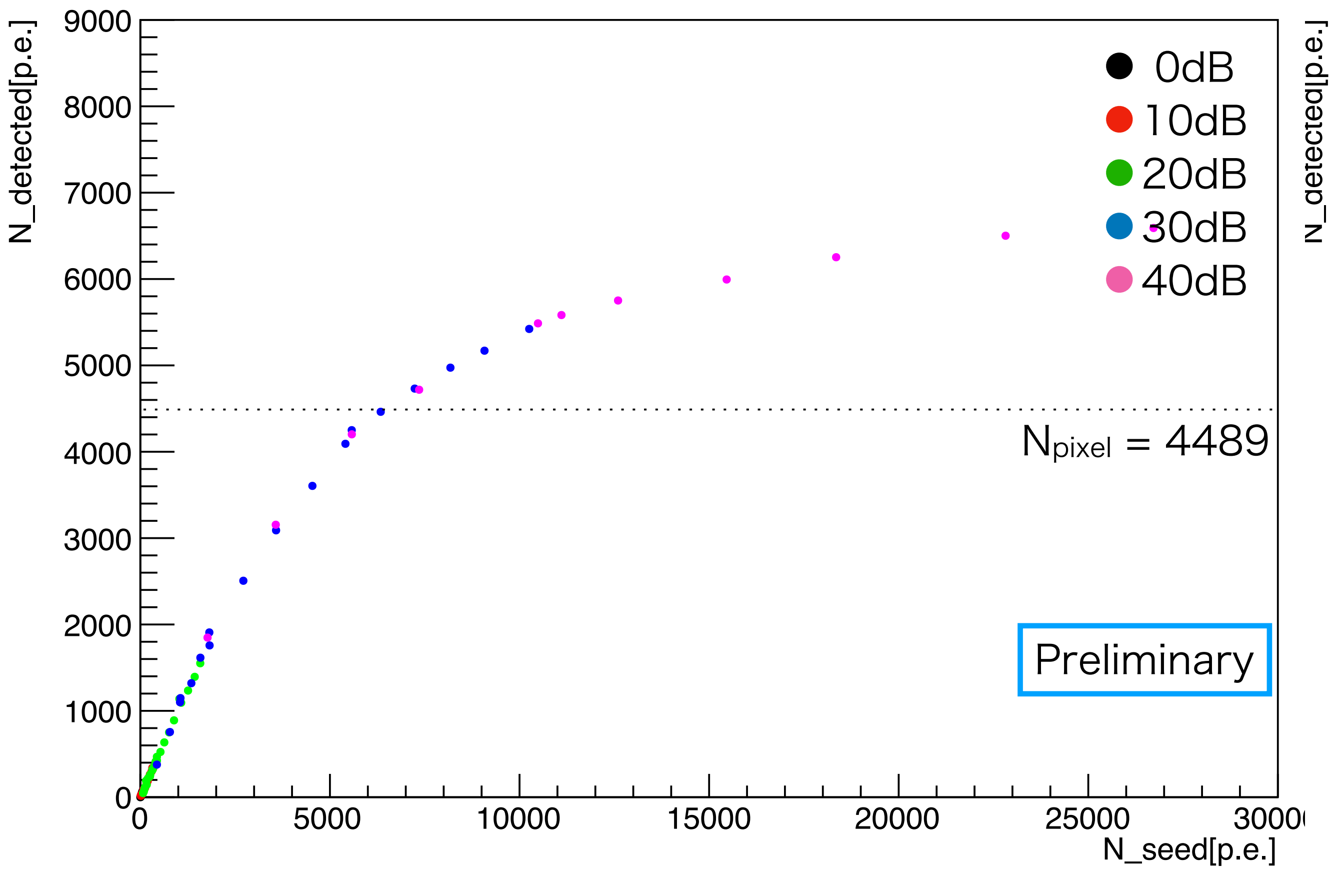
UV scan of S14160-1315PS (MPPC w/ trench)



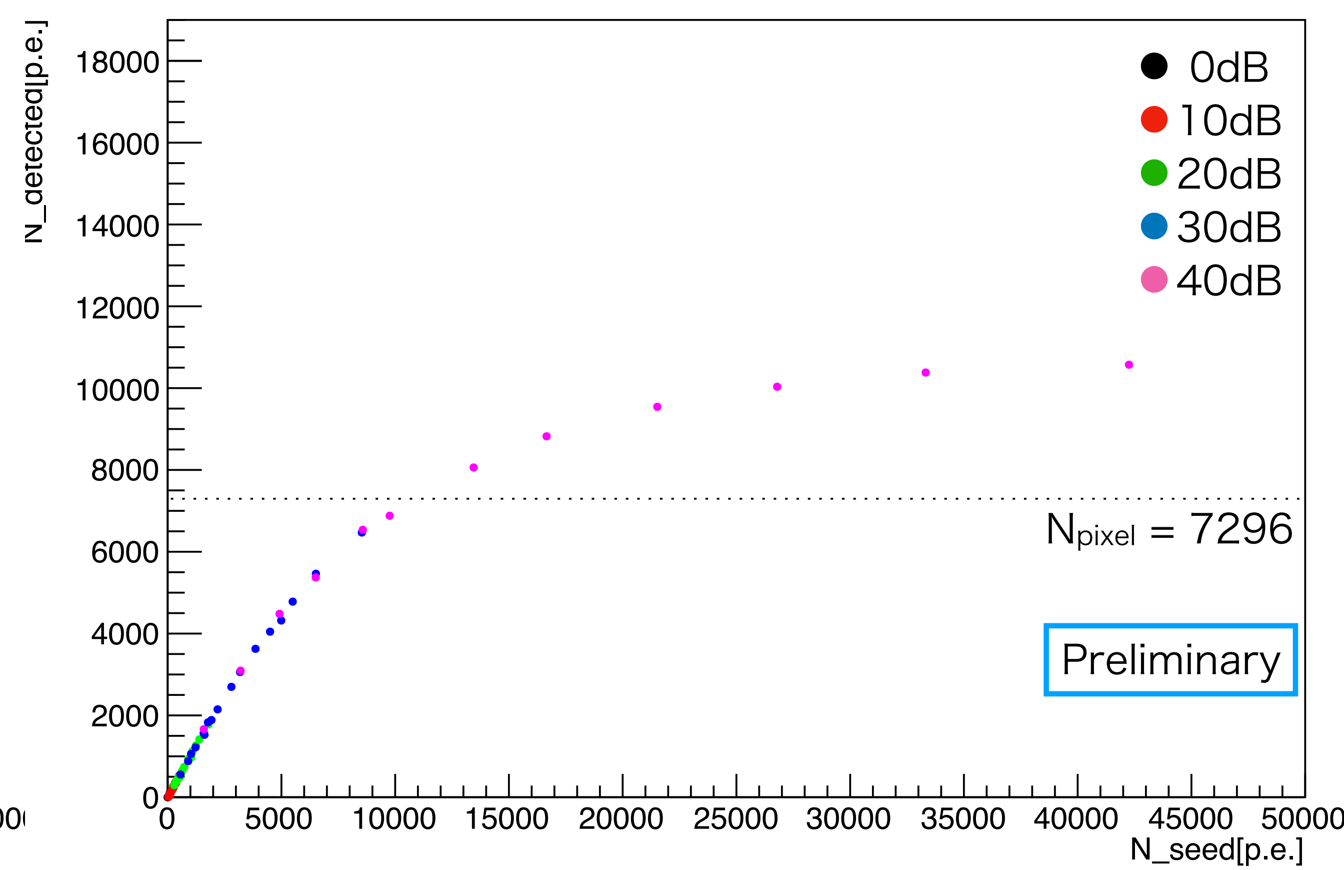
Saturation curve with 470 nm laser

- Saturation curve using 470 nm laser is measured to compare with 190 nm laser
- Stronger saturation compared to 190 nm laser is observed
- Over-saturation is still observed for both MPPCs
    - Due to after pulse and delayed crosstalk?
- N.B. still some uncertainties in estimation for signal attenuation factors

470 nm scan of S12571-015P (MPPC w/o trench)

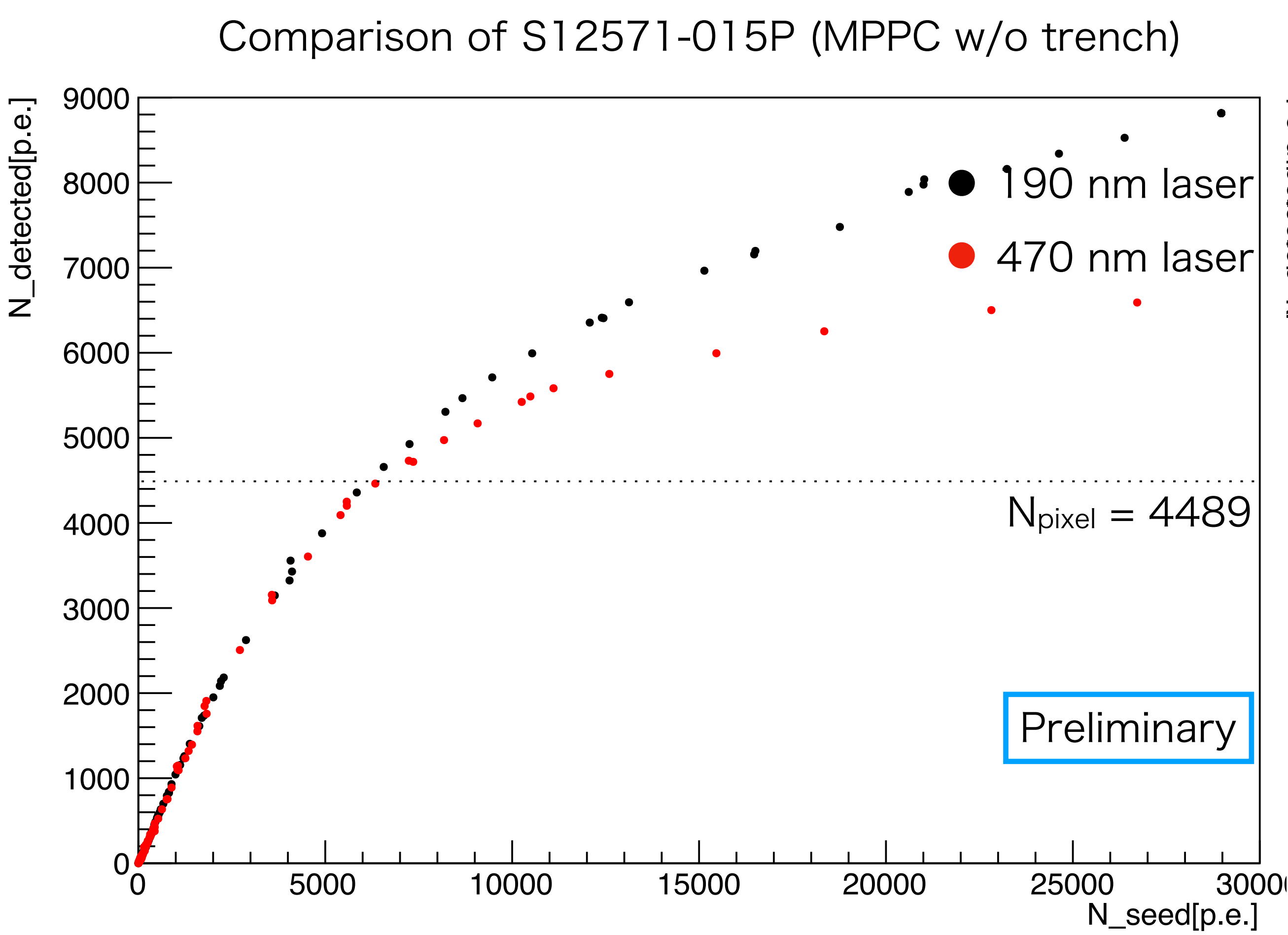


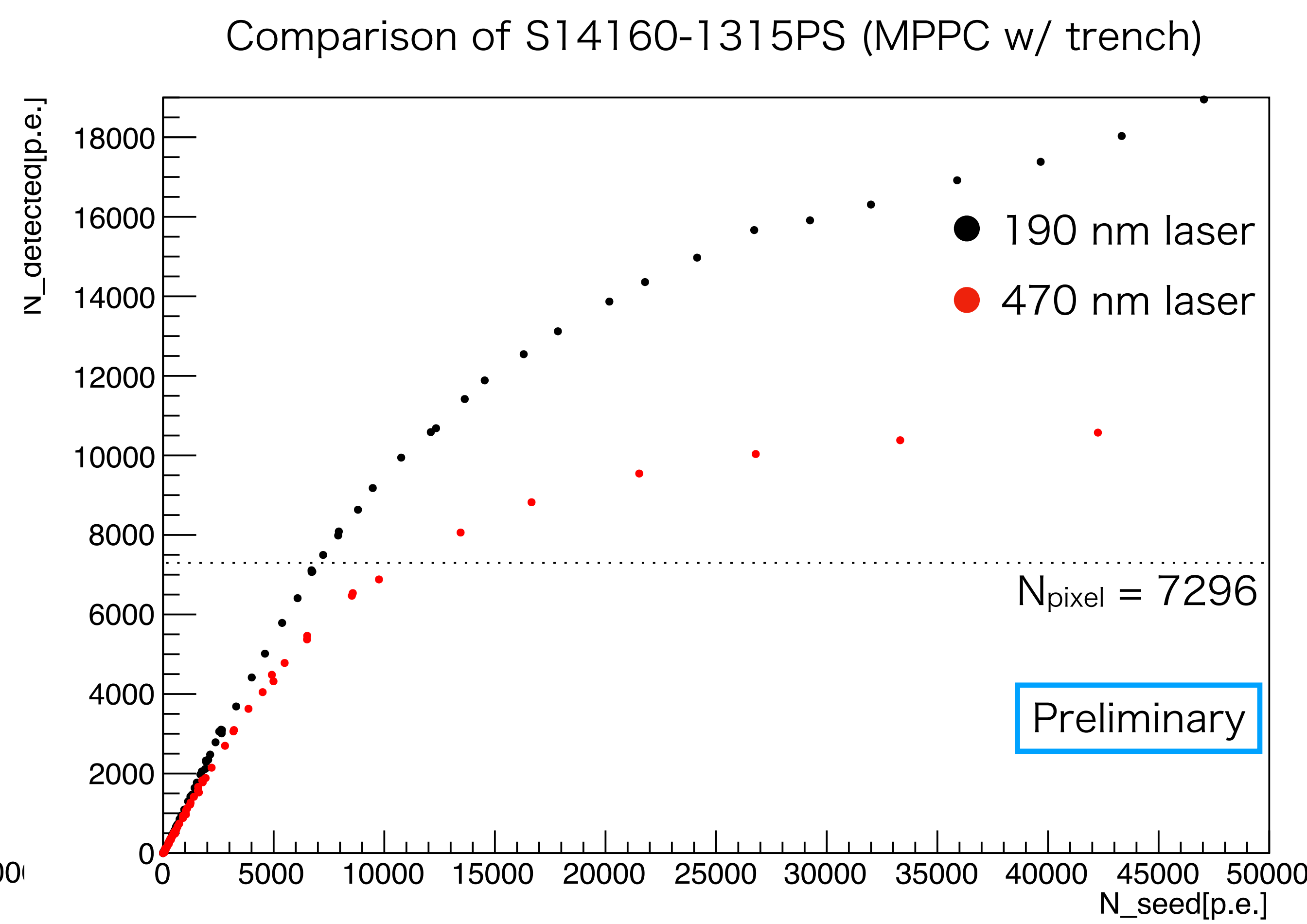
470 nm scan of S14160-1315PS (MPPC w/ trench)



Comparison of 190 nm and 470 nm laser

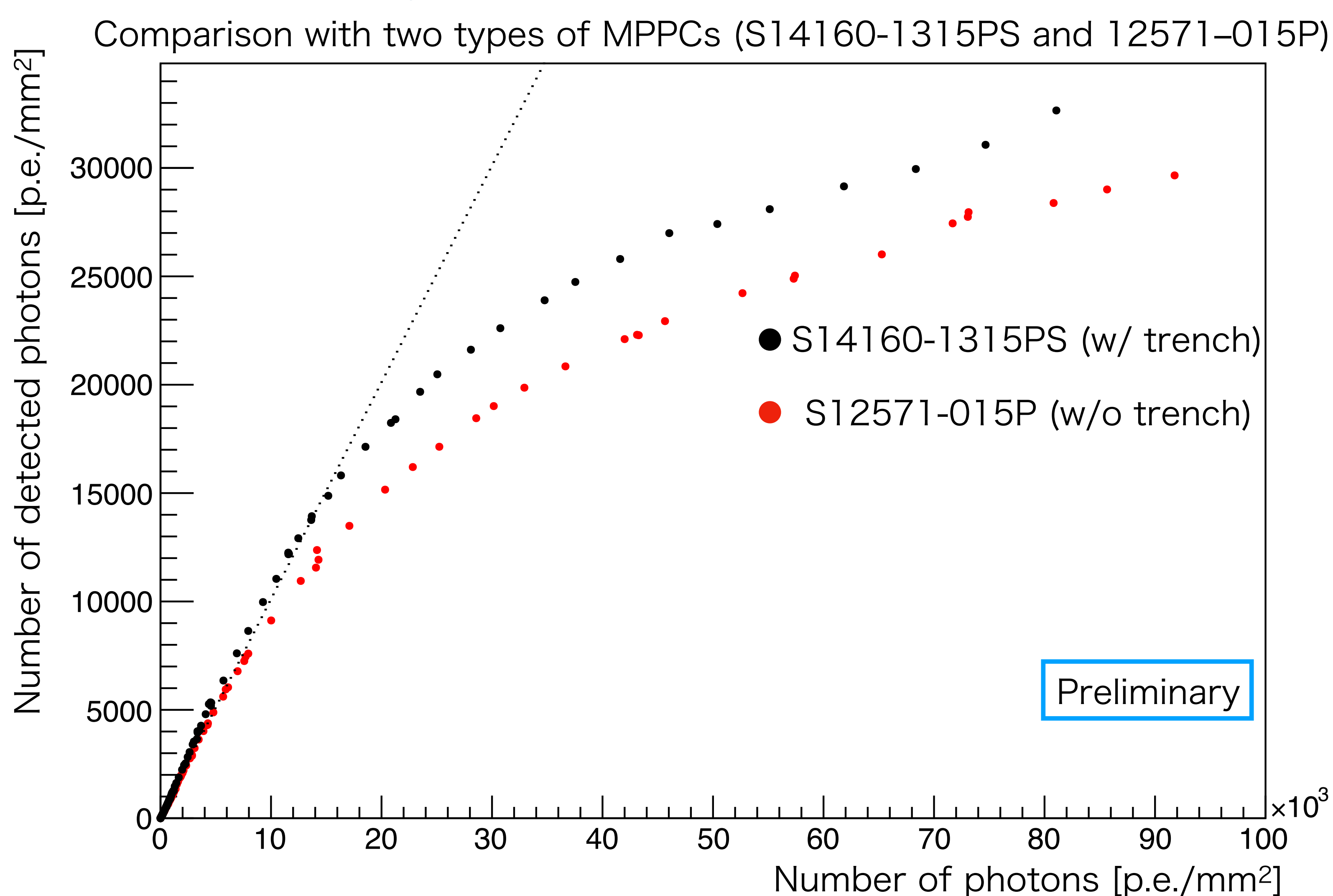
- Significant difference between saturation curves with 190 nm and 470 nm laser
- **The effect of time constant of scintillation light emission is observed**
  - Can be a big impact on saturation correction





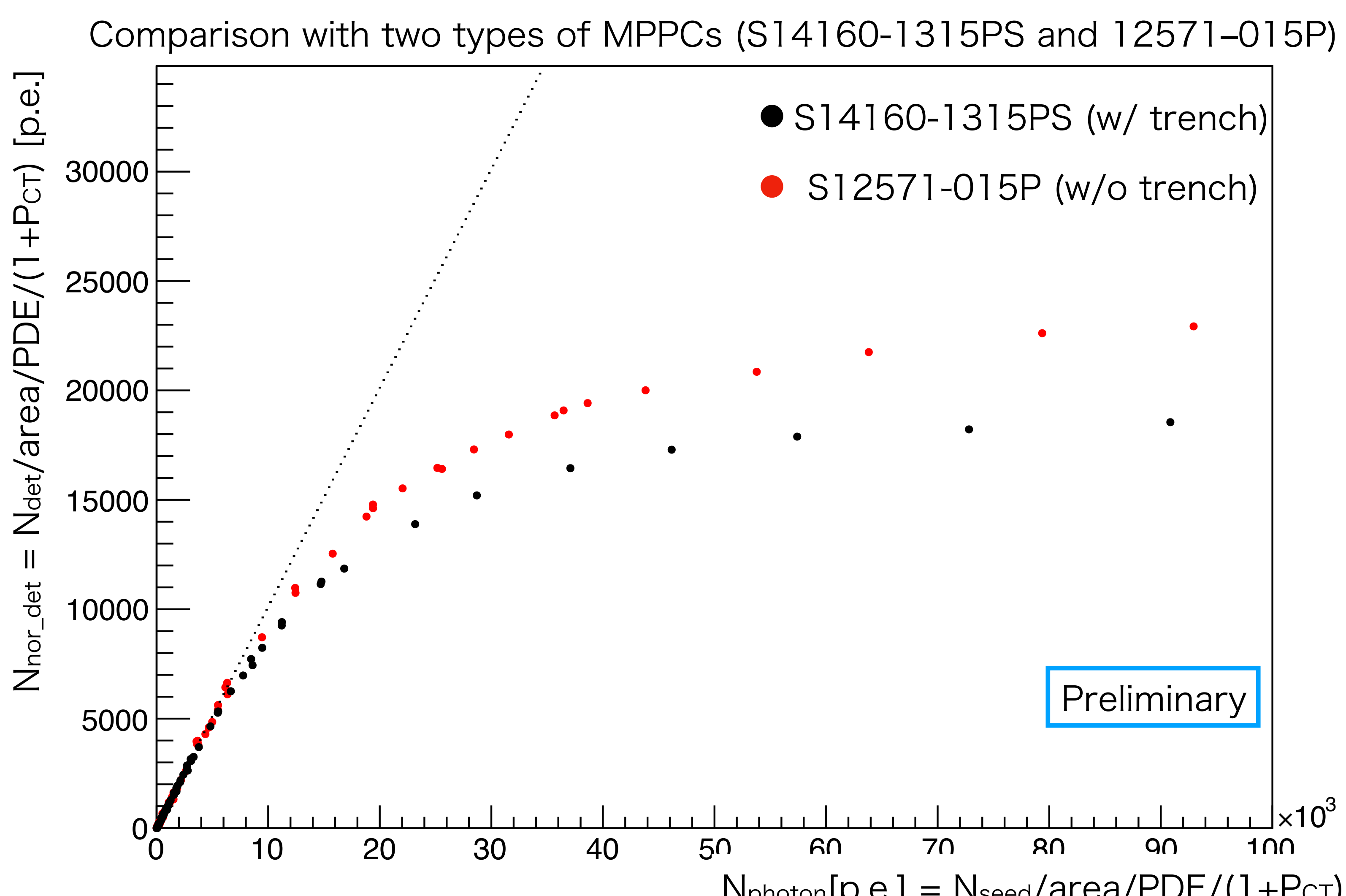
Comparison of two MPPCs with 190 nm laser

- Normalized by sensor area, PDE and crosstalk probability to compare saturation curves between two MPPCs
- MPPC w/ trench is less saturated compared to MPPC w/o trench
  - Few plots above the linear function (because of wrong attenuation factor?)
- **[For S14160-1315PS (w/ trench)]**
  (Lower crosstalk → saturation ↓) > (Longer recovery time → saturation ↑)
  - Effect of longer recovery time is small because of scintillation emission time



Comparison of two MPPCs with 470 nm laser

- S12571-015P (w/o trench) is less saturated compared to S14160-1315PS (w/ trench)
- **[For S14160-1315PS (w/ trench)]**
  (Lower crosstalk → saturation ↓) < (Longer recovery time → saturation ↑)
  - Effect of longer recovery time is large because of short duration of laser pulse



Summary & To do

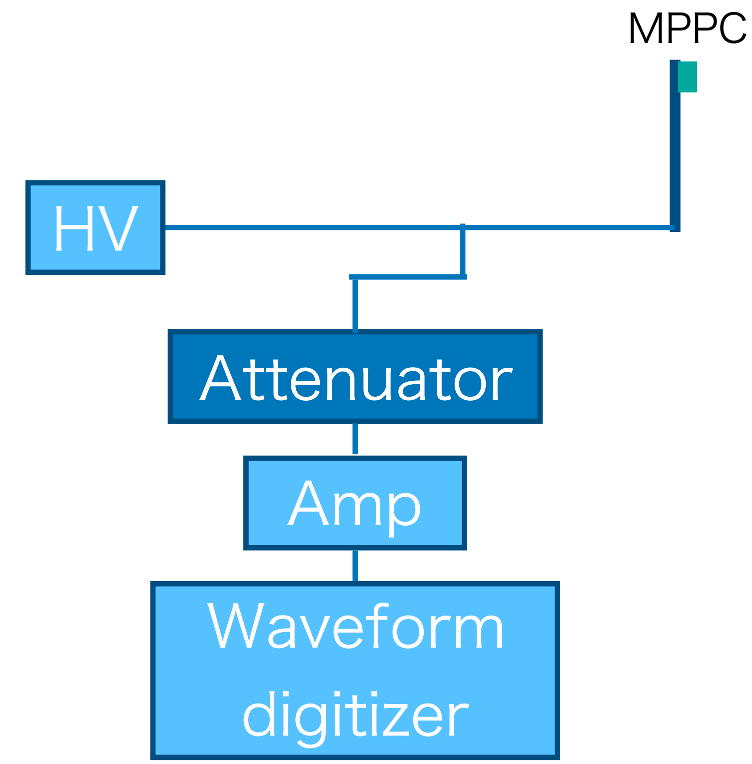
- Saturation curves for MPPCs are measured using scintillation light excited by fast UV-laser
- **Saturation recovery with scintillation light is observed.**
  - It should be taken into account for saturation correction
  - The measured saturation curves can directly be used for correction

- Saturation curves are measured for two types of MPPCs for Sc-ECAL (w/ and w/o trench)
- **The effect of longer recovery time of S14160 (MPPC w/ trench) is found small for scintillation light**
  - Longer-tail effect is observed when the measurement of fast pulse

- To do
  - Investigate light intensity dependence of attenuation factor
  - Compare with theoretical model of saturation

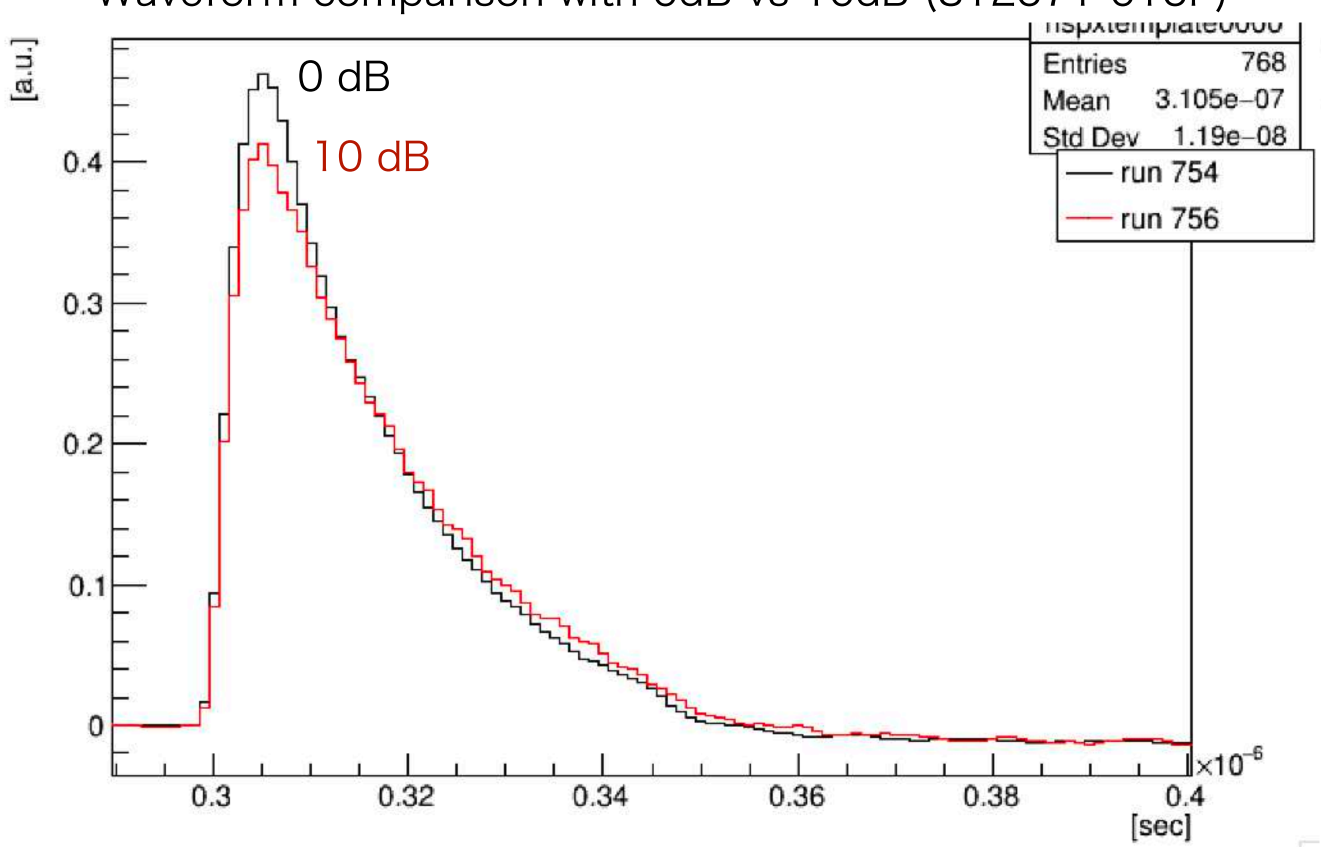
Backup

Attenuation factor

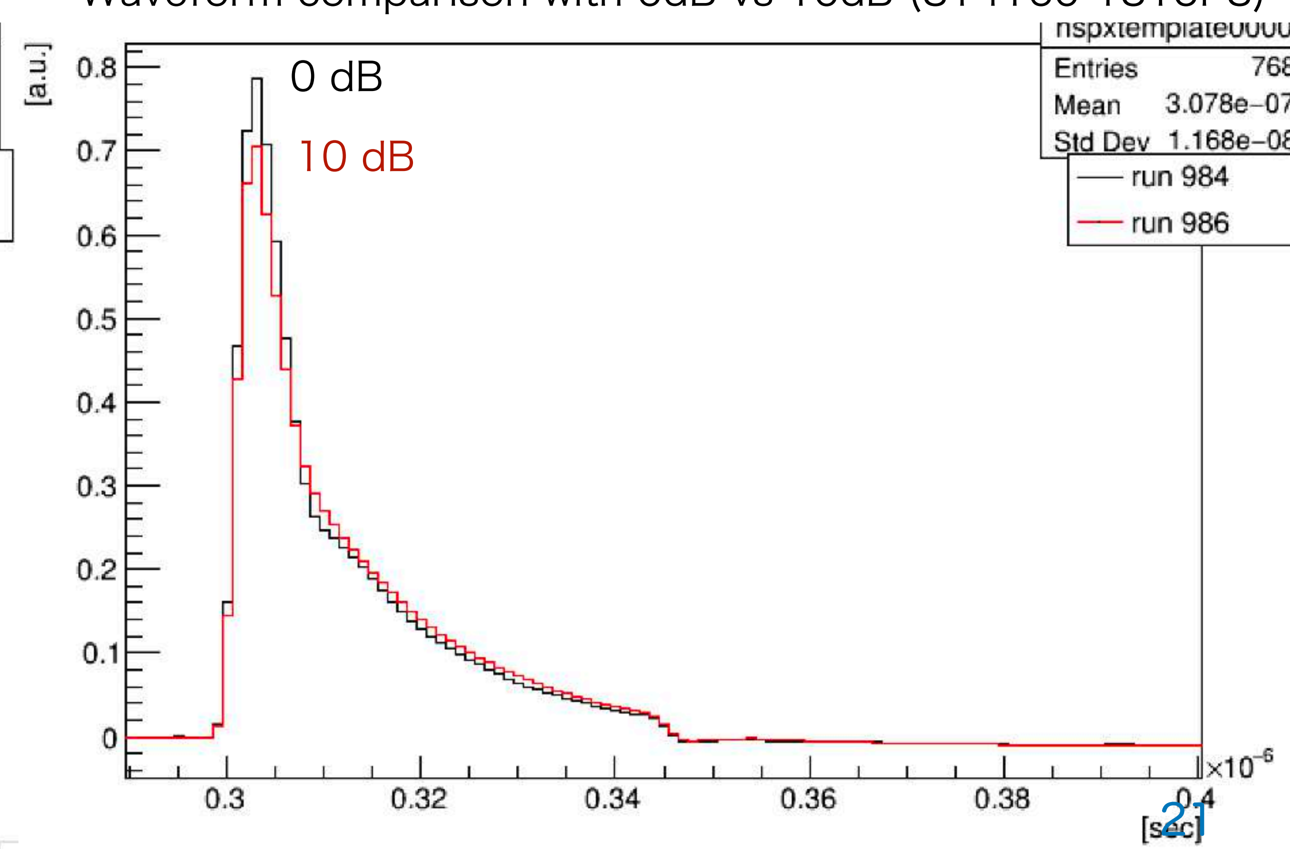


- Dynamic range of DAQ is not sufficient to cover whole light intensity range
  - Need signal attenuation to avoid saturation in electronics
  - 10-40 dB attenuator used
- There is a frequency dependence of attenuator
  - Attenuation rate depends on input pulse shape

Waveform comparison with 0dB vs 10dB (S12571-015P)



Waveform comparison with 0dB vs 10dB (S14160-1315PS)

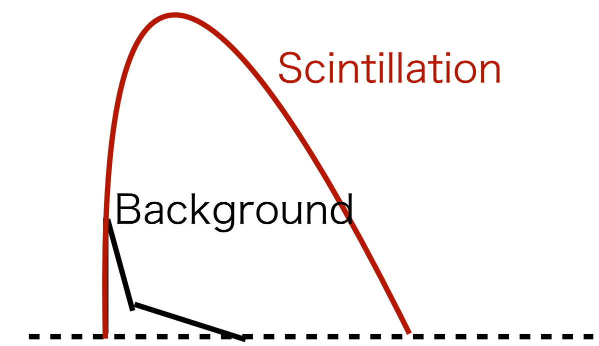


Variation of waveform

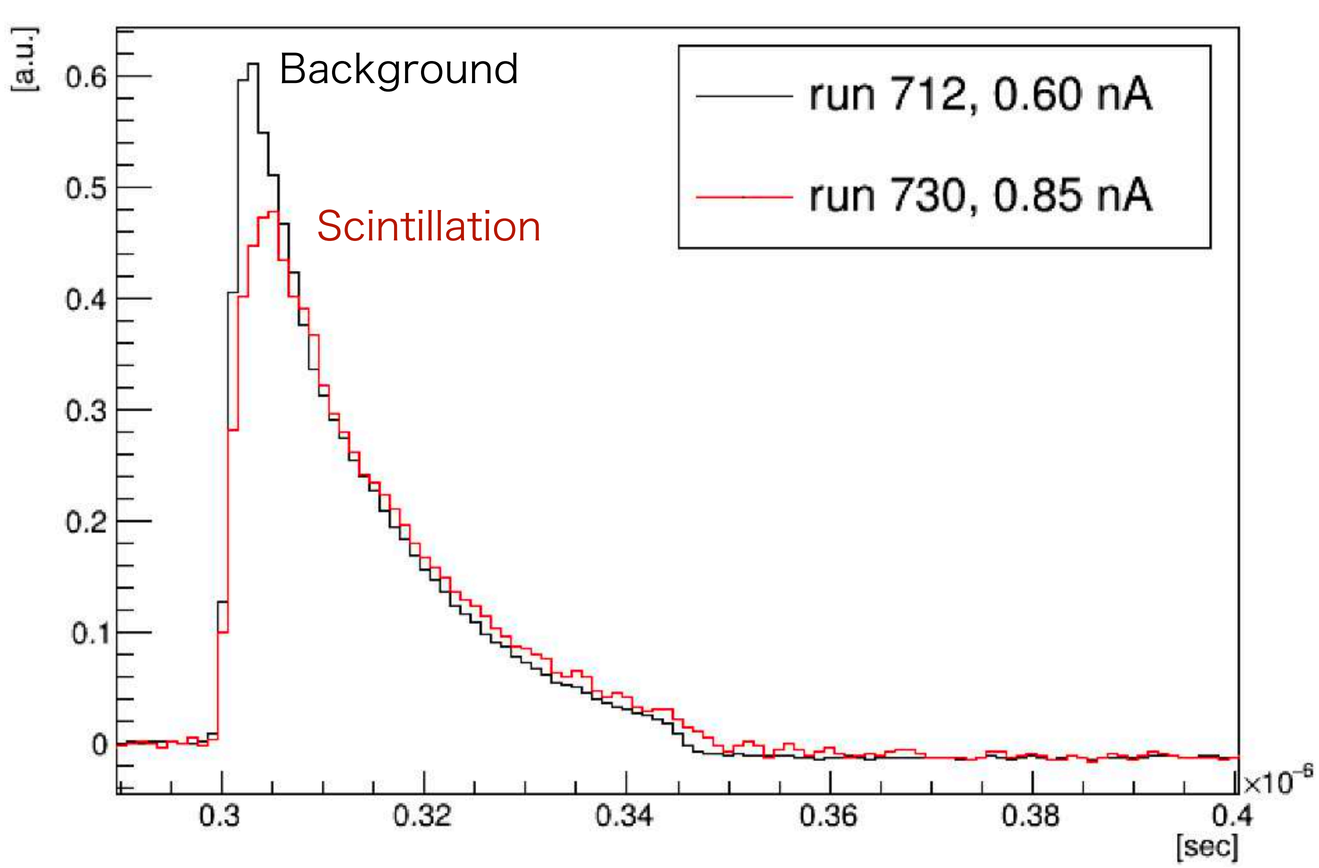
- Variation of waveform depending on light intensity was observed
- Effect of constant background light at low light intensity
  - Background light comes from optical setup and laser reflection
    - Faster than scintillation light because directly injected to MPPC
  - Significant contribution from fast component of background at low light intensity

At low light intensity, background is dominant

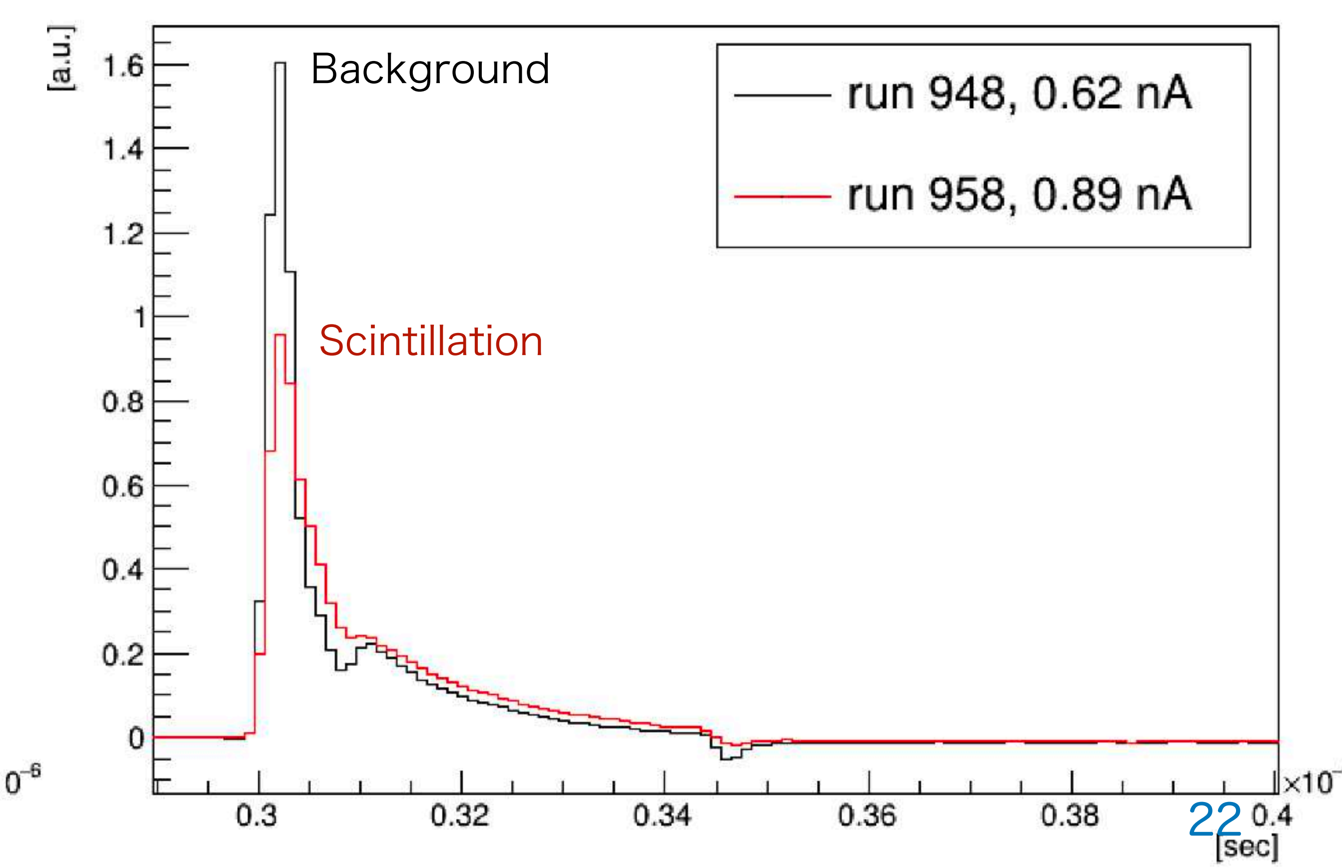
At higher light intensity, background is negligible



Waveform comparison with 0dB attenuator (S12571-015P)



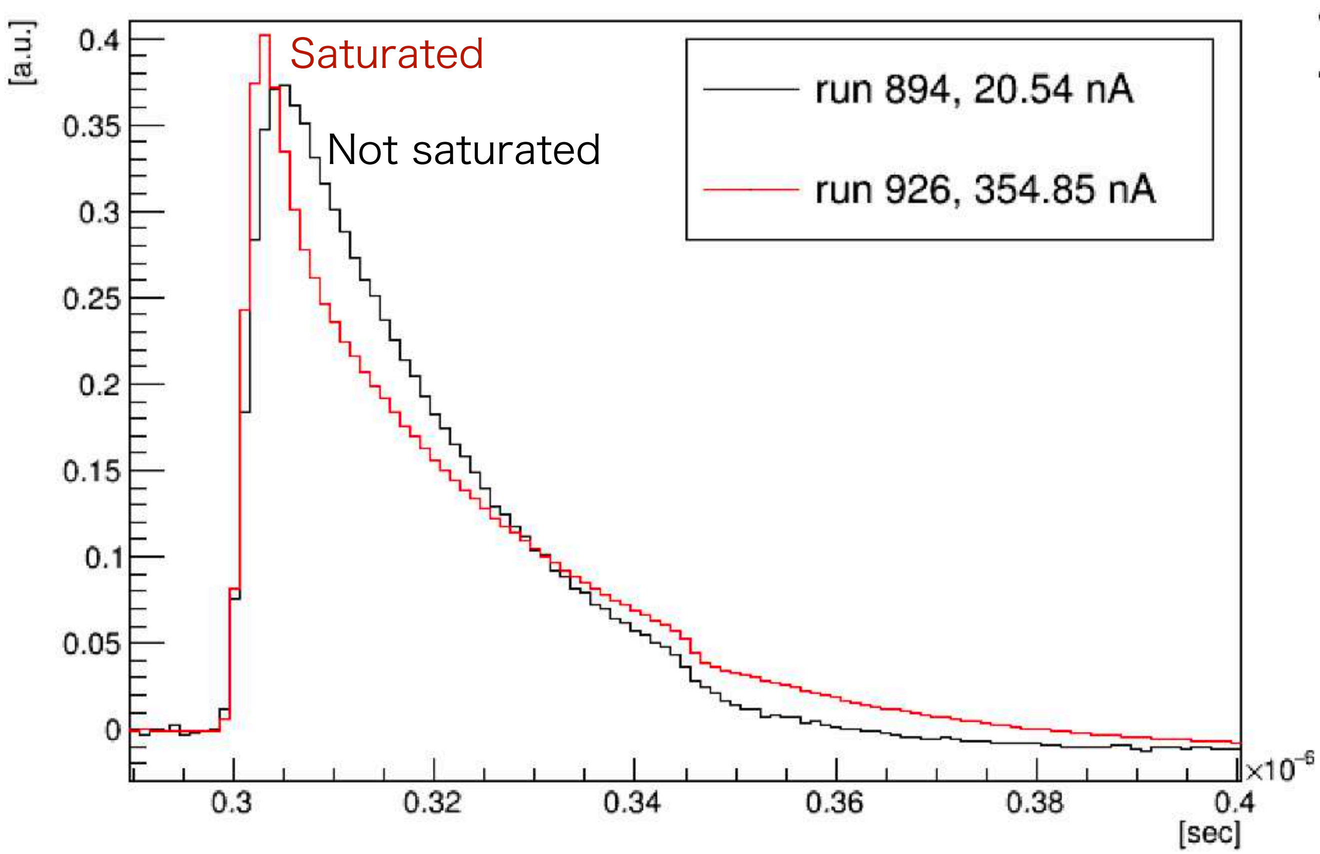
Waveform comparison with 0dB attenuator (S14160-1315PS)



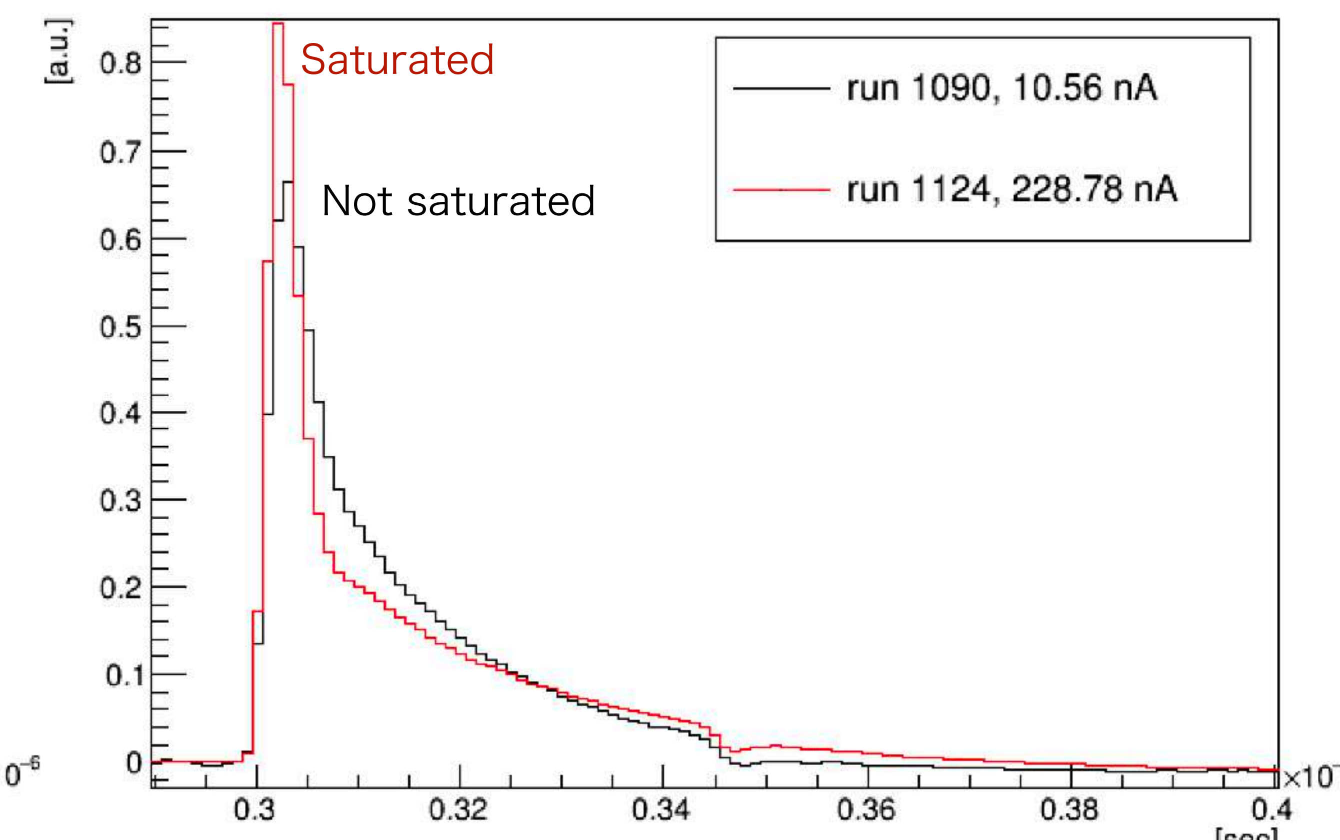
Variation of waveform

- Effect of SiPM saturation at high light intensity
  - Saturation deforms waveform at very high light intensity
- These effects change the attenuation rate depending on light intensity
  - Not yet calibrated

Waveform comparison with 40dB attenuator (S12571-015P)



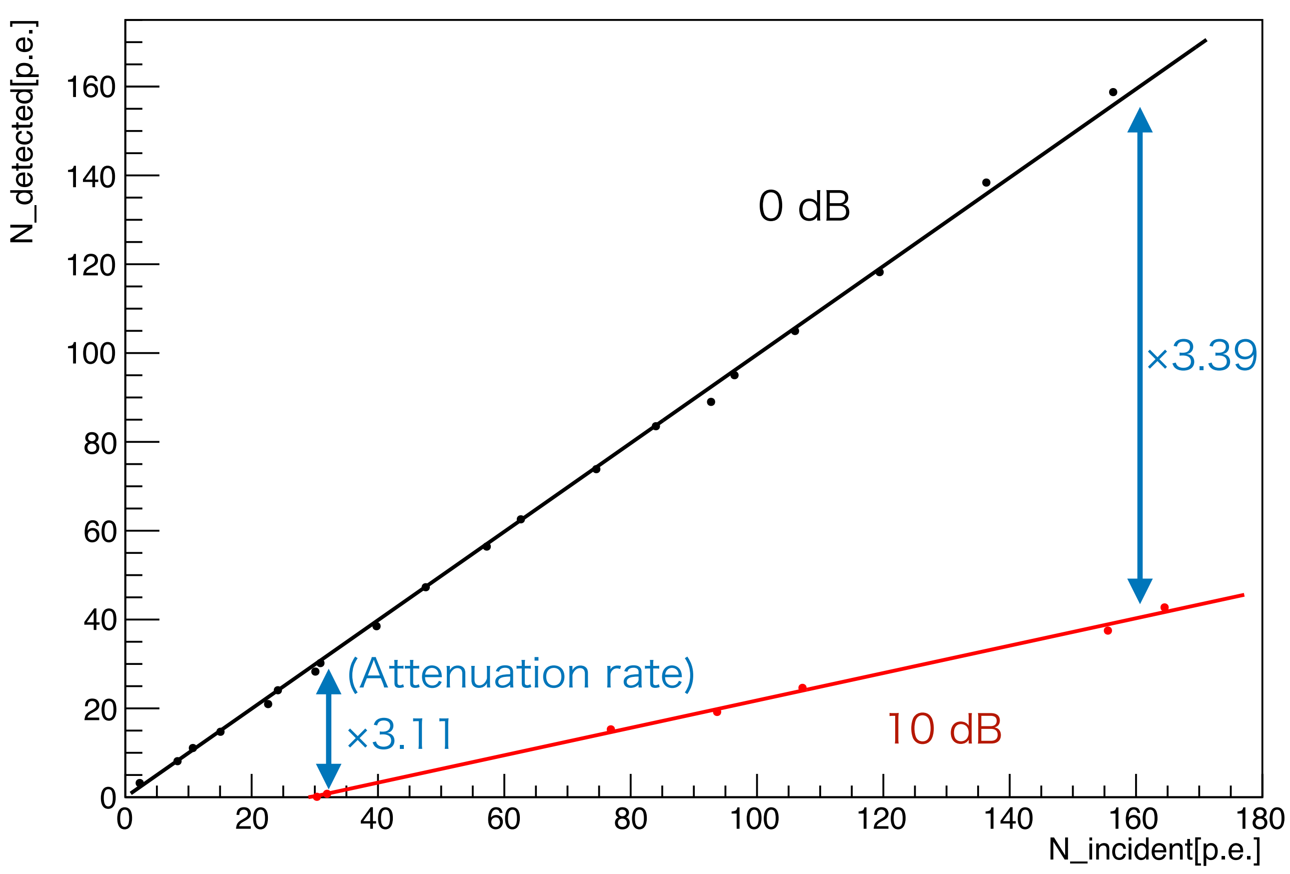
Waveform comparison with 40dB attenuator (S14160-1315PS)



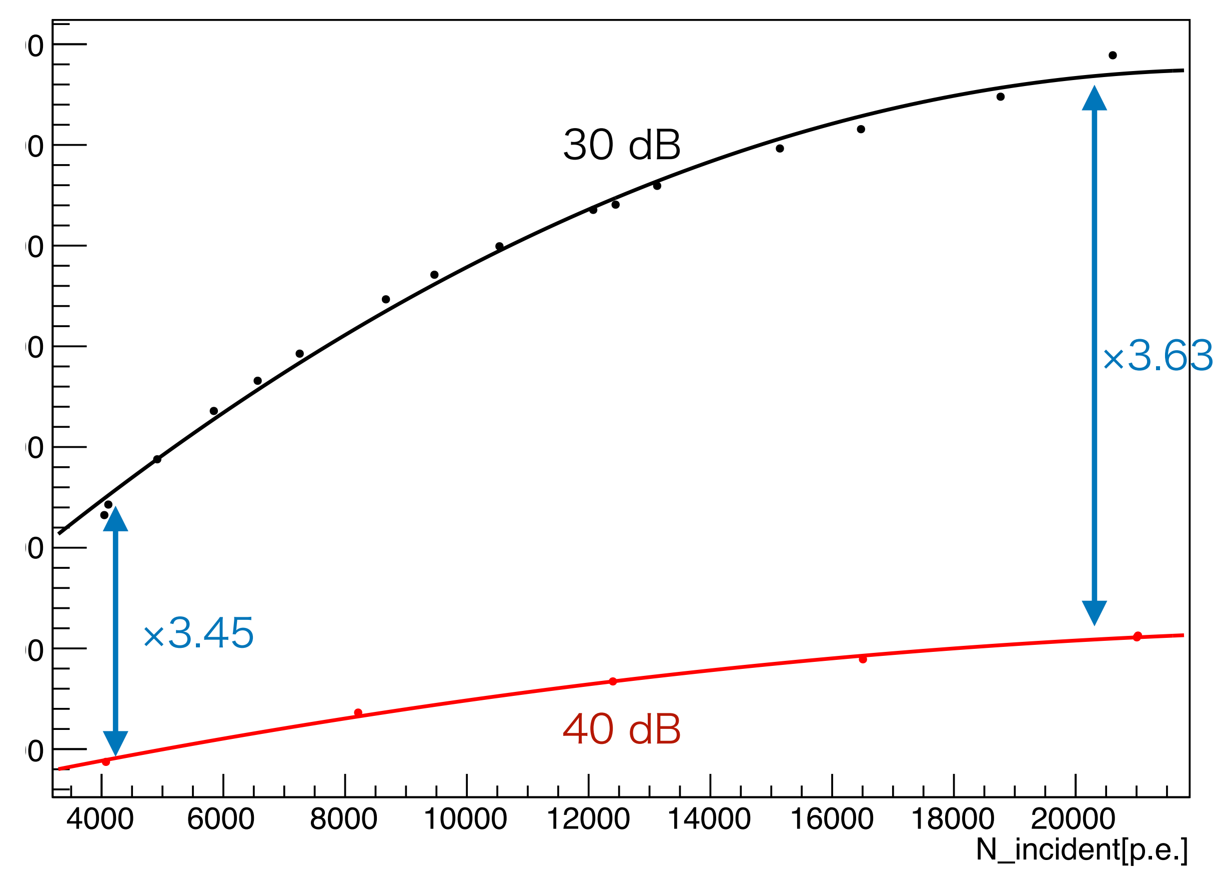
Attenuation Calibration

- Attenuation rate is optimized with factor and offset : $N_{opt} = A * N_{pe} + B$
  - Fit with linear function and calculate coefficients to match the lines
- Specious factor and offset are used at high light intensity
  - Saturation and waveform variation change the attenuation rate depending on light intensity
  - Fit with polynomial function

Comparison with 0dB vs. 10dB (S12571-015P)



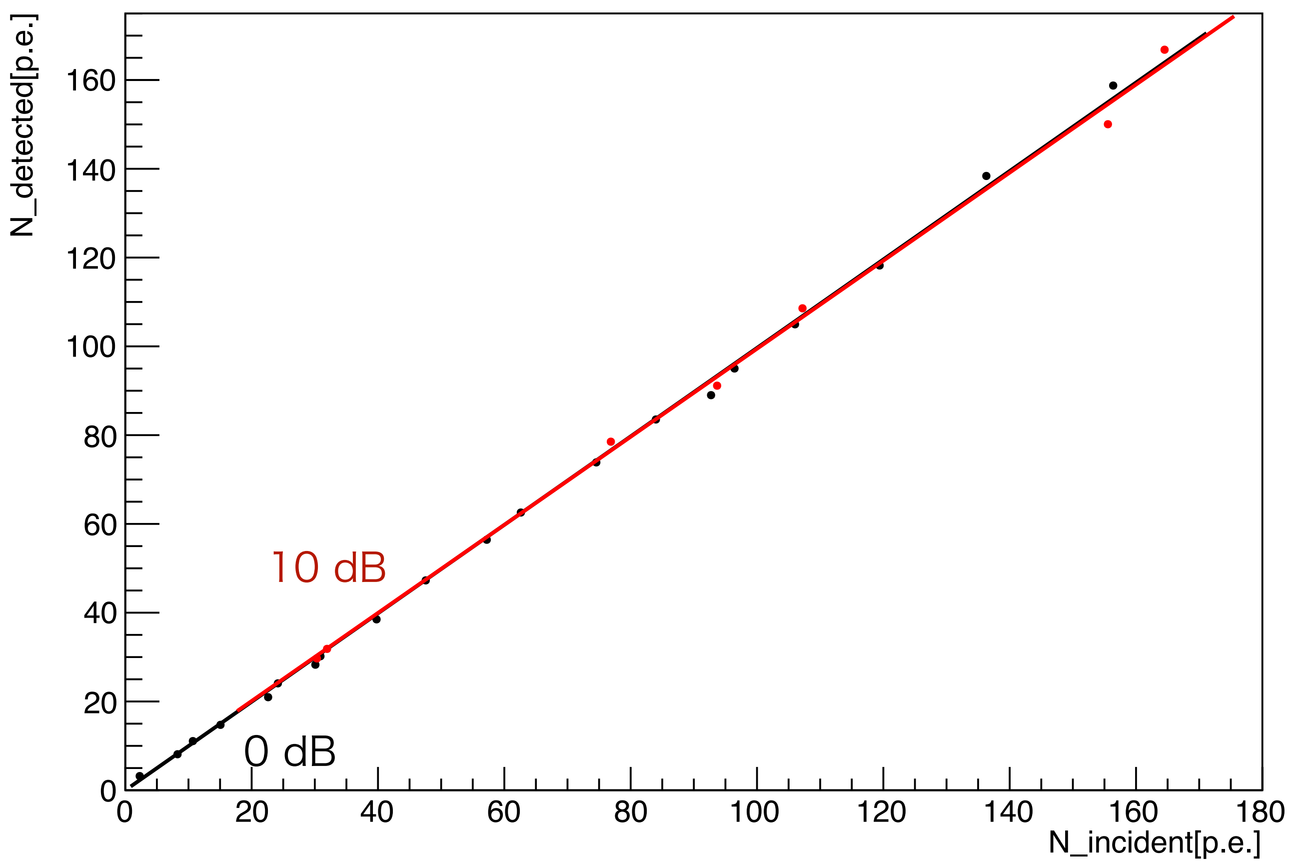
Comparison with 30dB vs. 40dB (S12571-015P)



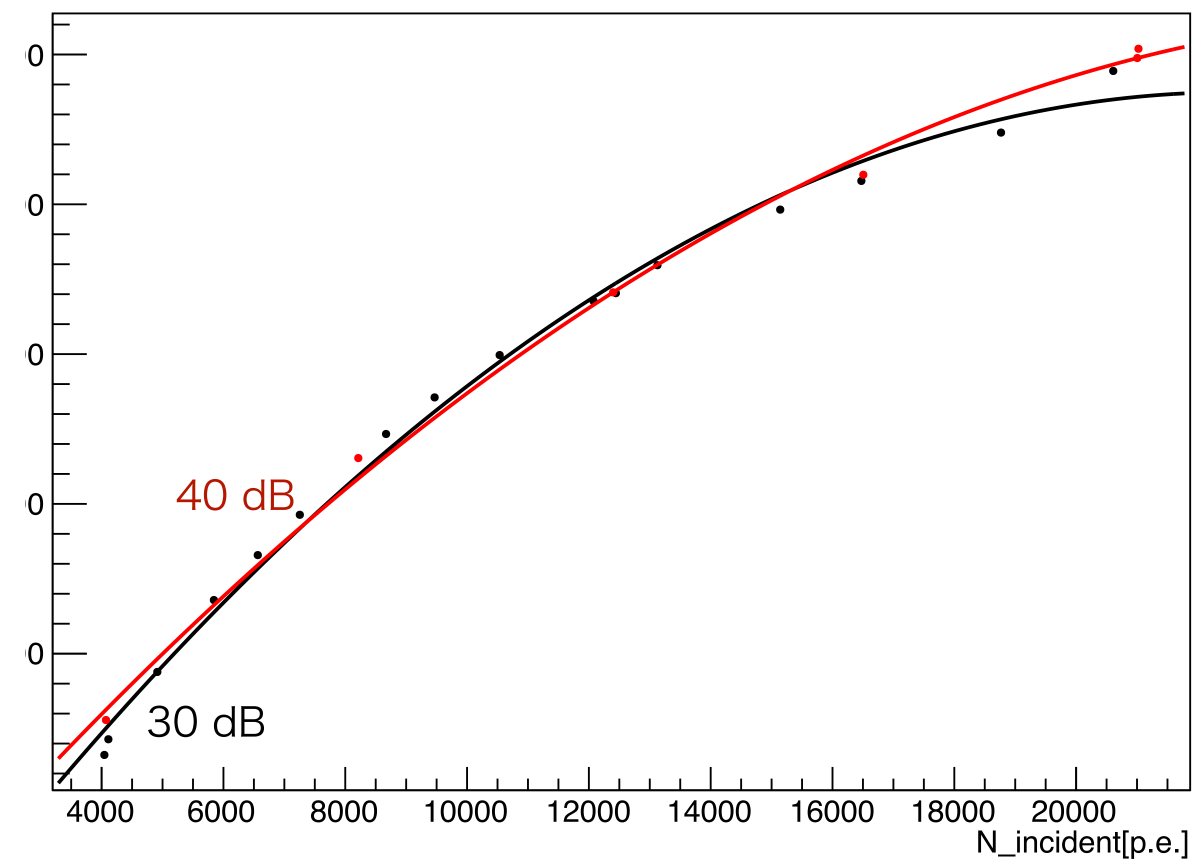
Attenuation Calibration

- Attenuation rate is optimized with factor and offset : $N_{opt} = A * N_{pe} + B$
  - Fit with linear function and calculate coefficients to match the lines
- Specious factor and offset are used at high light intensity
  - Saturation and waveform variation change the attenuation rate depending on light intensity
  - Fit with polynomial function

Calibrated results with 0dB vs. 10dB (S12571-015P)

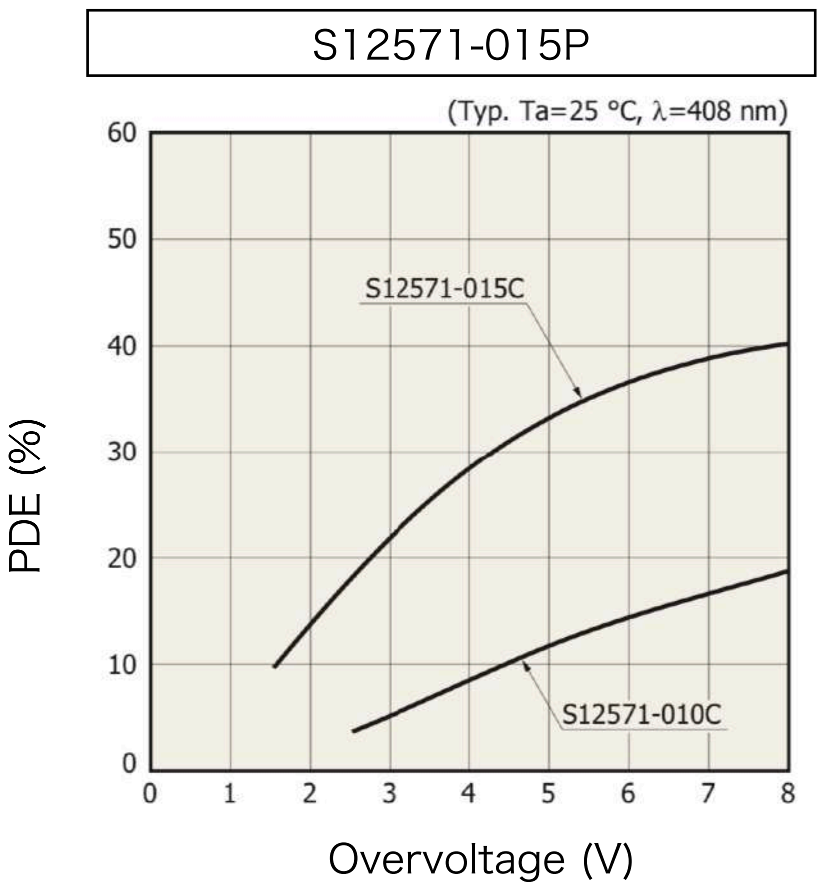


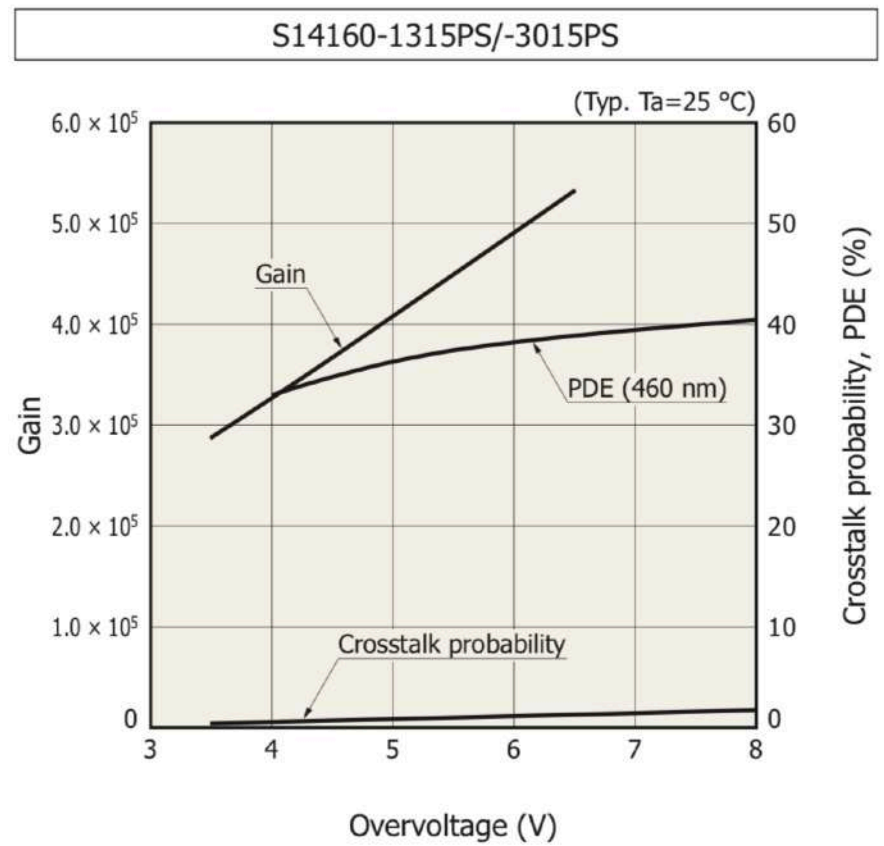
Calibrated results with 30dB vs. 40dB (S12571-015P)

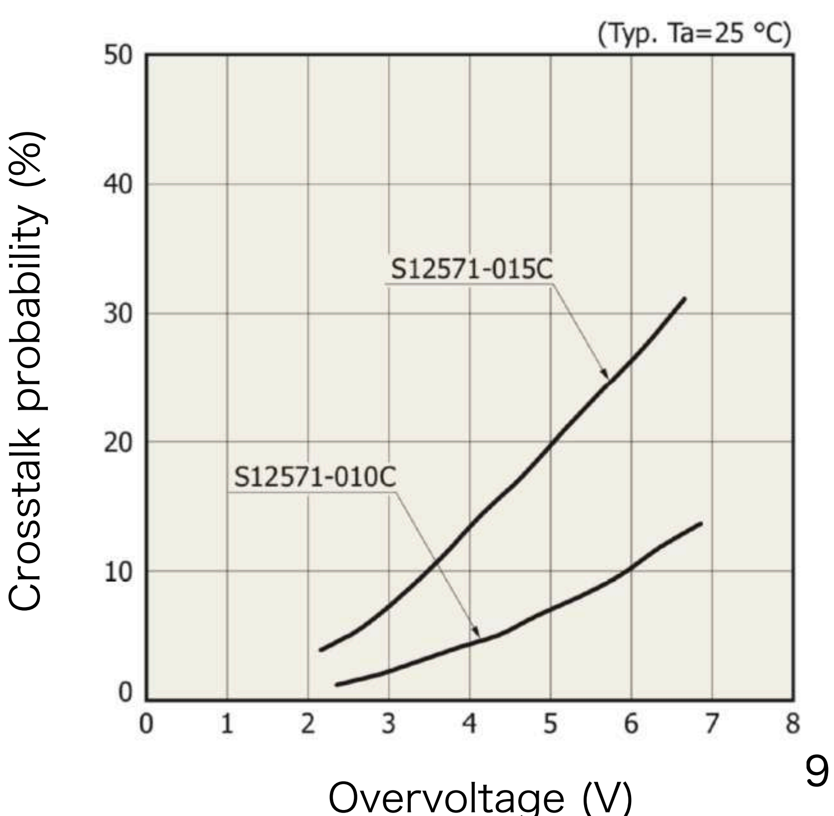


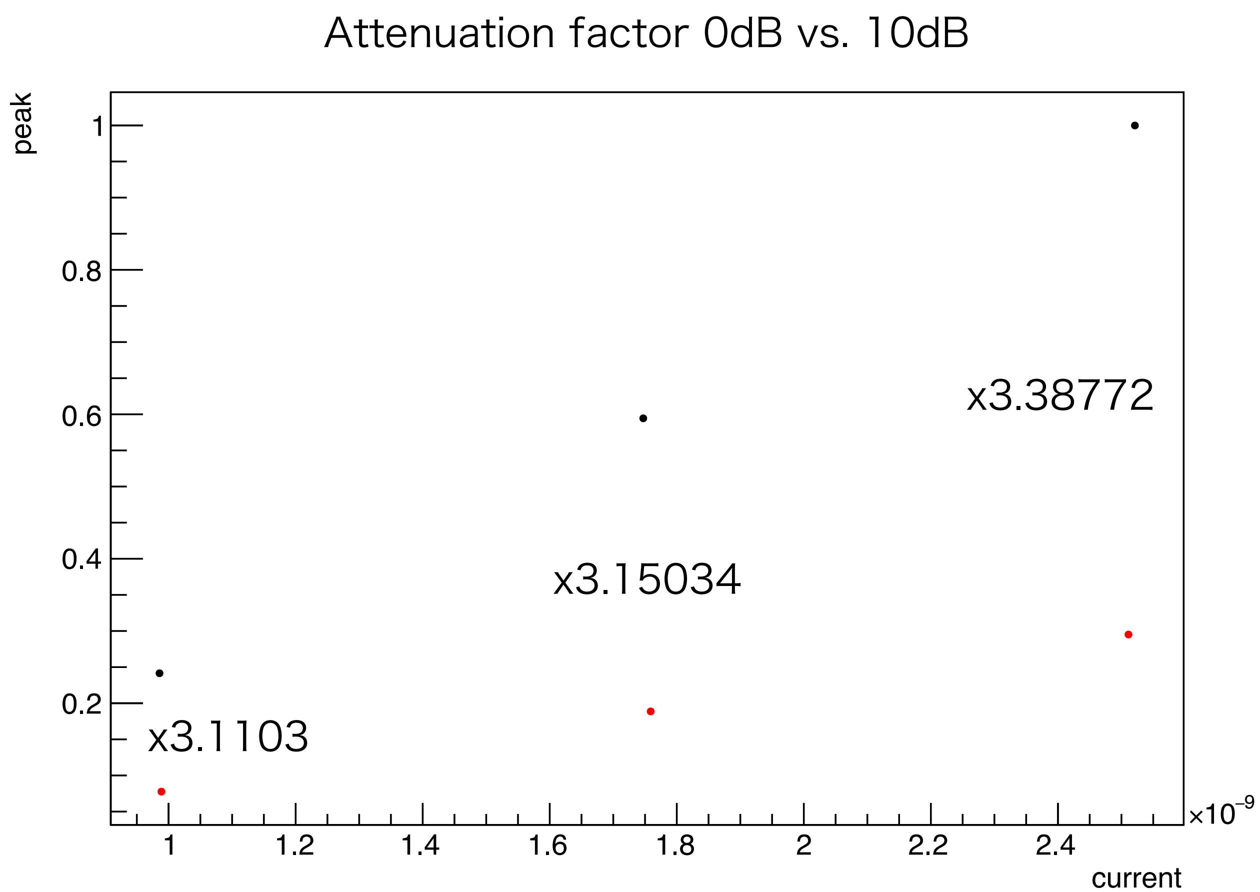
Comparison of two types of MPPCs

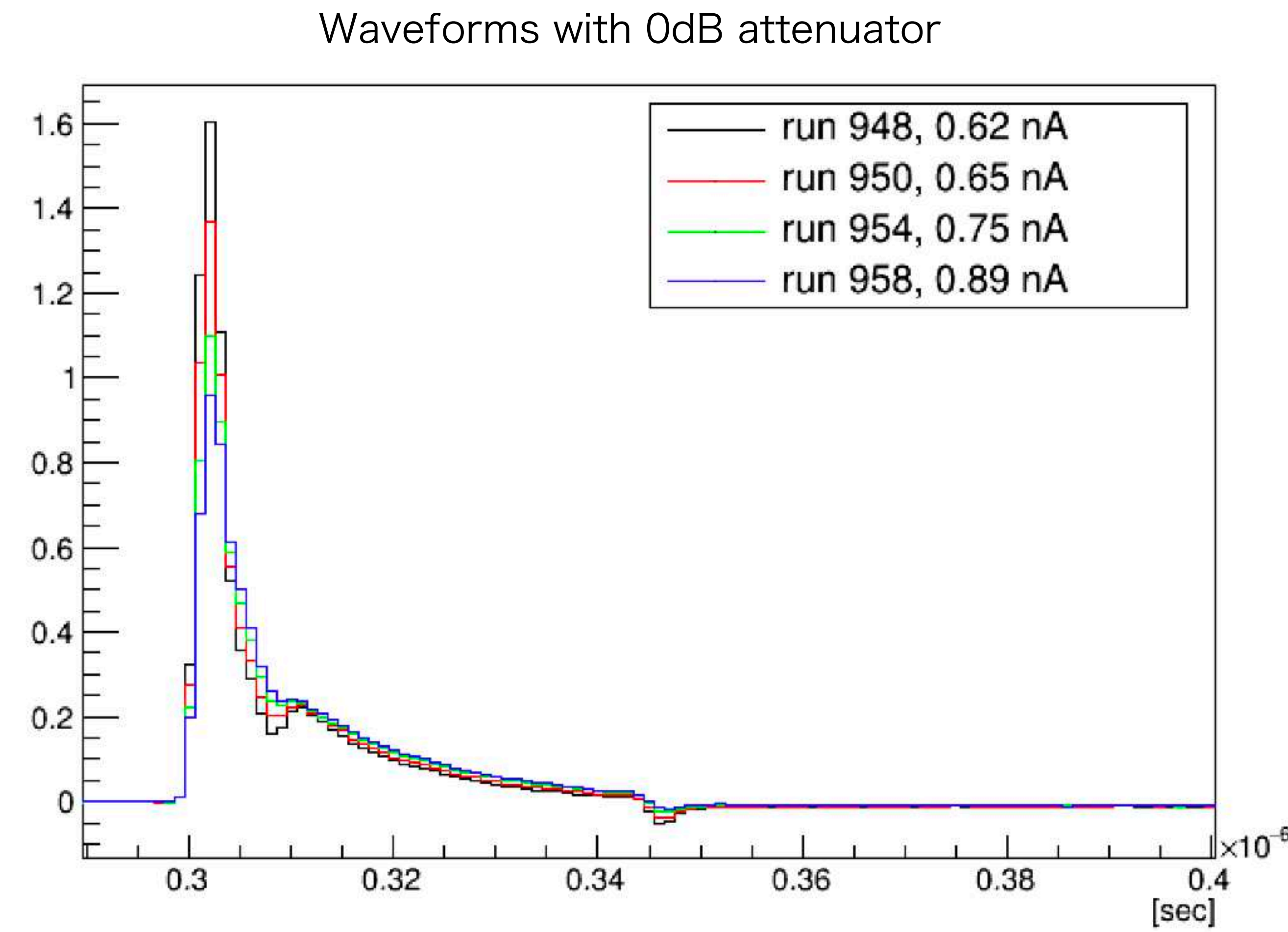
- These plots contain the difference of active area, crosstalk probability and PDE between two types of MPPCs
- N_{seed} and N_{det} are divided by each active area, crosstalk probability, PDE for comparison purpose
  - N_{seed} is converted into number of inserted photon (N_{photon})
  - N_{det} is converted into normalized number of detected photons (N_{nor_det})
- Then, we can see directly saturation tendency of each MPPC

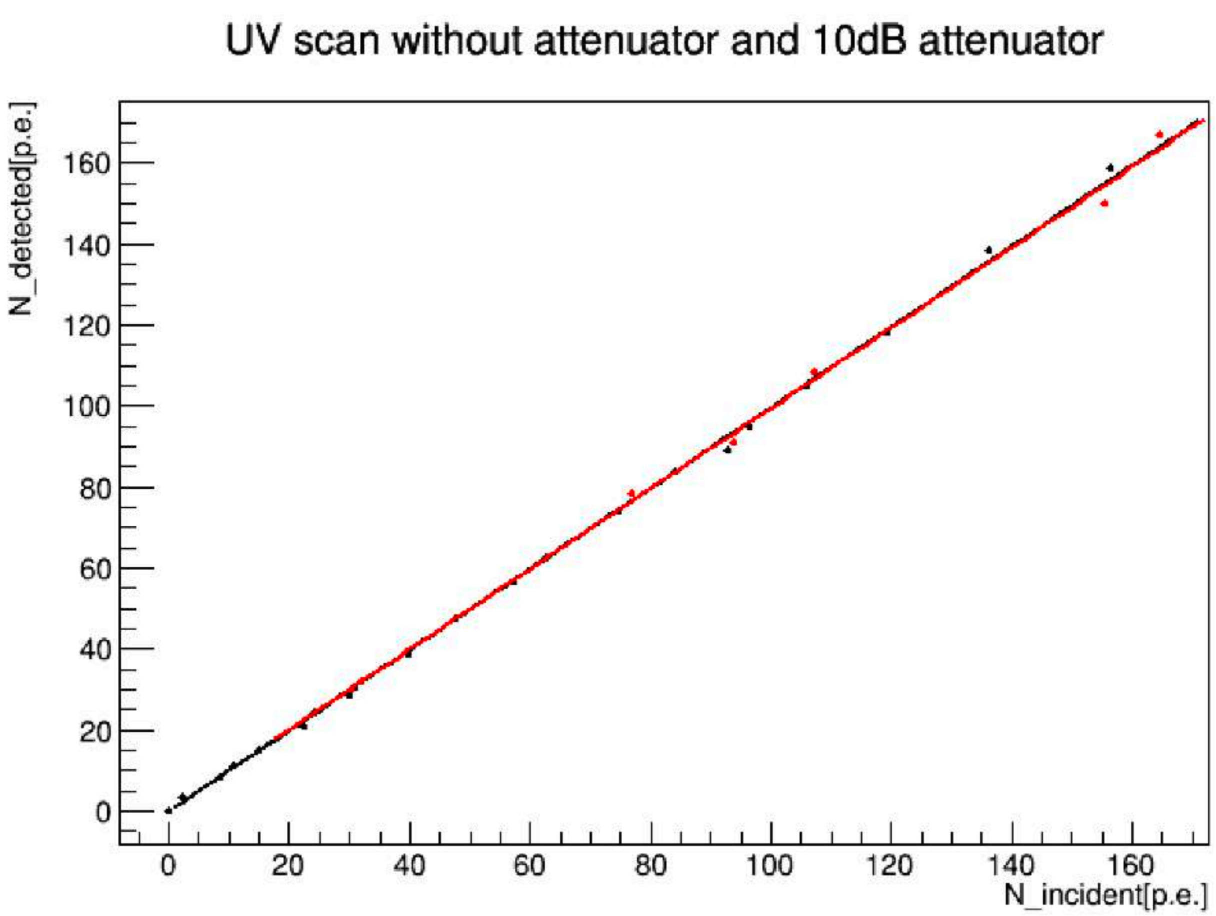


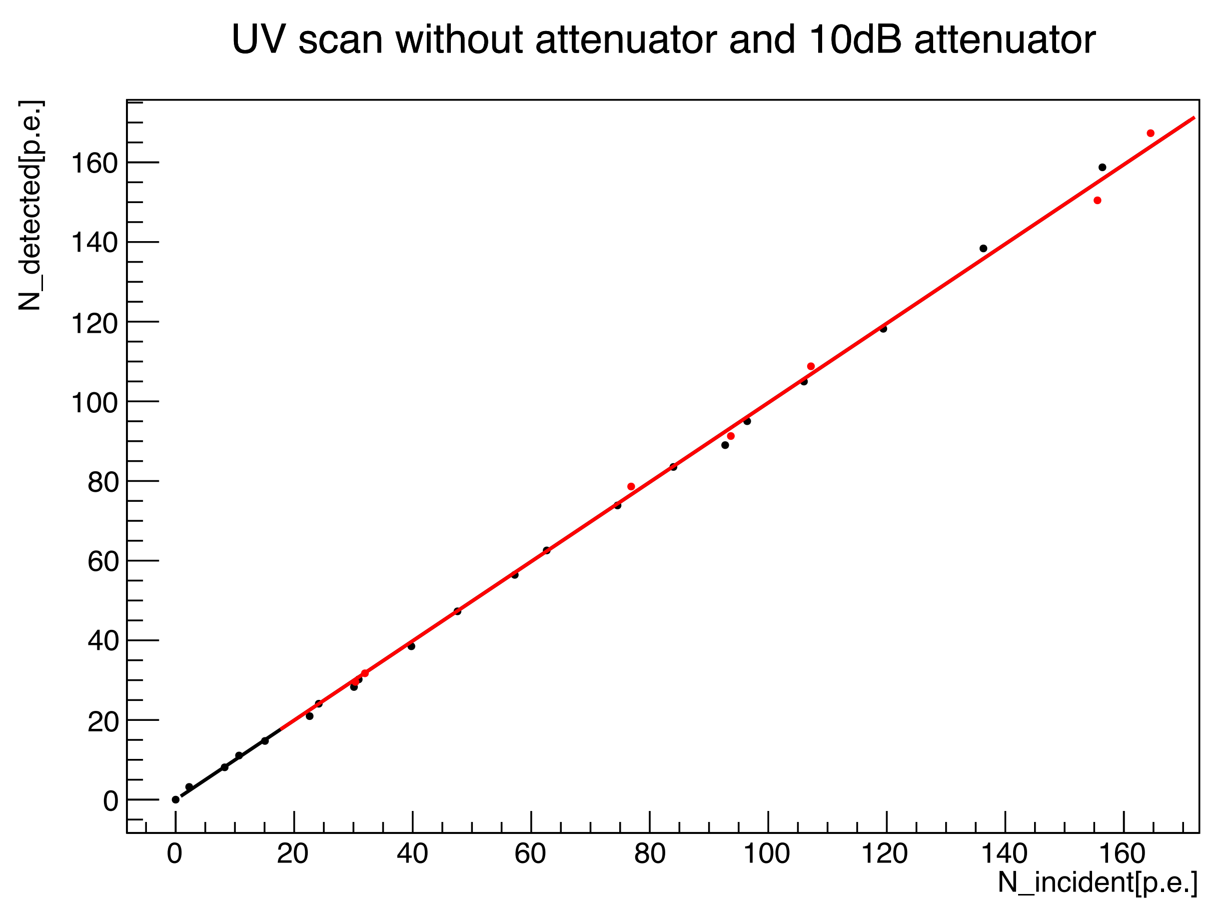




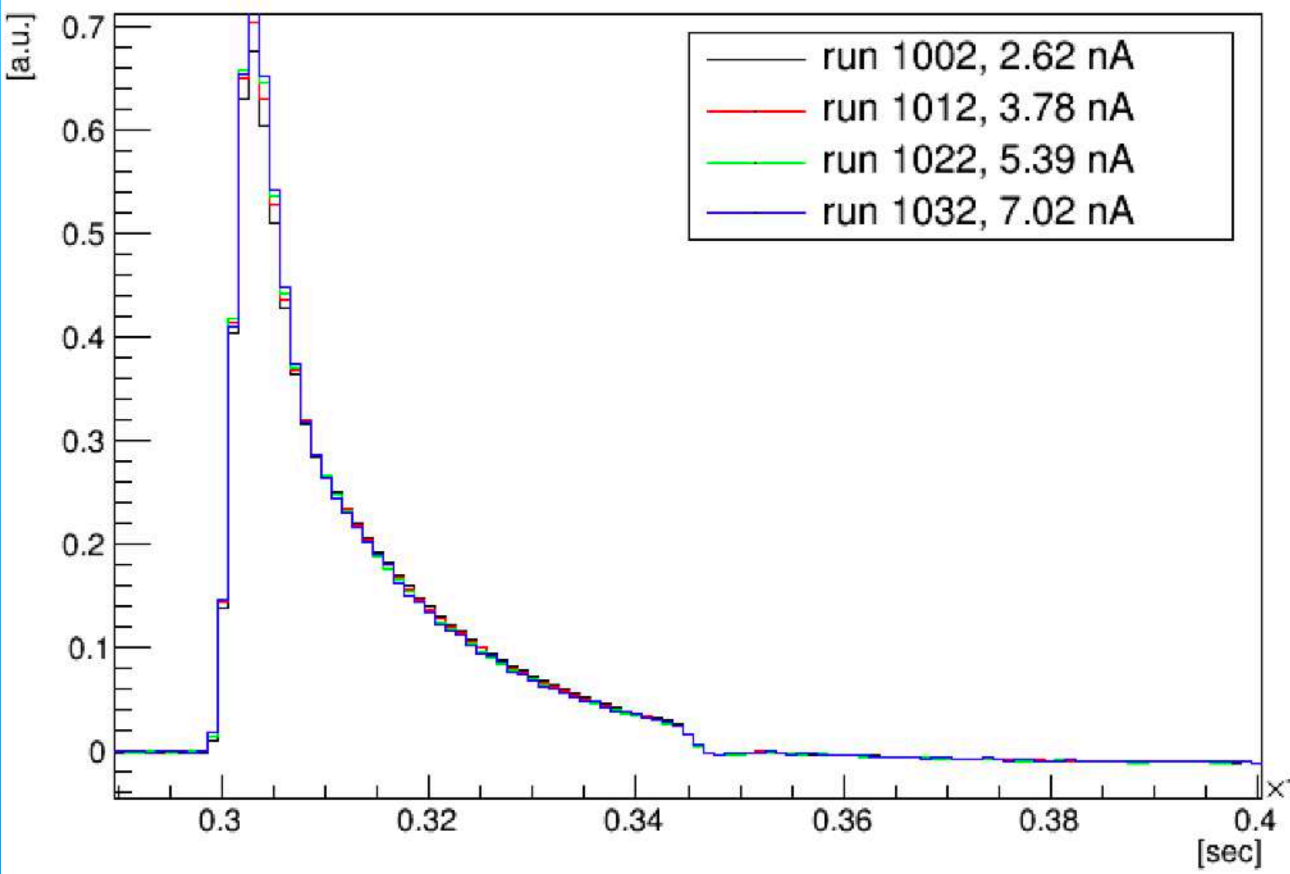

Attenuation factor 0dB vs. 10dB
peak
current
×10^-9
x3.1103
x3.15034
x3.38772


Waveforms with 0dB attenuator
run 948, 0.62 nA
run 950, 0.65 nA
run 954, 0.75 nA
run 958, 0.89 nA
[sec]

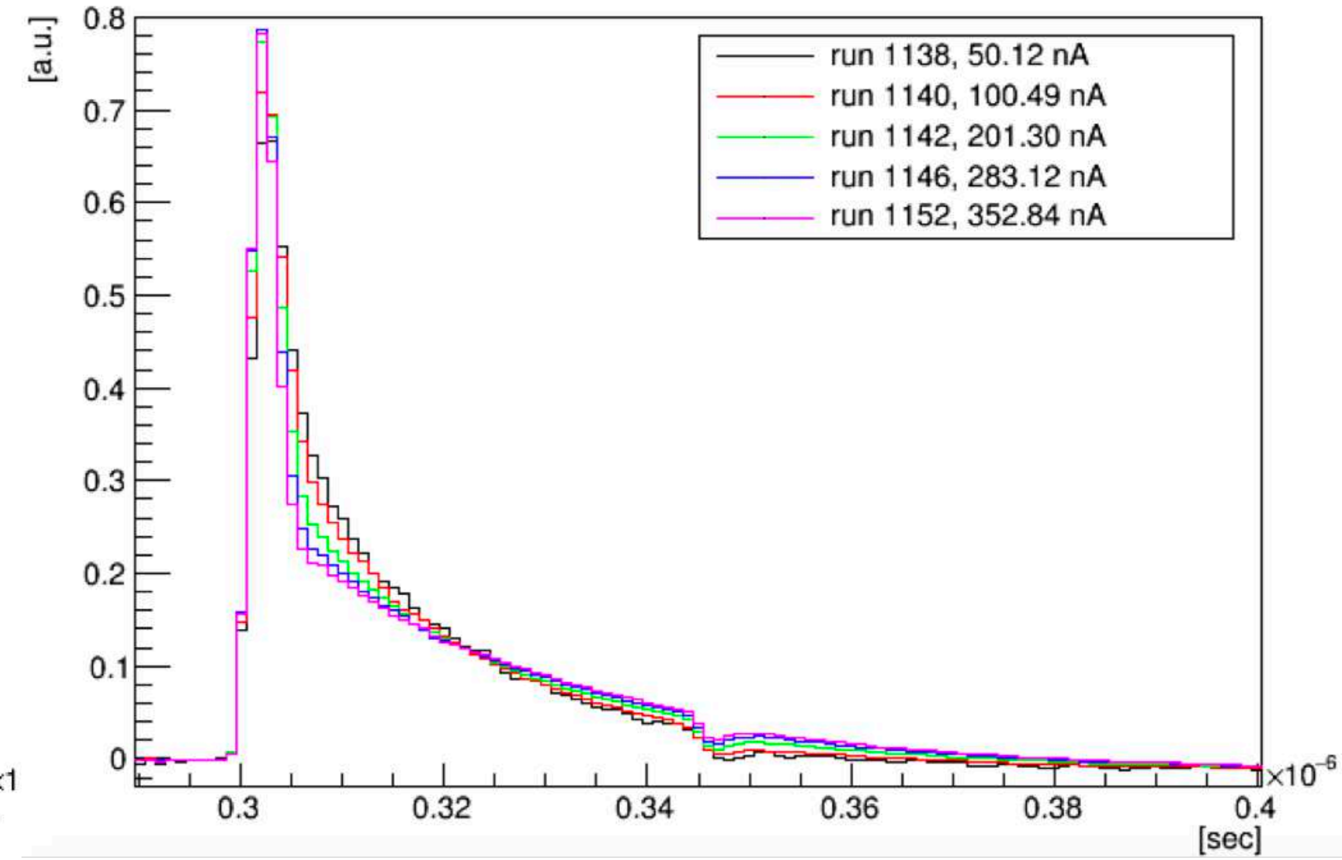

UV scan without attenuator and 10dB attenuator
N_detected[p.e.]
N_incident[p.e.]


UV scan without attenuator and 10dB attenuator
N_detected[p.e.]
N_incident[p.e.]

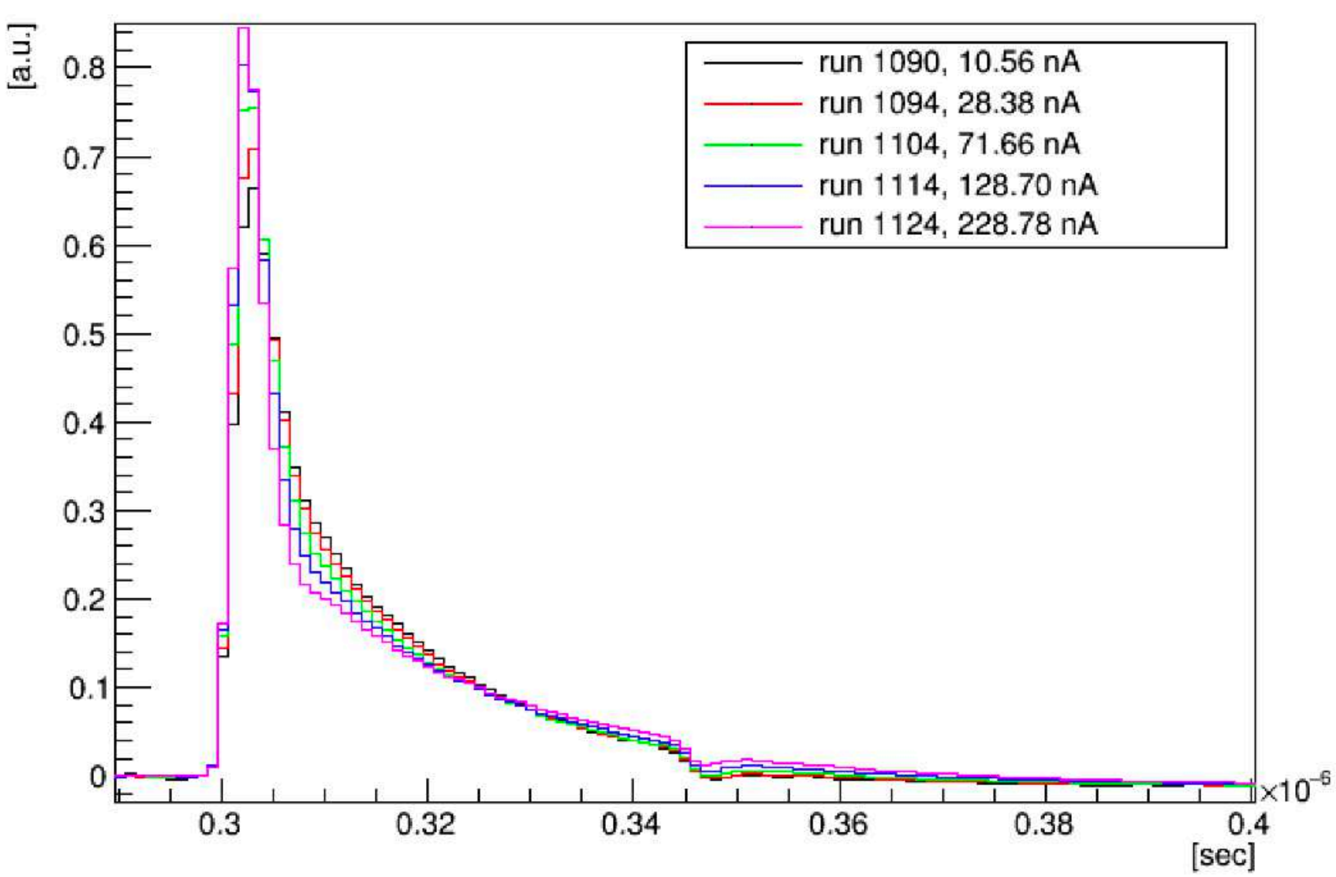
Waveforms with 10dB attenuator



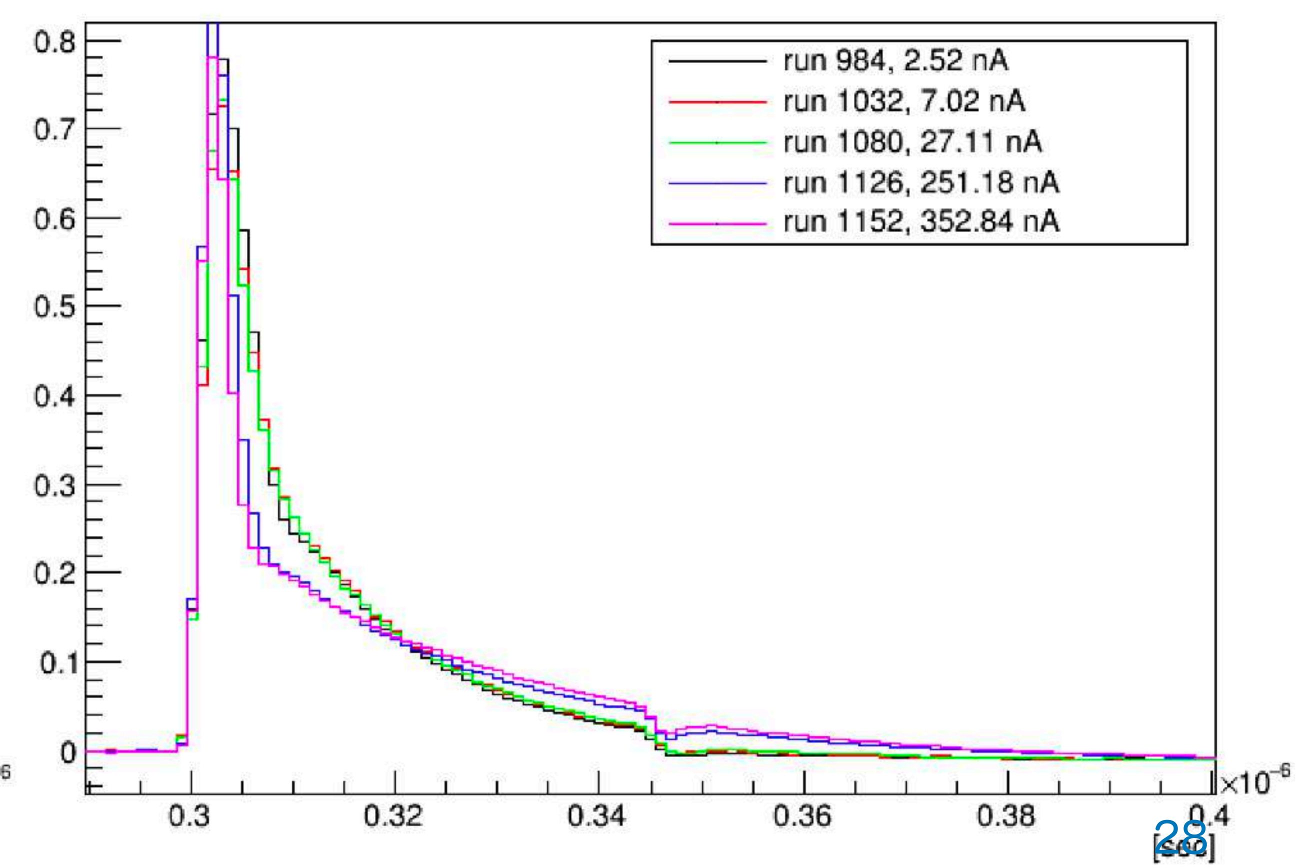
Waveforms with 30dB attenuator

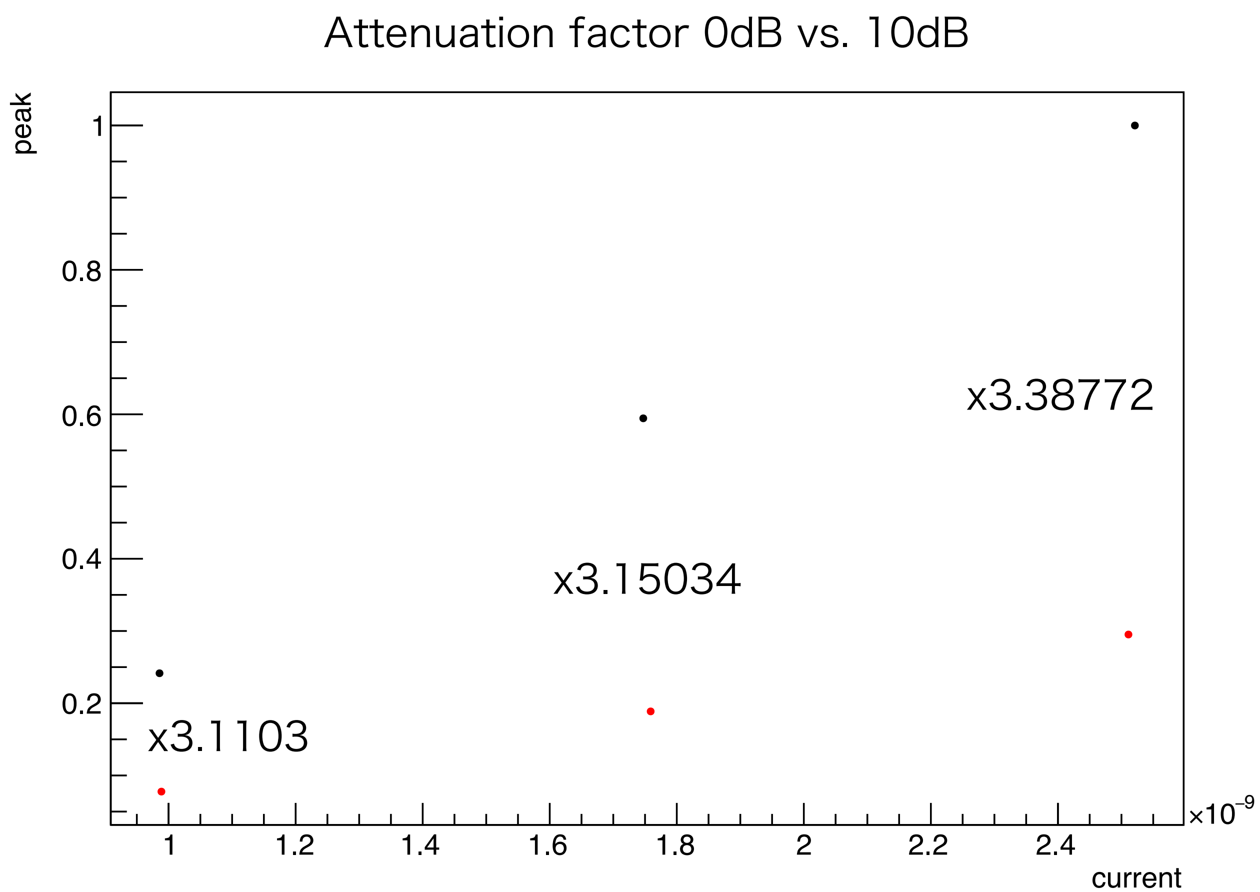


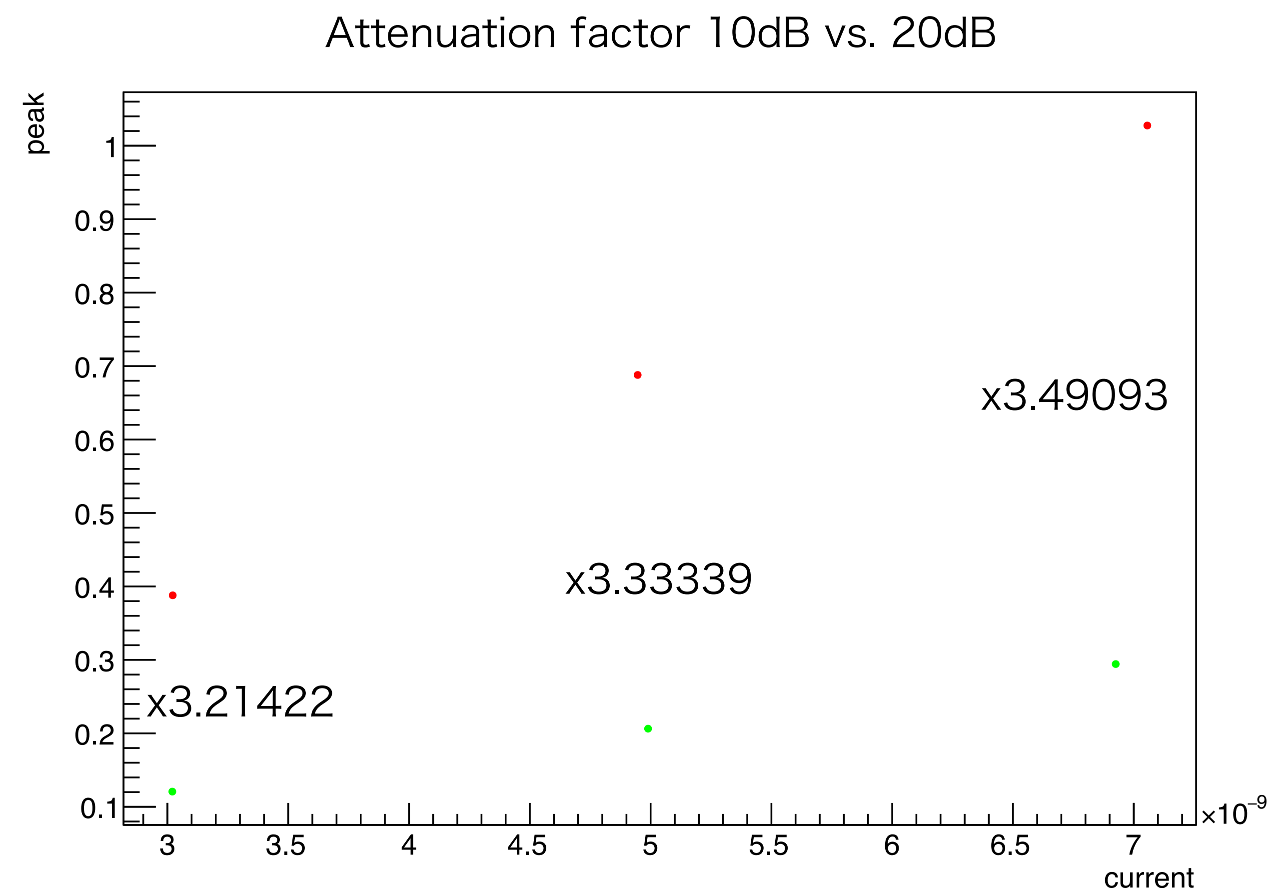
Waveforms with 40dB attenuator

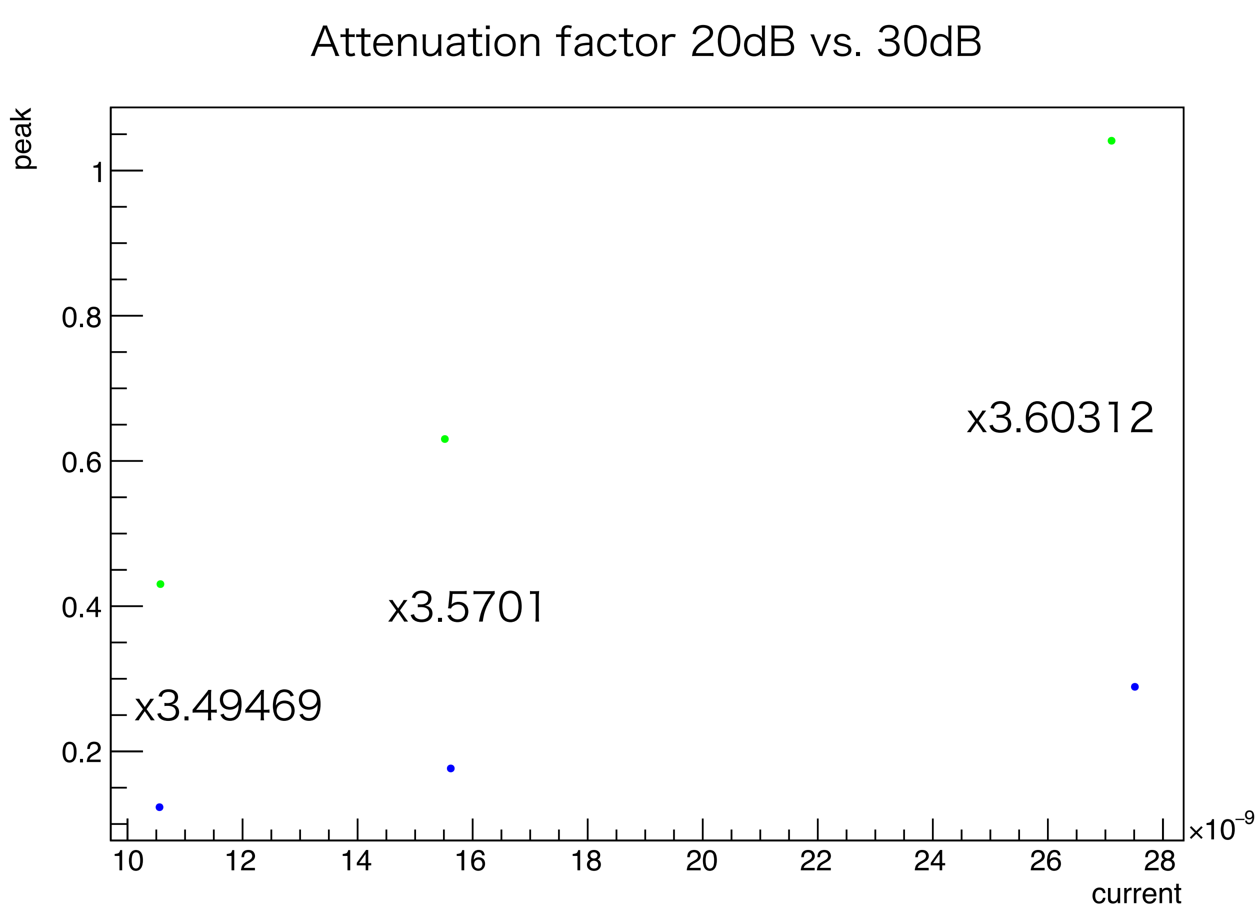


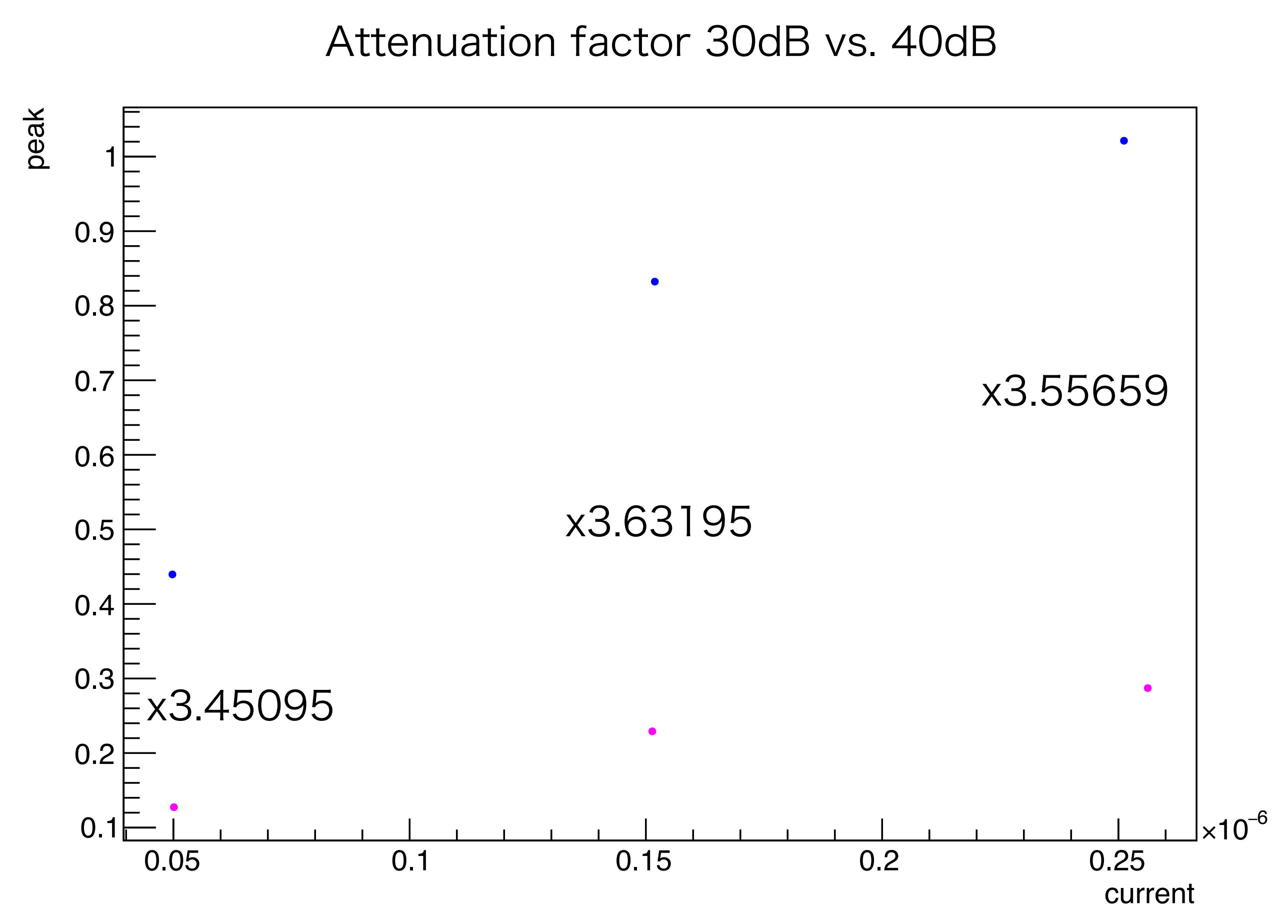
Waveform transition with 0 - 40dB attenuator

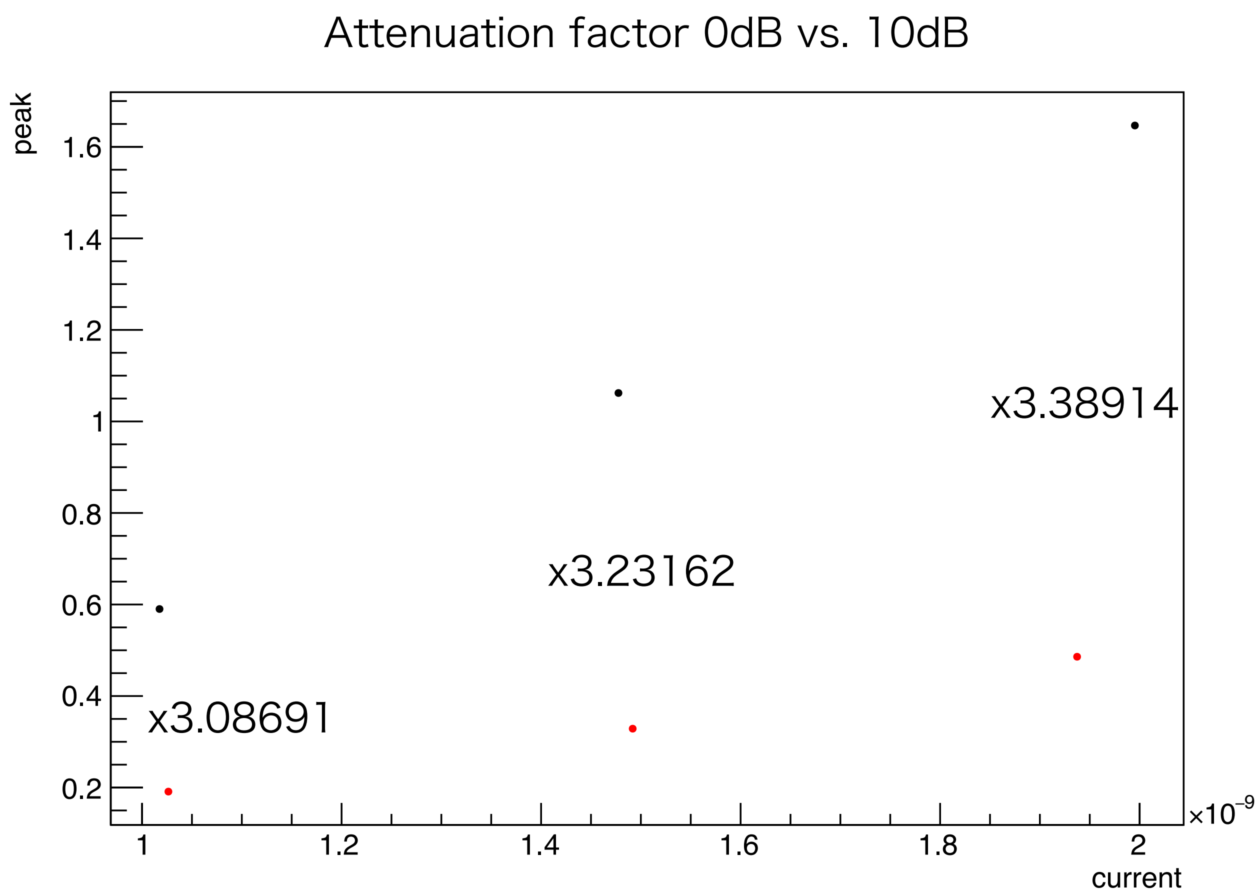


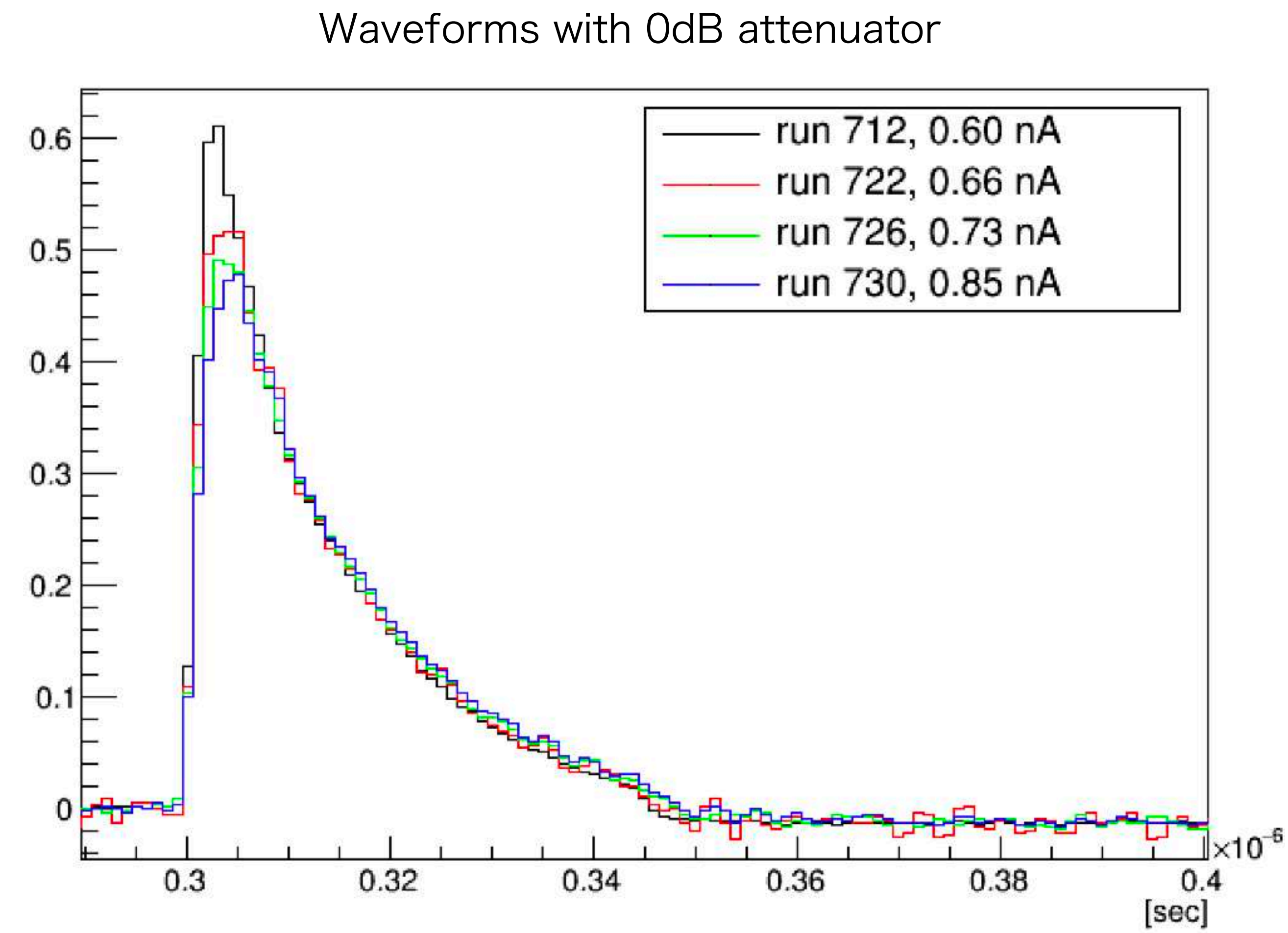

Attenuation factor 0dB vs. 10dB
peak
current
×10⁻⁹
x3.38772
x3.15034
x3.1103

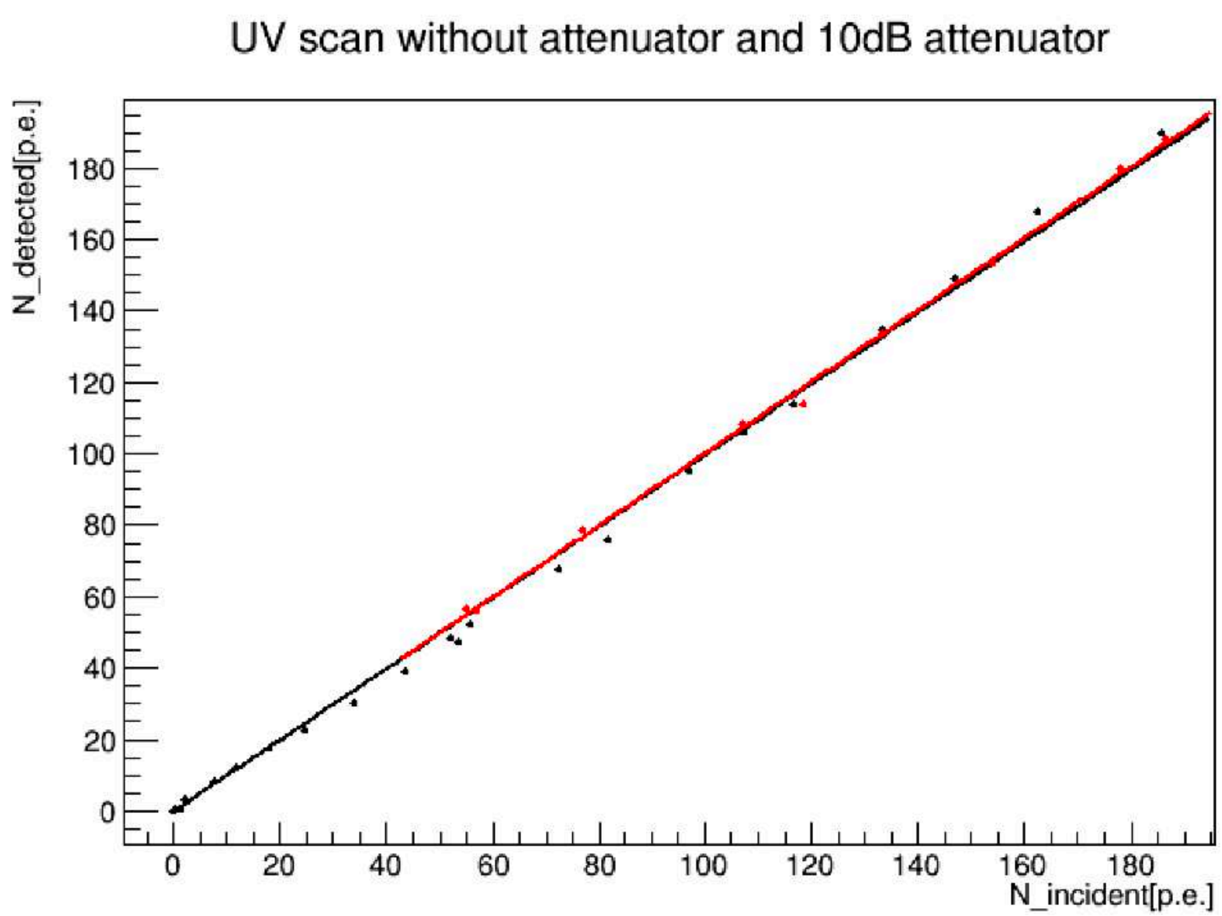

Attenuation factor 10dB vs. 20dB
peak
current
×10⁻⁹
x3.49093
x3.33339
x3.21422

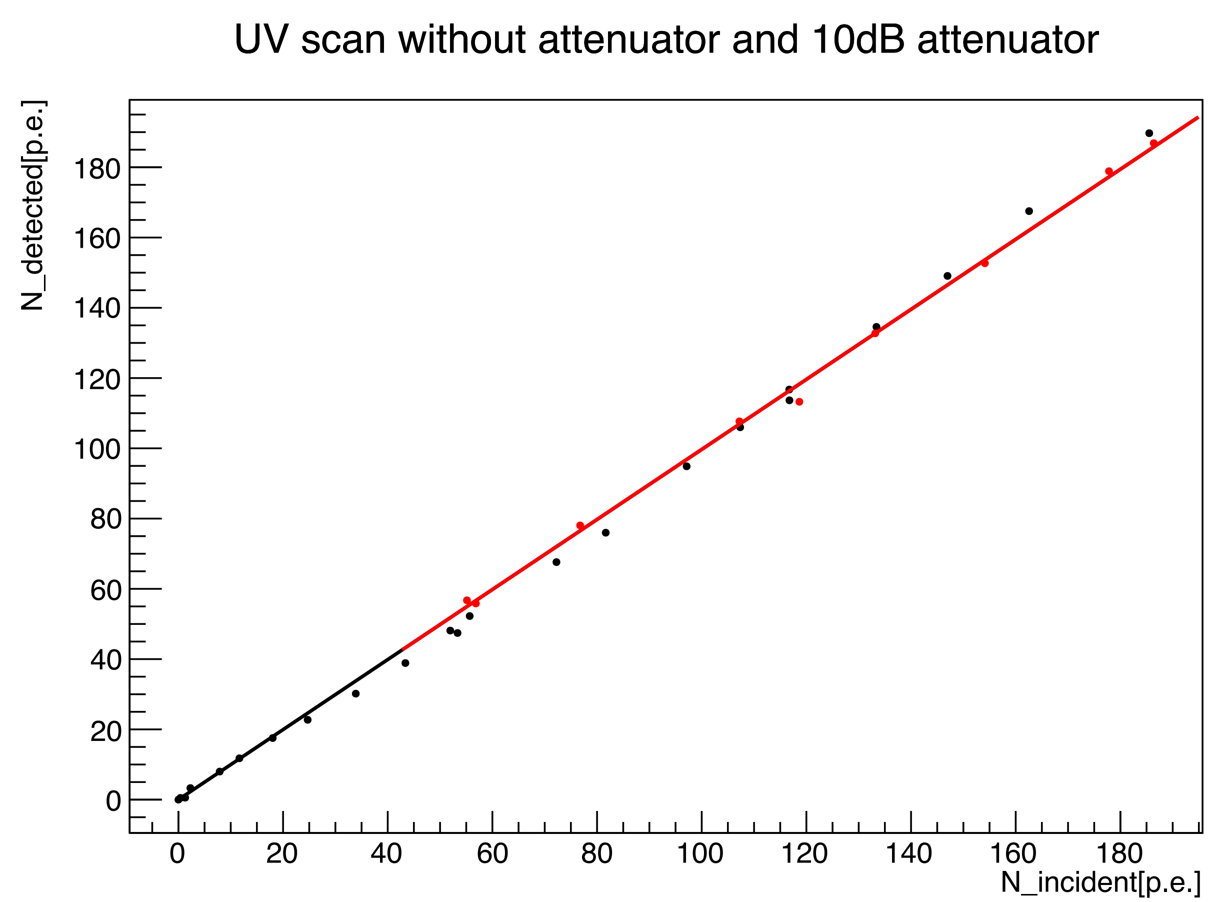

Attenuation factor 20dB vs. 30dB
peak
current
×10⁻⁹
x3.60312
x3.5701
x3.49469


Attenuation factor 30dB vs. 40dB
peak
current
×10⁻⁶
x3.55659
x3.63195
x3.45095

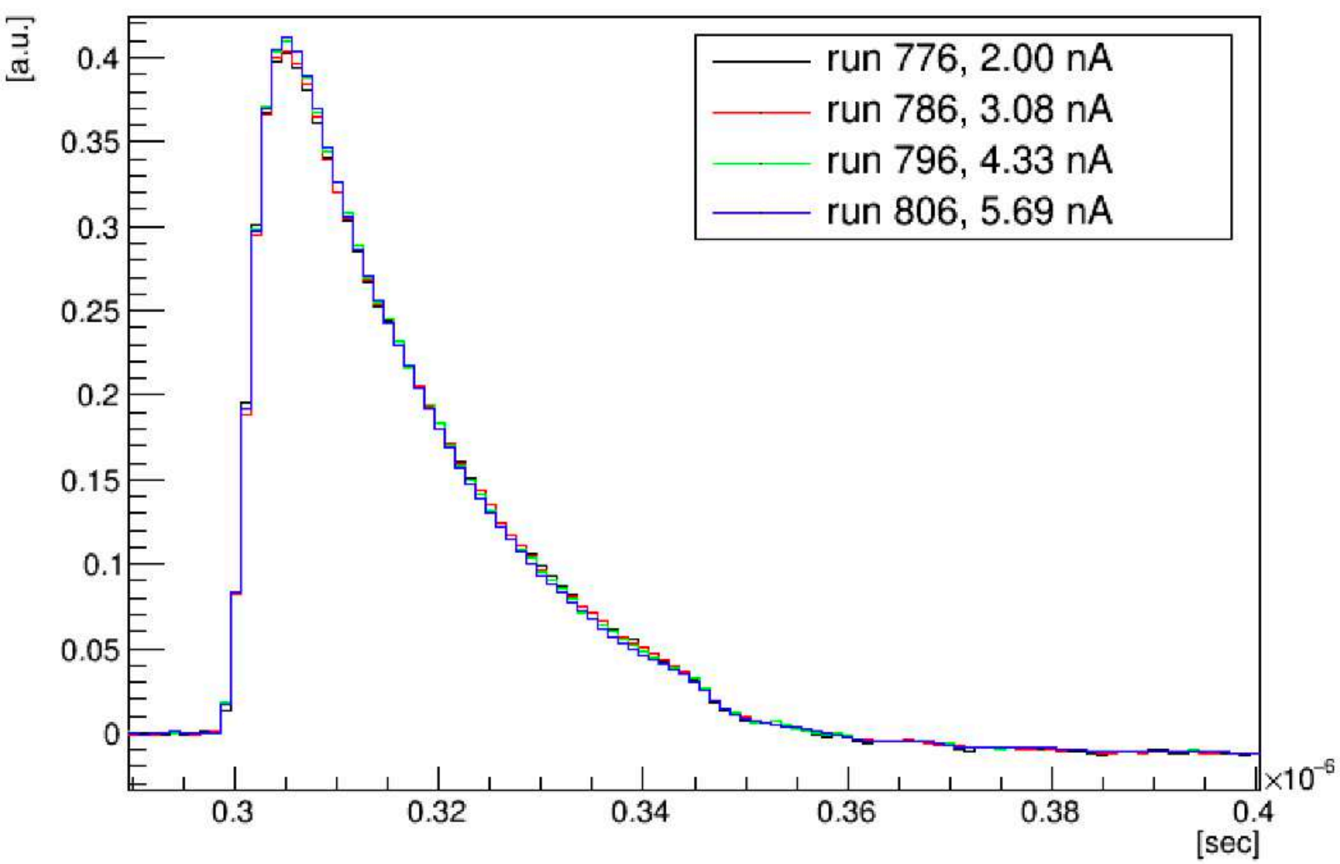

Attenuation factor 0dB vs. 10dB
peak
current
$\times10^{-9}$
x3.08691
x3.23162
x3.38914


Waveforms with 0dB attenuator
run 712, 0.60 nA
run 722, 0.66 nA
run 726, 0.73 nA
run 730, 0.85 nA
$\times10^{-6}$
[sec]

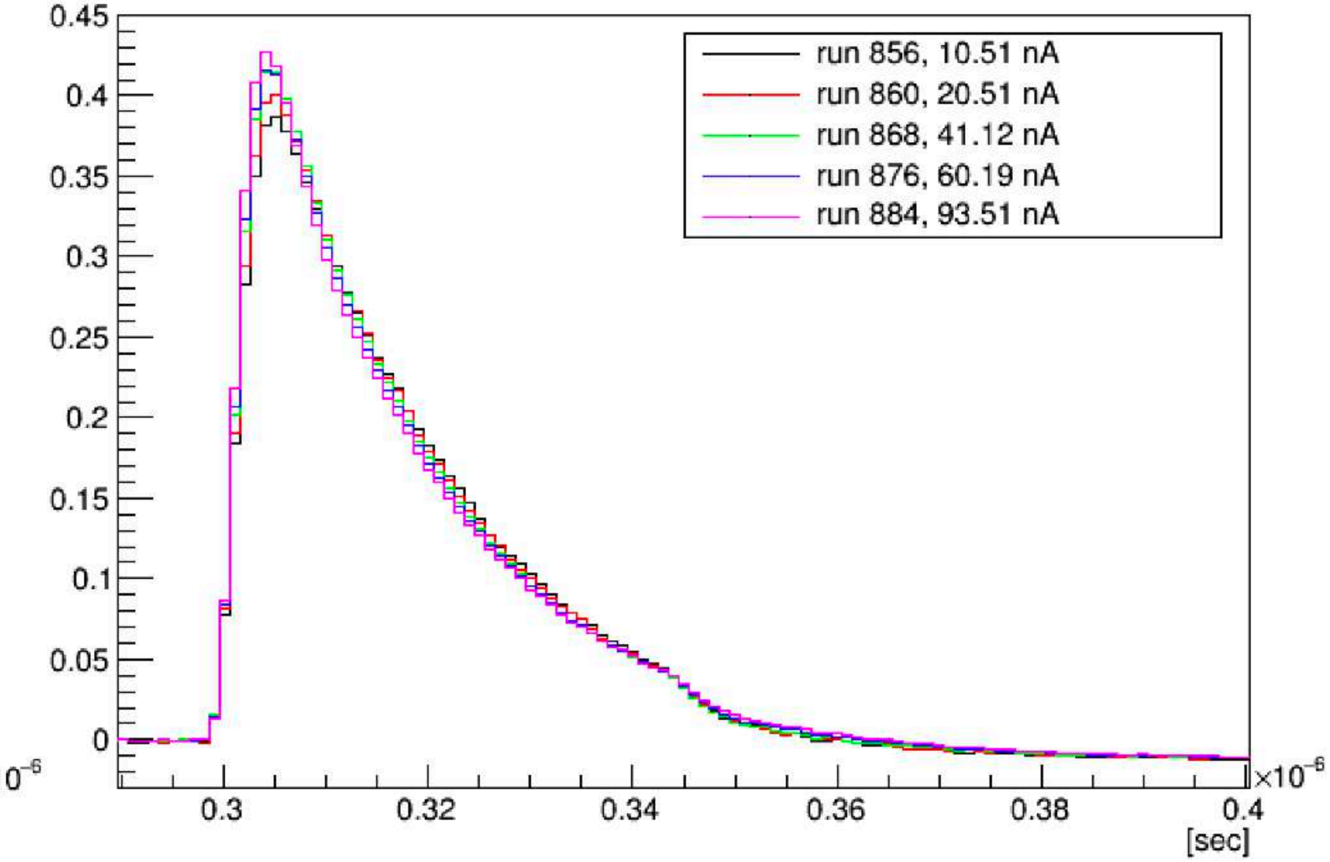

UV scan without attenuator and 10dB attenuator
N_detected[p.e.]
N_incident[p.e.]


UV scan without attenuator and 10dB attenuator
N_detected[p.e.]
N_incident[p.e.]

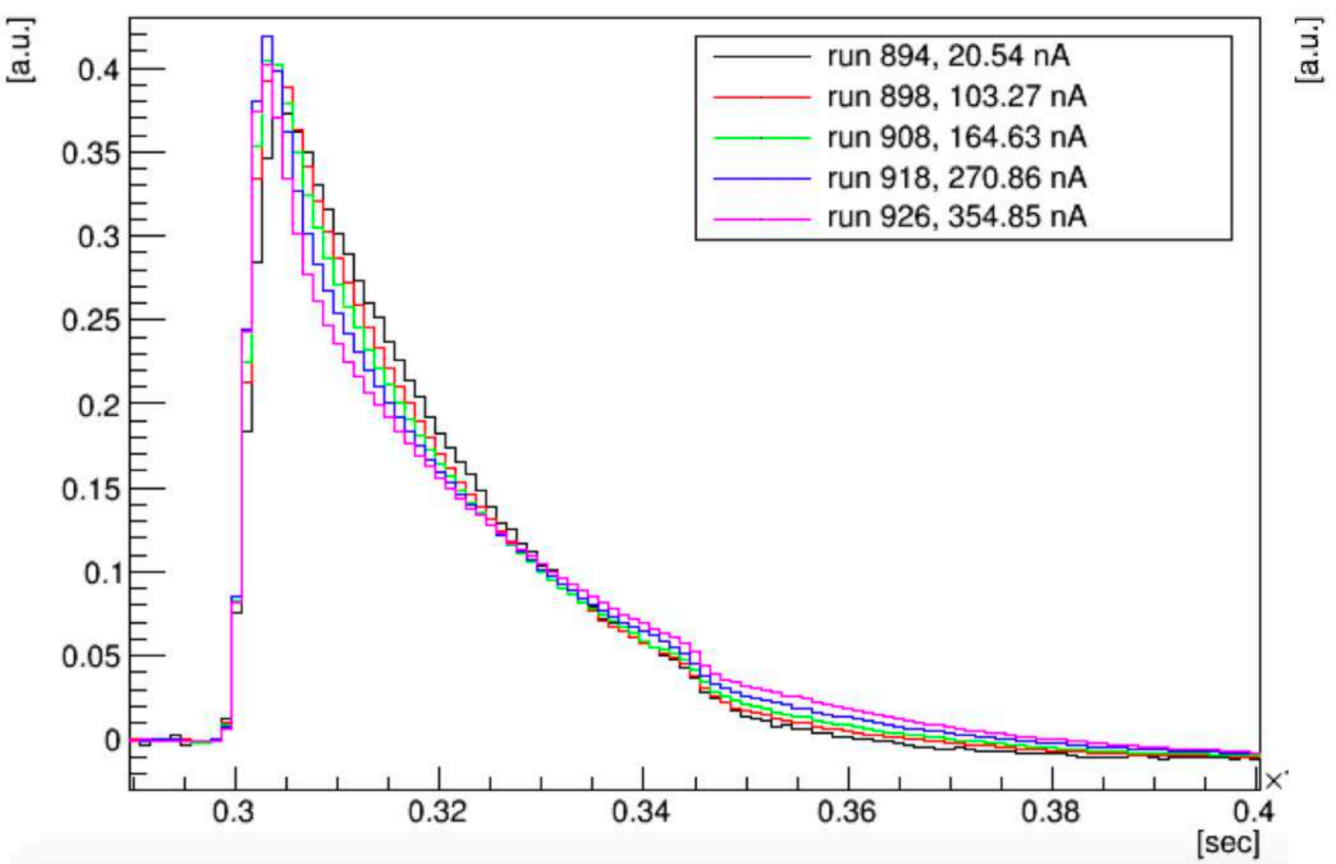
Waveforms with 10dB attenuator



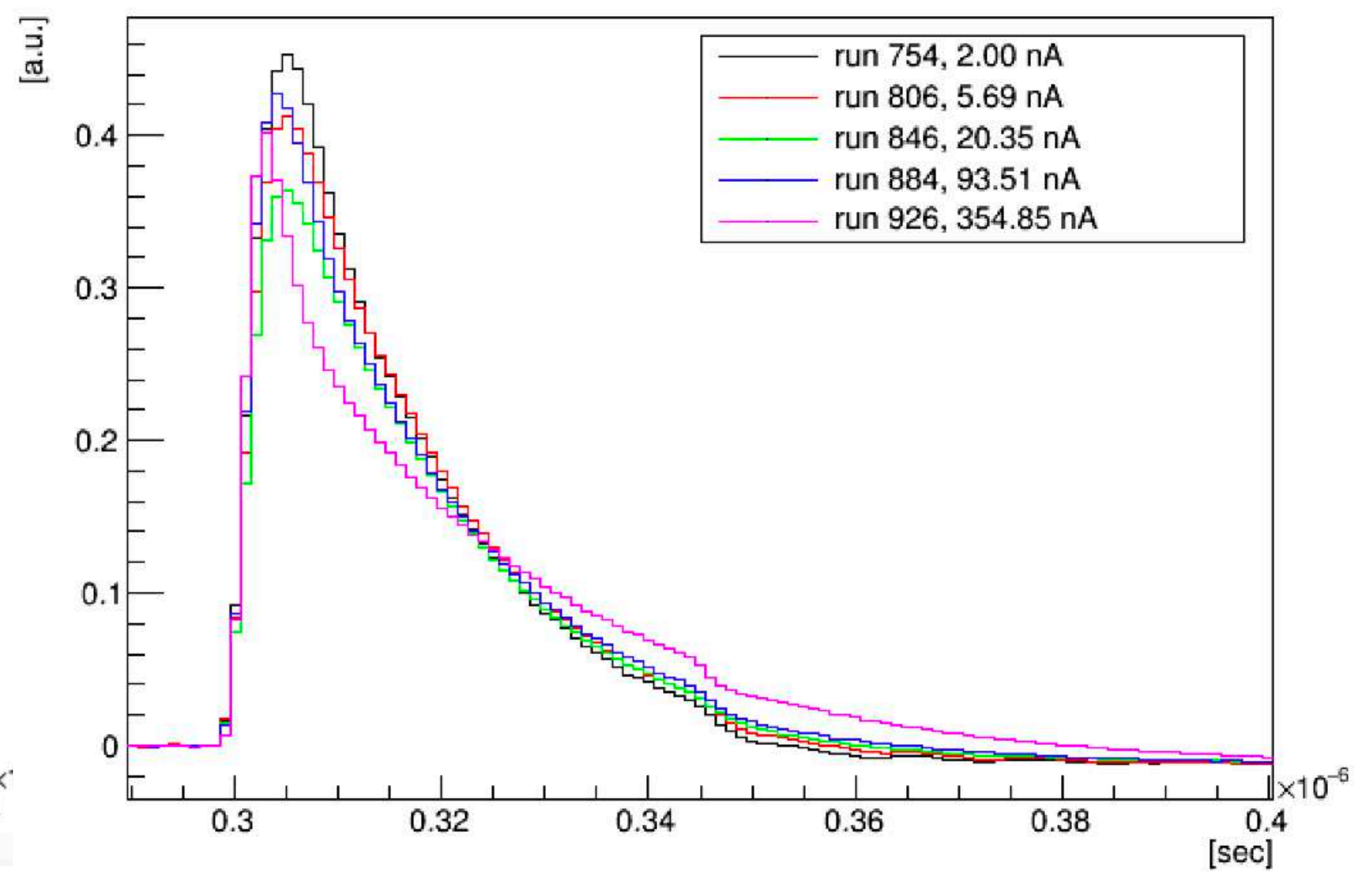
Waveforms with 30dB attenuator

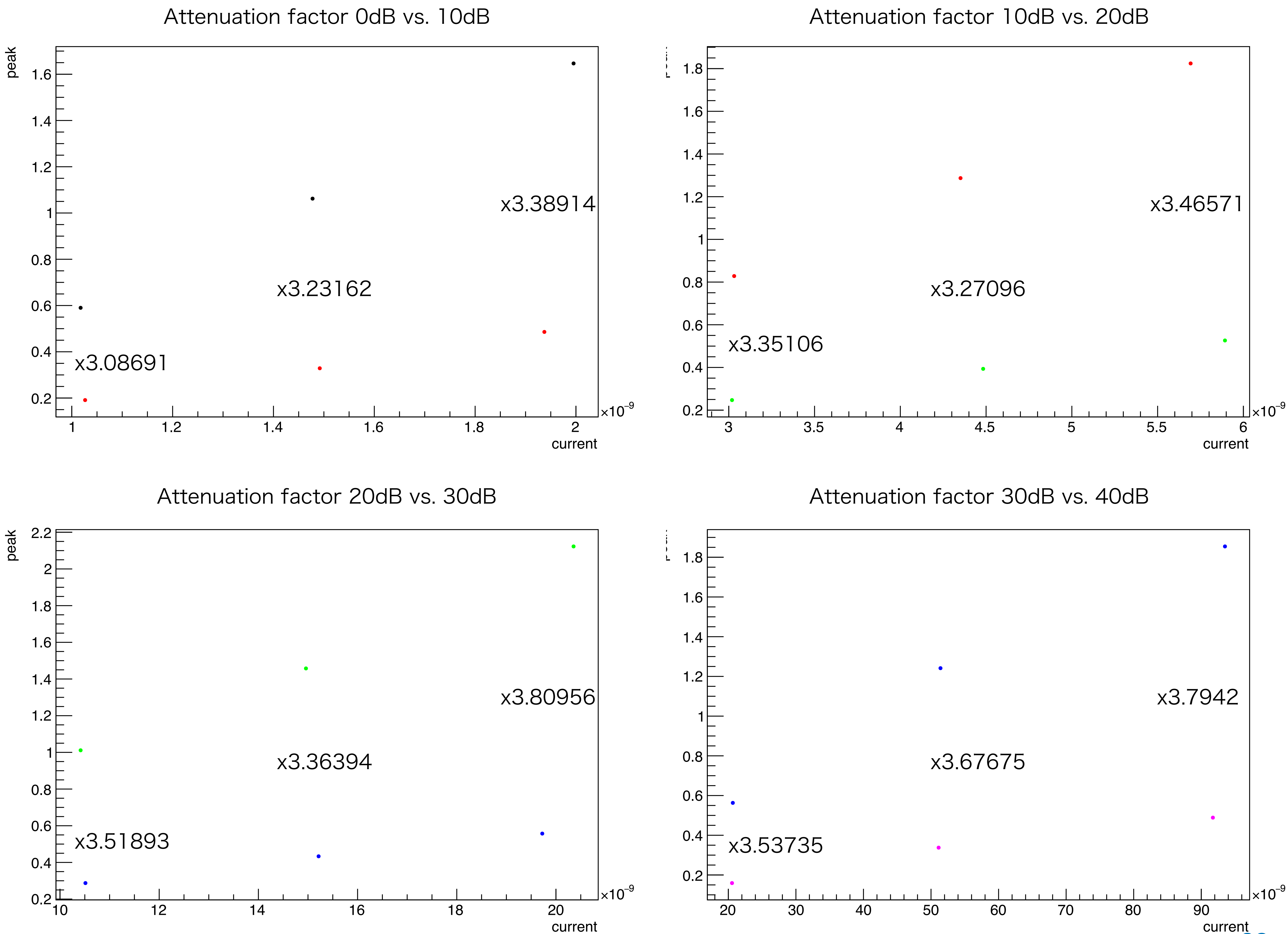


Waveforms with 40dB attenuator



Waveform transition with 0 - 40dB attenuator




Attenuation factor 0dB vs. 10dB
peak
current
×10⁻⁹
x3.38914
x3.23162
x3.08691
Attenuation factor 10dB vs. 20dB
current
x3.46571
x3.27096
x3.35106
Attenuation factor 20dB vs. 30dB
peak
current
x3.80956
x3.36394
x3.51893
Attenuation factor 30dB vs. 40dB
current
x3.7942
x3.67675
x3.53735

Comparison with two types of MPPCs

- The difference of two plots should be consistent with the difference of PDE
  - However, S14160-1315PS is less saturated compared with S12571-015P even after correction
- Need further verification
  - We plan to do the same measurement with fast 400 nm laser