Study on the Dynamic Range of SiPMs with Large Pixel Number

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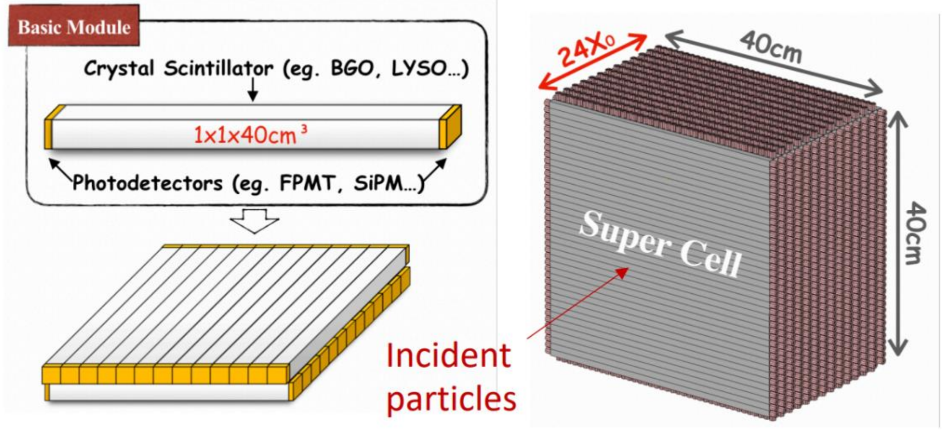
CEPC Calorimeter Working Group

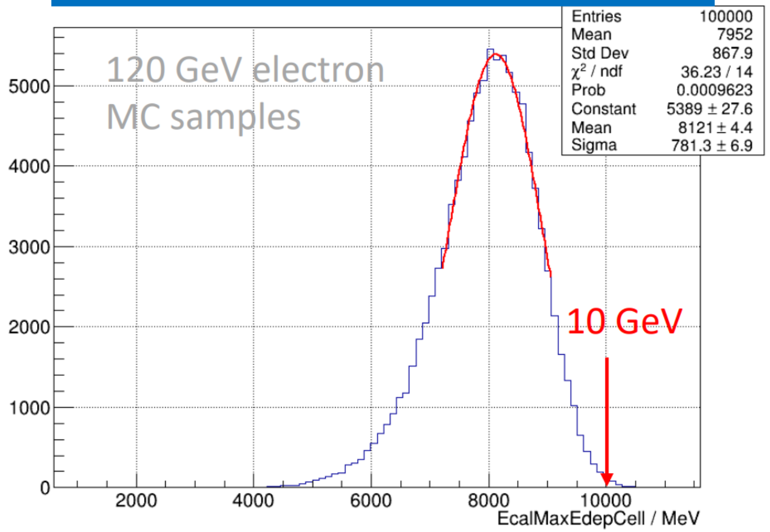
The 2022 International Workshop on the High Energy Circular Electron Positron Collider

Motivation

Baohua Qi (IHEP)



Maximum energy deposition within a bar



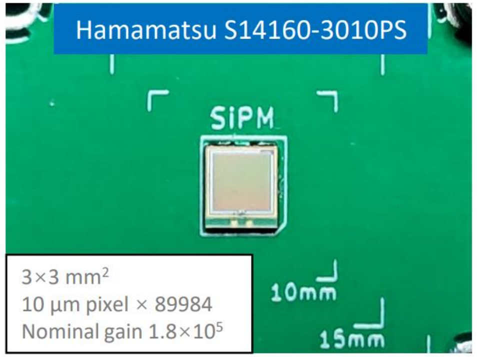
- Highly granular crystal electromagnetic calorimeter for CEPC:
  - EM energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Fine segmentation: PFA capability for jets (3~4% resolution)
- Dynamic range requirement:
  - Maximum energy deposition (from Bhabha electrons): ~10GeV → 50000 photons(1 side)
  - Low energy detection: ~1MeV → 5 photons(1 side)
- To cover the range form 5 to 50000 photons, SiPMs with large dynamic range are needed.

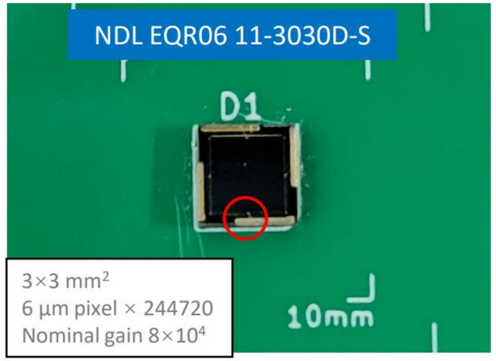
Outline

- Measurement
  - SiPMs
  - Setup
  - Linear region selection
  - PMT gain calibration
  - Final results
- Simulation
  - Without recovery
  - With recovery

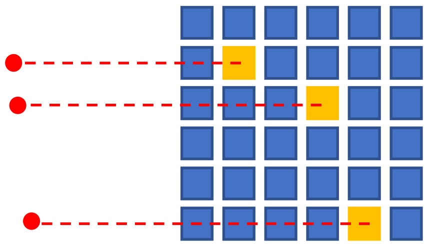
SiPM Types and Response

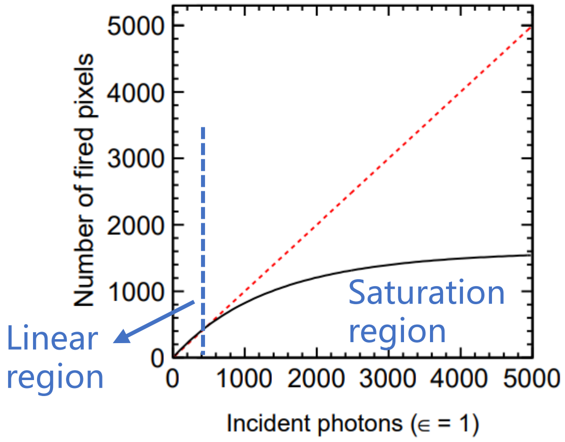
- Some large dynamic range SiPMs

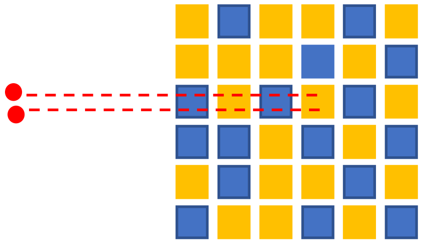




- Linear region and saturation region



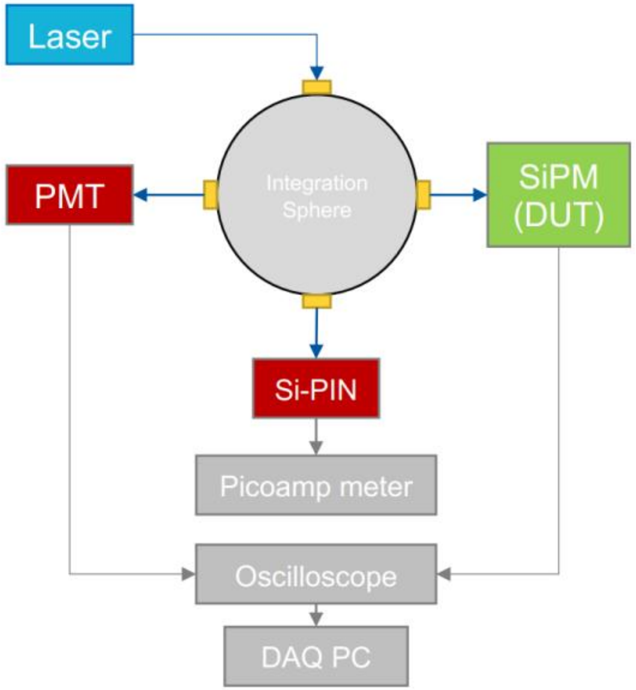


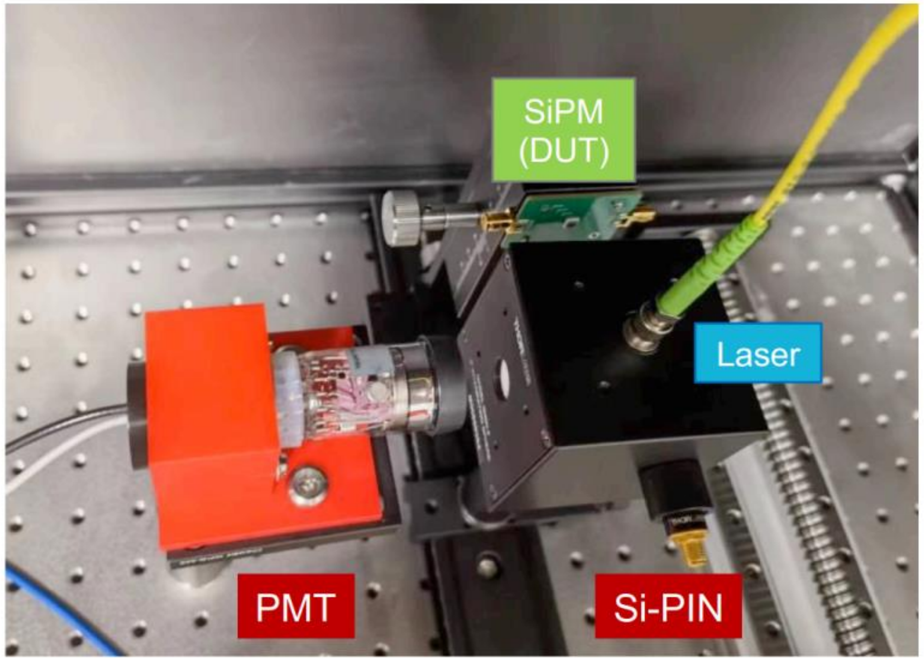


[1] 1510.01102.pdf (arxiv.org)

Dynamic Range Test Experiment: Setup I

- Pico-second laser: ~40ps pulse width
- Integration sphere: uniform distribution of light intensity
- PMT, Si-PIN: reference photosensors





Linear region selection at different bias voltage

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PMT gain calibration

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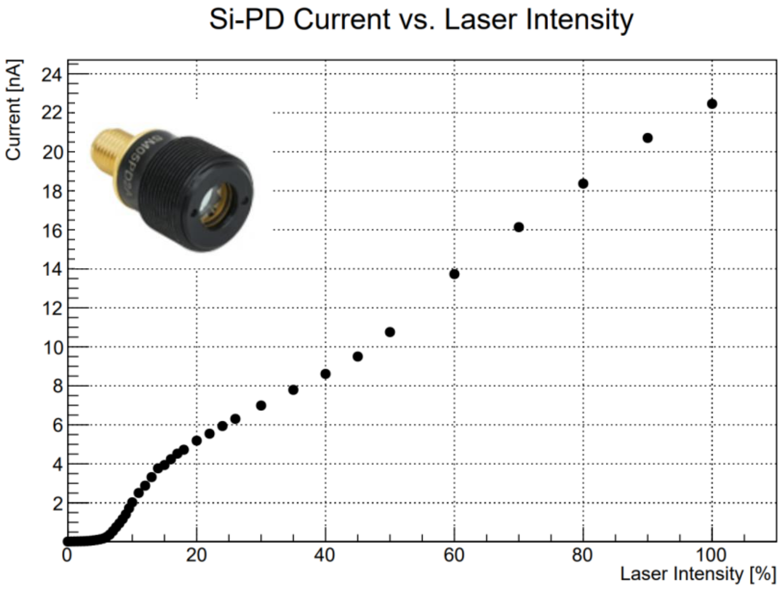
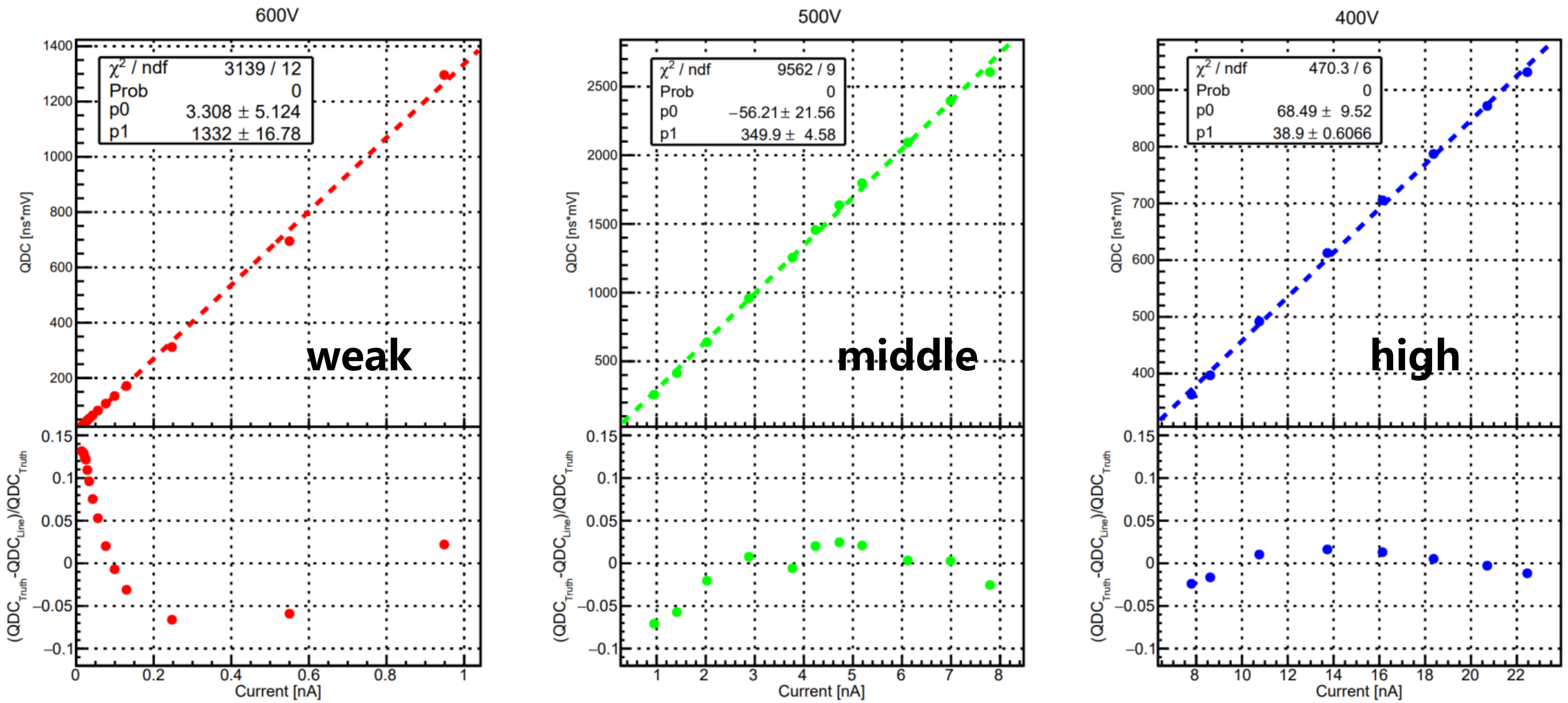
PMT QDC calibration

↓

Response of SiPM with PMT readout

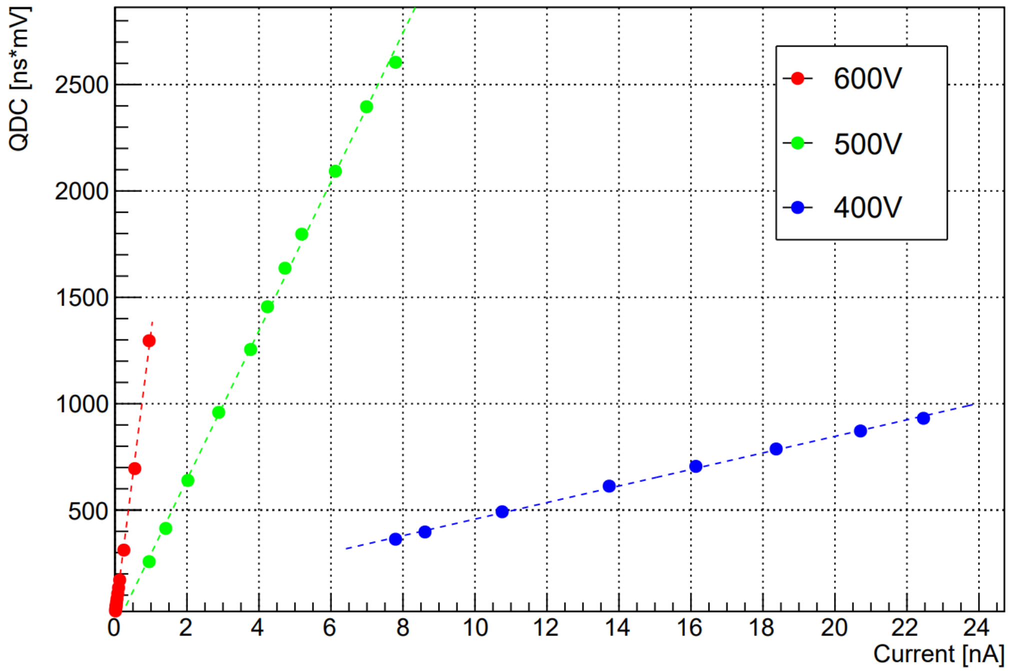
Linear Region Selection for PMT

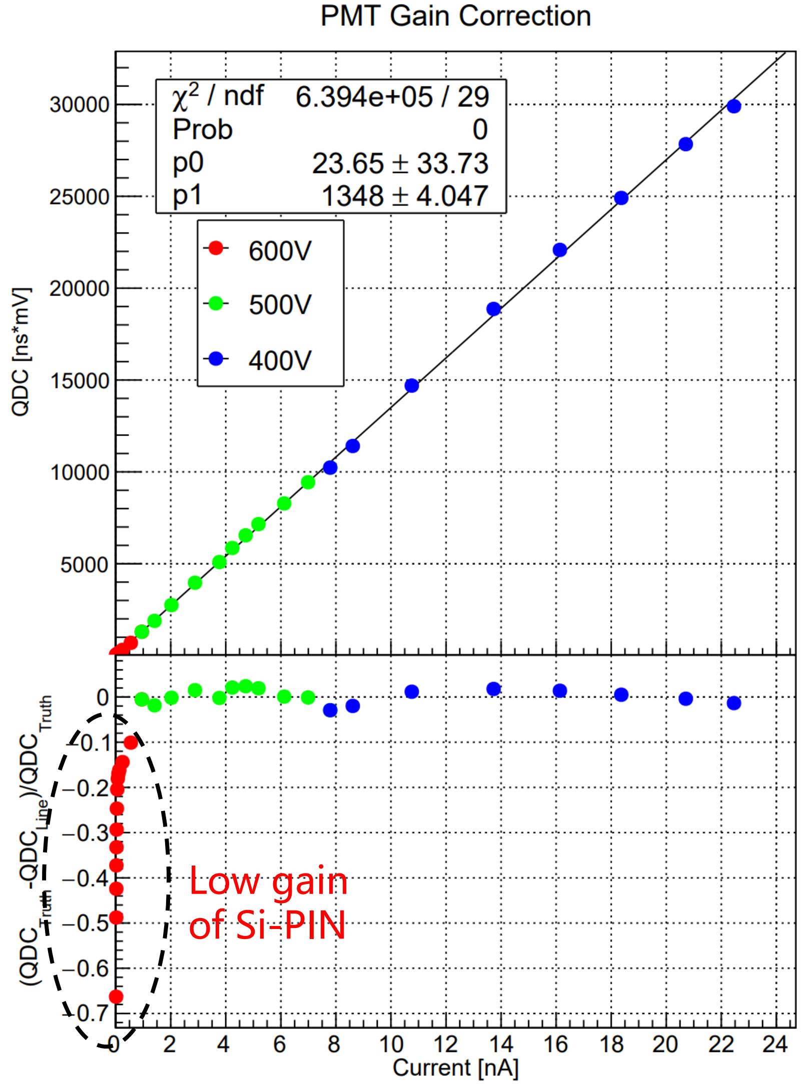




- Si-PIN: A reference device for nonlinearity of laser output.
- The linear region of PMT gets wider as its bias voltage decreases, while we should also make sure that the gain of PMT is big enough to detect light in weak intensity region.

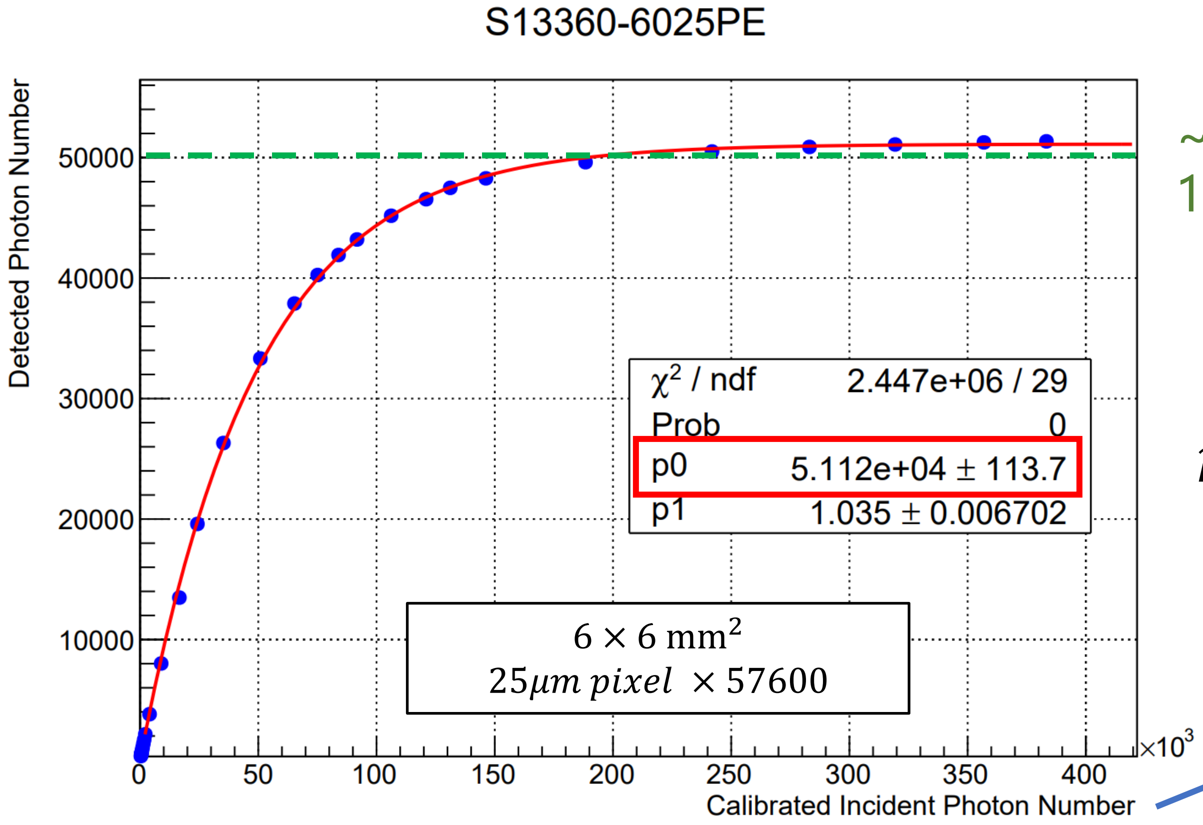
PMT Gain Calibration





- The slopes represent gains at different voltages. Make the slope of 500V and 400V lines the same as the 600V line. And different lines are connected end to end.

Response of S13360-6025PE



~50000 photons for 10GeV deposition energy

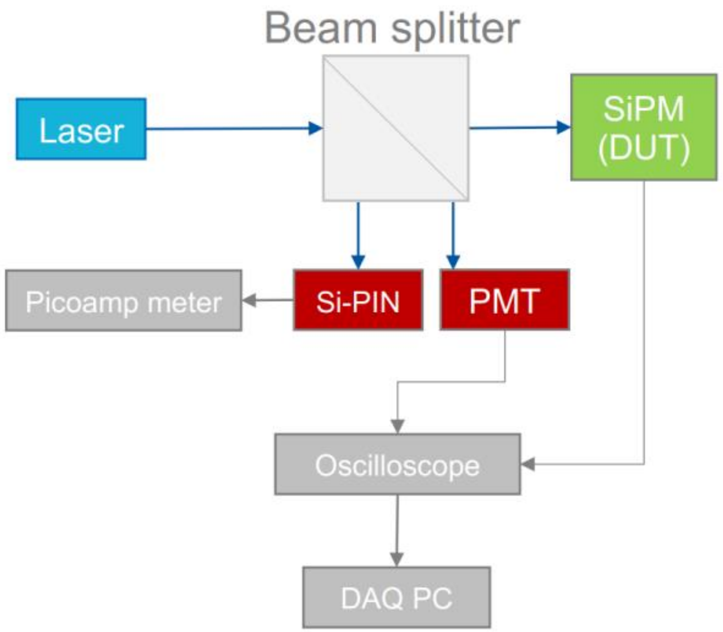
$$p_0 * \left(1 - e^{\frac{-p_1 * x}{p_0}}\right)$$

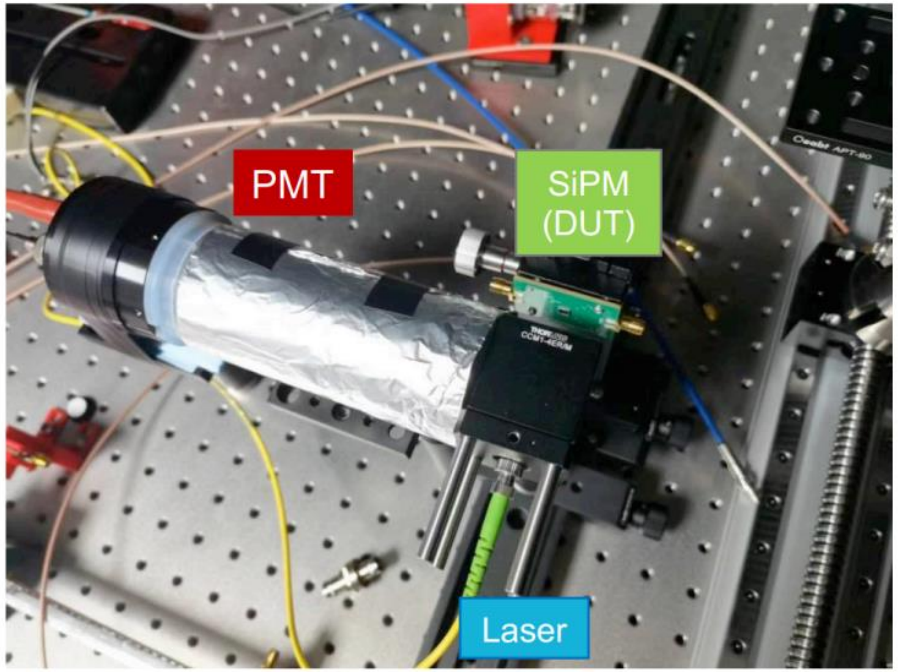
Fired pixel number without considering saturation

- X axis: PMT signal. The photon number was calibrated by SiPM with the first few points.
- Y axis: SiPM signal.
- $p_0 < 57600$: Fluctuation of temperature, stability of laser intensity over time, limitation from readout electronics

Dynamic Range Test Experiment: Setup II

- For SiPMs with larger pixel number
  - Pico-second laser: ~40ps pulse width
  - Beam splitter: achieve much higher light intensity
  - PMT, Si-PIN: reference photosensors





Linear region selection at different bias voltage

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PMT gain calibration

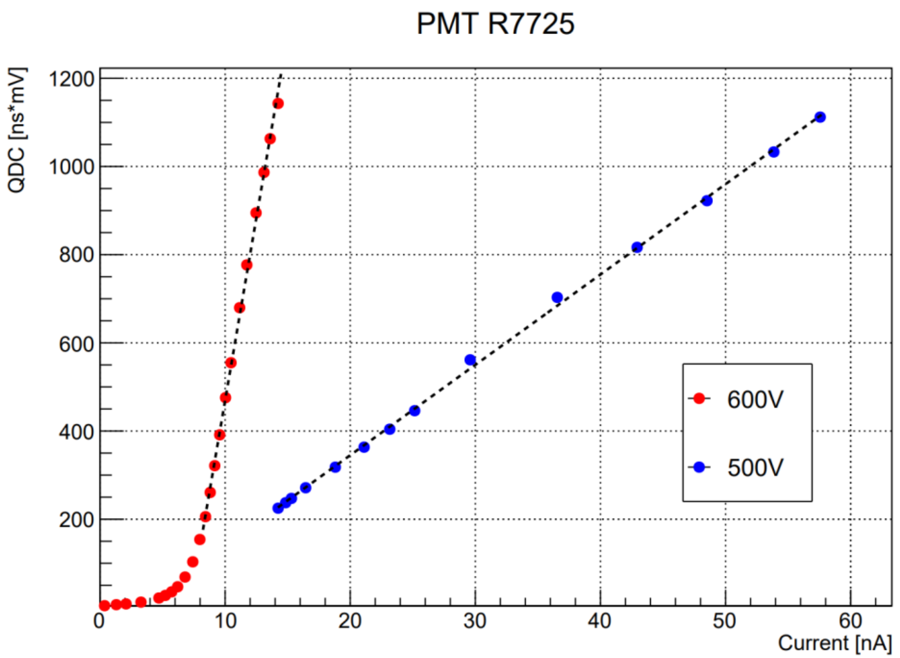
↓

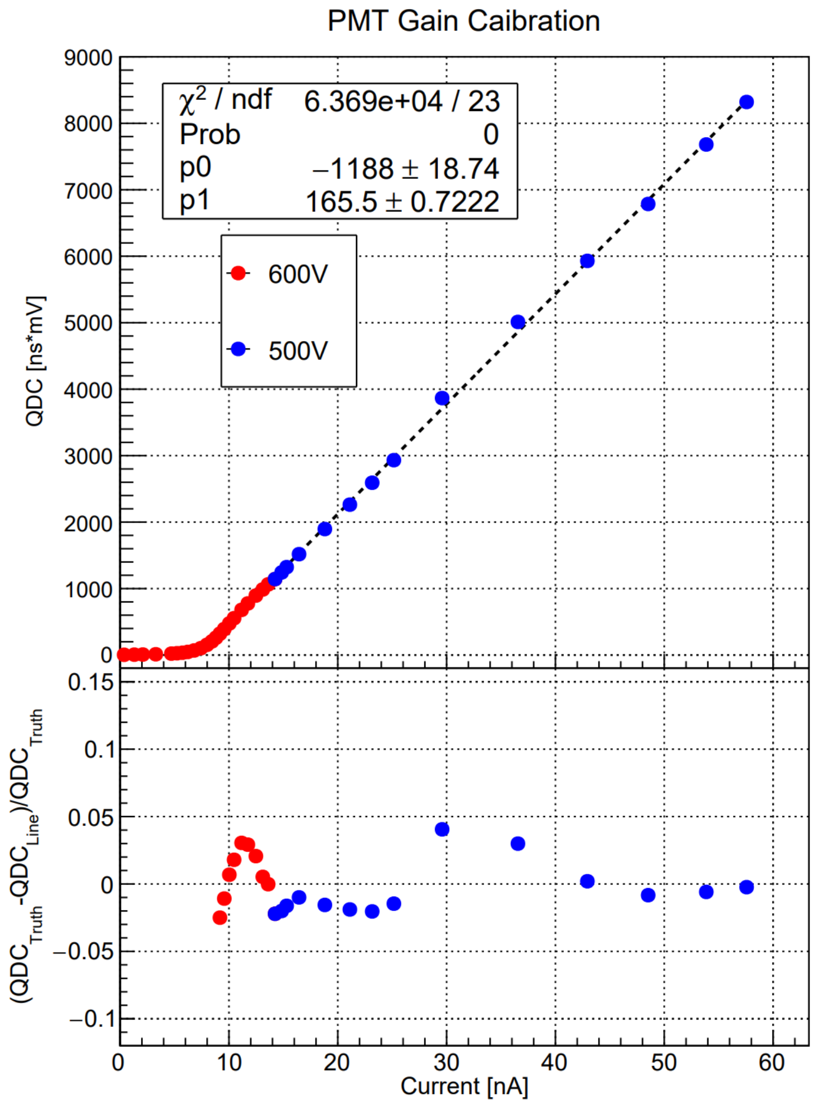
PMT QDC calibration

↓

Response of SiPM with PMT readout

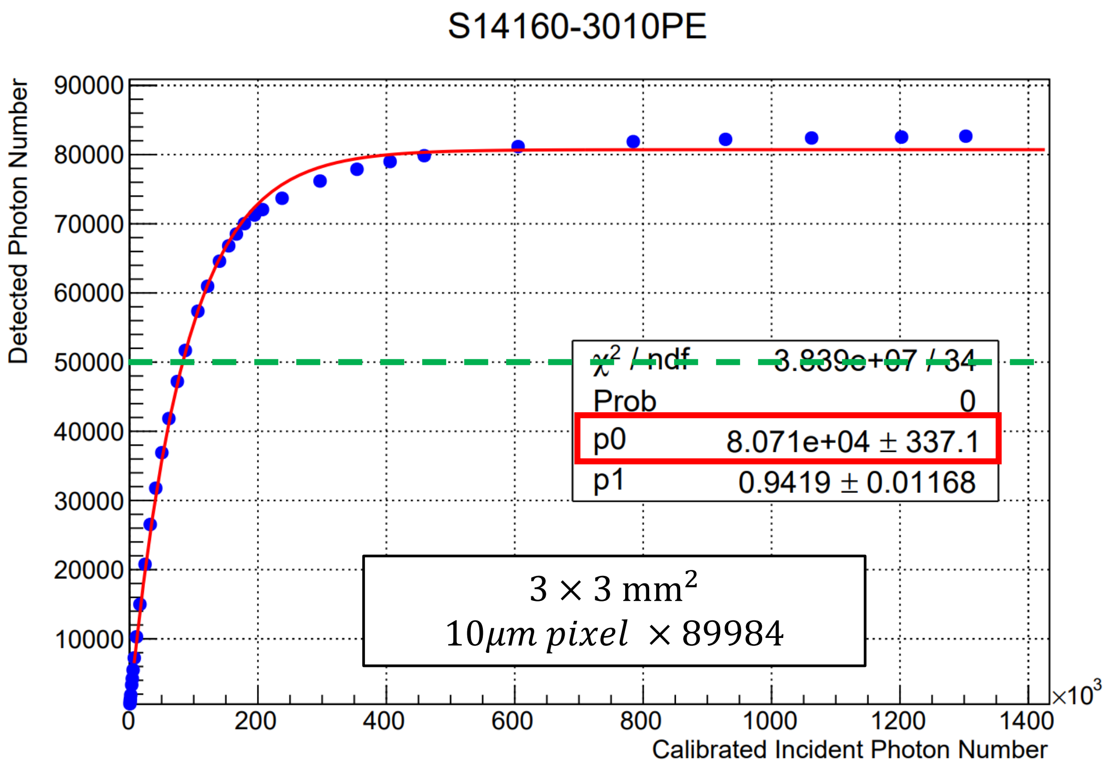
PMT Gain Calibration

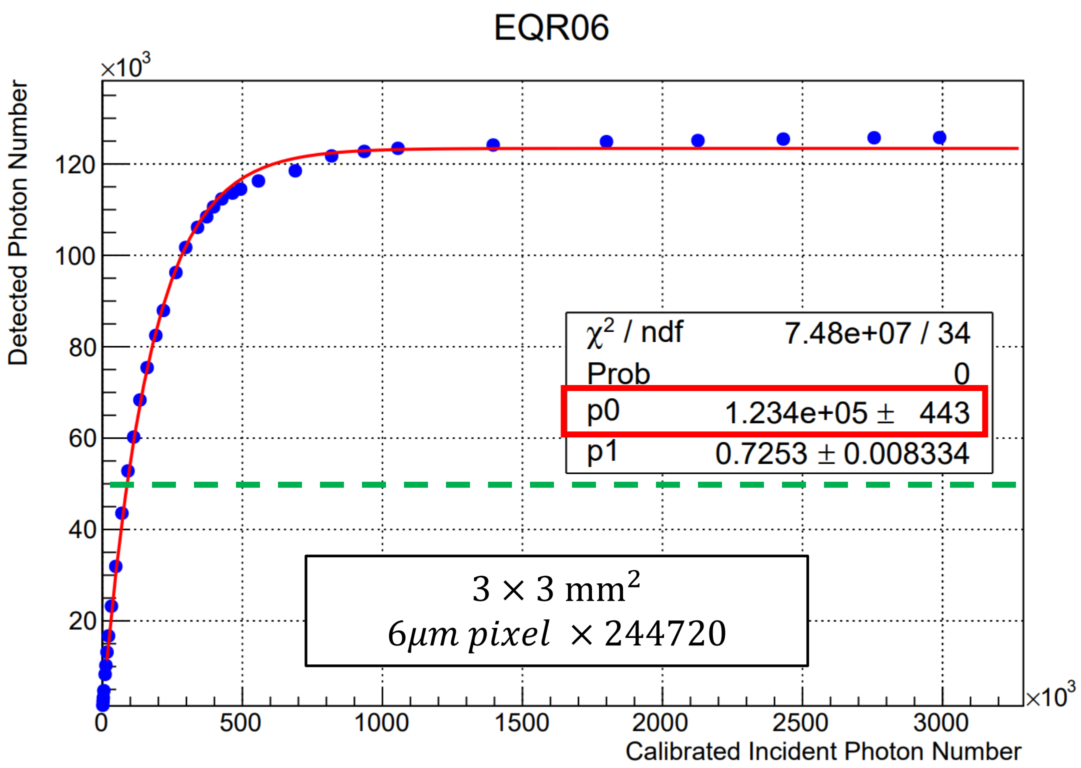




- Did not use the weak intensity region in calibration. Because the Si-PIN is not sensitive to weak light.

Response of S14160-3010PS and EQR06

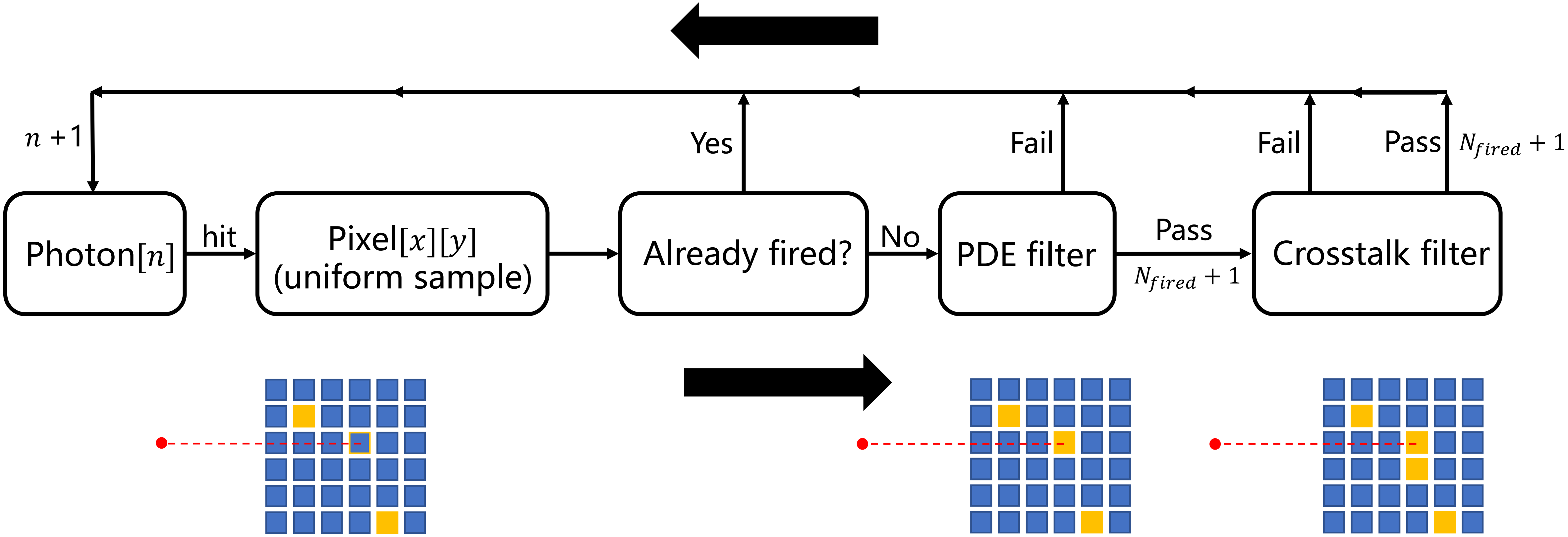




Outline

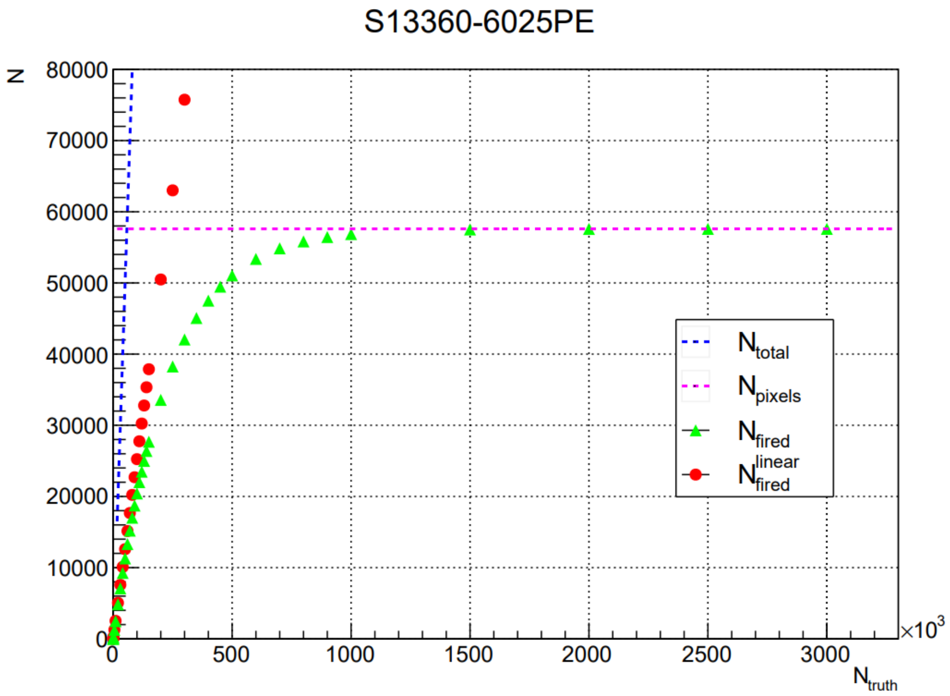
- Measurement
  - Measured SiPMs
  - Setup
  - Linear region selection
  - PMT gain calibration
  - Final results
- Simulation
  - Without recovery
  - With recovery

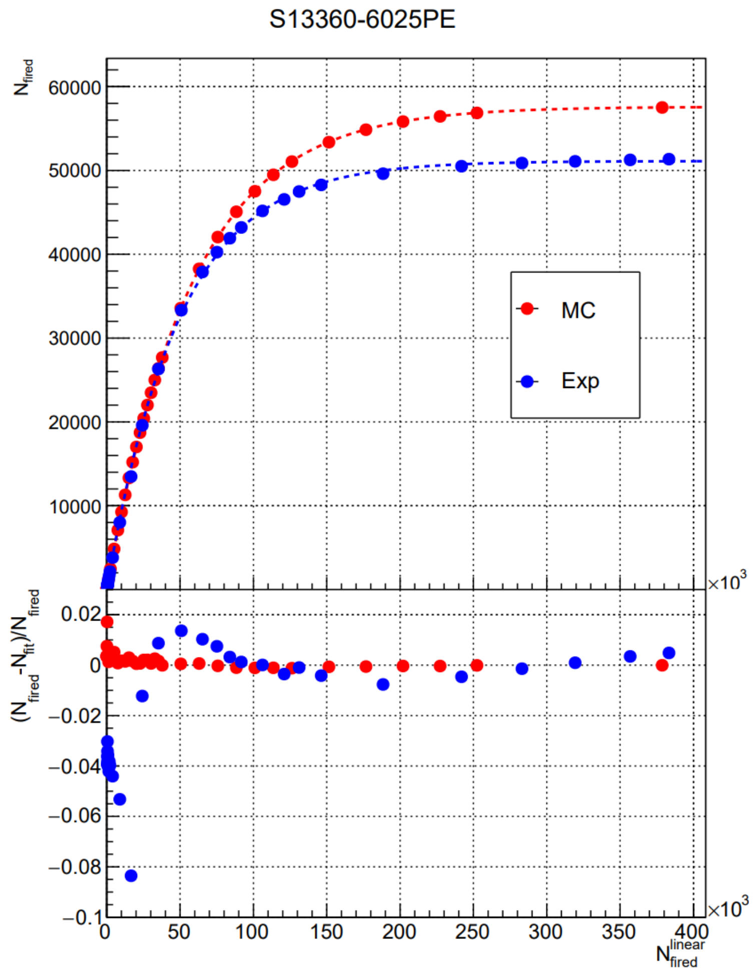
Simulation Workflow



- PDE filter: the random number is smaller than PDE
- Crosstalk filter: random number smaller than crosstalk probability && at least one adjacent pixel is not in fired

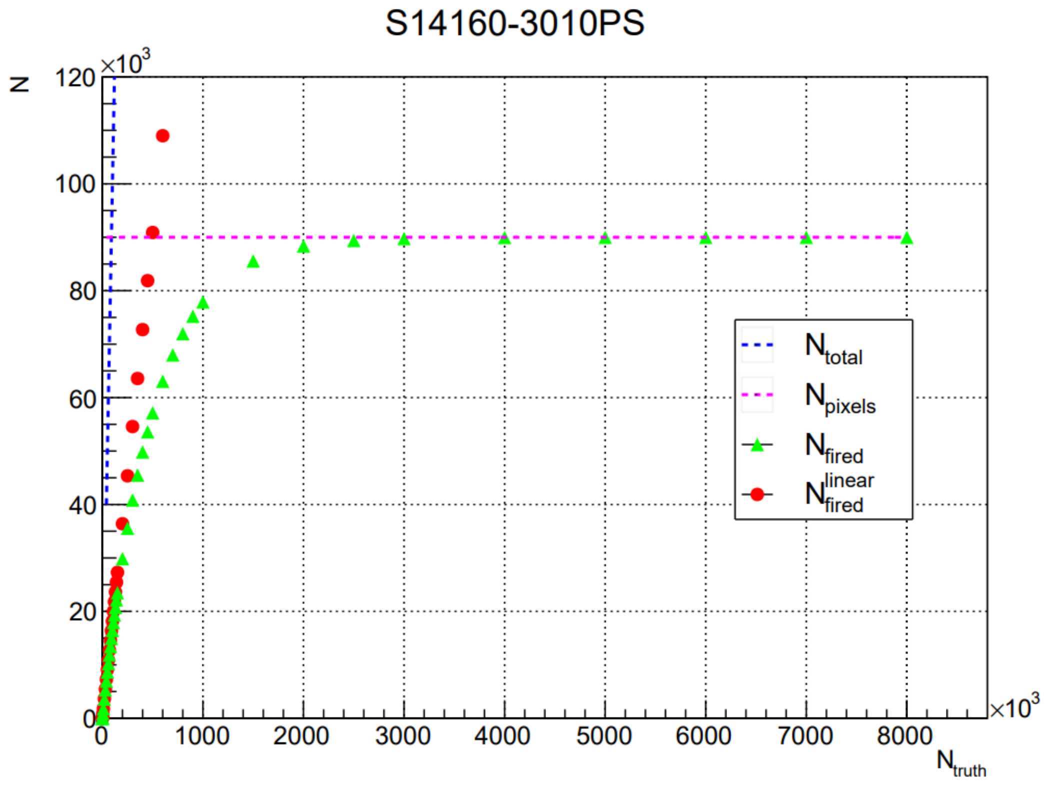
S13360-6025PE – Without Recovery

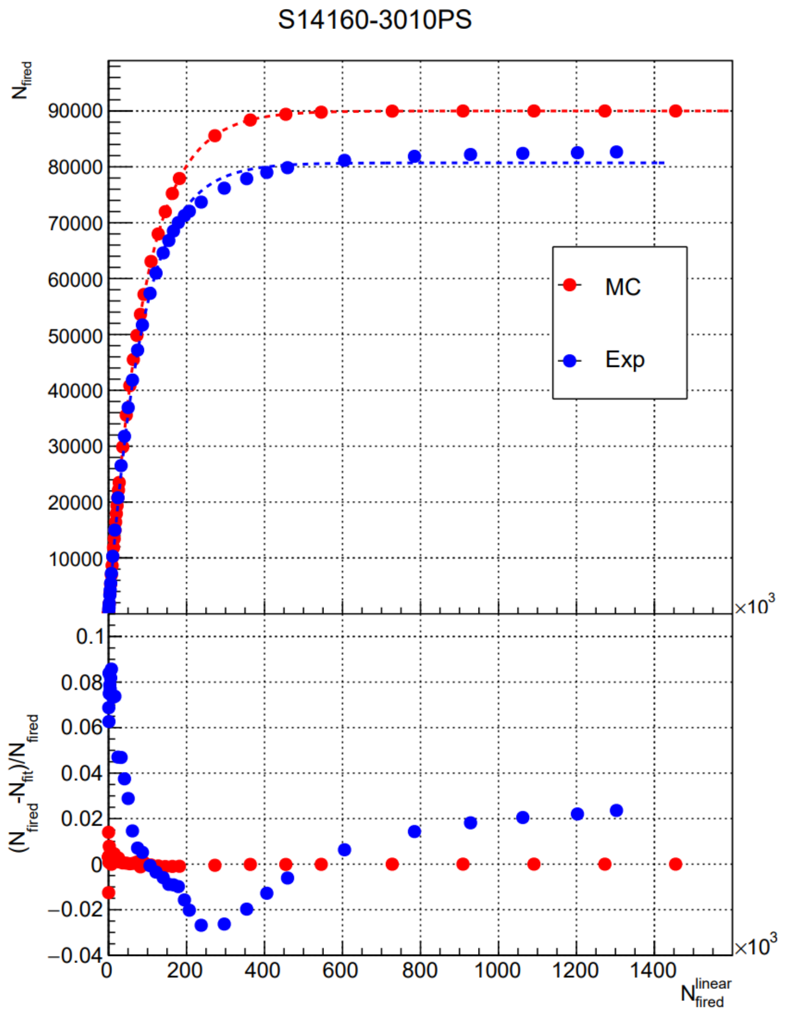




- S13360-6025PE: $6 \times 6mm^2$ sensor size, 57600 pixels, PDE=25%, Crosstalk=1%
- N_{total}: incident photon number
- N_{pixel}: pixel number
- N_{fired}: The number of pixels in which avalanche discharge occurred(consider saturation)
- N_{fired}^{linear}: The number of pixels in which avalanche discharge occurred(saturation is not considered)

S14160-3010PS – Without Recovery

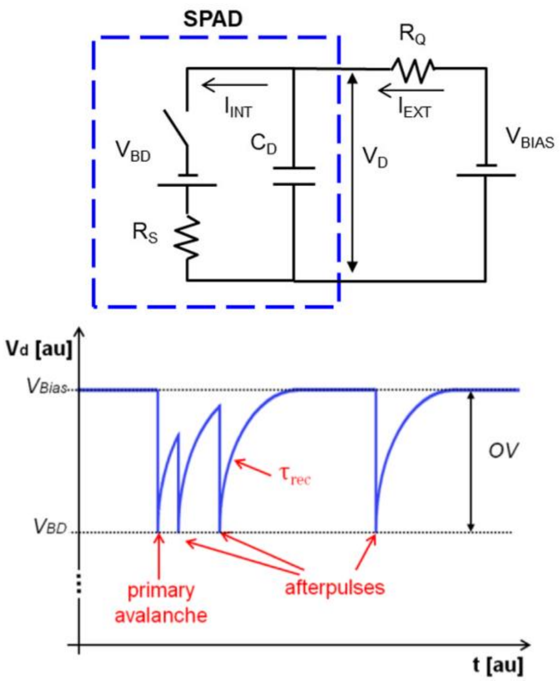




- S14160-3010PS: $3 \times 3mm^2$ sensor size, 89984 pixels

  PDE=18%, Crosstalk=1%

Microcell Electronical Model



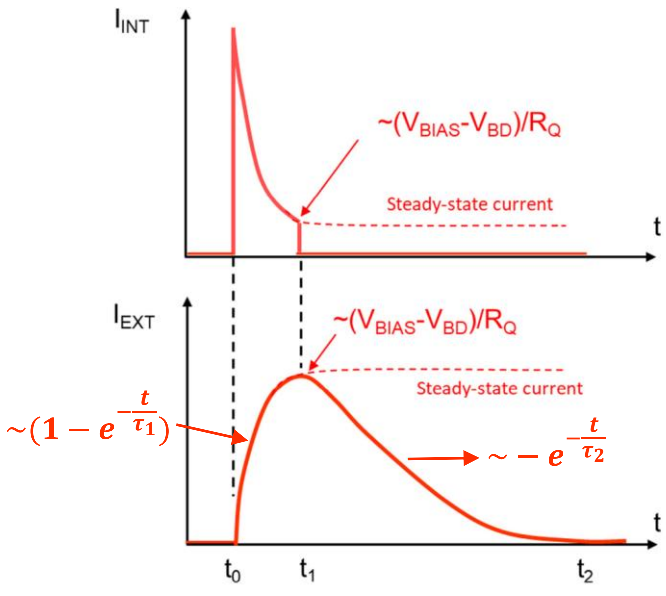
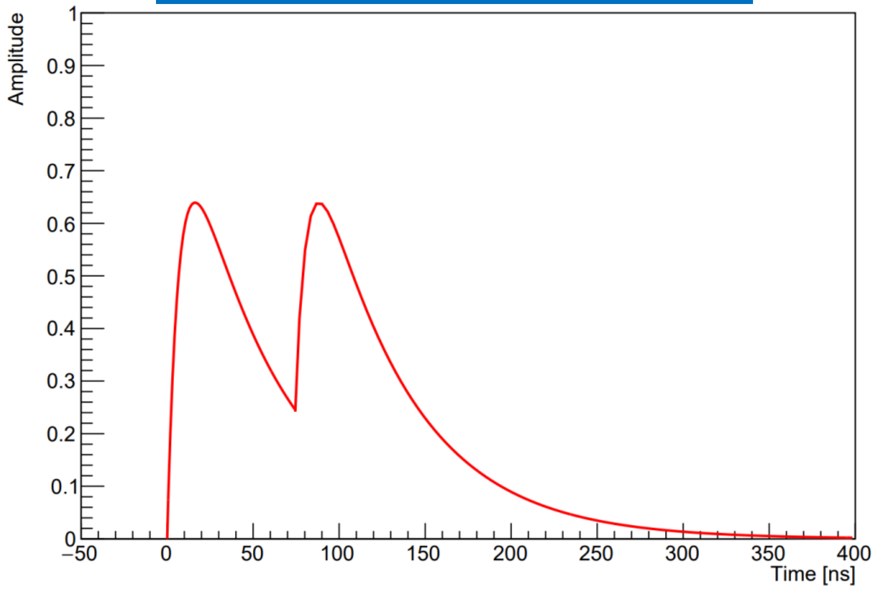


Fig. 2. Currents flowing during a discharge of the SPAD.

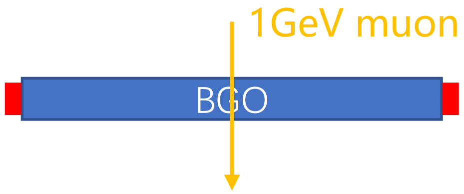
2 photons hit on 1 pixel

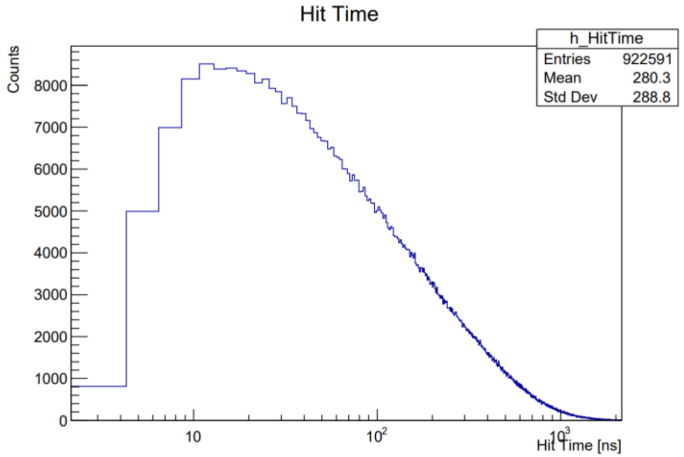


- When an avalanche occurs in a microcell, the junction capacitance (C_D) discharges and the voltage across the junction (V_d) drops back to V_{BD}(OV=0). Once the avalanche has been quenched, C_d will be recharged by the small current through R_Q.
- If an avalanche is being triggered in a non-completely recovered microcell, because the overvoltage is smaller than $(V_{Bias}-V_{BD})$, the magnitude of output signal will be smaller, so as the PDE.

[1] https://doi.org/10.1016/j.nima.2014.04.045 [2] https://doi.org/10.1016/j.nima.2018.11.119

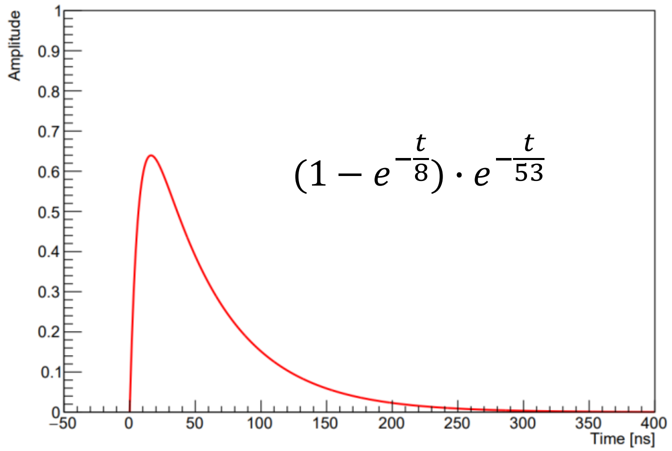
Time Properties

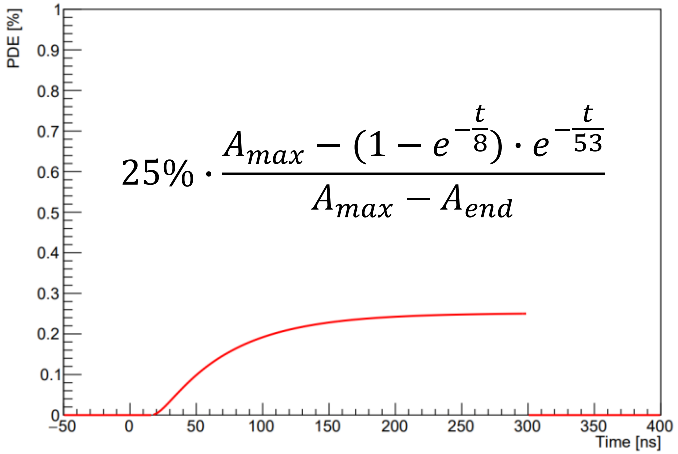




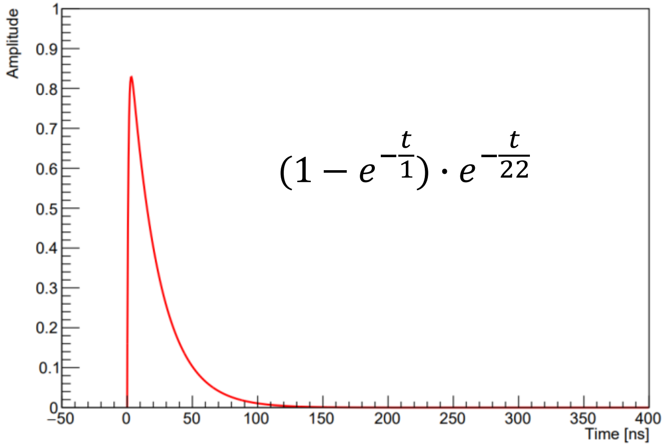
- $40 \times 1 \times 1 cm^3$ BGO, dual readout
- 1GeV muon, incident from the middle of the crystal

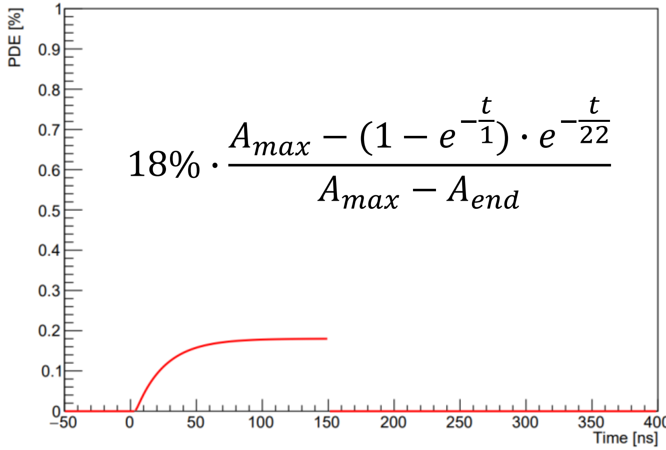
S13360-6025PE





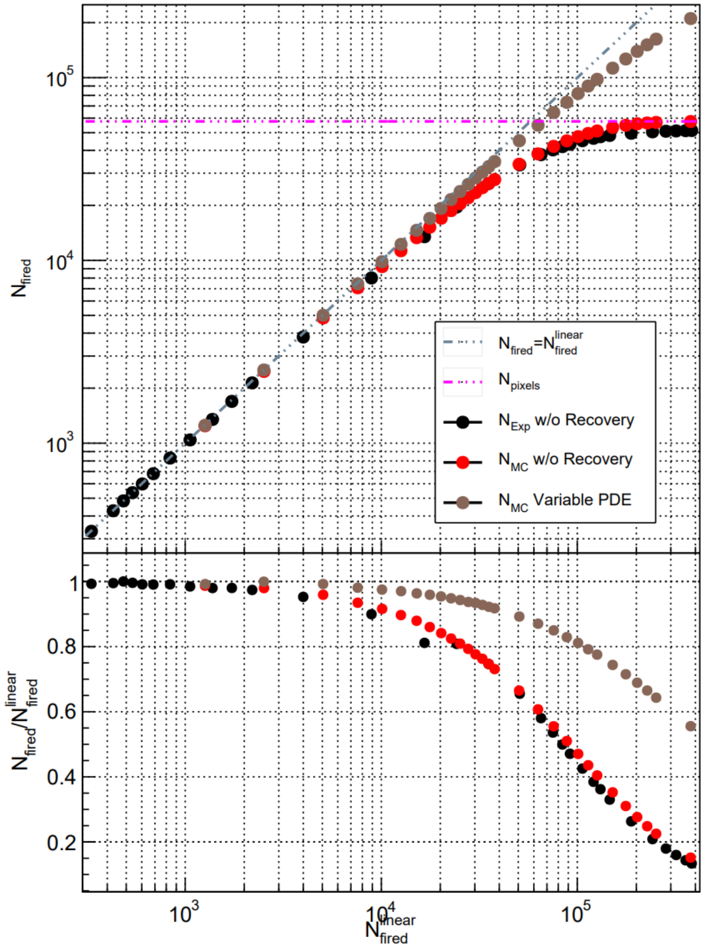
S14160-3010PS



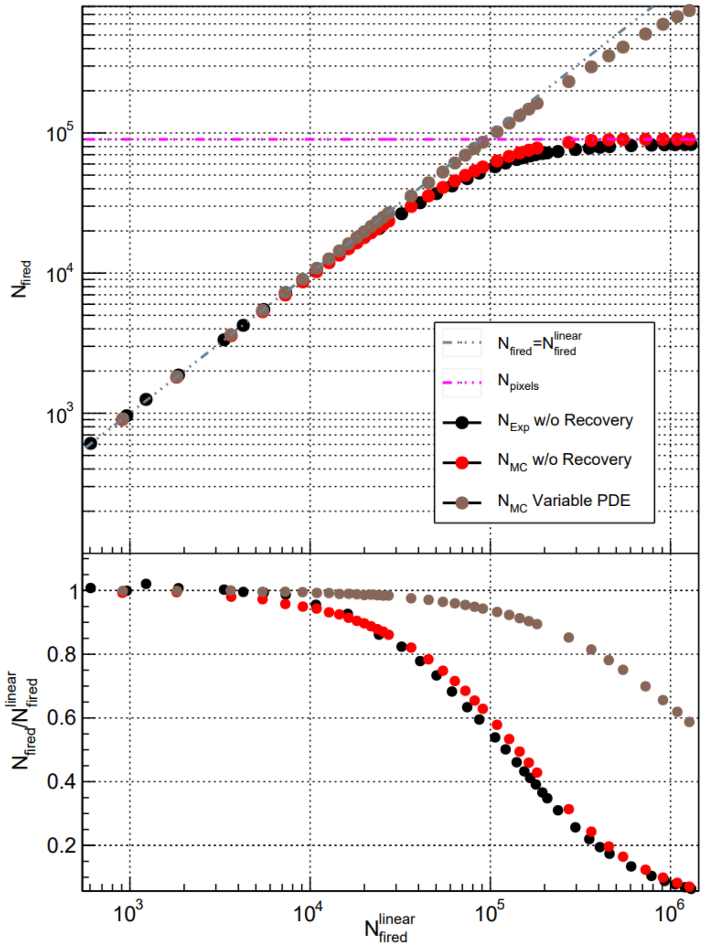


Final results – With Recovery

S13360-6025PE



S14160-3010PS



- N_{MC} Variable PDE: simulation result with recovery, pixels can be fired multiple times, the PDE of the target pixel at hit time depends on its current state
- Use UV LED that can excite the atom in crystal scintillator to make a experimental comparison.

Summary & Next

- Summary
  - Develop a method to measure the dynamic range of SiPM with large pixel number
  - Some factors that may deviate the results of the experiment from expectations:
    - Limitation of readout electronics
    - Temperature
    - Stability of devices over time
    - Laser intensity limit
    - Change bias voltage of PMT

- Next
  - Multi-dynodes-readout PMT, not to change bias voltage
  - SiPM electronics optimization
  - UV LED to excite scintillator