Study on the Dynamic Range of SiPMs with High Pixel Densities

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On behalf of CEPC Calorimeter Working Group

The 2025 International Workshop on the High Energy Circular Electron Positron Collider

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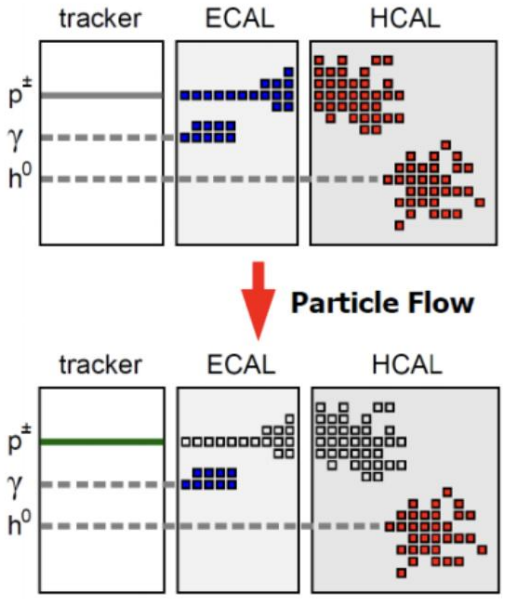
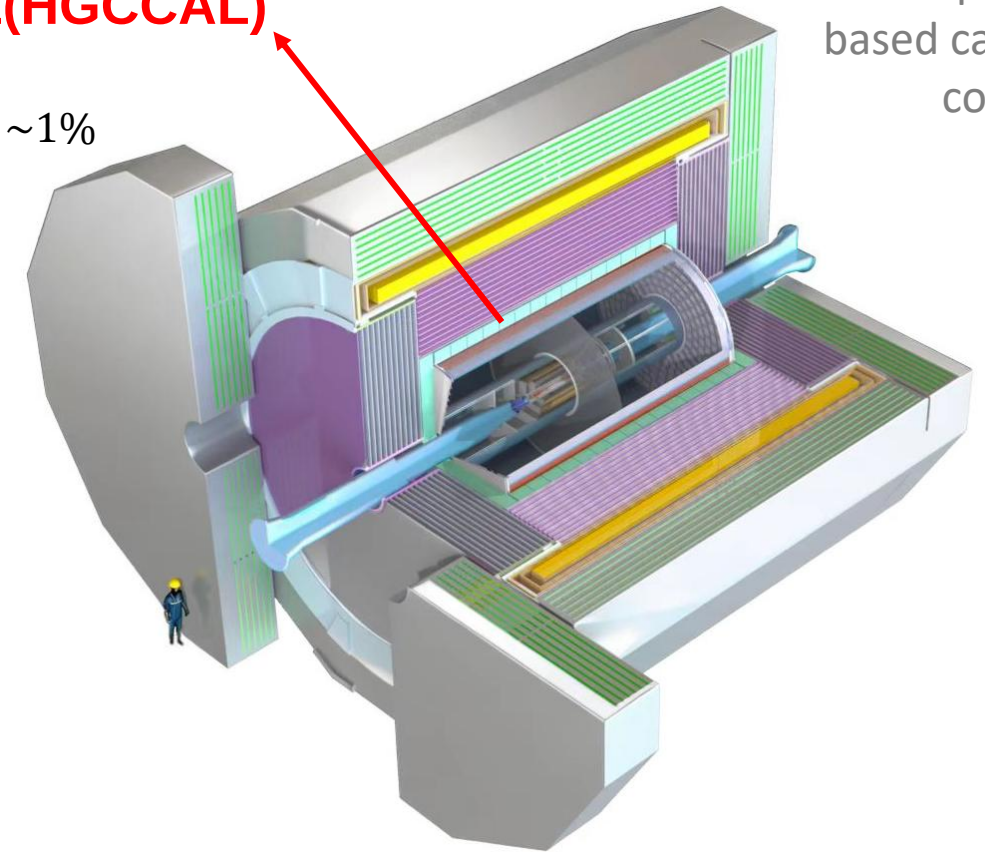
High Granularity Crystal ECAL for Future Lepton Collider

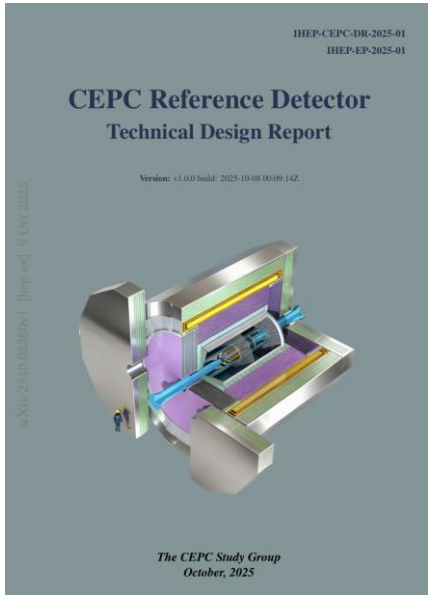
- **CEPC: future lepton collider**
  - Higgs/W/Z bosons, top, BSM searches, etc.
  - Requirement: Boson Mass Resolution(BMR) < 4%
  - Particle-Flow Algorithm oriented detector
- **High granularity crystal ECAL(HGCCAL)**
  - 3D spatial + energy + time
  - EM energy resolution: $< 3\%/\sqrt{E} \oplus \sim 1\%$
  - Precisie γ/π^0 reconstruction





Work Package 3 - Optical Calorimeter

develop new concepts of scintillator-based calorimeters with full shower-containment prototypes



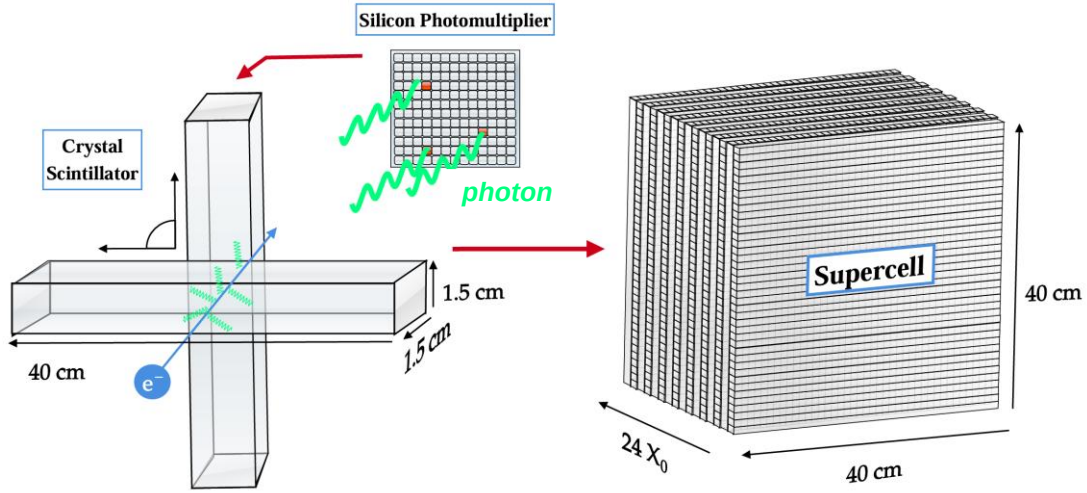
CEPC Ref-Detector TDR

Dynamic Range Specification of Crystal ECAL

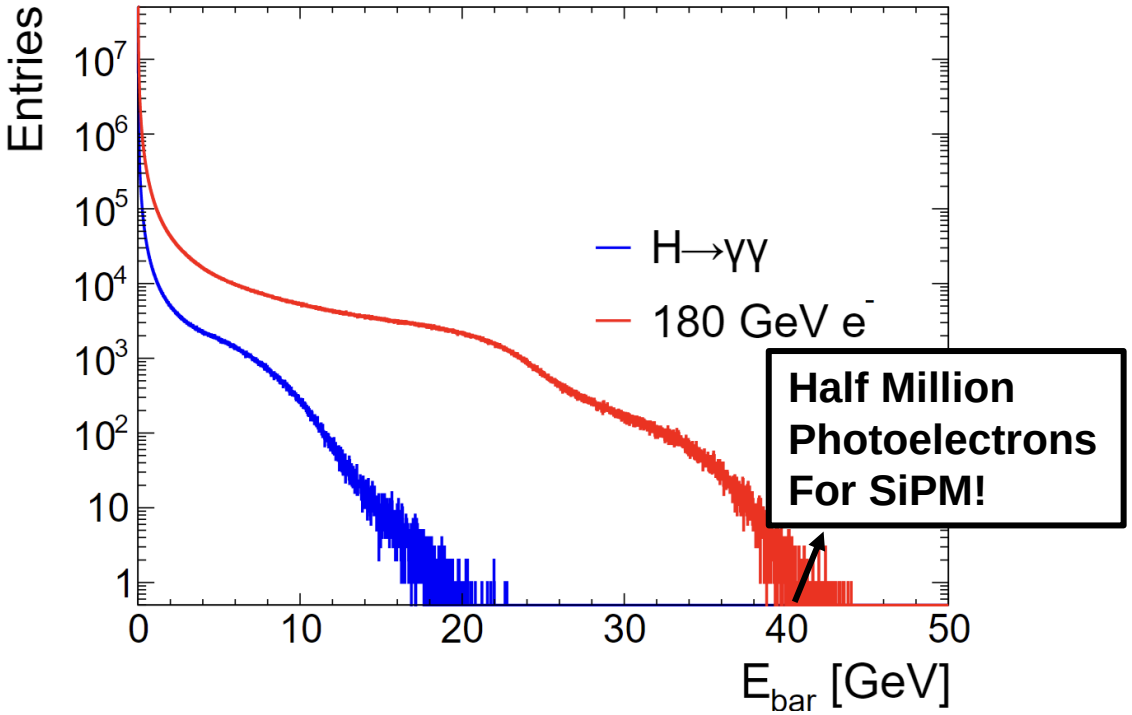
- SiPM dynamic range requirement: up to $\mathbf{5 \times 10^5}$ $\boldsymbol{p.e.}$ **(with BGO scintillation)**
  - **How to determine and correct SiPM nonlinearity?**
  - Challenge the design of the readout electronics

Table 7.1: Specifications for crystals and their properties

Parameters	Value	Remarks
MIP response	300 p.e/MIP	For EM energy resolution < 3 %
Energy Threshold	0.1 MIP	To balance EM resolution and SiPM noise suppression
Crystal response uniformity	< 1%	For consistent responses in crystals
Dynamic Range	0.1 MIP to 3000 MIP	The range of the maximum and minimum responses per unit
Time Resolution	0.5 ns	For MIP signals
Temperature Gradient	≤ 6 K	For crystal response uniformity and SiPM noise control

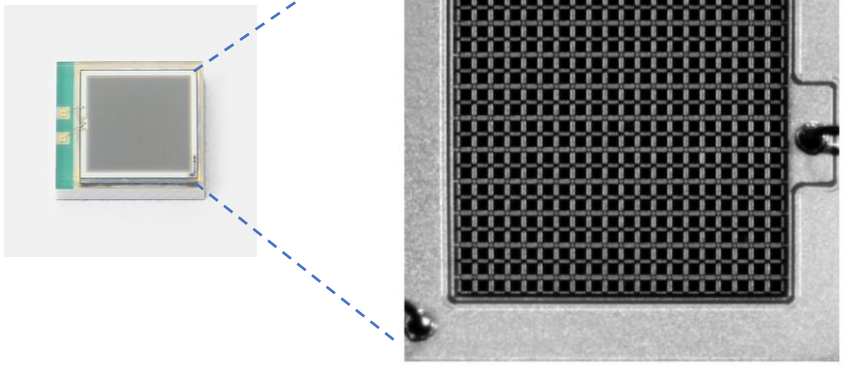


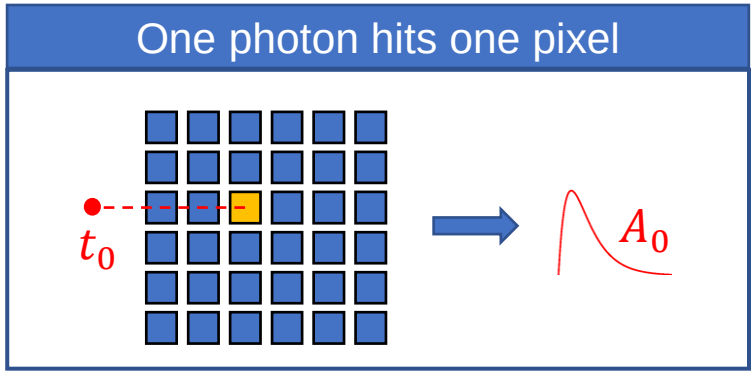
Energy deposition in single crystal (full ECAL simulation)

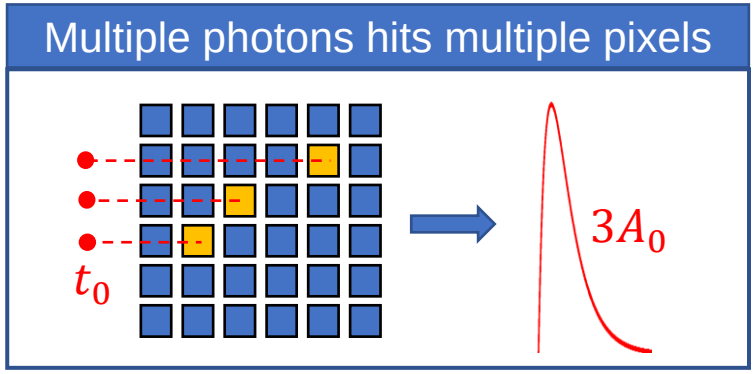


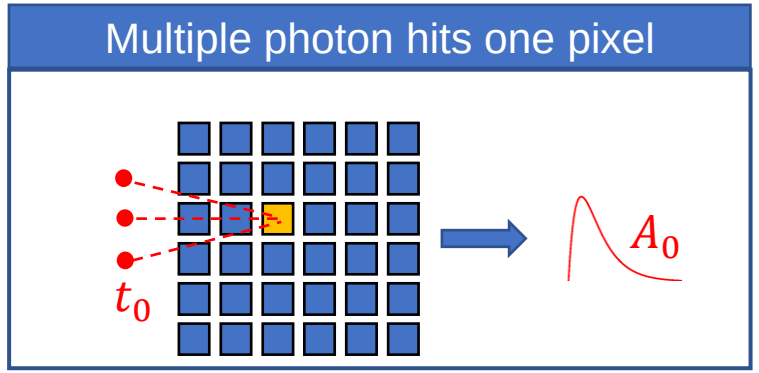
SiPM Response Principle: Simultaneous Illumination

- SiPM is an array of pixels operating in Geiger mode, and intrinsically a nonlinear device
- In the scenario of **"simultaneous illumination": detected photoelectrons ≤ total #pixels**
  - No pixel recovery effect, as in the ultrafast laser case







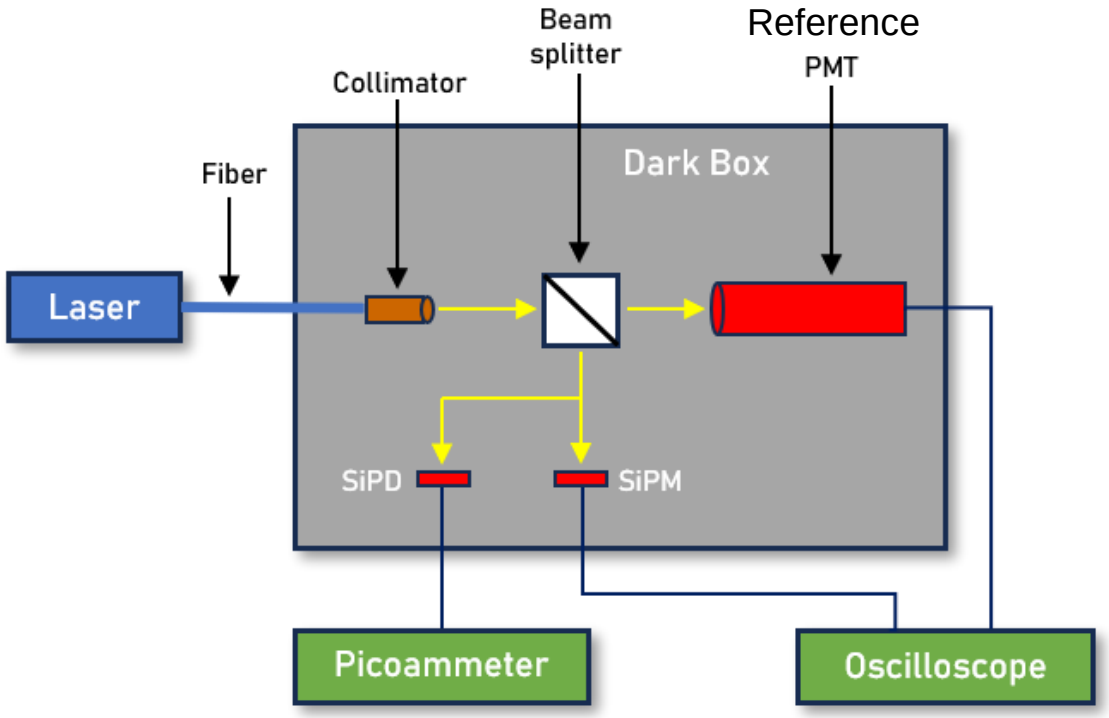


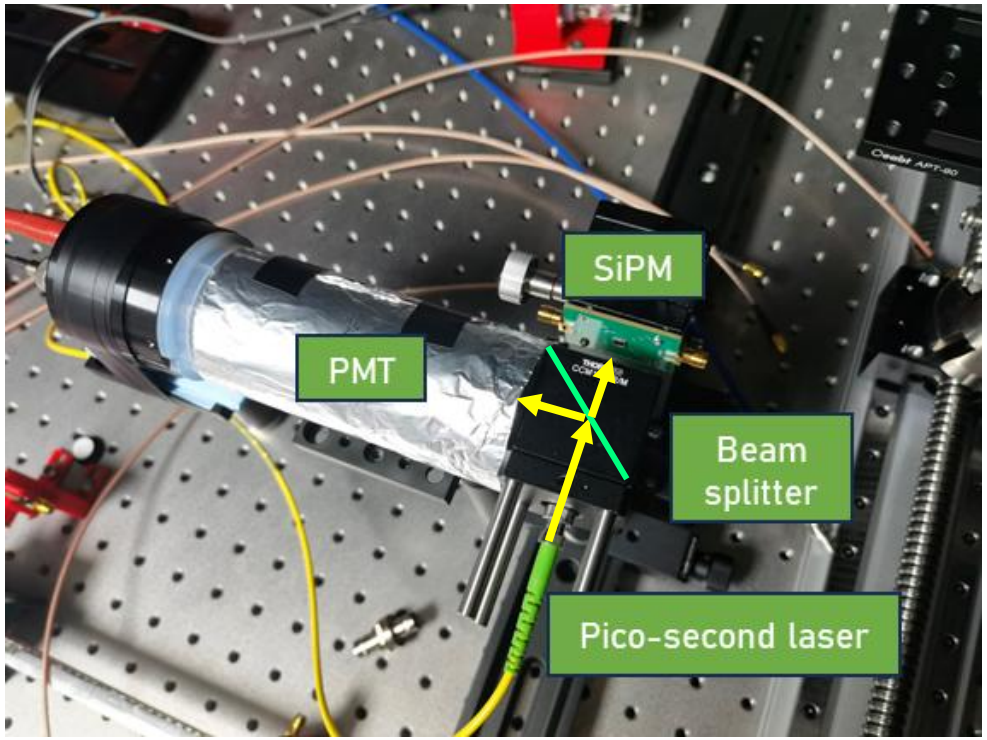
Pixel is not ready to recover, no extra amplitude

SiPM Nonlinearity Measurement with Pico-second Laser

- Laser pulse is shorter than 40 ps, simultaneous illumination for SiPM
- PMT used as a reference to monitor pulse-to-pulse intensity variation
- PMT remains linear in response when operated at sufficiently low bias voltage

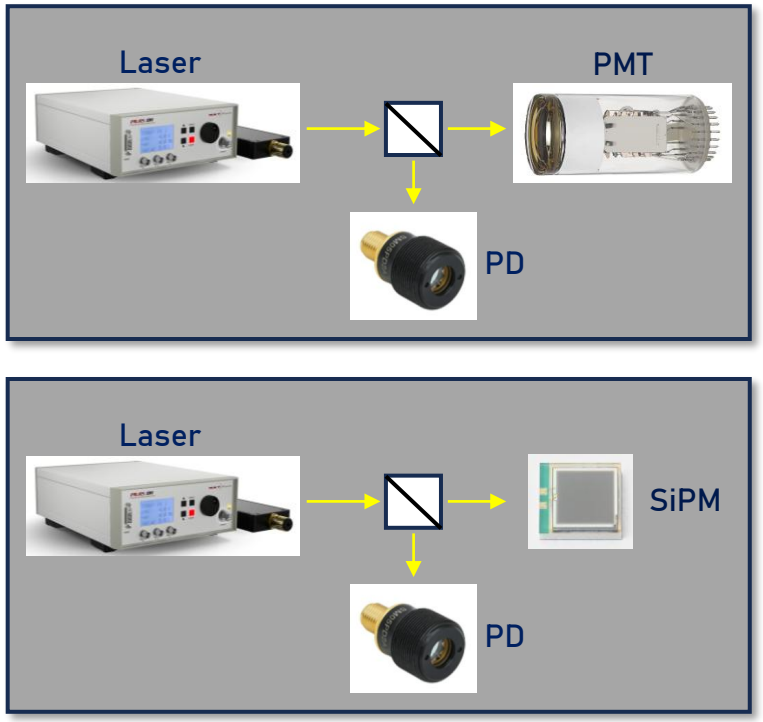
Dynamic Range of SiPMs with High Pixel Densities

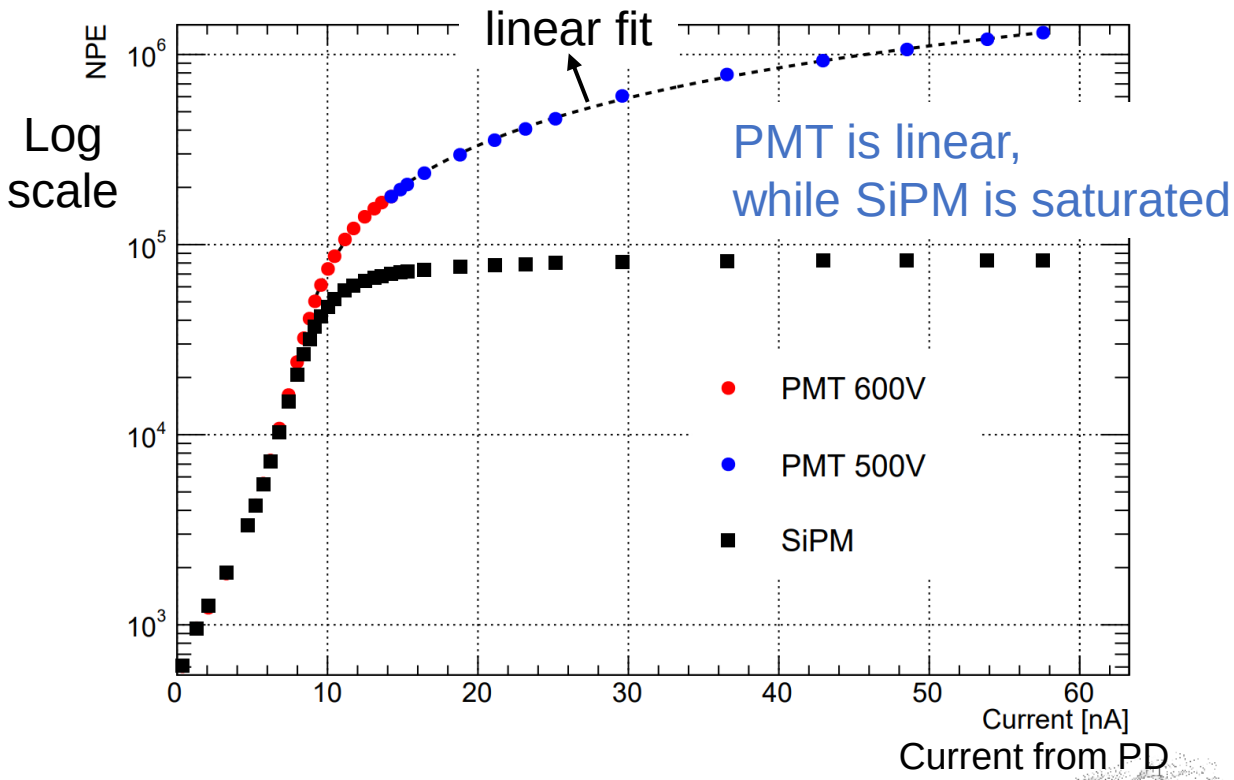




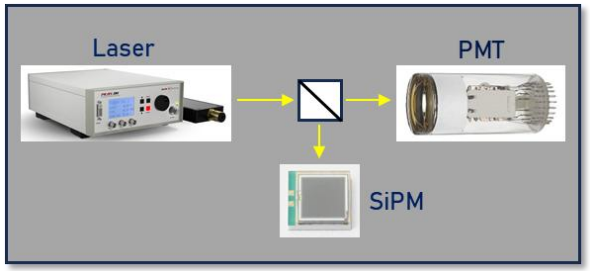
Linearity Test with Photodiode

- Adjust PMT bias voltage to balance linearity and precision
  - 500V bias for large-signal runs; 600V bias for small-signal runs to increase sensitivity
  - **PMT response remains sufficiently linear**





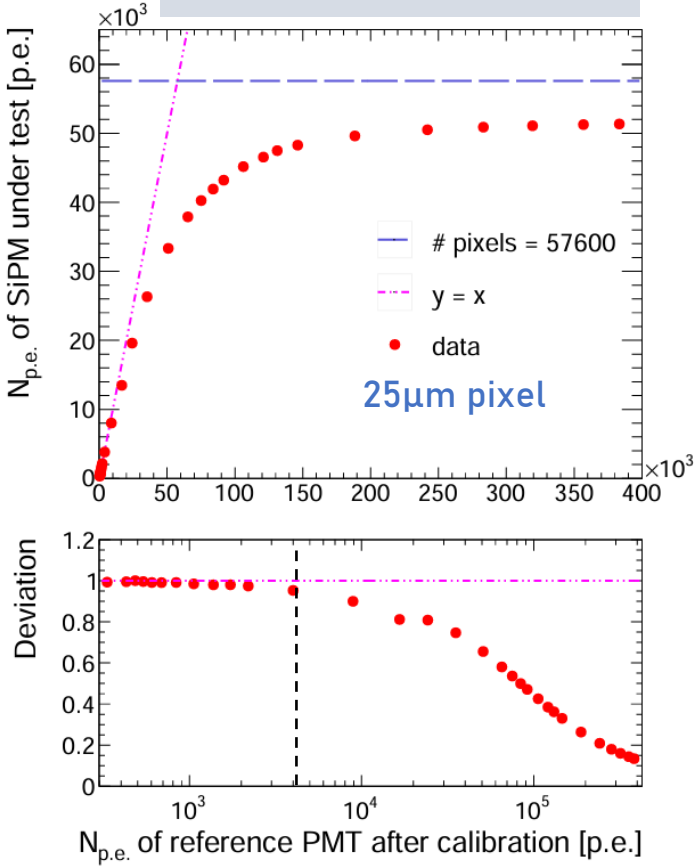
SiPM Response Under Pico-second Laser



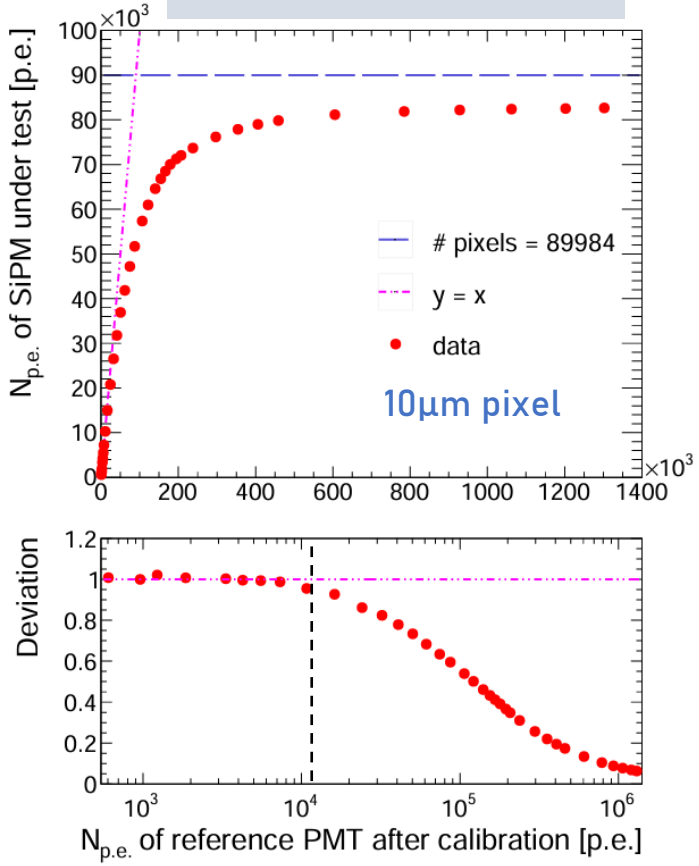
SiPM	Number of pixels	Max. p.e. measured	5% deviation
HPK S13360-6025PE	57600	51347	4246
HPK S14160-3010PS	89984	82664	11750
NDL EQR06 11-3030D-S	244719	125775	2433

~10% of total #pixels

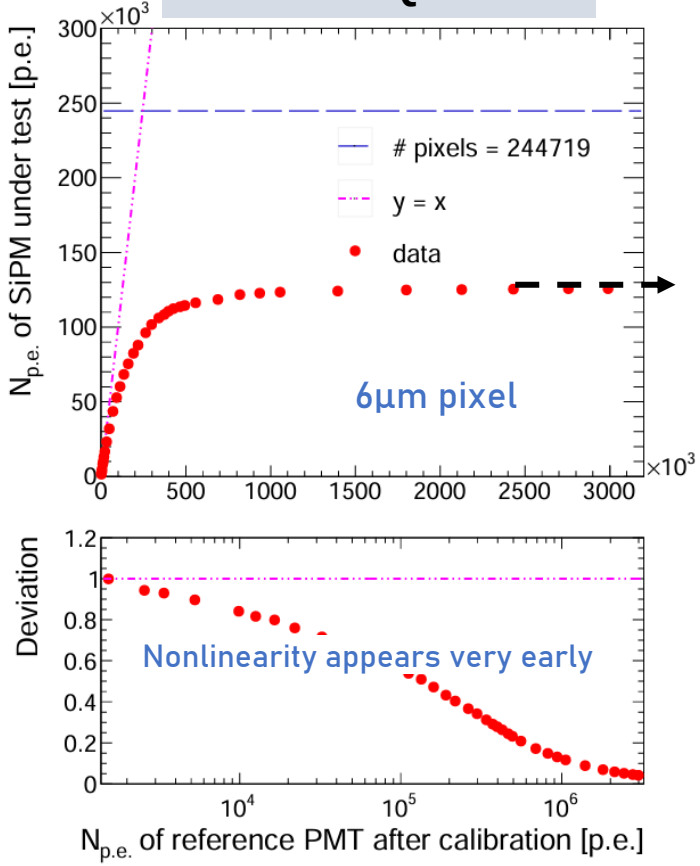
HPK S13360-6025PE



HPK S14160-3010PS



NDL EQR06

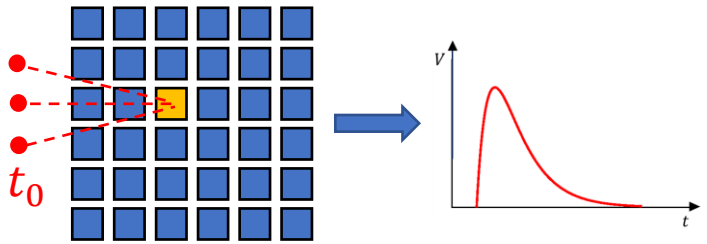


Only half of #pixels, need further study

SiPM Response: Laser vs. Scintillator

- During slow scintillation time, SiPM pixels can be fired multiple times due to **pixel recovery effect**
- How to measure and correct SiPM non-linearity behavior in scintillator case?

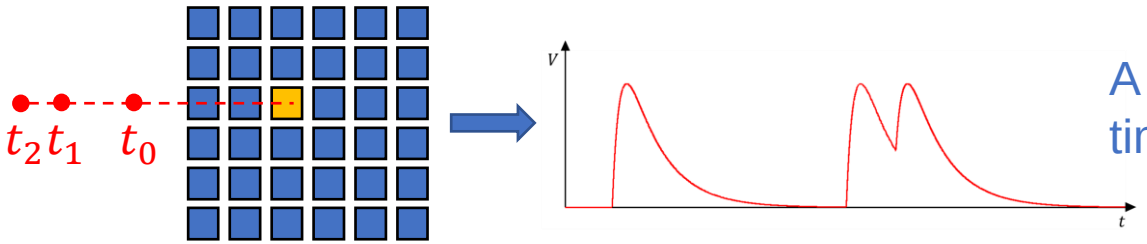
Laser case



Following a discharge, the pixel can't recover quickly enough to detect a subsequent photon

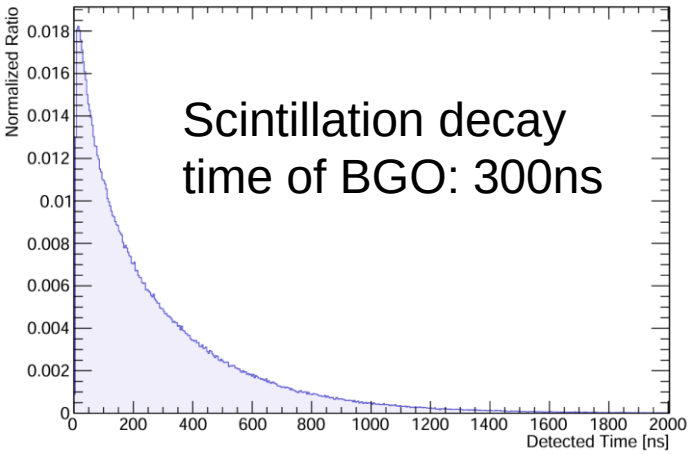
Scintillator case

✓ **Detector**



A pixel can be fired multiple times during scintillation

Detected time distribution (BGO, simulation)



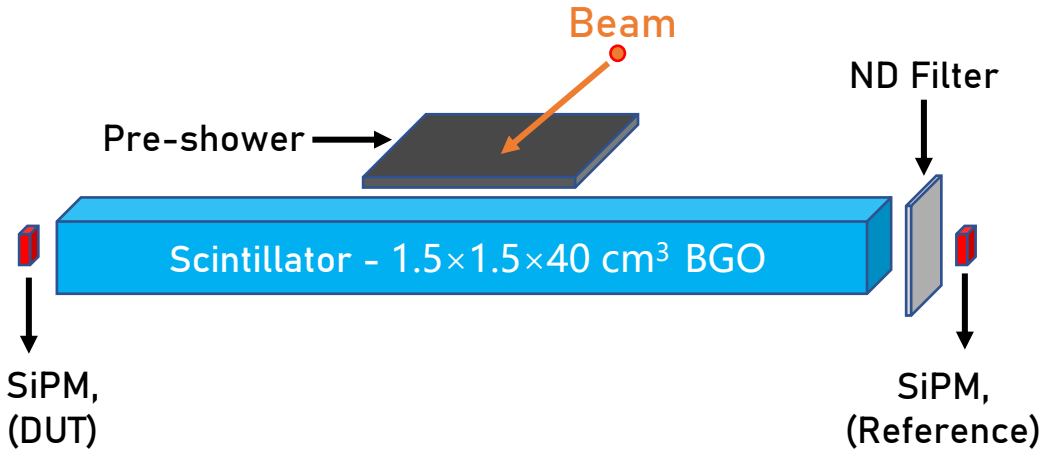
Scintillation decay time of BGO: 300ns

Design for Measuring the Nonlinearity of Crystal-SiPM Unit

Goal: measure the non-linearity in response of crystal-SiPM unit

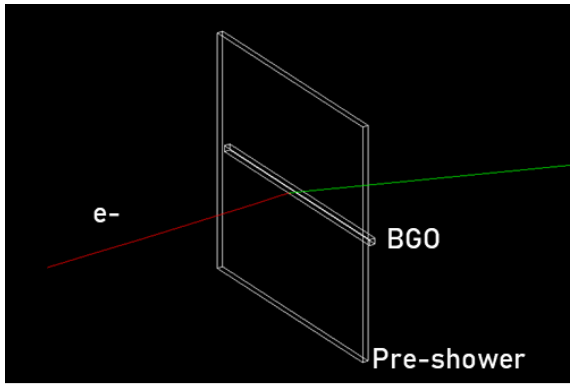
- How to make a **single crystal absorb enough energy**?
  - **High energy beam, high-Z pre-shower, particle along crystal longitudinal axis**
- How to calibrate the actual energy absorbed by the crystal?
  - **Two-ends readout and good uniformity**: measurement at one end, ND-filtered reference at the other end

Taking advantage of two-ends readout:

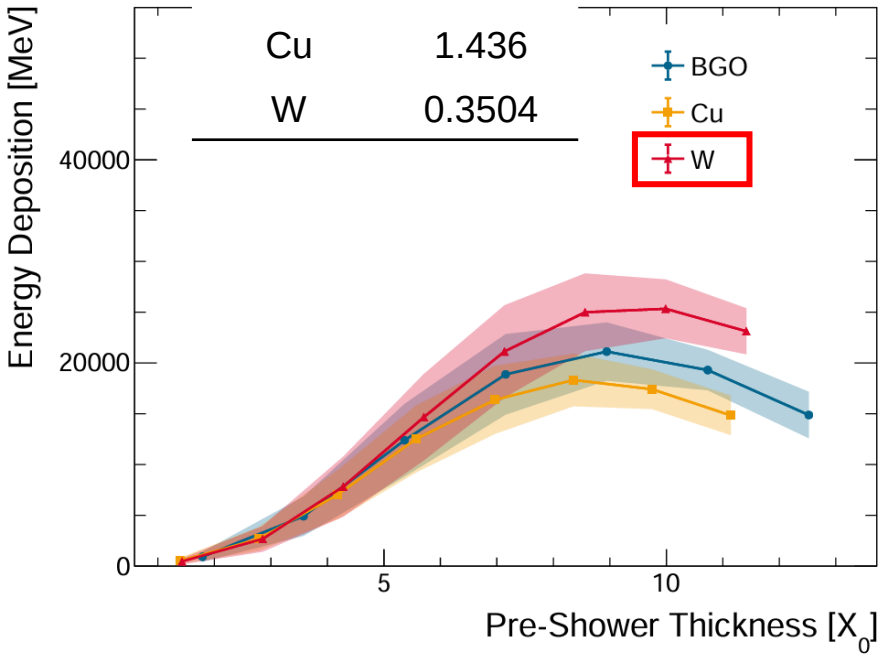


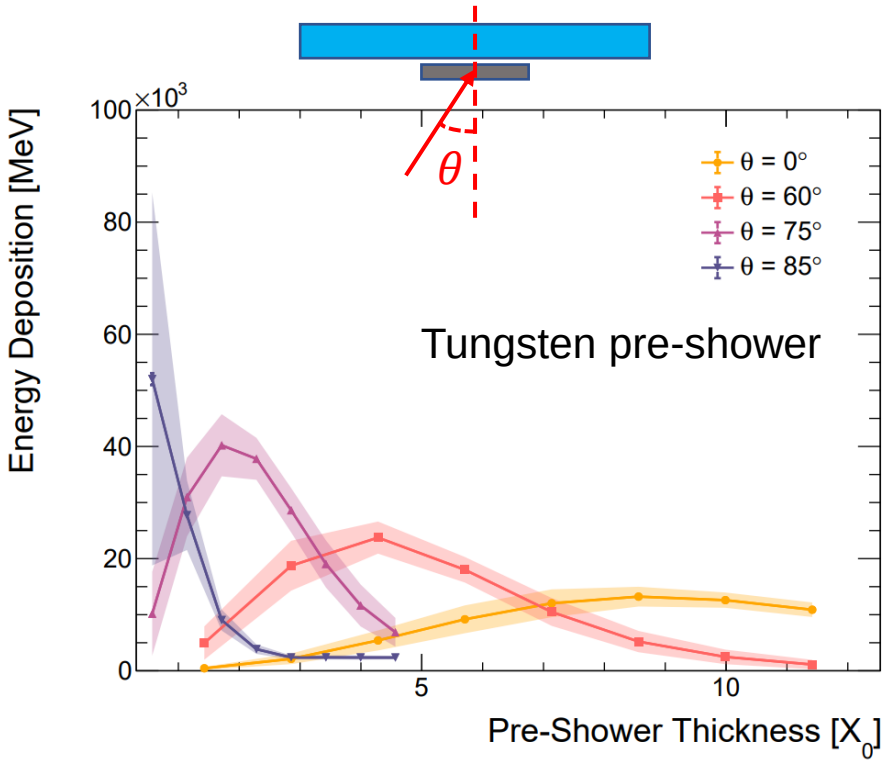
G4 Simulation for Pre-shower Selection

- **Tungsten pre-shower (0.8 X_0) + large incident angle** → crystal unit can absorb **>80 GeV**



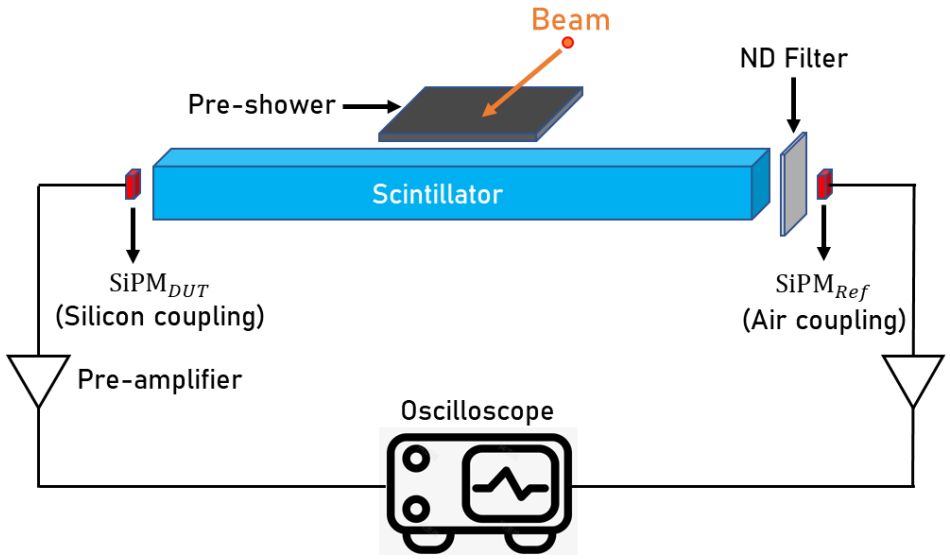
Material	X_0 (cm)
BGO	1.118
Cu	1.436
W	0.3504



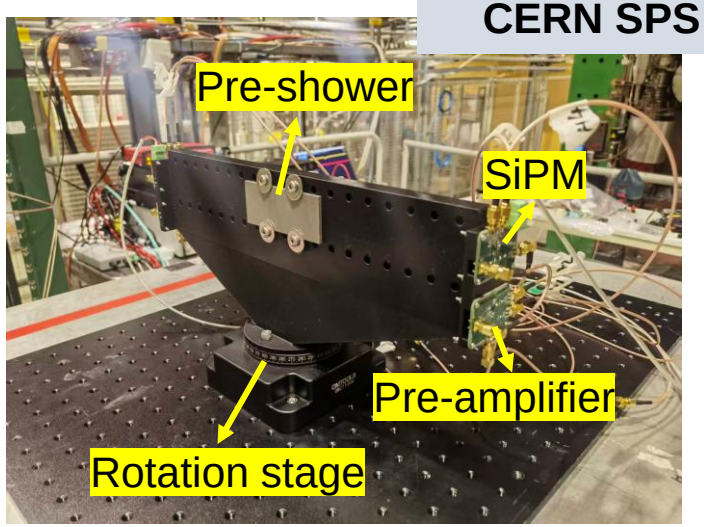


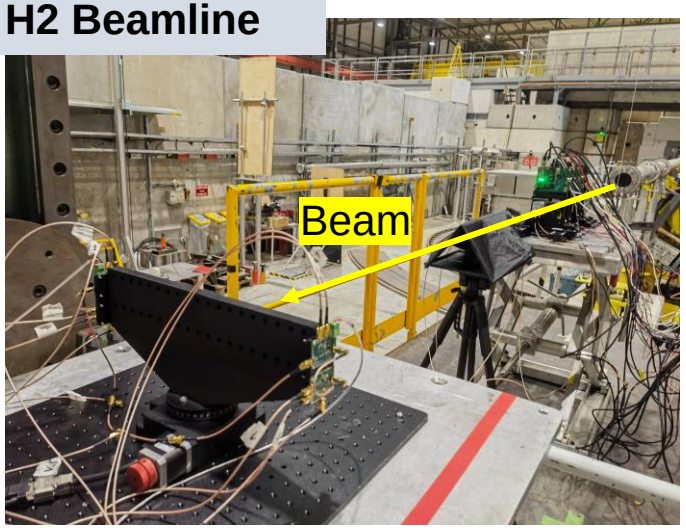
Beam Test Setup

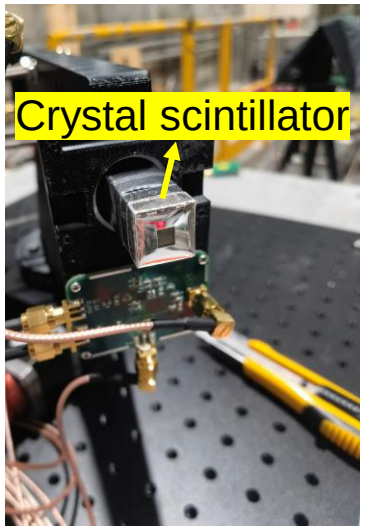
- CERN SPS H2 beamline
- Particles used in beam test
  - e^-: 50~300 GeV
  - π^+: 160 GeV

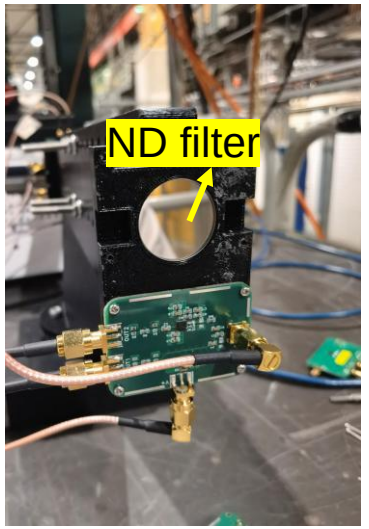


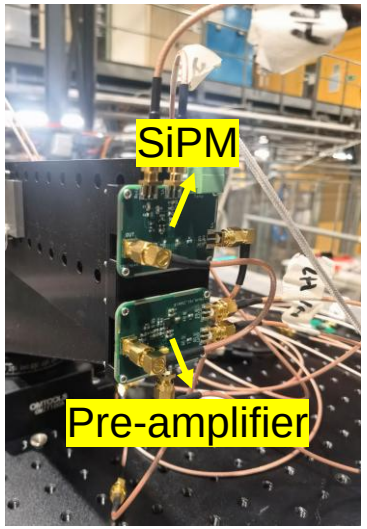
CERN SPS H2 Beamline





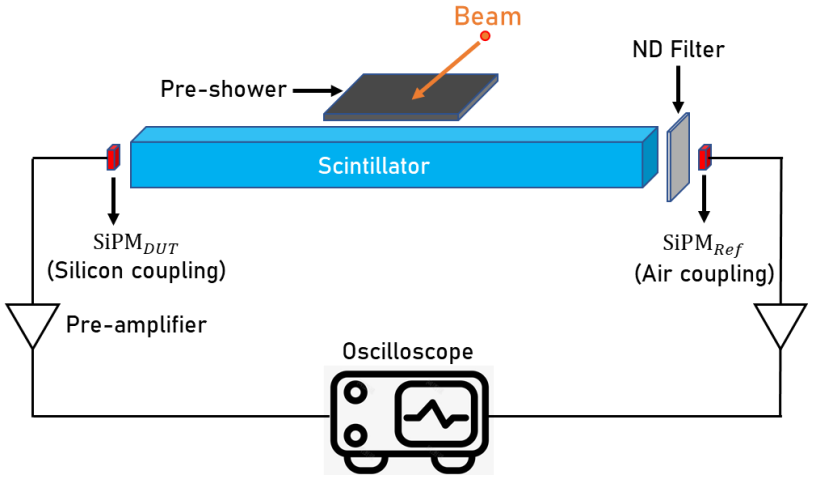




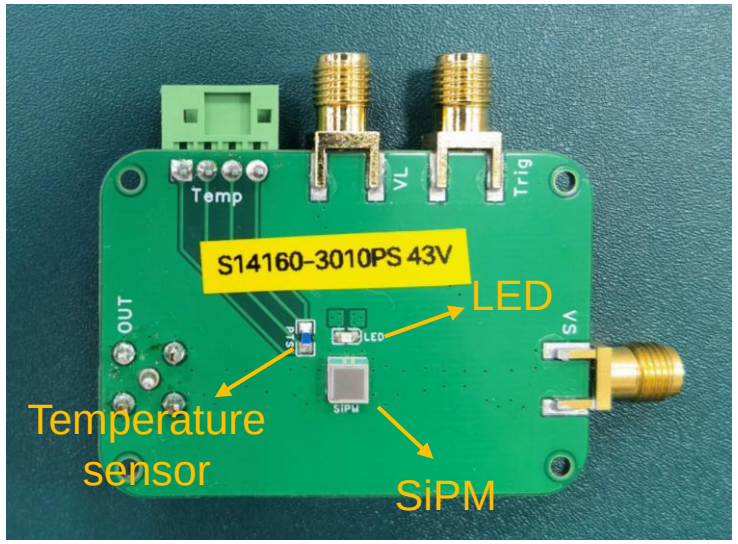


Readout Electronics

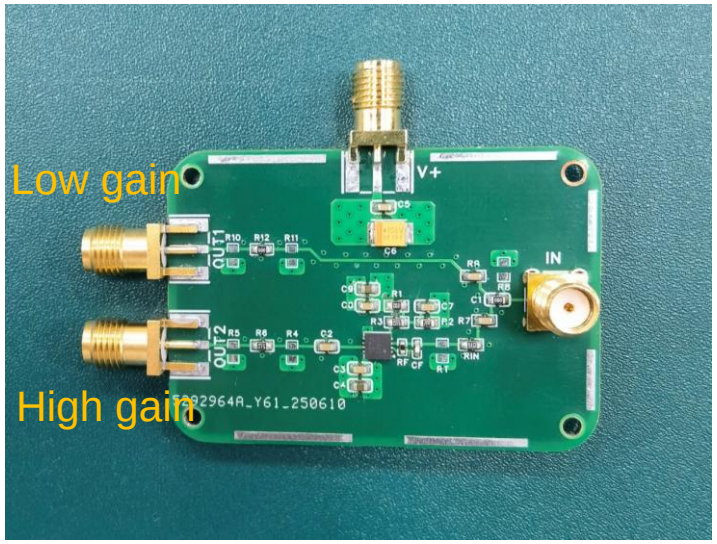
- **SiPM readout board**:
  - SiPM readout and power, temperature sensor, LED driver circuit
- **Pre-amplifier board**:
  - Transimpedance amplifier, high/low gain dual-readout
- **Oscilloscope**:
  - Picoscope 6426E, 1GHz, 1.25GS/s



SiPM readout board

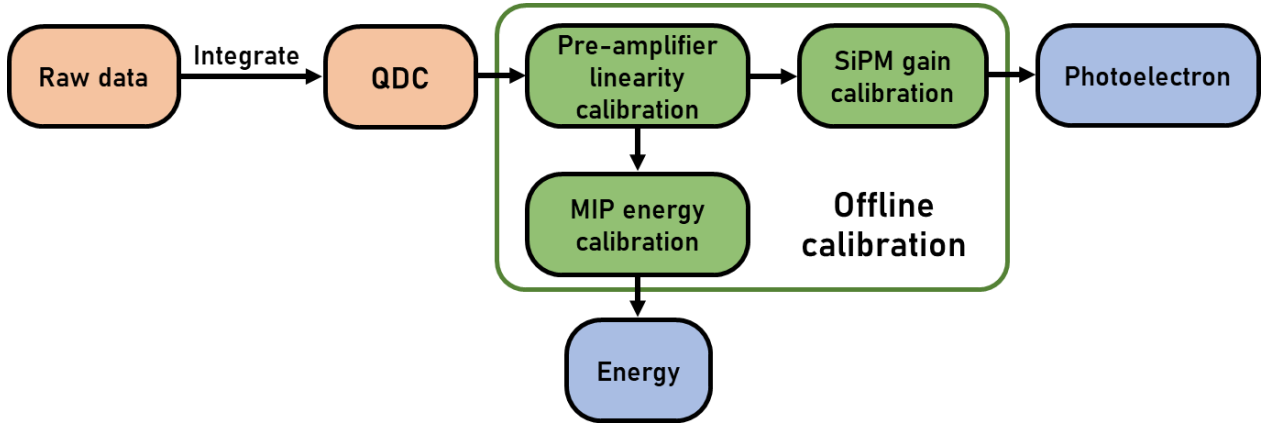


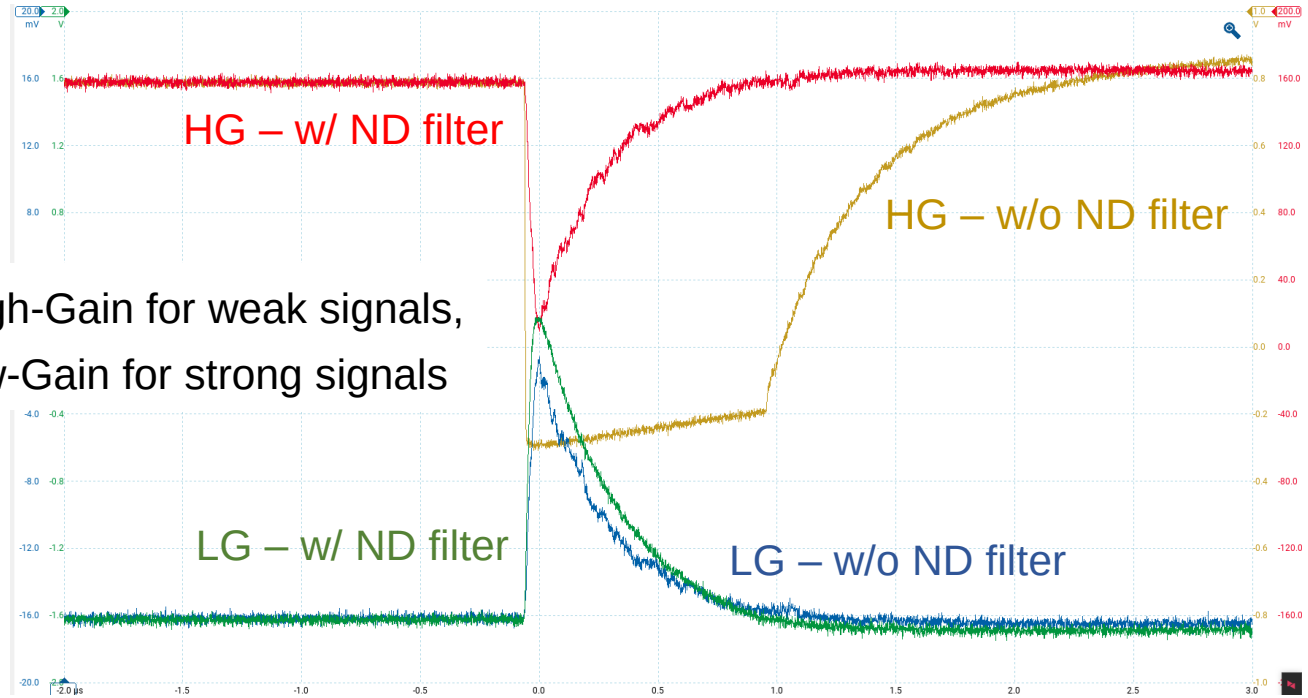
Transimpedance pre-amplifier with 2 readout channels



Oscilloscope

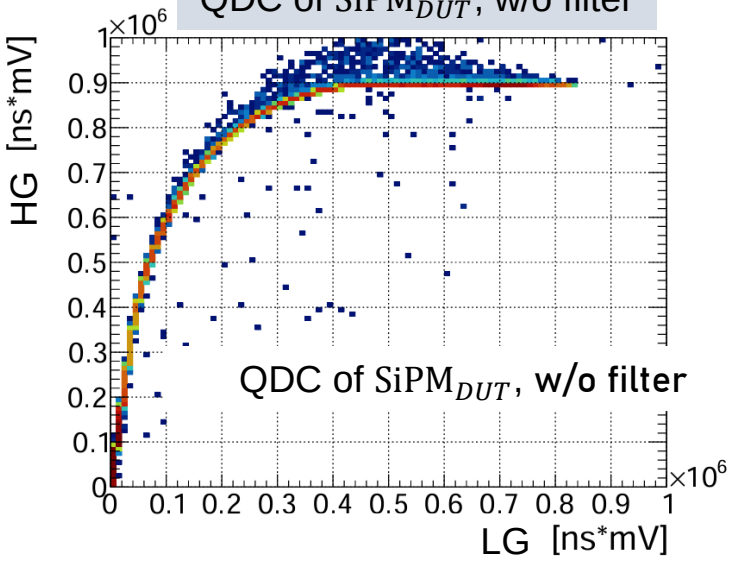
Signal Processing and Calibration Procedure



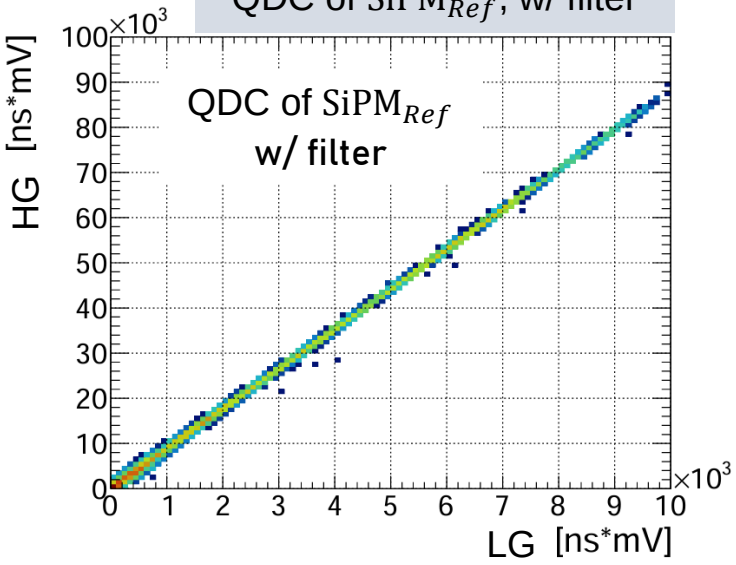


High-Gain for weak signals,
low-Gain for strong signals

QDC of SiPM_{DUT}, w/o filter

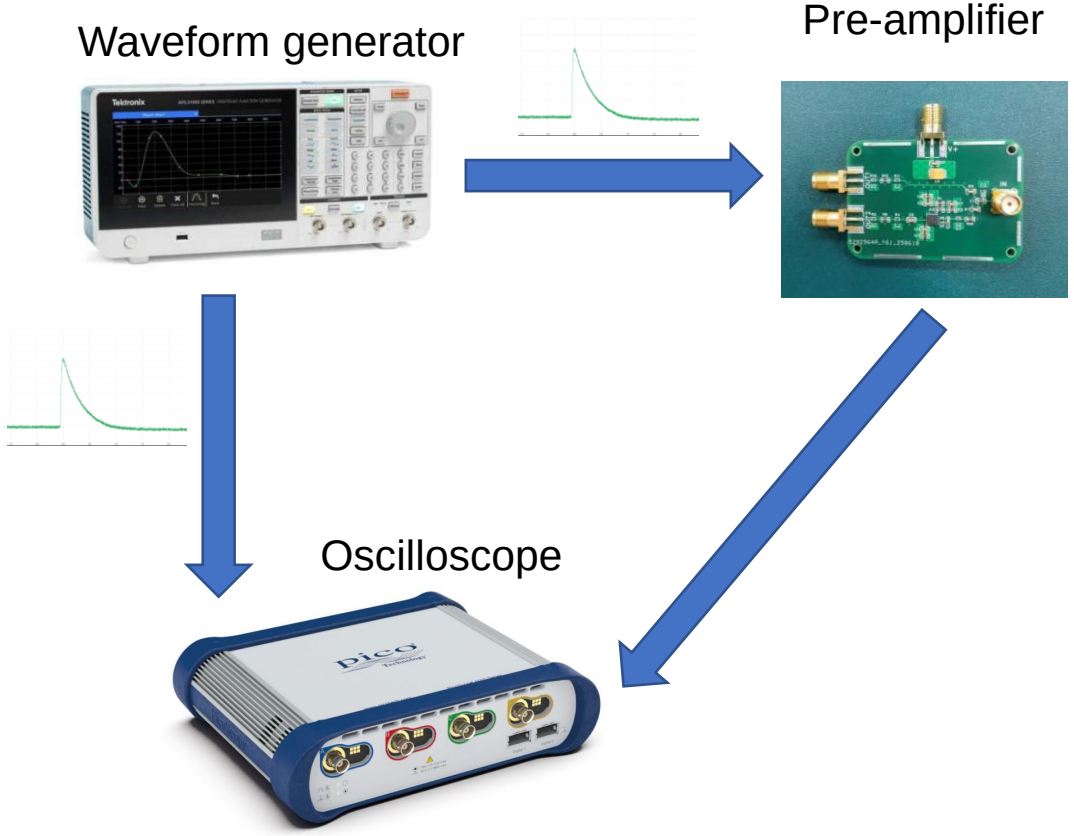


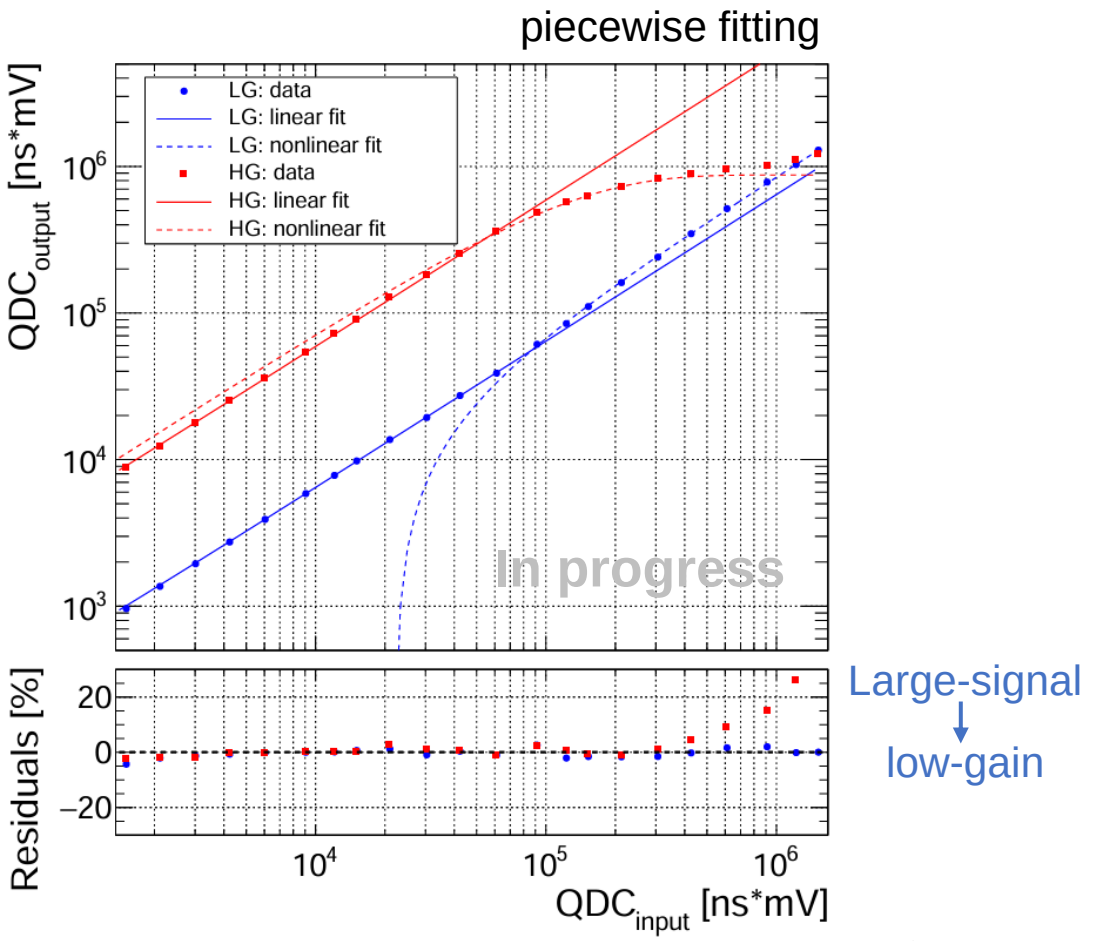
QDC of SiPM_{Ref}, w/ filter



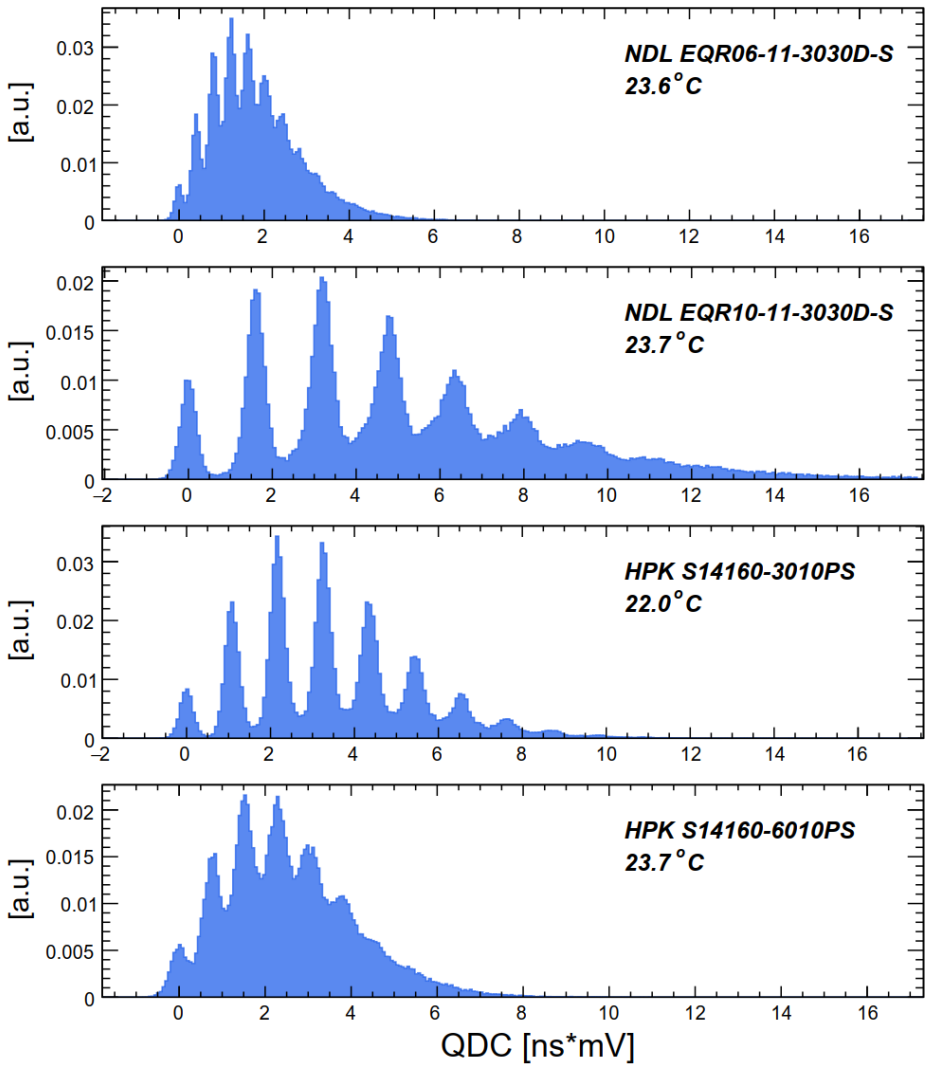
Gain Calibration for the Pre-Amplifier

- Charge injection into the pre-amplifier with waveform generator
- Nonlinearity of pre-amplifier after calibration is **1.7% (RMS)**





Single Photoelectron Calibration for SiPM



- SiPM gain is related to temperature
- Calibration was performed in temperature-control chamber, according to the recorded temperature in beam test

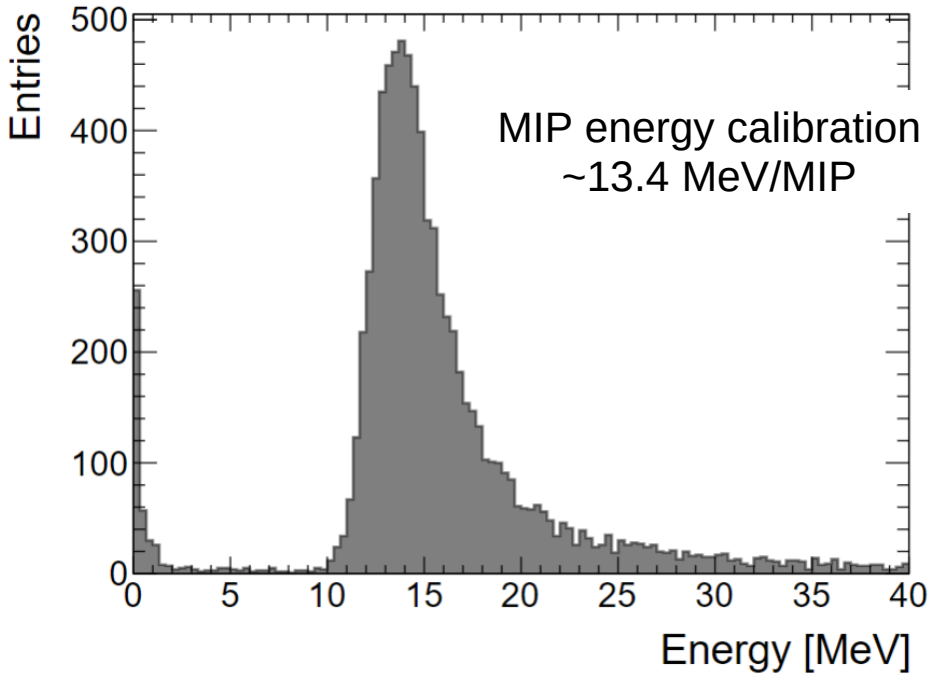
Energy Deposition in Crystal - Testbeam Data

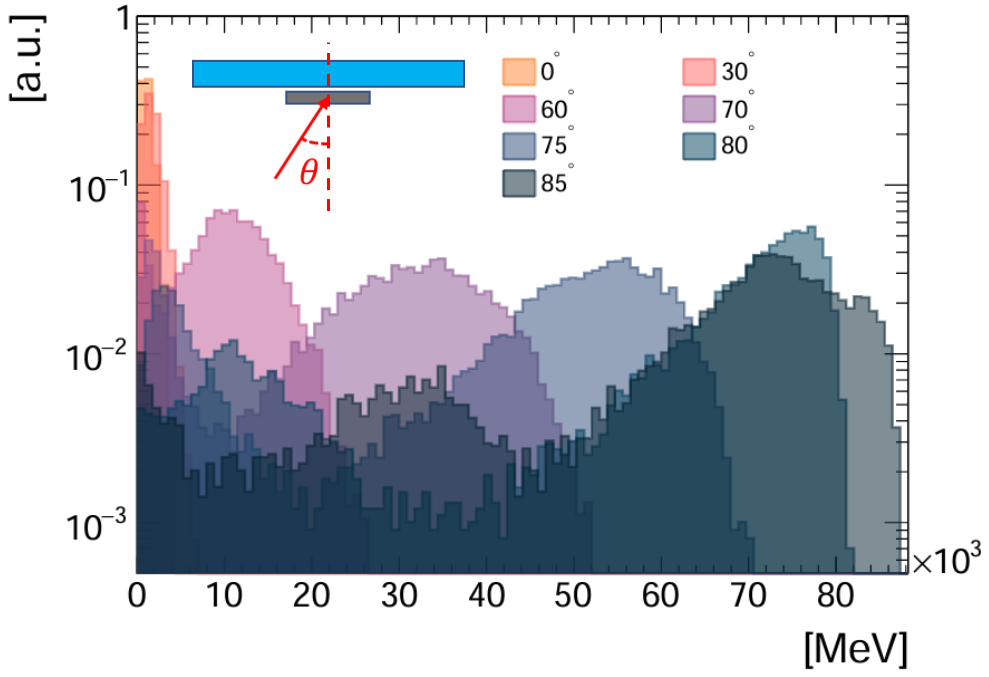
- **MIP calibration** with **160GeV pion** beam
- Up to **87 GeV** energy deposited in a single crystal unit

160 GeV π^+ beam

$40 \times 1.5 \times 1.5 cm^3$ BGO
HPK S14160-3010PS

300 GeV e^- beam

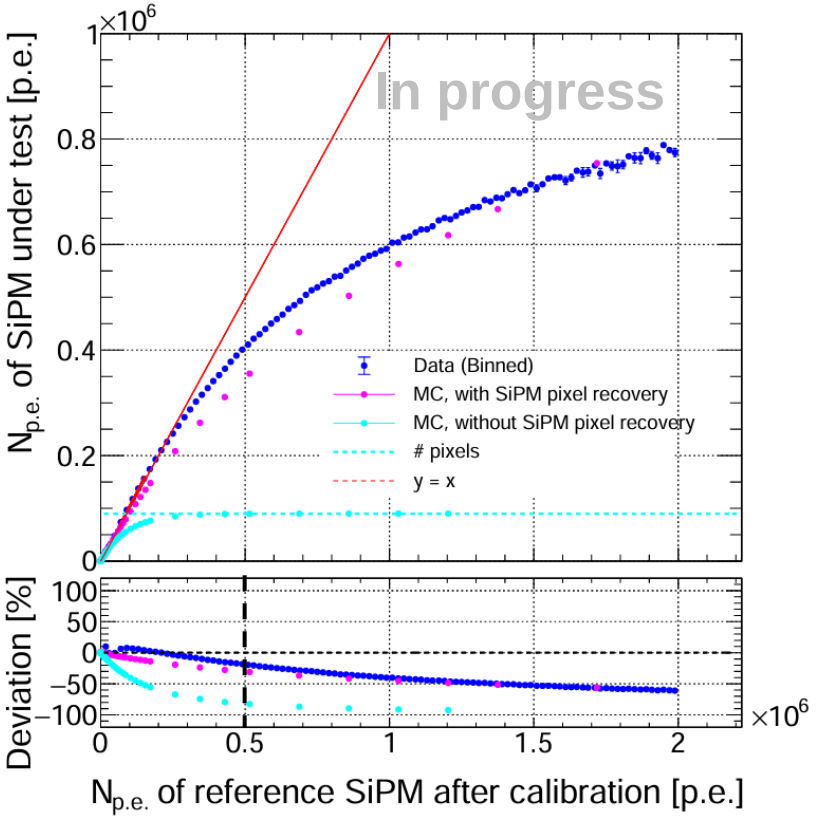




Nonlinearity of SiPM to Scintillation Light

- #p.e. detected by the tested SiPM gradually saturates as the input increases
- **Deviation @5×10^5 p.e. is within 20%**
- SiPM response agrees with simulation within **15%**
  - Simulation includes SiPM pixel density, PDE spectrum, crosstalk, BGO emission spectrum, etc.

$40 \times 1.5 \times 1.5 cm^3$ BGO
HPK S14160-3010PS



The data curve can be used to correct nonlinearity in application

Nonlinearity of SiPM to Scintillation Light

Crystal	SiPM	Pixel pitch	#pixels	Terminal capacitance	Deviation at 5×10^5 p.e.
BGO $40\times1.5\times1.5\text{cm}^3$ **ECAL config.**	HPK S14160-3010PS	10 μm	89984	530 pF	-18.9%
	HPK S14160-6010PS	10 μm	350911	2200 pF	-9.6%
	NDL EQR06 11-3030D-S	6 μm	244719	45.9 pF	-58.6%
	NDL EQR10 11-3030D-S	10 μm	90000	31.5 pF	-47.0%
BGO $12\times2\times2\text{cm}^3$	HPK S14160-6010PS	10 μm	350911	2200 pF	-8.5%
BSO $12\times2\times2\text{cm}^3$	HPK S14160-6010PS	10 μm	350911	2200 pF	-20.2%

Nonlinearity appears earlier than expected, same case as laser test

Scintillation is faster than BGO

Summary & Prospects

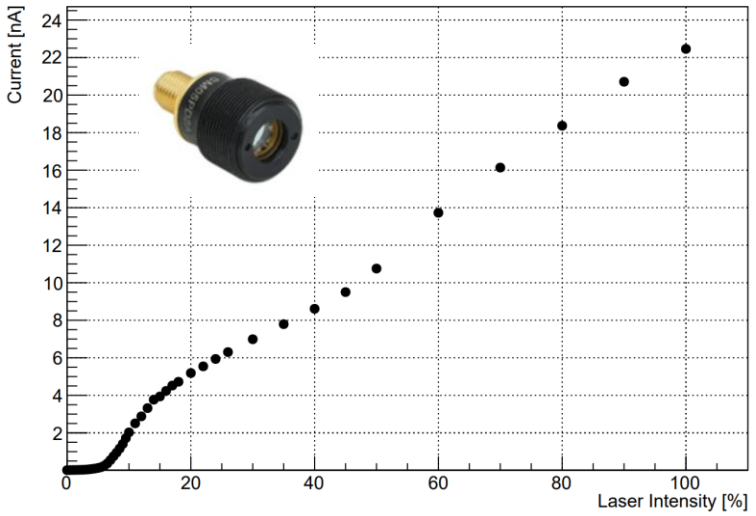
- SiPM dynamic range requirement: $\mathbf{5 \times 10^5\ p.e.}$ **with BGO scintillation**
- Nonlinearity of SiPM without pixel recovery appears at ~10% of #pixels
- **Successfully measured the nonlinearity of SiPM response to scintillation light**
  - >80 GeV energy deposition in crystal unit
  - The HPK 10μm SiPMs exhibits nonlinearity within 20% at $5 \times 10^5\ p.e.$
  - NDL SiPMs with 6μm and 10μm pixels demonstrate earlier nonlinearity than expected, which needs further study
- **SiPM nonlinearity can be corrected using the measured response curve** – precision of the correction method need to be studied

Thanks!

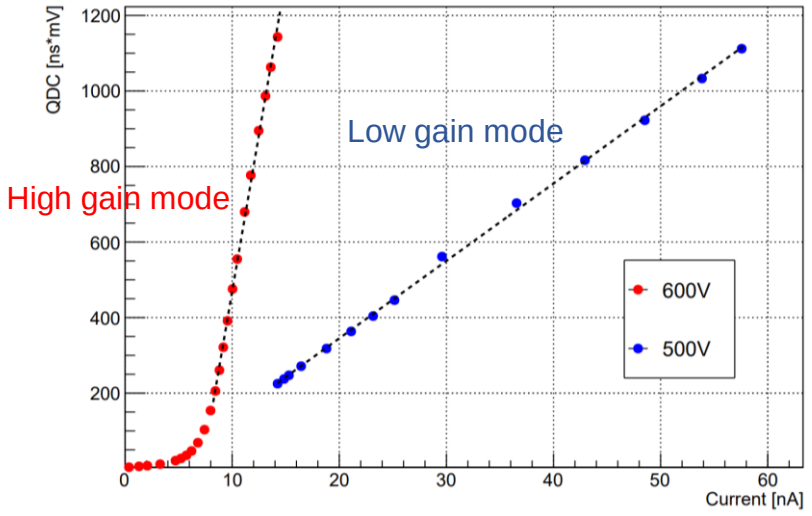
Operation Modes Selection for PMT

- Select the linear regions of PMT with a Si-PIN at different light intensities
  - High gain mode: 600V bias voltage, applied in weak light
  - Low gain mode : 500V bias voltage, applied in strong light
- Combination of discrete linear regions can keep PMT's linear output within the whole light range

Si-PD Current vs. Laser Intensity

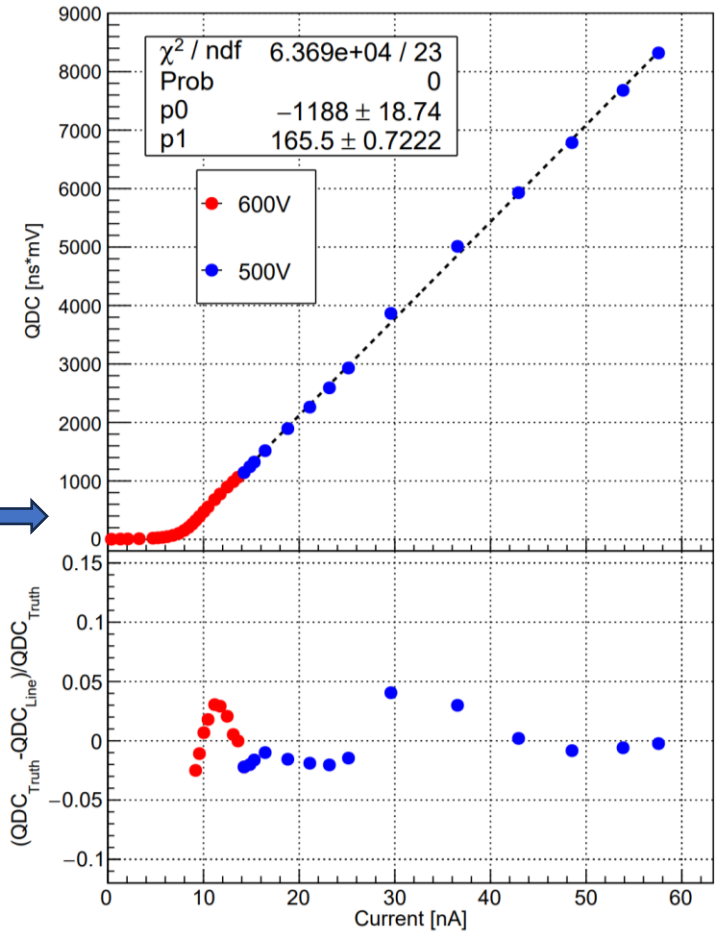


PMT response



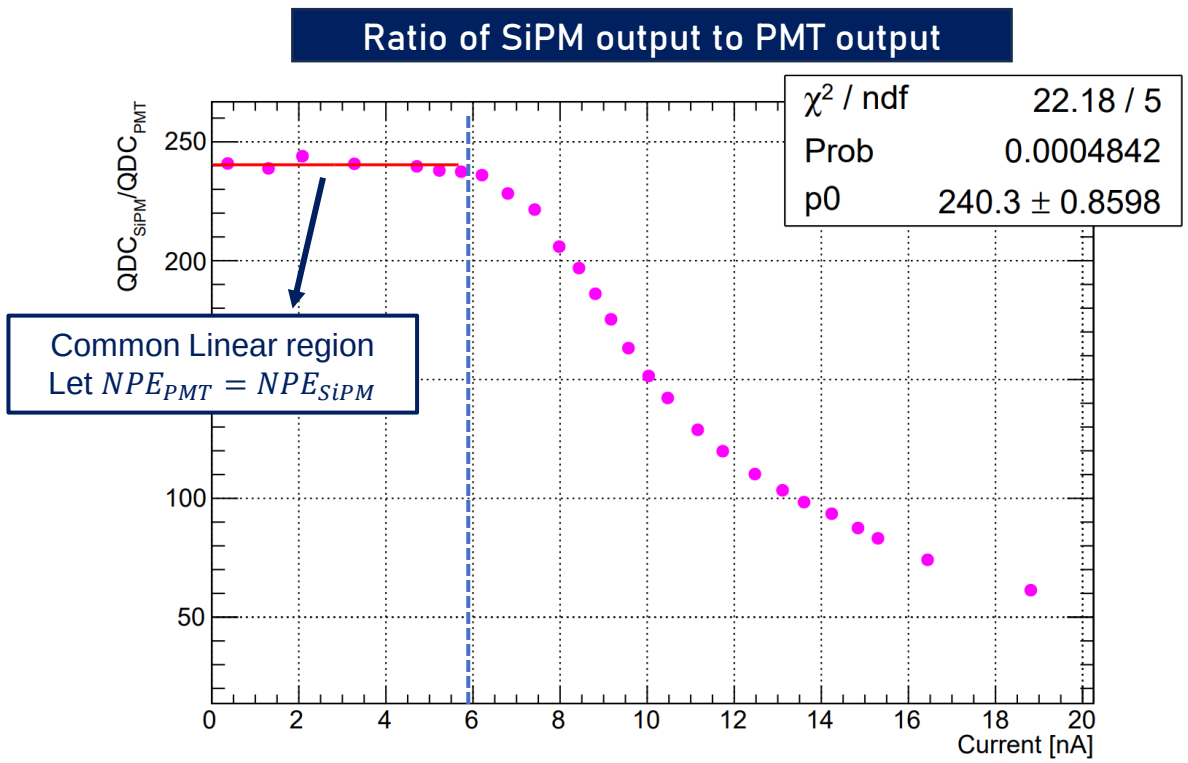
- Low gain mode has a wider linear area

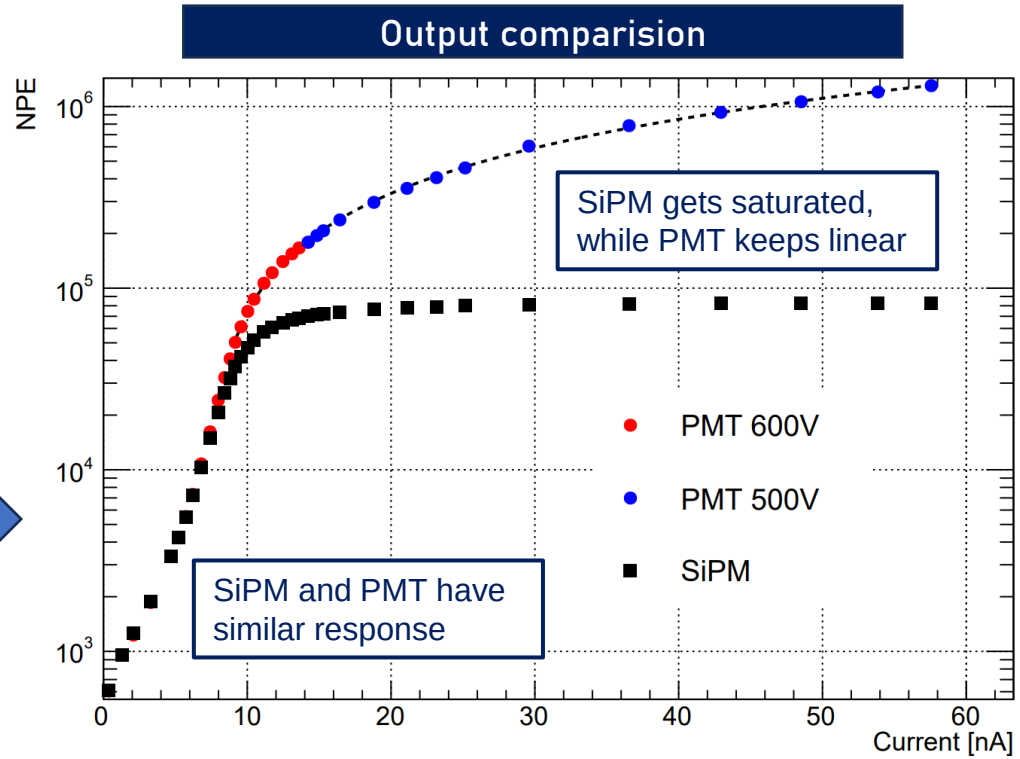
PMT response after modes combination



PMT Gain Calibration

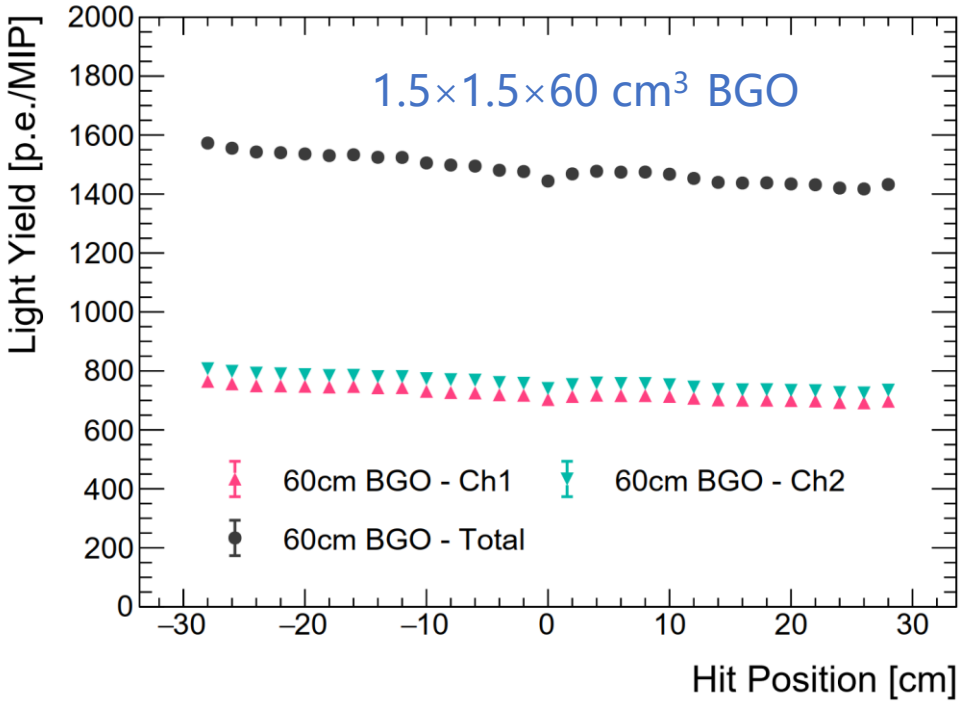
- Gain of PMT at 600V is not high enough to discriminate single pe
- Let the number of pe detected by PMT same as that by SiPM at weak light region
- After calibration, Linear region of PMT can cover the response range of SiPM





Response Uniformity Along Crystal Bar

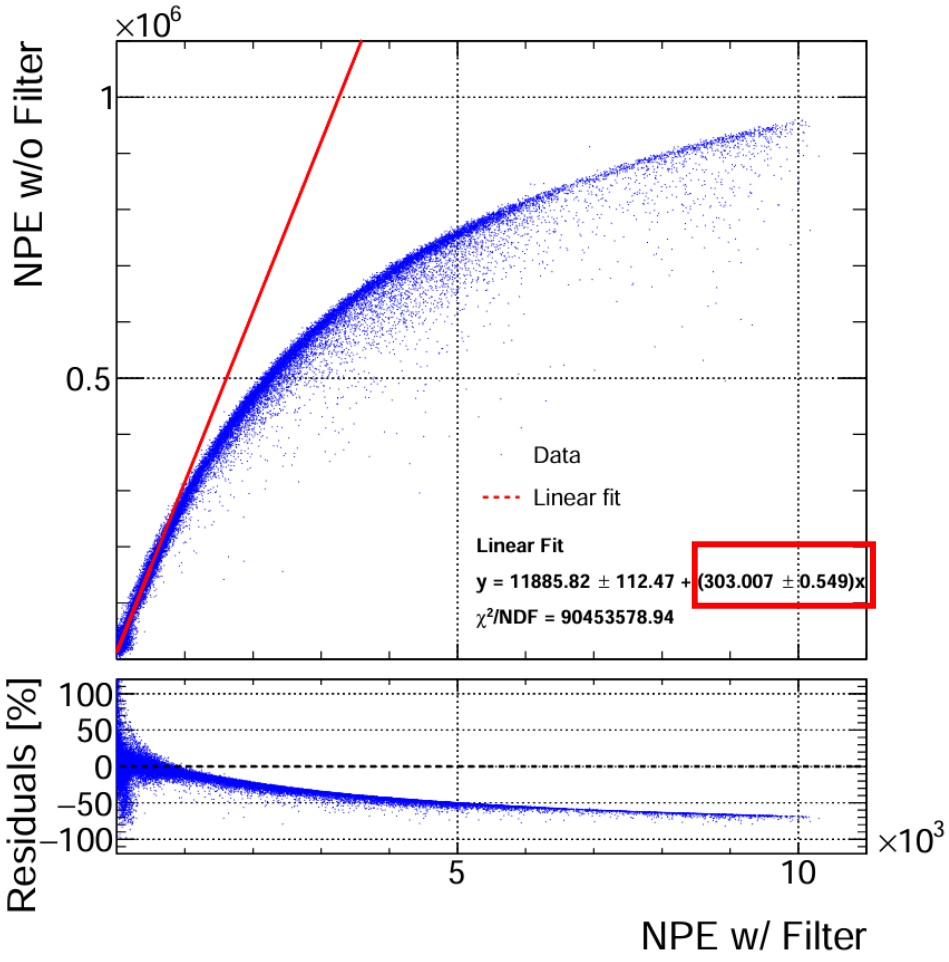
- Scan along the crystal's longitudinal axis with 10 GeV pion beam, to measure the variations in light output
- Response uniformity (RMS): 3%



Overview of Crystal-SiPM Dynamic Test at SPS

Crystal	SiPM	Coupling	Beam
$40 \times 1.5 \times 1.5\text{cm}^3$ BGO	NDL EQR06	Silicon oil, air	e^-: 160, 250, 300 GeV π^+: 160 GeV
	NDL EQR10	Silicon oil	e^-: 300 GeV π^+: 160 GeV
	HPK S14160-3010PS	Silicon oil, air	e^-: 160, 300 GeV π^+: 160 GeV
	HPK S14160-6010PS	Silicon oil	e^-: 300 GeV π^+: 160 GeV
$12 \times 2 \times 2\text{cm}^3$ BGO	HPK S14160-6010PS	Silicon oil	e^-: 300 GeV π^+: 160 GeV
$12 \times 2 \times 2\text{cm}^3$ BSO	HPK S14160-6010PS	Silicon oil	e^-: 300 GeV π^+: 160 GeV

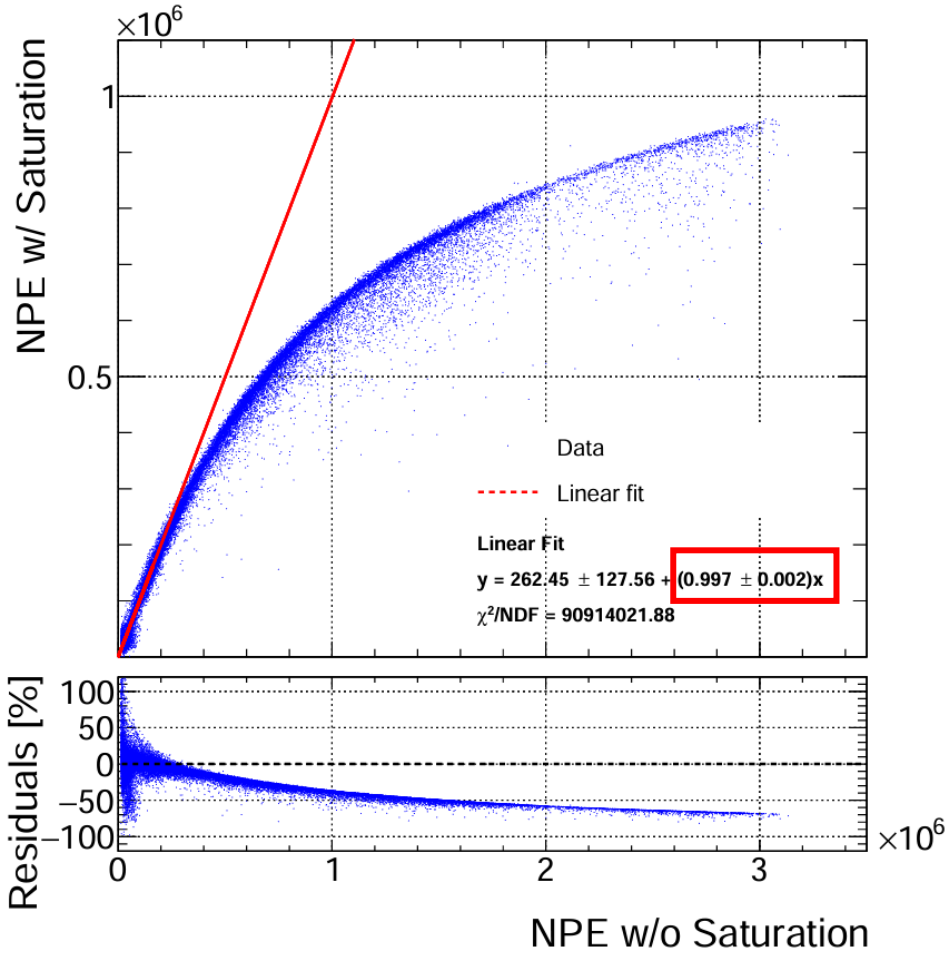
Number of Photoelectrons – S14160-3010PS, 40cmBGO



$$x' = a + b \cdot x$$

Contribution of “b”

- Transmittance of ND filter
- Light collection efficiency varies due to the thickness of the filter
- Silicon coupling
- Inconsistency between the devices at the two ends



Response of Different Crystal-SiPM Units

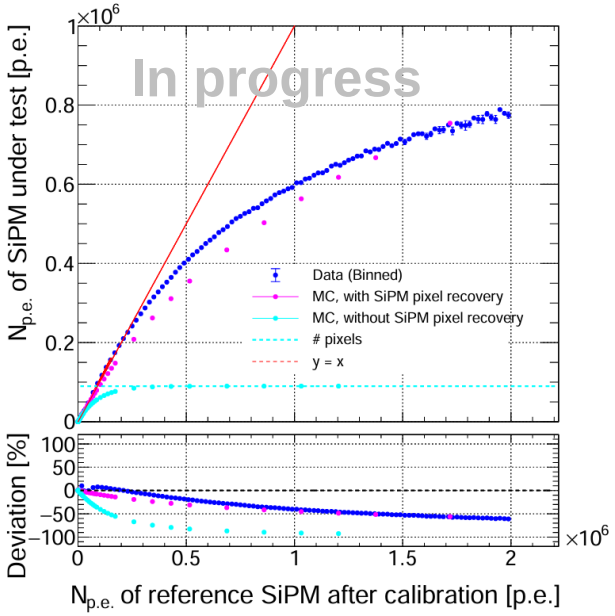
$40 \times 1.5 \times 1.5 cm^3$ BGO

Nonlinearity appears earlier than expected, similar case in laser test

HPK S14160-3010PS

$3 \times 3 mm^2, 10 \mu m$ pixel

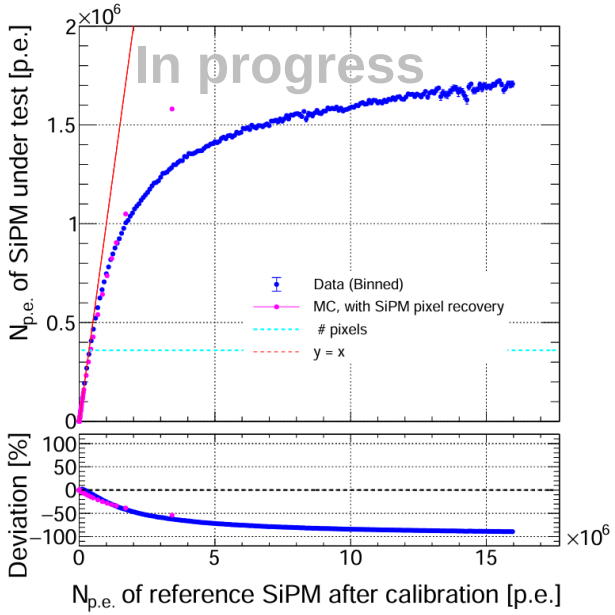
~90k pixels



HPK S14160-6010PS

$6 \times 6 mm^2, 10 \mu m$ pixel

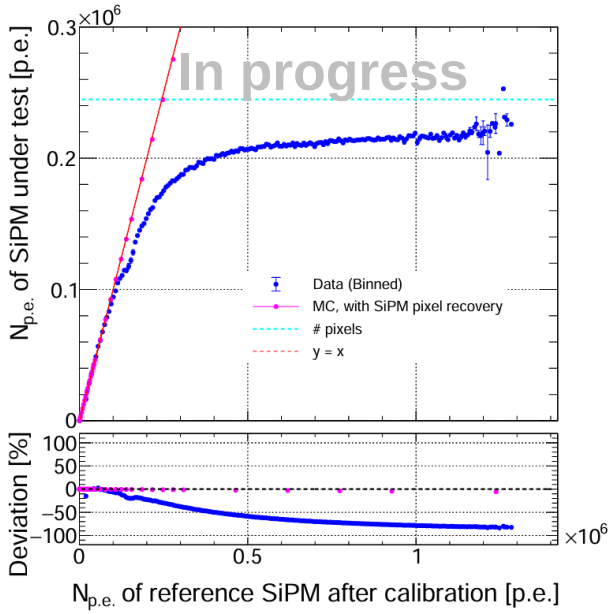
~360k pixels



NDL EQR06

$3 \times 3 mm^2, 6 \mu m$ pixel

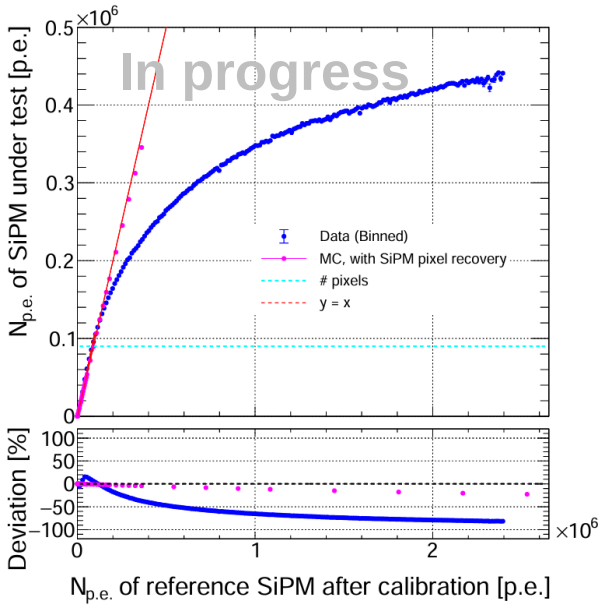
~250k pixels



NDL EQR10

$3 \times 3 mm^2, 10 \mu m$ pixel

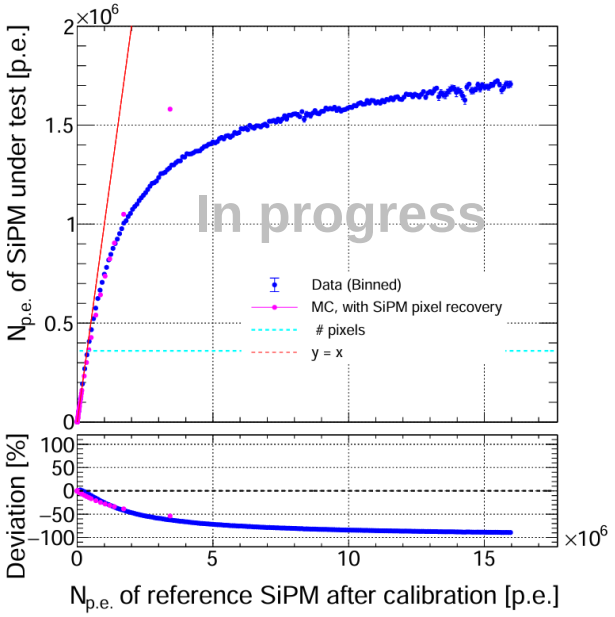
~90k pixels



Response of Different Crystal-SiPM Units

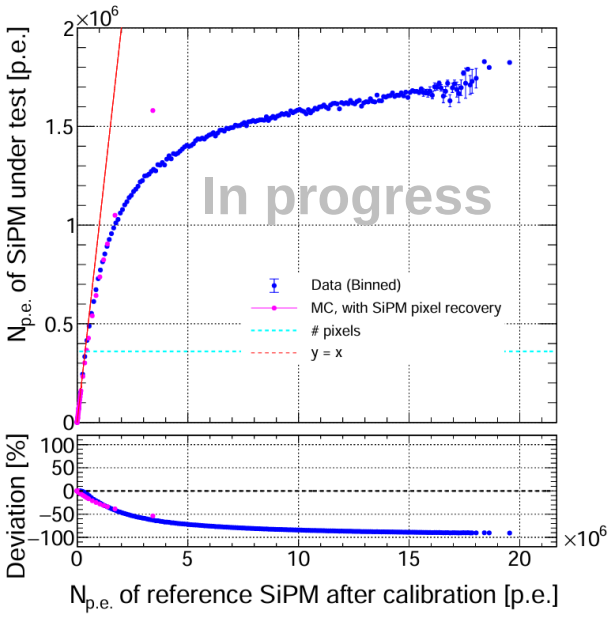
$40 \times 1.5 \times 1.5 cm^3$ BGO

HPK S14160-6010PS



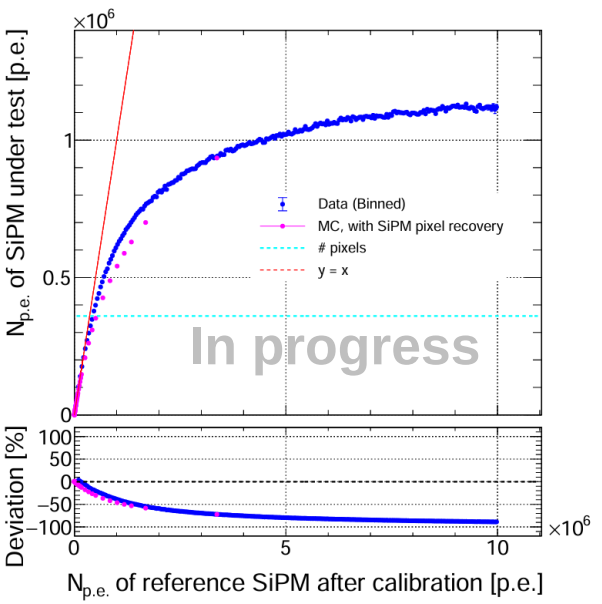
$12 \times 2 \times 2 cm^3$ BGO

HPK S14160-6010PS



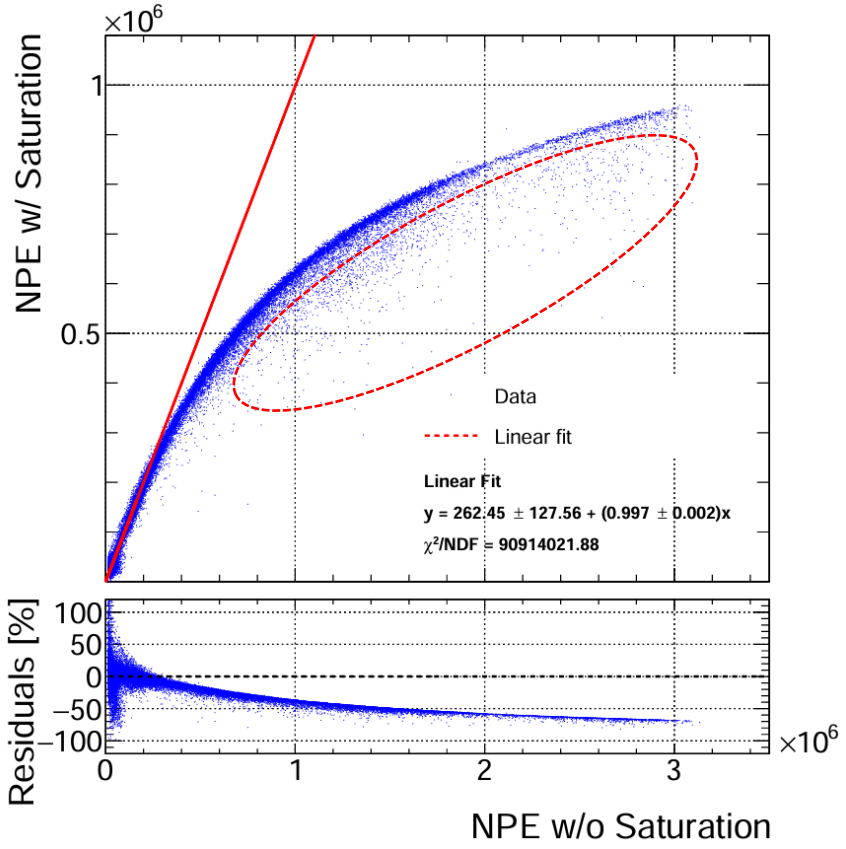
$12 \times 2 \times 2 cm^3$ BSO

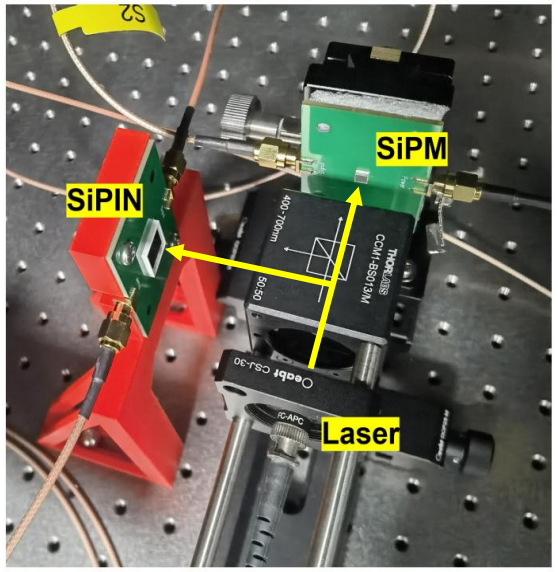
HPK S14160-6010PS

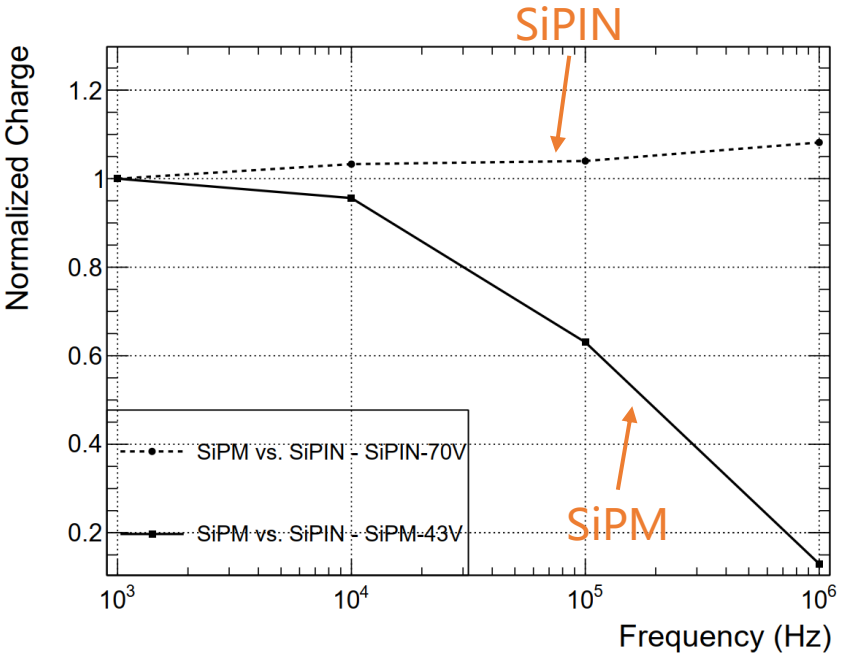


SiPM Signal Reduction Under High Repetition Rate

- The SiPM signal decreases with increasing signal repetition rate

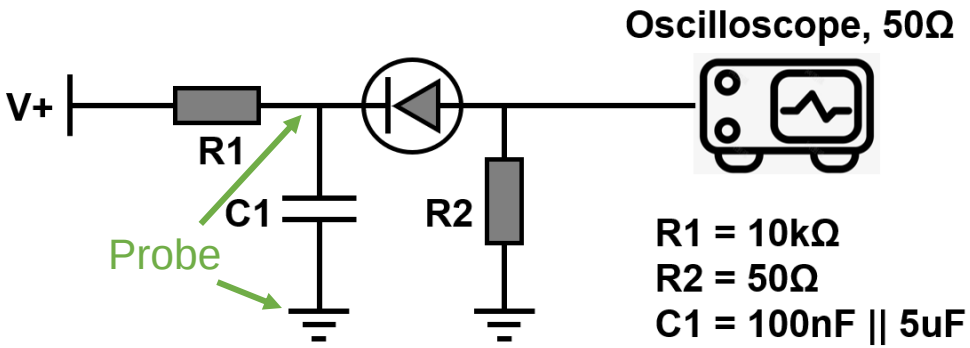




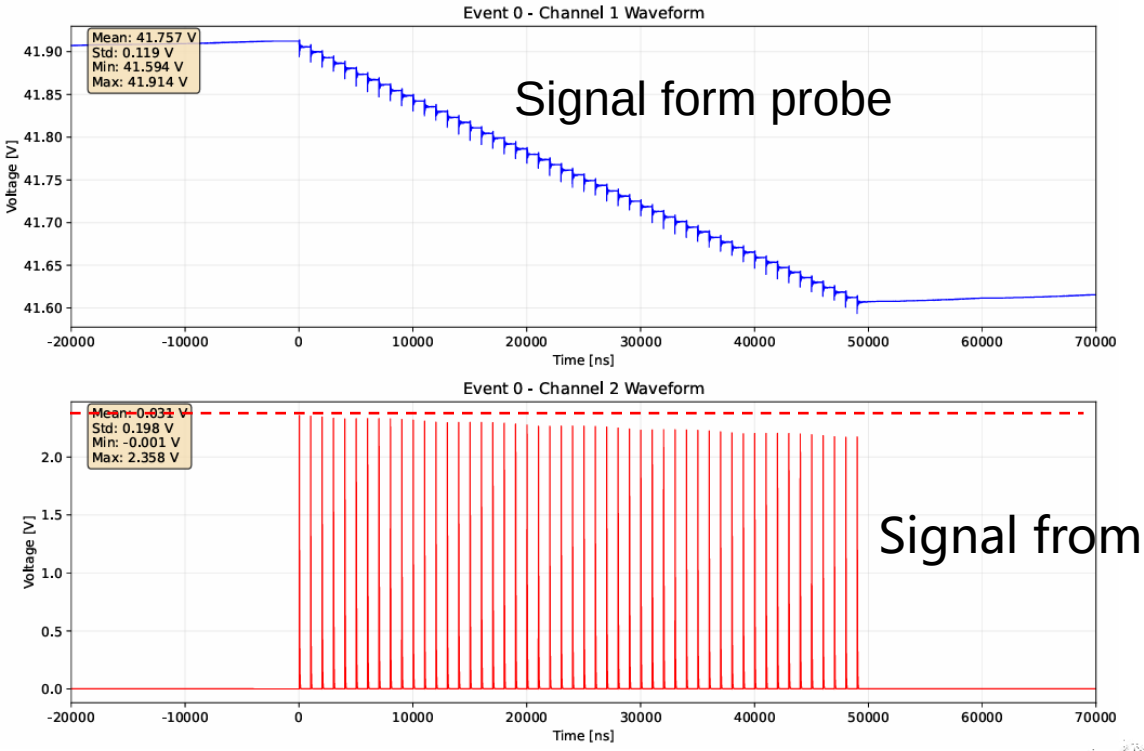


SiPM Signal Reduction Under High Repetition Rate

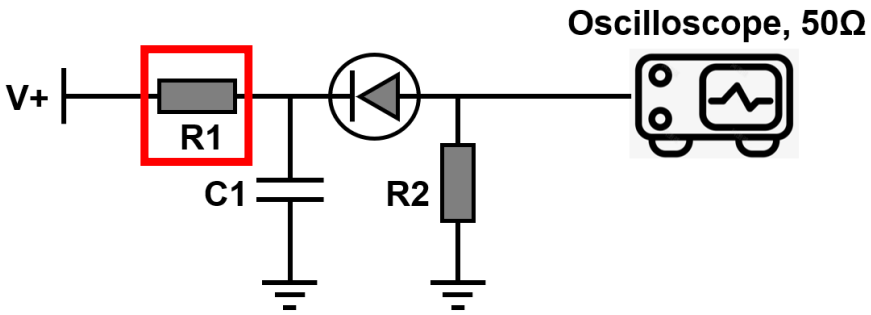
- Part of the SiPM bias voltage is diverted by the resistor in the circuit. At high signal repetition rate, the bias across the SiPM cannot recover promptly, resulting in reduced gain and diminished signals

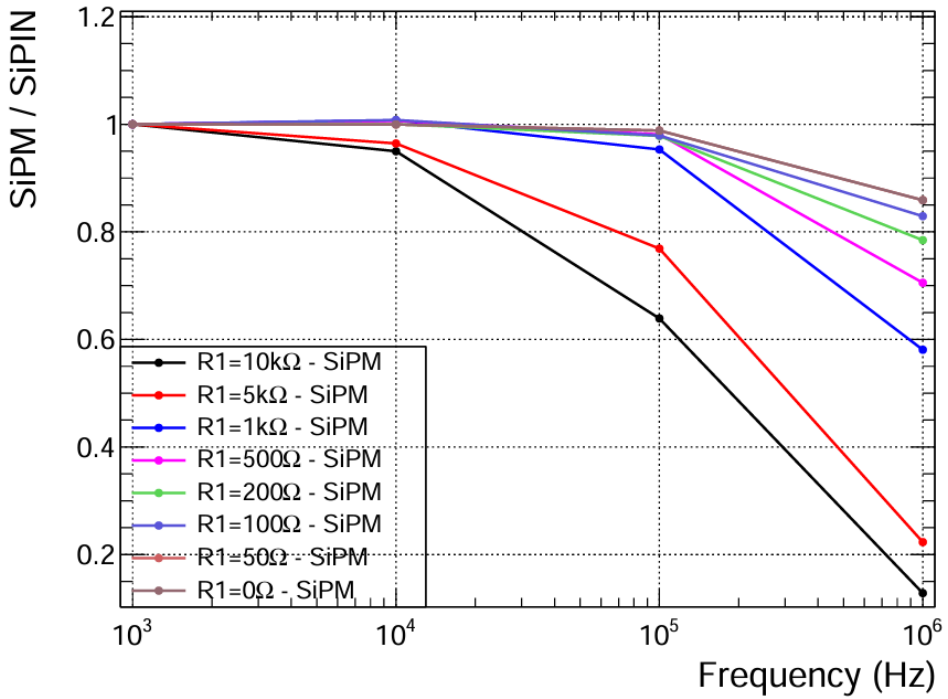


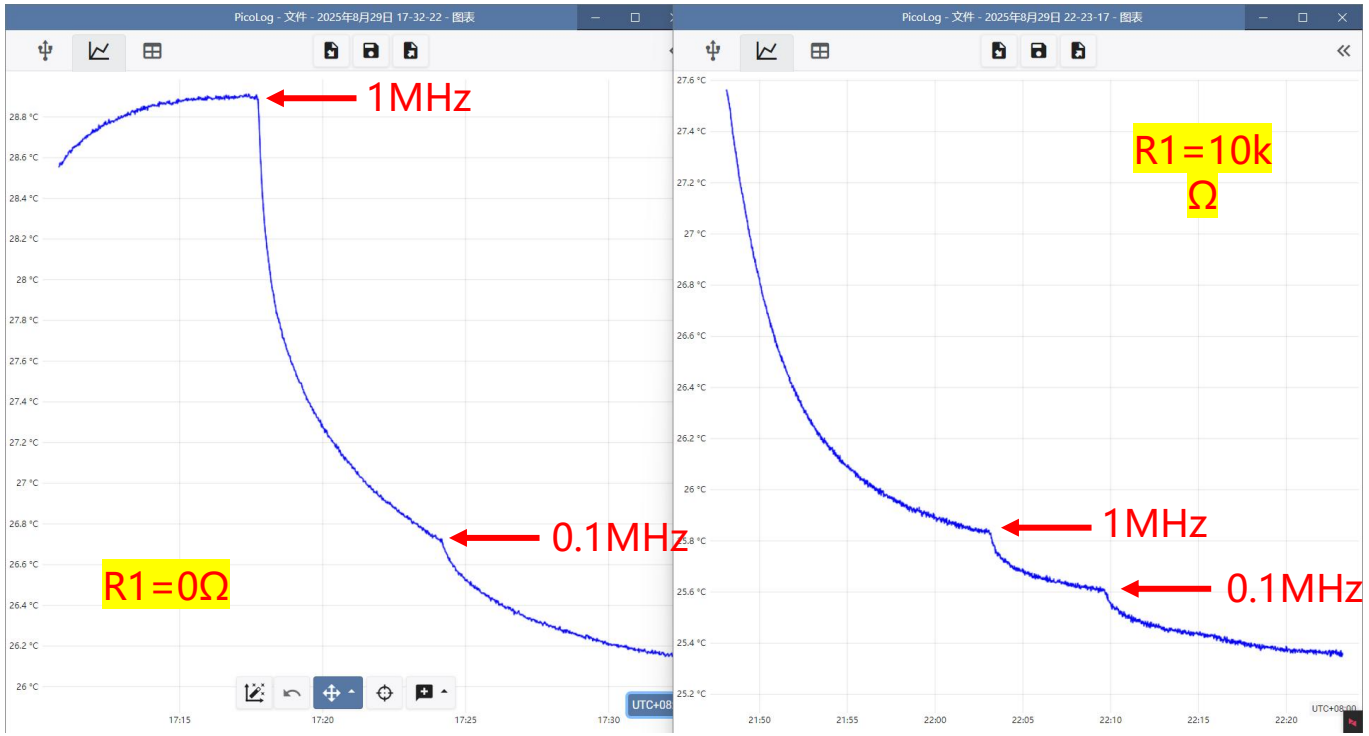
The voltage was measured with a probe under the burst mode (1 MHz) of the laser



Effect of Power-end Resistance







0 Ω	50 Ω	100 Ω	200 Ω
0.338℃/min	0.277℃/min	0.243℃/min	0.245℃/min

500 Ω	1 kΩ	5 kΩ	10 kΩ
0.192℃/min	0.191℃/min	0.063℃/min	0.035℃/min