Studies on the dynamic range of SiPMs with high pixel densities

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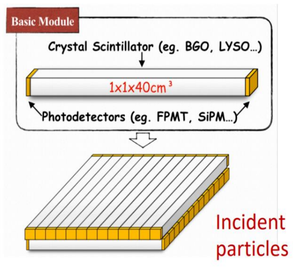
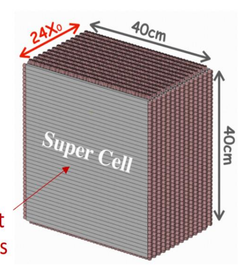
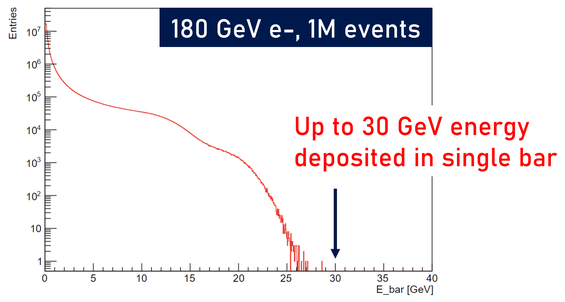
Energy dynamic range of CEPC Crystal ECAL

- The future Circular Electron-Positron Collider (CEPC) is envisioned as a large-scale Higgs factory. A highly granular crystal ECAL has been proposed to address major challenges in jet reconstruction and achieve optimal EM resolution of around 2–3%/$\sqrt{E}$ for CEPC. This calorimeter features a homogeneous structure with BGO long crystal bars as the active material, and SiPMs as optional photon sensors.







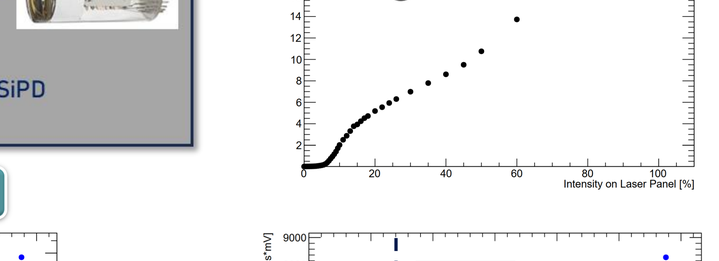
- At center-of-mass energies ranging from 240GeV to 360GeV, the energy deposition in a single crystal bar can reach up to 30GeV, potentially resulting in the detection of approximately 337k photoelectrons per channel. This places significant demands on the dynamic range of SiPMs.

Experiment setup

- An experiment using PMT operated at different gains as a scaler to measure the intrinsic dynamic range of SiPM with large pixel densities.

PMT – main scaler: by applying different bias voltages to operate at different gains, linear response is maintained across the entire input range

Pico-second laser – light source: 405nm wavelength with a pulse width of less than 40ps to prevent multiple firing of SiPM pixels

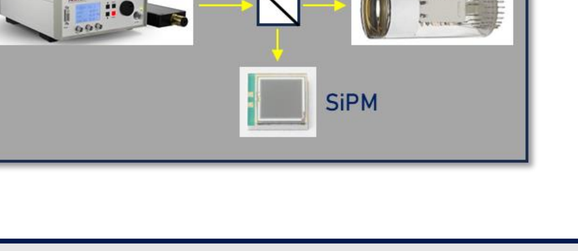


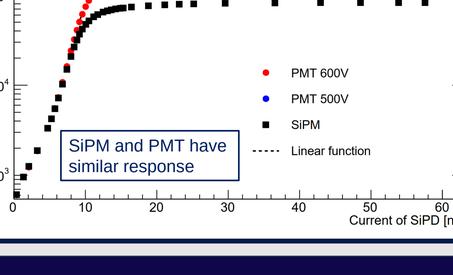
SiPD – auxiliary scaler: calibrated the laser intensity and selected the linear region for PMT

SiPM – DUT with different pixel densities

Scaler Calibration

- Selection on PMT's operation modes under different light intensities.





Response of PMT

PMT gain calibration

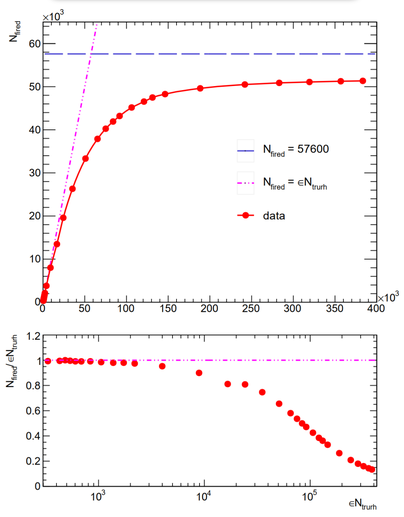
- After calibration, PMT can always keep a linear response within the whole input range. And the number of incident photons on SiPM can be evaluated by PMT's output.

Responses of PMT and SiPM

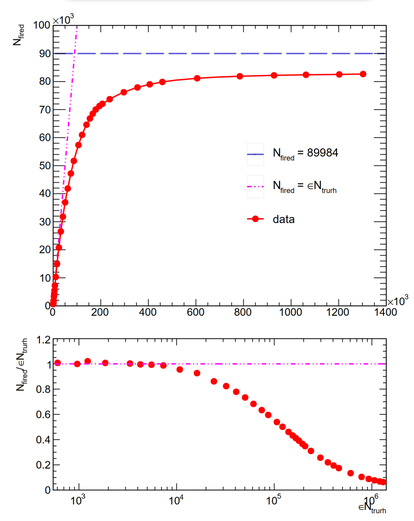
SiPM response to pico-second laser

SiPM	Pixel Pitch (μm)	Active Area (mm^2)	Nominal pixel counts	PDE (%) $\lambda = \lambda_p$
HPK S13360-6025PE	25	6.0×6.0	57600	25%
HPK S14160-3010PS	10	3.0×3.0	89984	18%
NDL EQR06 11-3030D-S	6	3.0×3.0	244719	30%

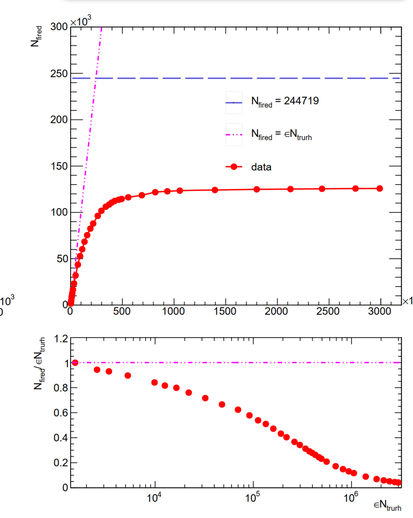
HPK S13160-6025PE



HPK S14160-3010PS



NDL EQR06 11-3030D-S

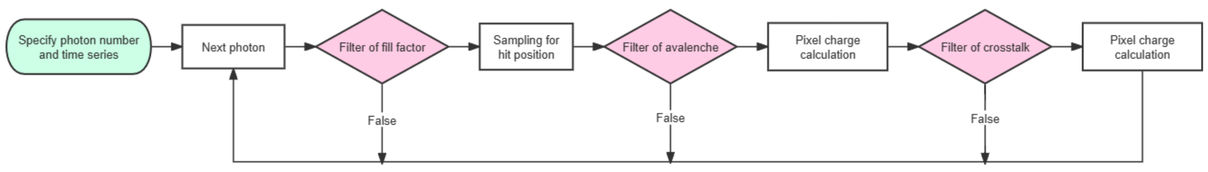


- Saturation values are close to but a little smaller than their pixels number.
- Non-linearity starts at very beginning region, and saturation value is only half of its pixel number. (Further researches are need for this type of SiPM)

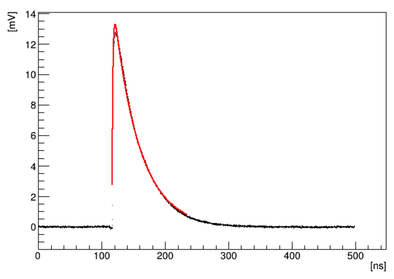
SiPM	Nominal pixel counts	Max. photon counts	5% non-linearity
S13360-6025PE	57600	51347	4246
S14160-3010PS	89984	82664	11750
EQR06 11-3030D-S	244719	125775	2433

Simulation – SiPM response to BGO scintillation

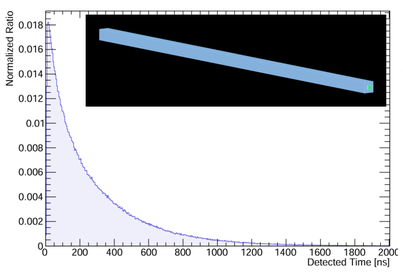
- A Monte Carlo model to simulate the SiPM response to BGO($40 \times 1 \times 1 cm^3$) scintillation light. The model includes both BGO and SiPM properties.



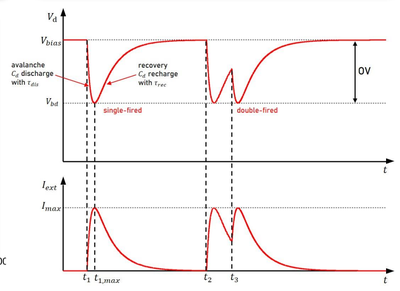
Single photon waveform



BGO optical simulation

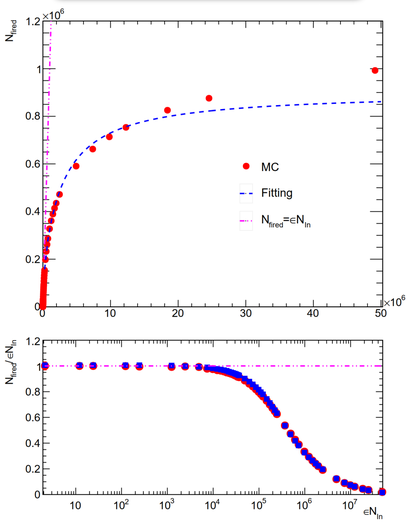


SiPM response model



SiPM pixels can be fired multiple times due to the recovery effect

HPK S13160-6025PE



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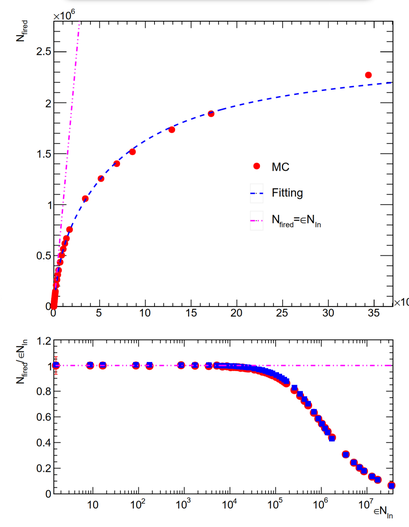
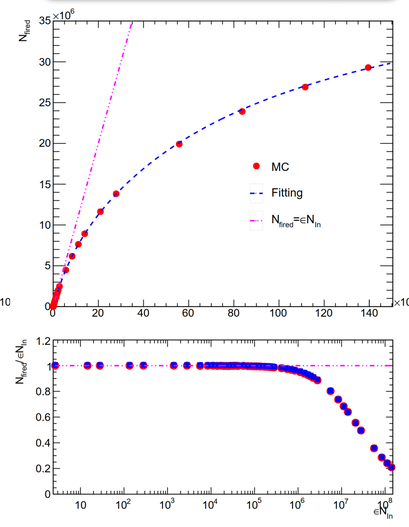


NDL EQR06 11-3030D-S



SiPM	Max. photon counts	5% non-linearity
HPK S13360-6025PE	57600	19592
HPK S14160-3010PS	89984	53747
NDL EQR06 11-3030D-S	244719	1106210

- The non-linear behaviors of SiPM are delayed due to the long decay time of BGO scintillation.
- SiPMs with 10μm pixels are potentially sufficient for CEPC crystal ECAL.

Summary

- Design an experiment to measure the intrinsic dynamic range of SiPMs with large pixel numbers under pico-second laser.
- Build a MC model for simulating the SiPM response to BGO scintillation. The simulation results show that SiPM with 10μm pixels can keep a linear response within the 30GeV (337k p.e. per channel) energy dynamic range.