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Highly Granular Crystal Calorimeter: Development Status

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On behalf of CEPC Calorimeter Working Group

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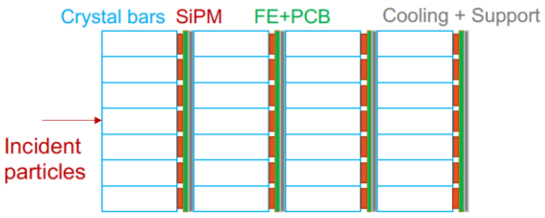
Motivations

- Background: calorimeter for future lepton colliders (e.g. CEPC)
  - Precision measurements with Higgs and Z/W
  - Jet energy resolution of 3-4%@100GeV is required
  - Particle flow approach: high-granularity calorimeter
- Why crystal calorimeter?
  - Homogeneous structure
    - Intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Energy recovery of electrons: to improve Higgs recoil mass
  - Capability to trigger single photons: precision γ/π^0 reconstruction
  - Focus on low energy particle measurement

Physics process	Measurands	Critical detector	Required performance
$ZH \to l^+l^-X$	m_H, σ_{ZH}	Tracker	$\Delta(1/P_T) = 2\times10^{-5} \oplus \frac{10^{-3}}{P(GeV)\sin^{\frac{3}{2}}\theta}$
$H \to \mu^+\mu^-$	$B(H \to \mu^+\mu^-)$		
$H \to b\bar{b}, c\bar{c}, gg$	$B(H \to b\bar{b}, c\bar{c}, gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(GeV)\sin^{\frac{3}{2}}\theta}(\mu m)$
$H \to q\bar{q}, W^+W^-, ZZ$	$B(H \to q\bar{q}, W^+W^-, ZZ)$	Calo	$\sigma_E^{jet} = 3 \sim 4\%\ @100GeV$
$H \to \gamma\gamma$	$B(H \to \gamma\gamma)$	ECAL	$\frac{\Delta E}{E} = \frac{0.20}{\sqrt{E(GeV)}} \oplus 0.01$

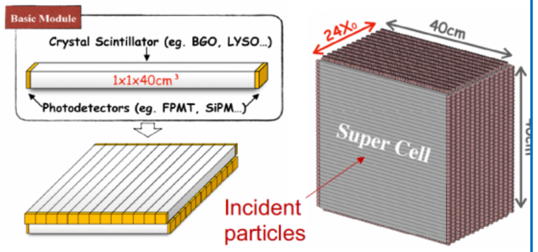
Our major concern

Design 1: short bars

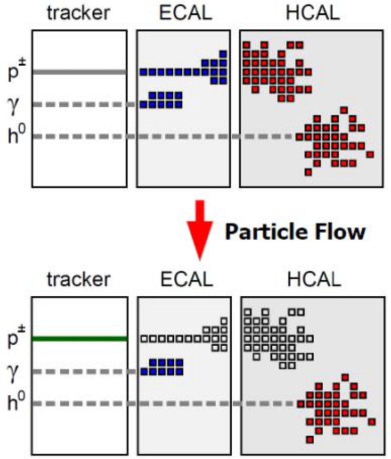


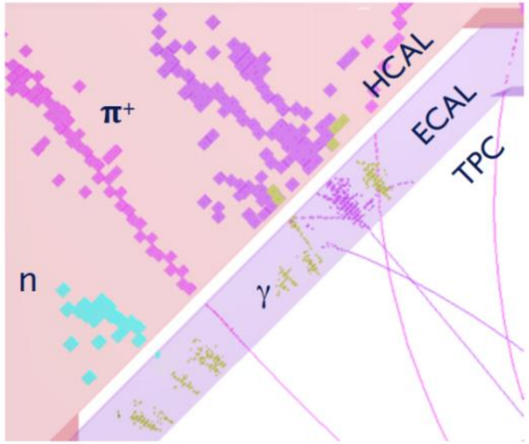
- A natural design compatible with PFA
  - Fine segmentation in Both longitudinal and transverse
  - Single-ended readout with SiPM

Design 2: long bars



- Long bars: 1×40cm, double-sided readout
  - Super cell module: 40×40cm
  - Crossed arrangement in adjacent layers
  - Fine longitudinal granularity
- Save #channels and minimize dead materials
- Timing at two sides: positioning along bar





Overview of this report: development status

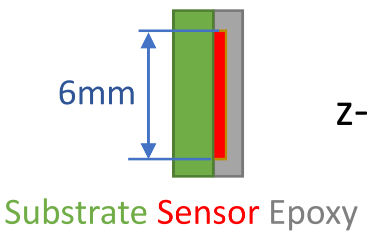
Development of crystal ECAL:

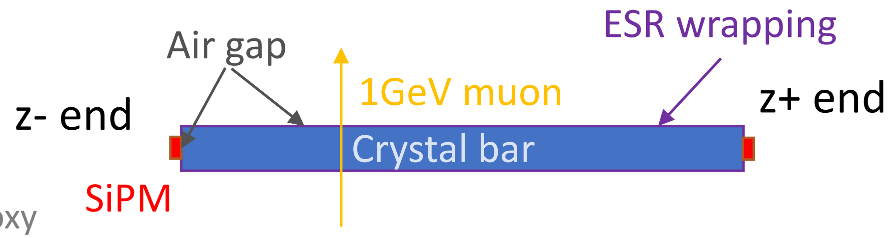
- Geant4 full simulation study
  - Response uniformity of a single crystal bar
  - 2D uniformity scan of crystal module
  - Non-uniformity: Impact on energy resolution
- Characterizations of crystals and SiPMs
  - SiPM calibration with picosecond laser
  - Uniformity scan with 400 mm BGO crystal bar
- Small-scale detector module design: first glance

Simulation study: response uniformity of a single crystal bar

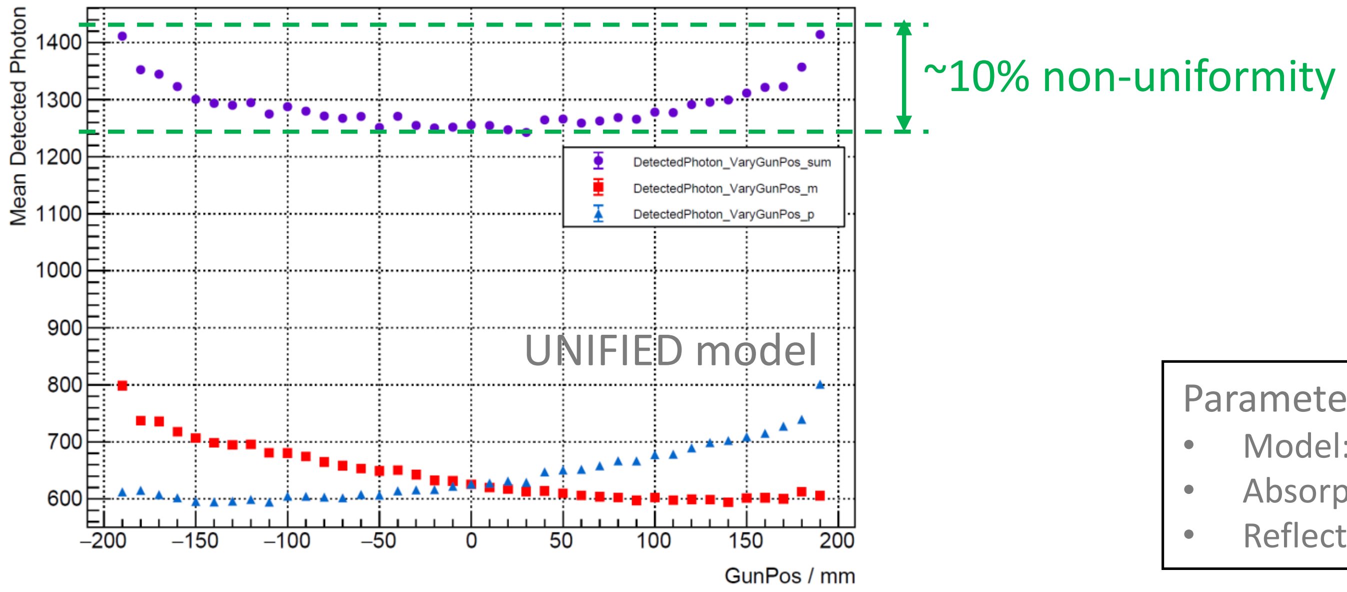
Geant4 Simulation (v10.7.3)

- Geant4 optical simulation
  - A single BGO crystal bar wrapped with ESR reflector
- Physics processes
  - Scintillating & Cherenkov
  - Boundary processes and absorption
  - SiPM modelling: geometry and response (PDE)





MIP response vs hit position



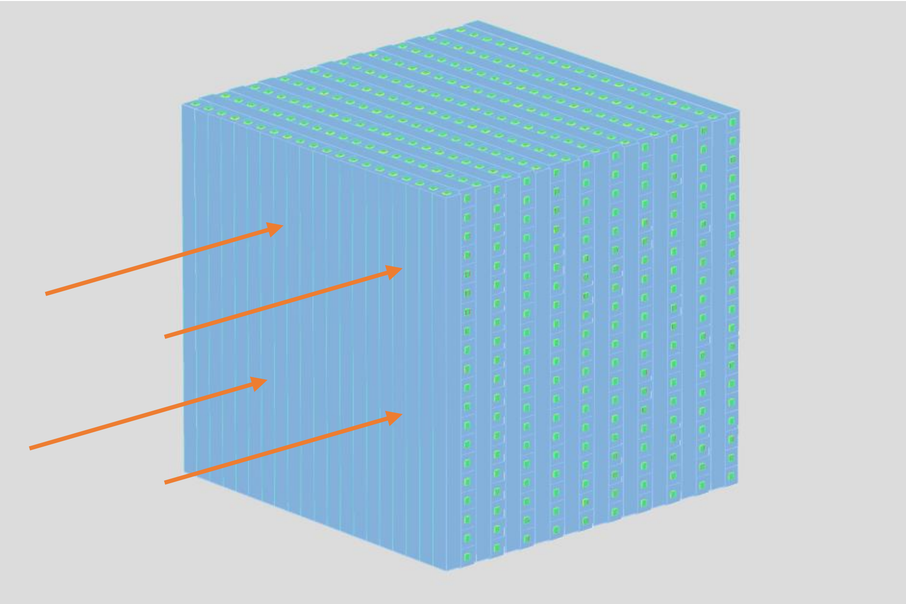
- Over 1000 photons detected in a single crystal bar
- ~10% non-uniformity under the current simulation parameters
- Simply described by a quadratic function

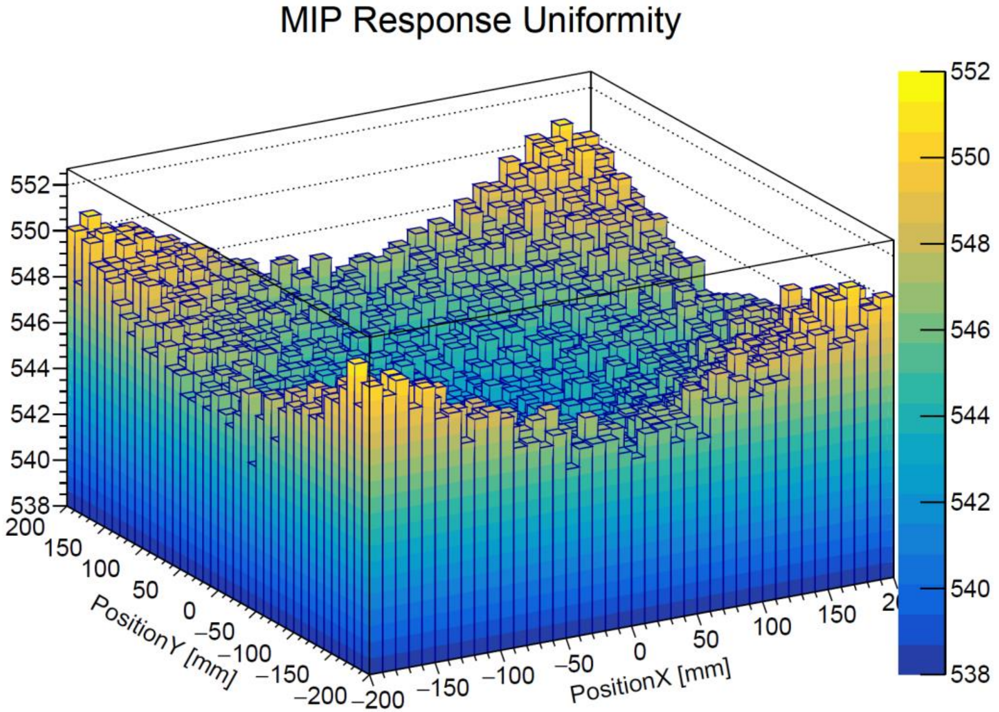
Parameters
- Model: UNIFIED, with adjustable surface roughness
- Absorption length, emission spectrum: measured data
- Reflectivity, Rindex, SiPM PDE…: available data from documentations

Simulation study: response uniformity of crystal ECAL module

Geant4 Simulation (v10.7.3)

- Simulation setup
  - 10×10×400 mm^3 BGO crystal Bar
  - Crossed bar, 40×40×60 module
  - 1 GeV muon, 2D uniformity scan
  - Response has been parameterized (simulated without optical process)



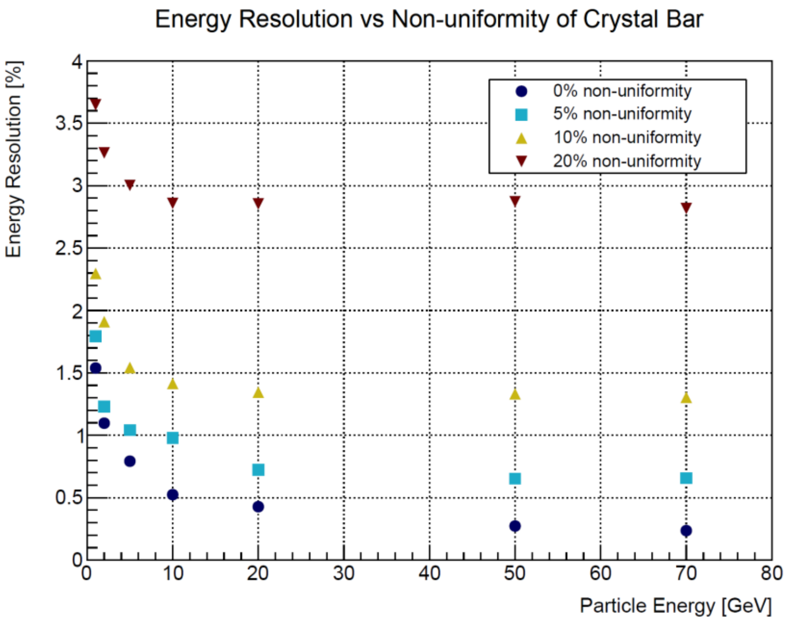


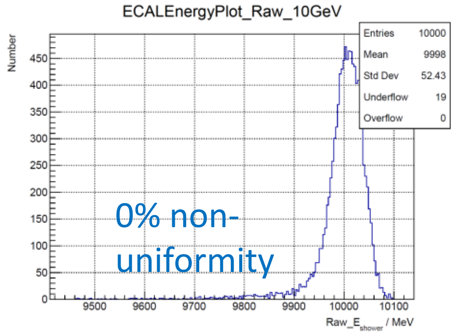
- MIP Response of four corners is higher
- 2D non-uniformity seems lower than 10%
- Calibration constants depend on hit positions
  - Good reconstruction algorithm is required

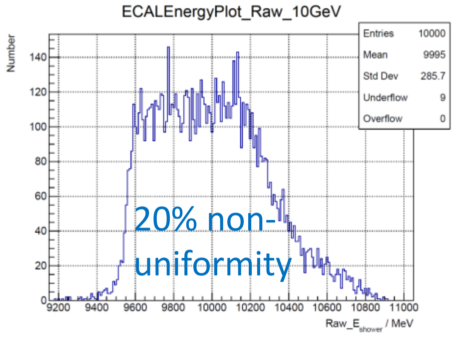
Simulation study: response uniformity of crystal ECAL module

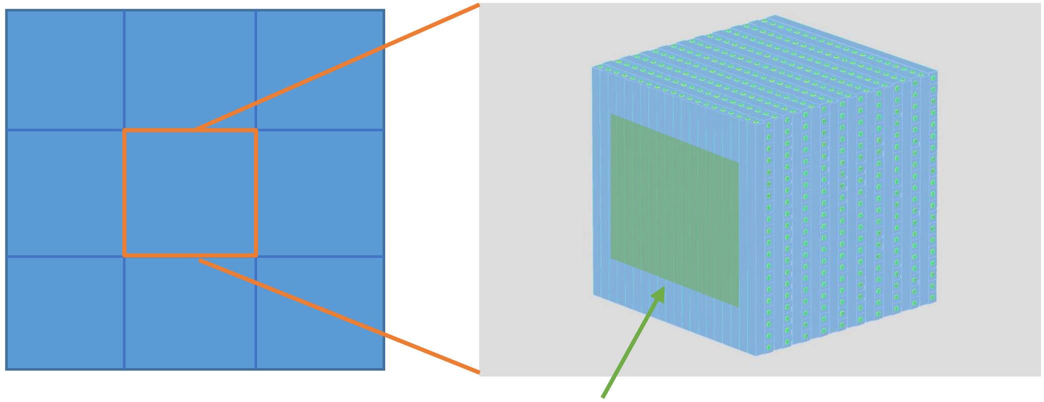
Geant4 Simulation (v10.7.3)

- Impact on energy resolution
  - 1-100 GeV electron
  - 3×3 modules are used to prevent energy leakage
  - Digitization and energy calibration have been implemented
  - Energy resolution = Mean/StdDeV









Incident particles randomly hit this area of the middle module

- For higher value of non-uniformity, the distribution of energy tends to be non-Gaussian
- Severe distortion of energy resolution
- Response non-uniformity of a single crystal bar need to be considered

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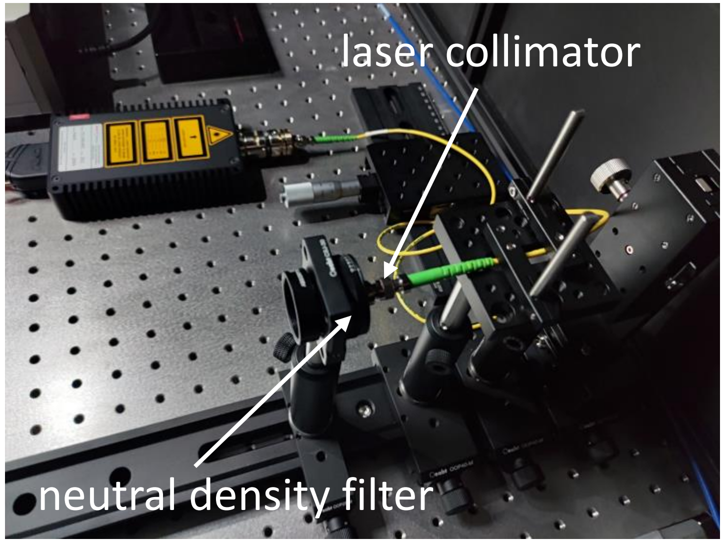
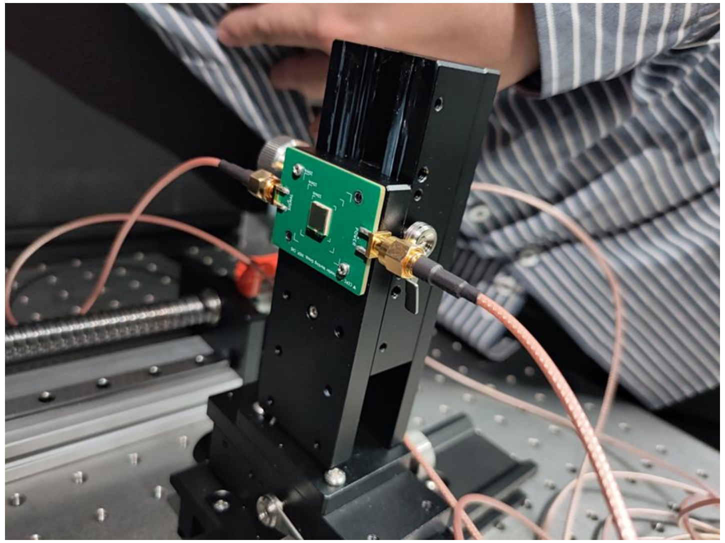
Characterizations of crystals and SiPMs: laser calibration of SiPMs

- Test stand setup
  - 405nm picosecond laser
    - Pulse width typically < 60 ps
    - Timing jitter < 3 ps rms
  - 0.1% transmittance neutral density filter to reduce laser intensity
  - Laser collimation: spot diameter < 1mm
  - Preamplifier with adjustable gain

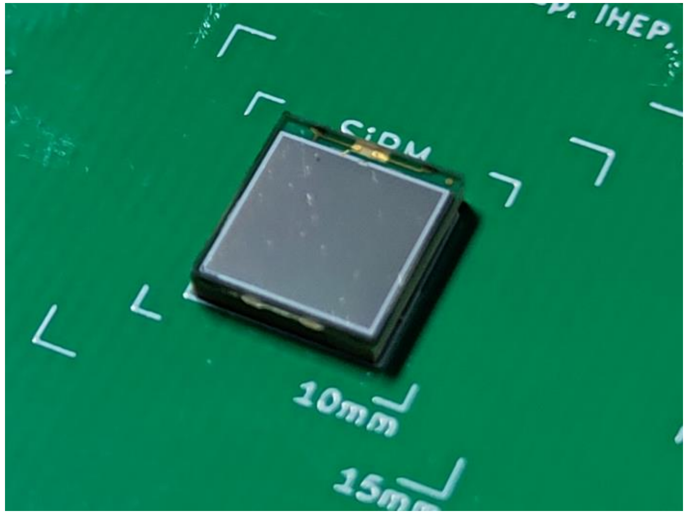




Characterizations of crystals and SiPMs: laser calibration of SiPMs

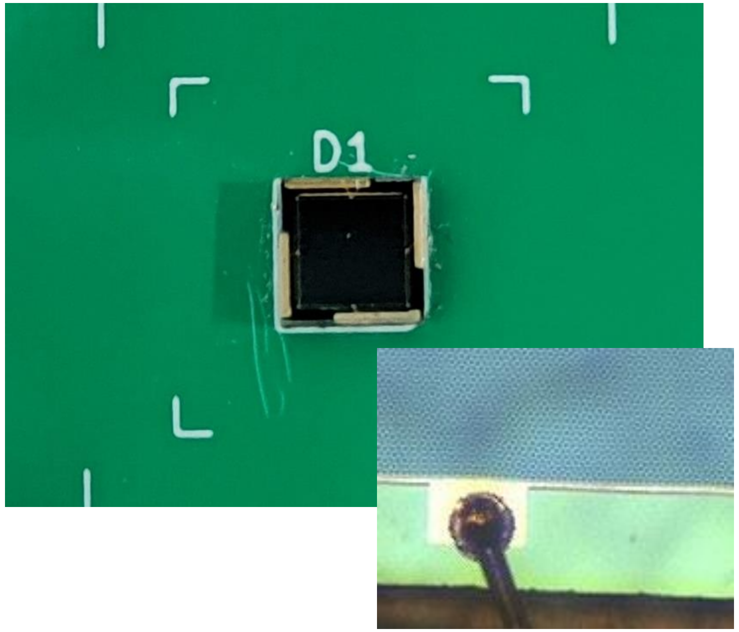
- DUT: HPK & NDL SiPMs

HPK S13360-6025PE



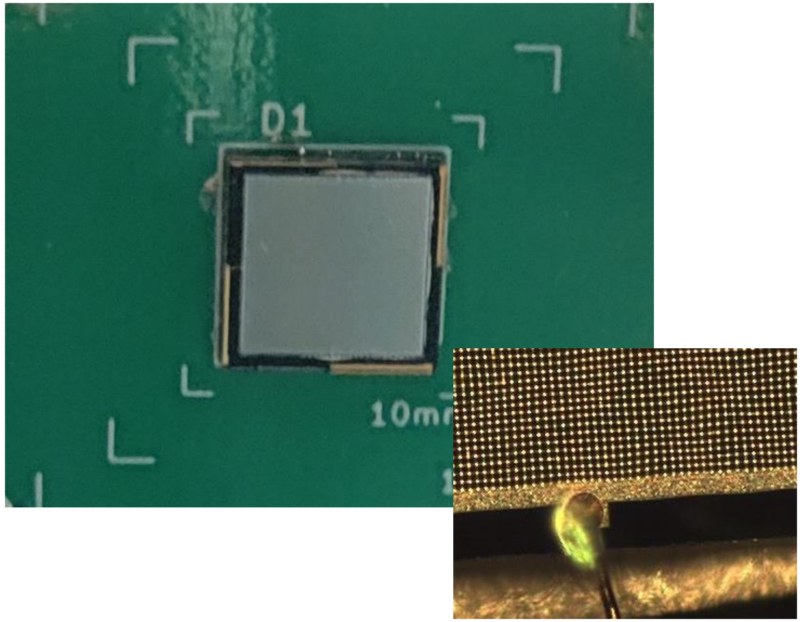
- 6×6 mm^2
- 25 µm pixel × 57600
- Nominal gain 7×10^5

NDL EQR06 11-3030D-S



- 3×3 mm^2
- 6 µm pixel × 244720
- Nominal gain 8×10^4

NDL EQR15 11-6060D-S

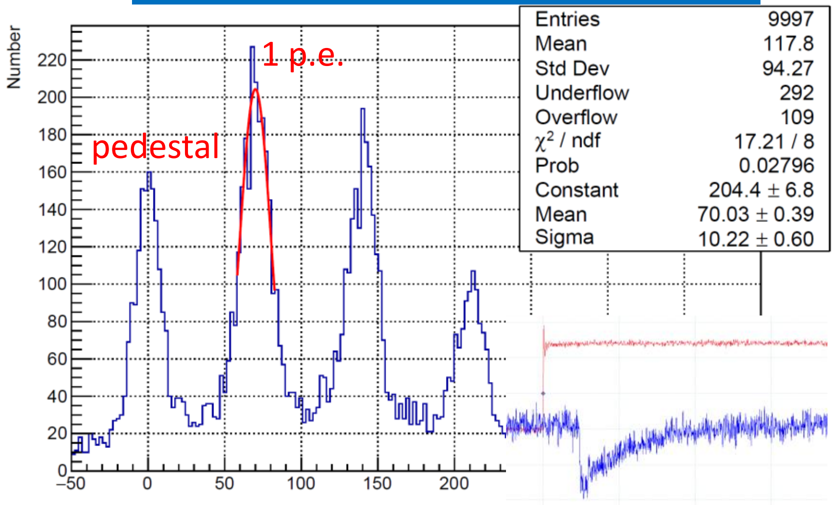


- 6×6 mm^2
- 15 µm pixel × 160000
- Nominal gain 4×10^5

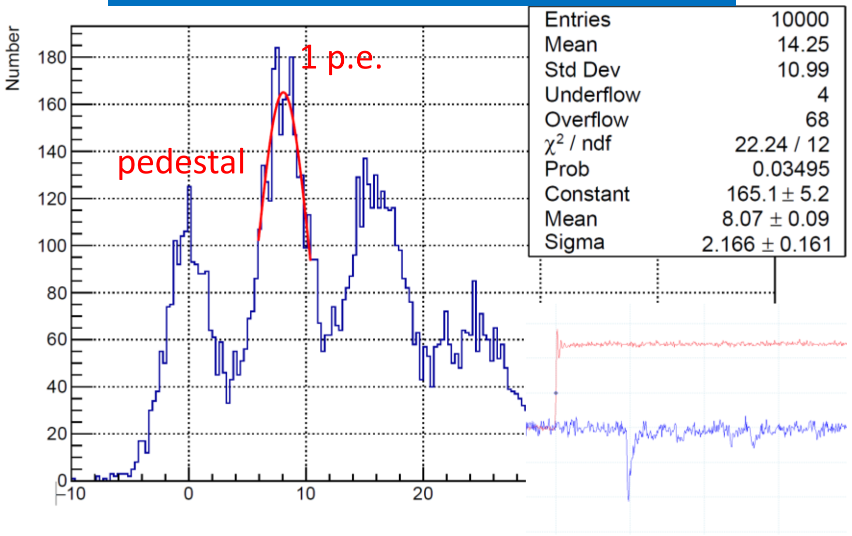
Characterizations of crystals and SiPMs: laser calibration of SiPMs

- Single photon spectrum

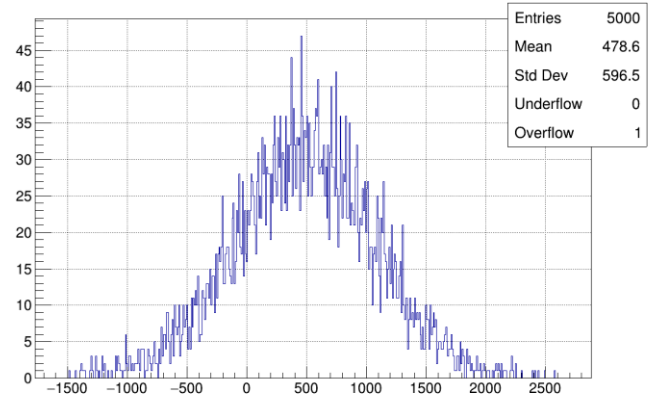
HPK S13360-6025PE

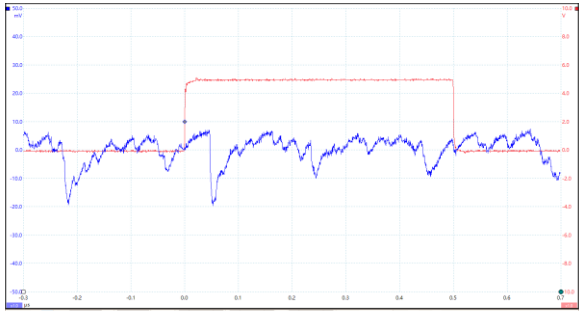


NDL EQR06 11-3030D-S



NDL EQR15 11-6060D-S





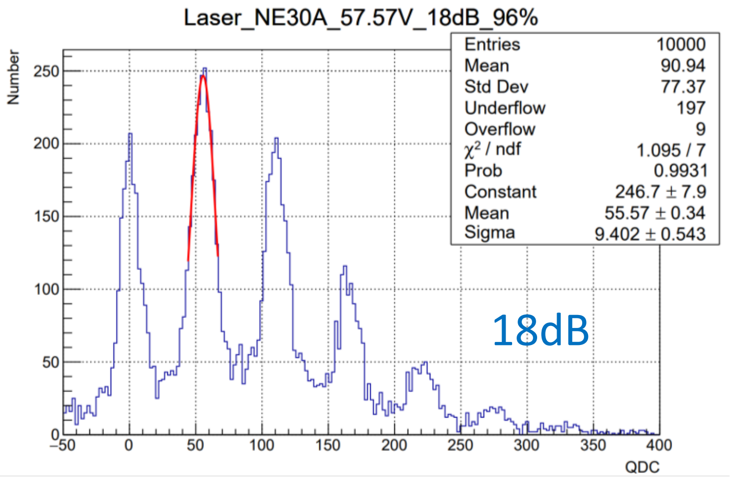
- Gain crosscheck: HPK S13360-6025PE vs NDL EQR06 11-3030D-S
  - 7×10^5 / 8×10^4 ≈ 70.03 / 8.07
- NDL EQR06 11-3030D-S
  - More pixels, narrower pulse shape
  - Worse single photon peak resolution
- Criteria for SiPMs: pixel size / gain / capability of single photon detection…

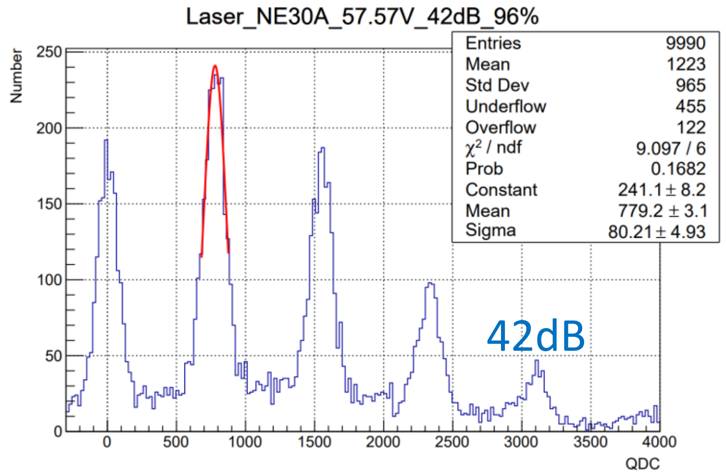
- Too many thermal noise signals
- Unstable baseline
- Unable to perform single photon calibration

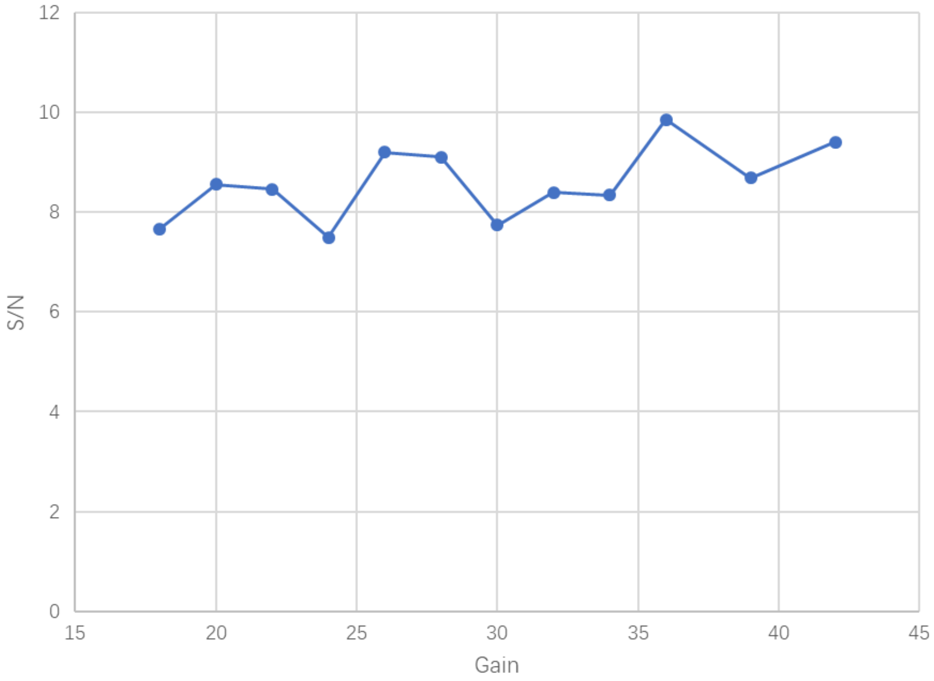
Characterizations of crystals and SiPMs: laser calibration of SiPMs

- S/N versus gain of preamplifier

$$S/N = \frac{\mathrm{Mean}_{1p.e.}}{\mathrm{Sigma}_{pedestal}}$$





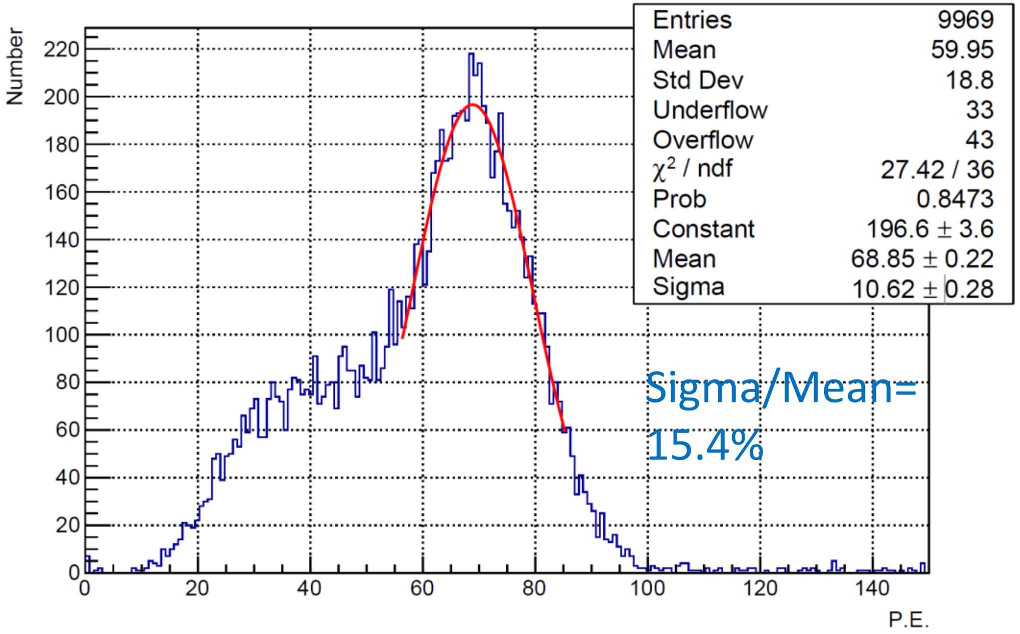


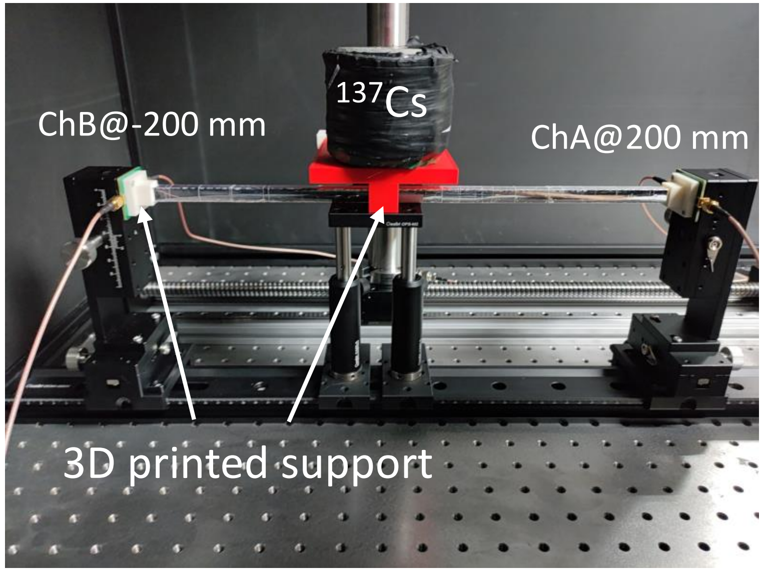
- S/N did not change significantly form 18 dB to 42 dB
- Operation under low gain can increase the dynamic range

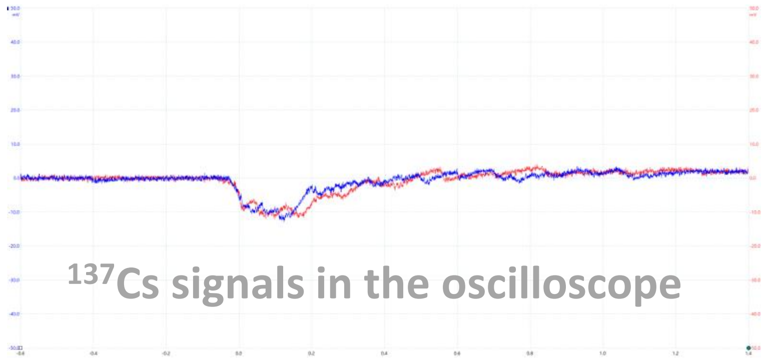
Characterizations of crystals and SiPMs: radioactive source test of BGO crystal

- Uniformity scan: 662keV gamma form ^{137}Cs, change hit positions
  - 400×10×10 mm^3 BGO crystal bar, ESR wrapping
  - 6×6 mm^2 SiPMs, air coupling
  - Fit the 662keV photopeak to get corresponding #photons

Detected photon: ChA



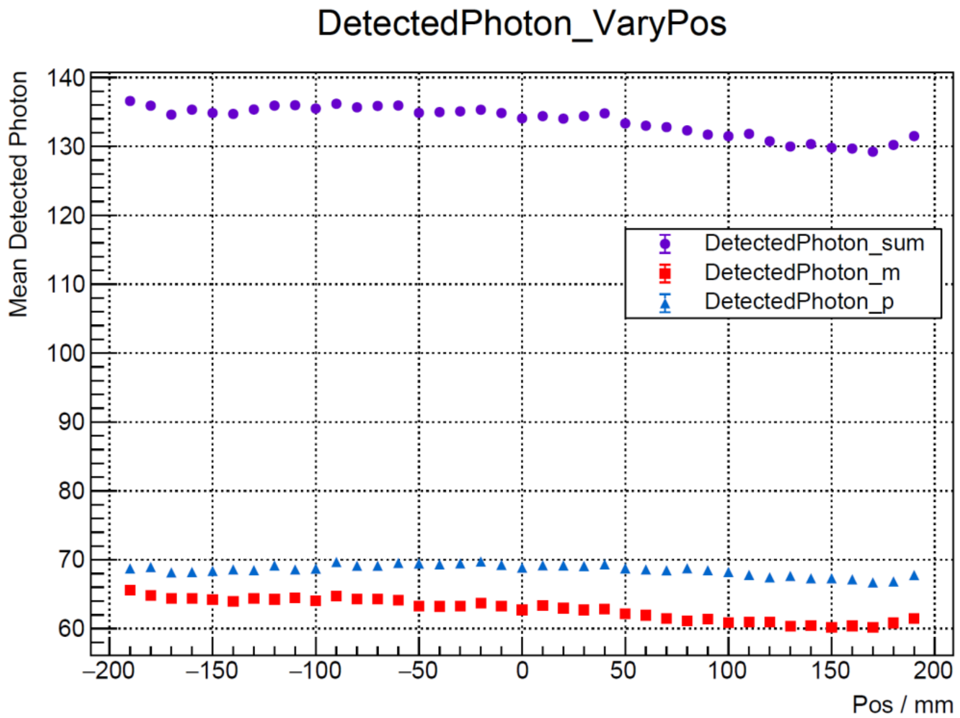


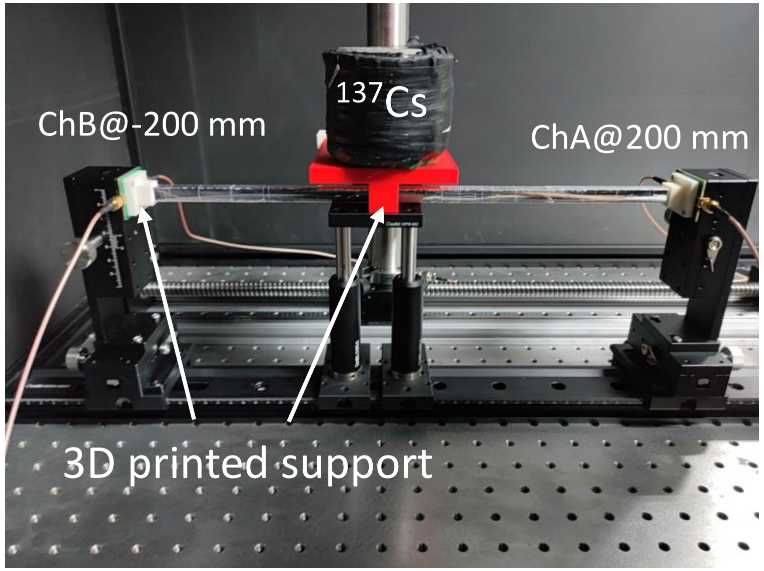


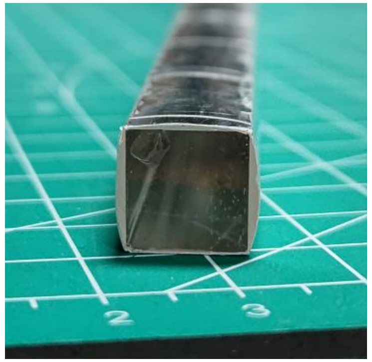
- Energy resolution for 662keV photon: 15.4%

Characterizations of crystals and SiPMs: radioactive source test of BGO crystal

- Uniformity scan: 662keV gamma for ^{137}Cs, change hit positions







- Attenuation effect seems different than expected in simulation, relatively low response near one side
- Potential factors related to crystal manufacture
  - Light yield / transmittance difference along the direction of crystal growth
  - Difference between the surfaces of two ends

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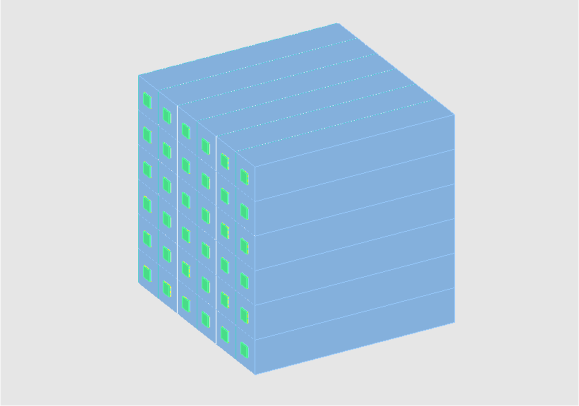
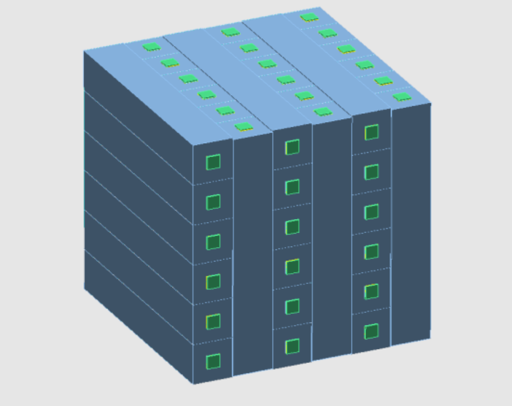
Small-scale detector module design: first glance

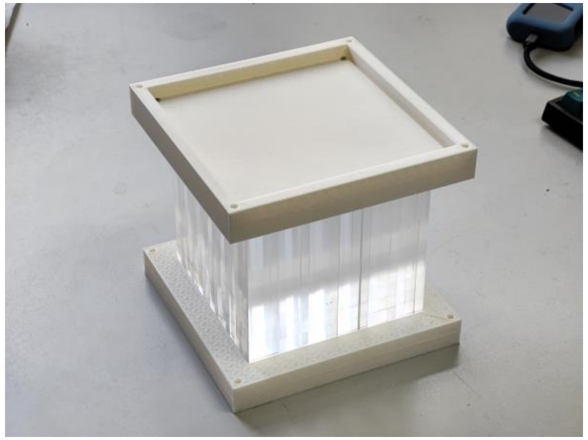
- Motivations: crystal module development
  - EM shower profiles are intrinsically compact
    - e.g. R_M = 2.26 cm for BGO
  - Small-scale modules is sufficient for EM showers
  - Crucial to have beam tests for system level studies
  - Identify critical questions/issues for the final detector
  - Evaluate performance with data and to validate simulation
- Geant4 simulation studies
  - Crystal module ($12\times12\times12$ cm^3)
    - 6×6 crystal matrix (36 ch ASIC readout)
    - 6 layers of crystal bar with crossed arrangement, double-sided readout (4×18 ch ASIC readout)
  - Beam test setup:
    - Use two modules to provide sufficient longitudinal depth (21.4 X_0)



6×6 crystal matrix



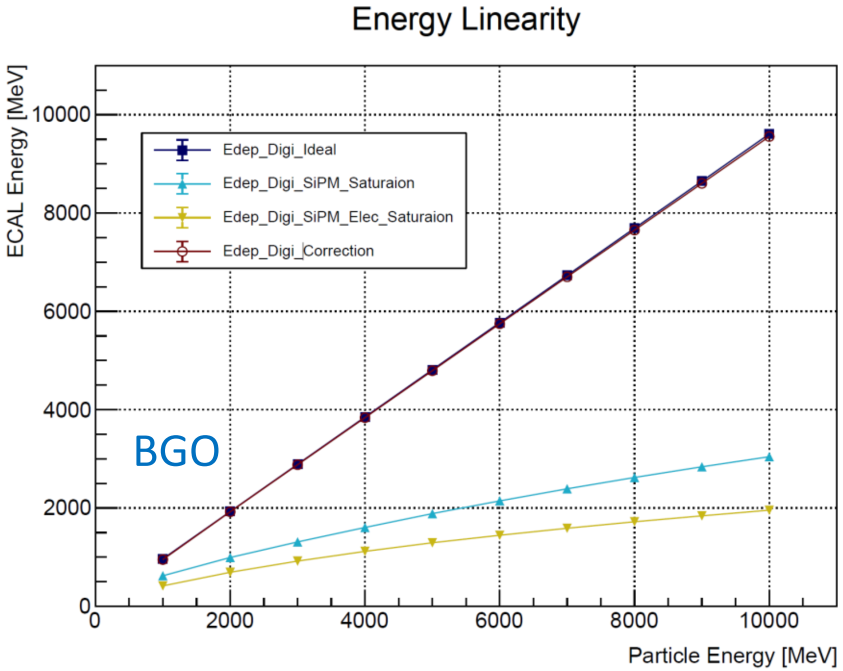
crossed crystal bar

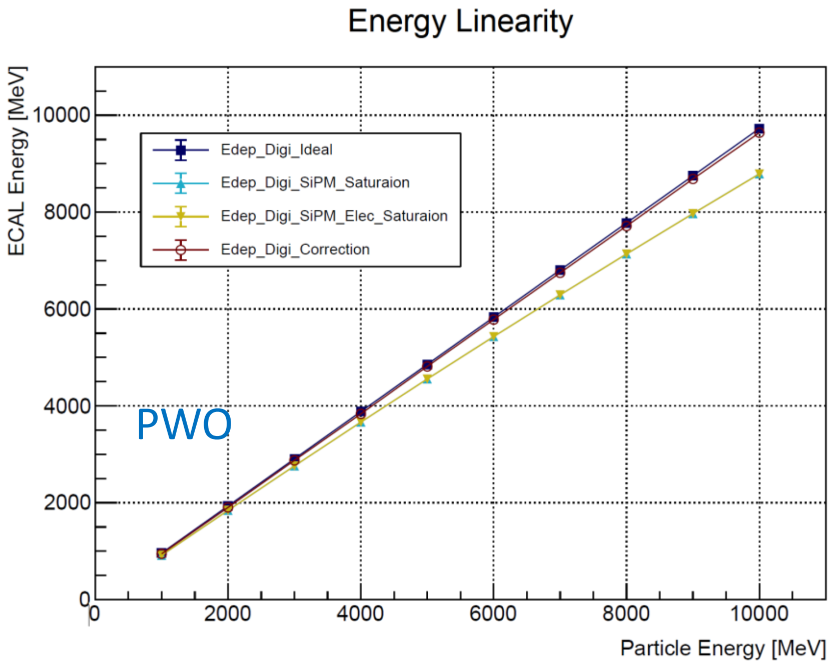


A dummy crystal matrix with 3D printed support structure

Small-scale detector module design: first glance

- Simulation of BGO/PWO crystal matrix for beam test





- DESY: 1-6 GeV electrons; CERN PS: 1-15 GeV muons/electrons/hadrons
- Saturation effects: severely degrade energy linearity (as well as resolution)
- Deal with saturation
  - Adjust the fluorescence property of BGO crystal (collaboration with SIC, CAS), neutral density filter, Si-PIN photodiode…
- Realistic mechanical and electronic design

Summary

- Geant4 full simulations
  - Response uniformity from single crystal bar to ECAL module
- Measurements on SiPMs and crystals
  - SiPM laser calibration, radioactive source test and cosmic-ray test
- Small-scale detector module design
  - Preparing for beam test, still many issues to be addressed