



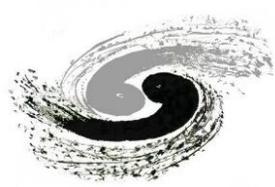
BSO crystal R&D progress: status report

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CEPC Physics and Detector Plenary Meeting

March 18, 2026

1. Shanghai Institute of Ceramics, Chinese Academy of Sciences
2. Institute of High Energy Physics, Chinese Academy of Sciences
3. Shanghai Jiao Tong University and Tsung-Dao Lee Institute
4. Lanzhou University



Outline

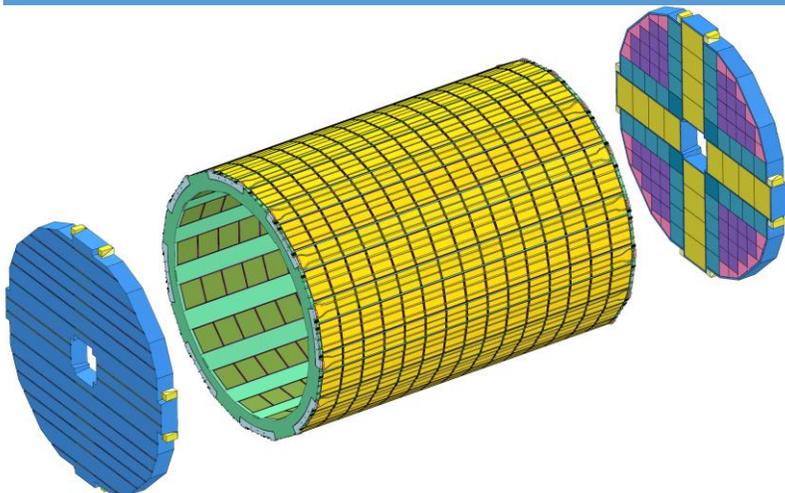
- Motivation: why BSO?
- Recent breakthroughs on large BSO crystals at SIC
- BSO crystal performance studies: lab and beam tests



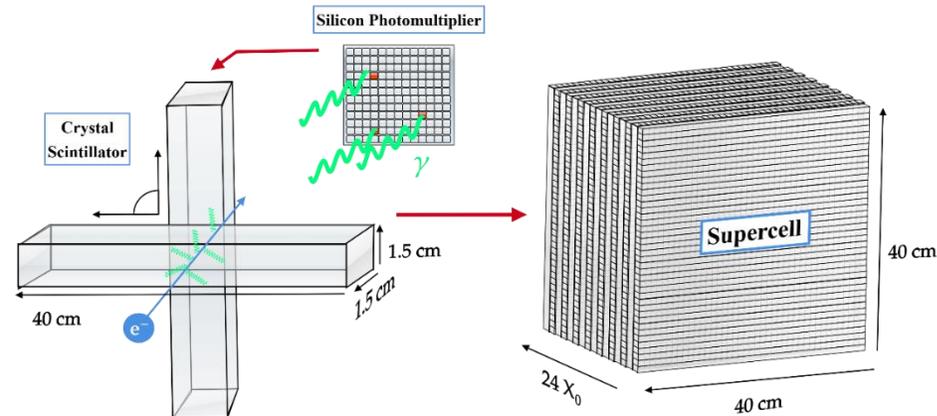
High-granularity crystal calorimeter (HGCCAL): recap

- **Baseline ECAL option for the CEPC Reference Detector**
- **Compatible for PFA:** Boson mass resolution (BMR) < 4%
- **Optimal EM performance:** $\sigma_E/E < 3\%/\sqrt{E(\text{GeV})} \oplus 1\%$
- Long crystal bars in orthogonal arrangement
 - Minimum longitudinal dead material
 - Significant reduction of readout channels

Mechanics design: barrel + endcaps



Module schematics



- **ECAL design features: high granularity, modularity and hermeticity**
 - Nominal crystal bar dimensions: $15 \times 15 \times \sim 400 \text{ mm}^3$
 - Transverse (effective) granularity: $15 \times 15 \text{ mm}^2$
 - Total depth of $24 X_0$ with 18 longitudinal layers
- In total ~ 700 modules, 571k channels, **$\sim 24.2 \text{ m}^3$ crystals**
- BGO selected as the baseline crystal option: mature technology
- BSO as an alternative option: potentially **cost effective**



Motivation: why BSO?

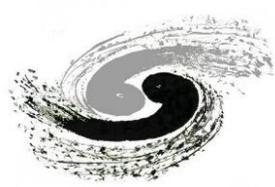
- CEPC Reference Detector: cost breakdown
 - ECAL based on BGO crystals: 34.5% of the total cost
- BSO as an alternative crystal option
 - **Potentially cost effective**, without using Germanium (*a major cost driver for BGO*)

Table 16.1: The CEPC Reference Detector cost breakdown.

System	Cost (MCHF)
The Reference Detector	333.3
Machine detector interface and luminosity measurement	1.8
Vertex detector	4.5
Silicon tracker	29.7
Time projection chamber	6.2
Electromagnetic calorimeter	115.0
Hadron calorimeter	68.3
Muon detector	2.5
Detector magnet system	22.0
Readout electronics	19.3
Trigger and data acquisition	12.2
Offline software and computing	23.1
Mechanics and integration	28.9

- BSO performance advantages
 - **Faster scintillation time** (100ns) than BGO (300ns)
 - **High transmittance in UV region**: capable to exploit Cherenkov photons (e.g. dual-readout, fast timing)
- BSO technical challenges: to be addressed
 - **Difficult for large-scale crystal growth**
 - **Limited optical quality**: defects, low transmittance, etc.

CEPC Technical Design Report - Reference Detector: [arXiv:2510.05260](https://arxiv.org/abs/2510.05260)



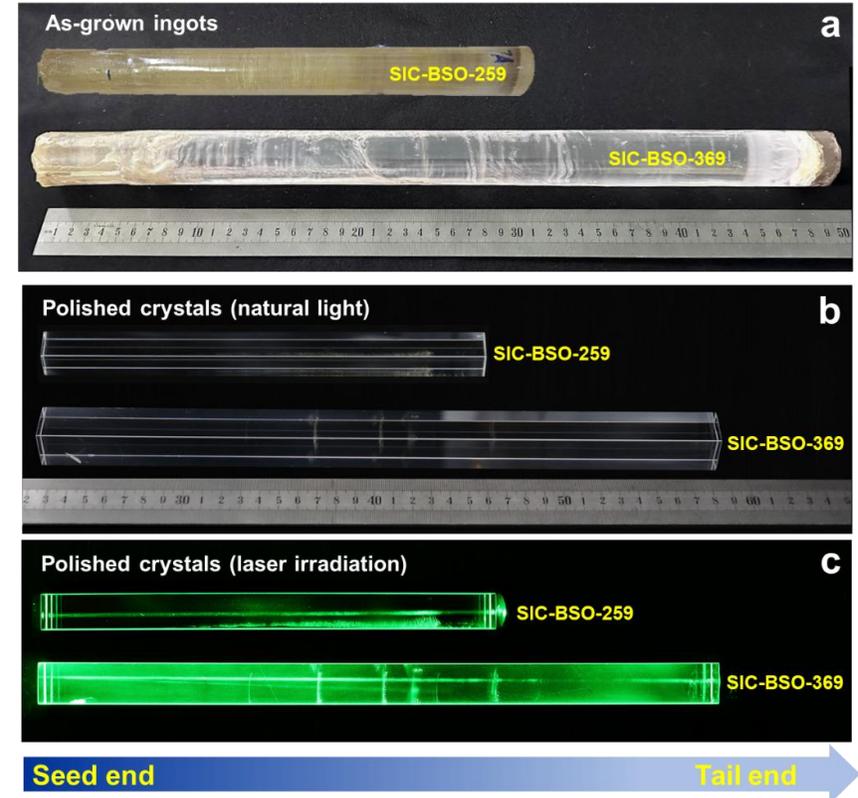
History and Recent Breakthroughs on Large BSO Crystals

- The challenge of growing high optical quality BSO crystals to large size has remained unsolved for 54 years.

Year	Growth technique	Size (mm ³)	LO	ER	LRU
1971	Czochralski	-	-	-	-
1983	Czochralski	φ25×50	20%	30%	-
1996	Bridgman	φ25×90	20%	31%	-
1997	Bridgman	φ28×187	25%	22%	±2%
2002	Bridgman	23×23×188	20%	32%	±2%
2008	Micro-pulling-down	φ0.1–1.0	-	-	-
2011	Czochralski	10×8×5	26%	22%	-
2012	Bridgman	40×40×210	21%	17%	< ±2%
2013	Bridgman	φ25×100	-	-	-
2016	Bridgman	30×30×210	25%	19%	-

The maximum dimension is 210 mm.

Junfeng Chen, Mingxue Deng (SIC-CAS)

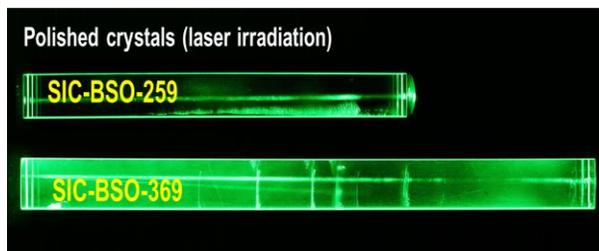
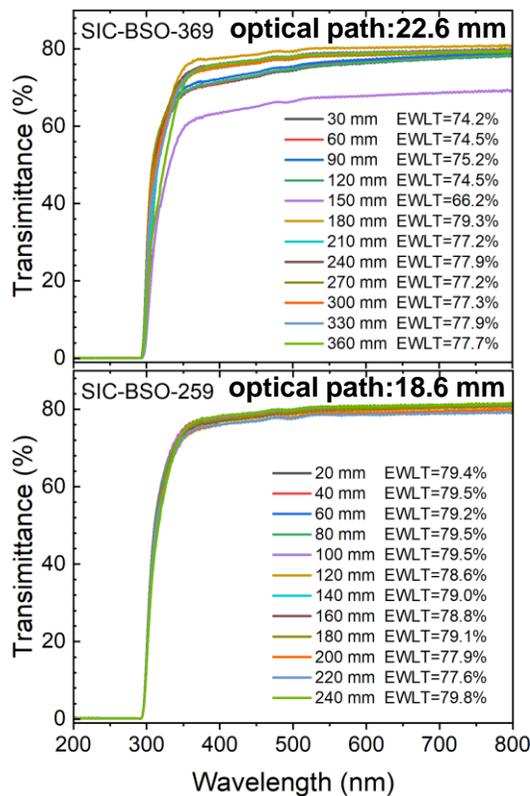


- BSO crystals ingots with φ30 mm × 300 mm and φ33 mm × 495 mm were grown at SICCAS.
- Crystals with dimensions of 22.6 mm × 22.6 mm × 369 mm and 18.6 mm × 18.6 mm × 259 mm have been cut and processed from the ingot.

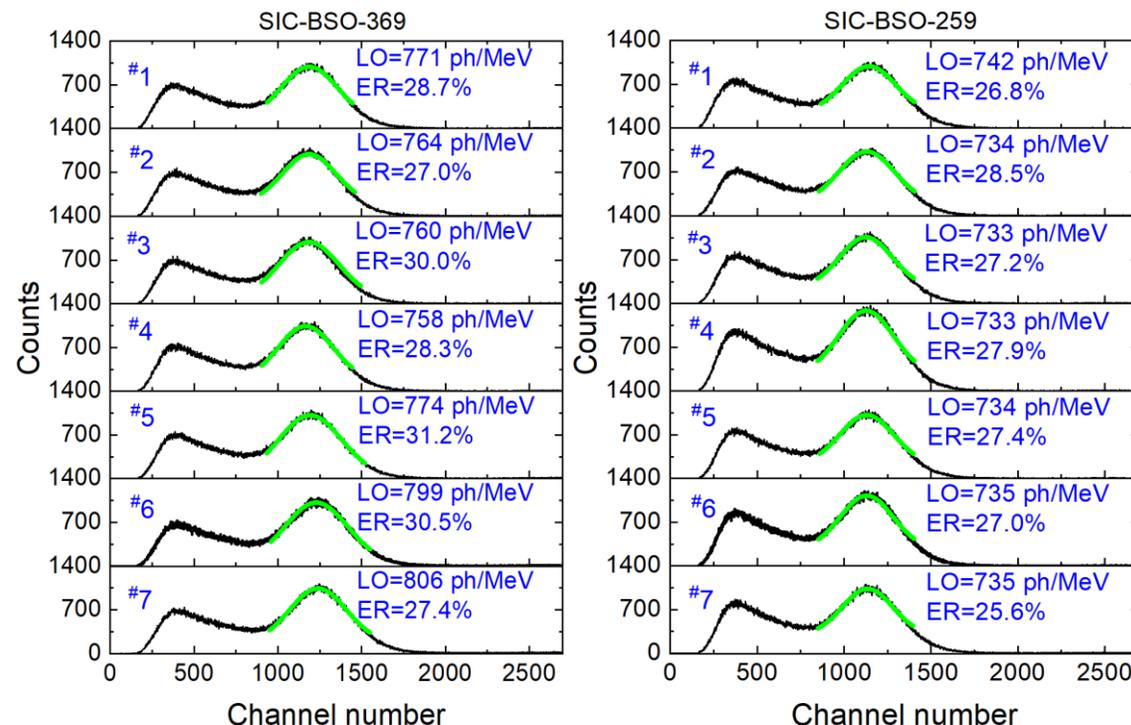
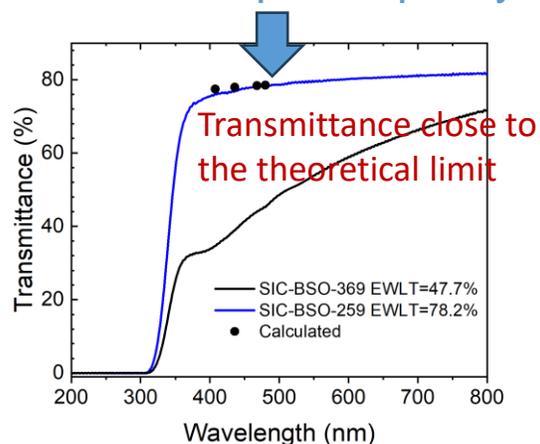


Optical and Scintillation Properties of Large BSO Crystals

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Excellent optical quality

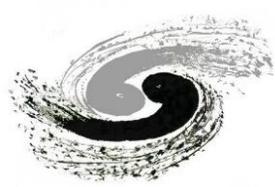


ORTEC TrumpTM-PCI-2k MCA card, shaping time: 0.5 μ s). ESR reflective layer. Hamamatsu R2059 PMT with 2000V, silicone grease (Dow Corning DC-200).

Transverse vs Longitudinal transmittance

Pulse height spectra

- **SIC-BSO-259 crystal:** 78.32% @480nm(LT), nearly 80% in 350–800nm (uniform TT), LO: 735 ph/MeV
- **SIC-BSO-369 crystal:** 45.27% @480nm(LT), 60-79% in 350–800nm (TT), LO: 776 ph/MeV



Light Response Uniformity (LRU) of Large BSO Crystals

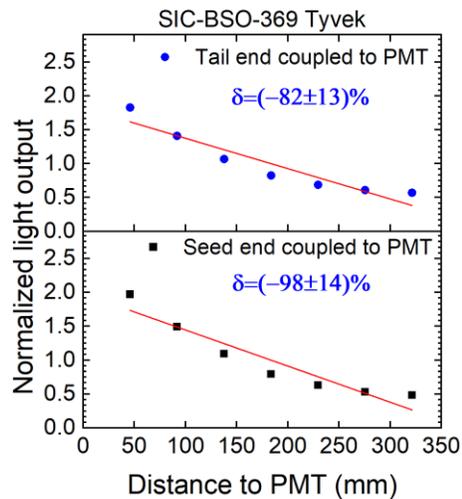
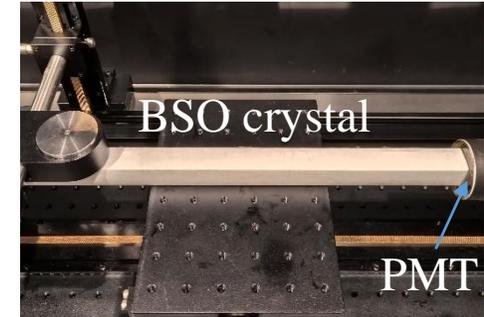
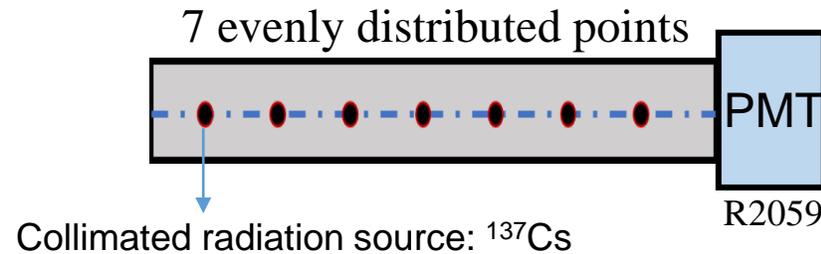
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Effects of different surface treatments on light response uniformity (LRU)

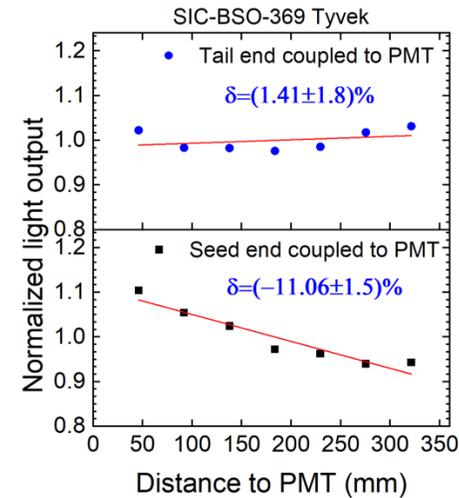
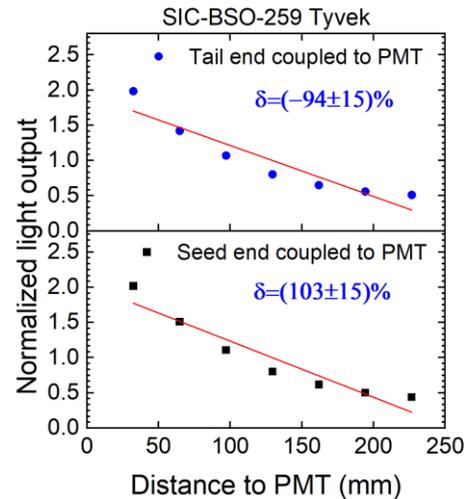
Calculation method of LRU:

$$\frac{LO}{LO_{ave}} = 1 + \delta \left(\frac{X}{X_{mid}} - 1 \right)$$

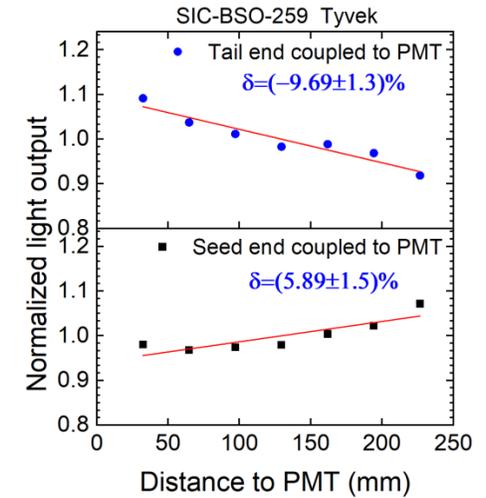
δ : the deviation of LRU.



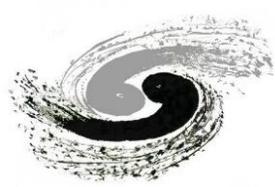
LRU of BSO: Frosting



LRU of BSO: All surfaces polishing



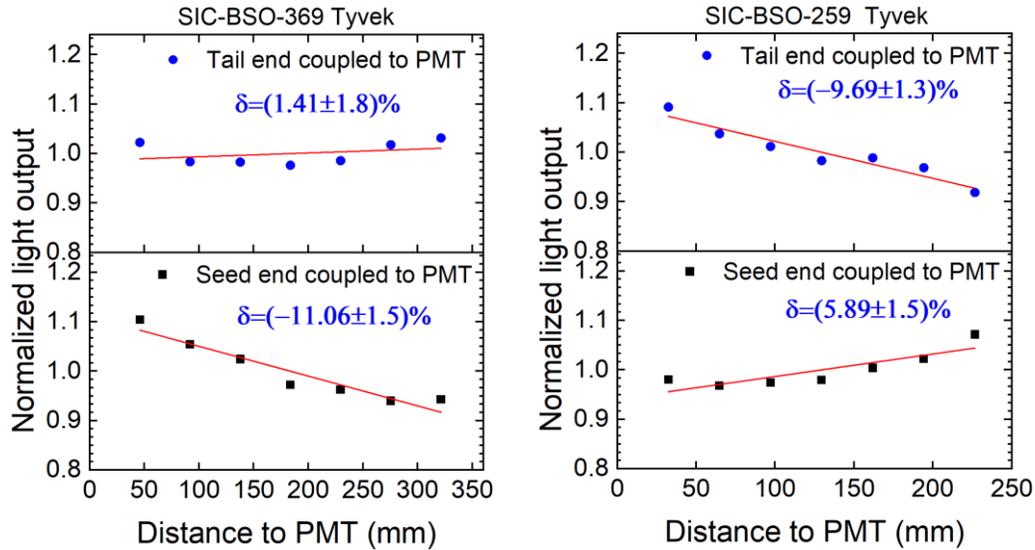
- After polishing, the uniformity of light response was significantly improved compared to the frosting state.



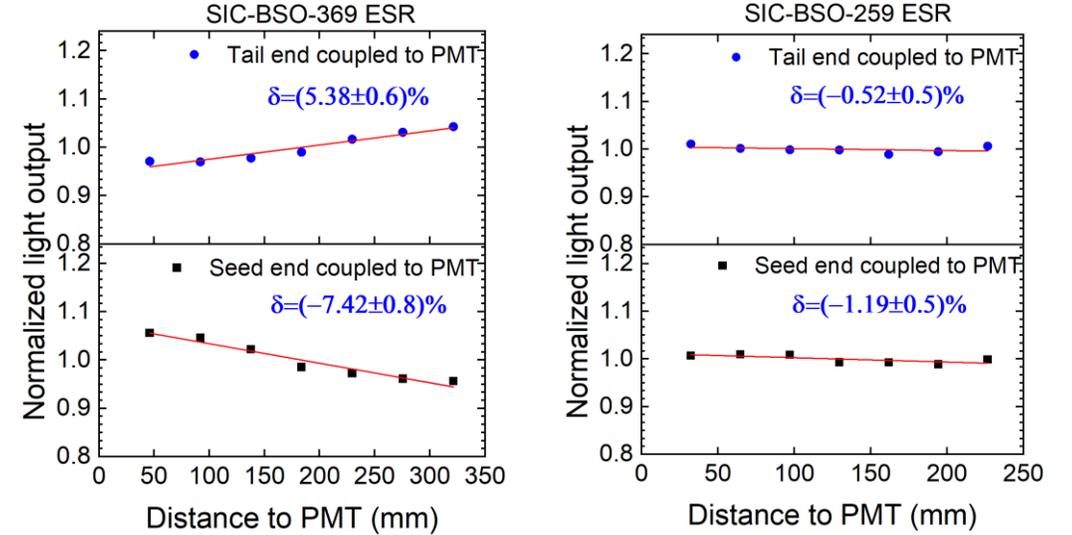
Light Response Uniformity (LRU) of Large BSO Crystals

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Impact of the Reflector Layer (Tyvek and ESR) on LRU



LRU of BSO with Tyvek wrapping layer



LRU of BSO with ESR wrapping layer

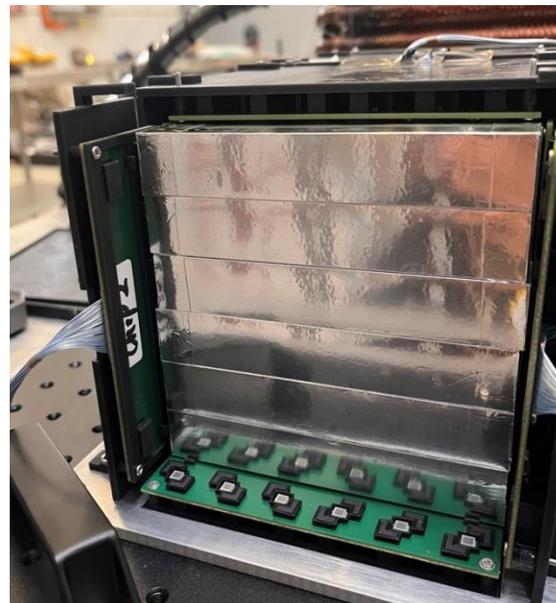
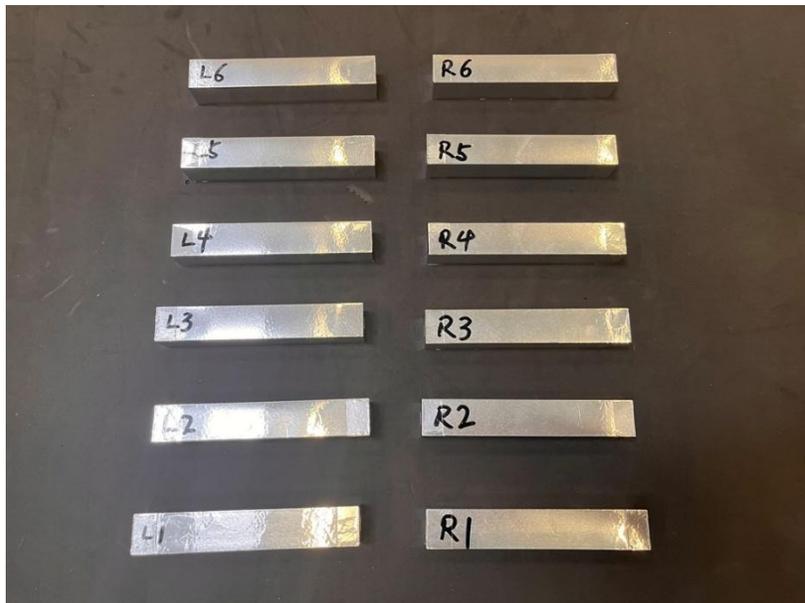
- ESR wrapping crystals further enhances light response uniformity.
- SIC-BSO-259 shows excellent light response uniformity ($\delta = -1.19 \pm 0.5\%$ and $-0.52 \pm 0.5\%$ at seed and tail ends) when fully polished and wrapped with ESR. This is superior to the uniformity of $\pm 2\%$ for the 188/187 mm long BSO crystals reported by M. Kobayashi.

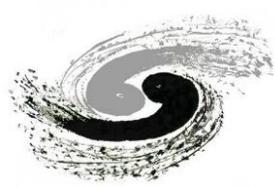




BSO crystal performance studies

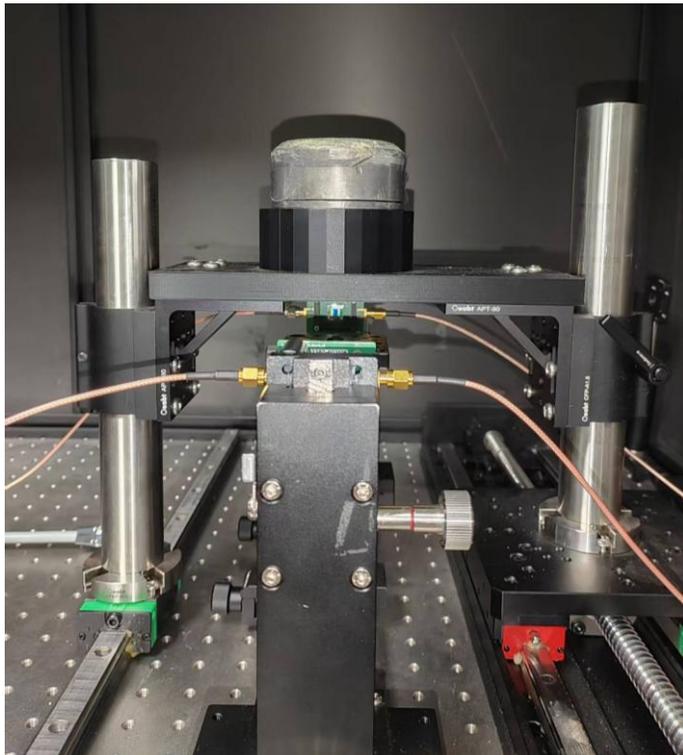
- Motivation
 - To quantify performance of first batches of 15 BSO crystals ($2 \times 2 \times 12 \text{ cm}^3$)
- Beam and lab tests
 - BSO crystals (**wrapped with ESR**) were tested with Cs-137 and with pion beams
 - Response and intra-uniformity were measured **with SiPMs at both ends**





BSO crystals: radioactive source tests

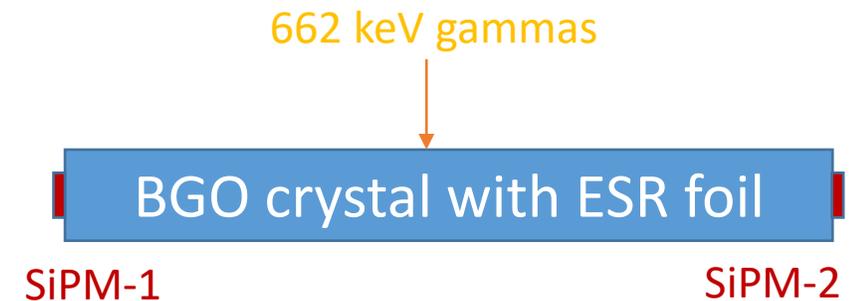
- Lab test stand
 - One crystal bar was tested once (readout with SiPMs at both ends)
 - 1D moveable stage with Cs-137 source
 - Capable to scan along crystal length: **compatible with long crystals (up to 40 cm)**



- Full energy spectrum of 662 keV gammas
 - Mean response in $N_{p.e.}$
 - Energy resolution in percentage
 - Response uniformity in percentage

Setup technical details

- Two SiPMs: HPK S13360-6025PE
- Readout electronics: preamplifier + oscilloscope for waveform sampling
- Temperature: $21 \pm 0.5^\circ\text{C}$



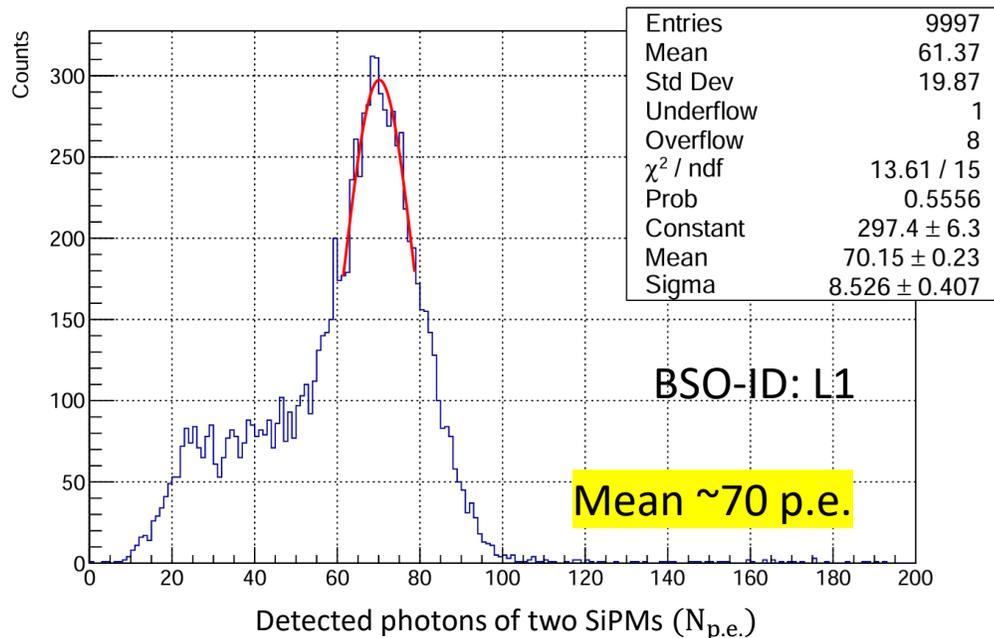


BSO crystals: Cs-137 test results

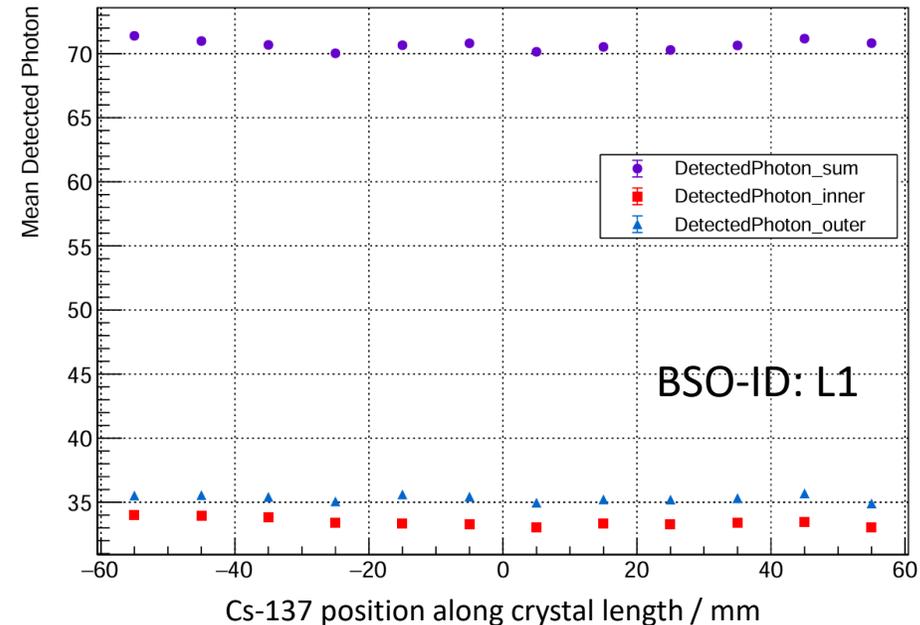
Baohua Qi, Rui Yang

- Full energy spectrum of 662 keV gammas
 - Response of two SiPMs: ~ 70 p.e. for BSO-L1
 - Energy resolution 12% for BSO-L1
 - Intra-crystal uniformity (along the length): typically 0.5% (standard deviations) for BSO-L1

662keV gammas: full energy spectrum



Response uniformity along crystal length



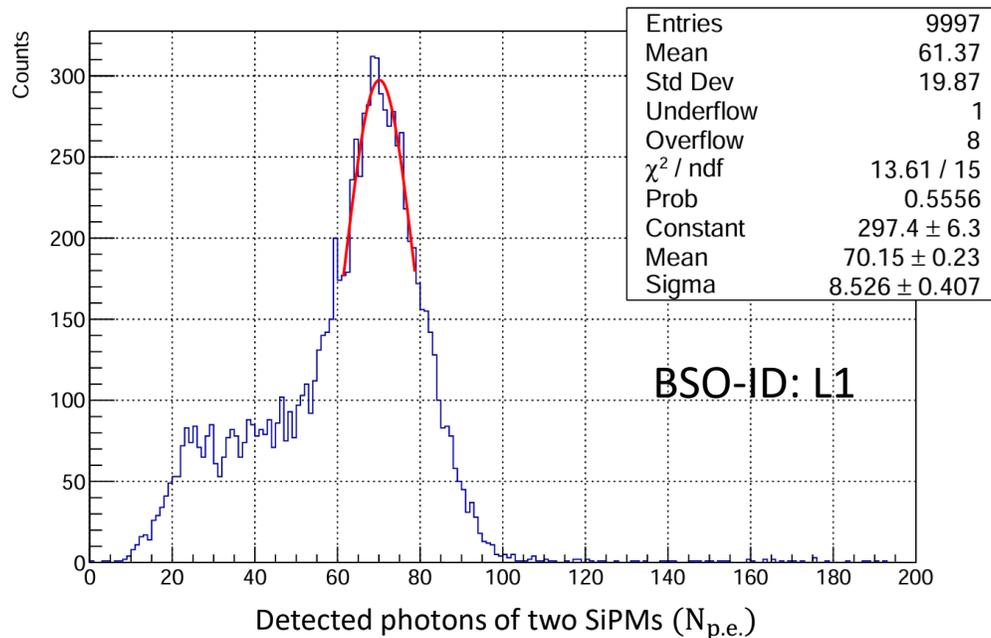


BSO crystals: Cs-137 test results

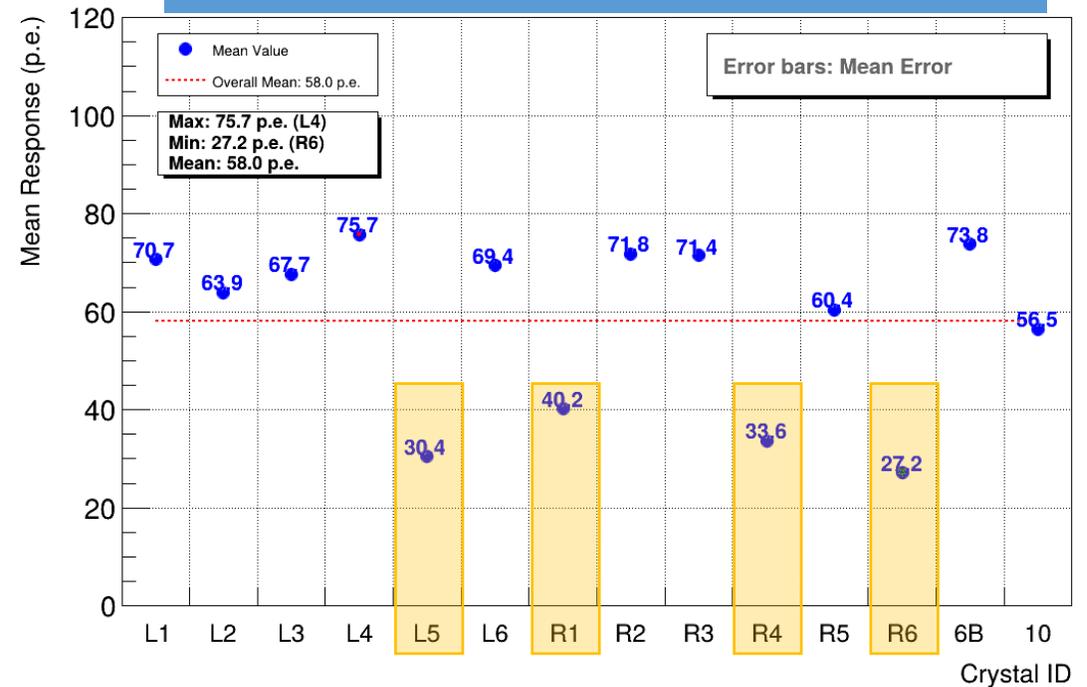
Baohua Qi, Rui Yang

- 14 BSO crystals: mean response to 662 keV gammas
 - Generally good uniformity for 10 crystals: **response in range of 56.5 – 75.7 p.e.**
 - 4 outliers identified with lower light output (labelled as L5, R1, R4, R6)

662keV gammas: full energy spectrum



Mean response versus Crystal ID

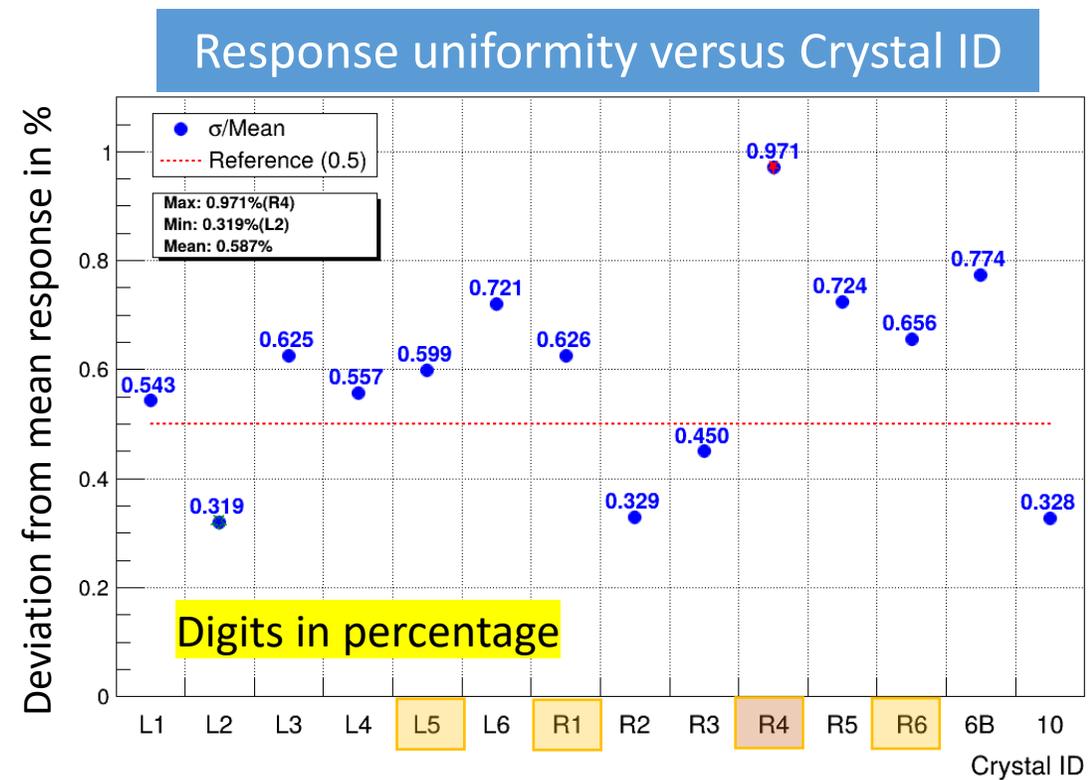
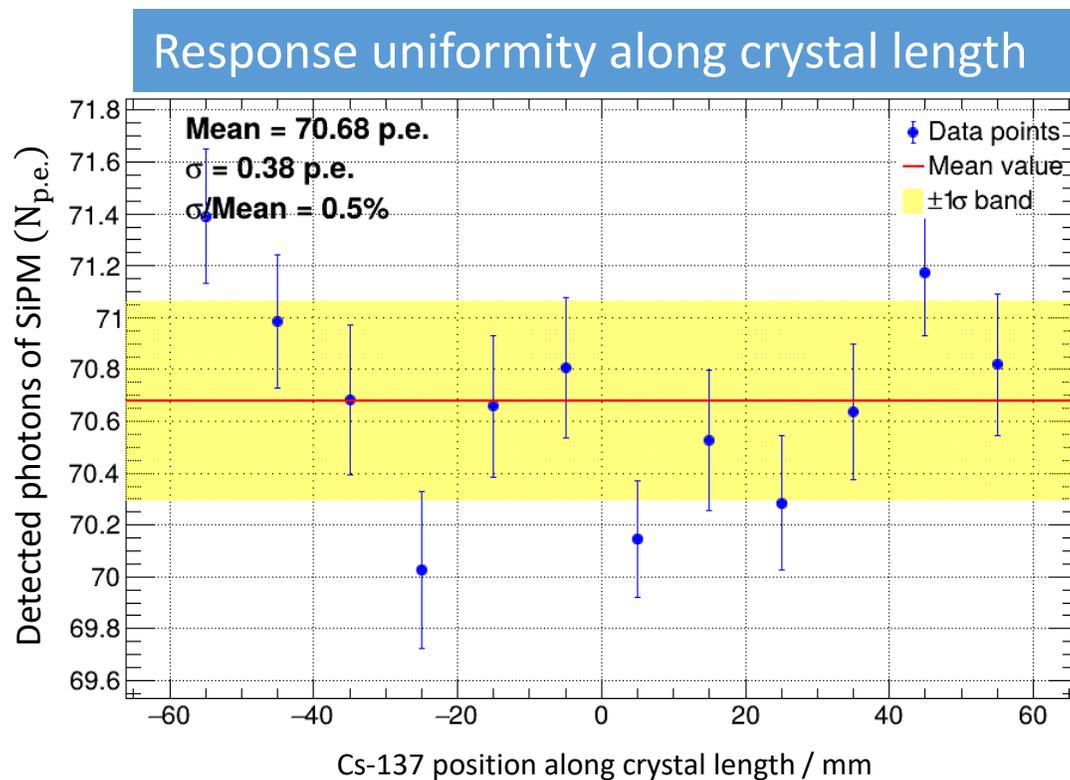




BSO crystals: Cs-137 test results

Baohua Qi, Rui Yang

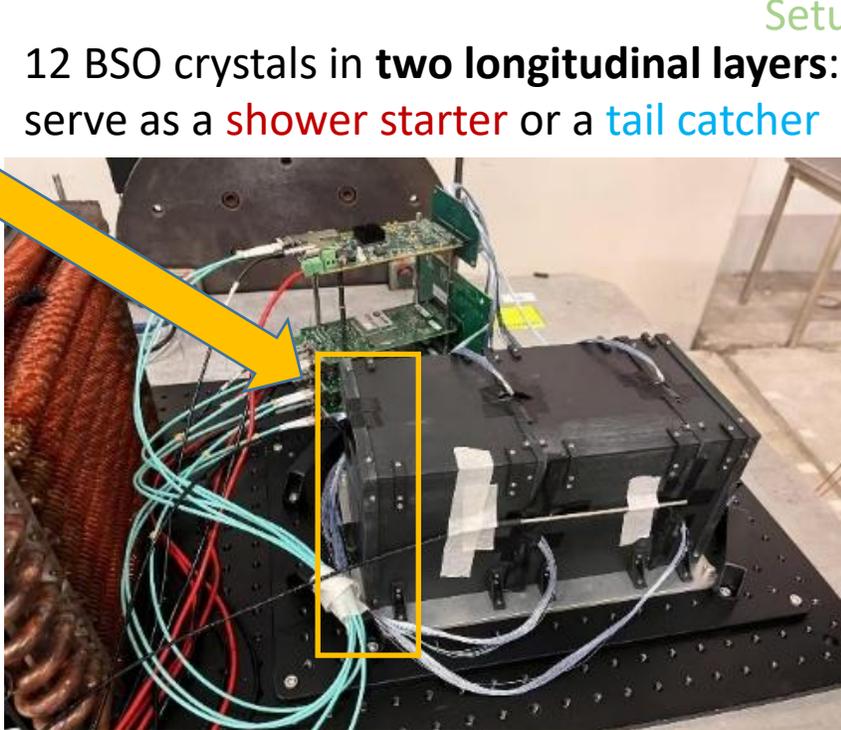
- 14 BSO crystals: uniformity along the length
 - Excellent intra-crystal uniformity: **below 1% for all crystals**
 - No significant correlation of (worse) intra-crystal uniformity and (lower) light output





BSO crystals in beam-tests in 2025

- Two different beam-test setups at CERN PS-T9 and SPS-H2
 - 12 BSO crystals fully integrated in the *HGCCAL prototype*: using ASIC readout
 - 3 BSO crystals tested separately: using waveform sampling (via oscilloscope)



Setup 1

12 BSO crystals in **two longitudinal layers**:
serve as a **shower starter** or a **tail catcher**

HGCCAL prototype (12×12×24 cm³): 12 BGO layers

Setup 2
3 BSO crystals tested using the same setup
as in the lab: preamps + oscilloscope



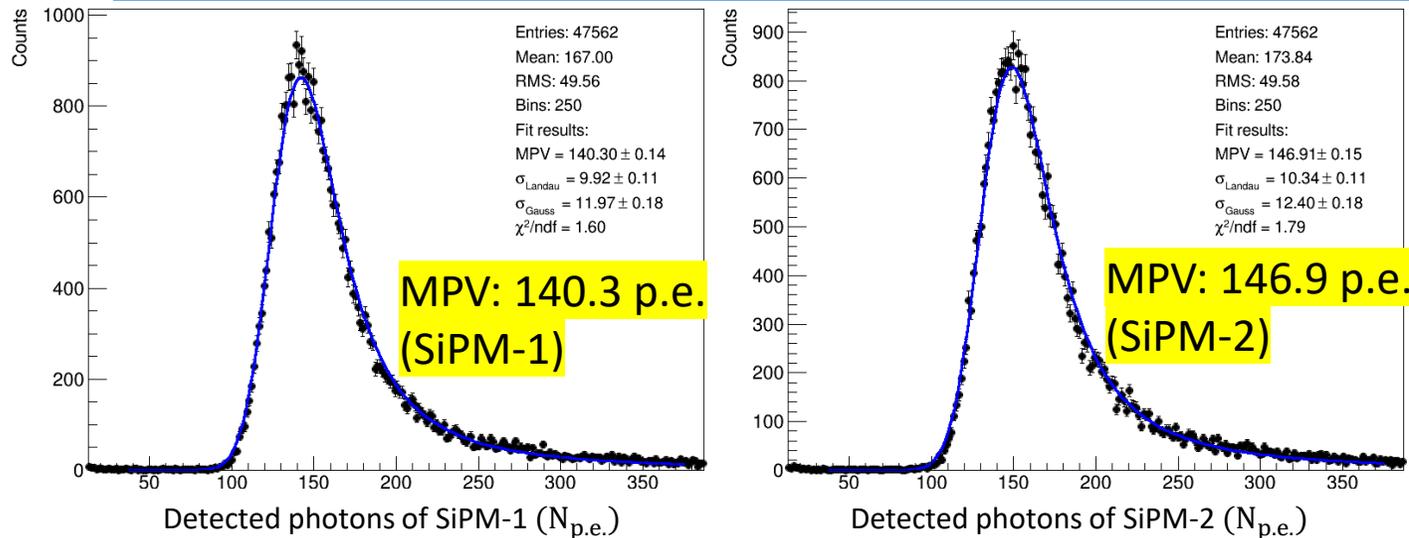
Results not presented here (to be updated)



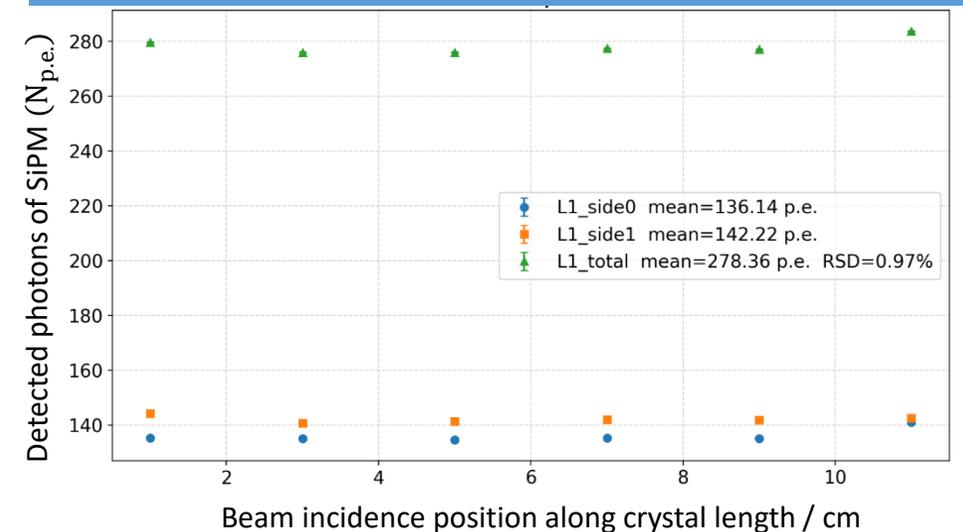
BSO crystals: beamtest results with 10 GeV pions

- MIP response of each BSO crystal (readout with SiPMs at two sides)
 - Converted to $N_{p.e.}$ based on single photon calibration (done separately)
 - Typically ~ 280 p.e./MIP (after summing up two SiPMs)
- Intra-crystal uniformity was scanned: 6 positions with the step size of 2 cm
 - Deviation from mean response: typically better than 1%

Typical MIP response spectra of a BSO crystal



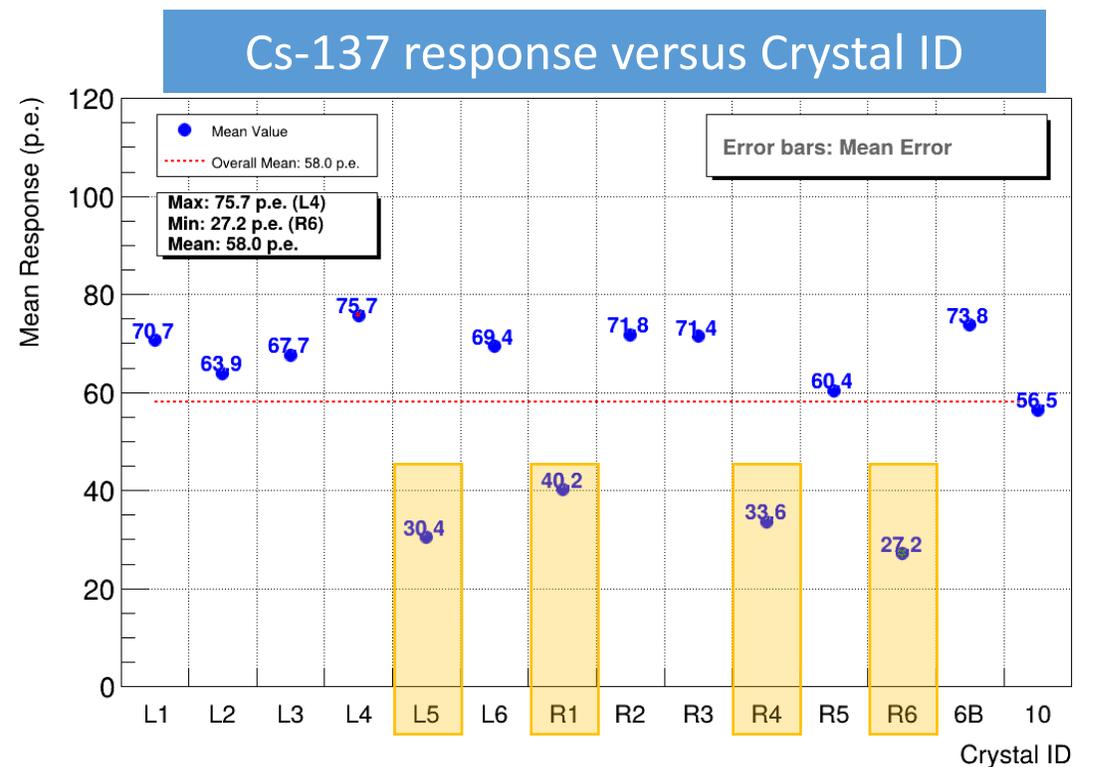
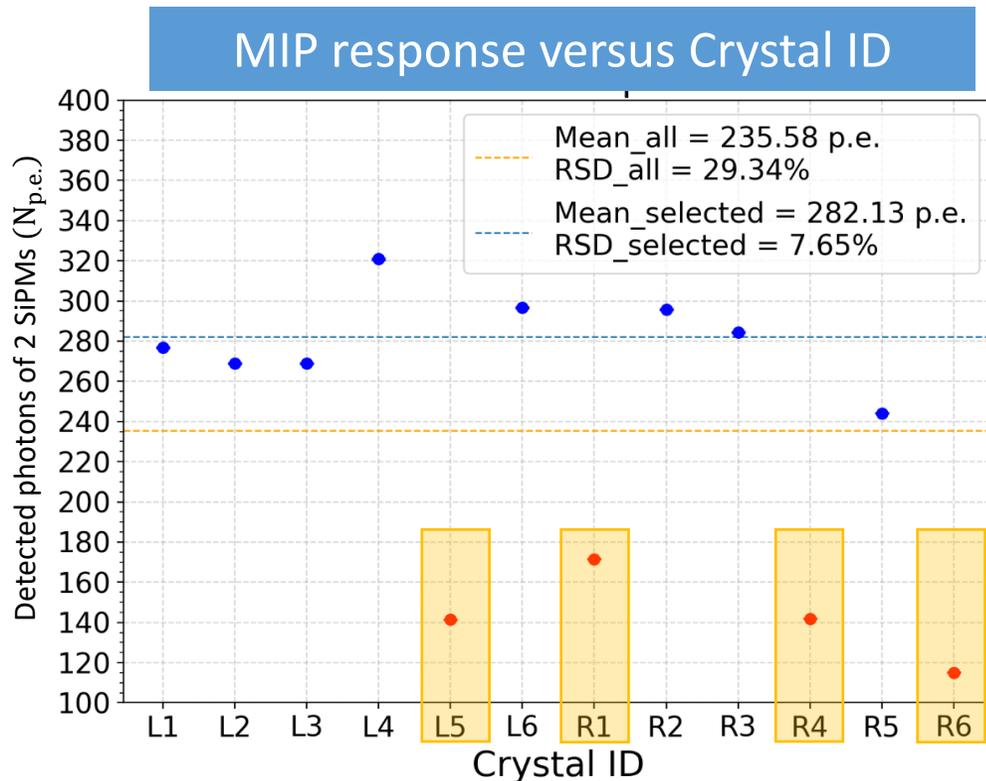
MIP response vs beam incidence position

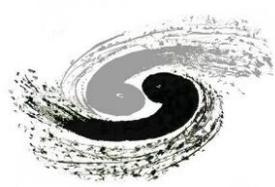




BSO crystals: beamtest results with 10 GeV pions

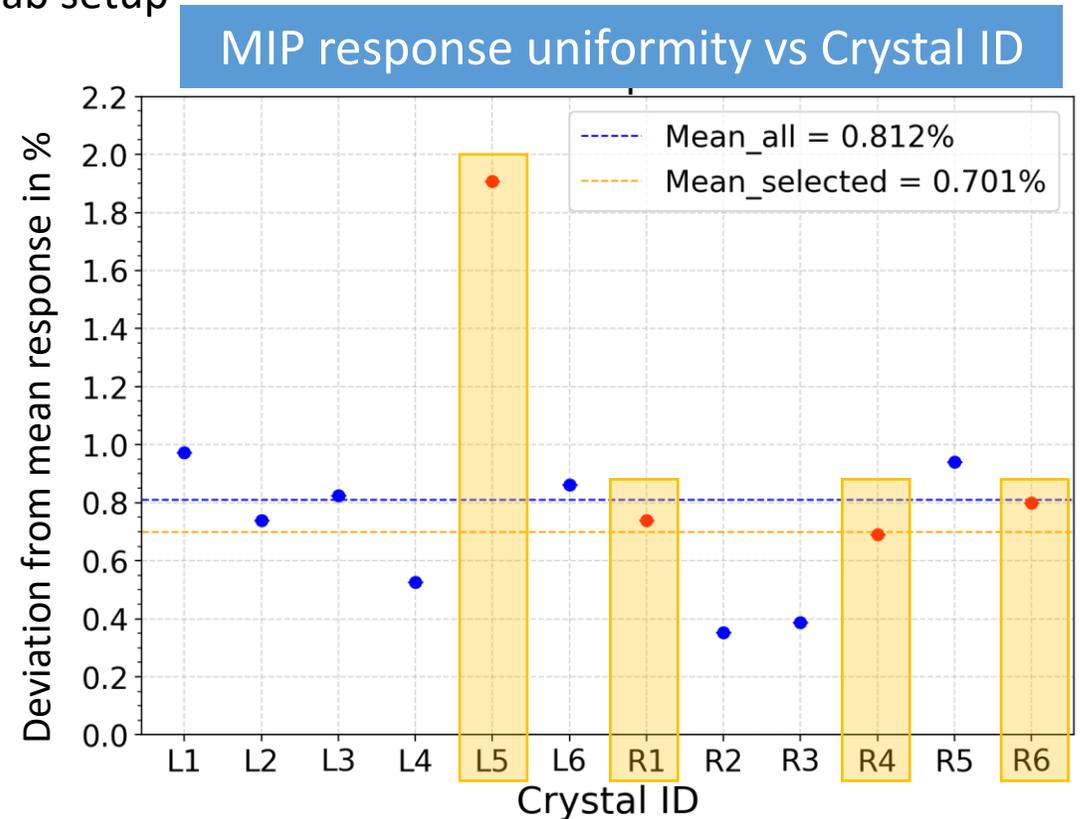
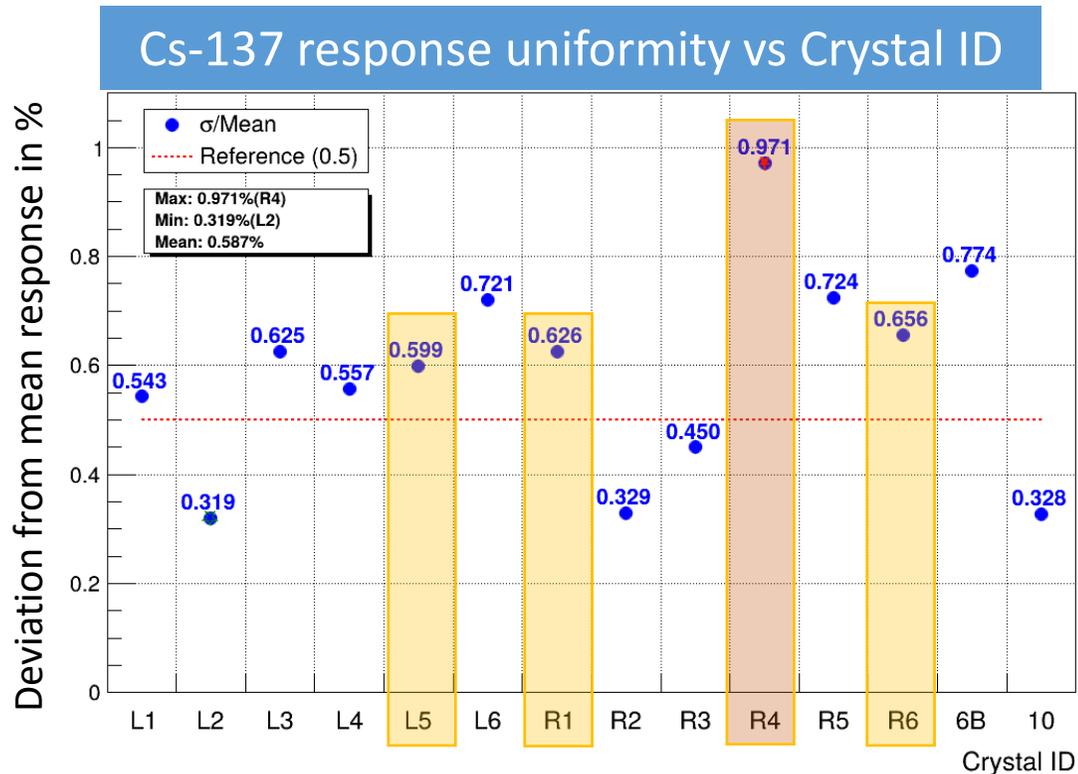
- BSO crystals generally show a good signal-to-noise ratio
 - 8 crystals: 282 p.e./MIP (average) with non-uniformity of 7.65 %
 - 4 outliers with significantly lower light output: IDs consistent with lab tests





Intra-crystal response uniformity: comparison

- Response uniformity: comparison Cs-137 and beam tests
 - Excellent intra-crystal uniformity: variation less than 1% in most cases
 - But Cs-137 tests still show better uniformity than beam tests: needs further understandings
 - Possible reasons could be related to crystal-SiPM coupling quality/stability – HGCCAL prototype mechanics might not guarantee the coupling as good as the lab setup





Summary and prospects

- BSO as an alternative crystal option for ECAL in CEPC Reference Detector
 - Promising in cost effectiveness and performance advantages
 - Challenges in large-scale crystal growth and optical quality
- Recent breakthroughs in large-scale BSO crystals at SIC : very encouraging progress
 - **BSO crystal ingots in length up to ~50cm with promising optical quality**
- Lab and beam tests for first batches of 12cm long BSO crystals
 - **Good performance achieved** in light output and signal-to-noise ratios
 - **Excellent intra-crystal uniformity** (typically variations less than 1%)
- Future activities
 - Crosschecks of BSO lab and beam tests, especially for two readout schemes
 - EM performance with two BSO layers in HGCCAL prototype (12 BGO layers): as a shower starter or as a *tail catcher* (important for high-energy electron data at SPS)