3D Crystal Calorimeter for CEPC: R&D status

Yong Liu (Institute of High Energy Physics, CAS),
on behalf of the CEPC Calorimetry Working Group

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https://indico.cern.ch/event/932973/
Motivations

• Background: future lepton colliders (e.g. CEPC)
  • Precision measurements with Higgs and Z/W

• Why crystal calorimeter?
  • Homogeneous structure
    • Optimal intrinsic energy resolution: $\sim 3\% / \sqrt{E} \oplus \sim 1\%$
  • Energy recovery of electrons: to improve Higgs recoil mass
    • Corrections to the Bremsstrahlung of electrons
  • Capability to trigger single photons
    • Rich flavour physics at Z-pole, potentials in search of new physics, …

• Fine segmentation
  • PFA capability for precision measurements of jets
3D crystal ECAL: past workshops

• Ideas firstly proposed: CEPC calorimetry workshop (March 2019)
• Follow-up workshop: Mini-workshop on a detector concept with a crystal ECAL
• R&D efforts targeting key issues and technical challenges

Virtual mini-workshop on a detector concept with a crystal ECAL, July 22-23, 2020, https://indico.ihep.ac.cn/event/11938/
R&D efforts targeting key issues and technical challenges

• Key issues: performance studies and optimization
  • Segmentation: in longitudinal and lateral directions
  • Performance: single particles and jets with PFA -> separation, energy splitting
  • Impacts from dead materials: upstream tracker, services (cabling, cooling)
  • Fine timing: e.g. for positioning
  • Dual-gated or dual-readout techniques (to improve hadronic energy resolution)

• Critical technical questions/challenges
  • Detector unit: crystal options (BGO, PWO, etc.), SiPMs (HPK, NDL, etc.)
  • Front-end electronics: cornerstone for instrumentation of high-granularity calorimetry
    • Multi-channel ASIC: high signal-noise ratio, wide dynamic range, continuous working mode, minimal dead time, etc.
  • Cooling and supporting mechanics design
  • Calibration schemes and monitoring systems: SiPMs, crystals and ASICs
  • System integration: scalable detector design (modules), mass assembly, QA/QC
3D crystal ECAL: 2 major designs

Design 1
- Longitudinal segmentation
- Fine transverse segmentation
- Single-ended readout with SiPM
- PFA-oriented design
- High channel-count, impact from services

Design 2
- Long bars: 1×40cm, double-sided readout
  - Super cell: 40×40cm cube
- Crossed arrangement in adjacent layers
- Significant reduction of #channels
- Timing at two sides: positioning along bar
3D crystal ECAL: 2 major designs

Design 1

- Design optimisations
  - Transverse: separation power
  - Longitudinal: impact from dead material, leakage correction (backup)
  - Neutral pion reconstruction (working)

Design 2

- Multiplicity of incident particles (jets)
  - Based on physics benchmarks (backup)
  - Digitisation in each long bar: done
  - Reconstruction algorithm under development
  - Event display and (pattern) reconstruction
Longitudinal segmentation optimisation

- Full simulation with SiW-ECAL via the benchmark Higgs to 2 gluons
  - 10 longitudinal layers or more in ECAL can help achieve better than 4% of BMR
  - Expect small impact from ECAL intrinsic energy resolution (PFA fast simulation)
- Guidance for the longitudinal segmentation
  - Will perform more benchmark studies for crystal ECAL in the CEPC detector simulation
Crystal transverse size optimisation

• Study of the separation performance of $\gamma$ and merged $\pi^0$
  • Can not be distinguished in transverse shower profiles
• Energy-related variables defined for TMVA
  • $S_{1}/S_{4}$, $S_{1}/S_{9}$, $S_{1}/S_{25}$, $S_{9}/S_{25}$, $S_{4}/S_{9}$, $F_{9}$, $F_{16}$

$S_{1}$, $S_{9}$, $S_{25}$: energy of seed, $3 \times 3$ and $5 \times 5$

$F_{9} = \frac{S_{9} - S_{1}}{S_{9}}$

$S_{4}$ chooses the energy maximum within the four $2 \times 2$ arrays

$F_{16} = \frac{S_{16} - S_{4}}{S_{14}}$

$S_{16}$
Crystal transverse size optimisation

- Separation performance of the 40GeV $\gamma$ and merged $\pi^0$

Crystal transverse size: 1x1 cm²

Crystal transverse size: 2x2 cm²

100% separation with most variables

100% separation with variables like S1/S4, S1/S25 and F9

Preliminary studies show that 2x2 cm² transverse size can well separate $\gamma/\pi^0$ up to 40 GeV. Next: what would be the performance of $\pi^0$ reconstruction (with different transverse sizes)?
Longitudinal segmentation: impact from services

- Energy resolution with different numbers of sampling layers
  - 24X0 total depth for crystals: fixed in all scenarios
  - Used copper to model the inter-layer services (e.g. cooling)
    - Light materials will be considered for realistic cooling designs: Al, carbon-fibre…

Note: energy fluctuations and leakages dominate; impacts of digitization in the next page
Longitudinal segmentation: with digitisation

- Digitisation tool
  - Photon statistics (crystal and SiPM): reasonably high light yield
  - Electronics resolution for single photons: taken from the existing ASIC

6 longitudinal layers in depth: 4X0 crystal/layer

Note: for copper, X0=14.36mm, 1mm Cu = 0.07X0; for Aluminum, 0.07X0 = 6.2mm (X0=88.97mm)

- 0.84X0 copper in total will degrade the stochastic term to ~2.5%

ECAL-Crystal: Energy Resolution

- Cu: 0mm/layer
- Cu: 1mm/layer
- Cu: 2mm/layer
High-granularity crystal ECAL: 2 major designs

### Design 1: short bars
- Crystal bars
- SiPM
- FE+PCB
- Cooling + Support

### Design 2: long bars (current focus)
- Basic Module
  - Crystal Scintillator (e.g., BGO, LYSO...)
  - Photodetectors (e.g., FPMT, SiPM)

- Super Cell
  - 24 layers, 1X0/layer
  - 40cm x 40cm

### Advantages
- Longitudinal granularity: 24 layers, 1X0/layer
- Save #channels, ~15 times less
- De facto 3D calorimeter: timing for hit positions for transverse granularity

### Key issues
- Ambiguity: multiple incident particles within one super cell
- Separation of nearby showers
- Impact on the Jet Energy Resolution (JER)

### Design optimisations
- Transverse: separation power
- Longitudinal: impact from dead material, leakage correction (backup)
- Neutral pion reconstruction (working)
cReconstruction with 2 incident particles

Patterns in event display: 2 photons

- 2 parallel 5GeV γ
  - distance ~20cm along the diagonal → can be separated.

Shower profiles: 2 photons

- Digitized Long Bar Hits (E_{dep} > 1 MIP)
- Reconstructed positions using time difference of 2 ends
- Transverse plane
  - γ (gamma) 5cm
  - γ (gamma) 2cm
  - 5cm ~ 2R_{μ} for BGO (R_{μ}=2.26cm)
- Longitudinal plane
  - E_{dep} distribution
- Transverse plane
  - Reconstructed positions
  - Time resolution ~10ps
Patterns with jets in Event Display

• Patterns for first impression, but still complex…
• Need further studies on positioning and energy splitting
Shower profiles studies in simulation

- How can we separate two close-by EM showers?
- EM shower profiles in 3D with highly granular cells: ongoing studies
  - Input to the weights for energy splitting
Latest progress in the new CEPC software

- Crystal calorimeter in **CEPCSW** (common framework)
  - Geometry of long crystal bars: implementation in DD4HEP (done)
  - Digitisation: based on the Geant4 full simulation of a single crystal bar (done)
  - Reconstruction with single particles and two close-by showers: ongoing

Crystal ECAL geometry (barrel) in CEPCSW

400×10×10 mm³ BGO Crystal

SiPM

1GeV mu-

ESR wrapping

SiPM

Time stamps of detected photons

Geant4 full simulation established
Critical questions for 3D crystal ECAL: technical part

• Detector unit: crystal options (BGO, PWO, etc.), SiPMs (HPK, NDL, etc.)

• Front-end electronics
  • Cornerstone for successful instrumentation of high-granularity calorimetry: e.g. CALICE prototypes, CMS HGCAL project
  • Multi-channel ASIC: high signal-noise ratio, wide dynamic range, continuous working mode, minimal dead time, etc.

• Cooling and supporting mechanics design
  • Power consumption (solid inputs from electronics)
  • Impacts of cooling structure to performance

• Calibration schemes and monitoring systems
  • For SiPMs, crystals and ASICs in the long term

• System integration: scalable detector design (modules), mass assembly, QA/QC
Studies with PWO crystal bar and NDL-SiPM

- Firsts tests with a PWO crystal using cosmics
  - Read out with a 3x3mm² SiPM, 90k pixels (not ideal sensor)
  - SiPM designed by Novel Device Lab (NDL) in Beijing Normal University

PbWO crystal (produced by SIC), 10x10x45 mm³

Example of pre-cut Tyvek paper

NDL-SiPM 3x3mm² with 10um pixels

MIP response: ~20pe/MIP with 3x3mm² SiPM

Note: a larger SiPM (e.g. 6x6mm² or larger) can be used for better light collection efficiency
First studies on new-generation of NDL-SiPM

- Tests made for a NDL-SiPM prototype of the latest generation
  - Many improvements: lower dark-count noise, higher PDE,…
- Foresee further tests with new NDL-SiPMs (better candidates for crystal readout)
  - High density: 3×3 mm², 6µm, 245k pixels, PDE~30% (e.g. for BGO)
  - Large area: 6×6 mm², 15µm, 170k pixels, PDE~40% (e.g. for PWO), under test

<table>
<thead>
<tr>
<th>NDL-SiPMs Parameters</th>
<th>11-3030C-S</th>
<th>Latest prototype NDL 22-1313-15S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown Voltage</td>
<td>27.5 V</td>
<td>19 V</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>10 µm</td>
<td>15 µm</td>
</tr>
<tr>
<td>Peak PDE</td>
<td>31% @420nm</td>
<td>45% @400nm</td>
</tr>
<tr>
<td>Pixels</td>
<td>90k</td>
<td>7.4k</td>
</tr>
<tr>
<td>Sensitive Area</td>
<td>3×3 mm²</td>
<td>2.6×2.6mm²</td>
</tr>
<tr>
<td>MIP response with 10x10x45 mm³ PWO bar</td>
<td>19.5 p.e./MIP</td>
<td>16.6 p.e./MIP</td>
</tr>
</tbody>
</table>
Crystal studies: near-future plans

- BGO and PWO crystal samples: varying dimensions, surface treatment
  - With a major focus on timing performance: e.g. Cherenkov photons

Two long BGO bars ready (1×1×40 cm³)

Short BGO bars with different dimensions and surface treatment

PWO crystals (SIC) also delivered to IHEP

BGO crystal samples already delivered to IHEP (photo by courtesy of Junfeng Chen, SIC-CAS)
Front-end electronics for SiPM readout

- ASIC “KLauS”: developed within the CALICE collaboration
  - Designed by U. Heidelberg (KIP), originally for CALICE AHCAL (scintillator-SiPM)
  - Promising candidate: 36-channel, low-power
    - Excellent S/N ratio: stringently required by high-dynamic SiPMs (small pixels)
    - Continuous working mode: crucial for circular colliders (no power pulsing)
  - Need to quantitatively verify its performance and power consumption
Klaus5 tests with NDL-SiPM

- NDL-SiPM features: small pixel pitch (10µm or smaller), high PDE
  - Requires high S/N ratio in electronics to resolve single photons (small gain)
- Klaus5 proved to be able to resolve the single photons (32fC/p.e.)
  - Benefits from its high S/N ratio and high resolution

Single photon spectrum in 10-bit ADC mode: can not be resolved

Single photon spectrum in 12-bit ADC mode: after corrections

NDL-SiPM: nominal gain $2 \times 10^5$ with 10µm pixels
Klaus5 dynamic range: charge injection

- Testing of all 36 channels
  - Different working modes (high gain and low gain)
  - Dynamic range: ~550pC as the maximum charge (preliminary results)

![Adapter PCB to inject charge pulses injection to 36 channels](image)

![ADC after pedestal subtraction (mid High Gain mode)](image)

![ADC after pedestal subtraction (ultra Low Gain mode)](image)

![Output ADC versus Input Voltage](image)
Klaus5 dead time measurements

- Varying time interval between 2 injection pulses: 100ns - 10µs
- When time interval > 500ns, 100% efficiency of separating the two pulses
  - Promising feature for 100% duty cycle at circular colliders
  - To be noted: tests were made for a single channel
  - 36 channels: bottleneck of data transmission speed in DAQ (RaspberryPI-based)

Similar results at arXiv:2005.08745

Tested at IHEP (at 20 °C)
Summary

• 3D crystal ECAL: high granularity
  • Aim to achieve optimal energy resolution and PFA capability
  • Key issues for optimization and technical challenges (partially) identified
    • Further studies, discussions and iterations
• Steady R&D progress
  • Optimisation studies: longitudinal/transverse segmentation, depth
  • Simulation studies on the detector layout with long bars
  • Technical developments:
    • SiPMs and crystals
    • Characterisations of SiPM-dedicated low-power readout ASIC (KLauS)
      • Dynamic range: TOT technique (in backup)
• Welcome broader collaborations: synergies with FCC-ee
  • Early R&D stage, many open questions/issues
  • In the common software framework (Gaudi, Key4HEP, DD4HEP, …)
Backup slides
LOI for US Snowmass 21

• Letter of Intent on crystal calorimeter in the Instrumentation Frontier

High-Granularity Crystal Calorimetry Letter of Intent

Future lepton colliders provide a unique opportunity to probe the Standard Model and potentially uncover new physics beyond the Standard Model with Higgs, W, and Z bosons richly produced in the exceptionally clean environment. The recently released European Strategy Updates on the Particle Physics [1] elaborates this consensus that an electron-positron Higgs factory is the highest-priority next collider, including implementations such as the Circular Electron Positron Collider (CEPC) [2,3], the Future Circular Collider (FCC-ee) [4], and International Linear Collider [5]. The precision physic programs set a stringent requirement on the jet energy resolution to separate and measure hadrons and jets. Detectors based on the Particle-Flow Approach (PFA) [6] provide an essential and feasible option to meet this goal and achieve an unprecedented jet energy resolution of around 30% $/\sqrt{E}$ (GeV), which further requires calorimetry to be finely segmented in 3 dimensions. Within the CALICE Collaboration [7], as proof-of-principles, various high-granularity calorimetry options have been extensively studied with prototyping and beam tests.
Considerations on detector layouts

Layout 1: same module for each layer

- Pros
  - Modular design
  - Uniform structure (easy calibration)

- Cons
  - Material budgets (cooling, mechanics)

Layout 2: every two layers share the same cooling service and mechanics

- Pros
  - Save material budget (e.g. a factor of two)

- Cons
  - Non-uniform sampling structure: will need specific considerations for calibration
Studies on physics requirements

- Estimate the multiplicity level of jets: fast simulation
  - Mean ~4 particles within the hottest tower

Multi-jet events at generator level:
- Calculate the impact point of visible final states on the inner surface of ECAL
- 240GeV, ZH (Z→qq, H→gg) (4-jet event) as an example

Parameters in calculation:
- A simple cylinder ECAL
- Inner Radius, R=1800mm
- Barrel Length, L=4700mm
- Magnetic Field, B=3T

Analysis level:
- Hottest tower (with maximum energy)
  - multiplicity and energy ratio to J/ψ
- Average proportion of towers with multi-particle
Studies on physics requirements

- Estimate the multiplicity level of jets: fast simulation
- Detailed studies with 2 incident particles (from a jet) hitting the hottest tower
Longitudinal segmentation: impact from services

- Stochastic and constant terms (extracted from the previous page)
  - Varying thickness of dead materials between layers (services as cooling, cabling, etc.)
  - Effects digitisation in the next page (photon statistics and electronics resolution)

Note: digitization not implemented yet; so energy fluctuations (and leakages) dominate
Digitizer in simulation

Energy Deposition in a scintillator tile

- Geant4 hit (energy deposition) → ADC signal in electronics (charge)
- Realistic factors that influence energy resolution
  - Photon statistics: #p.e./MIP, guided by Geant4 full simulation (optical photons)
  - Electronics resolution for single photons: #ADCs/p.e.
Impact from photon statistics: 100 p.e./MIP vs 300 p.e./MIP

Impact from electronics resolution for single photons: Sigma of SiPM gain ~7%/p.e. vs 20%/p.e.

- Quantitative studies for the impacts of photostatistics and electronics
  - Stochastic terms: ~5% for lower light yield (e.g. PWO), ~2% for higher light yield (e.g. BGO)
  - Negligible impact from single photon resolution at energy regions > 5GeV
Dynamic range: simulation with high-energy electrons

- Maximum energy deposition per cell
  - Depends on the crystal segmentation configurations
  - Provide inputs for the SiPM and its readout electronics

- 60 GeV electrons
  - 2x2x4 cm³ crystal: ~13 GeV/cell
  - 2x2x6 cm³ crystal: ~19 GeV/cell
  - 2x2x10 cm³ crystal: ~21 GeV/cell
Crystal granularity optimisations

• Longitudinal depth
  • Use shower profiles in segmented layers to correct for tails (energy leakage)
  • Aim for shorter crystal depth (cost), balance with performance (correction precision)

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Energy (MeV)

\[
\frac{dE}{dt} = E_0 b \left(\frac{t}{\alpha} \right)^{\alpha - 1} e^{-\frac{t}{\alpha}} \frac{1}{\Gamma(\alpha)}
\]

Crystal Layer / 3cm

Energy sum (measured)

Energy leakage (to be corrected)

100GeV gamma

Energy resolution

wo Correction: 0.219%

w/ Correction: 0.166%

30cm long BGO (~27X0), 10 layers, 3cm per layer
Crystal cells: dynamic range

- Silicon Photomultiplier (SiPM)
  - Non-linear response due to finite #pixels (each as a binary counter)
- Crystal such as BGO produces (too) many photons
  - Stringent requirement on the readout: response linearity

Geant4 simulation of BGO crystal

~40 MeV energy deposition for 1 GeV muons passing through a 45 mm crystal bar (BGO)

~350k photons/MIP
detected by 3×3mm² SiPM (side-coupled)

~3k photons/MIP
detected by 3×3mm² SiPM (side-coupled)

References:
- arXiv:1510.0110

2020/11/12  Yong Liu (liuyong@ihep.ac.cn)
Crystal cells: dynamic range

- Geant4 full simulation of TOT with BGO crystals
  - Realistic simulation of BGO scintillation: detailed properties
    - 8200 photons/MeV, time constants $\tau_1=60\text{ns}$, $\tau_2=300\text{ns}$
    - TOT: time duration of the rising and trailing edges at a fixed threshold

Computing intensive for the simulation (>1M photons); techniques developed to fasten the procedure
Dynamic range: TOT simulations

- Energy depositions in a crystal cell: 10MeV – 8 GeV
  - TOT values will go beyond 1.5 µs for energy deposition larger than 8 GeV
  - Energy spread: fluctuations due to BGO scintillation long slow slope
- Future studies: impact from TOT threshold, design with multiple thresholds

1ns time slice; scan the range 0-1.5 µs
Front-end electronics for SiPM readout

- Test boards for KLauS-5 in BGA
  - Boards produced after several iterations of designs/debugging
  - Boards tested first at Heidelberg and later at IHEP
  - Synergies with the JUNO-TAO team
Klaus5: first tests with SiPM and light sources

- LED for SiPM gain calibration: done for various SiPMs
- Laser for the first test of dynamic range: qualitative results

**LED calibration in High Gain**

\[
\chi^2 / \text{ndf} = 2.824 / 13 \\
p_0 = 725.9 \pm 0.2531 \\
p_1 = 8.772 \pm 0.02783
\]

8.8 ADC/p.e.

HPK S13360-3025CS

**Charge injection with HG and Mid-HG**

**Laser tests in Low Gain modes**

- High Gain modes: HG (1:1), Mid-HG (1:7)
- Low Gain modes: LG (1:40), Ultra-LG (1:100)
Crystal options

• PWO
  • Pros
    • Compact (smallest X0, cost saving), fast scintillation (timing)
    • Dynamic range suitable for the linear region of SiPM (high-density pixels)
  • Cons: low intrinsic light yield: ~100 photons/MeV

• BGO
  • Pros: high intrinsic light yield: 8k~12k photons/MeV, therefore high sensitivity to low energy particles
  • Cons
    • Less compact than PWO, larger volume for the same depth (e.g. 24X0)
    • Much slower scintillation → other techniques (e.g. TOT) considered to enlarge the dynamic range (studies placed in the backup)

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Density (g/cm³)</th>
<th>PWO</th>
<th>BGO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.13</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>Radiation Length X₀ (cm)</td>
<td>1.12</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Moliere Radius R₀ (cm)</td>
<td>2.259</td>
<td>1.959-2.19</td>
<td></td>
</tr>
<tr>
<td>Minimum ionization (MeV/cm)</td>
<td>8.918</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>Refractive Index</td>
<td>2.15</td>
<td>2.20</td>
<td></td>
</tr>
<tr>
<td>Decay Time (ns)</td>
<td>fast 50 slow 300</td>
<td>fast &lt;10 slow 30</td>
<td></td>
</tr>
<tr>
<td>Light Yield (photons/MeV)</td>
<td>8000-12000</td>
<td>100-150</td>
<td></td>
</tr>
</tbody>
</table>