Development of a novel highly granular hadronic calorimeter with scintillating glass tiles

Dejing Du (Institute of High Energy Physics, CAS)
On behalf of CEPC Calorimeter Working Group
Motivations

• Future electron-position colliders (e.g. CEPC)
  • Main physical goal: precision measurements of the Higgs and Z/W bosons
  • Challenge: unprecedented jet energy resolution \( \sim 30\% \sqrt{E(\text{GeV})} \)

• Particle Flow Algorithm (PFA)
  • Choose sub-detector best suited for each particle type (charged, photons, neutral hadrons)
  • Require good separation power of close-by particles in calorimeters

• High granularity calorimetry for PFA
  • Hardware challenge: readout channels on the order of 1~10 million
  • Software challenge: complex reconstruction algorithms
Motivations

- CEPC physics programs
  - Hadronic decays of Higgs/Z/W bosons: abundant hadrons (<10 GeV) within jets
- CEPC 4th concept detector: crystal ECAL + scintillating glass HCAL
  - A leap in terms of sampling fractions
  - Aim to improve the energy resolution: esp. the hadronic resolution
  - Physics performance goal: Boson Mass Resolution (BMR) 4% → 3%

Yuexin Wang (IHEP)
Outline

Scintillating glass HCAL

Physics motivations
CEPC Full Detector + PFA

Design
HCAL alone simulation

Performance

Hardware
Measurements + Tile simulation
Outline

• Performance of scintillating glass HCAL
  • Geant4 simulation with single hadrons
    • Hadronic energy resolution: scintillating glass vs. plastic scintillator
    • Varying thickness of glass tiles and steel plates
  • Physical performance: BMR

• Scintillating glass material R&D
  • Measurements of scintillating glass samples

• Studies on the performance of basic detected unit
  • MIP response: optical simulation and cosmic ray test
  • Uniformity scan with varying tile thickness
  • Estimated performance

• Summary and prospects
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HCAL setup in Geant4 simulation

• Geometry: a la CALICE-AHCAL
  • Transverse plane: 108 × 108\(cm^2\)
    • Tile size: 3 × 3\(cm^2\)
  • 60 longitudinal layers, each with
    • Scintillator: 3mm
    • PCB: 2mm
    • Absorber (steel): 20mm

• Scintillator materials
  • Plastic scintillator as baseline reference
  • Replace plastic scintillator with scintillating glass
    • Component: \(B_2O_3 – SiO_2 – Al_2O_3 – Gd_2O_3 – Ce_2O_3\)
    • Density = 4.94 g/cm\(^3\) (goal: > 6 g/cm\(^3\))

Note: HCAL with 40 layers in CEPC CDR as baseline. Hereby use 60 layers to evaluate leakage effects
HCAL: plastic scintillator vs scintillating glass

• Incident particle: $K_L^0$
• Preliminary performance comparison
  • Same thickness of sensitive materials: 3mm
  • No energy threshold applied
• Scintillating glass: better hadronic energy resolution in low energy region (<30GeV)
  • Note that majority of hadrons in jets at CEPC are with low energy
• More details in the next pages
Impact of thickness to hadronic energy resolution

- Varying thickness: scintillating glass tiles and steel plates
  - Each layer fixed with $\sim0.12\lambda_I$ : the same as AHCAL (3mm plastic tile, 20mm steel)
  - $\lambda_I = 22.4 cm$

- Threshold=0 MIP
- Threshold=0.3 MIP

- Energy threshold significantly impacts hadronic energy resolution
- The empirical formula ($A/\sqrt{E(GeV)} + C$) can not well describe curves
  - (Note the $\chi^2/ndf$ values) Not fully follow the Poisson distribution

2022/5/20 CALOR 2022
Impact of thickness to hadronic energy resolution

- Varying thickness: scintillating glass tiles and steel plates
- Extraction of stochastic and constant terms

- Energy threshold has a significant impact on the energy resolution
- With the 0.3 MIP threshold, resolution will not be improved when glass thicker than \(0.08 \lambda_I\) (18mm)
- Higher threshold significantly degrades the constant term
- Lower threshold would always be desirable for better resolution
Categorize energy depositions

- Categorize energy depositions of hadronic showers: EM, hadronic, invisible

**Component Energy Ratio**

**Energy Sum (Raw) of all tiles**

- EM energy deposition usually detected with higher efficiency
- EM component fraction: incident energy dependent
- EM/hadronic energy depositions: non-Gaussian fluctuations

Yong Liu (IHEP)
Physical performance: BMR

- Ideal homogenous scintillating glass HCAL
  - Preliminary results: ~10% improvement in BMR
  - Expect further improvements: e.g. optimization of PFA
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• Summary and prospects
Measurements of scintillating glass samples

- Comprehensive measurements of key properties
  - Transmission/emission spectra, light yield and decay time
- Over 30 pieces of scintillating glass have been tested, most of which have poor performance
- The best performance glass with the composition: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$

Zhehao Hua (IHEP)
Measurements of light yield

\[ LYS = \frac{\text{Mean}_{\text{energy}} \times 1000\text{keV}}{\text{Mean}_s \times \text{PDE}_w \times \text{PCE} \times \text{Energy}} \]

 photon=146
LY=536 ph/MeV

 photon=185
LY=680 ph/MeV

 photon=180
LY=660 ph/MeV

 photon=192
LY=705 ph/MeV

 photon=219
LY=802 ph/MeV

Zhehao Hua (IHEP)
Transmission spectrum, emission spectra and decay time

- Transmittance of samples can reach up to 78%
  - air bubbles, heavy metal ratio will affect its transmittance
- Emission peak is around 393 nm
  - can be matched with the detector band by adjusting the composition
- The decay time of GS5 is 354 ns (18%), 760 ns (82%)

Sample: GS5

Zhehao Hua (IHEP)
Measurement results of scintillating glass samples

<table>
<thead>
<tr>
<th>Number</th>
<th>Density (g/cm³)</th>
<th>Transmittance (%)</th>
<th>Light yield (ph/MeV)</th>
<th>Energy Resolution (%)</th>
<th>Decay time (ns)</th>
<th>Emission peak (nm)</th>
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</thead>
<tbody>
<tr>
<td>#1</td>
<td>~4.5</td>
<td>50</td>
<td>546</td>
<td>30.84</td>
<td>273,1004</td>
<td>394</td>
</tr>
<tr>
<td>#2</td>
<td>~4.5</td>
<td>78</td>
<td>536</td>
<td>37.87</td>
<td>334,939</td>
<td>392</td>
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<tr>
<td>#3</td>
<td>~4.5</td>
<td>75</td>
<td>680</td>
<td>29.41</td>
<td>351,1123</td>
<td>393</td>
</tr>
<tr>
<td>#4</td>
<td>4.65</td>
<td>74</td>
<td>660</td>
<td>31.82</td>
<td>308,1363</td>
<td>396</td>
</tr>
<tr>
<td>#5</td>
<td>4.94</td>
<td>64</td>
<td>705</td>
<td>27.97</td>
<td>354,760</td>
<td>392</td>
</tr>
<tr>
<td>#6</td>
<td>4.53</td>
<td>67</td>
<td>802</td>
<td>26.77</td>
<td>318,1380</td>
<td>393</td>
</tr>
</tbody>
</table>

- The light yield of scintillating glass sample could reach 800 ph/MeV (until December 2021)
- Latest sample measurement result: light yield reached 1600 ph/MeV, but density < 4 g/cm³
- Next plans
  - Improve both light yield (2000 ph/MeV) and density (6 g/cm³)
  - develop large-sized samples
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• Summary and prospects
MIP response: cosmic-ray test

- Glass sample size: $4.5 \times 4.5 \times 3.5 \text{mm}^3$
- MIP response: 274 p.e./MIP
- Plastic scintillator triggers cover larger area than sample does, some cosmic rays cross part of the sample
MIP response: optical simulation

- Simulation setup
  - Scintillating glass (4.5×4.5×3.5mm³)
  - 6×6 mm² SiPM
  - Small air bubbles are included
  - 1 GeV mu- (regard as MIP particle)
  - Vertical incidence in tile center

Properties of scintillating glass
- Component: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$
- Density: 4.94 g/cm³
- Refractive index: 1.67
- Transmittance: 64%
- Emission peak: 394 nm
- Light yield: 881 ph/MeV
  (All data based on measurements)

- MIP response
  - Energy deposition: 2.0 MeV/MIP
  - Detected photons: 263 p.e./MIP

- The difference between simulation and experiment result: ~4%

Detected photons at SiPM: 263.1 p.e./MIP
Uniformity scan: impact of tile thickness

- Projected performance of a realistic AHCAL tile size
- Assumption: larger tile properties remain the same as small glass samples (transmittance: 86%)

- When the thickness is 10mm, the detected photons is the largest and the uniformity is the best.
- Plan to develop scintillating glass with thickness >10mm, transmittance is an important parameter
Impact of scintillating glass tile size

- Assumption: larger tile properties remain the same as small glass samples
- Vary transverse size, fixed tile thickness at 3 mm (AHCAL baseline design)

- Realistic parameters: ~65 p.e./MIP, using large size $6 \times 6\ mm^2$ SiPM
- Ideal parameters: ~160 p.e./MIP → possible to use smaller SiPM
- Next plans:
  - Improve uniformity through tile-designs: “SiPM-on-Tile” is a feasible option
  - Scintillating glass R&D: improve both density and light yield
Summary and prospects

- A novel HCAL concept with high-density scintillating glass
  - Aim to improve energy resolution, especially hadronic energy resolution

- Performance of scintillating glass HCAL
  - Better hadronic energy resolution in low energy region (<30GeV)
  - Homogeneous glass HCAL improves the BMR by at least 10%

- Measurements of scintillating glass samples
  - Transmission/emission spectra, light yield, energy resolution and decay time

- Studies on the performance of basic detected unit
  - MIP response: cosmic-ray test and simulation
  - Impact of uniformity and tile size

- Prospects
  - To further improve the energy resolution: e.g. “Software compensation” technique
  - Improve uniformity of a scintillating glass tile through tile-designs
  - Scintillating glass R&D: improve both light yield and density, develop large-sized samples
Backups
Definition of energy resolution

- Calibration constant: 0.086
- Fit range: (-1σ, +1σ)
- Energy resolution: $\frac{\sigma}{E_{\text{beam}}}$
HCAL: evaluate leakage effects

- **Geometry size**
  - Baseline: 108cm×108cm×60layers (~1.5m)
  - Ideal: 540cm×540cm×300layers (~7.5m)

- **Incident particle**: kaon0L (1-100 GeV)

- The impact of shower leakage to energy resolution in the 60 layer is estimated (~1% level)
Homogeneous HCAL: energy deposition with $K_L^0$

Categorize energy depositions: EM, hadronic, invisible
Homogeneous HCAL: energy deposition with $K_L^0$
Uniformity scan: impact of tile size

- Projected performance of a realistic AHCAL tile size
- Assumption: larger tile properties remain the same as small glass samples
- Larger tile size leads to less detected photons and more significant non-uniformity

Projected performance of a realistic AHCAL tile size
Assumption: larger tile properties remain the same as small glass samples
Larger tile size leads to less detected photons and more significant non-uniformity
Calculation of light yield

---Absolute light yield: The formula of the light yield: \[ LY_s = \frac{\text{Mean}_{\text{energy}} \cdot 1000 \text{keV}}{\text{Mean}_{s} \cdot \text{PDE}_w \cdot \text{PCE} \cdot \text{Energy}} \]

Calculated by different Almighty peak of radioactive source, the light yield of #6 glass is 802 ph/MeV;

---Relative light yield: Calculate the relative light yield of glass through BGO standard crystal, the light yield of #6 glass is 845 ph/MeV;

---The light yield of the glass calculated by the two methods is the same.