The Detector at the CEPC: Calorimeters

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Outline

- Introduction
- Calorimeters
  - ECAL with Silicon and Tungsten
  - ECAL with Scintillator and Tungsten
  - HCAL with RPC and Stainless Steel
  - HCAL with Thick GEM and Stainless Steel
- Future R&D Plan
- Summary
## Requirements for CEPC Detector Design

### Critical Physics Benchmarks for CEPC Detectors design.

<table>
<thead>
<tr>
<th>Physics Process</th>
<th>Measured Quantity</th>
<th>Critical Detector</th>
<th>Required Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z H \rightarrow \ell^+ \ell^- X$</td>
<td>Higgs mass, cross section</td>
<td>Tracker</td>
<td>$\Delta(1/p_T) \sim 2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$H \rightarrow \mu^+ \mu^-$</td>
<td>BR($H \rightarrow \mu^+ \mu^-$)</td>
<td></td>
<td>$\Theta 1 \times 10^{-3}/(p_T \sin \theta)$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}, c\bar{c}, gg$</td>
<td>BR($H \rightarrow b\bar{b}, c\bar{c}, gg$)</td>
<td>Vertex</td>
<td>$\sigma_{x\phi} \sim 5 \Theta 10/(p \sin^{3/2} \theta) \mu m$</td>
</tr>
<tr>
<td>$H \rightarrow q\bar{q}, V^+V^-$</td>
<td>BR($H \rightarrow q\bar{q}, V^+V^-$)</td>
<td>ECAL, HCAL</td>
<td>$\sigma_E^{jet}/E \sim 3 - 4%$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>BR($H \rightarrow \gamma\gamma$)</td>
<td>ECAL</td>
<td>$\sigma_E \sim 16%/\sqrt{E} \Theta 1% (GeV)$</td>
</tr>
</tbody>
</table>

**Goal:** Jet Energy Resolution  $3 - 4\%$ or $30\% / \sqrt{E} @ 100\text{GeV}$
Particle Flow Algorithms and Imaging Calorimeter

The idea...

<table>
<thead>
<tr>
<th>Particles in jets</th>
<th>Fraction of energy</th>
<th>Measured with</th>
<th>Resolution [σ²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged</td>
<td>65 %</td>
<td>Tracker</td>
<td>Negligible</td>
</tr>
<tr>
<td>Photons</td>
<td>25 %</td>
<td>ECAL with 15%/√E</td>
<td>0.07² E_jet</td>
</tr>
<tr>
<td>Neutral Hadrons</td>
<td>10 %</td>
<td>ECAL + HCAL with 50%/√E</td>
<td>0.16² E_jet</td>
</tr>
<tr>
<td>Confusion</td>
<td></td>
<td>Required for 30%/√E</td>
<td>≤ 0.24² E_jet</td>
</tr>
</tbody>
</table>

Requirements for detector system

→ Need excellent tracker and high B-field
→ Large $R_i$ of calorimeter
→ Calorimeter inside coil
→ Calorimeter as dense as possible (short $X_0$, $λ_i$)
→ Calorimeter with extremely fine segmentation

18%/√E
Global R&D of Imaging Calorimeters

https://twiki.cern.ch/twiki/bin/view/CALICE/CalicePapers

Absorber:
- Tungsten
- Iron

Readout:
- Analog
- Digital

Active:
- Silicon
- Scintillator
- MAPS
- RPC
- GEM
- Micromegas

**Readout cell size:**
- 144 - 9 cm² → 4.5 cm² → 1 cm² → 0.25 cm² → 0.13 cm² → 2.5x10⁻⁵ cm²

**Technology:**
- Scintillator + SiPM/MPPC
- Scintillator + SiPM/MPPC
- Gas detectors
- Silicon
- Silicon
- Silicon (MAPS)

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CEPC Calorimeters - H. Yang (SJTU)
Imaging Calorimeters

Two electrons ~ 5cm apart

CALICE SiW ECAL

~20 muons in 1m² area

CALICE RPC DHCAL

This is exactly what PFA needs: distinguishing individual showers within jet environment, in order to get excellent jet energy/mass resolution
The ECAL consists of a cylindrical barrel system and two large end caps.
- One Barrel: 5 octant wheels
- Two Endcaps: 4 quarters each
- 2 active sensors interleaved with tungsten absorber
  - silicon pixel 5 x 5 mm²
  - PCB with Very Front-End ASIC

\[ \text{JER is determined using } Z \rightarrow \text{qqbar decay at rest} \]

\[ \text{Based on PandoraPFA} \]

\[ \text{SiW ECAL: 5}\times5 \text{ mm}^2 \]
\[ \text{with AHCAL: } 3\times3 \text{ cm}^2 \]
\[ \text{with sDHCAL: } 1\times1 \text{ cm}^2 \]
Active Cooling System

- CEPC is designed to operate at continuous mode with beam crossing rate: $2.8 \times 10^5$ Hz. Power pulsing will not work at CEPC.

- Compare to ILD, the power consumption of VFE readout electronics at CEPC is about two orders of magnitude higher, hence it requires an active cooling
  - Evaporative CO$_2$ cooling in thin pipes embedded in Copper exchange plate.
  - For CMS-HGCAL design: heat extraction of 33 mW/cm$^2$, allows operation with $6 \times 6$ mm$^2$ pixels with a safety margin of 2

- To be modelled for Mokka simulation

- Transverse view of the slab with one absorber and two active layers.

- The silicon sensors are glued to PCB with VFE chips, cooled by the copper plates with CO$_2$ cooling pipes.
ECAL with Scintillator-W option

- A super-layer (7mm) is made of
  - tungsten plate (3 mm thick)
  - 5 x 45 mm$^2$ plastic scintillator strips (2 mm thick)
  - a readout/service layer (2 mm thick)

- The energy resolution of 25 GeV electron is about 3.3\% (cf. CALICE TB results)
- To achieve required energy resolution, the number of layers should be ~ 25.
Hadron Calorimeter

- The HCAL consists of
  - a cylindrical barrel system: 12 modules
  - two endcaps: 4 quarters
- Absorber: Stainless steel

- Active sensor
  - Glass RPC
  - Thick GEM
- Readout (1×1 cm²)
  - Digital (1 threshold)
  - Semi-digital (3 thresholds)
DHCAL with RPC

- Mylar layer (50μ)
- PCB (1.2 mm) + ASICs (1.7 mm)
- PCB support (polycarbonate)
- Gas outlet
- HV connection
- Gas inlet
- Readout pads (1 cm x 1 cm)
- Readout ASIC (Hardroc2, 1.6 mm)
- Gas gap
- Ceramic ball spacer (1.2 mm)
- Cathode glass (1.1 mm) + resistive coating
- Anode glass (0.7 mm) + resistive coating
- Glass fiber frame (≈1.2 mm)
- Mylar (175μ)

Large GRPC R&D

- Negligible dead zone (tiny ceramic spacers)
- Large size: 1 × 1 m²
- Cost effective
- Efficient gas distribution system
- Homogenous resistive coating
ASICS : HARDROC2
64 channels
Trigger less mode
Memory depth : 127 events
3 thresholds
Range: 10 fC-15 pC
Gain correction → uniformity

Printed Circuit Boards (PCB) were designed to reduce the cross-talk with 8-layer structure and buried vias.

Tiny connectors were used to connect the PCB two by two so the 24X2 ASICSs are daisy-chained. 1×1m² has 6 PCBs and 9216 pads.

DAQ board (DIF) was developed to transmit fast commands and data to/from ASICSs.
Prototype of DHCAL with RPC

Prototype of DHCAL based on RPC
- ANL (J. Repond, L. Xia et.al.)
  1m³, 1 threshold, TB at CERN/Fermilab

Positron
High Energy Pion
Neutral hadron
Prototype of SDHCAL with RPC

Prototype of SDHCAL based on RPC
- IPNL (I. Laktineh, R. Han et.al.)
  1m³, 3 thresholds, Test Beam at CERN

![Prototype image]

![Graphs and data plots]

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CEPC Calorimeters - H. Yang (SJTU)
Three THGEM options are explored:

- Double - THGEM
- Single - THGEM
- WELL - THGEM

WELL-THGEM is optimal choice

- Thinner, lower discharge

40 x 40 cm² of THGEM (below) was produced in China
WELL-THGEM Test Beam at IHEP

Well-THGEM, Ar/3%C₄H₁₀; 500MeV p

500MeV π
Absorber: 2cm stainless steel
Drift gap: 3mm
Number of layers: 40, 50
Ecell = 1, 5 and 10 MIPs if the charge is above the thresholds typically placed at 0.1, 1.5 and 2.5 MIPs

Simulation of DHCAL

σ/E of π⁺
Future Plan: Critical R&D

- Detector optimization
  - Granularity of calorimeters
  - Number of layers of calorimeters

- Readout Electronics (PCB, low power VFE ASIC)

- Cooling system
  - Power pulsing will NOT work at the CEPC, effective cooling and power saving strategy need to be developed and tested

- Gas recirculation system

- High voltage distribution system

- Calibration system
  - Energy, position and density calibration etc.

- Mechanical: self-support and compact module
Summary

- As a starting point, two alternative technology options are explored for both ECAL and HCAL in preCDR based on CALICE and ILD R&D efforts.
  - ECAL (Silicon-W and Scintillator-W)
  - HCAL (RPC-Steel and THGEM-Steel)
- Identify some critical R&D plans which is best fit for CEPC calorimeters.
- Calorimeters detector design and optimization are ongoing and more international collaboration are needed. Other technology options are welcome for the design of CEPC calorimeters in CDR phase.
Many thanks to all members of CEPC Physics and Detector working group who made significant efforts to prepare the CEPC-SPPC preCDR!
Overview of the CEPC Detector

- Yoke/Muon
- Coil
- HCal
- ECAL
- TPC
- Vertex
- QD0
- LumiCal
- IP

Dimensions:
- 7050mm
- 4400mm
- 3380mm
- 1810mm
- 329mm
- 6657mm
- 4000mm
- 1300mm
Si-W ECAL: Physics & Technological prototype

**Physics prototype: 2005-2011**

- PFA proof of concept with comparison to MC (PandoraPFA etc.)
- Electronics outside
  - 1 cm x 1 cm pixels
  - full 30 layers
(used for PAMELA sat.)

**Technological prototype**

- Embedded electronics
  - SKIROC2 analog/digital ASICs
    - auto-triggered, zero suppr., PP
  - pixels 5×5 mm²

Assess the feasibility
Establish procedures and develop test benches for mass production

16.5% (stochastic) 1–2% (constant) obtained with 1–45 GeV e/e⁺ at 2006/2008 BT
CALICE Si/W ECal:
- Physics prototype* tested in beam (1\times1\text{cm}^2)
- R&D/construction for Technical prototype**
- Readout cell reduced to 0.25\text{cm}^2 for 2\text{nd} prototype
- First test beams of new prototype soon

CALICE Sci/W ECal:
- Physics prototype tested in beam (1\times4.5\text{cm}^2)
- Technical prototype R&D/construction
- Started first beam tests

* Physics prototype: proof of principle device
** Technical prototype: prototype close to a real detector
**ECal efforts**

**SiD Si/W ECal:**
- Target at very compact readout and small cell (~0.13cm²)
- Address all technical issues from the beginning
- Push technical limits in many aspects
- Total active medium thickness targets at ~1mm
- Test beam module being assembled
- First beam exposures in particle beams

**CALICE MEPS Digital ECal:**
- Extremely small cell size (0.005x0.005cm²)
- Working on sensor R&D
- Did sensor test beam

\[ \sigma_{E} / E = a \oplus b / \sqrt{E} \text{(GeV)} \]
\[ a = 0.9, \ b = 12.8\% \]
\[ a = 1.1, \ b = 16.0\% \]
HCal Efforts

CALICE Sci/SiPM Analog HCal (AHCal):
- Physics prototype (Fe/W) tested in beam
- R&D/construction for Technical prototype
- First test beam of components

CALICE RPC Digital HCal (DHCal):
- Physics prototype (Fe/W) tested in beam (1cm² pad size)
- Embedded Front End readout, 480K (!) readout channels
- Data analysis on-going
- R&D for Technical prototype started

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HCal Efforts

CALICE RPC semi-Digital HCal (sDHCal):
- Large prototype (1m$^3$) constructioned (1cm$^2$ pad)
- Beam test at CERN with Fe absorbers
- Addressed several technical issues for real detector
- Explore 3-threshold readout
- R&D towards real detector

CALICE Micromegas/GEM Digital HCal:
- Prototype layer constructed/expected (1x1cm$^2$)
- Prototype layer beam test done/expected
- Both technologies can handle very high rates