Status Report about the CEPC Calorimeters

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Motivation and goal

Calorimeters
- ECAL with Silicon and Tungsten
- ECAL with Scintillator and Tungsten
- HCAL with RPC and Stainless Steel
- HCAL with ThGEM/GEM and Stainless Steel

Future plan for CEPC-Calor CDR

CEPC preCDR documents: http://cepc.ihep.ac.cn/preCDR/volume.html
## 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>$ZH \rightarrow \ell^+\ell^-X$</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>$\oplus 1 \times 10^{-3}/(p_T \sin \theta)$</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>$\sigma_{r\phi} \sim 5\oplus 10/(p \sin^{3/2} \theta) \mu m$</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>$\sigma_{\text{jet}}/E \sim 3 - 4%$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>BR($H \rightarrow \gamma\gamma$)</td>
<td>ECAL</td>
<td>$\sigma_E \sim 16%/\sqrt{E} \oplus 1% ,(\text{GeV})$</td>
</tr>
</tbody>
</table>

**Goal:** Jet Energy Resolution $3 - 4\%$ or $30\% / \sqrt{E} @ 100\text{GeV}$ based on Particle Flow Algorithm (PFA)
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 $[\sigma^2]$</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>$0.07^2 E_{jet}$</td>
</tr>
<tr>
<td>Neutral Hadrons</td>
<td>10 %</td>
<td>ECAL + HCAL with 50%/√E</td>
<td>$0.16^2 E_{jet}$</td>
</tr>
<tr>
<td>Confusion</td>
<td></td>
<td>Required for 30%/√E</td>
<td>$\leq 0.24^2 E_{jet}$</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 $X_0$, $\lambda_i$)
→ Calorimeter with extremely fine segmentation

thin active medium
Imaging Calorimeters

Two electrons ~5cm apart

CALICE SiW ECAL

~20 muons in 1m$^2$ 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.
Global R&D of Imaging Calorimeters

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

Absorber:
- Tungsten
- Iron

Readout:
- analog
- digital

Active:
- Silicon
- Scintillator

Readout cell size:
- 144 - 9 cm$^2$ \(\rightarrow\) 4.5 cm$^2$ \(\rightarrow\) 1 cm$^2$ \(\rightarrow\) 0.25 cm$^2$ \(\rightarrow\) 0.13 cm$^2$ \(\rightarrow\) 2.5x10^{-5} cm$^2$

Technology:
- Scintillator + SiPM/MPPC
- Scintillator + SiPM/MPPC
- Gas detectors
- Silicon
- Silicon
- Silicon (MAPS)
The ECAL consists of a cylindrical barrel system and two large end caps.

Two detector active sensors interleaved with tungsten absorber
- silicon pixel 5 x 5 mm²; PCB with VFE ASIC
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

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.
CEPC ECAL: ScW Simulation

Standalone Simulation of ScW ECAL with Geant4 package.

- Plastic scintillator (2mm)
- Tungsten plate as absorber (3mm)

- The energy resolution of 25GeV electron is about 3.3% (cf. CALICE TB results)
- To achieve required energy resolution, the number of layers should be ~ 25.
The SiPM dynamic range is determined by the number of pixels.
The manufactures have developed the SiPM with 10um pixel which extends the SiPM dynamic range. **But, the photon detection efficiency of 10um SiPM is only 1/3 of 25um SiPM.**

Scintillator strip irradiated with β collimated (1mm) from Sr-90
Tests of SiPM at IHEP

SiPM pe spectrum

pulse height spectrum.

Excellent photon counting

Crosstalk rate = Events (> 1.5p.e)/Events (>0.5p.e)
Scintillator Strip Structure Optimization

With normal design, the signal is not uniform with peak response for hits near SiPM. What’s more, the dead gap between strips is large due to SiPM installation.

Need MC simulation and experimental tests to optimize the strip structure design.
SiPM sensor area $1 \times 1 \text{ mm}^2 \Rightarrow 0.25 \times 4 \text{ mm}^2$:

- to increase photon acceptance
- It is easy to make this shape of MPPC with current technology
Calibration for Scintillator and SiPM

The ScW ECAL consists of ~8 million channels of scintillator strip units. The stability of the light output has to be monitored. A light distribution system is under study to monitor possible gain drifts of the SiPMs by monitoring photoelectron peaks.

LED – Fiber calibration system:
- A pulse generator, a chip LED connect to notched fibers
- Notched Fiber distribute lights to ~ 80 scintillator strips
The HCAL consists of
- a cylindrical barrel system: 12 modules
- two endcaps: 4 quarters
- Absorber: Stainless steel

- **Active sensor**
  - Glass RPC
  - Thick GEM or GEM

- **Readout (1×1 cm²)**
  - Digital (1 threshold)
  - Semi-digital (3 thresholds)
**RPC Construction & Performance Study**

**Large GRPC R&D**

- Negligible dead zone (tiny ceramic spacers)
- Large size: $1 \times 1$ m$^2$
- Cost effective
- Efficient gas distribution system
- Homogenous resistive coating

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**RPC Construction & Performance Study**

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

Ran Han (NCEPU)
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 ASICs are daisy-chained. 1x1m² has 6 PCBs and 9216 pads.

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

Prototypes of DHCAL based on RPC

- ANL (J. Repond, L. Xia et al.)
  1m$^3$, 1 threshold, TB at CERN/Fermilab

- IPNL (I. Laktineh, R. Han et al.)
  1m$^3$, 3 thresholds, TB at CERN in 2014.12
Three THGEM options are explored:
- Double - THGEM
- Single - THGEM
- WELL - THGEM

WELL-THGEM is optimal choice
Thinner, lower discharge

40 × 40 cm² of THGEM (below) was produced in China (UCAS, GXU, IHEP)
Detection efficiency of well-THGEM was measured with BEPC pion / proton beams.

- Efficiency:
  - Ar/iso (97/3), Gain ~ 2000; Eff (proton) > 93%; Eff(Pion) > 82%
  - Ne/CH4 (95/5), Gain ~ 9000; Eff (proton) > 99%; Eff(Pion) > 94%
7 THGEMs were installed, and 5 of them were used, and flushed with Ar/iso-butane = 97:3.

1 threshold, binary readout

900 MeV proton beam was used

5cm x 5cm sensitive region
Large-area GEM @ USTC

GEM assembly using a novel self-stretching technique

APV25 GEM readout

INFN APV25 chip

- Large-area GEM (0.5x1m²) is one of main detector R&D focuses at USTC recently.
- Technology has been developed and matured to produce high-quality GEM detectors as large as ~1m² that are also applicable to CEPC DHCAL.

Resolution uniformity ~11%
Gain uniformity ~16%
Can reach gain of $10^4$ at 4000V
Conceptual Design for DHCAL GEM

- Detector size: 1m*0.5m, limited by GEM foil size
- Double-GEM structure (3mm-1mm-1mm) adopted to minimize the thickness of detectors to accommodate the compactness requirement of DHCAL.
- Double-GEM can still produce reasonable gain under safe operation condition according to our measurements and experience.

Mechanical design already finished!
DHCAL Detector Optimization

- DHCAL Simulation and Optimization
  - Standardalone ➔ Full simulation (eg. single particle, ZH→qqbb events)
  - Number of layers
  - Thickness of Absorber
  - Readout cell size
  - Thresholds (1, 3, ..)

1×1cm²-50 Layers-100GeV π+
Flexible simulation toolkit:
local geometry (cell size, layer thickness, global size), used to explore energy response, saturation, PID performance etc.

ECAL saturation at 1000 MIP

$L_{1\sigma}$: ECAL E response is $1\sigma$ lower than the non-saturation case.
Future Plans for CDR: Critical R&D

- Detector design and optimization
  - Granularity of calorimeters
  - Number of layers of calorimeters
  - Absorber thickness

- Detector R&D (SiW/ScW+SiPM, RPC/THGEM/GEM+Iron)

- 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

- Mechanical: self-support and compact module
Many thanks to all members of the CEPC Calo working group.

We need more manpower, more concept designs, more dedicated efforts for the CEPC-CDR!
Overview of the CEPC Detector
Future R&D Plans

- Detector simulation and optimization based on PFA (open)
  - Full detector simulation with different geometry
  - Optimizing layers number, size of readout pad, absorber;
- Large area gaseous detector research (open)
  - Design and produce large area RPC, WELL-THGEM
  - Performance test and study
- PCB and ASIC readout (open)
  - ASIC chip design and test
  - Small readout board design and domestic production;
- DHCAL cooling system (open)
  - Design and calculation of cooling system;
- DHCAL calibration system (open)
  - Design the calibration system;
Towards to CEPC CDR

- Full Detector simulation and optimization, based on ILD (with simulation group, ~ 4 students), eg.
  - Layers: ECAL 30→24 layers, HCAL 48→40 layers
  - Cell size: ECAL 0.5x0.5→1x1 cm², HCAL 1x1→2x2 cm²
- Sensors performance (eg. Si, Sct, RPC, ThGEM, GEM): counting rate, acceptance, linearity, time response, energy resolution etc., large area sensors
- Electronics (existing technologies and performance, ASIC design, comparison of 1 vs. 3 thresholds)
- Active Cooling system: simulation and calculation of heat dissipation, design etc. for CDR
- Longer term: PCB and ASIC design and test
Well-THGEM, Ar/3%\text{C}_4\text{H}_{10};
CEPC Muon System

Functions of muon system
- To separate muons from hadrons
- A tail catcher of HCAL
- Solenoid return roke & support structure

Performance requirements
- nLayer >=8, iron thickness >= 6\(\lambda\)
- Eff >=95%, resolution<=2cm
- Misidentification rate (pi->mu)@40GeV <1%

The standalone simulation results show the number of layers and the thickness of iron are reasonable.
Single- or double-stage SRWELL detector?

- Double-stage detector expected to be more stable in hadronic showers
- Can be accommodated in the same space at the expense of the drift and conversion gap
- But: more expensive...

R&D Activities (Amos Breskin, Weizmann group, Israel)

- Optimization studies & R&D on large-area detectors.
- Preparing high energy pion beam test.
Geant4-based simulation of scintillation photon propagation. Monte Carlo simulation parameters are still to be optimized. Only relative comparison makes sense for the moment.