IDEA Dual-readout calorimeter in Key4hep

Sanghyun Ko
Seoul National University
on behalf of the dual-readout calorimeter team

8th June 2023, FCC week
IDEA detector

Concepts of the IDEA detector

- Silicon vertex detector

- Ultra-light drift chamber with a low material budget ~ O(10^{-2}) X_0
  → minimize interaction within tracker volume

- Thin (~ 0.7 X_0), 2 T solenoid inside the calorimeter

- Dual-readout calorimeter + preshower
  - Good EM & excellent hadronic energy resolution
    (crystal option also provides exceptional EM energy resolution)

- μ-RWELL muon chambers
Dual-readout calorimetry

- The major difficulty of measuring energy of hadronic showers comes from the fluctuation of EM fraction of a shower, \( f_{EM} \).

- \( f_{EM} \) can be measured by implementing two different channels with different h/e response in a calorimeter:
  
  \[
  S = E [ f_{em} + \left( \frac{h}{e} \right)_S (1-f_{em}) ] ,
  \]

  \[
  C = E [ f_{em} + \left( \frac{h}{e} \right)_C (1-f_{em}) ]
  \]

  \[
  f_{em} = \frac{(h/e)_C - (CIS)(h/e)_S}{(CIS)[1-(h/e)_S] - [1-(h/e)_C]}
  \]

  \[
  \tan \theta = \frac{1 - (h/e)_S}{1 - (h/e)_C} \equiv \chi,
  \]

  \[
  E = \frac{S - \chi C}{1-\chi}
  \]

- Excellent energy resolution for hadrons can be achieved by measuring \( f_{EM} \) and correcting the measurement event-by-event.

- Dual-readout fiber-sampling calorimeter is a key element of the IDEA detector concepts.
Dual-readout calorimeter

- Longitudinally unsegmented fiber-sampling calorimeter
  → measure both EM & hadronic components with two different channels in h/e
  → excellent energy resolution for hadrons via event-by-event correction

- Projective geometry with a uniform sampling fraction
  → fine unit structure with high granularity
  → more fibers in the rear than the front
Dual-readout calorimeter

- Longitudinally unsegmented fiber-sampling calorimeter
  - measure both EM & hadronic components with two different channels in h/e
  - excellent energy resolution for hadrons via event-by-event correction
- Projective geometry with a uniform sampling fraction
  - fine unit structure with high granularity
  - more fibers in the rear than the front

Simulation

Tower

SiPM

Rear

1.5 mm

Čerenkov

Scintillation

Front

Rear

Copper (3D printed)
SiPM emulation

Simulating SiPM response with SimSiPM

- SiPM is a major candidate for the photodetector
  → SiPM simulation library is developed [link][FCCSW meeting]
- Parameterized inputs from the datasheet
  → Dark counts, crosstalk, afterpulses, saturation, noise, …
- Included in the Key4hep stack as an external library
Dual-readout technique with Key4hep

A brief look at the dual-readout performance

- A full-scale 4π geometry has been implemented into DD4hep [git]
- Interfaced to G4 via k4SimGeant4, including a module for optical transportation
- Sensitive detectors are interfaced to EDM4hep – common event data model across Key4hep community
- Preliminary results show reasonable agreement with standalone G4 simulations
Bucatini calorimeter

Bucatini module with DD4hep

- A variety of options for DRC are being tested to answer physics & engineering challenges – Bucatini module is one of the major testbeds
- It has been extensively tested at beam sites in DESY & SPS [arXiv] 2021 (also planned for this Summer)
- Also working on implementing Bucatini module into DD4hep (hardware → software) [link]
Crystal DRC

Crystal option with DD4hep

- An alternative option that provides excellent EM resolution
- 1 $X_0$ timing layer (LYSO) + 2 layers of PbWO$_4$ crystals inside the IDEA magnet [JINST]
- Dual-readout technique with crystals can be carried out using different wavelengths of Čerenkov & scintillation light
- Detector geometry with crystal option has also been implemented in DD4hep [git]
Reconstruction with Key4hep

Reconstructing & displaying calo hits

- Reconstruction codes are implemented as Gaudi algorithms
  - (traditional) 2D dual-readout correction
  - Novel 3D reco using Fourier analysis with timing [git][CALOR]
  → can be put together with other key4hep services & sequences
- Able to promote the resulting EDM4hep calorimeter hits for usage in other key4hep software, e.g. Phoenix event display
Summary

Dual-readout calorimeter and Key4hep

- DRC has migrated its components to Key4hep successfully
  - Detector description
  - Simulation interface & event data model
  - Digitization & reconstruction

- A wide variety of dual-readout communities are seeking to reach the Key4hep infrastructure (Bucatini, crystal DRC, …)

- The team is now working on further integration
  → consolidating SW organization to Key4hep repositories
  (k4geo, k4SimGeant4, k4RecCalorimeter)

- Anticipating synergies with other Key4hep softwares by benefiting common infrastructures (event display, clustering algorithm, …)
Optical physics simulation

- Timing is crucial for longitudinally unsegmented calorimeter to measure shower depth
- Optical physics gives detailed timing information, but at a high cost of CPU
- Incorporating modularized G4 Physics Lists to achieve detail & speed simultaneously
  - FTFP_BERT (full simulation)
    - + GEANT4 optical physics [code] (inactive in default G4)
    - + Fastsim module applied to optical photons [link][code]
EDM4hep

Migration to EDM4hep

- EDM4hep is a common EDM that can be used by all communities in the Key4hep project to aim to boost synergy between associated SW (simulation, clustering, event display, etc).

- Interfaced G4Event/G4VHit of the DRC simulation to EDM4hep calorimeter hits

<table>
<thead>
<tr>
<th>Data</th>
<th>EDM4hep class</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC truth (Edep)</td>
<td>edm4hep::SimCalorimeterHit</td>
</tr>
<tr>
<td>Readout (# of p.e.)</td>
<td>edm4hep::RawCalorimeterHit</td>
</tr>
<tr>
<td>Digitization (# of ADC)</td>
<td>edm4hep::RawCalorimeterHit</td>
</tr>
<tr>
<td>Reco (2D/3D)</td>
<td>edm4hep::CalorimeterHit</td>
</tr>
</tbody>
</table>
SiPM emulation

Expected: 200 kHz
MC DCR: 200.18 kHz
Measured: 200.49 ± 0.8 kHz

Expected: 10 %
MC XT: 11.2 %
Measured: 10.2 ± 0.5 %

Rate [kHz]

Staircase
Expected DCR: 200
Expected XT: 10 %

Threshold

Simulated peak value

Jun 8, 2023
Optical properties in simulation

Detection eff of SiPM

Rear end of a tower

Detection eff of SiPM

Transmission eff of filters

For optical tracking [link]

Attenuation loss diverges at 400nm → applied filter to S channel to mitigate it

Scintillation spectra of PS

Light yield = 13.9/keV
k_B = 0.126mm/MeV

Attenuation loss of Polystyrene (PS) & PMMA

PS

PMMA

k = 0.434dB/m ⇔ l = 10 m
Speeding up optical photon tracking

Fast optical photon tracking

- Tracking optical photons is necessary, however it dominates CPU consumption
- Optical photons inside fibers can be tracked efficiently, by skipping intermediate steps
  → developed fastsim for optical photons (presented at GEANT4 R&D meeting [link])

\[
\text{# of reflections} = \text{std::floor}(\frac{(\vec{x} - \vec{x}')}{\text{step} \cdot \hat{i}})
\]

\[
\vec{x} = (0, 0, 0)
\]

\[
\vec{x}'
\]

\[
\text{Center of fibre} \quad (\vec{f})
\]

\[
\text{End of fibre} \quad (\vec{f})
\]

\[
\text{L}/2
\]
Calibration

Calibration using 20 GeV e-

- Measure Energy deposit, scintillation p.e. & Čerenkov p.e. at i-th tower (0th - 91st)
- Energy can be expressed as a linear combination with simulations of 92 towers
  → Estimate calibration constants
- Uniform calibration constants as a function of the tower number

\[
E = E_{\text{dep}}^i \approx \sum_j \text{Hit}_j^i \times C_{\text{Čeren}}^j
\]

\[
E = E_{\text{dep}}^i \approx \sum_j \text{Hit}_j^i \times C_{\text{scint}}^j
\]
Shower shape & timing – SiPM waveform

- Unsegmented calorimeter fully depends on the timing to reconstruct longitudinal shower shape
- Is dV/dt → dE/dx possible? 
  → very challenging due to many hidden layers
- A SiPM yields exponentially decaying waveform to 1 photon
- FFT can be used to mitigate exponential tail, while preserving time translation & amplitude information

\[
\begin{align*}
\langle \vec{x} \rangle, & \quad \text{Photon propagation } \langle \vec{k} \rangle \\
\dot{t} & = \frac{|\vec{x}|}{c} + \frac{|\vec{k}|}{v} \approx \frac{t - |\vec{l}|/c}{1/v - 1/c} \\
\vec{x} & \approx \vec{l} - \frac{t - |\vec{l}|/c}{1/v - 1/c} \hat{k}
\end{align*}
\]
Longitudinal shower shape

Shower shape & timing – Dispersion

- Waveform is unlikely a shower shape even after FFT processing
- Late-component of the timing is dominated by the modal dispersion
- Mitigate dispersions by using slower phase velocity for late-components
  → Tune group velocity as a function of $\Delta t$ using EM shower

$$v \approx \frac{\|\vec{l}\| - \|\vec{x}\|}{t - \|\vec{x}\|/c}$$

Tune velocity $v$ according to cumulative distribution of $x$ & $t$
3D reconstruction

Reconstructed

MC truth

EM

Hadronic

\[ E_{\text{scint}} = 19.96 \]
\[ E_{\text{ch}} = 20.84 \]

\[ E_{\text{scint}} = 17.29 \]
\[ E_{\text{ch}} = 10.22 \]
\[ E_{DR} = 20.04 \]

\[ E_{\text{scint}} = 13.05 \]
\[ E_{\text{ch}} = 8.410 \]
\[ E_{DR} = 14.85 \]

\[ |\vec{B}| = 2 \, T \]

MIP

\[ E_{\text{scint}} = 1.550 \]
\[ E_{\text{ch}} = 1.243 \]

\[ \pi \rightarrow \mu + \nu \] before entering the tower

*tracks are both MC truth

*hadronic showers often have additional “legs”

*reaches end of the tower

*for all 4 cases

Jun 8, 2023