Advanced R&D of the Dual-Readout Calorimeter

Hwidong Yoo (Yonsei Univ.)

On behalf of
the Dual-Readout Calorimeter Collaboration

CPAD workshop, Mar. 19, 2021
Dual-Readout Calorimeter (DRC)

- DRC offers high-quality energy measurement for both EM particles and hadrons
- DRC consists of two different optical fibers (S, C) in a single component
- The main culprit of poor hadronic energy resolution is fluctuations of the EM shower components of hadron showers ($f_{em}$)
- $f_{em}$ can be determined using the measured values of scintillation and Cerenkov signals
- Excellent hadron energy resolution can be achieved by correcting the energy of hadron event-by-event
DRC Geometry and Module

- Korean team led the design of the Dual-Readout Calorimeter (DRC) for IDEA detector
  - Included in the CDRs of both FCC-ee and CEPC, published at the end of 2018
- **Calorimeter design for EIC project** with Korea HI community is also on-going
Energy Resolution

- Production of calibration constant with full GEANT4 simulation is on-going
  - Both barrel and endcap have been done
- Excellent EM and hadronic energy resolutions obtained by GEANT4 simulation
  - EM energy resolution: $\sim 11\% / \sqrt{E}$
  - Jet energy resolution: $\sim 26\% / \sqrt{E}$
- Many other simulation studies for performance and ML applications on-going
International Collaboration

Prof. Hyonsuk Jo (KNU)
Prof. Yongsun Kim (Sejong U.)
Prof. Jason Lee (UoS)
Prof. Sehwook Lee (KNU)
Prof. Hwidong Yoo (YU)

Prof. Yuji Enari (Active from 2021)

Prof. Rong-Shyang Lu
Prof. Chia Ming Kuo

Taiwan

Korea

Japan

Prof. Richard Wigmans
Prof. John Hauptman

Prof. Sarah Eno
Prof. Chris Tully

USA

Europe

Prof. Paolo Giacomelli (Bologna)
Prof. Romualdo Santoro (Insubria)
Prof. Roberto Ferrari (Pavia)
Prof. Franco Bedeschi (Pisa)
Prof. Iacopo Vivarelli

Prof. Valery Chmill

International collaboration forms
- Regular meeting
- Compensated R&D options
- Combine efforts

Full-size prototype detector

KISTI

Bucatini prototype
Korea Prototype Detector

- Primary goal: build a prototype detector for the detector design of CEPC experiment
  - 5 year (2020.Mar. - 2025.Feb.) R&D funding supported by Korea NRF ($~0.4M/year, total $~2M for 5 years)
  - Contain almost (97.5%) full hadronic shower energy
  - Demonstrate engineering aspects for full geometry detector

- Secondary goal: train next generations as experts of the (DRC) detector

<table>
<thead>
<tr>
<th>Stage</th>
<th>Topic</th>
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<tr>
<td>Design</td>
<td>Propose a design of Dual-Readout Calorimeter to IDEA detector concept</td>
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<tr>
<td>R&amp;D</td>
<td>Perform R&amp;D (including engineering aspects) based on HW &amp; SW</td>
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<tr>
<td>Prototype</td>
<td>Build 4x4 detector and perform test beams</td>
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<tr>
<td>Production</td>
<td>TBD</td>
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## Test-beam at 2021

<table>
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<tr>
<th>Goal</th>
<th>Details</th>
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<tr>
<td><strong>Physics</strong></td>
<td>Measurement of nuclear interaction length using proton beam</td>
</tr>
<tr>
<td></td>
<td>Measurement of energy and position resolution using electron beam</td>
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<tr>
<td><strong>R&amp;D</strong></td>
<td>Readout test (MCP vs. SiPM)</td>
</tr>
<tr>
<td></td>
<td>Time resolution (&lt; 50 ps)</td>
</tr>
<tr>
<td></td>
<td>Optical fibers (various types)</td>
</tr>
<tr>
<td><strong>Training</strong></td>
<td>Next generation experts for DRC HW</td>
</tr>
</tbody>
</table>

### Module #1 (2x2)
- Tower 1
- Tower 2
- Tower 3
- Tower 4

### Module #2 (3x3)
- Tower 1
- Tower 2
- Tower 3
- Tower 4
- Tower 5
- Tower 6
- Tower 7
- Tower 8
- Tower 9

### Specification of fibers
- 0.97 mm Polystyrene (LSOCF)  
- 0.99 mm PMMA (C-971)  
- Fluorinated Polymer

### Diagram
- 424 input channels from PMTs, MPPCs, MCP, PMTs, or SiPMs + extra inputs for trigger system
- Voltage inputs for 400 SiPMs
- Preamp Board
- FEE
- DRS (480ch)
- DRS Board
- TDC (10 bit)
- ADC (10 bit)
- FPGA
- Control PC + storage

Signal starting time difference: 2 ns/m

- Time resolution: 10 ps -> 5 mm precision
- Time resolution: 50 ps -> 25 mm precision
- Time resolution: 100 ps -> 50 mm precision
Module Building in 2016

- For 2016 test beam, two Cu modules were produced by cutting

- This technical approach has already been proved well by previous module building

- Testing innovative 3D printing for alternative possibility at 2020
Previous Copper Forming R&D

• We tried many options (by John Hauptman et al in CERN RD52)
Is It Possible with 3D Metal Printing?

• Ok, German company …, let’s check it out

4.3 3D Printing

A German company advertises a 3-D printer for tungsten, and it seems copper cannot be more difficult. I have not looked into this, but the largest 3d printer I have seen is less than a square meter, but it should not be a problem to extend one dimension to 3 meters.
3D Copper Printing Technology

- Copper is not easy to be used for 3D metal printing

- But technology is being developed very fast …

- We contact a local 3D consultant company
3D Printing Module R&D

- Two major questions on the DRC for engineering aspects
  - Complex design
  - Projective shape
- Use 3D metal printer to produce Cu blocks with fine structure holes
  - ~1 mm diameter for a hole
  - ~0.5 mm wall thickness between holes

3D printing can be a solution!

Stack 10 pieces (25 cm per each Cu block)

With 3D printing consultant company in Korea
- have world-wide expert networking
1st Trial: Finland Company

- The 1st trial is not hopeless, but the hole size is < 0.7 mm, therefore cannot assemble the optical fibers.

Nose (not sufficient quality)

60x60 holes

9.1 cm

9.1 cm

5 cm

EOS (Germany)
How to Do Additive Manufacturing

Movie link (click)
2nd Trial: Finland Company

- Very successful projective shape and ~1.1mm diameter of the hole, but failed for < 0.5 mm wall thickness
3rd Trial: China Company

- Scan various values and designs for the diameter and wall thickness

- Achieve < 0.5 mm wall thickness with ~1.0mm diameter of the hole!!

<table>
<thead>
<tr>
<th>Samples</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall diameter (mm)</td>
<td>Designed</td>
<td>1.0</td>
<td>1.1</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
<td>1.3</td>
<td>1.1</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Outcome</td>
<td>0.9-0.95</td>
<td>0.9-0.95</td>
<td>1.0-1.05</td>
<td>0.8-0.85</td>
<td>0.8-0.85</td>
<td>1.1-1.15</td>
<td>0.9-0.95</td>
<td>1.0-1.05</td>
<td>1.0-1.05</td>
</tr>
<tr>
<td>Wall thickness (mm)</td>
<td>Designed</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>0.7</td>
<td>0.5</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Outcome</td>
<td>0.52</td>
<td>0.6</td>
<td>0.62</td>
<td>0.5</td>
<td>0.45</td>
<td>0.81</td>
<td>0.6</td>
<td>0.4</td>
<td>0.65</td>
</tr>
</tbody>
</table>
Toward Prototype 3D Module

- Under test and design: check alignment of holes and very successful!
- Ordered five 3D-printed copper blocks (10 cm length each) for the prototype module
• Excellent opportunity to

• Integrate US and world-wide research campaign

• Increase visibility our local activity to internation colleagues

• International dual-readout team prepared a single interest (LoI): overview of dual-readout activities


• Additional 7 LoIs related to the dual-readout calorimeter R&D project have been submitted too!

• Various MC production such as multi-jets, Higgs and tau events are underway with GEANT4 + DD4hep infrastructure
SM2021 with DRC in Korea

• Topic 1: Feasibility study of combining a MIP Timing Detector with the Dual-readout Calorimeter at future e+e- colliders (link)
  Collaborators: D. Stuart (UCSB), C.S. Moon (KNU), J.H. Yoo (Korea Univ.)

• Topic 2: Heavy flavor tagging using machine learning technique with silicon vertex detector and Dual-Readout Calorimeter at future e+e- colliders (link)
  Collaborators: J. Huang (BNL), Q. Hu (LLNL), S.H. Lim (PNU)

• Topic 3: tau reconstruction and identification using machine learning technique with Dual-Readout Calorimeter at future e+e- colliders (link)
  Collaborators: M. Murray (U. of Kansas), Y.S. Kim (Sejong Univ.), Y.J. Kwon (Yonsei Univ.)

• Topic 4: Sensitivity study of H->Zgamma with Dual-Readout Calorimeter at future e+e- colliders (link)
  Collaborators: Y. Maravin (Kansas State Univ.), K.W. Nam (Kansas State Univ.)

• Topic 5: Multi-object identification with Dual-Readout Calorimeter at future e+e- colliders (link)
  Collaborators: P. Chang (UCSD)

• Topic 6: Dual-Readout Calorimeter for the future Electron-Ion Collider (link)
  Collaborators: S.H. Lim (PNU), H.S. Jo (KNU), Y.S. Kim (Sejong Univ.)

• Topic 7: Fast optical photon transport at GEANT4 with Dual-Readout Calorimeter at future e+e- colliders (link)
• Dual-Readout Calorimeter R&D project for future $e^+e^-$ collider in Korea is very active

  • Build and test full size prototype DRC detector by 2025
  • HW R&D and simulation studies for performance and ML applications on-going
  • Under preparation for test beam 2021
  • Calorimeter design for EIC project with Korea HI community is also on-going

• Innovative 3D-printing module is on-going

  • Collaborating with world-leading 3D metal printing frontier companies
  • Prototype module design and production are underway

• Various Snowmass 2021 studies are on-going