Longitudinal Segmentation of Multi-readout Fiber Calorimeters by Timing for 3D Imaging Calorimetry

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Challenge in Hadron Calorimetry

- Invisible energy:
  In hadron-nuclei interactions, large fraction of hadron energy goes to nuclear dissociation and becomes invisible. We need to estimate the invisible energy from a visible quantity.

- Large volume:
  Very high granularity may be a preferable option to deal with the “invisible” energy problem but the cost gets big quickly as the granularity increases.

We need a cost-effective way to estimate the invisible energy!
Invisible Energy in Had Shower in Cu Absorber

- 30 GeV $\pi^+$ and 200 GeV $\pi^+$ on Cu absorber were simulated with GEANT4.
- Clear correlation between the total invisible energy vs the total number of hadronic vertices (left) and the invisible energy vs the number of charged pions in the first interaction (right).

- How to estimate invisible energy?
  - Simple idea: count the vertices and apply some corrections depending on features at each vertex.
  - Better idea: use 3D imaging capability of ML methods.
Showers in high granularity calorimeters can be viewed as 3D images:
- Fiber calorimeters with depth segmentation by timing

Detailed information on *multiplicity and production angle of the secondaries* can be extracted from the visible signal and used to improve the energy reconstruction.

Convolutional Neural Networks (CNN) are very good at image classification:
- Raw images are used
- Higher level features extracted using sequential convolutional operations
- Regression performed
Copper / Silicon sampling calorimeter is simulated with GEANT4

- Alternating Cu 17 mm (absorber), Si 3mm (active) layers, with size of 1.0x1.0x1.5m$^3$
- Readout granularity is 2x2x2cm$^3$
- Signal is integrated over 5 ns with correction for the longitudinal propagation time
- Energy threshold of 0.6 MeV per cell is applied, with MIP MPV at about 1.0 MeV
- No electronics/noise

![Energy per cell, MeV](image)
Energy Reconstruction with More Traditional Techniques

The performance of the energy reconstruction with CNN is compared to:

1. Simple energy sum over all channels in the volume
2. Reconstruction with correction for the fluctuations in the EM-fraction
CNN Performance – single hadron Cu/Si

CNN trained with **single pions** outperforms other conventional methods for energy reconstruction.

\[
\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus c
\]
CNN Test with Electron

Electron reconstruction with CNN \textit{trained on single pions}.

CNN maintains good performance for electron energy reconstruction – comparable to traditional techniques.
CNN Performance – multi-particles: jets

CNN trained on *single pions* (0.5-150 GeV) performs very well with jet reconstruction in extended energy range – up to 1 TeV
Reconstructing the EM Fraction with CNN

CNN can also be trained to reconstruct the EM-fraction in hadron showers

Geant4 EM Fraction

CNN/GEANT4
CNN Performance – Compensating Calorimeter

*Uranium – Silicon sampling calorimeter.* U-3.3mm, Si-0.7mm
Signal is integrated in 5ns and the cells are combined in 1.6x1.6x1.6cm³ channels for the CNN reconstruction. CNN is trained on single pions 0.5-150 GeV.
3D Imaging Fiber Calorimeter

Done
- Study of a simple calorimeter with CNN.
  - Cu(17mm)/Si(3mm), 2x2x2 cm$^3$ cube structure.
  - 2x2 cm$^2$ transverse size matches Cu Moliere radius (1.6 cm).

Next
- Design and prototype a 3D imaging calorimeter.
- First option: Fiber calorimeter with longitudinal segmentation with timing.
  - Evaluate the limitation of current HW (SiPM, FEE, ...) and prioritize R&D tasks.
  - Build a prototype to verify the prediction of the CNN study with GEANT simulation.
Fiber Calorimeter with Longitudinal Segmentation with Timing

Signal Time = $L_1/c + L_2/kc$
- $c =$ velocity of particle
- $kc =$ velocity of light in fiber ($k \approx 0.6$)
- $\Delta L = 2 \text{ cm} = 44 \text{ ps}$

- Channel counts reduction:
  3D Calo: $N_x \times N_y \times N_z$
  $N_z \rightarrow 1$

- Major Components:
  - Absorber
  - Fibers
  - SiPMs
  - Frontend Electronics
    - Amplifiers
    - Waveform digitizers
  - DAQ

- R&D on bench started!
Bench Test Setup

SensL MicroFC-30020-SMT (evaluation board)

2.5 GHz scope

Fiber-Filter-SiPM-Cooling (in dark box)

Dark box and NALU Scientific AARDVARC
SiPM- Pulse Shape for Single Photon

- Fast photon counting is required for timing measurement.
- SensL SiPM has two outputs. Fast Output is used for photon counting.

Hamamatsu

1 photon equivalent pulse output

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(Typ. Ta=25 °C, Vi=Vop)

- 2 photons signal (4 ns apart)
  - peak 2.3 ns
  - 4ns
  - (2.5 Gs/s on scope)

SensL MicroFC-30020SMT (Fast output)
SiPM – Photon Counting with Precision Timing

- SiPMs are excellent photon counting devices and have potential to be excellent timing device to map time structure of showers in calorimeter with high performance waveform digitizer.
  - R&D is required!

![Single photon event](image1)
![Two photon event (simultaneous)](image2)
![Two photon event (5ns apart)](image3)

Fast output
2 mV / photon

Standard output
2 mV / photon

SensL MicroFC-30020SMT
Longitudinal Coordinate Resolution

- Pulse shape of single photon signal from SensL SiPM was measured with NALU’s AARDVAC V3.
- The pulse shape was used to simulate waveforms of convoluted pulses of two photon events.

- Recurrent Neural Network (RNN) was used to reconstruct the timing of two photons.
- Resolution of 7 cm (2 cm) will be achieved for 1 (5) photon-equivalent signal.
  - Improvement expected with “better” SiPM and FEE.

\[
\Delta t(\gamma_1-\gamma_2) = \sigma(\Delta t) 204 \text{ ps}
\]
NALU Scientific AARDVARC V3 – System on Chip

- Compact, high performance **waveform sampling and digitizing**.
  - 10-14 Gsa/s, 12 bits ADC, 4-8 ps timing resolution, 32 k sampling buffer, SoC
  - DOE SBIR project

- NALU provided TTU an evaluation board (4 ch).
  - Waveform sampling/digitizing: performed well on our test bench.
  - System on Chip: not yet tried.
  - We have regular discussions with the NALU team for improvements and further development

**NaluScope – 03.20**

SiPM single photon signal
- green: Fast output
- magenta: Standard output
IDEA prototypes include TDC. We evaluate the current design and look for further improvement of timing measurement toward 3D imaging calorimetry. We focus on R&D in the following area.

- **Fibers:** We have been studying quartz fibers, plastic and rare-earth-doped quartz fibers at TTU. We evaluate fibers for best timing measurement.

- **SiPMs:** We have been characterizing silicon sensors for the CMS HGCAL using TCAD and testbench measurements. Use of TCAD for SiPM characterization and further development of fast SiPM is under discussion.

- **FEE:** We have not investigated a potential of SoC technology yet. AARDVARC is under evaluation by IDEA. We evaluate the SoC on AARDVARC and explore further use of the SoC technology.

**IDEA: Fiber Layouts:**
- Capillary-tubes
- Plate-absorber
- 3D-printing matrix

**IDEA: TDC aiming at < 50ps**
IDEA plans

- **Short-term plan:** build and test on beam a module with EM shower containment (10x20x100 cm$^3$) and highly granular core (3.5x3.2x100 cm$^3$) equipped with SiPMs
  - Testbeam at DESY in early summer (delayed from Nov ’20 due to Covid19)
  - Cosmic muon stand under development

- **Mid-term plan:** design, build & qualify on beam a scalable system with hadronic containment, partially equipped with SiPM for cost/performance optimization
  - TTU plan under development

Capillary-tube design

3D printing matrix design
Summary

- We simulated a simple 3D imaging calorimeter with GEANT4.
  - Convolutional Neural Network (CNN) reconstructed energy well. It outperforms conventional calorimeters, e.g. EM-fraction corrected one.

- We started R&D of multi-readout fiber calorimeter with longitudinal segmentation with timing.
  - Bench tests of HW components (fibers, SiPM, FEE) are in progress.
    - SiPM has good potential for precision timing measurement.
  - Full Monte Carlo simulation program will be developed with realistic parameters from the bench tests.
  - The MC program will be used to develop HW design and ML algorithms.

- We are working with the IDEA collaboration on both HW and SW.
  - Longitudinal segmentation with timing will be evaluated with the IDEA prototypes.