Development of a High-Granularity Calorimeter Insert for the Electron-Ion Collider
HEPCAT Progress Report

Sean Preins

University of California, Riverside
(Dated: March 2024)

I. INTRODUCTION

SiPM-on-tile technology, where a unit cell of calorimeters is a small plastic cell readout by a SiPM, represents a key pillar in next-generation calorimetry for future colliders. It was originally developed by the CALICE collaboration for the ILC [1], and is now being deployed for the LHC and the EIC, specifically within the forward region of the ePIC detector.

Calorimetry in the forward region of ePIC, within the pseudorapidity range of $3 < \eta < 4$, poses a significant instrumentation challenge for several reasons. Firstly, the 25 mrad EIC beam-crossing angle creates a complex geometry that the detector must both stay clear of, but also envelop as closely as possible to extend the kinematic range of ePIC. Secondly, this far-forward region of ePIC is expected to receive the largest radiation dose out of the entire detector, expecting to receive a neutron fluence of 10e12 1-MeV n_{eq}/cm^2 during one run, and so the detector will need to be able to operate under these conditions. And finally, the calorimeter will need to have a high granularity to disentangle nearby particles, given the high particle density expected in this region.

A SiPM-on-tile approach to calorimetry in the forward region of ePIC provides a natural solution to these challenges. The use of small tiles leads to a highly granular design, which allows each layer to uniquely tessellate around the complex geometry of the beampipe, and works well with a design that would allow regular access to the SiPMs during maintenance periods to mitigate the effects of radiation damage.

This report will discuss the progress made developing high granularity SiPM-on-tile hadronic calorimetery for ePIC, to be used in the Calorimeter Insert (CALI) [2] and ZDC, covering the dates from 1/1/23 to 3/31/24. Section two will describe initial characterization studies for the building blocks of a SiPM-on-tile calorimeter. Section three will detail the results of the first CALI prototype at the Hall D pair spectrometer at Jefferson National Laboratory. Finally, section four will cover the current status of assembling and installing the second-generation CALI prototype, to be tested on the East platform of the STAR detector at the Relativistic Heavy-Ion Collider.

II. CHARACTERIZATION STUDIES

To begin development on the Calorimeter Insert sub-detector using SiPM-on-tile technology, we first performed several bench-top tests to characterize its building blocks, and compare different designs. In May 2023, this culminated in our paper "Studies of time resolution, light yield, and crosstalk using SiPM-on-tile calorimetry for the future Electron-Ion Collider" Ref. [3].

The time resolution was determined by measuring the time differences between two back-to-back scintillating tiles, with a Sr-90 source placed above them, and a trigger tile placed below. This resulted in a single SiPM timing resolution of $3180 ps/\sqrt{n_{pe}}$. This Sr-90 setup, along with a similar setup designed to receive cosmic rays, were used to determine the light yield from MIPs, which measured a most probable value of around 60 photoelectrons.

In these studies, we tested two new innovations with the SiPM-on-tile design. First, we tested the method of using 3D-printed frames to segment the scintillating tiles from each other, and found that it significantly reduced optical cross-talk and minimized dead space when compared to the method of cutting groves in a single, connected mega-tile, shown in Fig. 1. This test was done by shining a pulsed LED into one tile, and measuring the signal within that tile, and a neighboring tile. We also tested the process of painting the edges of the scintillating tiles with reflective paint, and only using reflective foil on top and below the tile, instead of fully wrapping the tiles in foil.

III. JEFFERSON LAB PROTOTYPE

In January 2023, we performed our first test beam of a CALI prototype at Jefferson National Laboratory. The purpose of the test beam was to characterize the performance of our high granularity, tile-on-SiPM design for the HCAL insert, under actual beam conditions. The prototype was a sampling calorimeter composed of ten layers of iron

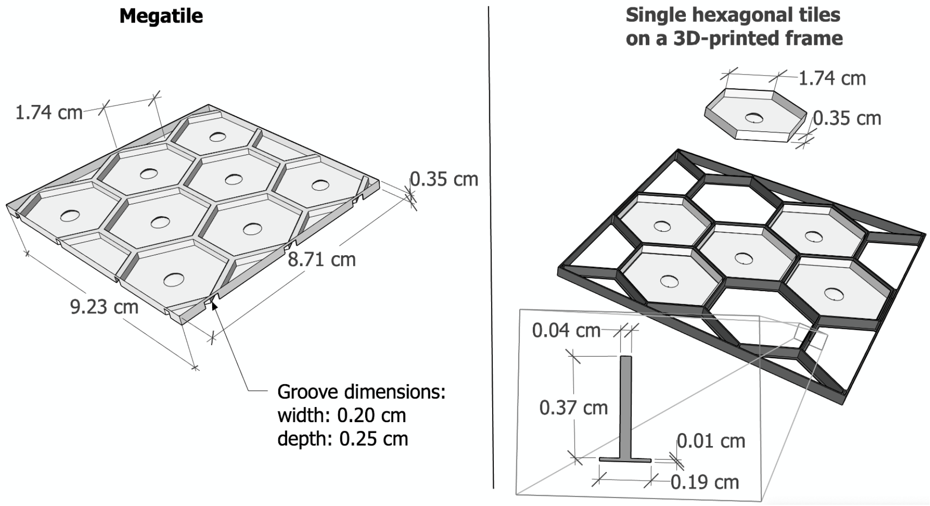

FIG. 1. A render of hexagonal tiles machined within a megatile (left), and hexagonal tiles separated with a 3D printed frame (right). Ref. [3]

absorbing blocks interspersed with scintillating tiles on silicon photomultipliers, with four tiles per layer, shown in Fig. 2. The scintillating tiles were machined, polished, painted, and assembled with the PCBs at UCR. This prototype was much smaller than the design for the entire insert, at only 11.4 radiation lengths long, and a cross sectional area of 2 by 2 Moliere radii.

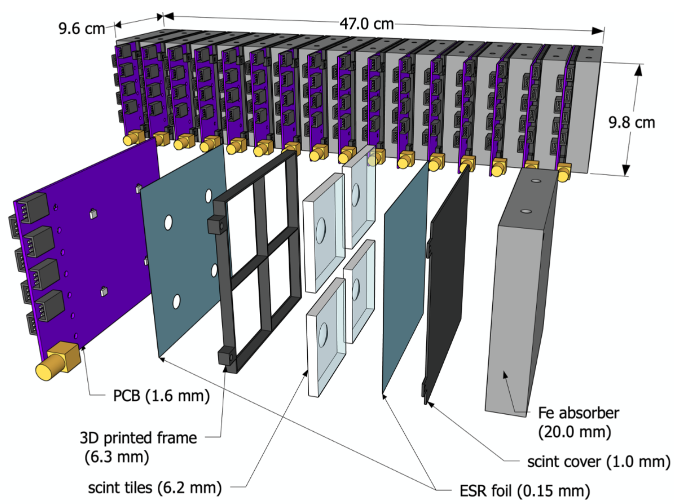

FIG. 2. The SketchUp model of the HCAL insert prototype. Ref. [4]

Within each tile, we used 3 mm^2 Hamamatsu 14160 SiPMs, which were both biased and individually read out using a CAEN digitizer unit. We tested two different shapes of scintillating tiles along the length of our detector, square and hexagonal. These tiles were held in place by 3D printed frames.

Before our prototype was installed in Hall-D, we performed calibration measurements. We assembled our tile-on-SiPM layers vertically without the iron absorber plates, and observed minimum ionizing particle events from cosmic rays. As each channel could be read out individually, we could determine the MIP energy scale separately for each channel. Once this was completed, we were able to fully assemble the prototype and install it in Hall-D.

The prototype was installed in front of the Hall-D pair spectrometer, in front of the Glue-X experiment. Here, our prototype received 4 GeV positrons at a variable luminosity, reaching a maximum of approximately 3 kHz. The installed prototype is shown in Fig. 3. The test beam conditions were recreated in the DD4HEP simulation framework, and the same analysis was performed on both. As seen in Fig. 4 and Fig. 5, the data was found to be in good agreement with the simulation. In addition, the data displayed asymmetries consistent with a vertical misalignment of 15 mm, and a polar tilt of approximately 42 mrad relative to the beamline, displaying the potential of this detector design to track the trajectories of incoming particles.

FIG. 3. Photos of the HCAL insert prototype just after assembly (left) and installed in front of the Glue-X experiment at Jefferson Lab (right). Ref. [4]

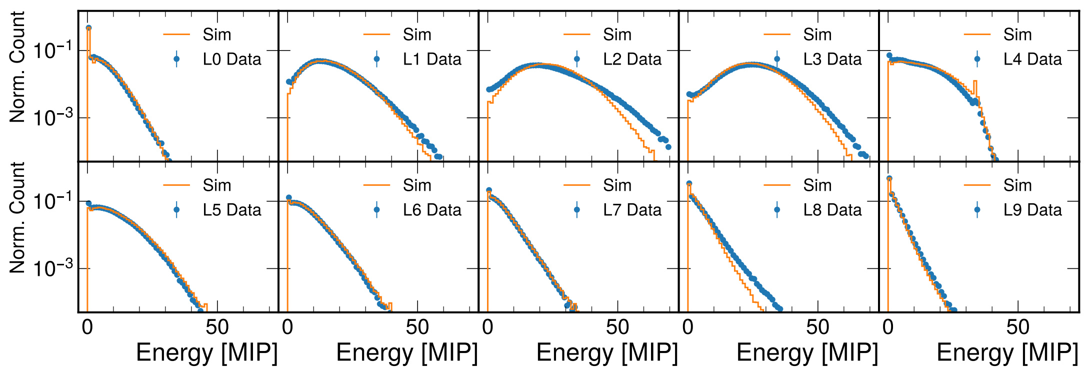

FIG. 4. The energy spectra for the summed energy for each layer in the HCAL insert prototype, comparing test beam data with a Monte Carlo simulation in DD4HEP. Ref. [4]

This test helped validate our SiPM-on-tile calorimeter design, as well as proving the feasibility of using an ASIC-away-of-SiPM design, allowing most of the electronics to operate outside of the detector region. In October 2023, this test culminated in our published paper "Beam Test of the First Prototype of SiPM-on-Tile Calorimeter Insert for the Electron-Ion Collider Using 4 GeV Positrons at Jefferson Laboratory" Ref. [4].

IV. BROOKHAVEN LAB PROTOTYPE

Following the prototype test at Jefferson Lab, we constructed a second generation prototype to be tested within the STAR hall at Brookhaven National Laboratory. This prototype consists of 300 channels across 20 layers, and has four times the cross-sectional area of the Jefferson Lab prototype. It also consists of a three layered hodoscope in front, to track the trajectories of incoming charged particles. Again, the scintillating tiles were machined, painted, and assembled with the PCBs at UCR, shown in Fig. 7. This prototype was installed in February 2024 on the east platform of STAR within the range of $3.2 < \eta < 3.6$ to best emulate the conditions of CALI in ePIC, shown in Fig. 6.

The goals of this test will be to demonstrate in-situ calibration and operation under realistic radiation fluence using MIPs, π^0 mass reconstruction, and by monitoring various physics quantities over time. The testing will extend throughout 2024, after which the SiPMs will undergo removal, annealing, and re-installation for continued testing in 2025. This process aims to evaluate the efficacy of annealing in reversing the impacts of radiation damage.

The large number of channels used requires the use of multiple synchronized CAEN units, and as such required the development of a more sophisticated DAQ system. Bench-top tests at UCR resulted in the system shown in Fig. 8, where the CAEN units are synchronized using a DT5215 concentrator, triggered externally using single SiPM-on-tile

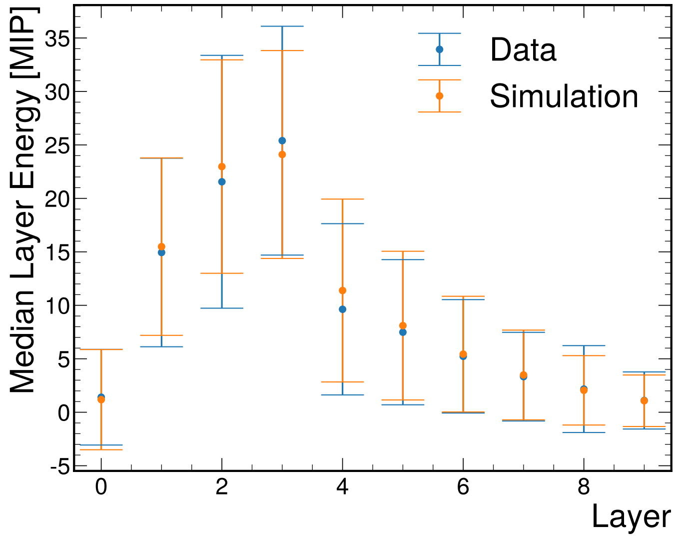

FIG. 5. The mean energy deposited in each layer of the HCAL insert prototype from the test beam and a DD4HEP simulation. The error bars correspond to the standard deviation of the energy spectra. Ref. [4]

FIG. 6. The generation 2 CALI prototype being installed in the East platform of STAR (left), facing the IP with minimal material obstructing it (right).

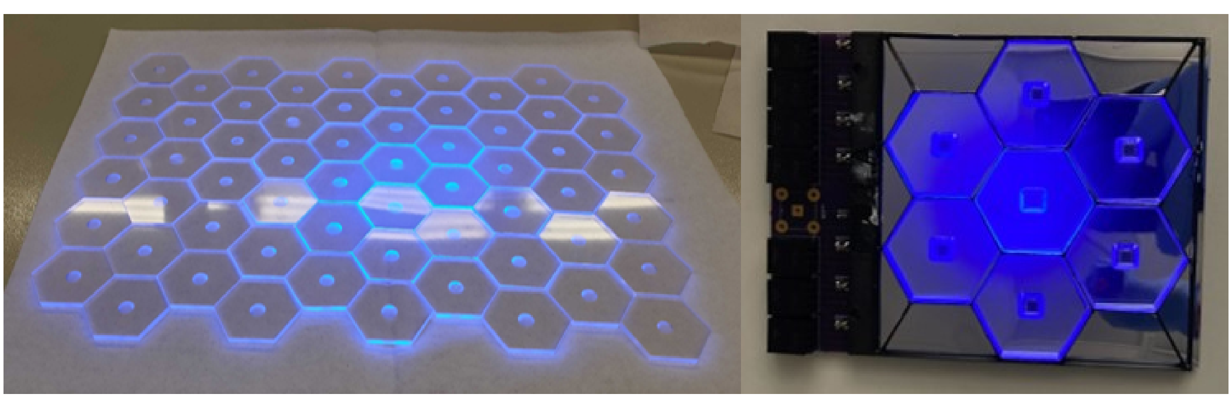

FIG. 7. Hexagonal scintillating tiles machined at UCR (left) and installed in a PCB with reflective foil (right).

boards positioned in the front and middle of the prototype. The trigger logic is then controlled using a DRS4 digital oscilloscope, allowing us to switch between a charged particle trigger, or a hadronic shower trigger. The prototype is controlled via a fiber-optic USB connected to a DAQ laptop in the STAR control room.

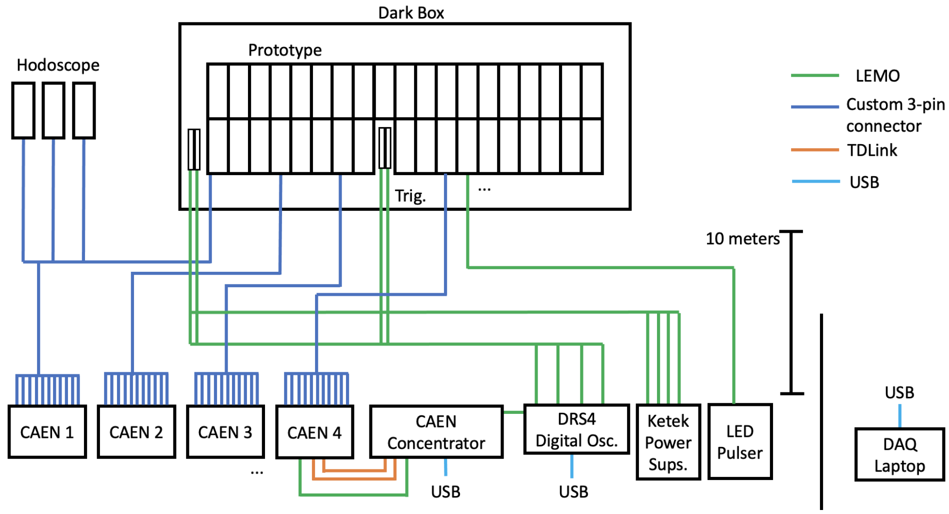

FIG. 8. The DAQ system for the generation 2 CALI prototype at Brookhaven National Lab.

V. FUTURE WORK AND SUMMARY

Significant progress has been made on the development for a SiPM-on-tile based hadronic calorimeter for the future Electron-Ion Collider. Bench-top tests helped characterize the building-blocks of the ePIC Calorimeter Insert, with regards to light yield, time resolution, and optical crosstalk. These tests also validated the method of segmenting the scintillating tiles with 3D printed frames, and the use of reflective paint on the edges of the tiles.

A 40 channel CALI prototype was tested at the Hall-D pair spectrometer at Jefferson National Laboratory, where it received 4 GeV positrons. Cosmic rays were used to calibrate each channel of the prototype individually, and various physics quantities were compared with DD4HEP Monte-Carlo simulations. The data was found to be in good agreement with simulations, again validating the 3D printed frame SiPM-on-tile design, as well as testing an ASIC-away-of-SiPM design.

A larger, second generation CALI prototype was designed and constructed, consisting of near 300 channels and four times the cross-sectional area of the previous prototype. The increased number of channels required a more complex DAQ system, consisting of multiple, synchronized CAEN units and an external trigger system. The prototype is currently installed on the East platform of the STAR detector at the Relativistic Heavy-Ion Collider, and is accumulating cosmic ray data before the beam is turned on.

More beam tests have been planned to study the performance of future CALI prototypes, as well as characterizing the radiation hardness of SiPMs and the effects of annealing to mitigate the effects of radiation damage. These tests are planned to occur at Fermilab in Fall of 2024, and the UC Davis cyclotron and again at Jefferson Lab in the later part of 2024.

[1] Antoine Laudrain and on behalf of the CALICE Collaboration. The calice ahcal: a highly granular sipm-on-tile hadron calorimeter prototype. *Journal of Physics: Conference Series*, 2374(1):012017, nov 2022.

[2] Miguel Arratia et al. A high-granularity calorimeter insert based on SiPM-on-tile technology at the future Electron-Ion Collider. *Nucl. Instrum. Meth. A*, 1047:167866, 2023.

[3] Miguel Arratia, Luis Garabito Ruiz, Jiajun Huang, Sebouh J. Paul, Sean Preins, and Miguel Rodriguez. Studies of time resolution, light yield, and crosstalk using sipm-on-tile calorimetry for the future electron-ion collider. *Journal of Instrumentation*, 18(05):P05045, may 2023.

[4] Miguel Arratia, Bruce Bagby, Peter Carney, Jiajun Huang, Ryan Milton, Sebouh J. Paul, Sean Preins, Miguel Rodriguez, and Weibin Zhang. Beam test of the first prototype of sipm-on-tile calorimeter insert for the eic using 4 gev positrons at jefferson laboratory. *Instruments*, 7(4), 2023.