ePIC LFHCal R&D Proposal - eRD107

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1 Introduction

1.1 Requirements for the ePIC forward calorimeters

In electron-proton (ep) or electron-ion (eA) collisions, many highly-energetic hadrons are created in the process of probing the partonic structure of the target proton or ion using the electron. However, since the incoming proton/ion has a significantly larger kinetic energy than the incoming electron, most of the hadrons are emitted in the same direction as the hadron beam, into the hadron end cap, which is defined as the "forward" direction at the EIC. Thus jets of particles, with single-particle energies of up to 150 GeV, are expected to reach the forward hadronic calorimeter, e.g. based on simulated PYTHIA events for ep collisions at 18×275 GeV^2. Typical jets consist of 10-12 particles contained within a jet radius of $R = 1$, with R being the angular distance $\sqrt{\eta^2 + \phi^2}$. These jets also contain nontrivial substructure within this cone, which carries important information about QCD dynamics. Unfortunately, the tracking momentum and angular resolution worsens rapidly above $\eta = 3$. Because of this, the hadronic and electromagnetic calorimetry in that region are required to provide both excellent energy resolution and sufficient spatial resolution to resolve particles within the jets. Thus, the forward calorimeter system has to be finely-segmented and built with minimal dead space between the towers. This design will provide shower containment for highly energetic particles while still providing good energy resolution down to low energies. The R&D for the hadronic calorimeter will be coordinated within this eRD project, while the developments for the ePIC forward electromagnetic calorimeter (known as pECal) are being carried out in eRD106.

1.2 Modified LFHCal and Insert Design

The ePIC forward HCal (LFHCal) will be based on a longitudinally-segmented steel-scintillator tower design with a tungsten-scintillator collimator section (modified design based on [1]). The design is based on the SiPM-on-tile concept first introduced by CALICE collaboration [2], which is now being further developed for the CMS HGCAL upgrade [3]. It has been adapted to satisfy the physics performance requirements of the EIC Yellow Report [4] and will include an insert surrounding the beam pipe with even higher granularity readout following the same general concept.

parameter	**LFHCal**
inner x, y	60 cm
outer radius (envelope)	270 cm
η acceptance	$1.2 < \eta < 3.5$
tower information	
x, y	5 cm
z (active depth)	130 cm
z read-out	10 cm
# scintillator plates	65 (0.4 cm each)
# absorber sheets	61 (1.52 cm steel)
	4 (1.52 cm tungsten)
interaction lengths	6.5 λ/λ_0
Sampling fraction f	0.035
# towers	8916
# modules	
8M	1077
4M	75
# read-out channels	7 x 8916 = 62,414

Table 1: Overview of the calorimeter design properties for the LFHCal.

The LFHCal is positioned at $z = 3.58$ m from the interaction point, and is preceded by the inner tracker and PID detectors as well as the pECal. The calorimeter is comprised of two half-disks with an outer radius of about 2.7 m.

The LFHCal towers have an active depth of $\Delta z = 1.3$ m with an additional space for the readout of about 10 cm, as summarized in Table 1. Each tower consists of 65 layers with alternating layers of about 1.6 cm absorber and 0.4 cm scintillator, with transverse dimensions of 5×5 cm^2. The first 4 absorber layers, after the steel front plate, consist of tungsten, followed by 60 layers of steel absorber. The tungsten layers act as a collimator for the initial shower and enable a maximization of the hadronic interaction length within the available space.

The towers are constructed in units of 8- and 4-tower modules, to ease the construction and reduce the dead space between the towers. Each scintillator tile ($5\,\text{cm} \times 5\,\text{cm} \times 0.4\,\text{cm}$) is individually wrapped in reflective foil and then sheets of 2×4 or 2×2 tiles are assembled for each layer of the 8M or 4M modules respectively. These tile assemblies consist of a layer of kapton tape on the top and bottom for stability, the wrapped scintillator tiles and a flexible PCB carrying the SiPMs and an LED system for monitoring purposes, see Figure 1 top center. The flexible PCBs are connected to a long carrier PCB on one side of the module, which transfers the electrical signals from each individual tile to the back of the calorimeter. In order to reduce the number of readout channels within each tower SiPM signals from the first 5 tiles, and 10 tiles thereafter, are combined using an intermediary summing board at the back of the calorimeter. These signals are then processed by an ASIC based on the CMS HGCROC chip [3].

For the majority of the calorimeter we will be using SiPMs with an active area of $1.3\,\text{cm} \times 1.3\,\text{cm}$ (ie. Hamamatsu S13360-1325PE or S14160-1315PS) and injection molded scintillator tiles. However, in the current design neither the scintillator tiles nor the SiPMs can be accessed after the calorimeter has been assembled for radii below 1 m we are therefore considering using larger SiPMs with an area of $3\,\text{cm} \times 3\,\text{cm}$ (ie. Hamamatsu S13360-3025PE or S14160-3015PS) together with cast and machined scintillator tiles to mitigate the expected radiation damage. The full LFHCal consists of 62 414 readout channels grouped into 8916 tow-

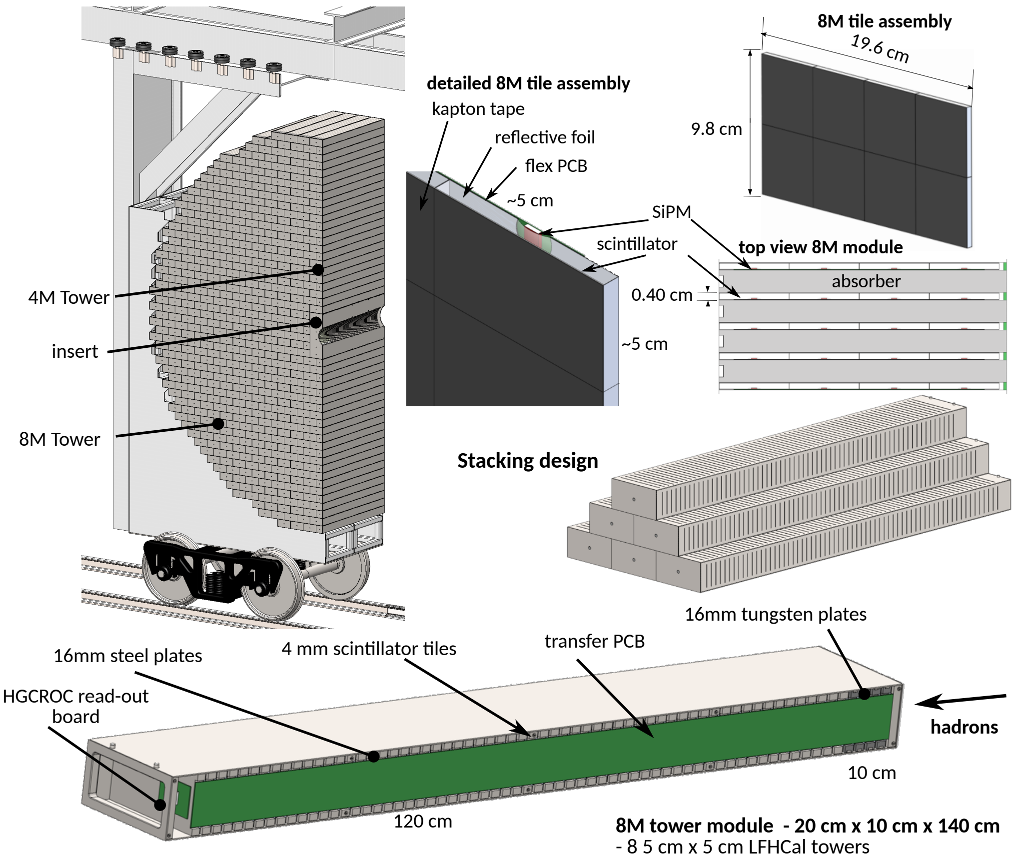


Figure 1: Renderings of the forward calorimeter assembly (top left), tile assembly of 8 scintillator tiles of the LFHCal with the SiPMs sitting in a dimple on each tile, detailed stacking example (middle right) and 8-tower module design (bottom).

ers.The majority of the calorimeter is built of 8-tower modules ($\sim$1077) which are stacked in a support frame using a "lego"-like system for alignment and internal stability. The remaining 4M modules are necessary to fill the gaps at the edges to allow for maximum coverage. It is complemented with an insert surrounding the beam pipe $60\,\mathrm{cm} \times 60\,\mathrm{cm} \times 140\,\mathrm{cm}$ using the same technology and absorber geometry. By using asymmetric and layer by layer varying cutouts around the beam pipe radius the coverage can be increased up to $\eta \approx 3.8$. This inlay will also serve as internal support structure around the beam-pipe for the LFHCal.
The internal structure of the 8M modules is as follows. The absorber plates in the modules are mounted to the sheet metal frame using e-beam welding on three sides, keeping them in place while adhering to the tolerances and providing internal stability. On the left side of each module, a channel is left for installation of the scintillator sheet assemblies and the transfer PCB, which is afterwards closed with a cover to protect the electronics, as can be seen in Figure 1 (bottom). For internal alignment we rely on the usage of $1-2$ cm steel pins at the end of each module which are directly anchored to the back plate and a bolt in the front which is mounted to a continuous steel plate covering the front face of the calorimeter. This steel plate simultaneously serves as support plate for the forward ECal. Consequently, the modules are

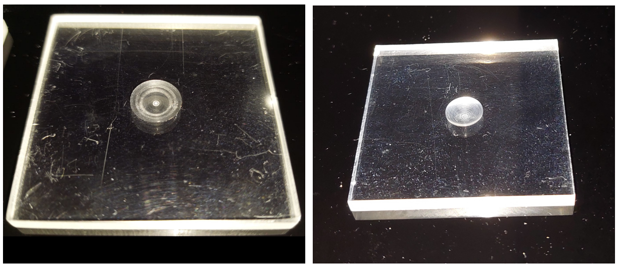
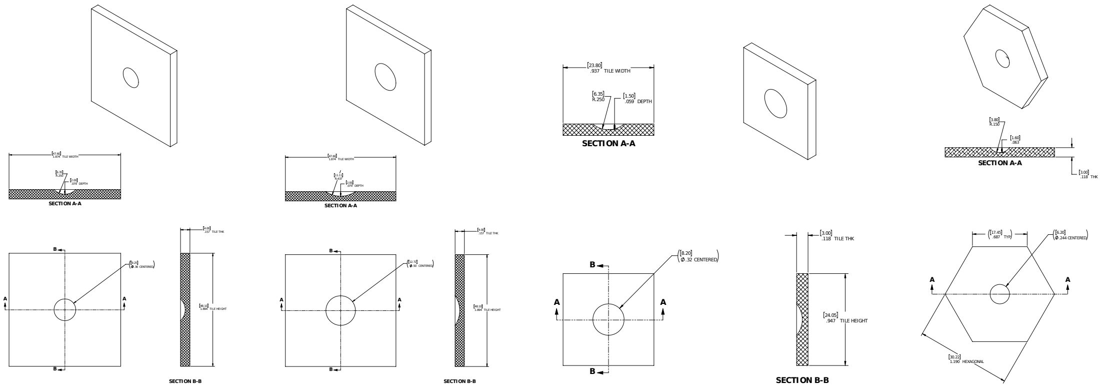


Figure 2: Picture of machined tiles with different machining procedures. Left: Tiles cut with water jet. Right: Tiles cut with modified wet tile saw. Dimples extruded using ball nose end mill.



(a) 5 cm × 5 cm, 0.5 inch ball mill

(b) 5 cm × 5 cm, 0.875 inch ball mill

(c) 2.5 cm × 2.5 cm, 0.5 inch ball mill

(d) hexagonal, 0.5 inch ball mill

Figure 3: Tile models to be injection molded using the same mold.

self-supporting within the outer support frame.

The support frame for the half disks is arranged on rails which allows the HCal and ECal to slide out to the sides and gives access to the inner detectors. In addition, the steel in the LFHCal serves as the flux return of the central 1.7 T magnet. As a consequence, a significant force is exerted on the calorimeter, which needs to be compensated for by the frame and internal support structure.

2 R&D Progress FY23

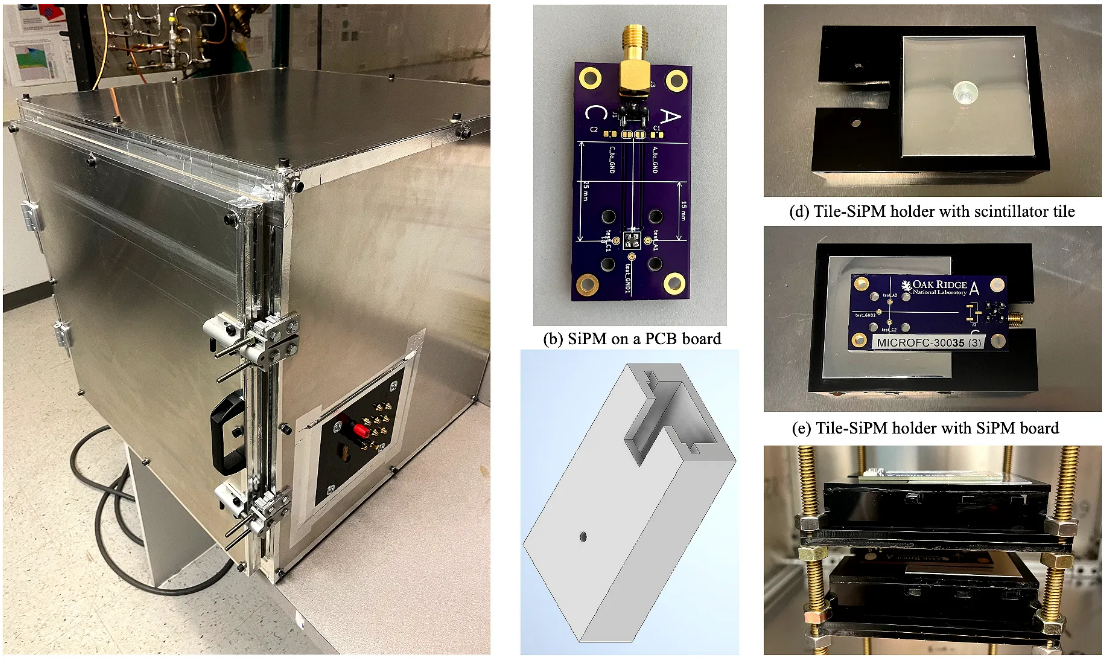
2.1 Production of tiles

After receiving the R&D money for FY23 in March 2023 at ORNL, we conducted a market survey for obtaining cast and machined scintillator material from different vendors. The most promising vendors for the cast material are Eljen and Luxium Solutions. Both vendors are able to provide the cast material with similar light yield for 60K tiles within one year. Their machining capabilities and prices are however very different. As such, several studies have been conducted at ORNL on how the machining of these delicate materials could be done for large quantities. An example of the first attempt carried out by the ORNL machine-shop can

be found in Figure 2 (left). The machining was done using a water jet cutter with the standard settings for plastics. As can be clearly seen the material is too sensitive to be handled in this manner resulting in cracks at the outer edges. The dimple was extruded with a ball nose end mill, which had been used prior to this for other materials. This lead to scratches in the material.
With the help of our local scintillator expert Michael Febbraro the procedures for the different steps were improved leading to significantly improved production results. The tiles are cut using a modified wet tile saw (i.e. RIDGID 9) with the protective foil still attached. The speed of the tile saw is decreased to about 10-30% of the factory setting by running it off a variac and a higher volume water pump is used to increase the cooling. Using this setup a current precision of 1.5 mm can be achieved on the outer edges. This could be further improved by creating a more precise rig for the tiles to be held by. Only distilled water is used as the cooling solution to avoid crazing due to chemical interactions. Afterwards the exact dimensions are reached using a fly cutter. This can be done for multiple tiles at once. During this whole process the protective foil is left in place. Only for cutting the dimple it is removed on the top. Similar to the ORNL machine shop the dimple was created using a ball nose end mill, however the process was significantly slowed down and cutting tool was only used for scintillator materials before. Afterwards, the dimple and edges were polished using a buffing wheel combined with a tiny drop of unscented Dawn-soap, 0.3μ Alumina power and water. This improved procedure resulted in significantly better quality tiles. Nonetheless, minor scratches on the surface arising from handling and dust particle are visible in Figure 2 (right). Estimates by the expert suggest that in a production setup 200-300 tiles could be cut per hour. The drilling and polishing of the dimples could be achieved with a rate of about 150-200 tiles per hour.
In parallel we have asked Eljen an Luxium to produce some test samples of the final product and we are waiting to receive them to test their production quality. An order of 600 tiles provided by Eljen should be received before the parasitic test beam at CERN in September 2023.
In parallel to the machining efforts a mold for injection molding four different tile types has been ordered by Fermilab recently. Within this mold during one inject one tile of each type will be produced. Two of these tiles correspond to the standard LFHCal tile sizes but different dimple geometries, while the other two are being evaluated for use in the insert. Compared to the cast scintillator, we are expecting about 30% reduced light yield, as seen in previous experiments. However, the production tolerances are significantly better and the tiles can be produced at a reduced price as well as in a shorter amount of time. Using the first samples using our mold we will try to optimize the tile geometry as well as production mechanisms using injection molding, similar to what has been done for the machining within this R&D program.

2.2 Dark Box and Test Setup

Two different light-tight dark boxes were designed and assembled at Yale and ORNL, respectively. They feature a panel with throughputs for SMA, SHV, 20 pin headers, and banana connectors and a door or removable panel for easy access to the setup inside as shown in Figure 4(a). The dark box is also a Faraday cage that shields external interference, in turn allowing for investigation into intrinsic properties of the SiPM's, and the characterization of both the SiPM's and scintillation tiles.
PCB boards holding a SiPM as shown in Figure 4(b) are used for testing and characterizing



(a) Light-tight Faraday box with connector panel

(b) SiPM on a PCB board

(c) SiPM Holder with hole to shine 400 nm LED photons

(d) Tile-SiPM holder with scintillator tile

(e) Tile-SiPM holder with SiPM board

(f) Two Tile-SiPM holders on shelf

Figure 4: (a) Setup to provide a light-tight environment for testing the SiPM's including a light-tight box with a panel with throughputs for connectors at Yale, (b) SiPM on a PCB board, PCB board holder with a hole for an LED pulser for single photon efficiency tests, (c) a Tile-SiPM holder that holds the SiPM and tile together and aligned during testing (d and e), and a shelf with slots holding the Tile-SiPM holders at different distances for coincidence tests.

the scintillator tiles for the LFHCal. The functionality of the SiPM's were tested using an LED pulser that was held vertically above the SiPM chip using the SiPM PCB holder shown in Figure 4(c).

For future coincidence tests, Tile-SiPM Holders with the PCB boards screwed for stability were created as shown in Figure 4 (d) and (e).

2.3 SiPM Characterization

Silicon Photomultipliers (SiPM's) are produced by various vendors in different packaging and pixel size options. While we are anticipating to obtain our SiPMs from the largest vendor, Hamamatsu, we are also characterizing SiPMs of similar pixel density and packing size from other vendors to ascertain whether they can fullfil our performance criteria for the LFHCal. All obtained SiPMs with their corresponding main characteristics can be found in Table 2, according to the vendors.

In order to verify the functionality of the SiPMs and to determine the spread of the breakdown voltage, IV-curves were determined at ORNL and Yale for every SiPM using a Source-Measurement unit or PicoAmmeter and Voltage Source, respectively. Repeating the measurements at Yale allowed to verify the SiPM's and PCB's (Printed Circuit Boards) were not dam-

Table 2: SiPM types obtained with their characteristic features. Gain for Onsemi SiPMs given at $V_{bd} + 2.5$ V

SiPM type	Vendor	size	pixel pitch	# pixels	fill factor	V_{bd}	opt. λ	PDE	Gain (V_{bd} + 5 V)	# tested
S14160-1315PS	Hamamatsu	1.3 cm × 1.3 cm	15 µm	7284	49%	(38 ± 3) V	460 nm	32%	$3.6 \cdot 10^5$	5
S14160-3015PS	Hamamatsu	3 cm × 3 cm	15 µm	39984	49%	(38 ± 3) V	460 nm	32%	$3.6 \cdot 10^5$	-
S13360-1325PE	Hamamatsu	1.3 cm × 1.3 cm	25 µm	2668	47%	(53 ± 5) V	450 nm	25%	$7.0 \cdot 10^5$	-
S13360-3025PE	Hamamatsu	3 cm × 3 cm	25 µm	14400	47%	(53 ± 5) V	450 nm	25%	$7.0 \cdot 10^5$	-
S4K33C0115L	Broadcom	3 cm × 3 cm	15 µm	38400	-	(29.5 ± 1.0) V	430 nm	29%	$7.0 \cdot 10^5$	9
S4K33C0135L	Broadcom	3 cm × 3 cm	35 µm	7396	-	(29.5 ± 1.0) V	430 nm	41%	$40.0 \cdot 10^5$	12
S4K33C0147L	Broadcom	3 cm × 3 cm	47 µm	4096	-	(29.5 ± 1.0) V	430 nm	44%	$70.0 \cdot 10^5$	2
MICROFC-10010	Onsemi	1 cm × 1 cm	10 µm	2880	28%	(24.5 ± 0.3) V	420 nm	18%	$2.0 \cdot 10^5$	3
MICROFC-30035	Onsemi	3 cm × 3 cm	35 µm	4774	64%	(24.5 ± 0.3) V	420 nm	41%	$30.0 \cdot 10^5$	3

aged during their transportation from ORNL to Yale. The obtained data is fitted with a two component fit to determine the V_{bd}, as seen in Figure 5(a). As seen in Figure 5(b) the spread of the break down voltages for the different SiPM types is in agreement with the numbers provided by the vendors, except for those given for the S4K33C0115L, which showed a significantly lower V_{bd} and a larger spread.
Due to delays in the delivery some of the Hamamatsu SiPMs types (S14160-3015PS, S13360-1325PE, S13360-3025PE) could not yet be tested. The corresponding evaluations will follow once they are delivered.

For the tile lab-test setup a CAEN DT5202 [5] digitizer is used. After calculating the V_{bd}, characterizing the dark count rateat a given over voltages (V_{op}) with the staircase plot, and conducting the different readout component tests, the single photon spectrum (SPE) was then characterized for the SiPM's. For this a CAEN LED Driver was mounted atop the SiPM and the signal was read out using the digitizer unit. Figure 6 shows an SPE spectrum recorded using the CAEN LED Driver for different two SiPM types. The wiggles in the blue line correspond to different PE peaks and fitting them gives the ADC/PE rate (orange line).
This fit gives an equivalence of 99 ADC/PE for the SiPM S4K33C0147 at $V_{op} = 2$ V, while for the MicroFC-10010 it is 86 ADC/PE at $V_{op} = 2$ V. Similar measurements will be performed for all SiPM types as a function of V_{op} to cross check the expected gain parameters, given in the data sheets.

2.4 Optimization and Granularity of the LFHCal & Insert

During the review of the calorimeter by the project in Dec. 2022, the initial concept of the LFHCal using wave length shifting fibers was put into question, mainly because of its significant complications during assembly. Afterwards, we started implementing different geometry options within the ePIC software stack in order to evaluate their performance in terms of resolution as well as acceptance and η-, ϕ dependence of the reconstruction performance. We compared there different designs:

1. The standard LFHCal, just replacing the WLS fiber readout with SiPMs in each layer.
2. A 90 degree rotated option of the LFHCal, letting the absorber align with the z-axis of the experiment (GFHCal), but keeping a similar sampling fraction and readout-channel count.

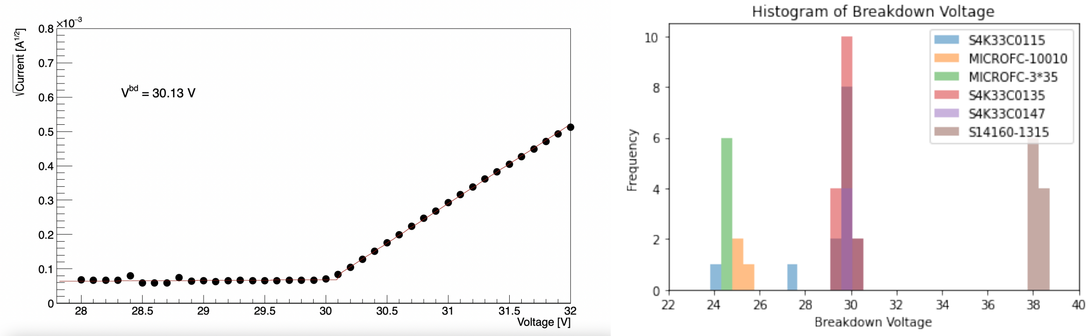


Figure 5: Left: IV Curve for SiPM S4K33C0147L. Right: Measured V_{bd} for all tested SiPMs.

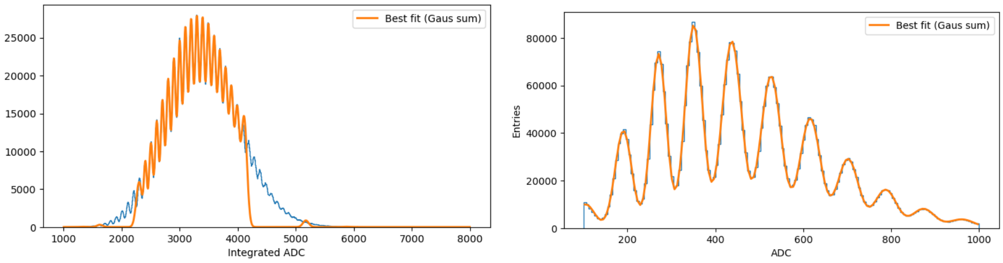


Figure 6: Single Photon spectrum (SPE) (blue histogram) together with its fit (orange line) for the SiPM S4K33C0147 ($V_{op} = 2\,\mathrm{V}$, left) and MicroFC-10010 ($V_{op} = 2\,\mathrm{V}$, right).

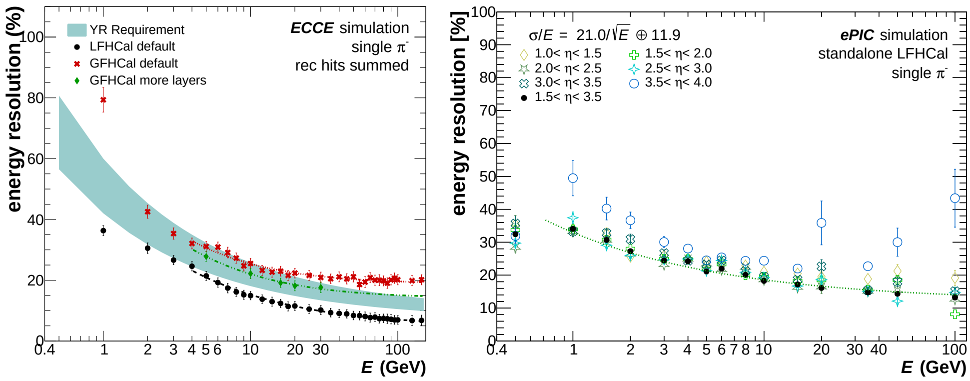


Figure 7: Resolution studies for different geometries (left) and η regions (right).

3. A 90 degree rotated option of the LFHCal, letting the absorber align with the z-axis of the experiment (GFHCal, increased layers) with increased number of layers.

The obtained energy resolutions without material in front of the detector can be found in Figure 7 (left). Based on these studies it has been concluded that rotated design would yield a significantly worse performance especially above and below the beam pipe as well as at higher η. Thus the design was rejected and the decision was taken to follow the LFHCal design with buried SiPMs in each layer.
Further studies of the η dependence of the resolution close to the beam pipe (Figure 7 (right))

in combination with the inaccessibilty of the SiPMs and scinitillator tiles after construction, yielded the inclusion of the insert into the baselined forward HCal design. Further studies on the exact granularity needed for the insert are, however, still pending. The SiPM-on-tile design for the LFHCal also allows to determine at a later stage the exact needed granularity in the longitudinal direction, as the reading out more or less layers would primarily affect the number of H2GCROCs needed per module and the summing boards. In order to address some of these concerns ORNL hosted an EIC calorimetery workshop in April 2023, which focused on the implementation of realistic geometries and reconstruction algorithms for all calorimeters within ePIC. Moreover, first attempts at machine learning based clusterization algorithms were developed during this workshop, which are being further explored during a similar workshop for graduate students at the end of July in Germany.

3 Remaining R&D Needs FY24

3.1 Scintillator Tiles

Using the improved design of the LFHCal the challenges for the scintillator tile production have shifted slightly compared to our original proposal. The proposed single tile geometry should be easily feasible to produce both using machining as well as injection molding. Thus the main concerns now are regarding the stability of the light yield and geometric tolerances in both production processes and optimizing those at minimal cost. Consequently we are proposing a systematic study of the influence of imperfections resulting from machining, as well as, different machining processes and their long term impact on the stability of the light yield. Using the machined tiles we would like to study the impact of different dimple geometries in combination with the slightly different SiPM dimensions.
Similar studies will also be performed for the injection molded tiles, however, here only two dimple geometries will be studied and the main free parameters are to be adjusted during the injection molding process itself. In particular, controlling the cool-down process of the tiles as well as their ejection from the mold can be studied in order to reduce geometric deformations and thus keep the light yield stable within the same batch of tiles. Moreover, different raw materials and dopants will be evaluated to maximize the light yield for the given geometry.

3.2 Scintillator Characterization and Optimization

All produced tile modules need to be characterized for their light yield, cross-talk and response uniformity in order to validate the optimum machining and molding technique, whilst minimizing the cost of the LFHCAL. Further optimization studies regarding the wrapping and 8M-scintillator assembly will be performed. These initial characterization routines will be important starting points to expand to a fully integrated quality assessment of each 8M-scintillator assembly prior to integration into the full LFHCal 8M module. As part of this R&D process we propose to develop a robost quality assurance procedure for single tiles, sheet assemblies as well as the full module. These procedures should included the characterization of the scintillator tiles, assembled SiPMs and variations within the module layer to layer. Moreover, a first concept of the monitoring system of the LFHCal is needed, which can be used during assembly, installation and operation to track the light yields in each tile, temperatures and humidity within the calorimeter, as well as, the characteristics of the SiPMs.

3.3 Readout Electronics

Significant development work needs to be performed to design, implement and test readout electronics that can scale to all 90 000 channels of the combined pECAL/LFHCal system. The requirements for the readout ASIC are low power consumption, to avoid active cooling, and a very low noise while maintaining the large dynamic range required for the signals, from a single MIP signal up to 200 GeV hadron showers. In addition, significant radiation hardness of the ASIC is required closer to the beam pipe. For these requirements, we consider the H2GCROCv3 developed for the CMS forward calorimetry upgrade at the LHC. The H2GCROCv3 has 78 channels in total and a large dynamic range, from 0.1 fC to 10 pC, while having a low power consumption of 20mW per channel. The dynamic range is achieved by combining the 10-bit ADC ($0 - 160$ fC) and 12-bit TOT (160 fC $- 10$ pC).

The H2GCROC is controlled by fast commands and I2C protocol for slow control. It is designed to work with the 40 MHz LHC clock (320 MHz for the fast commands and clocks). Some R&D is needed to adopt the 40 MHz clock for the EIC needs, which will be developed on an XILINX FPGA driving the ASIC. Each chip outputs 2 data links with a speed of 1.28 Gbps and 4 trigger links which can be configured as a sum of 4 or 9 channels. The time measurement of the 10-bit TOA is also read out via the data links. The data can then be connected to a FELIX board, e.g. as used by sPHENIX, or other EIC specific readout units by optical links.

Since the larger topic of readout electronics and ASICs is treated in eRD109, no specific request on R&D funds for the full forward calorimetry readout is made here. For the first test beams with small-scale setups, we will be using a universal waveform sampling readout system to obtain the largest possible amount of information from each channel. However, for the foreseen common test beam between pECAL and LFHCAL in 2025 a close to final version of a common readout board should be available, to exercise the full detector system.

Some electrical engineering expertise will be required to design the PCBs holding the SiPM sensors in each layer as well as the signal transfer boards on the sides of the each module. Until the final readout architecture is decided on, preliminary sensor boards do not necessarily need to contain any complex electronics apart from the sensors, a bias voltage distribution and potentially symmetric buffer amplifiers.

3.4 Prototypes and Test beams

The construction and testing of successively-larger R&D prototypes of the LFHCal will be important stepping stones towards the construction of the full LFHCal system. It serves to emphasize the expected performance numbers and to exercise all parts of the LFHCal project step-by-step, in order to build the needed confidence in the design required for a full scale prototype.

First components of the LFHCal will be taken to parasitic test beams at CERN during September and October 2023 in order to ascertain the saturation behaviour of the combined tile + SiPM system by adding layers of absorber material between individual tiles and measuring the individual and combined response of tiles to electromagnetic showers. In FY24 we plan to follow up on these initial tests with one 8M module constructed out of the injection molded tiles and another constructed using machined tiles. Once these campaigns have been concluded successfully, we anticipate to have the necessary information to finalize all aspects of the LFHCal design and to construct an LFHCal prototype on the lateral scale of 4 8M modules and full depth, to be extensively tested in an extended test beam campaign together with a similarly sized prototype of the pECAL. This combined full tower prototype module will be equipped with the final pECAL/LFHCal readout.

3.5 Optimization of the Reconstruction Algorithms & Granularity of the LFHCal

While significant progress has been made during the past year, regarding the geometry implementation within the ePIC software stack the reconstruction software of the LFHCal still relies on a fairly simple clustering algorithm. This approach can recover the energy of single particles hitting the calorimeter with a satisfactory energy resolution, however, it cannot correctly differentiate energy deposits within a jet from individual particles. Moreover, it cannot yet correctly take into account the additional information encoded in the different longitudinal segments. To further discriminate single particle within a high density environment we thus would like to explore different machine learning algorithms to distinguish showers originating from different particles. Including the HCal insert into our base line design for the LFHCal poses another challenge as its transverse granularity is different. Thus as part of this R&D process, we plan to evaluate not only the optimum size of the tower front-face as a function of the radial distance to the beam pipe for separation of particles within the jets but also its depth segmentation in conjunction with the foreseen electromagnetic calorimeter and tracking detectors to discriminate between different types of hadrons. In order to achieve this goal we will be working towards a full particle flow algorithm in the ePIC forward region.

4 Plans and Milestones for FY24

In the following the R&D milestones and their respective expected deliverables are listed, assuming a funding start of Oct. 2023

- **Tile production optimization using machining & injection molding (April 2024)**
  - Evaluation of different scintillator machining techniques and comparative review of different vendor capabilities regarding adherence to tolerances as well as optimizing the light yield and its stability for large number of tiles
  - Documentation of procedures for optimizing the light yield of injection molded tiles during the production process
  - High quality prototype tiles to equip two 8M modules for test beam studies
- **Reconstruction optimization (September 2024)**
  - Write-up of optimization results from simulations
- **Sensor board development (March 2024)**
  - First prototype of 8M-module-sized sensor board for Si-PM readout compatible with LFHCAL module geometry (together with eRD109)
- **Test module assembly (April 2024)**
  - First functional prototype of a full 8M module

- **Tile Characterization (August 2024)**
  - Write-up of test bench & test beam measurement for all assembled tile-prototypes
  - First concept of a monitoring system to be installed in the LFHCal

4.1 Money Matrix

The total funding requests broken down per institution and R&D activity can be found in Table 3 and 4, respectively. Time of students, postdocs and staff scientist for analysis of the various measurements is treated as contributed labor.

Table 3: Total funding request and breakdown by institution.

institute	**cost in FY24 k$**				**total cost**
	eng. and tech.	**material**	**equipment**	**travel**	**in FY23 k$**
ORNL	13.0	20.0	0	5.0	38.0
FNAL	11.6	0	0	0.0	11.6
Yale	0	5.0	16.0	3.0	24.0
Total	24.6	25.0	16.0	8.0	**73.6**

Table 4: Total funding request by institution for each R&D activity.

activity	**cost in FY24 k$**			**total cost**
	ORNL	**FNAL**	**Yale**	**in FY24 k$**
Tile Production R&D	15.0	11.6	5.0	31.6
Tile Char. (Lab)	0	0	19.0	19.0
Sensor Board	23.0	0	0	23.0
Total	38.0	11.6	24.0	**73.6**

5 Plan for FY25-26

CD2/CD3A end of FY23, from then on R&D shifts towards prototypes and project execution. R&D still necessary to answer open questions in time:

- Development and verification of robotic assembly stations, including fiber QA while laying, reproducibility etc.
- Development of QC procedures of finished tiles.
- Continuation of optimization of reconstruction algorithms with full EIC software
- Continued mechanical engineering support
- FY25 common testbeam with ECAL for final characterization of the full detector system

Moreover a common test beam campaign together with the pECal is foreseen for FY25 and FY26 in order to obtain the final characteristics for the full detector system.

Table 5: Estimated funding requests for LFHCAL R&D efforts in FY25-26.

Task	**Estimated cost in $ per year**	
	FY25	**FY26**
mechanical engineering	30K	20K
electrical engineering	30K	20K
materials	40K	40K
test beam support	10K	10K
total	110K	90K

A Appendix

B Detailed Funding Allocation for R&D in FY24

Table 6: Funding allocation and approximate completion dates for respective milestones for FY24.

Institute	Item	Cost per item in $	Number of items	Total cost in $	To be compl. by
	Tile Production R&D:				Q2/2024
ORNL	cast material			15K	
FNAL	raw material + dopant			(in kind) 0K	
FNAL	injection molder setup + operation	180/h	64h	11.6K	Q4/2023
ORNL/UTK/Yale	tile assembly		40h	(in kind) 0K	Q1/2024
ORNL	travel			5K	
	Tile Characterization (Lab Bench):				Q3/2024
Yale	scintillator material characterization		100h	(in kind) 0K	Q1/2024
Yale	source measurement unit & led pulser, other material	19K	1	19K	
GSU/Yale/UCR	tile lightyield testing		160h	(in kind) 0K	Q3/2024
Yale	travel			3K	
	Sensor Board:				Q1/2024
ORNL	electrical engineering	180/h	72h	13K	Q4/2023
ORNL	connectors & cables			5K	Q4/2023
ORNL	sensor board production, assembly		160	5K	Q4/2023
ORNL/UTK	testing		40h	(in kind) 0K	Q1/2024
	Reconstruction Optimization:				2025
UTK/Yale/BNL	simulations/digitization/reconstruction/analysis		640h	(in kind) 0K	
Total				**73.6K**	

B.1 Specific Expertise of Contributors

B.1.1 Oak Ridge National Laboratory

The ORNL relativistic nuclear physics (RNP) working group is part of the ORNL physics division. The RNP group has been, and continues to be, involved in the design, construction and operation of the calorimeter systems of various collider based nuclear physics experiments such as the STAR EMCal, PHENIX EMCal, ALICE EMCal as well as the proposed ALICE FoCal upgrade. The RNP group is currently the main proponent of the LFHCAL proposal for EIC detector one.

The contributions from the RNP group have made a significant impact on the design of the ECCE calorimetry, tracking and PID systems from extensive studies based on detailed simulations and full reconstruction codes. The results from these studies have shaped the currently planned layout of EIC detector one to great extent. The mechanical design of the LFHCAL has been supported by mechanical engineers from the ORNL nuclear fusion group.

At ORNL, the RNP group operates its own electronics laboratory currently housing test setups for the sPHENIX MVTX streaming readout and slowcontrol. The RNP group owns several modern 3D printers and has extensive experience in producing fast turnaround mechanical mockups, which have been proven to be immensely helpful in designing the LFHCAL. In addition, the RNP group has been granted access to a fully equipped electronics laboratory of the ORNL electronics and embedded systems group, which has extensive equipment for climate controlled testing, silicon wafer probe stations, very fast oscilloscopes, optical test benches etc.

Within the ORNL physics division, the working group of Mike Febrraro is specialized in the design, production and characterization of organic scintillator materials. This working group has developed significant expertise in injection molding plastic scintillators for the LEGEND experiment and also developed 3D printing capabilities for organic scintillator materials.

B.1.2 Brookhaven National Laboratory

Brookhaven National Laboratory is the host lab for the EIC project and has research groups participating in many aspects of the EIC project and science efforts. In particular, the lab made major contributions to the design and construction of the sPHENIX calorimeter systems (EMCal and hadronic calorimeters). In both cases, the lab provided extensive mechanical and electrical engineering support, and provided the assembly areas, both in the physics department high bay areas, and nearby support buildings. BNL physics also provides a full complement of machine shops, detector labs and electronics labs, with many experienced engineers, technicians and research staff supporting them.

B.1.3 Fermi National Laboratory

The Fermilab Detector R&D group has built extensive experience in extruding and injection molding plastic scintillator materials used in various high energy physics experiments and related fields. Their plastic scintillator production facility has capabilities to co-extrude large plastic scintillator bars and to injection mold polystyrene based materials. Injection molding has been successfully used to produce prototype voxel elements for the DUNE 3D scintillating tracker detector (3DST) that will be part of the DUNE near detector complex. As part of the

CMS HGCAL project, the Fermilab group is currently exploring the possibilities to injection mold small plastic scintillator tiles in large quantities.

B.1.4 Georgia State University

Dr. Megan Connors was a level 3 manager in the sPHENIX project responsible for the Hadronic Calorimeter scintillator tiles. The tiles were ordered from Uniplast (Russia) and tested at Georgia State University. The tiles are made from extruded polystyrene with an embedded wavelength shifting fiber. The two ends of the fiber exit at one location which is aligned with an SiPM to measure the light collected. To test the performance of the tiles, GSU and BNL designed a test stand that allowed to easily test thousands of tiles in batches of 8 at a time with cosmic rays. Two reference tiles were selected for each tile shape. These reference tiles served as triggers during the tests and were placed on the bottom and top of each stack of eight tiles. The ten tiles were slid into the test stand that was composed of ten SiPMs on holders that aligned with the tiles, which were read out with the CAEN DT5702 module. The ADC distribution was recorded and the Most Probable Value (MPV) of each distribution was extracted in order to characterize each tile with respect to the reference tile performance. Several studies were done to confirm reproducibility and found that 30 minutes of collecting cosmic ray hits was sufficient for determining the PR of the smaller inner tiles.

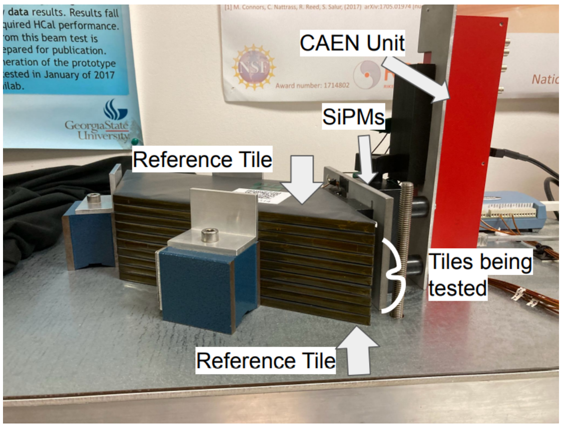


Figure 8: Test stand at Georgia State University for sPHENIX tile testing.

B.1.5 Iowa State University

The Iowa State Nuclear Experimental group has experience with trigger and data acquisition electronics with the PHENIX experiment as well as electromagnetic calorimetry with the MPC-EX detector (in PHENIX) and the hadronic calorimetry (in sPHENIX). Iowa State was responsible for the Global and Local Level-1 trigger systems in PHENIX, and managed the production of the inner and outer hadronic calorimeters in sPHENIX. Iowa State has electronics design and testing capabilities through collaborations with the Electrical Engineering Department, as well as relationships with local machine shops that offer manufacturing capabilities. The sPHENIX inner HCAL sectors were manufactured in Ames, IA.

B.1.6 University of Tennesee Knoxville

The University of Tennessee (UTK) group has experience with detector assembly and production, testing, and maintenance. Resources include offices and large experimental laboratory spaces in the UTK Science and Engineering Facility (SERF). This facility includes high bay areas and loading dock access. The Physics Department has a full machine shop with experienced technicians. UTK successfully performed specific assembly steps of for the production of all the IROCs (inner readout chambers) for the recent ALICE-USA Barrel Tracker Upgrade project. This involved attaching pad-planes and strong-backs to assembled aluminum frames and performing leak test qualification of the assembled IROCs. In addition to this ALICE-USA BTU project, the UTK group has participated in the detector assembly and subsequent detector maintenance for the PHENIX MuID, sPHENIX MVTX, and ALICE EMCal projects.

B.1.7 Yale University

The Yale group made, and continues to make, major contributions to the assembly, testing, calibration, installation and operation of the ALICE EMCal. The renovated Wright Lab at Yale allows the group access to large detector test and assembly areas, professional and student machine shop, CAD computers with latest versions of several design programs and prototyping shop with 3-D printers, a large water jet cutter, and a large laser cutter. Over the past few months members of the group have put together a lab test area with a light-tight box, test stand, PCB and tile holders and a CAEN digitizer module, and are gaining experience in testing the SiPMs and tile characteristics. The group also has significant experience in creating and tuning calorimeter reconstruction software and exploiting Machine Learning techniques.

B.1.8 University of California, Riverside

The UCR group has about 750 sf laboratory space and a 400 sf ISO 7 cleanroom, which is hosts standard equipment including: fast oscilloscopes, full-waveform fast digitizers (DRS4 boards), pico-second UV laser, picosecond pulse generator, source-measuring units, low-noise power supplies, function generators, frequency counters, rubidium frequency standard, LED drivers, calibrated photo-diodes, various optomechanical elements, dark boxes, environmental chamber, fully-equipped soldering stations, stereo microscope, FDM and resin 3D printers, computers with CAD software etc. Several UCR students have recent experience characterizing plastic scintillator tiles with SiPM readout, including with measurements of light yield, uniformity, time resolution, and cross-talk using radioactive sources, UV laser, and cosmic rays. UCR has a fully equipped machine shop capable of small production runs at a subsided rate (36 dollars per hour).

B.1.9 Valparaiso University, Valparaiso

The experimental nuclear and particle physics group at Valparaiso University (Valpo) has been active for more than 30 years and has participated in experiments including MEGA (LAMPF E969), NuSea (FNAL E866), the Crystal Ball (BNL-AGS E913), TWIST (TRIUMF E614), nEDM experiments at NIST and (currently) at LANL and ORNL, and the STAR experiment at RHIC. The faculty, staff, and undergraduate students at Valparaiso have been engaged in physics analysis, and also often in detector construction and operation. For STAR, components of the Endcap Electromagnetic Calorimeter (EEMC) were constructed at Valparaiso and we played a role in calibration, particle reconstruction, and an ongoing role in physics analysis with the EEMC. More recently, undergraduates from Valparaiso were involved in refurbishing the PHENIX sampling EMCal to become the STAR Forward Calorimeter System (FCS) EMCal. The slow controls software for the FCS was written at Valparaiso, and almost 10,000 scintillation tiles were polished, painted, and packaged at Valparaiso and recently installed in the FCS HCal.

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