# Longitudinally separated Forward HCal (LFHCal) Option Discussion

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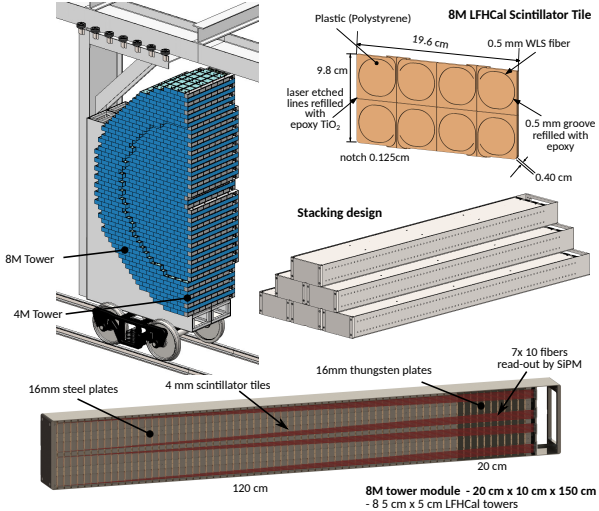
# Different Options

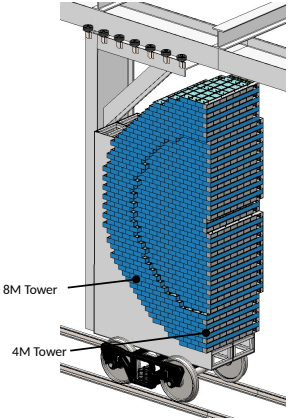
# Option 1 (Default)

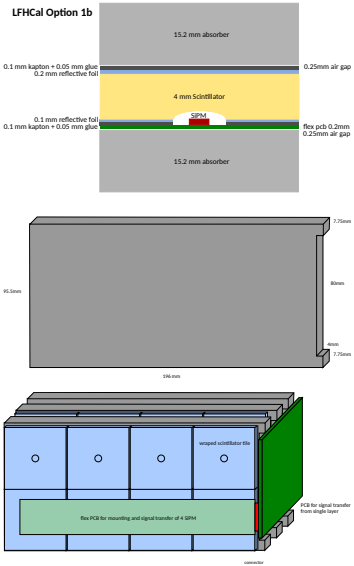



## Concept:

- PSD [link TDR] inspired inspired Fe/W-Scint calorimeter
  4 layers of W (160 mm)-Sci plates (4mm)61 layers of Steel (160 mm)-Sci plates (4mm) +
- Multiple towers combined in one module to reduce dead areas, increase granularity
- WLS fibers running into each tile, read out at the end
- Read-out:
  - 7 signals per tower (signals combined from 10 Sci-plates, 5 in tungsten section)
  - 63.3K channels read out
- Modules of different sizes (8M, 4M, 2M, 1M) to maximize coverage & assembly efficiency

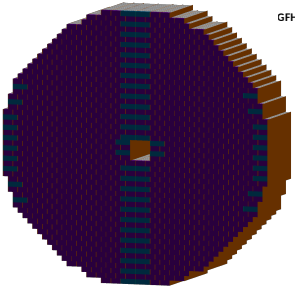
# Option 1b (Buried SiPM)

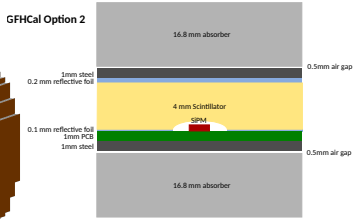


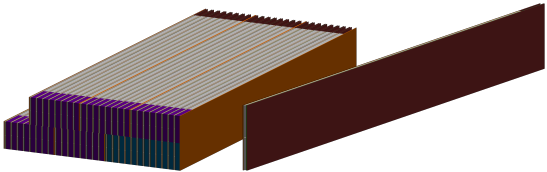




- Same general design as LFHCal option 1 replacing WLS fibers in each layer with SiPM on tile option and single wrapped tiles ( 5x5cm)
- Transfer of signals via small flex PCB to side of 8M module + long PCB to the end
- Signal summing of individual SiPMs at the end, same readout granularity at the end
- FEB boards removable similar to option 1, SiPMs not
- Simplified machining of absorber plates
- Upgrade option 1b+: Readout every SiPM by adding more HGCROCs & removing summing board, liquid cooling would be needed

# Option 2 - GFHCal

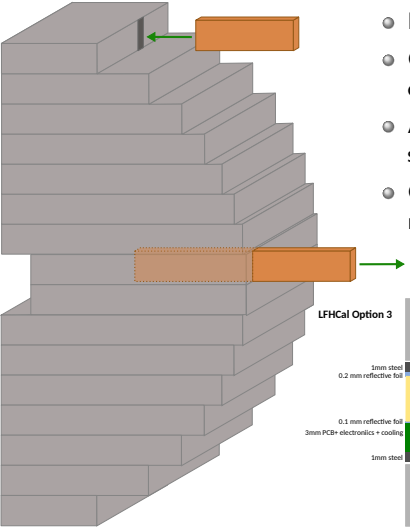




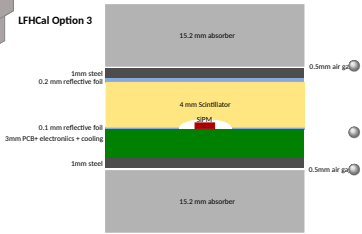



- Outer module dimensions + stacking stay largely the same replacing 4M with 12M modules
- Internal module design rotated by 90° absorber running in z direction
- Electronics + Scintiallator tiles pulled out towards the back in cassets
- SiPM on tile option with 5x5cm tiles
- Transfer of signals via long flex PCB to the end
- HGCROCs sitting in the back of HCal, cooling needed only in the back
- Signal summing of individual SiPMs at the end (2 tiles each) → increased granularity
- Simplified machining of absorber plates compared to option 1
- Upgrade option 2b+: Readout every SiPM by adding more HGCROCs & removing summing board, more liquid cooling would be needed

# Option 3 - Full casset design

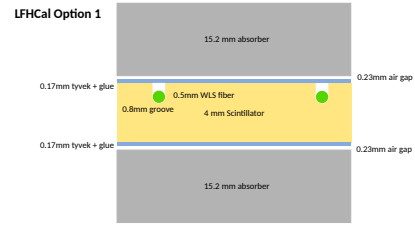


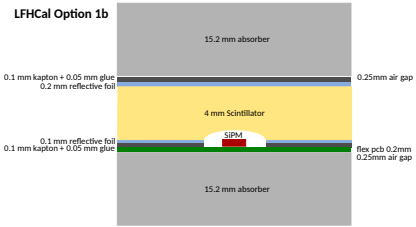
- Full redesign of everything
- Closest concept to HGCCal or CALICE AHCal SiPM on tile (5x5cm) & could incorporate insert with higher granularity
- Absorber structure of half detector (shell) + cradle build as a whole with slots on side for insertion of cassets
- Cassets $\sim$ 30cm x 250cm in worst case (center) with all scintillators + readout electronics inside

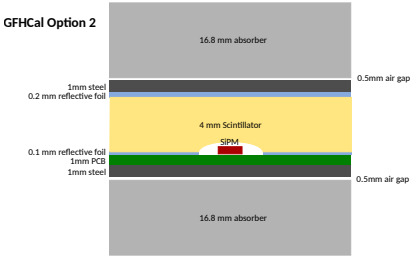


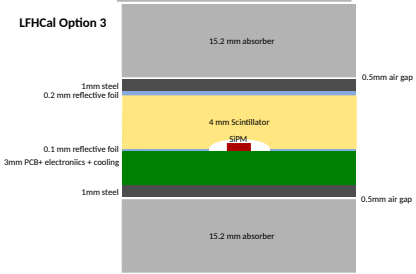

- HGCROCs would need to be integrated in layers
- Cooling absolutely necessary in layers
- Electronics + SiPM servicable no ganging trivially possible

# Comparison layer thickness




- Due to different needs, i.e. connections, cooling, readout out significant differences in sampling fraction
- Can't be fully adapted by changing layer thickness of steel/thungsten

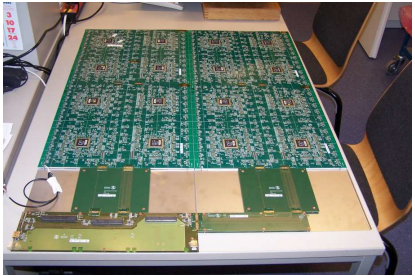
# Electronics comparsion

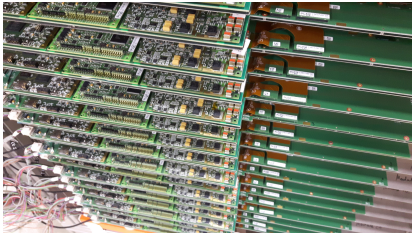
| | Option 1 | Option 1b | Option 1b+ | Option 2 | Option 3 |
|---|---|---|---|---|---|
| Channel # | 63,280 | 63,280 | 601,160 | 253036 | 601,160 |
| SiPM<br>$ | 63,280; 3x3mm<br>506 | 601,160; 1.5x1.5mm<br>4210 | 601,160; 1.5x1.5mm<br>4210 | 506,072; 1.5x1.5mm<br>3550 | 601,160; 1.5x1.5mm<br>4210 |
| Summing board | No | Yes (10channel) | No | Yes (2channel) | No |
| # HGCROC (FEB)<br>k$ | ~1,100<br>22 | ~1,100<br>22 | ~10,450<br>210 | ~4,500<br>90 | ~10,450<br>210 |
| ECON-D (FEB)<br>k$ | | | 1,800<br>9 | 750<br>1.5 | 1,800<br>9 |
| FPGA (RDO)<br>k$ | 46<br>90 | 46<br>90 | 90<br>180 | 37<br>150 | 90<br>180 |
| PCB | 135 | 135 | 270 | 113 | 270 |
| Cooling | 0 | back | back | back/inner | inner |
| Cables, etc | ? | ? | ? | ? | ? |
| Total cost k$ | 753 | 4457 | 4880 | 3829 | 4880 |

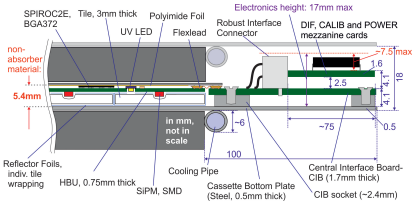
# Main Questions option 1b & 2

- Can one drive & readout the SiPM over $>$ 1m using PCB or capton flex without applification?
- If not cooling might become necessary
- Do we wanna gang SiPMs
- Do we wanna go for injection molded tiles‘?
- For option B, what does it to the physics?

# Additional infos from CALICE & CMS








**CMS:**

- In full cryo container, liquid Nitrogen
- No possibility to service HGCROCs or SiPMs ever

**AHCAL:**

- Cassets with fully integrated electronics $\sim$ 6mm on inside, 3mm electronics
- Clearance around casset $\sim$ 1 mm on both sides

# Costing

# Updated Cost Estimate - option 1

## Example 8M module costs:

| Material procurement | Units | Unit Pricing |
|---|---|---|
| Absorber plates W | 4 | $445 |
| Absorber plates Steel | 61 | $60 |
| module support | 1 | $320 |
| Scintilator plates | 65 | $65 |
| tyvek + capton | 4.04 | $0.4 |
| WLS fibers | 1360 | $2 |
| **8M module cost:** | 1091 | **$12770** |

| Assembly labor | hours | cost |
|---|---|---|
| installing fiber mech. engineer | 17.5 h | $2680.5 |
| tile wrapping PhD students | 7 h | $140 |
| tower assembly mech. engineer | 0.083 h | $12.8 |
| tower assembly PhD Student | 1.92 h | $38.4 |
| tower assembly Undergrad | 11 h | $220 |
| tower testing Postdoc | 1 h | $71 |
| tower testing PhD Student | 4.5 | $90 |
| **8M module cost:** | 1091 | **$3252.7** |

| Electronics | Units | Unit Pricing |
|---|---|---|
| SiPMs | 56 | $8 |
| SiPM mounting + summing boards | 1 | $90 |
| HGCROC | 1 | $20 |
| cable+HV/LV | 1 | ∼$822 |
| **8M module cost:** | 1091 | **$1392** |

## Additional costs:

- R&D cost: 393K
- Tooling: 200K
- Support Structure: 100K
- Installation: 382K
- FPGAs: 90K

## Total costs:

- estimated for:
  **1091x8M module, 76x4M modules, 2x2M modules, 4x1M modules**
- Module prices don't exactly scale as labor doesn't scale
- Cost adapted to most recent quotes for 8M steel, WLS, tungsten (not included before), scintillator with realistic design
- Labor hasn't been modified
- **total unescalated cost: $20.7M**

# Updated Cost Estimate - option 1b

## Example 8M module costs:

| Material procurement | Units | Unit Pricing |
|---|---|---|
| Absorber plates W | 4 | $364 |
| Absorber plates Steel | 61 | $45 |
| module support | 1 | $320 |
| Scintilator tiles (wrapped) | 520 | $7 |
| reflective wrap | 4.04 | $50 |
| flexcables | 130 | $2 |
| SiPMs | 520 | $7 |
| **8M module cost:** | 1091 | **$12003** |

| Assembly labor | hours | cost |
|---|---|---|
| tower assembly mech. engineer | 0.083 h | $12.8 |
| tower assembly PhD Student | 2 h | $40 |
| tower testing Postdoc | 1 h | $71 |
| tower testing PhD Student | 4.5 | $90 |
| **8M module cost:** | 1091 | **$213.8** |

| Electronics | Units | Unit Pricing |
|---|---|---|
| FEB + summing boards | 1 | $20 |
| HGCROC | 1 | $20 |
| cable+HV/LV | 1 | ∼$822 |
| **8M module cost:** | 1091 | **$1392** |

## Additional costs:

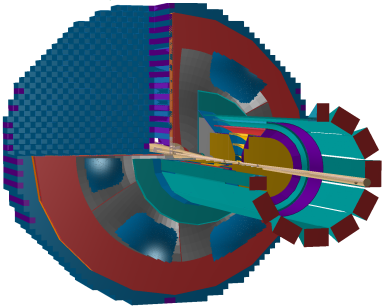
- R&D cost: 393K
- Tooling: 200K
- Support Structure: 100K
- Installation: 382K
- FPGAs: 90K
- Robotic assembly: 460K

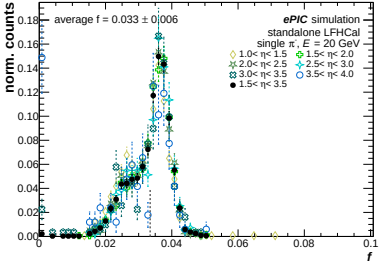
## Total costs:

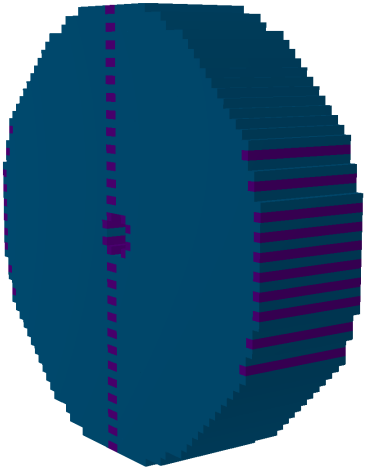
- estimated for same as std. option 1
- Assumed cost for absorber in option 1, 0.5 machining, scaled to 0.25
- not costed: long PCB on side, connectors layers & high density, testing of electric components and SiPMs, LEDs for each tiles
- **total unescalated cost: $16.8M**

# Simulation updates

# Realistic Geometry Implementation for EPIC

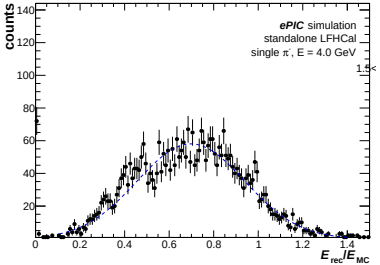


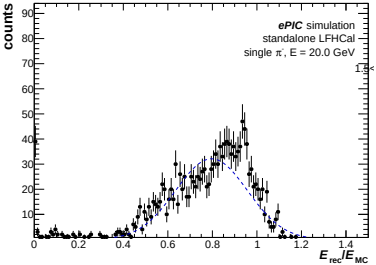


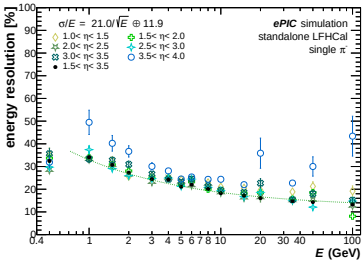



- Changes currently tracked in `lfhcal-dev-branch` , in the process of merging into eic/epic
- Readout now correctly structured in $x$, $y$, and 65 $z$ layers, working on combining them correctly for tower segments in $z$
- Reasonable digitization, including timing cut of 100ns, no min $E$/tile cut yet
- Sampling fraction 0.033

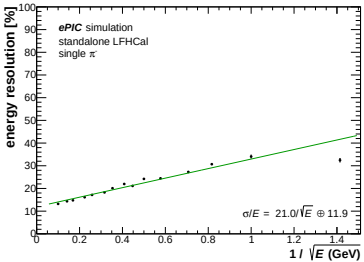
# First steps in eic-recon




- Currently still in private branch
- Full hit summation for single particles (no proper cut-offs yet in $E$ or clustering)
- Access to cell IDs from dd4hep
- No proper calibration yet (offset in energy)
- Next steps adapting hit classes to carry cell/tower IDs & build ID based clusterizer

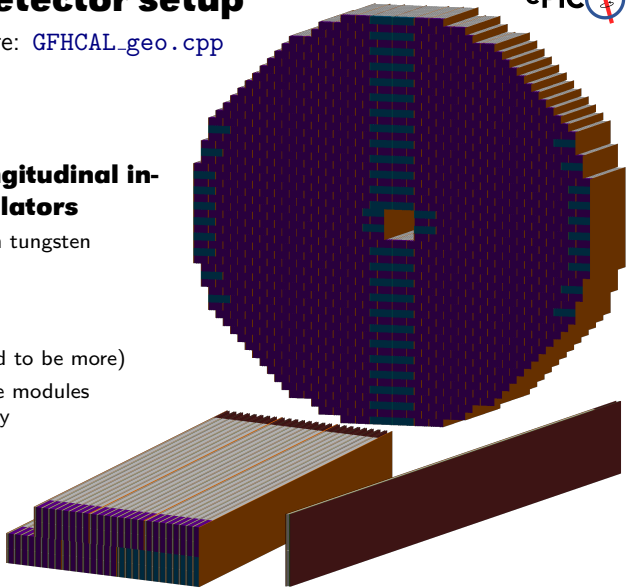


# gFHCal detector setup

source code here: `GFHCAL_geo.cpp`

**Alternative forward HCal design with longitudinal instead of transverse absorbers and scintillators**

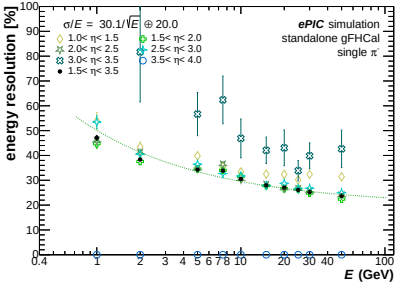
- Longitudinal absorber plates 120cm steel and 10cm tungsten
  → 16.8mm thickness
- Longitudinal 0.4x5x5cm$^3$ Scintillator tiles
- Removable Scintillator+pcb mini frames
  → 1mm PCB space in current simulation (will need to be more)
- Detector made of 20x10cm and 30x10cm front face modules
  → violet and cyan colors in right figure, respectively

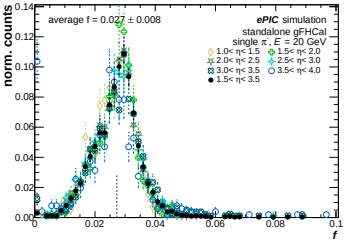


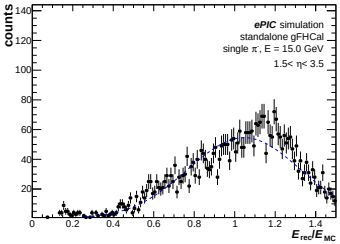
# Preliminary energy resolutions

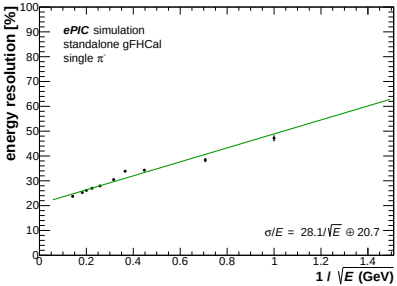
EICrecon code here: `calo_studiesProcessor.cc`

- Energy resolution determined from standalone single particle simulations
  → fixed energies simulated over full gFHCal acceptance
- No clusterizer used
  → simple summation of deposited energies in scintillators
- Sampling fraction of 0.027

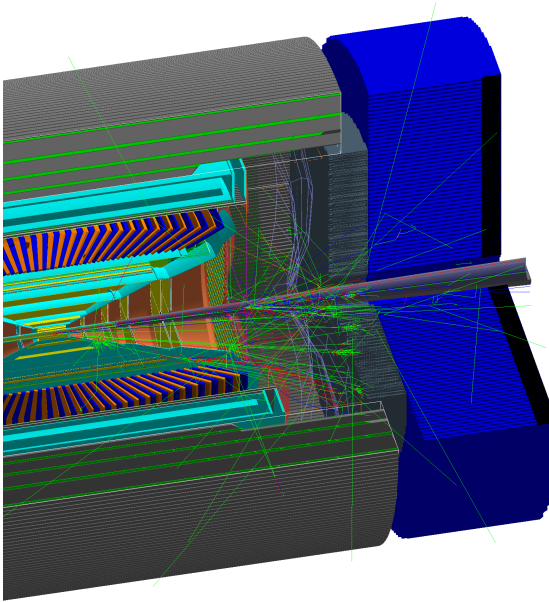


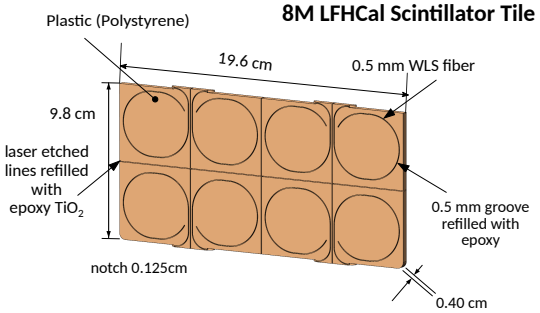



# Thanks!



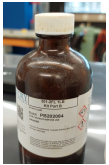
# Current 8M Scintillator Plate Design

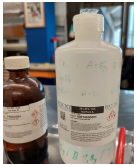
- Most scintillator plates produced as 1 unit of 100x200mm plates (8 single tower tiles)
- Separation of tiles edged into the plate (95%) through, refilled with Epoxy-$TiO_2$ mix
- Wrapped in Tyvek paper and Kapton tape or painted with $TiO_2$ rich paint

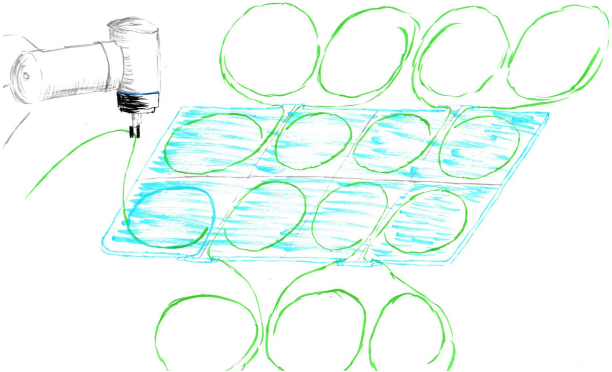



- Fiber thickness chosen for minimal light loss while bending (0.5mm)
  → other geometries for embedding under consideration (i.e. 1/4 circle)
- Originally costed from Uniplast as 1 unit of assembly + material
- Updated estimate including (material, fiber installation by engineer, wrapping by students, tooling)
  → new estimate driving by labor for fiber installation
- Exploring possible robot supported options for tile assembly

# Tile Assembly

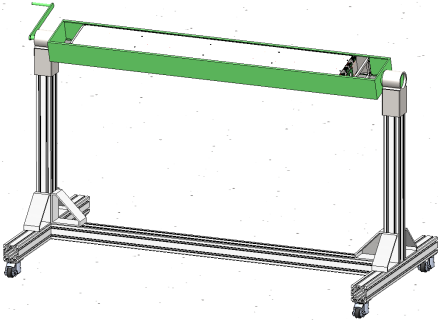



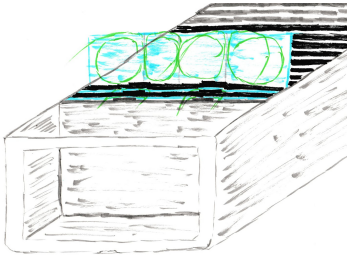


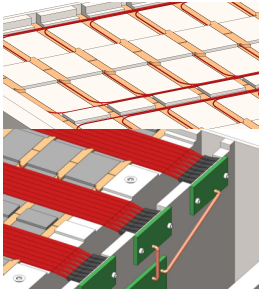


1. Refilling of gaps with $TiO_2$-Epoxy mix using collaborative robot
2. Measuring fiber quality & cutting to desired length
3. Laying WLS-fibers in groove, fixating them using a few glue dots
4. Roll WLS-fibers up on try with tile
5. Might need additional coating with white paint
6. Stack trays & transport to 8M assembly site

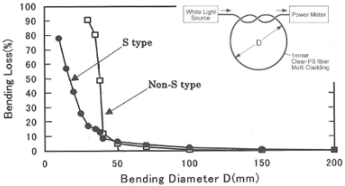
# 8M assembly detail



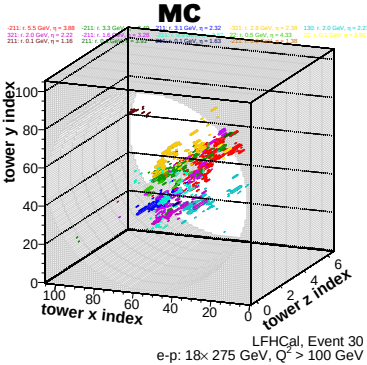


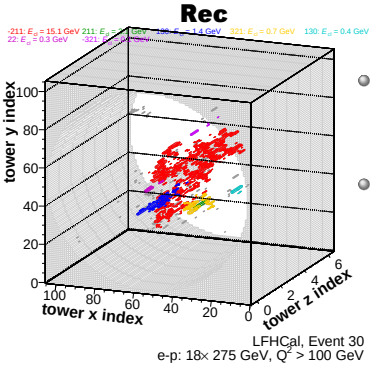


a) Mount assembled steel/tungsten frame in pivot
b) Slot scintillator tiles in frame from back to front
   Fibers for bottom side slotted through, caught by tray on bottom
c) After 10 tiles sort fibers 5/5 & place plastic strip as separator, tape on top
d) Continue till top side finished & cut length of fibers to fit readout
e) install cover plate
f) Flip module in pivot, remove tray
g) Sort fibers & assemble as on top



# Read-out 8M module

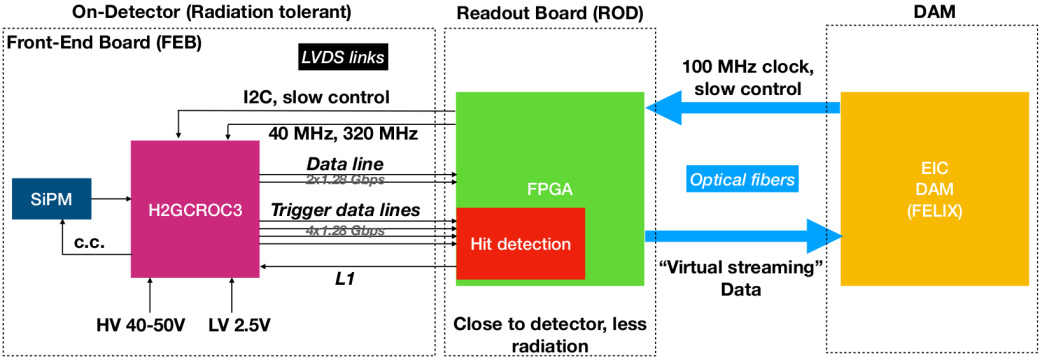



- High granularity needed to try to distinguish shower maxima close to beam pipe
- **HCal**:
  read out in 7 layers longitudinally
  desirable min measurable tower energy 3-5 MeV, max 20-30 GeV in single tower segment

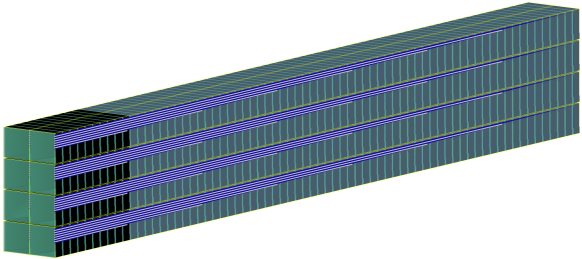
- LFHCal 1 SiPM per 10 fibers (7 per tower) -i.e Hamamatsu S13360-3025PE (14.4K pixels)
- HCal readout at end of module (max. 10cm )
- Small light collection prisms might be needed infront of SiPM
- Idea use each 1 H2GCROC3 (up to 70 channels) for readout of HCal (ideally common chip/board design with WSciFi-ECal & ALICE FoCal-H)

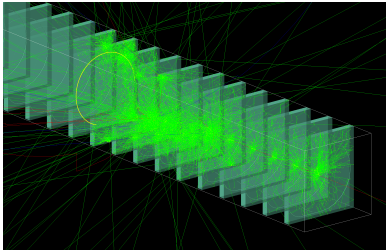
# Current Read-out Concept

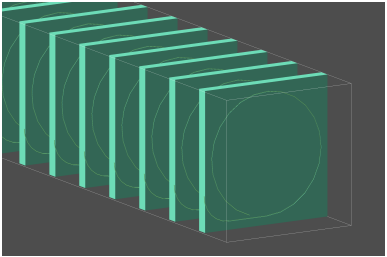


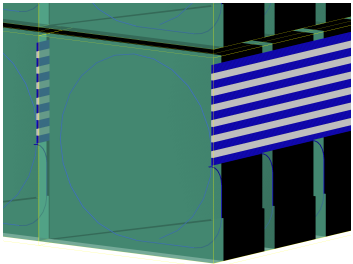

- The H2GCROC3 requires the L1 trigger for readout, with the maximum speed of 960 kHz
- The expected hit rate in one channel of LFHCal is up to 50 kHz:
  - With possible 4 sample readout we would reach a maximum of 200 kHz
  - "Virtual" streaming readout towards the EPIC DAQ system

# GEANT Implementation Fun4All



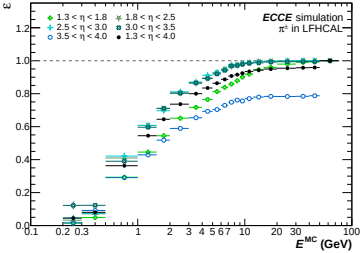


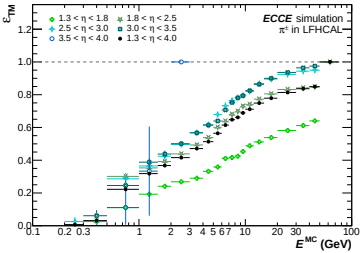


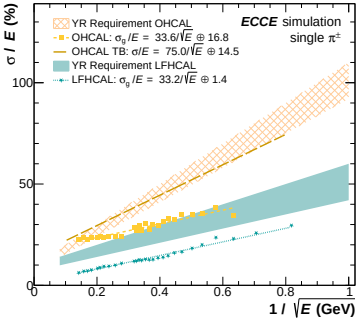


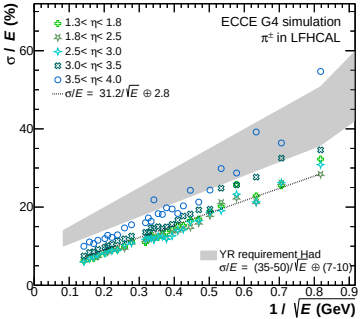
- largely realistic implementation of geometry , refinements for module edges needed
- first light propagation studies, cross checks planned with test sub-tiles at ORNL (fiber routing)

# LFHCAL Performance



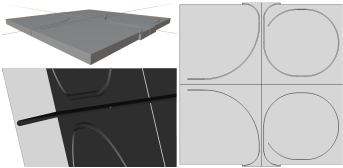



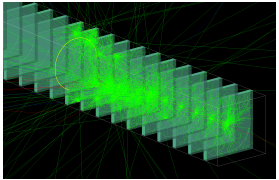

- Cluster finding and track matching efficiencies good in center of LFHCAL, losses towards edges
- Performance overestimated with standard response implementation in GEANT4 ( 1.5x from other setups)
- Small $\eta$ dependence for energy resolution
- Exploring possibility for high granularity insert with different composition & changing granularity of readout as function of $R$
- Studies to improve clusterization further using ML started

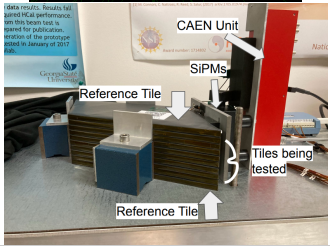
# R&D activities & plans

# eRD107 - Plans & Milestones

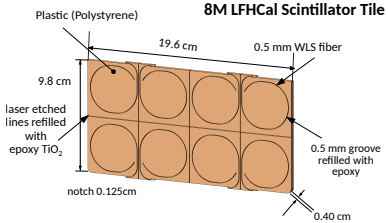
1. **Prototype tile production using machining & injection molding (04/23)**
   - Assembled prototype tiles using machined scintillator plates
   - Assembled prototype tiles using injection molded scintillator tiles
   - Documentation of procedures for manual assembly of tiles & WLS fibers
2. **Reconstruction optimization (09/23)**
   - Write-up of optimization results from simulations
3. **Sensor board development (07/23)**
   - First prototype of sensor board for Si-PM readout (together with eRD109)
4. **Small test module assembly (07/23)**
   - First prototype of single segment of 8M module
5. **First automated scintillator tile assembly (08/23)**
   - Assembled prototype tiles
   - Documentation and Evaluation of procedures for automated assembly of tiles & WLS fibers
6. **Tile Characterization (08/23)**
   - Write-up of test bench & test beam measurement for all assembled tile-prototypes

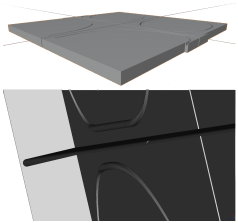


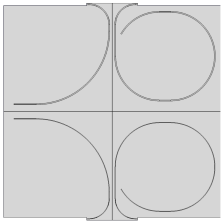




# Prototype tile production & assembly





## Prototype tile production using machining & injection molding

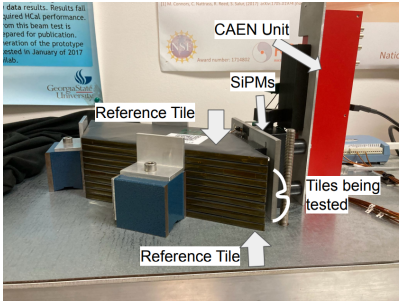
- Vendor replacement needed for Uniplast
  a) Machining plastic scintillator plates ($\sim$ \$80/tile)
  b) Injection molding tile ($\sim$ \$4 – 6/tile)
- Opportunity for significant cost reduction w/ injection molding
- Performance and mechanical stability tests needed in both cases

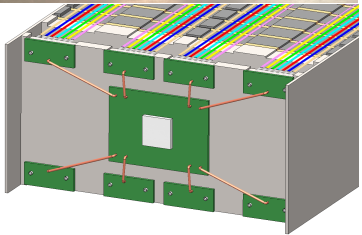
## First automated scintillator tile assembly

- Tile assembly time & labor extensive w/ classical methods
- Exploring automated assembly using collaborative robots for:
  - Refilling sub-segmentation with $TiO_2$
  - Fiber laying and fixating in groves
  - Automatic measurements of WLS-fiber quality

# Scintillator Characterization & Optimization

- Characterization of assembled tiles according to:
  - Light yield
  - Cross-talk among different tiles
  - Response uniformity
  - Durability and mechanical stability
- Initial geometry optimization using TracePro simulations
- Usage of available test-stands at universities for tile characterization
- Possibility to test multiple scintillator materials/dopant concentration in particular for injection molding
- Development of a SiPM board and WLS fiber connector suitable for production module



# Prototypes and Test beams

- Successively-larger R&D prototype assembly
  1. Scintillator tiles
  2. Single segment of 8M module (20cm) including initial read-out design
  3. Full mechanical mock-up of 8M module
  4. Full 8M modules including initial read-out design
- Main measurements
  - Characterization of spatial distribution and uniformity of MIP response for different tile types
  - Saturation behavior of combined tile and SiPM readout system for single segment
  - Measuring the individual and combined response of tiles to EM-showers
  - Spatial and energy resolution of partial and full module LFHCAL module
  - Combined test-beam w/ pECal to characterize LFHCal partial and full module response behind ECal
- Current Read-out electronics design based on CMS-SiPM-HGCROC (ASIC)
  Final electronics R&D for EIC specific readout board within eRD109 based on same ASIC with possible small modifications

# eRD107 Funding request

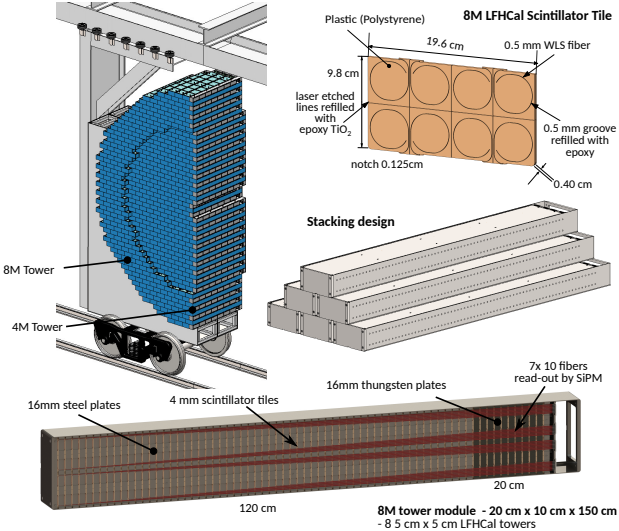
| activity | cost in FY23 k$ ORNL | FNAL | BNL | UTK | GSU | Yale | ISU | Valpo | UCR | total cost in FY23 k$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Machined Tiles | 11.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11.7 |
| Injection Molded Tiles | 2.0 | 52.9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 54.9 |
| Auto Tile Assembly | 20.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20.0 |
| Tile Char. (Lab) | 16.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16.0 |
| Sensor Board | 12.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12.2 |
| LFHCAL Mechanics | 21.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21.7 |
| Tile Char. (Beam) | 1.0 | 0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 1.0 | 2.0 | 14.0 |
| Total | 84.6 | 52.9 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 1.0 | 2.0 | **150.5** |

| institute | cost in FY23 k$ eng. and tech. | material | equipment | travel | total cost in FY23 k$ |
|---|---|---|---|---|---|
| ORNL | 29.8 | 16.8 | 36.0 | 2.0 | 84.6 |
| FNAL | 52.9 | 0 | 0 | 0.0 | 52.9 |
| BNL | 0 | 0 | 0 | 2.0 | 2.0 |
| UTK | 0 | 0 | 0 | 2.0 | 2.0 |
| GSU | 0 | 0 | 0 | 2.0 | 2.0 |
| Yale | 0 | 0 | 0 | 2.0 | 2.0 |
| ISU | 0 | 0 | 0 | 2.0 | 2.0 |
| Valpo | 0 | 0 | 0 | 1.0 | 1.0 |
| UCR | 0 | 0 | 0 | 2.0 | 2.0 |
| Total | 82.7 | 16.8 | 36.0 | 15.0 | **150.5** |

- Largest fraction of funding for engineers and technicians
- Additional funds used for material, test equipment & travel for test beam campaigns
- Significant in-kind contribution from universities and laboratories for assembly, simulation and data analysis ($\sim$ 2140h)
- Parallel PED request for mechanical & electrical engineering support will be submitted to further final design of LFHCAL

| Task | Estimated cost in $ per year FY24 | FY25 | FY26 |
|---|---|---|---|
| mechanical engineering | 40K | 40K | 20K |
| electrical engineering | 30K | 30K | 20K |
| materials | 30K | 30K | 40K |
| test beam support | 10K | 10K | 10K |
| **total** | 110K | 110K | 90K |

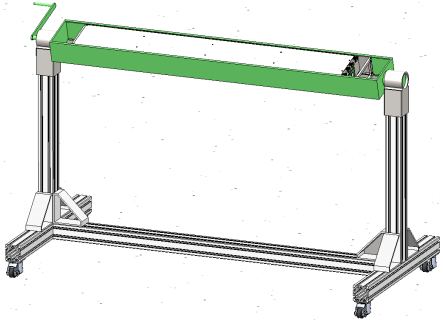
# Calorimeter Details & PED request

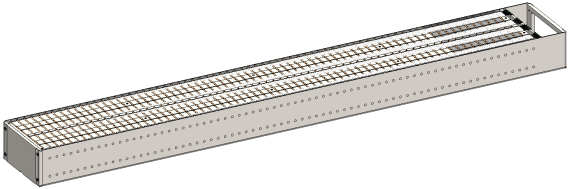


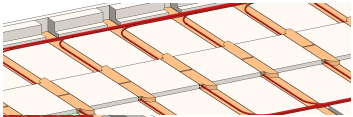

| parameter | LFHCal |
|---|---|
| inner radius (envelope) | 17 cm |
| outer radius (envelope) | 270 cm |
| $\eta$ acceptance | $1.2 < \eta < 3.5$ |
| tower information | |
| x, y ($R$ </> 0.8 m) | 5 cm |
| z (active depth) | 140 cm |
| z read-out | 10 cm |
| # scintillor plates | 70 (0.4 cm each) |
| # aborber sheets | 60 (1.6 cm steel) |
| | 10 (1.6 cm tungsten) |
| weight | $\sim$ 30.6 kg |
| interaction lengths | 6.9 $\lambda/\lambda_0$ |
| Molière radius $R_M$ | 21.1 cm ($\pi^{\pm}$ shower) |
| Sampling fraction $f$ | 0.040 |
| # towers (inner/outer) | 9040 |
| # modules | |
| 8M | 1091 |
| 4M | 76 |
| 2M | 2 |
| 1M | 4 |
| # read-out channels | 7 x 9,040 = 63,280 |

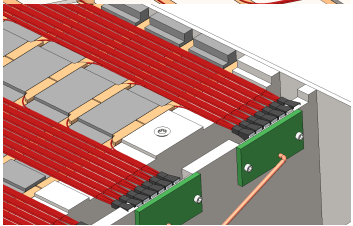
| activity | cost in FY23 k$ ORNL | BNL | total cost in FY23 k$ |
|---|---|---|---|
| Support structure desgin & integration with pECal | 75 | 0 | 75 |
| Rail/slide design | 0 | 50 | 50 |
| test production of module | 20 | 0 | 20 |
| tooling design + function test | 50 | 0 | 50 |
| Total | 145 | 50 | **195** |

# 8M assembly









a) single tile assembly (fiber embedding, glueing, wrapping)
b) tile testing
c) assembly of module, alternating steel plate first kept in place by e-beam point welding then Scint-tile
d) fiber channels layed out on front on back
e) SiPM & read-out card installation
f) tower testing
g) close up module with cover plates

# eRD107: Detailed cost table

| Institute | Item | Cost per item in $ | Number of items | Total cost in $ | To be compl. by |
|---|---|---|---|---|---|
| | **Machined Scintillator Tiles:** | | | | Q1/2023 |
| ORNL | BC-408 plastic scintillator sheet | ~ 150 | 20 | 3K | |
| ORNL | BCF-91A WLS fiber | 1500 | 1 | 1.5K | |
| ORNL | tile machining | 180/h | 40h | 7.2K | Q4/2022 |
| ORNL/UTK | tile assembly | | 40h | (in kind) 0K | Q4/2022 |
| | **Injection Molded Scintillator Tiles:** | | | | Q2/2023 |
| FNAL | mold design + production | 50 000 | 1 | 50K | Q4/2022 |
| ORNL | travel | | | 2K | |
| FNAL | raw material + dopant | | | (in kind) 0K | |
| FNAL | injection molder setup + operation | 180/h | 16h | 2.9K | Q1/2023 |
| ORNL/UTK | tile assembly | | 40h | (in kind) 0K | Q1/2023 |
| | **Automated Tile Assembly:** | | | | 2024 |
| ORNL | robotic arm | 20 000 | 1 | 20K | |
| ORNL | robot programming and evaluation | | 40h | (in kind) 0K | Q3/2023 |
| | **Tile Characterization (Lab Bench):** | | | | Q3/2023 |
| ORNL/UTK | scintillator material characterization | | 20h | (in kind) 0K | Q2/2023 |
| ORNL | waveform sampling readout (8ch) | 16000 | 1 | 16K | |
| GSU/Yale/UCR | tile lightyield testing | | 160h | (in kind) 0K | Q3/2023 |
| ISU/BNL | tile simulation | | 160h | (in kind) 0K | Q3/2023 |
| | **Sensor Board:** | | | | Q1/2023 |
| ORNL | mechanical engineer | 180/h | 15h | 2.7K | |
| ORNL | sensors: silicon photomultipliers | 30 | 300 | 9K | |
| ORNL | sensor board production, assembly | 50 | 10 | 0.5K | Q1/2023 |
| | **Reconstruction Optimization:** | | | | 2025 |
| UTK/Yale/BNL | simulations/digitization/reconstruction/analysis | | 640h | (in kind) 0K | |
| | **LFHCAL Mechanics:** | | | | Q3/2023 |
| ORNL | mechanical engineer | 180/h | 105h | 18.9K | |
| ORNL | absorber material + fasteners | 40 | 70 | 2.8K | |
| UTK/Yale | absorber machining | 100/h | 20h | (in kind) 0K | Q2/2023 |
| | **Tile Characterization (Test Beam):** | | | | Q3/2023 |
| ORNL | assembly and shipping | | | 1K | |
| All | test beam travel | | | 13K | |
| ORNL/UTK | test beam preparation | | 80h | (in kind) 0K | Q2/2023 |
| ORNL | test beam | | 120h | (in kind) 0K | Q3/2023 |
| Yale | test beam | | 120h | (in kind) 0K | Q3/2023 |
| BNL | test beam | | 120h | (in kind) 0K | Q3/2023 |
| UTK | test beam | | 120h | (in kind) 0K | Q3/2023 |
| GSU | test beam | | 120h | (in kind) 0K | Q3/2023 |
| ISU | test beam | | 120h | (in kind) 0K | Q3/2023 |
| Valpo | test beam | | 120h | (in kind) 0K | Q3/2023 |
| UCR | test beam | | 120h | (in kind) 0K | Q3/2023 |
| **Total** | | | | **150.5K** | |