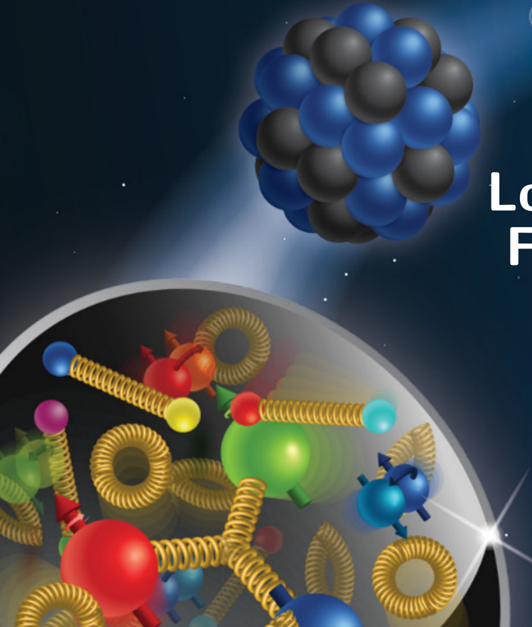


Longitudinally segmented Forward HCal (LFHCal)

Concept & R&D

Friederike Bock (ORNL)

EIC Project Detector Calorimetry Review

December 6-7, 2022

Electron-Ion Collider

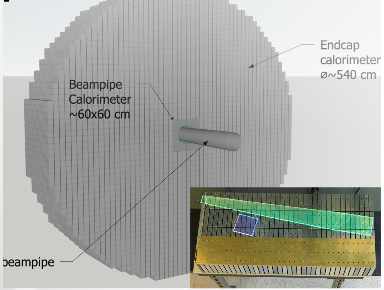
Brookhaven National Laboratory

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

EPIC Collaboration Decision

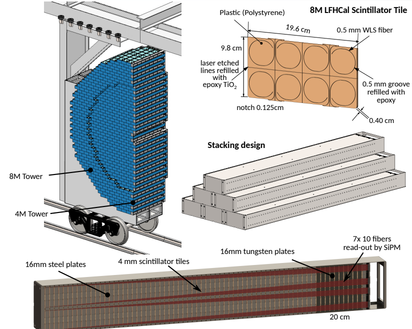
pHCal ATHENA



- Both detector concepts using longitudinally segmented Steel-Scintilator HCal
- ECCE LFHCal with additional W-layers offers larger shower containment
- Construction method allows to vary tower sizes as function of R to possibly reduce cost

⇒ Consensus within WG to recommend ECCE LFHCal for implementation & construction and change plans for eRD107 accordingly

⇒ Exploring highly granular/pixelized inlay around beam pipe similar to CALICE W-AHCAL design as future upgrade



LFHCAL ECCE

EPIC Collaboration Decision

General considerations

- Both concepts follow similar general idea: highly segmented HCal in $x - y$ & z
- Current simulations don't entirely reflect reality (Steel-HCal response too good) $\Rightarrow$ expecting $1.5 - 2x$ worse resolution in reality with same reco-algorithms
- SiPM-Readout & integration with ECal can be done in similar way for both

pHCAL

Pros

- Easy construction, tight tolerance assembly, solid mechanical structure
- Good understanding of general cost & risk (STAR FCS)

Cons

- Max. 4 long segments & effi loss due to signal splitting using time response
- Once installed segmentation is fixed
- Needs assembly at IP6

LFHCAL

Pros

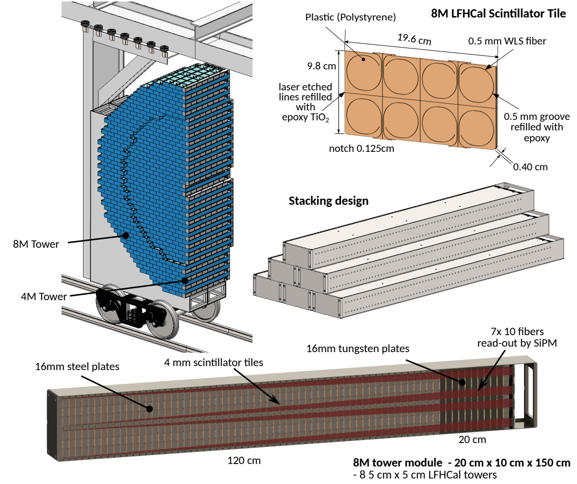
- Larger shower containment
- Somewhat flexible segmentation in x-y & z, better performance using ML possible
- Possibility for distributed module assembly & testing

Cons

- More complex assembly & integration (fiber routing)
- No test beam yet
- Higher cost

Concept

The General Idea



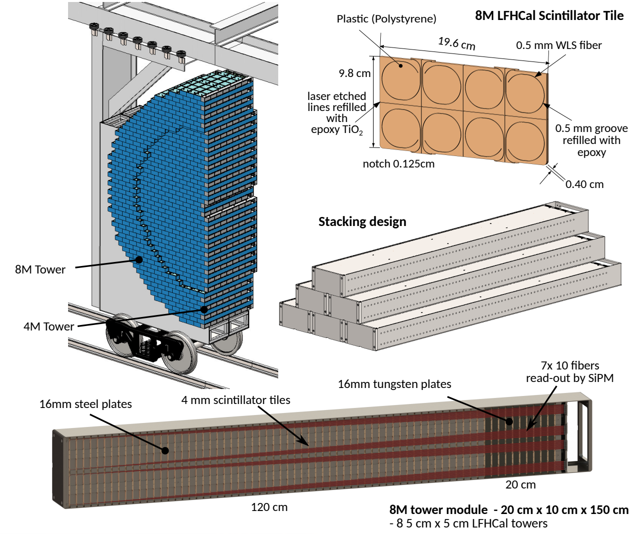
Concept:

- PSD [PSD TDR] inspired Fe/W-Scint calorimeter
  60 layers of Steel (16 mm)-Sci plates (4mm) +
  10 layers of W (16 mm)-Sci plates (4mm)
- Multiple towers combined in one module to reduce dead areas, increase granularity
- Read-out:
  - 7 signals per tower (signals combined from 10 Sci-plates)
  - readout position: after full HCal
- Modules of different sizes (8M, 4M, 2M, 1M) to maximize coverage & assembly efficiency

Participating institutes:

- ORNL, BNL, FNAL, ISU, GSU, Yale, UCR, UTK, Valpo

Calorimeter Details

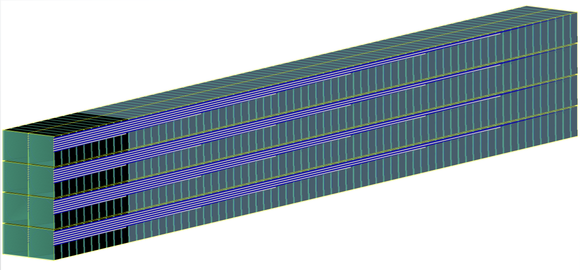


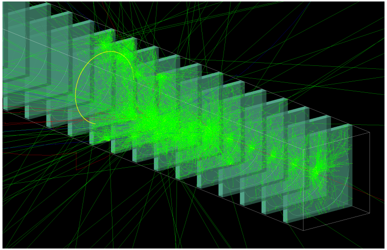
parameter	LFHCal
inner radius (envelope)	17 cm
outer radius (envelope)	270 cm
η acceptance	$1.2 < \eta < 3.5$
tower information	
x, y ($R </> 0.8$ m)	5 cm
z (active depth)	140 cm
z read-out	10 cm
# scintillor plates	70 (0.4 cm each)
# aborber sheets	60 (1.6 cm steel)
	10 (1.6 cm tungsten)
weight	$\sim$ 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

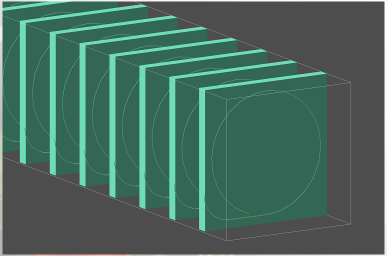
- Some flexibility in composition vs. length, current design $6.9\ \lambda/\lambda_0$
- Total of 9040 towers with $\sim$ 64K readout channels
- Total cost: \$17.7M (w/o read-out cards)

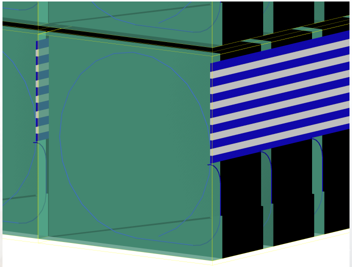
Simulated Performance

GEANT Implementation in Fun4All



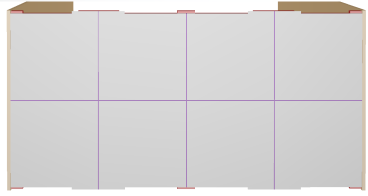


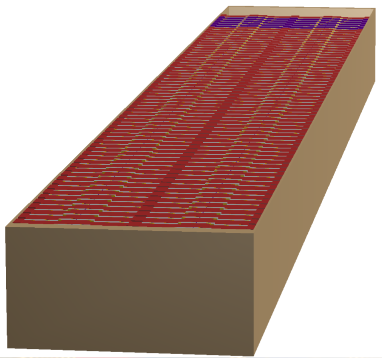


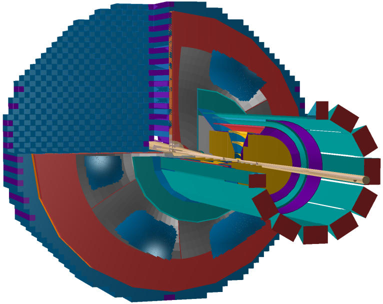


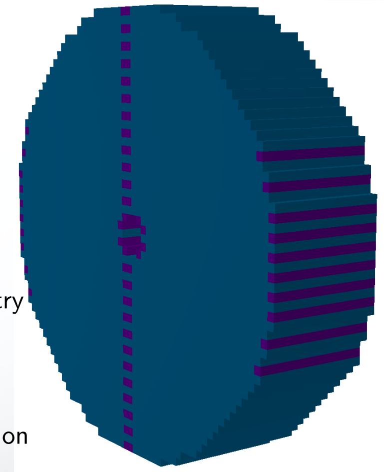
- Largely realistic implementation of geometry, refinements for module edges needed
- First light propagation studies, cross checks planned with test sub-tiles at ORNL (fiber routing)

Realistic Geometry Implementation for EPIC



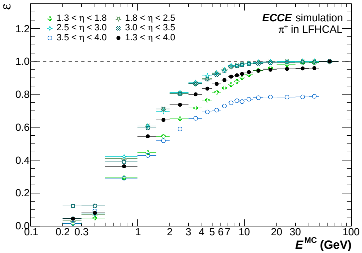


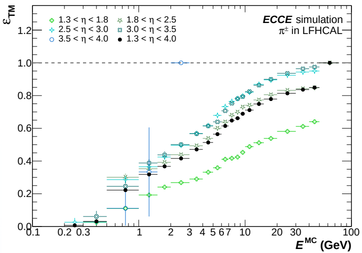


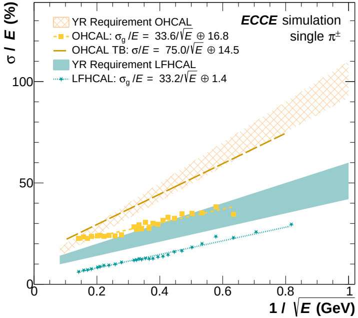


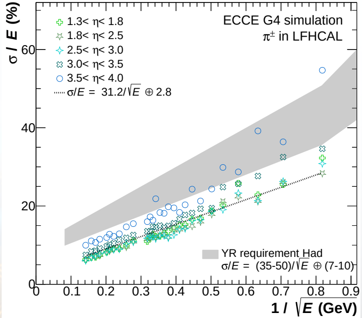
- Translation of detailed geometry into new EPIC software framework nearly completed
- First resolution studies with significantly simpler geometry on their way

LFHCAL Performance



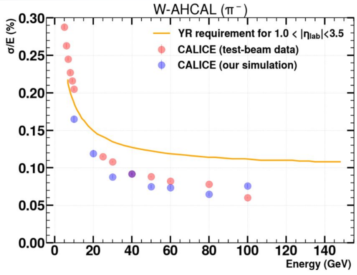


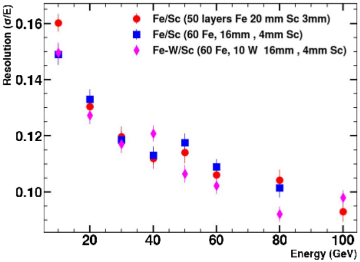


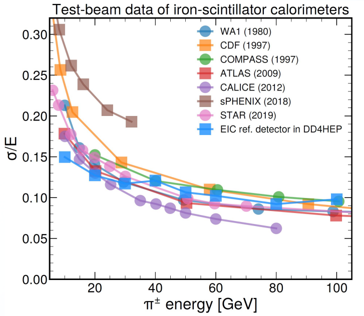


- Cluster finding and track matching efficiencies good in center of LFHCAL, losses towards edges
- Small η dependence for energy resolution
- Studies to improve clusterization further using ML started
- Exploring possibility to change granularity of readout as function of R
- Performance overestimated at the moment with standard response implementation in GEANT4 Fun4All (1.5x from other setups)

LFHCAL Performance - EPIC framework





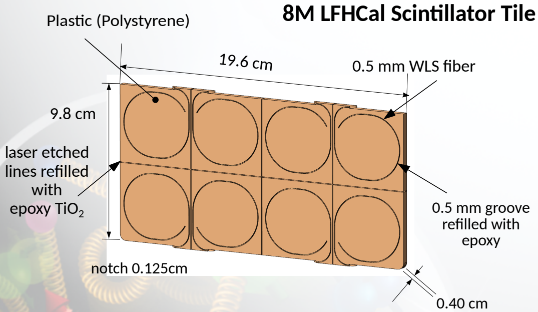


- Problem in original simulation for LFHCal identified through validation with CALICE geometry in DD4HEP
  - Integration over too long time
  - Improved lower energy cut - offs
- Updated resolution parameters with idealized geometry
- Results from realistic geometry including clusterization to follow soon

Mechanical Design, Assembly & Schedule

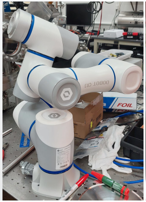
Current 8M Scintillator Plate Design

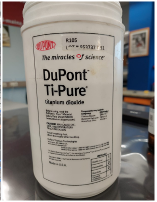
- Most scintillator plates produced as 1 unit of 100x200mm plates (8 single tower tiles)
- Separation of tiles edged into the plate (95%) through, refilled with Epoxy-TiO_2 mix
- Wrapped in Tyvek paper and Kapton tape or painted with TiO_2 rich paint

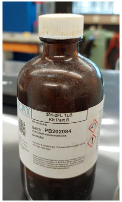


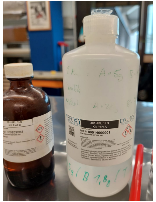
- Fiber thickness chosen for minimal light loss while bending (0.5mm)
  $\rightarrow$ other geometries for embedding under consideration (i.e. 1/4 circle)
- Originally costed from Uniplast as 1 unit of assembly + material
- Updated estimate including (material, fiber installation by engineer, wrapping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

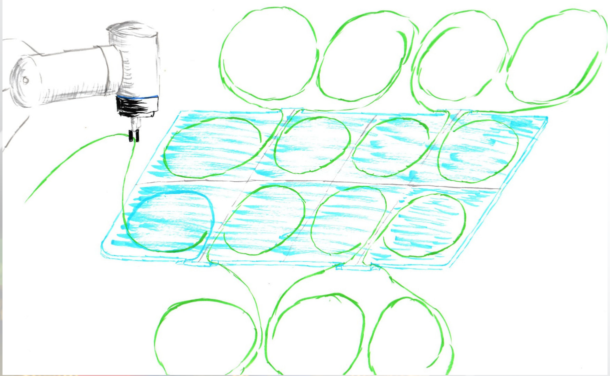
Tile Assembly





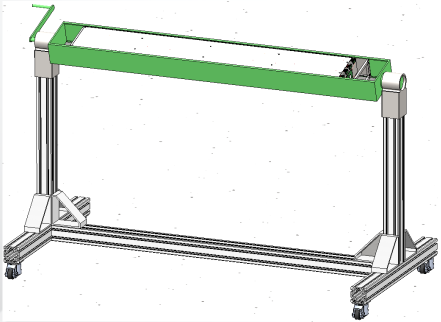


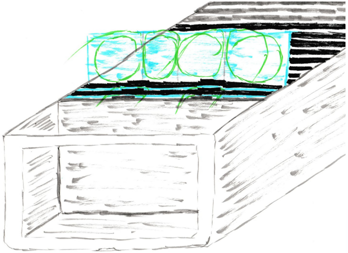


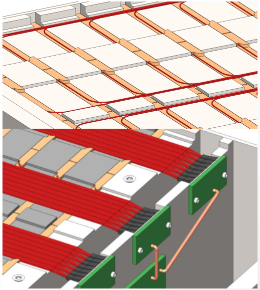


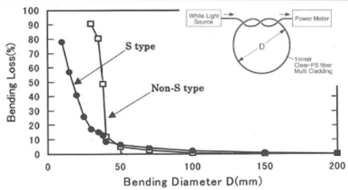
1. Refilling of gaps with TiO_2-Epoxy mix using collaborative robot
2. Measuring fiber quality & cutting to desired length
3. Laying WLS-fibers in groove, fixating them using a few glue dots
4. Roll WLS-fibers up on tray with tile
5. Tyvek or additional coating with white paint
6. Stack trays & transport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

8M assembly detail



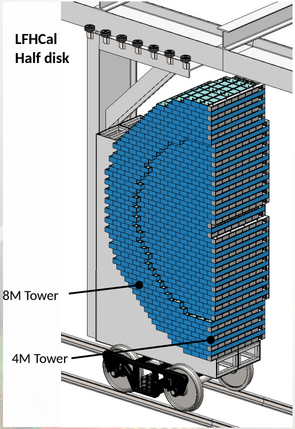


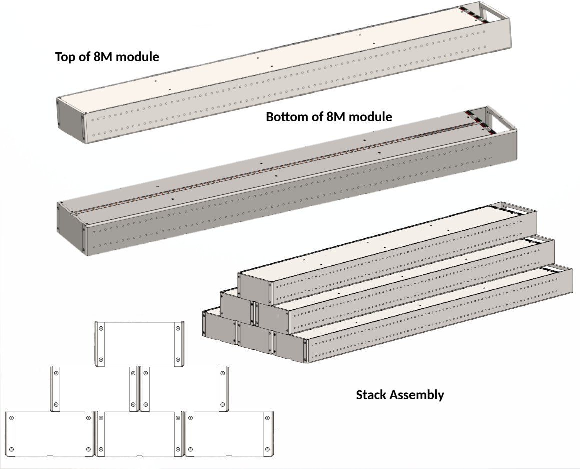




a) Mount assembled steel/tungsten frame in pivot
b) Slot scintillator tiles in frame from back to front
   Fibers for bottom side slotted through, caught by tray on bottom
c) After 10 tiles sort fibers 5/5 & place plastic strip as separator, tape on top
d) Continue till top side finished & cut length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

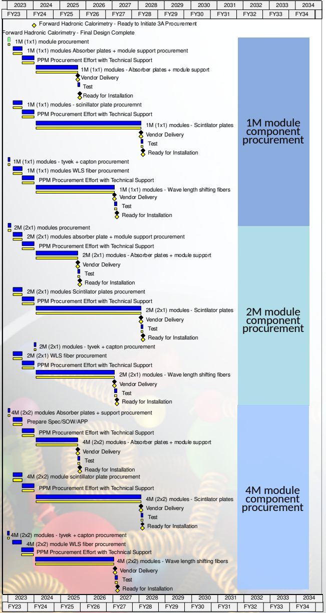
Stacking Design & Support structure

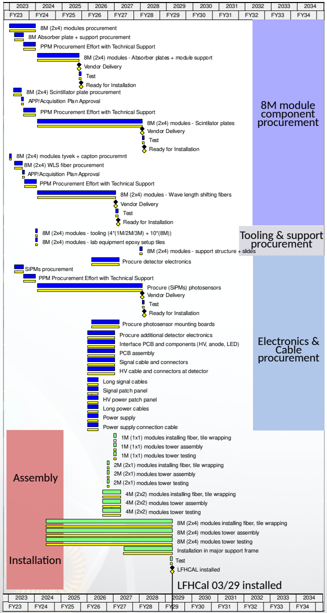




- Half disk assembled on trolley to be rolled to the side
- Single 8M-modules arranged in "brick-like-structure"
- Notch and groove design for alignment in x & z direction

Schedule



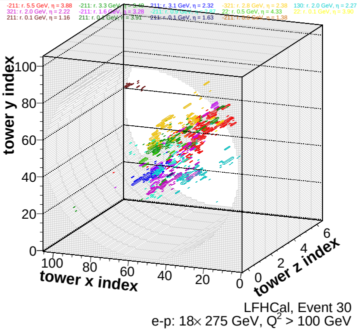


- Schedule fully developed with several long lead procurement items:
  - Steel, SiPMs, scintillator plastic, WLS fibers
- Partial deliveries from vendors with time allow earlier start of assembly
- Foresee multiple module production sites/stations, default: 6 stations
- Tile assembly simultaneous to scintillator & WLS procurement with slight offset
- Magnetic field map testing starting 04/29
- Single component testing foreseen during assembly
- Final module tests after each module assembly & in complete stack

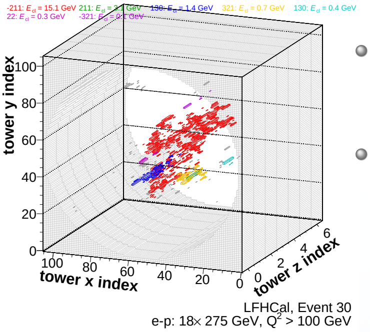
Read-out Concept

Read-out 8M module

MC



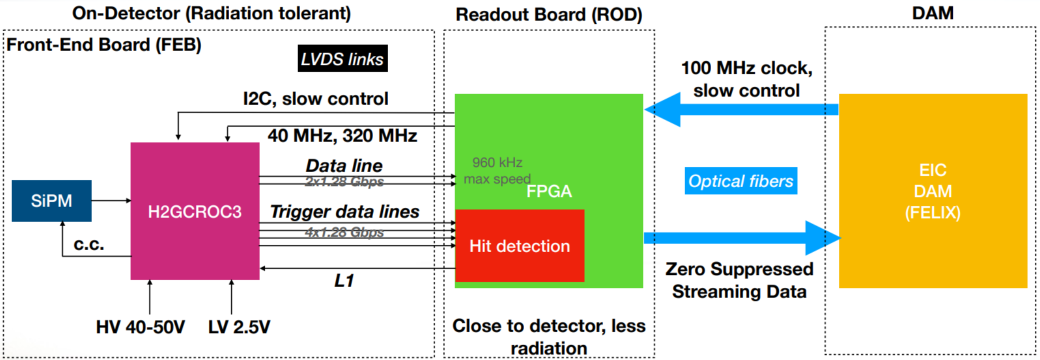
Rec



- 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 to 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

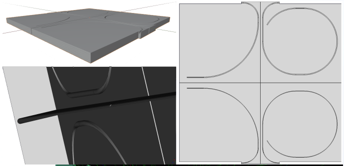


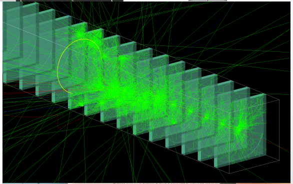
- The H2GCROC3 requires the L1 trigger for readout, with the maximum speed of 960 kHz
- The expected hit rate in one channel of LFHCal is up to 50 kHz:
  - With possible 4 sample readout we would reach a maximum of 200 kHz
  - Compatible with streaming readout towards the EPIC DAQ system

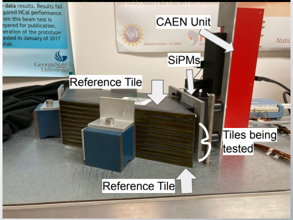
Details see Norbert's talk

R&D activities & plans

eRD107 - Plans & Milestones

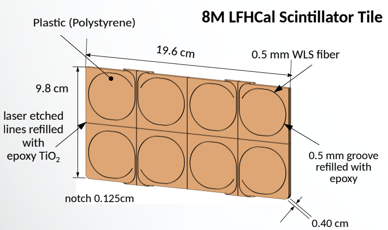


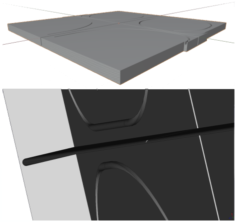


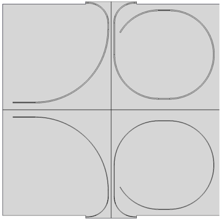


1. **Prototype tile production using machining & injection molding (04/23)**
   - Assembled prototype tiles using machined scintillator plates
   - Assembled prototype tiles using injection molded scintillator tiles
   - Documentation of procedures for manual assembly of tiles & WLS fibers
2. **Reconstruction 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

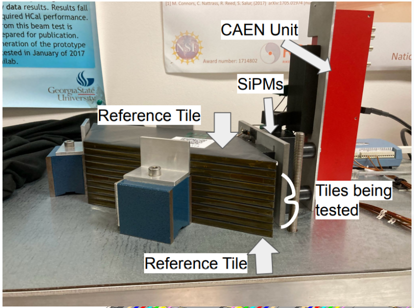
- Vendor replacement needed for Uniplast
  - a) Machining plastic scintillator plates ($\sim$ \$80/tile, 3 yr prod. time)
  - b) Injection molding tile ($\sim$ \$4 – 6/tile, 3 month prod. time)
- Opportunity for significant cost reduction w/ injection molding
- Performance and mechanical stability tests needed in both cases

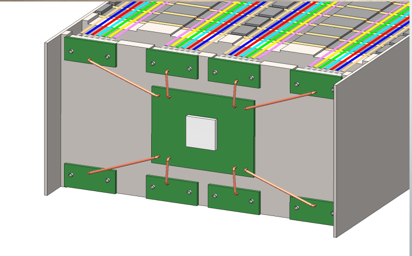
First automated scintillator tile assembly

- 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

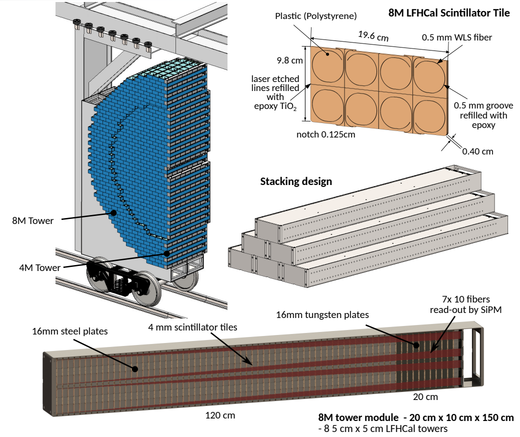




Prototypes and Test beams

- Full 8M module assembly with single component testing
  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

Summary



- LFHCal concept adapted from established calorimeter (PSD calorimeter)
- Mechanical design far advanced
- Simulation setups in good shape with realistic geometries
- Performance goals for EIC physics reached with proposed concept with potential for improvements with modern reconstruction techniques
- Workforce is experienced in building large scale calorimeter systems (ALICE EMCal, sPHENIX ECal)
- Challenges in construction process addressed by dedicated R&D plans
- Performance validation foreseen in test beams during next 2 years

Thanks!

Conservative Cost Estimate

Example 8M module costs:

Material procurement	Units	Unit Pricing
Absorber plates + support	1	\$1750
Scintilator plates	70	\$65
tyvek + capton	4.04	\$0.4
WLS fibers	1360	\$3
8M module cost:	1091	**\$9822**
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 assembly Postdoc	1 h	\$71
tower assembly PhD Student	4.5	\$90
8M module cost:	1091	**\$2252.7**
Electronics	**Units**	**Unit Pricing**
SiPMs	56	\$10
mounting boards	1	\$10
cable+HV/LV	1	~\$822
8M module cost:	1091	**\$1392**

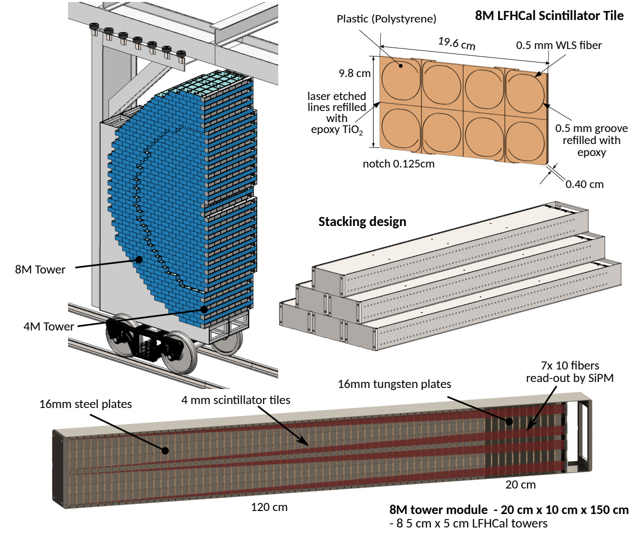
Additional costs:

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

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 US prices w/o relying on Uniplast
- **total unescalated cost: \$17.7M**
  → estimates w/ Uniplast quotes \$11.2M

Calorimeter Details & PED request



parameter	LFHCal
inner radius (envelope)	17 cm
outer radius (envelope)	270 cm
η 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**	**cost in FY23 k$ 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**

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

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**	