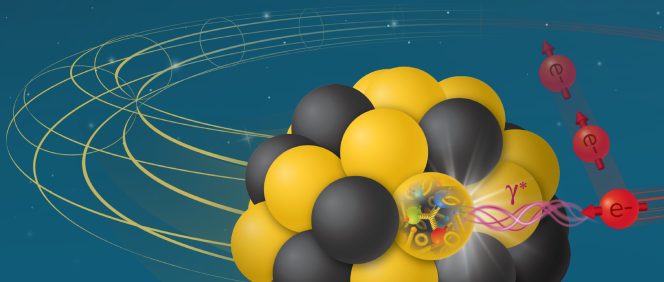
Brookhaven National Laboratory | Jefferson Lab | U.S. DEPARTMENT OF ENERGY | Office of Science

Forward Hadron Calorimeter

Longitudinally segmented Forward HCal (LFHCal)

Friederike Bock
October 30, 2026



Electron-Ion Collider
11th DAC Meeting - Oct 28-30, 2026

About me

Friederike Bock

- 2013-2017: PHD University Heidelberg & LBNL
- 2017-2019: CERN Research Fellow
- 2019-2021: ORNL Eugene Wigner Staff Fellow
- 2021-2026: ORNL Research Staff Scientist

Relevant Experience at CERN

- ALICE EMCal Calibration Coordinator
- ALICE Deputy Trigger Coordinator
- ALICE Gamma & Neutral Meson Physics Working group convener

Relevant Experience at EIC

- Former ECCE & ePIC calorimeter working group co-convener
- LFHCal Proponent & Detector Subsystem Leader (DSL) since 2021



Outline & Charge

Outline

1. Concept
2. Components & Technical updates
3. Construction & Assembly Plans

Charge Questions

1. Has progress since the June 2025 DAC comprehensive design review been satisfactory?
2. Have all recommendations that are relevant for detector CD-2 baseline been addressed?
3. Is the path towards a final design of the various sub-detectors defined and sound?
4. Are the detector integration and planning for installation and maintenance well developed?
5. Will the detector be ready for construction by end of CY2027?
6. Are plans sufficiently developed for the ePIC detector production phase beyond CD-3?

Concept

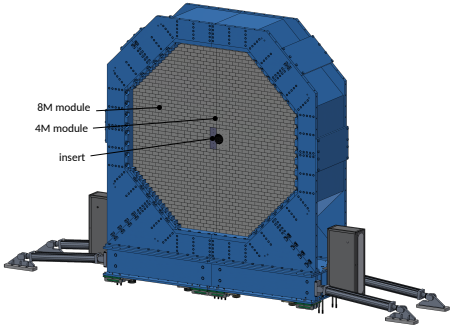


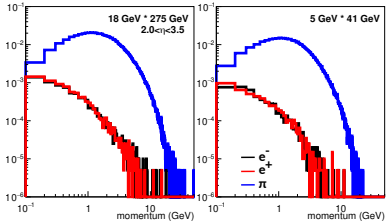
Electron-Ion Collider

The General Idea

Concept:

- CALICE AHCal inspired Fe-Scintillator calorimeter with SiPM on-tile-readout
- SiPMs, absorber & support structures part of LLP
- Two main parts:
  - Mostly built out of $10x20x132$ cm^3 8M modules & $10x10x132$ cm^3 4M modules
  - 2 insert modules surrounding the beam pipe
- **8M & 4M modules**
  - 60 layers of steel interleaved with scintillator material
  - Transverse tower size $5x5$ cm^2
  - Multiple consecutive tiles summed to 8 longitudinal segments per tower
- **Insert modules:**
  - 60 layers of steel interleaved with scintillator
  - Transverse tower size $5x5$ cm^2
  - Possibility to read out every layer

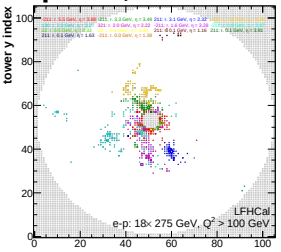




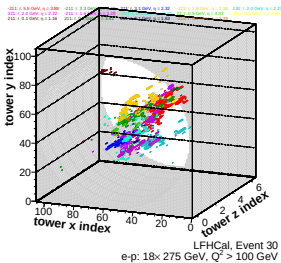
Electron-Ion Collider

Motivation & Requirements

MC particle, classical readout



MC particle, LFHCal readout



Motivation:

- Maximum coverage for charged & neutral hadron reconstruction even in region, where tracking dies out
- Reconstruct jets at high rapidities
- Exploration of hadronization processes within jets using identified particles within jets and jet-substructure

Requirements:

- Excellent energy resolution for hadrons & jets
  $\sigma(E)/E \sim 50\%/\sqrt{E} \oplus 10\%$ in junction with ECal
- Transverse granularity adequate to resolve deposits from different charged and neutral hadrons taking into account local particle abundance
  $\Rightarrow \sim$ 5x5 cm^2 for $\eta < 4.0$
- Longitudinal granularity adequate to identify showers starting at different depths and determine their shower maxima with increased segmentation for higher η due to higher particle density

LFHCal in Numbers

8M & 4M modules

- Acceptance: $1.2 < \eta < 3.5$
- Inner modules ($R < 1$m): machined scintillator tiles & 3mm SiPMs $\rightarrow \sim 11\% = 57800$ tile/ SiPMs
- Outer modules: injection molded tiles & 1.3mm SiPMs $\rightarrow \sim 89\% = 467320$ tile/ SiPMs

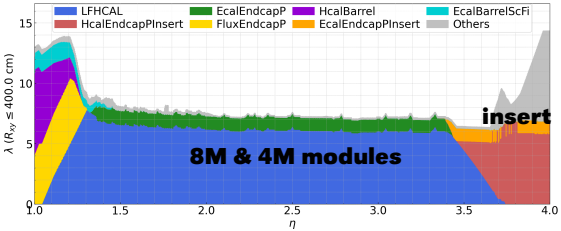
$\rightarrow$ 525120 SiPMs, 70016 read-out channels

Insert modules

- Acceptance: $3.5 < \eta < 4.0$
- ~ 94 tiles/layer with 1.3mm SiPMs

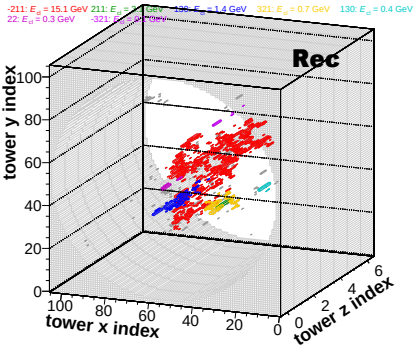
$\rightarrow \sim 5640$ SiPMs/tiles & read out channels

parameter	LFHCal 8M & 4M modules	insert modules
inner x,y (R)	-20 cm $> x > 40$ cm, -30 cm $> y > 30$ cm	$R > 17$ cm
outer R (x,y)	$R <$ 270 cm	-20 cm $> x > 40$ cm, -30 cm $> y > 30$ cm
η acceptance	$1.2 < \eta < 3.5$	$3.5 < \eta < 4.0$
tower information		
x, y	5 cm	5 cm
z (active depth)	120 cm	120 cm
z read-out	$\approx$ 8.4 cm	$\approx$ 8.4 cm
# scintillator plates	60 (0.4 cm each)	60 (0.3 cm)
# absorber plates	60 (1.52 cm)	60 (1.52 cm)
interaction lengths	5.8-6.5 λ/λ_0	5.8 λ/λ_0
# towers	8752	
# modules		2
8M	1058	
4M	72	
# read-out channels	8 x 8752 = 70016	5640



Electron-Ion Collider

General Facts on the Read-out



- High granularity needed to try to distinguish shower maxima (single particles/sub-jets) close to beam pipe
- **8M & 4M modules**:
  read out in 8 segments longitudinally (5 or 10 SiPMs summed in depth) desirable min measurable tower energy < 0.1 MIP/segment, max. ≈ 1500 MIP/segment
- **insert modules**:
  read out every single tile desirable min measurable energy < 0.3 MIP/tile , max. ≈ 500 MIP/tile
- SiPMs mounted to flexible PCBs, passive signal transfer to back side of calorimeter using long transfer PCB
- 2 (1) CALOROCs (32 ch. each) per 8M(4M) module in the back, 177 CALOROCs for insert readout

Electron-Ion Collider

Insert Module Changes

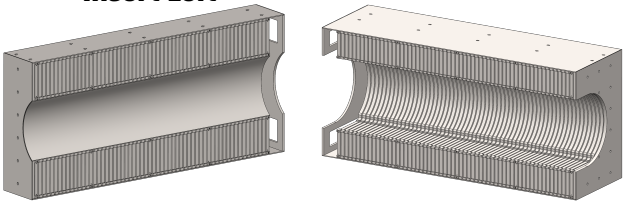
Changes:

- Increase area for long transfer boards by taking out conical structure and part of tilt
- Switch to square tiles to reduce channels/layer

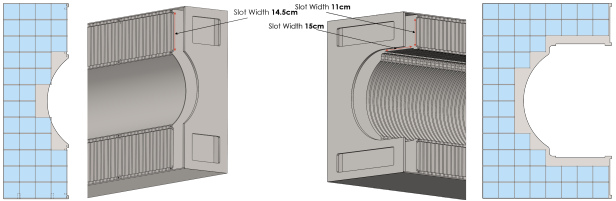
Implications

- Reduced acceptance in η
- **Insert Left: 2400 ch $\rightarrow$ 83 ch/cm**
  Insert Right: 3240 ch $\rightarrow$ 68 ch/cm
- Reduction of number of CALOROCs: 75 (left) & 102 (right)
- Could employ summing in the back in addition
- Could mechanically fit readout in back
- Alternatively could put part of CALOROCs on transfer board

Insert Left



Tile layout & PCB slot arrangement



Insert Module Changes

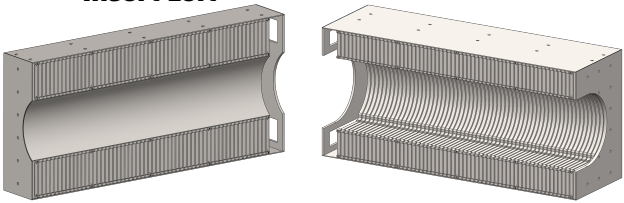
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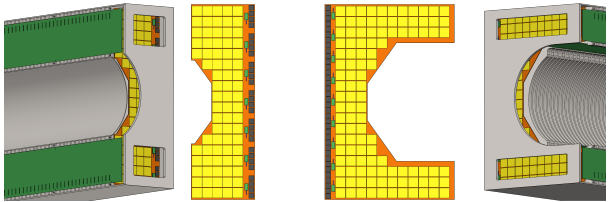
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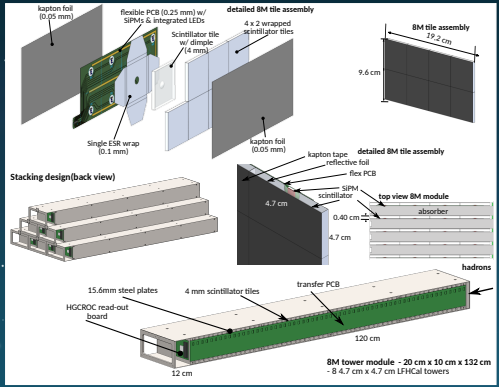
Insert Left

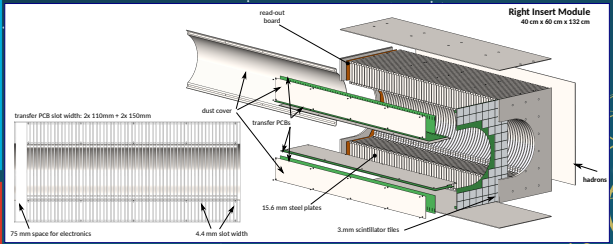


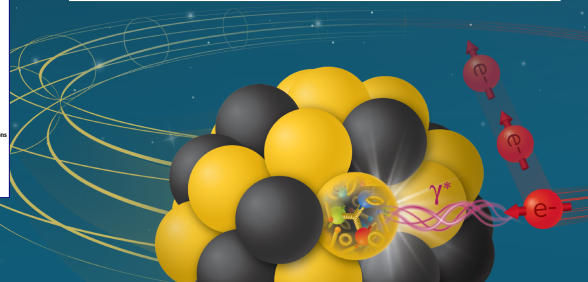
Read-out board layout



Components & Technical updates



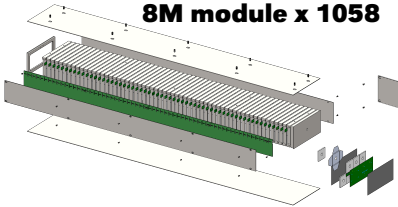




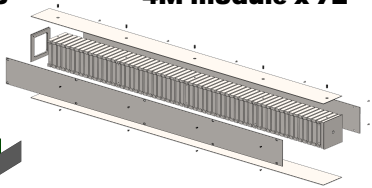
Electron-Ion Collider

Components: Absorber Structures (1)

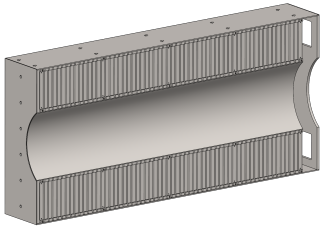
8M module x 1058



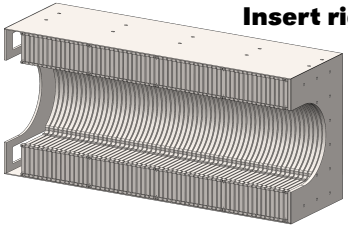
4M module x 72



Insert left

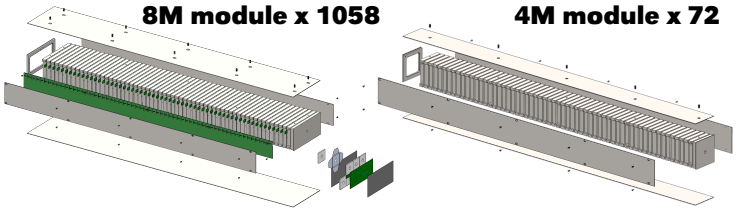


Insert right

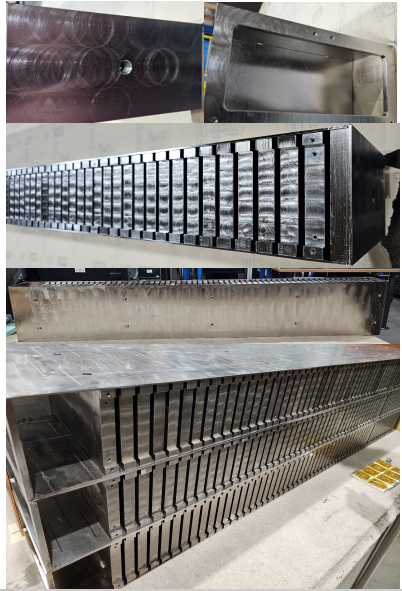


- 4 different module types designed using the same construction process
- 60 single absorber plates, front and back plate welded to top & bottom sheet metal panel
  → E-beam no longer needed for W-plates, changed to laser beam welding
  → No Nickel plating
- Side panels screwed to welded structure to cover slot with transfer PCB and remaining open side
- Simplified insert module design to allow maximum space for transfer PCBs & cost reduction
- 9 pre-production items produced with E-beam welding
- Absorber structure design concluded & CD3-A/B bid process concluded
- First production items expected 12/2026

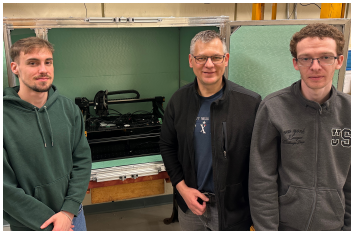
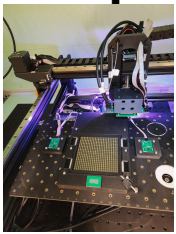
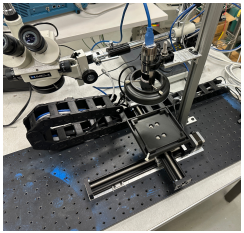
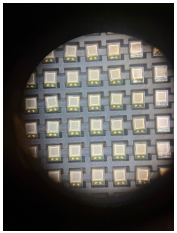
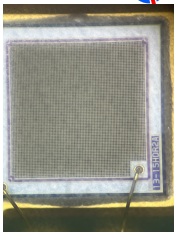
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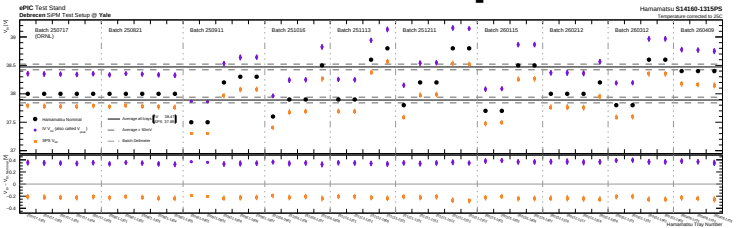
Components: SiPMs

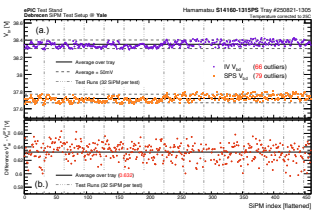






SiPM QA of CD-3A:

- 06/2025- 04/2026 33K SiPMs per month delivered (341.4K total)
- Established test procedure for 5% of trays for acceptance testing
  - 09/2025: Manual test stand at Yale (16 SiPMs/h supervised)
  - 02/2026: Automated test stand designed by Uni Debrezen at Yale (up to 1 tray/day (480 SiPMs) unsupervised)
- Tested 19.4K SiPMs at Yale focussing on break down voltage measurements and visual inspection
  → publication under preparation

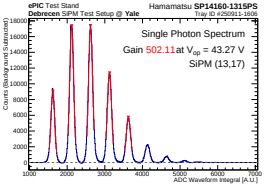
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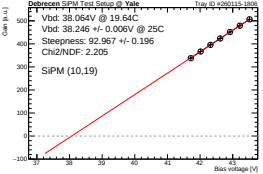




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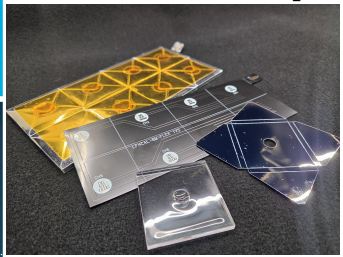


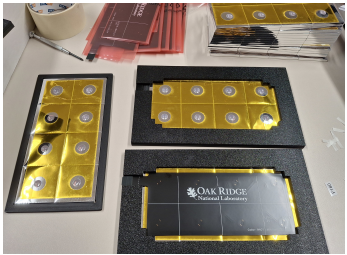
SiPM QA of CD-3C:

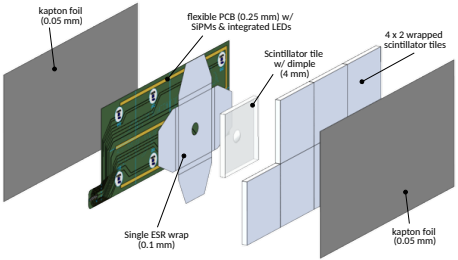
- Ready for next procurement phase: 175.4K 1.3mm SiPMs
- Small adaptation of setup needed for 51.4K 3mm SiPMs testing

Electron-Ion Collider

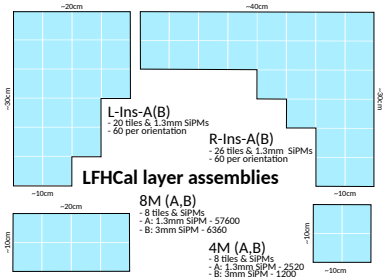
Components: Scintillator Tile Assemblies





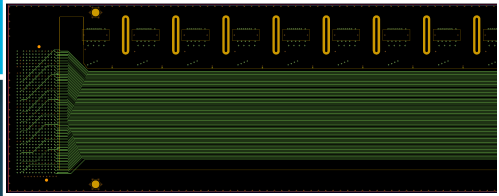


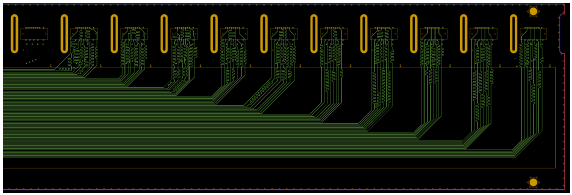
- Tile production at FNAL via injection molding with established processes & chemical composition
- ESR wrap cut with small scale laser cutter,outsourcing being explored
  → produced & manually wrapped ≈ 4500 tiles
- Tile wrap machine design based on CMS-HGCal wrapper under development
- 3rd iteration of 8M-layer flexible PCB design
  → 500 produced & tested
- Manual tile wrapping & layer assembly process well established
  → produced ≈ 600 8M layer assemblies for test beam operation
- Design for other layer types will be based on 8M baseline design



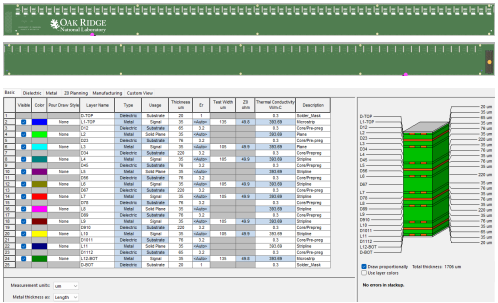
Electron-Ion Collider

Components: Long Transfer board (1)

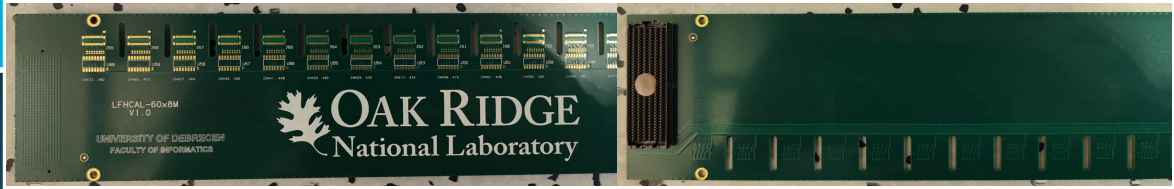




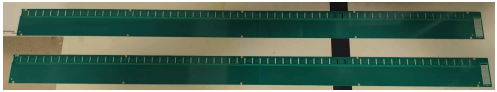
- First 8 test articles produced with 12 layer stackup (total ~ 1.7 mm) and full length of 125.7 cm
- Few vendors with capabilities to produce such boards (more common length up to 120 cm)
- Successfully tested 6 of them in test beam at CERN
- Updated insert module design satisfies similar trace density on transfer boards

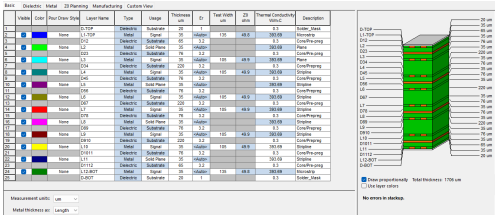


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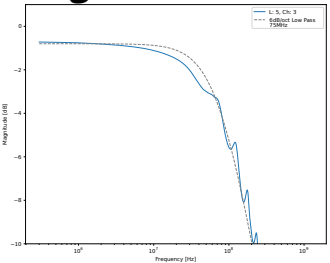
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Components: Long Transfer board - Lab tests

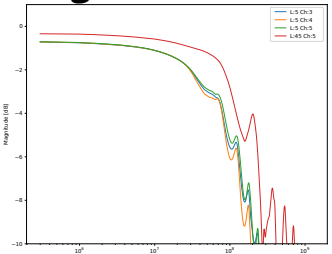


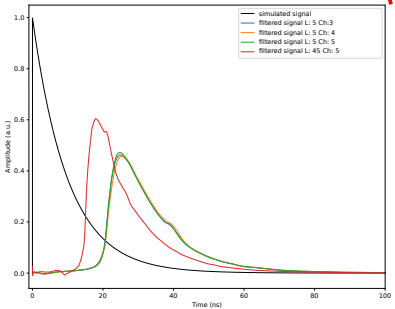


- Tested using VNA extracting transfer function & x-talk
- Transfer function extracted along same trace
  - Some DC (ohmic) loss up to -1dB depending on trace length
  - ≈ 60-100MHz lowpass filter (first order LP: -6dB/octave) - as expected
  - Simulated effect of transfer function: shape very little affected, delay introduced
- Cross-talk measured with ch 5 in different layers as aggressor
  - Cross-talk simulated using measured transfer function
    → negligible on surrounding trace (visible only when amplified with factor 200)

Components: Long Transfer board - Lab tests



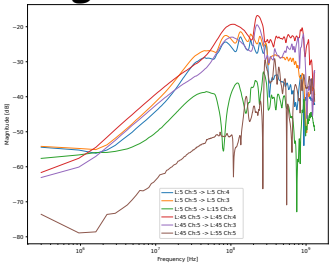


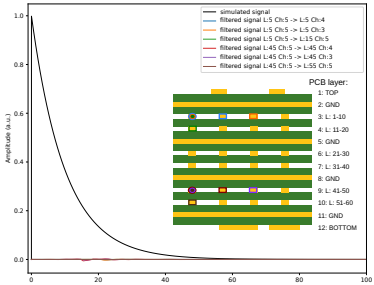


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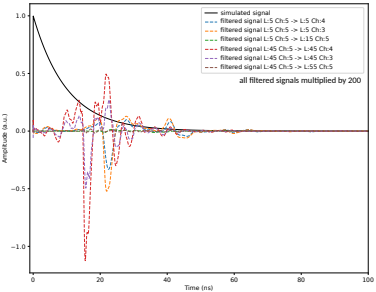
Components: Long Transfer board - Lab tests





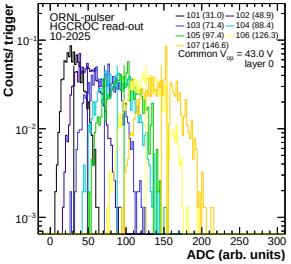


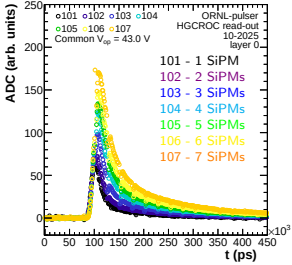
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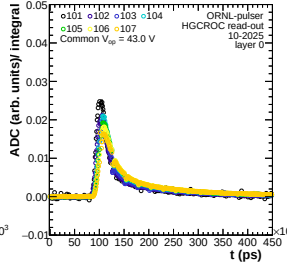


Electron-Ion Collider

Components: Passive Summing Board







Mini-switchable Summing Board



8M Summing Board V1



- Small switchable 16 SiPM summing board produced and tested
- Signal increases linearly with summing of additional SiPMs
- Minimal signal broadening observed for 1.3mm x 1.3mm SiPMs

⇒ Passive summing viable solution for 8M/4M modules with smaller SiPMs

- Similar evaluation needed for 3 x 3mm SiPM region
- 2 versions of 8M module test articles produced with different summing schemes
  - V1: Summing in depth 5-5-10-10-10-10-5-5 layers - 10 produced
  - V2: Summing in depth 5-5-5-5-10-10-10-10 layers - 10 produced
- Both test article versions tested during test beams at CERN

Electron-Ion Collider

Test beam campaigns

2023 (09 10) | 2024 (08/09) | 2025 (11) | 2026 (04 05)



Air-Stack
Location: CERN SPS H4
When: 09/2023

Setup: 12 scint. layer w/o absorber
Read-out: 1×CAEN DT5202
Goals:
- SiPM & tile characterization

Mini Module
Location: CERN PS T9
When: 10/2023



Setup: 4 layer W + 10 layers Steel 14 Scint. layers
Read-out: 2×CAEN DT5202
Goals:
- Absorber studies w/ external W layers
- Longitudinal shower profile



Single 8M-Module
Location: CERN PS T9
When: 08&09/2024

Setup: 8M module (64 layers)
Read-out: single layer
a) 8×H2GCROCs + 4×KCUs
b) 8×CAEN DT5202

Goals:
- Electronics characterization with single layer readout
- Full module electron E_{res}
- Hadron shower profile





Dual 8M-Module Stack
Location: CERN PS T9
When: 11/2025

Setup: 2×8M modules stacked (60 layers)
Read-out: single layer 8×H2GCROCs + 2×KCUs
Goals:
- Electron E_{res}
- Had. shower development



Dual 8M-Module Stack
Location: CERN PS T8
When: 04/2026
Setup: 2 stacked 8M, transfer+ summing PCBs (2 versions)
Read-out: summed layers 2×H2GCROCs + KCUs
Goals:
- Shower development
- PCB validation

Six 8M-Module Stack
Location: CERN SPS H2
When: 05/2026

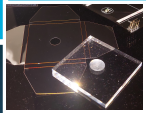


Setup: 2x3 stacked 8M, transfer+ summing PCBs (2 versions)
Read-out: summed layers, 6×H2GCROCs + 2×KCUs
Goals:
- E and position resolution studies
- Shower development & containment studies

Electron-Ion Collider

Component validation one test beam at a time

2023 09 10 | 2024 08/09 | 2025 11 | 2026 04 05



Tile studies

- ✓ Wrapping effectiveness
- ✓ Material
- ✓ Layer integration and uniformity
- ✓ Cross-talk



8M module integration

- ✓ First full module assembly
- ✓ Module weld structure
- ✓ Mechanical integration of electronics







Passive electronics development

- ✓ 2024 & 2025: Short transfer board integration & testing
- ✓ 2026: Long transfer board integration & testing
- ✓ 2026: Summing board tests
- ✓ 2026: High density flex cable tests



Flex-SiPM PCB development

Design optimizations:

- ✓ Signal integrity & Cross-talk
- ✓ Integration: connectors, thickness, assembly



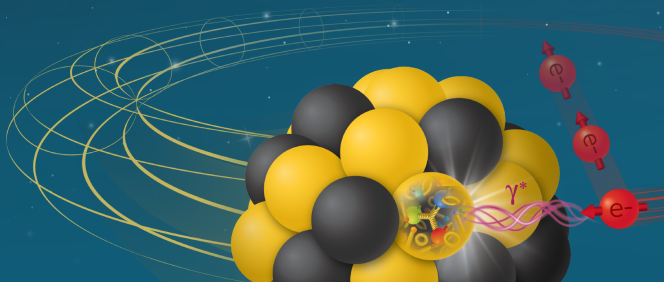
H2GCROC development

- ✓ 2024: First custom read-out tested
- ✓ 2025: Improve multi-chip synchronization
- ✓ 2025: Improve data throughput & data format

Final read-out validation & performance assessment planned for 2029/30

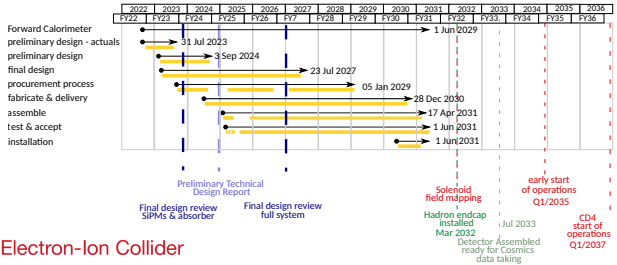
Electron-Ion Collider

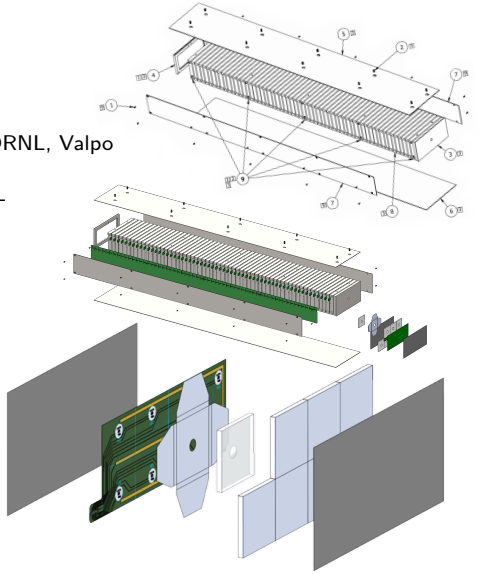
Construction & Assembly Plans



Construction Procedure

- Construction done in units of modules
- Assembly steps LFHCal
  1. Steel module construction at vendor, delivery to ORNL
  2. Tile production at FNAL, delivery to MSU
  3. ESR cutting & Tile wrapping at MSU, delivery to Vanderbilt, ORNL, Valpo
  4. PCB assembly at production house, delivery to ORNL
  5. Layer assembly & testing at various institutes, delivery to ORNL
  6. Transfer board assembly at production house, delivery to ORNL
  7. Layer insertion & transfer board installation at ORNL
  8. Storing & Transport of modules to BNL
  9. Assembly in cradle at IP6





Quality assurance plans

Steel modules

1. Full GD&T for first 5 modules
2. Vendor tests: go-/no-go gauge for full module dimensions & straightness, slot size
3. Acceptance test at ORNL: 5% same test as at vendor

SiPM flex PCB

1. Vendor tests: for SiPM connectivity (resistance test) & correct polarization
2. Acceptance test at ORNL: 5% same test as at vendor

Long Transfer Board

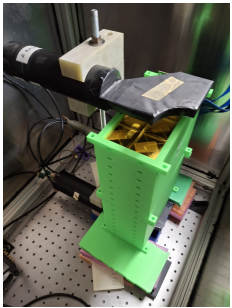
1. Vendor tests: for connectivity end to end
2. Acceptance test at ORNL: 5% same test as at vendor

Layer testing

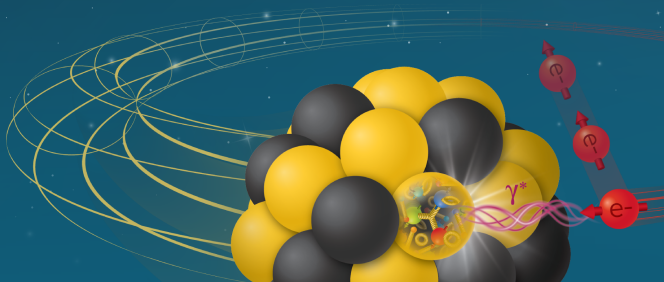
1. Fully assembled layers tested for connectivity (same as flex-PCB)
2. Full classification of response for single layers for all layers in small air stacks after assembly
3. Testing can be multiplexed using HGCROC setups (64 channels/HGCROC)
4. Need $\approx$ 2000 events per tile for mips for classification at V_{op}

Module testing

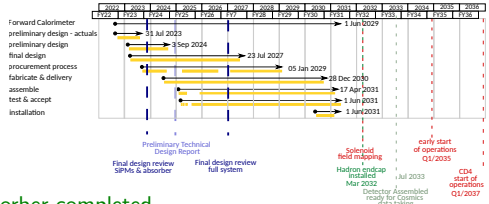
1. connectivity test whether all SiPMs are seen at output of transfer board



Summary



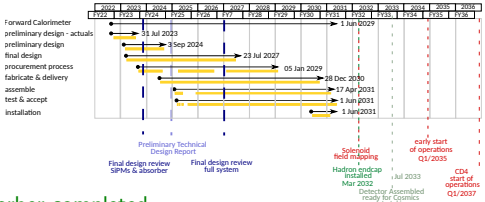
Where are we?



- ✓ FDRs for SiPMs & Absorber completed
- ✓ SiPMs included in CD-3A (∼ 341.4K received) & CD-3C (remaining)
- ✓ Steel modules included in CD-3[A-C], tender completed expecting first production modules by end of 2026
- Tile production and manual wrapping well developed
  → Finalize design for tile wrapping machine & procedures to create scintillator assemblies
- 8M Flex-SiPM PCBs well tested & integrated
  → design for 4M & insert modules
- First passive transfer boards produced & tested
  → Transfer design for 4M & insert modules
  → Might need to put CALOROCs partially on transfer board for insert

- First versions of summing board produced & tested
  → Integration with FEB under development
- H2GCROC read-out electronics tested under test beam conditions
  → Final FEB waiting for CALOROC
- Mechanical integration far advanced with produced components
- Simulation work far advanced, further studies needed for updated insert geometry

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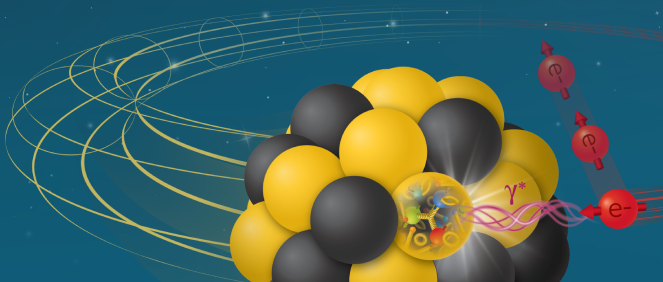
Ready for full system FDR early 2027!

All time critical components for 8M modules production ready!
Preparing equivalent designs for 4M modules.
Equivalent insert components under design evaluation.

Summary Charge Questions

1. Has progress since the June 2025 DAC comprehensive design review been satisfactory?
   Yes.
2. Have all recommendations that are relevant for detector CD-2 baseline been addressed?
   Yes. Insert granularity and construction method have been adapted to be more streamlined with remaining LFHCal modules.
3. Is the path towards a final design of the various sub-detectors defined and sound?
   Yes.
4. Are the detector integration and planning for installation and maintenance well developed?
   Yes.
5. Will the detector be ready for construction by end of CY2027?
   Yes.
6. Are plans sufficiently developed for the ePIC detector production phase beyond CD-3?
   Yes.

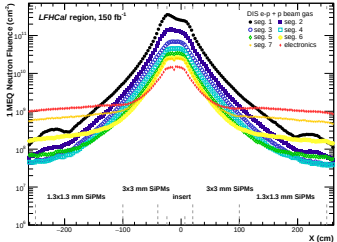
Backup

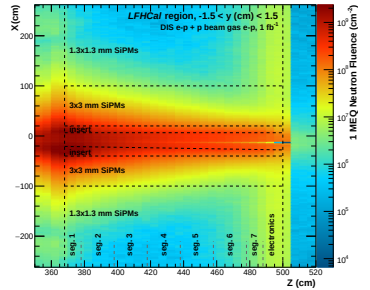


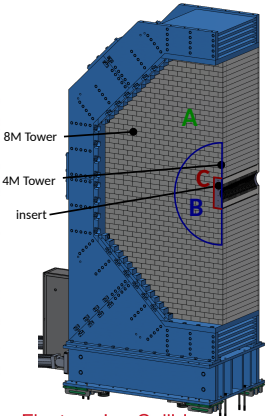
Impact of Radiation Damage on Design

Radiation Regions

- **A:** $R > 1$ m: $< 5 \cdot 10^9$ neq/cm^2/year
- **B:** $R < 1$ m: $10^9 - 10^{11}$ neq/cm^2/year
- **C:** $\sim 10^{11}$ neq/cm^2/year

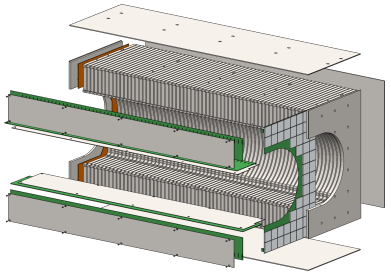






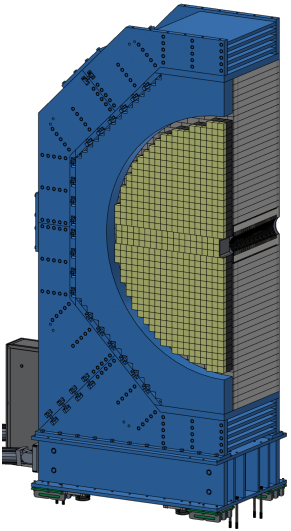
Mitigation for different regions:

- **A:** 8M & 4M modules with inaccessible SiPMs
  - 1.3×1.3 mm^2 SiPMs & injection molded scintillator
- **B:** 8M & 4M modules with inaccessible SiPMs
  - 3×3 mm^2 SiPMs & scint. mach. from cast material
- **C:** Insert modules
  - **Scintillator & SiPM assemblies accessible during longer shutdowns** (after removal of dust cover)
  - **Replacement or annealing of SiPMs & tiles possible**

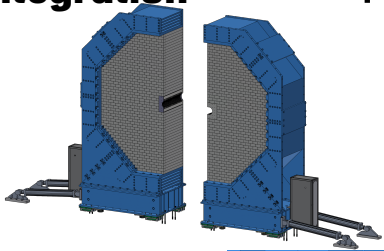


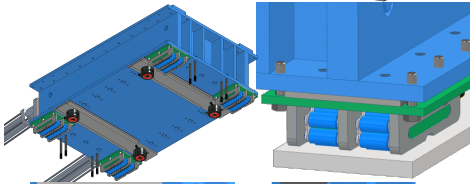
Electron-Ion Collider

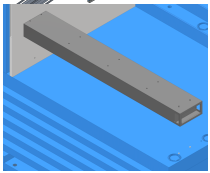
Support structure & ECal Integration

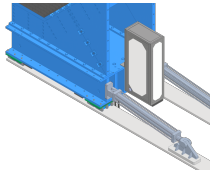


- Cradle build in multiple components
- Simultaneous construction of LFHCal stack and outer shell during installation at BNL
- 1-inch perforated steel plate mounted to front of LFHCAL serving as anchoring structure for both HCal & ECal modules
- Individual ECal blocks installed after completion of HCal construction
- Additional flux return steel mounted between Barrel HCal, forward ECal outer edge & LFHCal
- Purchase of support structures requested as part of CD3-B









Electron-Ion Collider

Facility Life Time

For EIC we define a 30-year lifetime; to define radiation doses one needs to have a rough split between the beam energies over this 30-year period. Here is the present assumption.

EIC is built to run the following beam energy combinations:
5 GeV x 41 GeV, 5 GeV x 100 GeV, 10 GeV x 100 GeV, 10 GeV x 275 GeV and 18 GeV x 275 GeV
For simplicity all hadrons are treated as protons, which should be okay for radiation purposes.
Based on this, one gets the following estimate for accelerator components:

Electron Energy			Hadron Energy		
5 GeV	10 GeV	18 GeV	41 GeV	100 GeV	275 GeV
10 years	10 years	10 years	5 years	12 years	13 years

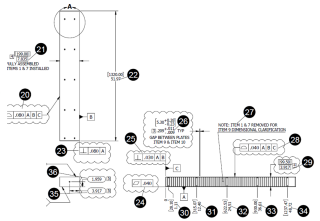
For ePIC a 30-year lifetime for radiation will be too long for certain detector components so the present assumption is 15 years with 5 years at the EIC commissioning and ramp up luminosities ($\int L = 38\ fb^{-1}$) and 10 years at full EIC capabilities.

Electron Energy			Hadron Energy		
5 GeV	10 GeV	18 GeV	41 GeV	100 GeV	275 GeV
3 years	4 years	4 years	2 years	3 years	5 years



5 x 41 GeV --> 2 years
5 x 100 GeV --> 1 year
10 x 100 GeV --> 2 years
10 x 275 GeV --> 2 years
18 x 275 GeV --> 3 years

Components: Absorber Structures (2)



8M Tower Assembly (1320mm) Assembly Dimensions based on Rev 02 GD&T Values											
Dimension #	Description	Importance Category	DRW Tolerance (in)	Prototype 1	Prototype 2	Prototype 3	Prototype 4	Prototype 5	Prototype 6	Prototype 7	Prototype 8
20	Left Side Surface Tol	High	0.08	0.017	0.036	0.052	0.043	0.045	0.028	0.03	0.025
21	Width	Basic	7.795 - 7.875	7.828	7.845	7.831	7.837	7.832	7.842	7.835	7.835
22	Length	Low	±0.05	51.965	51.872	51.917	51.924	51.94	51.92	51.93	51.93
23	Right Side Perpendicularity Tol	High	0.08	0.018	0.03	0.09	0.018	0.035	0.03	0.028	0.01
24	Bottom Flatness Tol	High	0.04	0.015	0.027	0.02	0.025	0.015	0.025	0.015	0.015
25	Front Perpendicularity Tol	Medium	0.04	0.035	0.028	0.045	0.004	0.012	0.025	0.018	0.012
26	Plate Spacing	High	+.011 - .009	.207 / .213	.207 / .216	.167 / .238	.208 / .212	.208 / .212	.210 / .215	.210 / .216	.210 / .213
28	Top Surface Tol	High	0.04	0.018	0.037	0.03	0.042	0.035	0.028	0.032	0.022
29	Height	Basic	3.897 - 3.937	3.96	3.949	3.945	3.946	3.94	3.923	3.925	3.916
30	Location Tapped Plate #1	Low	±0.067	1.114	1.107	1.06	1.114	1.052	1.11	1.108	1.118
31	Location Tapped Plate #2	Low	±0.067	12.413	12.365	12.346	12.38	12.46	12.4	12.39	12.375
32	Location Tapped Plate #3	Low	±0.067	24.52	24.438	24.409	24.461	24.53	24.5	24.486	24.478
33	Location Tapped Plate #4	Low	±0.067	36.624	36.521	36.479	36.56	36.51	36.56	36.65	36.555
34	Location Tapped Plate #5	Low	±0.067	48.73	48.597	48.574	48.634	48.64	48.63	48.635	48.63
35	Horizontal location M12 Hole	Inspection		-	-	-	-	3.917	3.917	3.916	3.918
36	Vertical Location M12 Hole	Inspection		-	-	-	-	1.959	1.959	1.958	1.958

Engineering module production

- Established reproducible production procedures for the 8M module production over the past year
- 9 pre-production items produced so far
- Initial modules not fully within tolerances for some less important measures
- Corrosion prevention by using Nickel plating the whole module
- Pre-production items used for test beams as single module or 2x4 module stack

