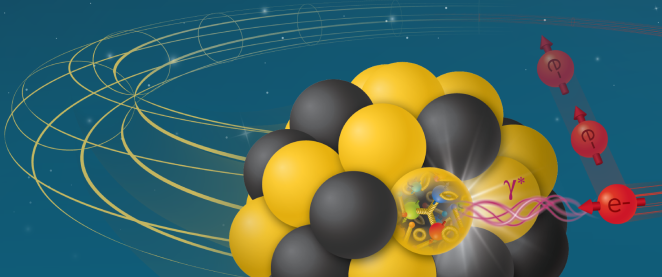
Forward Hadron Calorimeter & Insert

Longitudinally segmented Forward HCal (LFHCal)

Friederike Bock (ORNL)
June 13, 2025



Electron-Ion Collider
10th EIC DAC Meeting, June 11-13, 2025

Outline & Charge

Outline

1. Concept
2. Components & Technical updates
3. Assembly
4. Future work

Charge Questions

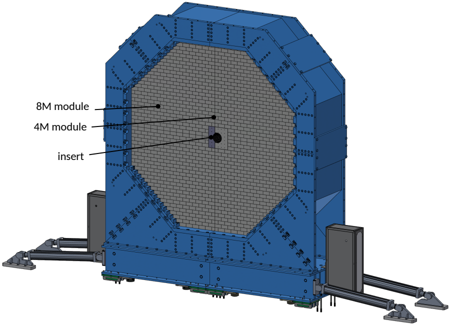
1. Is the design of the ePIC detector and its sub-systems appropriate and progressing well?
2. Are the remaining work and technical, cost and schedule risks adequately understood? Are there opportunities?
3. Will the detector be technically ready for baselining by late 2025?
4. Are the detector integration and planning for installation and maintenance progressing well? Are there areas where further ideas should be pursued?
5. Will the detector be ready for start of construction by late 2026?

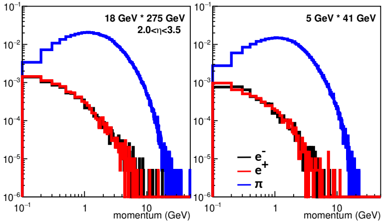
Electron-Ion Collider

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:
  - LFHCal built mostly out of 10x20x132 cm^3 8M modules
  - Insert built out of 2 halves surrounding the beam pipe
- **LFHCal:**
  - 60 layers of steel interleaved with scintillator material
  - Transverse tower size 5x5 cm^2
  - Multiple consecutive tiles summed to 7 longitudinal segments per tower
- **Insert:**
  - 60 layers of steel interleaved with scintillator
  - Hexagonal tiles of 8 cm^2 each read-out individually





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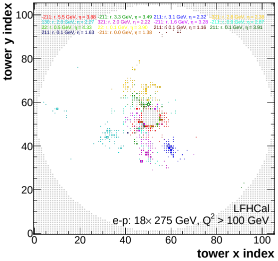
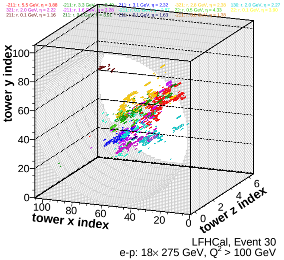
Motivation & Requirements

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 $\eta < 2.5$ & 3x3 cm^2 for $2.5 < \eta < 4$
- 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

$\rightarrow$ 525,120 SiPMs, 61,264 read-out channels

Insert modules

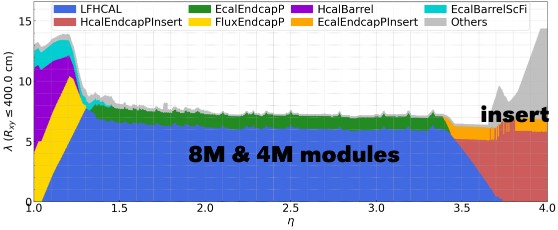
- Acceptance: $3.5 < \eta < 4.4$
- ~ 120 hexagonal tiles/layer for first 20 layers (4.2 cm width) and ~ 80 for remaining (6.5 cm width), staggered positions in different layers

$\rightarrow \sim 7000$ SiPMs/tiles & read out channels

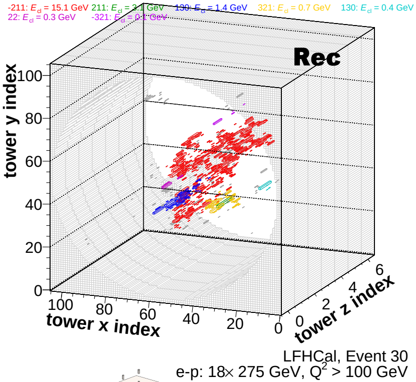
SiPMs part of CD3-A:

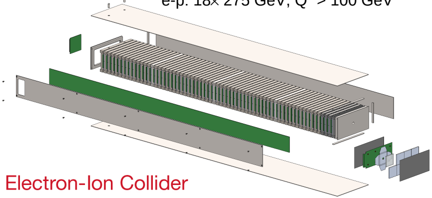
$\rightarrow$ First delivery (30K) in June 2025
$\rightarrow$ test stand under construction

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	$1.2 < \eta < 3.5$	$3.5 < \eta < 4.4$
tower information		
x, y	5 cm	$\approx$ 4.2 cm (layer 1-20) $\approx$ 6.5 cm (layer 21-60)
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	7 x 8752 = 61264	$\approx$ 7000



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 7 or 8 segments longitudinally (5 or 10 SiPMs summed in depth) desirable min measurable tower energy $<$ 0.5 MIP/segment, max. $\approx$ 1500 MIP/segment
- **insert modules**:
  read out every single tile desirable min measurable energy $<$ 0.5 MIP/tile , max. $\approx$ 500 MIP/tile
- SiPMs mounted to flexible PCBs, passive signal transfer to back side of calorimeter using long transfer PCB
- 1 CALOROC (up to 64 channels) per 8M(4M) module (56/64 channels) in the back, 110 CALOROCs for insert readout

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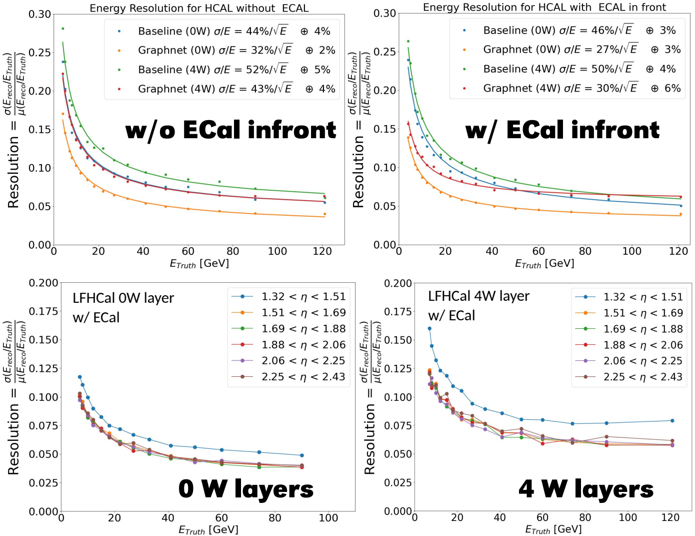
Performance in Simulations

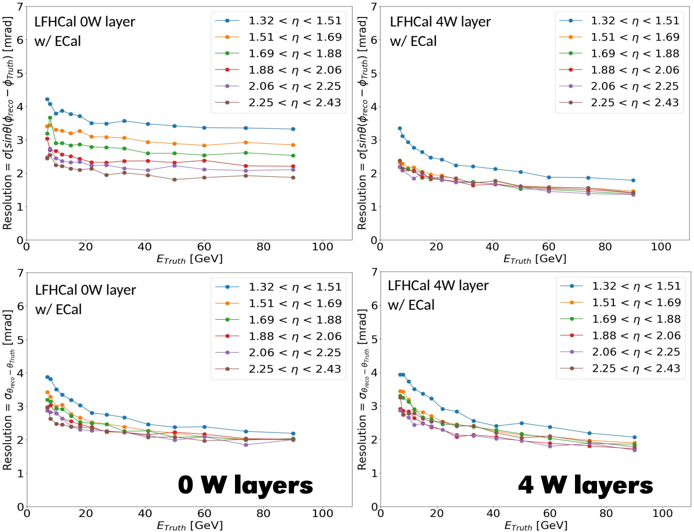


- Implementation of realistic geometry in ePIC software stack
- First version of clusterization algorithm working well at high E
- Absorber optimization with ML assistance and full software compensation
  - Initial concept with 4 layers of tungsten
  - Software compensation with full detector system optimized with graphnet-algorithmn
  - Improved E-resolution w/o tungsten layers
  - Little impact on spatial resolutions w/ or w/o tungsten layers

$\Rightarrow$ Tungsten layers removed & replaced with steel

Electron-Ion Collider

Performance in Simulations



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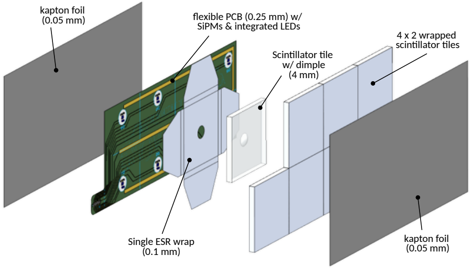
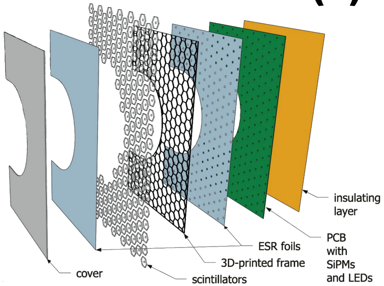
Components: Scintillator Tile Assemblies (1)





8M & 4M module layers:

- Square injection molded or machined tiles $\approx 0.4x5x5$ cm^3 with dimples individually wrapped in ESR foil assembled in a grid of 4(2)x2 tiles
- Backed by flexible PCB equipped with 8(4) SiPMs and LEDs sandwiched with Kapton foil
- Flexible PCB wrapped around side of absorber to connect with long PCB along the side of the module

Insert layers:

- Hexagonal tiles of different sizes per layer with edges painted with TiO_2
- Sandwiched between reflective foil, held in a 3D-printed frame and backed by a PCB equipped with a SiPM per tile
- Hole layer exchangeable at end-of-year shut-down

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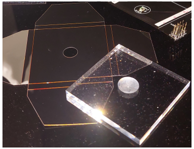
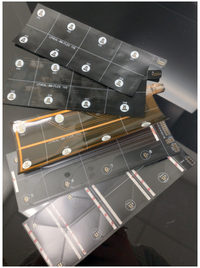
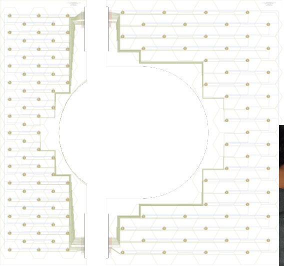
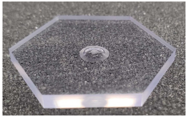
Components: Scintillator Tile Assemblies (2)









8M & 4M module layers:

- Tile production at FNAL via injection molding with established processes & chemical composition
- ESR wrap cut with commercial small scale laser cutter, exploring options to out-source process to local companies
- Finalizing Flexible PCB design, 3rd major iteration soon to be tested in test beam at CERN
- Manual tile wrapping & layer assembly process well established currently working on automatization for both

Insert layers:

- 2 hexagonal sizes foreseen with staggered positions in different layers
- Tile production established with injection molding & machining
- ESR cutting with commercial small scale laser cutter
- Tile frame printed with commercial 3D printer
- First version of PCB layout for each layer available space constraints largest challenge
- First larger scale prototype layers constructed for ZDC test beam with similar design approach

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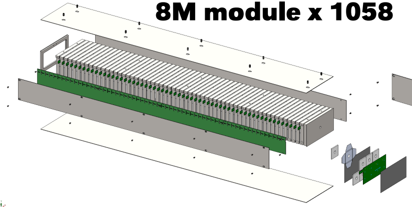
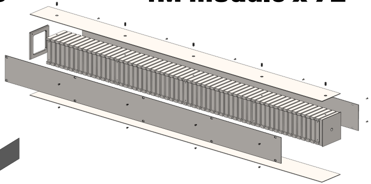
Components: Absorber Structures (1)

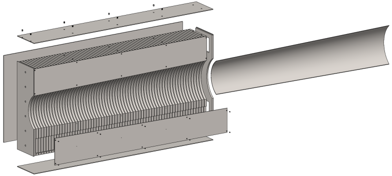
8M module x 1058



4M module x 72

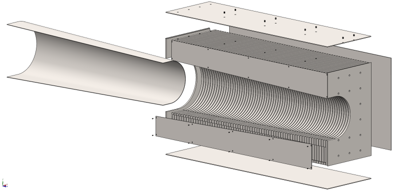


Insert left

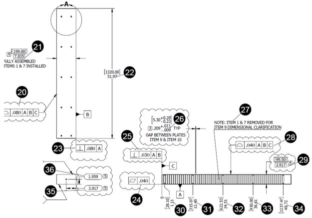


- 4 different module types designed using the same construction process
- 60 single absorber plates, front and back plate electron beam welded to top & bottom sheet metal panel
- Side panels screwed to welded structure to cover slot with transfer PCB and remaining open side
- Absorber structure design concluded & CD3-A procurement process started

Insert right



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

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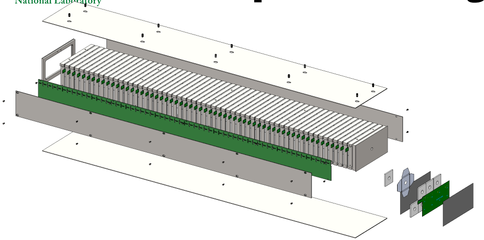
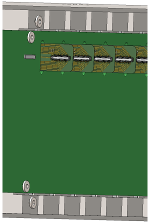
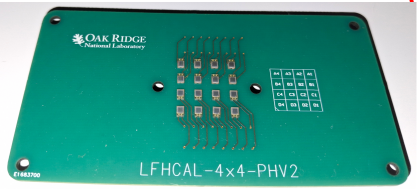
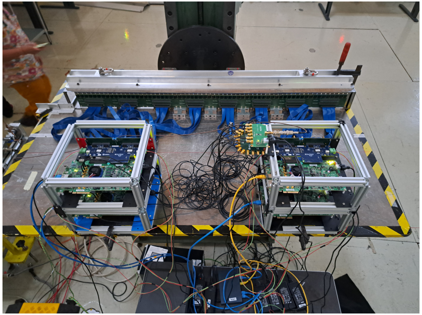
Components: Signal-Transfer and Read-out









- For maintenance the read-out cards will be placed in the rear of the modules
- Passive signal transfer to the rear with long transfer boards

→ First prototype ready for production

- To keep possibility of future upgrades signal summing done in rear as well

→ Test board employing passive summing produced & currently under test

- Read-out boards using CMS-HG2CROC (precursor to CALOROC) produced and have been operated in test beam since 2023

CALOROC details see F. Barbosa's talk

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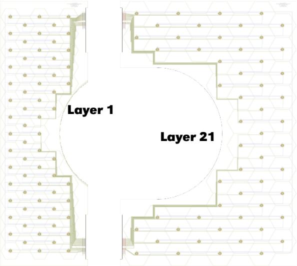
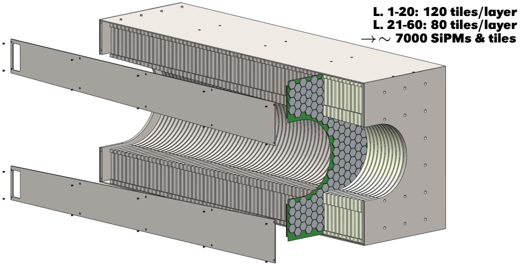
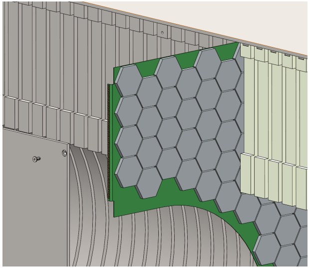
Insert Challenges



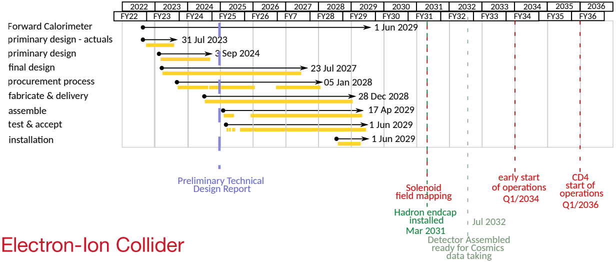


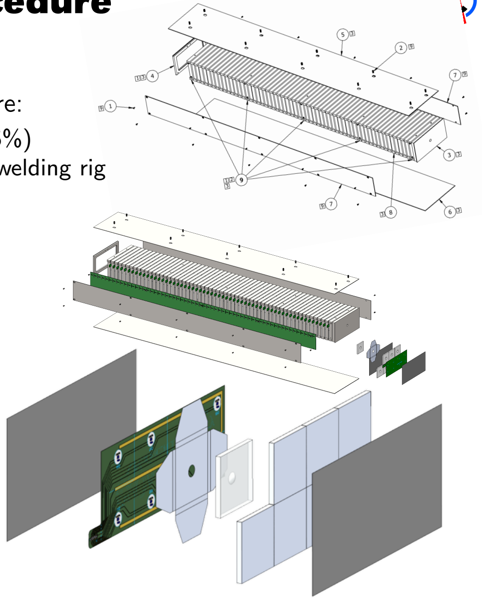


- Higher radiation load surrounding beam pipe, needs possibility to replace layers
  $\Rightarrow$ transfer PCBs situated between left and right module
- Limited space for connectors from each layer $\rightarrow$ worst case $\sim$ 80 SiPMs/layer
- Width of transfer PCB similar to 8M module needs to fit $\sim$ 4.5x number of traces
- Single channel read-out requires
  $\sim$ 110 CALOROC at the back of the module within tight spatial constraints
  $\Rightarrow$ cooling might be needed
- Joint efforts between mechanical & electrical engineers needed over coming month to realize concept

Construction Procedure

- Construction done in units of modules
- Construction & QA steps per unit regarding absorber structure:
  1. Dim. tolerance and material composition measurements ($\approx 5\%$)
  2. E-beam welding of absorber structure w/o cover-plate using welding rig
  3. Stacking tests at vendor
  4. Assembly of tile-assemblies and installation
  5. Mounting of transfer PCB & cover plate
  6. Storing & Transport of modules to BNL
  7. Assembly in cradle at IP6





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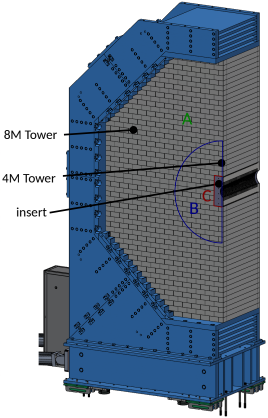
Impact of Radiation Damage on Design

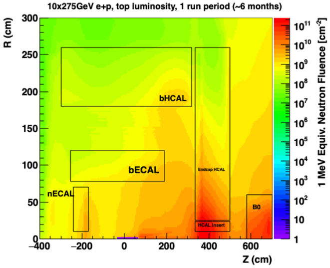


Radiation Regions

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

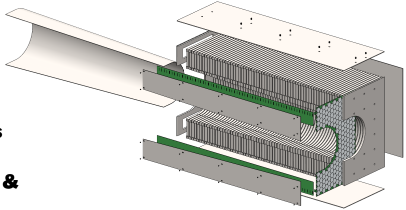
- 1.3×1.3 mm^2 SiPMs & injection molded scintillator

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**



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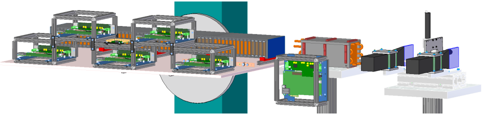
Test beam - August 2024 (1)

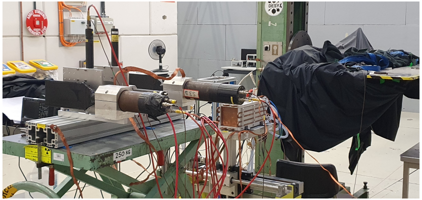


Dates: 28^{th} Aug-11^{th} Sept 2024 **Location:** PS - T09
Main purpose: First full module test & H2GCROC tests
Setup:

- Full 8M module testing 65 layers of absorber & scintillator per layer 8 channels (swapping scintillator geometry either 8M module or insert)
- Readout with multiple CAEN DT5202 64ch CITIROC SiPM readout units (2nd week) and H2GCROCs (1st week)

Main expected measurements:

- Energy resolution estimates for hadrons and electrons for full length module with both read-out versions
- Assessment of longitudinal leakage
- Longitudinal shower development
- Read-out validation
- Part of campaign with EEEMC in front



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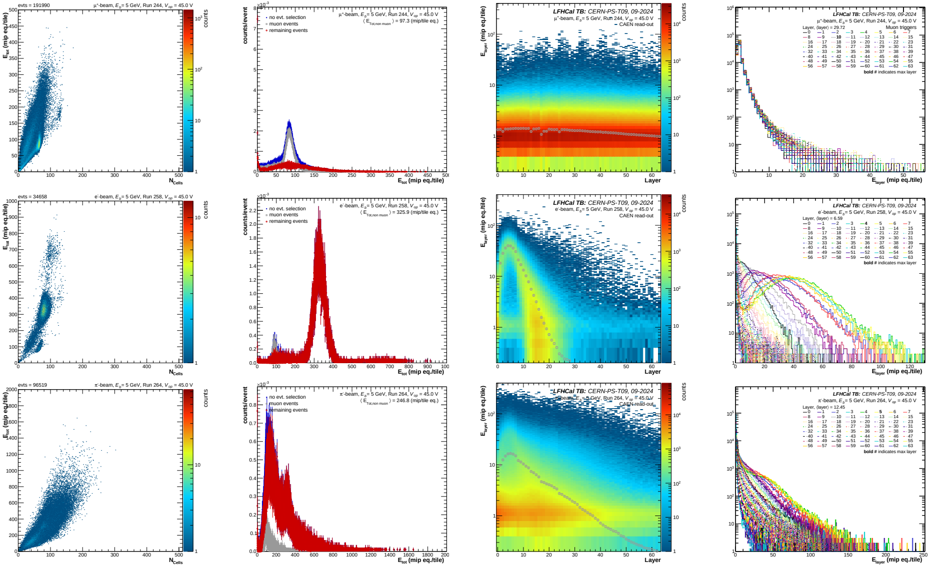
Test beam 2024: First Highlights



μ beam 5 GeV

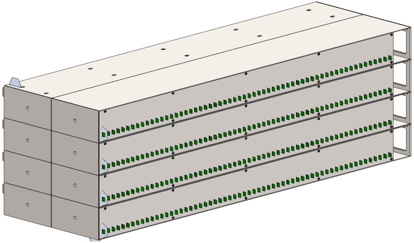
e- beam 5 GeV

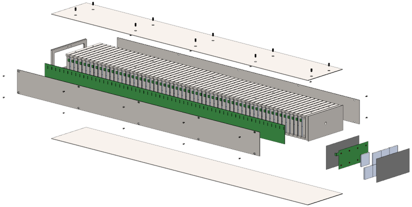
π^{-}- beam 5 GeV

Test Beam Plans 2025

Requested time: 1 week each
Main purpose: Resolution studies
Location: CERN SPS (29th Oct) & PS (19th Nov.)
Setup:

- Very similar to 2024 setup, with more modules
- 8 full 8M modules (ideally 40x40x132 cm)
- Readout with H2GCROCs
- Same setup in both areas





Main expected measurements:

- Energy resolution for hadrons and electrons
- Assessment of longitudinal/transversal leakage
- Longitudinal shower development
- Final-Flexible PCB validation & first long PCB & summing board validation

Electron-Ion Collider

Summary Charge Questions (1)

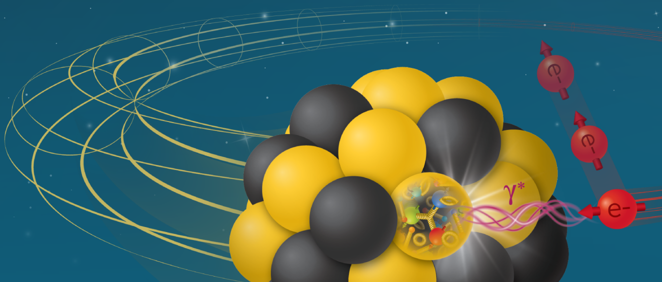
1. Is the design of the ePIC detector and its sub-systems appropriate and progressing well?
   Yes. The procurement process for the SiPMs and LFHCal absorber modules is under way and the remaining necessary electronic components are being addressed in the order in which they need to be available for the LFHCal construction. For the insert the basic mechanical engineering designs have been completed and the electro-mechanical integration is being addressed considering the high signal density and the limited space for the readout.
2. Are the remaining work and technical, cost and schedule risks adequately understood?
   Are there opportunities?
   Yes. Advanced pre-production items or prototypes are available for all components of the LFHCal. Their maturity level is adequate on the time scale which they need to be installed in the module. Test beam measurements are being pursued to validate their expected performance and ensure operational stability. Industrialization & automatization options are being explored for the production of the scintillating layers and their sub-components.

Electron-Ion Collider

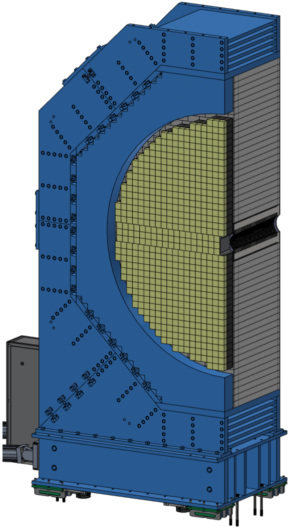
Summary Charge Questions (2)

3. Will the detector be technically ready for baselining by late 2025?
   Yes. The LFHCal will be ready for baselining by late 2025. Full FDR planned for Q4/25, absorber structure & SiPMs already included in LLP. The insert is currently slightly less mature and a concise effort is being made to reach a similar maturity level as well within the coming month.
4. Are the detector integration and planning for installation and maintenance progressing well? Are there areas where further ideas should be pursued?
   Yes. Advanced installation and integration plans are available for the forward endcap installation and a large fraction of the support structures has been included in the CD3-B procurement request. Maintenance plans for the LFHCal and insert focus on areas receiving possible large radiation damage, where the corresponding layers can be exchanged or annealed if need be during end of year shut-downs. Moreover, the read-out components are accessible at any time.
5. Will the detector be ready for start of construction by late 2026?
   Yes. For the LFHCal long lead time items have already started to be procured (SiPMs, absorber structure, supports) and the remaining components are in the final stages of their development cycle. The design of the insert modules is advanced, however the electrical integration challenges will need to be addressed within the next year.

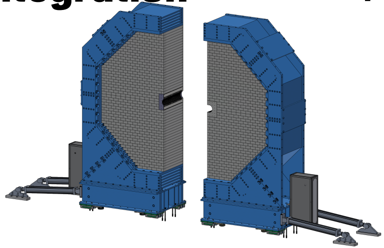
Backup

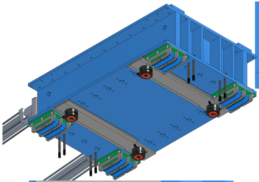


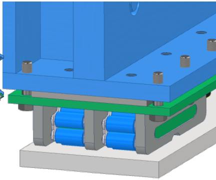
Support structure & ECal Integration

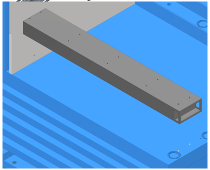


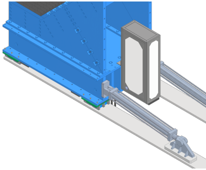
- Cradle build in multiple components
- Simultaneous construction of LFHCal stack and outer shell during installation at BNL
- 1-inch perforated steel plate mounted to front of LFHCAL serving as anchoring structure for both HCal & ECal modules
- Individual ECal blocks installed after completion of HCal 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 ($\int L = 38\ \mathrm{fb}^{-1}$) 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

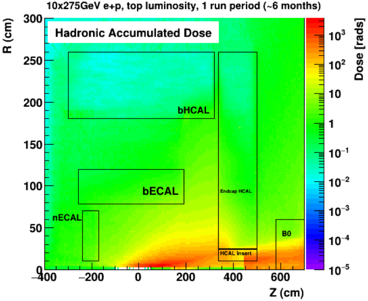
Electron-Ion Collider

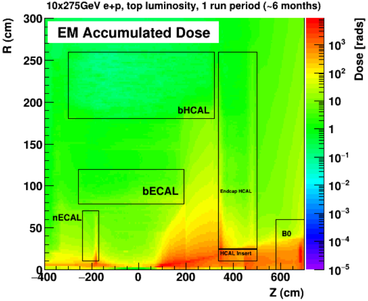
Radiation Doses

All the information is posted at https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses

To obtain the full radiation dose one needs to add the radiation dose due to electron-nucleon scattering + electron beam backgrounds and hadron beam backgrounds

The figures are for an integrated lumi of 1 fb^{-1}, so one needs to scale to the total integrated luminosity for the 15 years (5 years of commissioning and 10 years of full-lumi) as described earlier.
It is very important to have the material budget correct also along the beam pipe, like the SC magnets





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