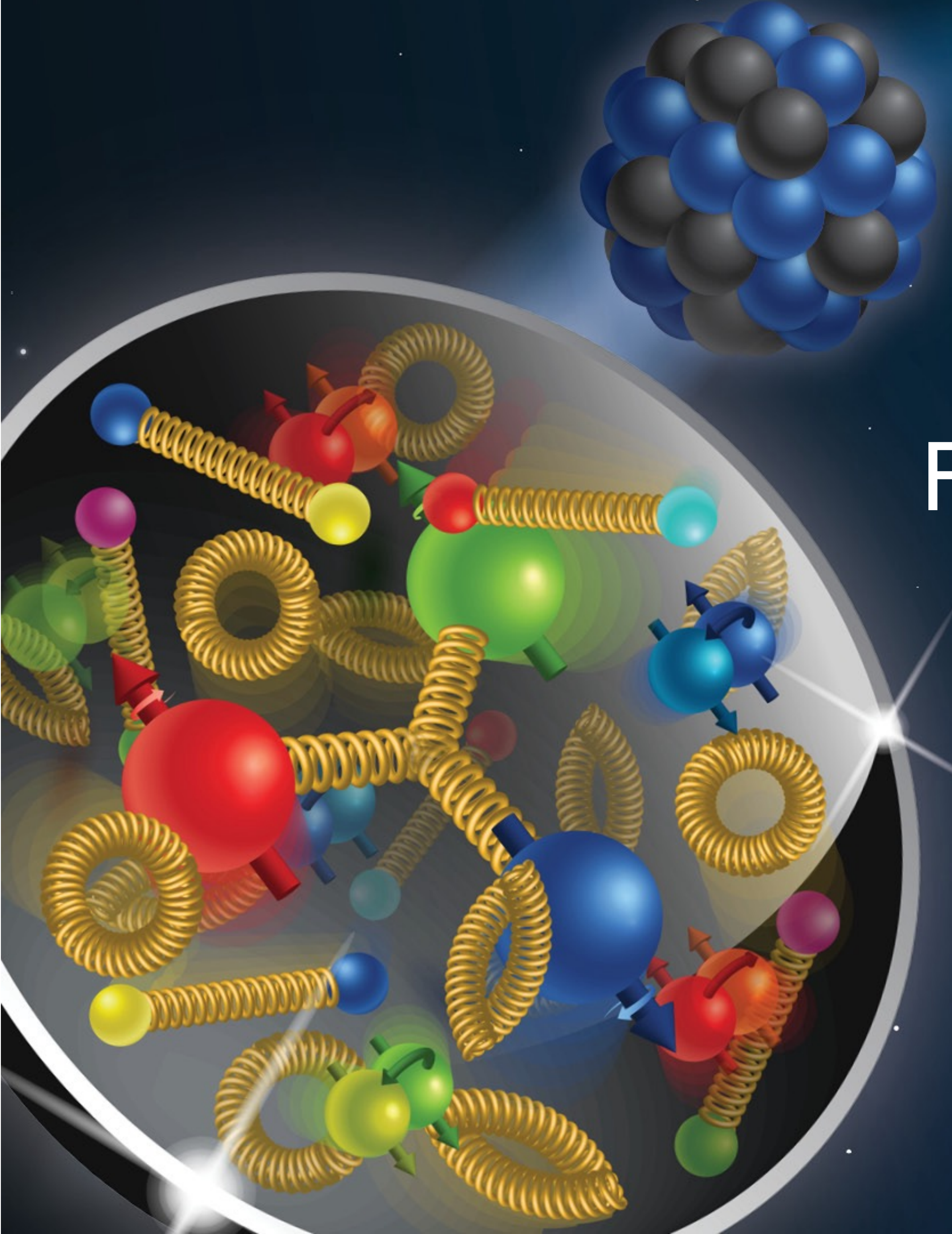


Forward Hadronic Calorimetry: physics goals & requirements

Alexander Kiselev, BNL

Final Design Review for ePIC LFHCal steel & tungsten

September 25, 2023

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline of the talk

- Goals of this review and charge to the Committee
- Requirements

- Cost and Schedule
- ES&H and QA

- Summary

Charge to the Committee

1. Are the LFHCAL technical performance requirements complete, documented, and understood? — this talk

2. Are the plans for achieving detector performance and construction sufficiently developed and documented for the present phase of the project? Specifically, are they commensurate with the initiation of the LFHCAL absorber and casing steel procurement (also hereafter referred to as the "procurement")? — Mostly covered in a talk by Elliot

3. Do the present LFHCAL design and the resulting absorber and casing steel specifications meet the abovementioned performance requirements with a low risk of cost increases, schedule delays, and technical problems? — Mostly covered in a talk by Friederike

4. Are the fabrication and assembly plans for the LFHCAL consistent with the overall project and detector schedule and appropriately developed to initiate the procurement? — Mostly covered in a talk by Elliot

Charge to the Committee

5. Are the plans for LFHCAL integration in the EIC detector appropriately developed to initiate the procurement? In particular, is the design consistent with a requirement that LFHCAL iron components should serve as part of the EIC detector solenoid flux return?

Mostly covered in a talk by Elliot

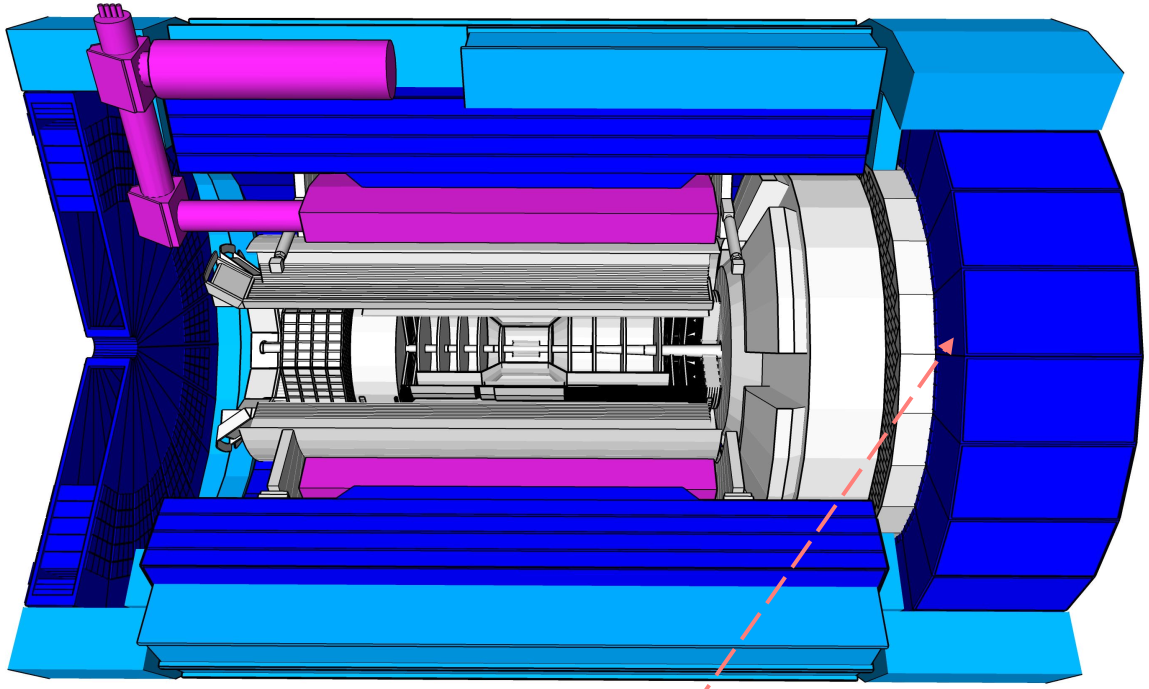
6. Have the December 2022 EIC Calorimetry Review recommendations been adequately addressed to initiate the procurement?

7. Have ES&H and QA considerations been adequately incorporated in the procurement planning? (This includes a quality assurance plan for receipt of material, in particular verification of the required permeability of the steel components.)

8. Is the procurement approach sound and the procurement schedule credible?

this talk

Hadronic Calorimetry of ePIC detector



- Jet energy measurement
  - Tag jets with a neutral component
- DIS kinematics reconstruction
  - Hadronic method

- Solenoid flux return

Barrel HCal	Refurbished sPHENIX barrel calorimeter
Backward HCal	Scintillator recycled from STAR endcap EmCal
Forward HCal	Brand new design

Overall requirements

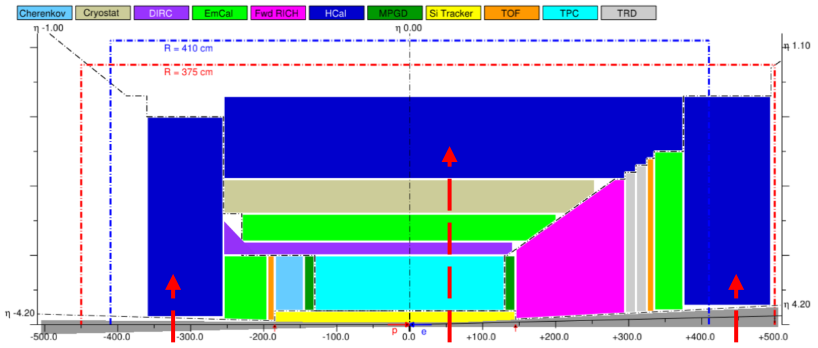
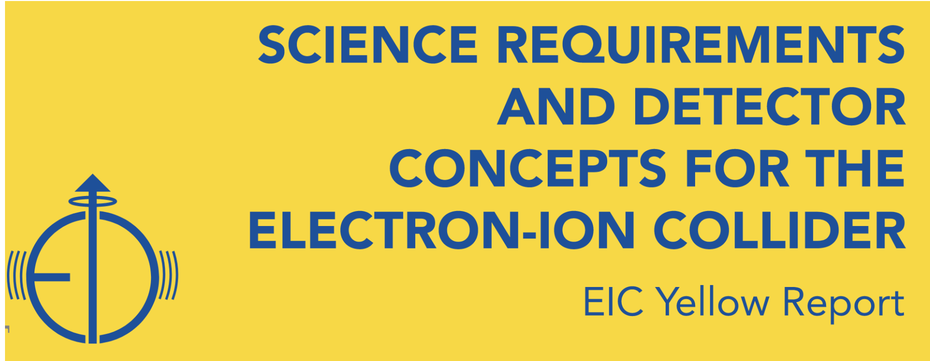


Figure 9.3: A 2D sketch of an EIC detector layout, horizontal cross cut.

Backward | Barrel | Forward

- The layout and most of the requirements for the forward hadronic calorimeter did not change much since the Yellow Report times
  - Energy resolution is driven by the needs of Particle Flow reconstruction, given a full tracker and e/m calorimetry coverage in the same η acceptance
  - Granularity is driven by the needs of neutral cluster isolation and jet substructure measurements

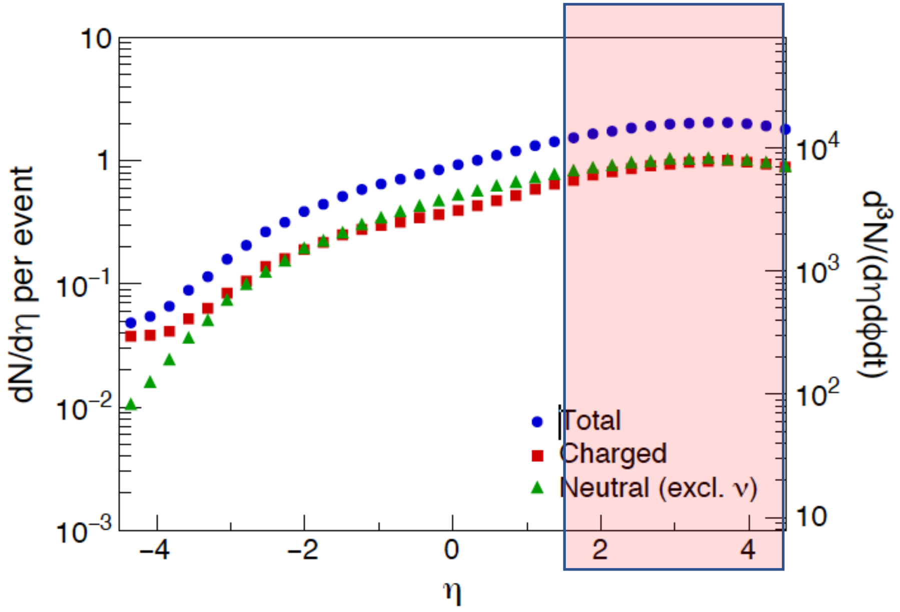


Hadron calorimetry In the mid-rapidity region, the energy resolution of hadron calorimeters is driven by single jet measurements. Neutral hadron isolation could also be important for jet energy scale and resolution. In the forward and backward rapidity region diffractive di-jets need a good hadron energy measurement, with a resolution of the level of $\sigma(E)/E \approx 50\%/\sqrt{E} \oplus 10\%$. The requirement on the constant factor at the highest rapidities is driven by the need for good energy resolution where tracking dies out. A minimum energy threshold of 500 MeV/c was assumed for all the studies performed.

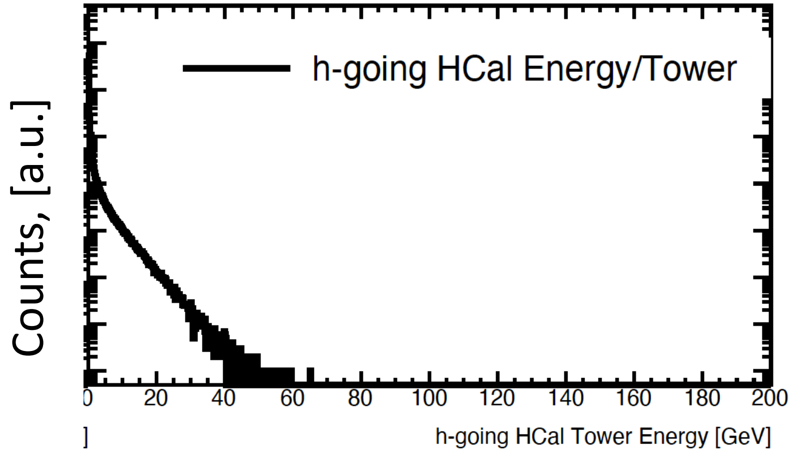
	"Ideal" configuration		Acceptable configuration	
η	σ_E/E, %	E_{min}, MeV	σ_E/E, %	E_{min}, MeV
-3.5 to -1.0	$45/\sqrt{E}+7$	500	$50/\sqrt{E}+10$	500
-1.0 to +1.0	$85/\sqrt{E}+7$	500	$100/\sqrt{E}+10$	500
+1.0 to +3.5	$35/\sqrt{E}$	500	$50/\sqrt{E}+10$	500

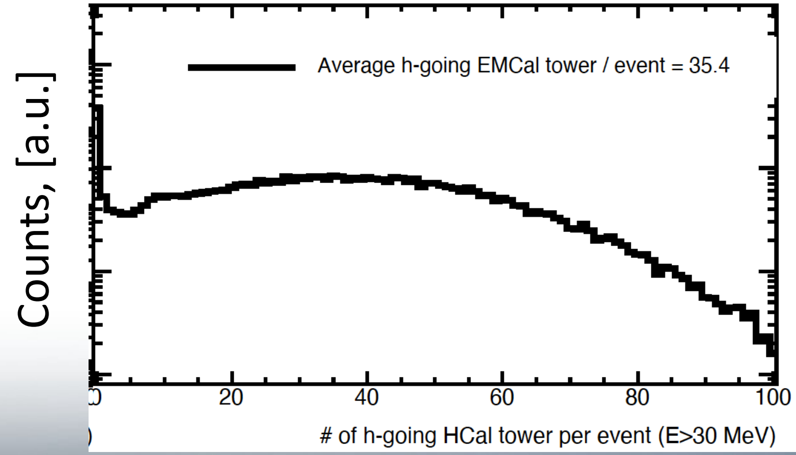
Occupancy and rates

- Typically, few towers hit per event, few GeV energy deposit per tower



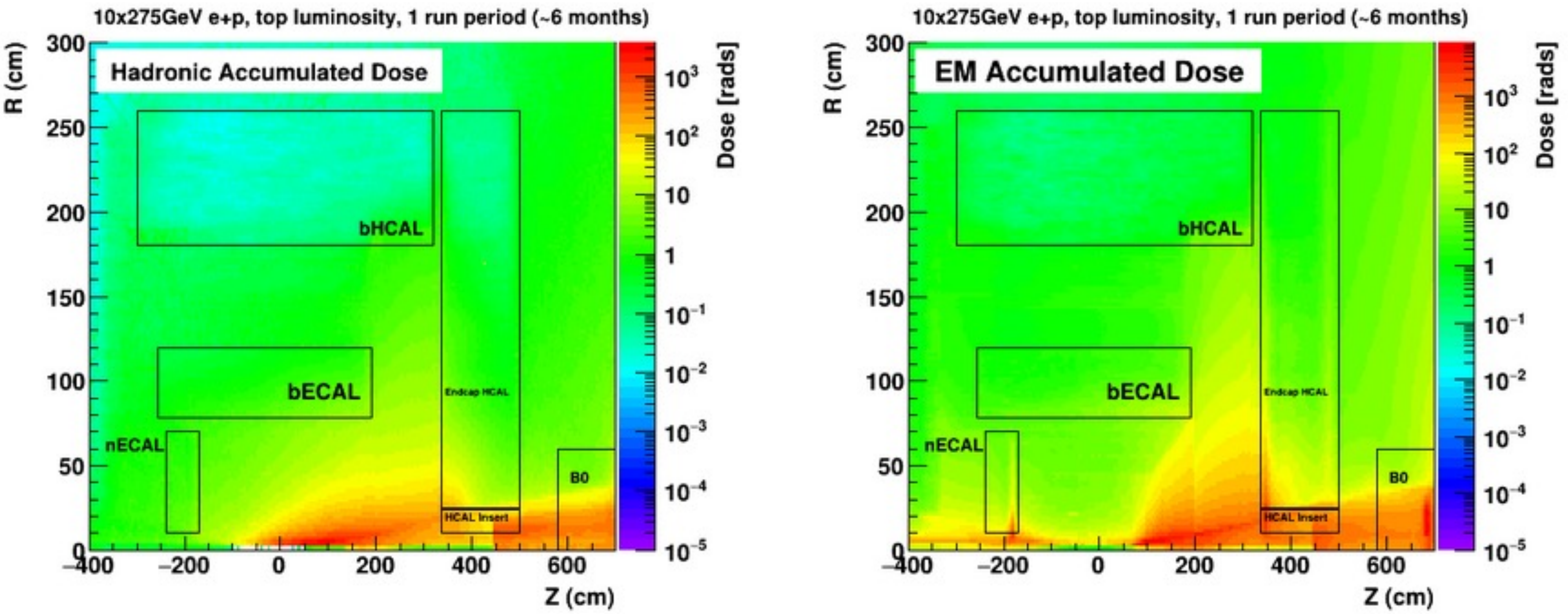
On average at most a few particles per unit of pseudorapidity per event, even at η ~ 4



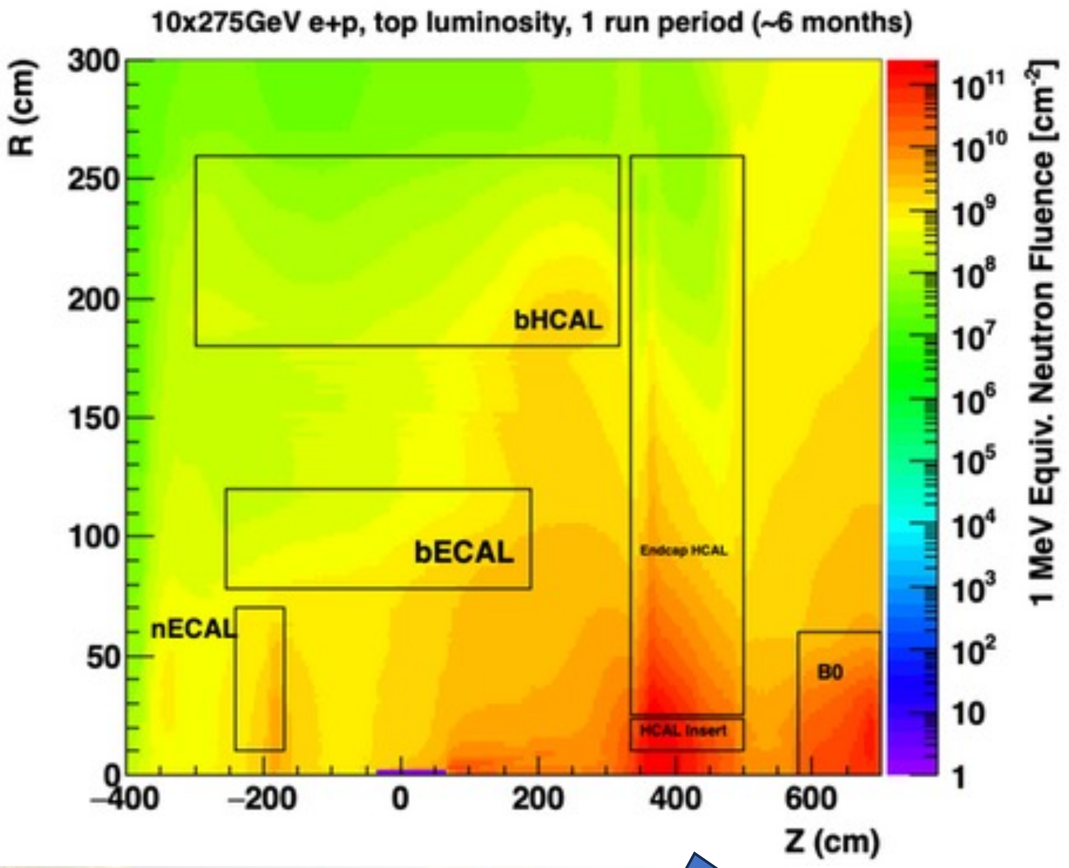


Accumulated dose

➢ Expected dose is very small



Neutron fluence



LFHCal $1.2 < \eta < 3.5$

- SiPMs not accessible after installation
- Operation of SiPMs w/o cooling
- $R > 1$ m: $< 5 \cdot 10^9$ neq/cm^2/year
  $\rightarrow$ No mitigation necessary
- $R < 1$ m: $10^9 - 10^{11}$ neq/cm^2/year
  $\rightarrow$ Moderate radiation damage expected, choose larger SiPMs & higher LY tiles to compensate

Insert $3.5 < \eta < 4.4$

- $\sim 10^{11}$ neq/cm^2/year
- Scintillator & SiPM assemblies accessible during end-of-year access
- SiPMs could be annealed or assemblies replaced if necessary

Requirements hierarchy

GENERAL REQUIREMENTS	
Name	Description
ward HCAL	
G-DET-HCAL-FWD.1	Forward HCal shall play a crucial role in jet energy and kinematics reconstruction in the hadron endcap, complementing tracking and e/m calorimetry in the particle flow algorithms, and be consistent with the ePIC detector solenoid design

FUNCTIONAL REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
F-DET-HCAL-FWD.1	Must provide hadron energy measurements up to the highest hadron energies in a 250(p) x 18(e) GeV beam configuration and pseudorapidity up to 3.5, with energy resolution defined by the community Yellow Report and subsequent ePIC simulation studies	**G-DET-HCAL-FWD.1**
F-DET-HCAL-FWD.2	The design must be coupled well with a compensated forward e/m calorimeter for high precision jet energy measurements.	**G-DET-HCAL-FWD.1**
F-DET-HCAL-FWD.3	The calorimeter structure must serve as part of the solenoid flux return	**G-DET-HCAL-FWD.1**

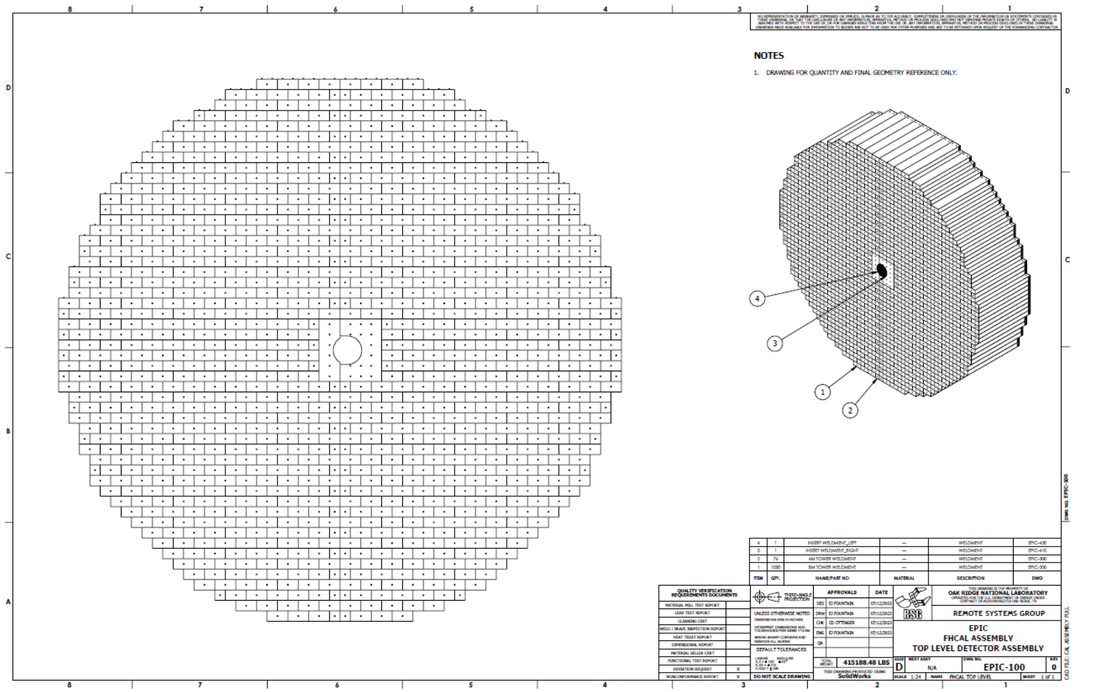
PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
P-DET-HCAL-FWD.1	Must cover pseudo rapidity range up to at least 3.5.	**F-DET-HCAL-FWD.1**
P-DET-HCAL-FWD.2	Shall have energy resolution s(E)/E ~ 50%/sqrt(E) + a 10 % constant term.	**F-DET-HCAL-FWD.1**
P-DET-HCAL-FWD.3	Granularity (transverse tower size) should be adequate to resolve deposits from different charged and neutral hadrons taking into account the local abundance, resulting in transverse tower sizes of at least ~5x5 cm^2 for \eta < 2.5 and 3x3 cm^2 for 2.5 < \eta < 4	**F-DET-HCAL-FWD.2**
P-DET-HCAL-FWD.4	Must have tower depth of 6-7 interaction lengths (together with the e/m section) in order to avoid longitudinal leakage for highest energy hadrons at the EIC.	**F-DET-HCAL-FWD.2**
P-DET-HCAL-FWD.5	Granularity (longitudinal tower size) should be adequate to allow for association of showers starting at different depth to the corresponding charged and neutral hadrons. At least 5 longitudinal segments should be read out to determine the shower maximum reliably. For higher rapidity the segmentation should be increased due to the higher particle density	**F-DET-HCAL-FWD.2**
P-DET-HCAL-FWD.6	Calorimeter absorber blocks in the volume allocated for the flux return must be partly built out of a magnetic steel with the permeability defined by the solenoid designers	**F-DET-HCAL-FWD.3**

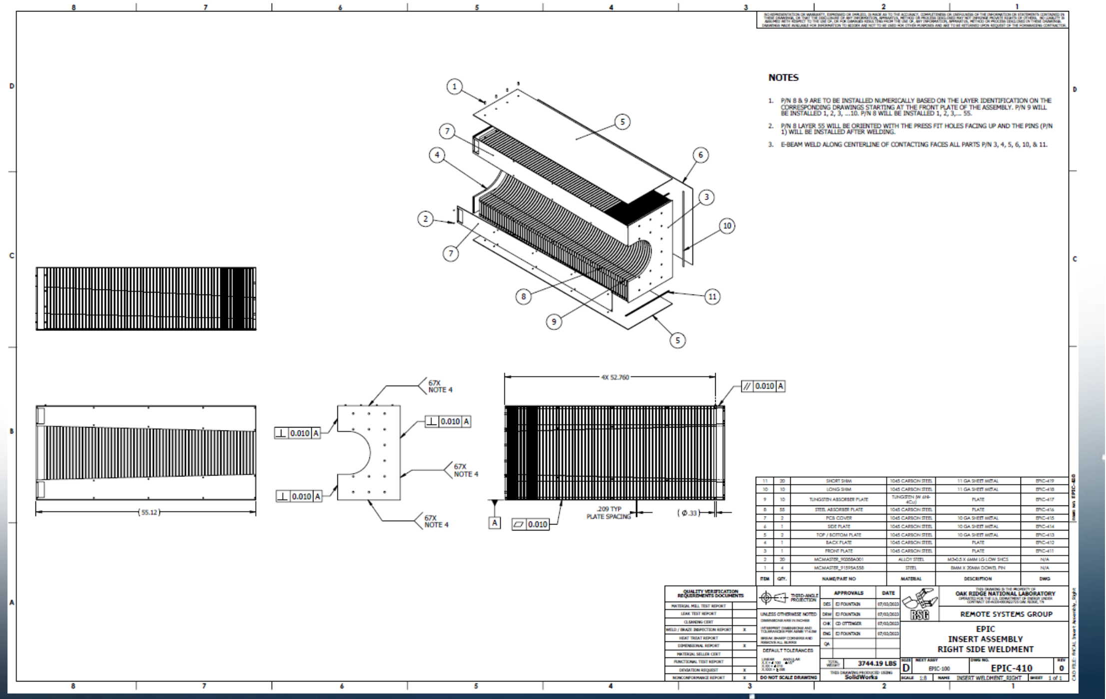
Design overview

- Inspired by CALICE AHCal
  - W/Fe-Sc calorimeter with SiPM-on-tile readout
- Two main parts: LFHCal & Insert

parameter	**LFHCal**	**insert**
inner x,y (R)	60 cm	$>$ 17 cm
outer R (x,y)	270 cm	60 cm
η acceptance	$1.2 < \eta < 3.5$	$3.5 < \eta < 4.4$
tower information		
x, y	5 cm	$\approx$ 3 cm
z (active depth)	130 cm	130 cm
z read-out	10 cm	2 cm
interaction lengths	$6.5\ \lambda/\lambda_0$	$7.5\ \lambda/\lambda_0$
# towers	8704	
# modules		2
8M	1050	
4M	76	
# read-out channels/tiles	7 x 8704 = 60,928	23400

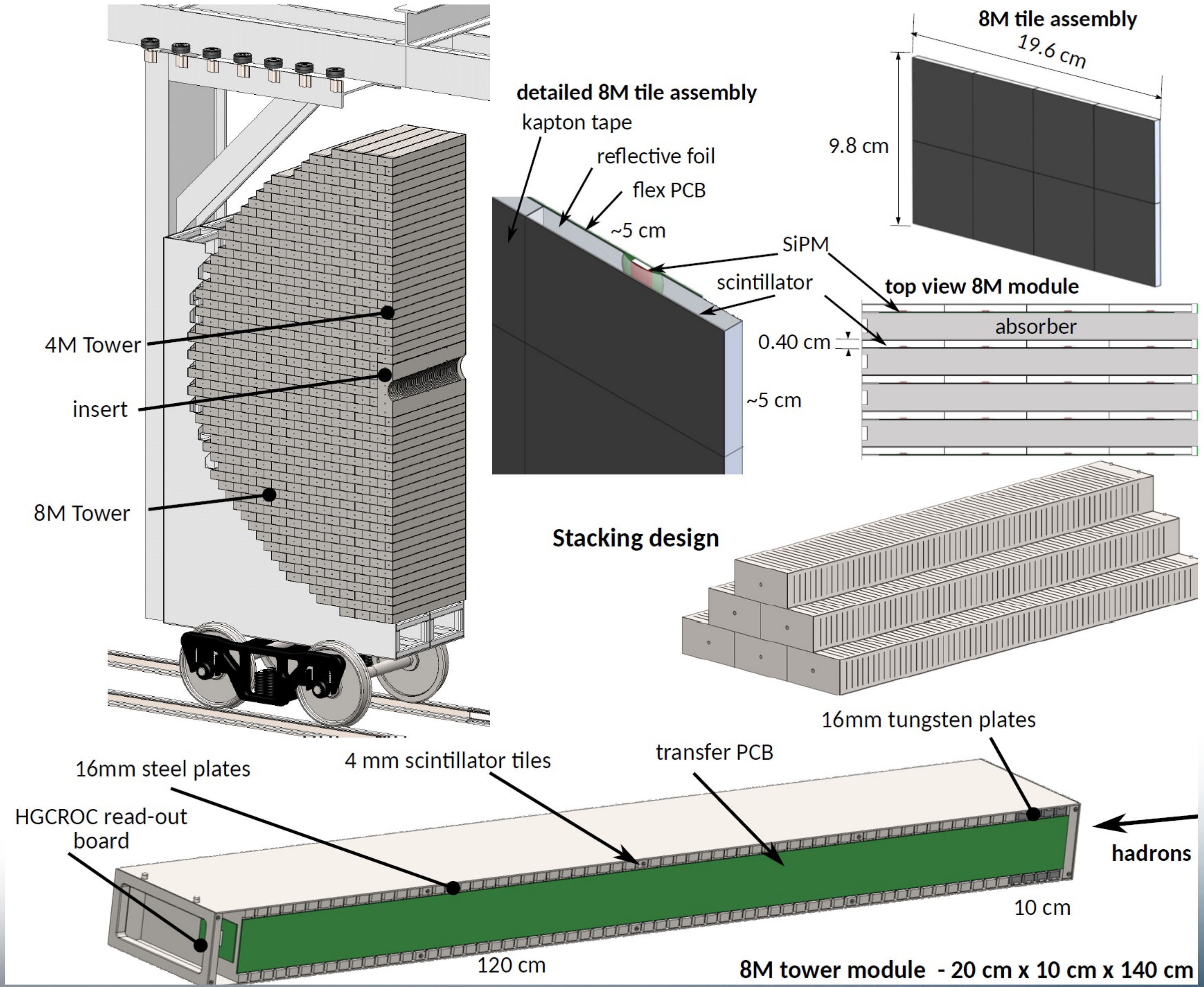
- PDR was completed in December 2022
- Full set of engineering drawings exists





Design Overview

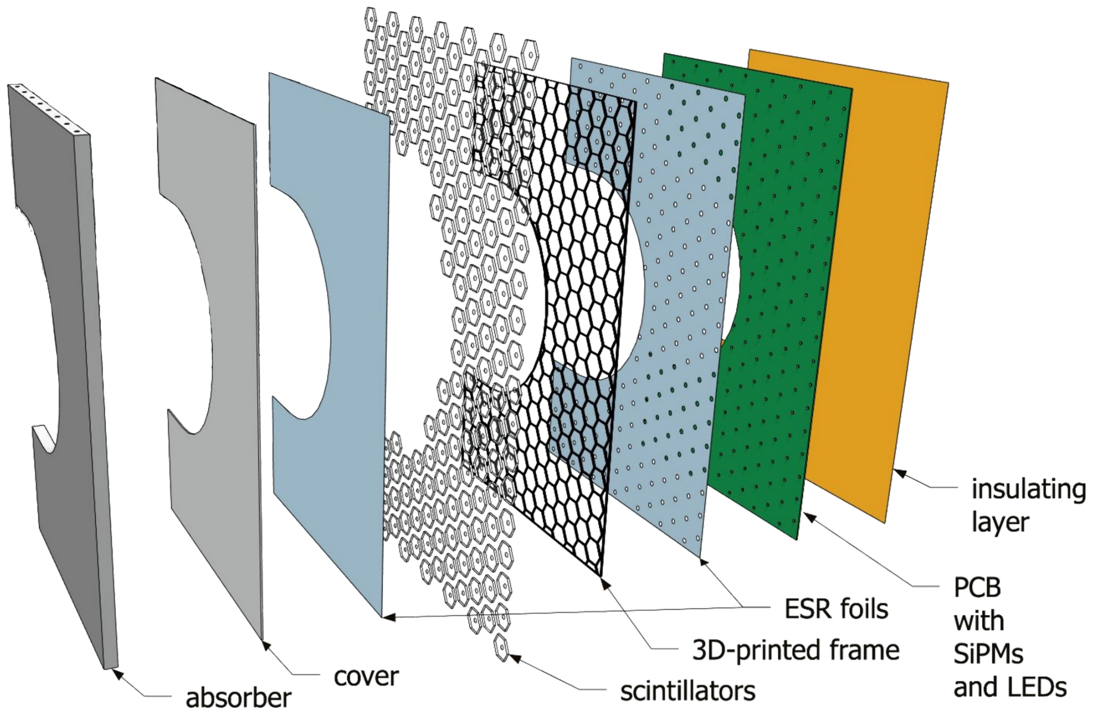
- **LFHCal**:
  - Mostly built out of 10 x 20 x140 cm^3 8M modules
  - 4 layers of tungsten + 61 layers of steel interleaved with scintillator material
  - Transverse tower size 5 x 5 cm^2
  - Multiple consecutive tiles analogously summed to 7 longitudinal segments per tower

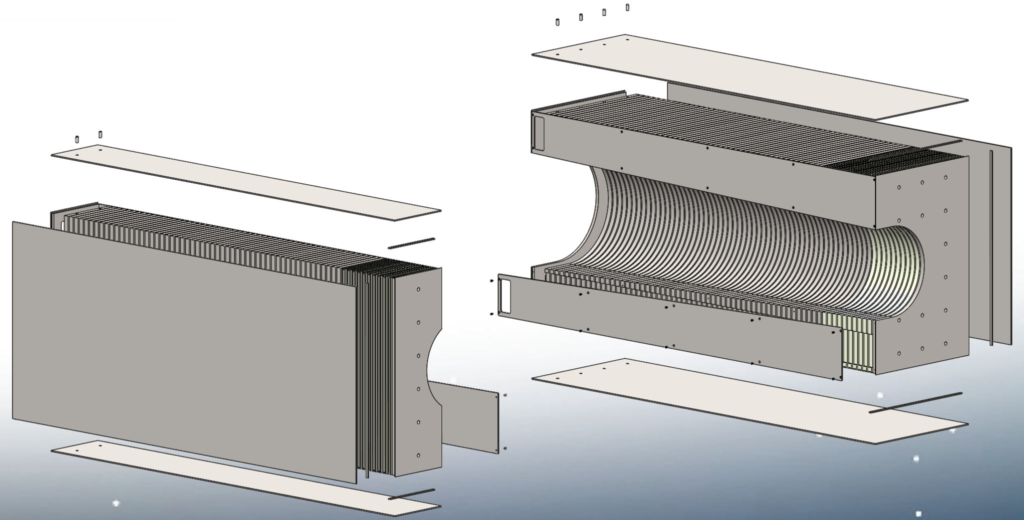


Design Overview

Forward rapidities: higher energy and higher particle density require increased granularity and depth

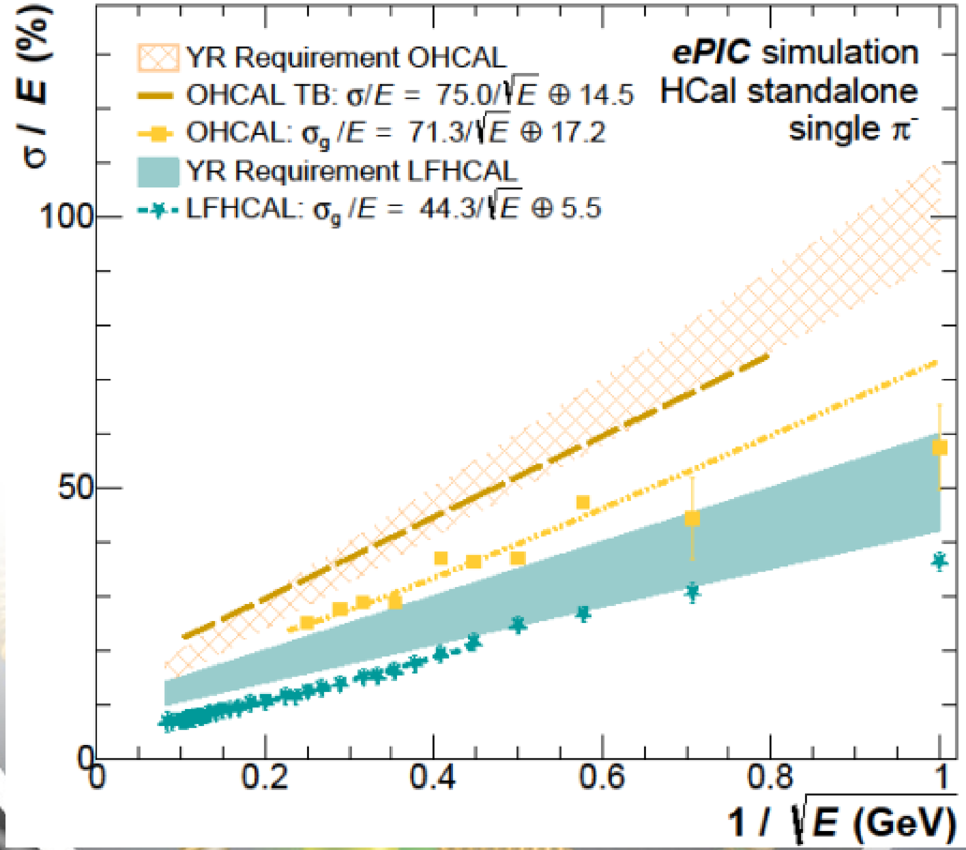
- **Insert at high η:**
  - 2 halves surrounding the beam pipe
  - 10 layers of tungsten + 54 layers of steel interleaved with scintillator
  - Hexagonal tiles of 8 cm^2 each read-out separately
  - Maximum η coverage with minimum dead area in combination with LFHCal



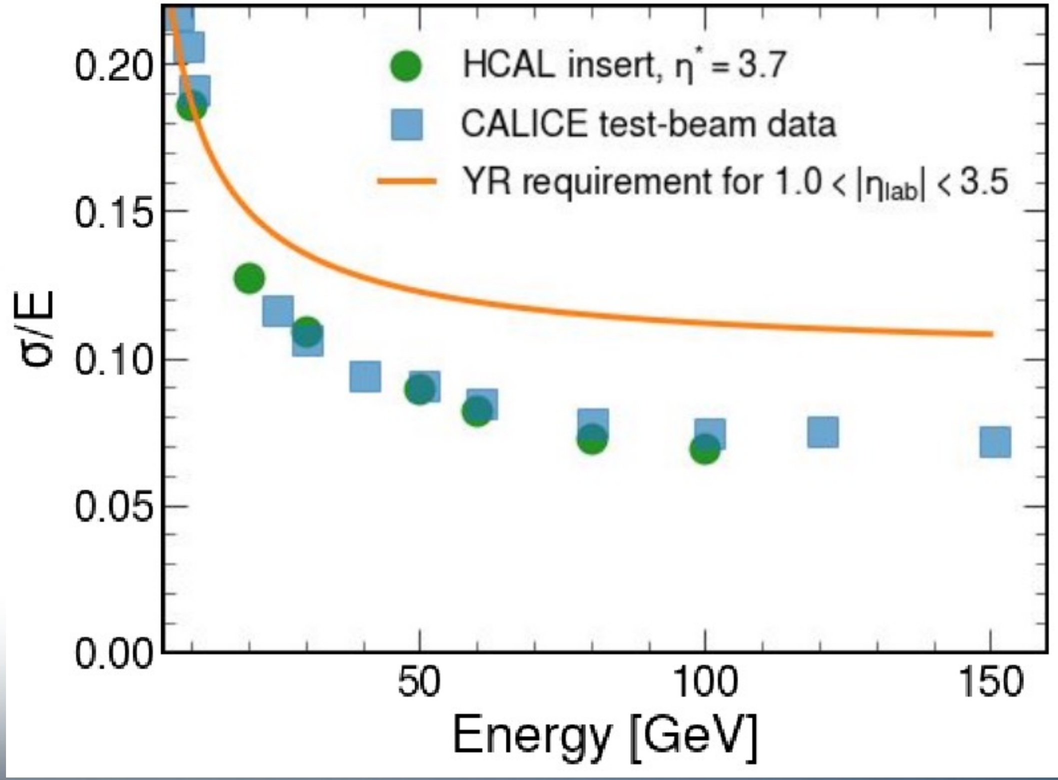


Energy resolution

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
P-DET-HCAL-FWD.2	Shall have energy resolution s(E)/E ~ 50%/sqrt(E) + a 10 % constant term.	**F-DET-HCAL-FWD.1**



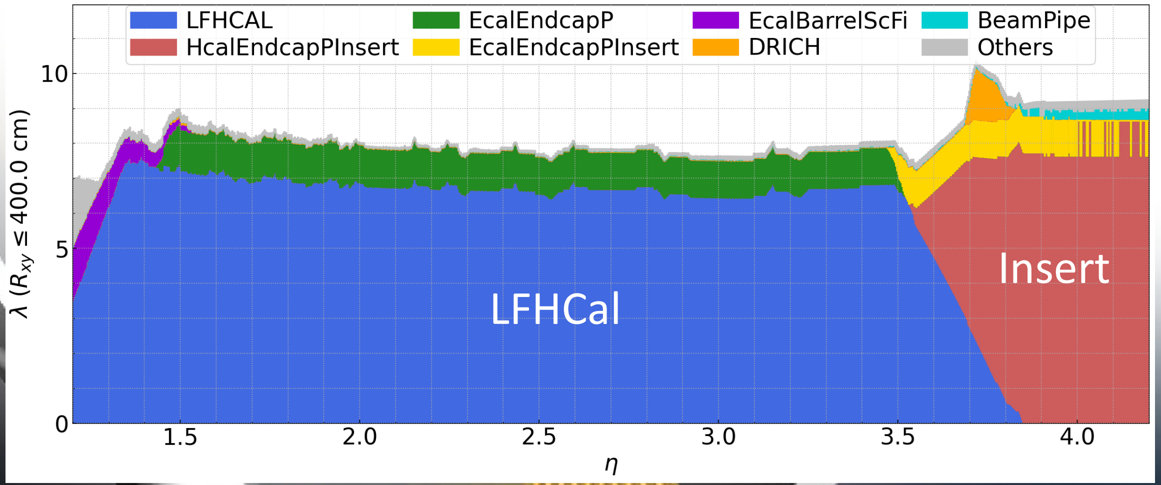
- Geometry fully implemented in ePIC software stack
- Standalone resolution for both LFHCal and insert surpasses Yellow Report requirement

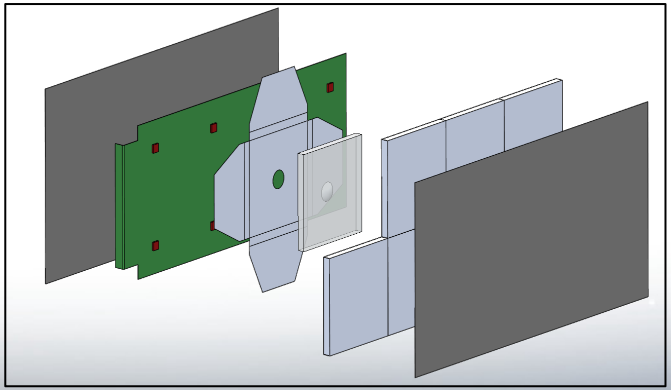


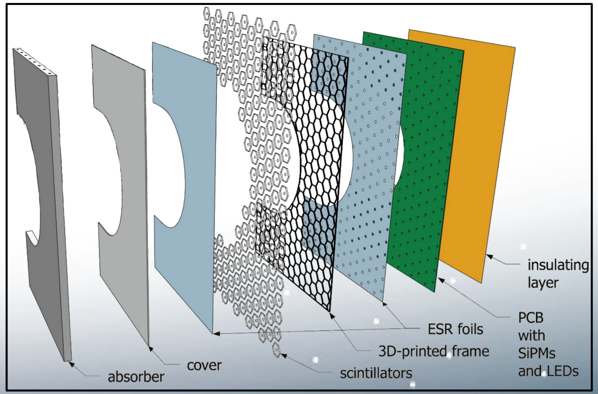
Granularity & nuclear interaction length

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
P-DET-HCAL-FWD.3	Granularity (transverse tower size) should be adequate to resolve deposits from different charged and neutral hadrons taking into account the local abundance, resulting in transverse tower sizes of at least ~5x5 cm^2 for \eta < 2.5 and 3x3 cm^2 for 2.5 < \eta < 4	F-DET-HCAL-FWD.2
P-DET-HCAL-FWD.4	Must have tower depth of 6-7 interaction lengths (together with the e/m section) in order to avoid longitudinal leakage for highest energy hadrons at the EIC.	F-DET-HCAL-FWD.2
P-DET-HCAL-FWD.5	Granularity (longitudinal tower size) should be adequate to allow for association of showers starting at different depth to the corresponding charged and neutral hadrons. At least 5 longitudinal segments should be read out to determine the shower maximum reliably. For higher rapidity the segmentation should be increased due to the higher particle density	F-DET-HCAL-FWD.2

- Depth: LFHCal ~6.5 λ/λ_0 & insert ~7.5 λ/λ_0
- Transverse tower size: square tiles 5x5 cm^2 for LFHCal & hexagonal tiles of 8cm^2 for insert
- Longitudinal segmentation: 7 segments for LFHCal & 65 layers for insert





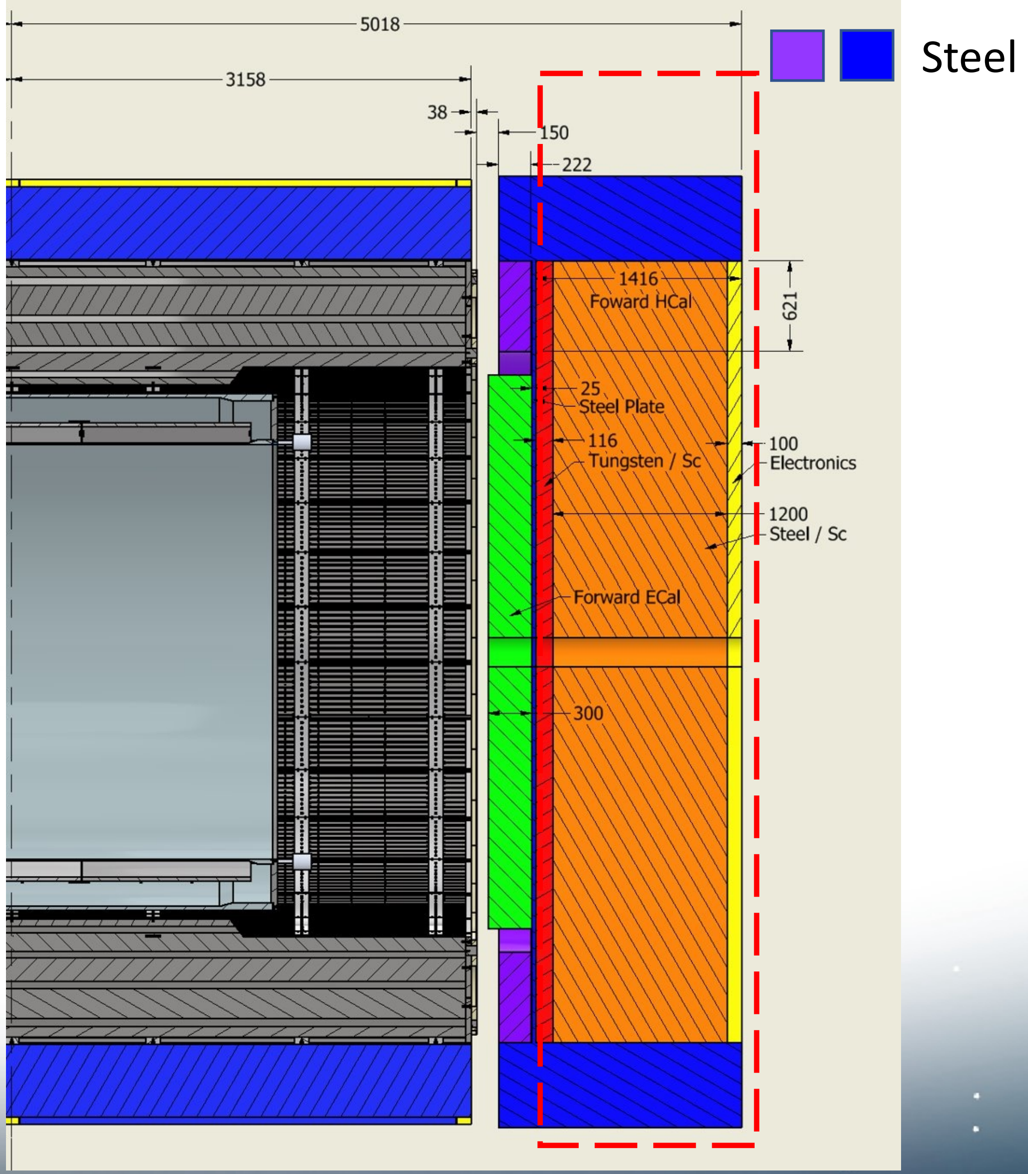


Flux return requirement

PERFORMANCE REQUIREMENTS		
Name	Description	Parent
Forward HCAL		
P-DET-HCAL-FWD.6	Calorimeter absorber blocks in the volume allocated for the flux return must be partly built out of a magnetic steel with the permeability defined by the solenoid designers	F-DET-HCAL-FWD.3

- Absorber structure consisting of:
  - LFHCal: 4 cm steel + 4 layers of 1.52 cm tungsten + 60 layers of 1.52 cm steel
  - Insert: 4 cm steel + 10 layers of 1.52 cm tungsten + 55 layers of 1.52 cm steel
- 1045 Carbon steel used as main flux return

These are all Long Lead Procurement items, as well as the SiPMs



Integration

December 2022 review recommendations

Forward HCal

- **Findings**
  For ePIC the LFHCAL design was adopted following the concept of Projctile Spectator Detectors of other heavy ion experiments like CBM. The detector towers consist of steel and W tiles as absorbers sampled by scintillator tiles and WLS fibers read out by SiPMs. The dynamic range from 3MeV to 30GeV is quite large with a factor of 10,000. The readout is segmented in longitudinal direction to obtain shower profile information.

  No beam tests have been done yet. The Monte Carlo response was tuned with CALICE Data. The effective segmentation (fiber ganging) and dynamic range of front-end electronics are not yet optimized.

- **Comments/Concerns**
  Seeing the interplay between EMCal and LFHCAL we observe a shift of the LFHCAL towers to mount the EMCal. One should verify the EMCal integration if this is really the optimal solution.

December 2022 review recommendations

Regarding the manufacturing of the scintillator tiles, laser etching is labor intense, the presented alternative with molds is promising and a proven technique employed elsewhere. There are concerns that super-tiles break at groves if they are too deep. One should consider smaller super-tiles or single tiles with sliding guides to form larger assemblies.

Carefully plan fiber bending to avoid breakage, as they run in one plane through the tile and then in an orthogonal plane towards the readout. It should be considered to mount

SiPMs directly on the tiles, connecting electronics with Kapton strips, possibly electrically ganged, which could be a robust alternative.

One should check crosstalk between tiles to see if cladding with Ti color or Tyvek are effective, and the grooves are sufficiently deep.

As an additional idea one could consider simulations/tests with W section in front instead of the steel sections and compare elm. response with and without W/SciFi calorimeter in front.

- **Recommendations**
  R12. Perform full simulations to optimize electronic segmentation and dynamic range to assess the benefit of measuring longitudinal shower profiles.

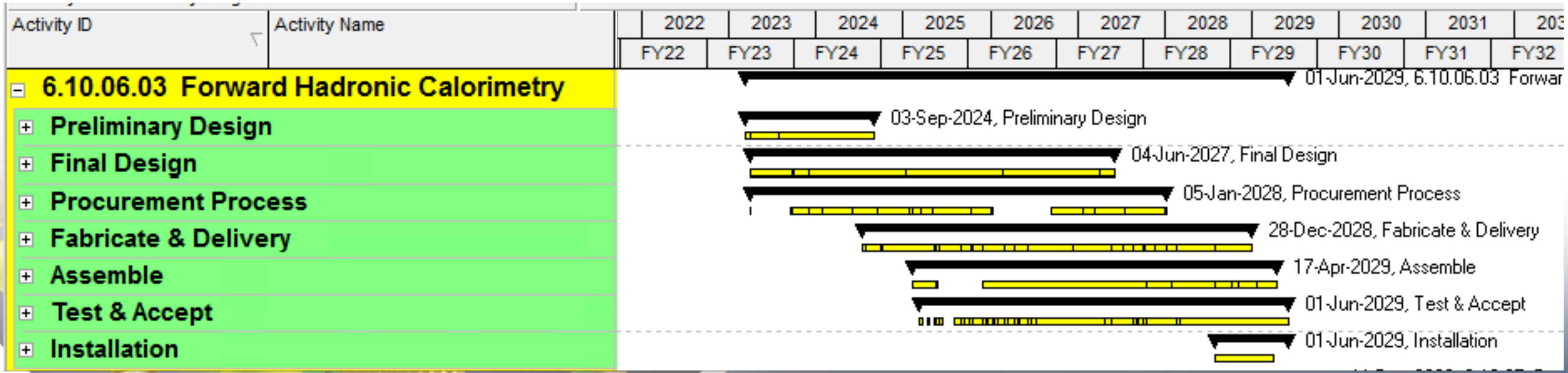
Long Lead Procurement items

- Forward hadronic calorimeter must be available for the solenoid magnet acceptance test in Fall 2029

LLP Category	LLP Item	EXPECTED AWARD DATE	CAM / ESTIMATOR	LAB	PMC REP	DIRECT MATERIAL COST	Total Cost (Burd&Esc)
HCal SiPMs	Forward HCal SiPMs	7/12/2024	A. Kiselev	BNL	T. Lewis	2,218,970	2,302,584
Forward HCal Steel and Tungsten	Forward HCal Absorber Plates Steel	8/9/2024	A. Kiselev	BNL	T. Lewis	1,075,750	1,116,813
	Forward HCal Module Casing Steel	7/26/2024	A. Kiselev	BNL	T. Lewis	271,483	282,166
	Forward HCal Absorber Plates Tungsten	7/26/2024	A. Kiselev	BNL	T. Lewis	1,690,000	1,752,997
						5,256,203	**5,454,560**

Basis of Estimates:

- Steel & tungsten absorber and casing steel:
  - June 2023 quote, production time less than two years
- SiPMs:
  - June 2023 quote from Hamamatsu
    - ~340k pieces @ a production rate ~30k/month



ES&H and QA considerations

- Permanent test setup of 8× 8M-modules included in purchase order, allows for
  - test beam measurements of final modules during construction and operation phases
  - final qualification of performance without significant shower leakage
  - reproduction of possible problems in the lab
- Procurement of SiPMs includes 1% margin for possible production losses
- Foreseen SiPM testing process:
  - Vendor testing and qualification for V_{op} within 0.1V/ delivery unit
  - Testing at PCB vendor after flex-PCB assembly (connectivity)
  - Tile assembly testing connectivity after assembly
  - Cosmics tile assembly testing & classification (5-10%)
  - Cosmics testing of modules prior to installation (10%)
  - Cosmics data taking after installation

Summary

- Technical performance parameters are taken from the EIC community Yellow Report, adjusted via subsequent studies by the proto-collaborations
- Technological challenges for this ePIC subsystem are solved
- Proposed LFHCal + Insert solution meets the known requirements
- Fabrication and assembly plans are consistent with the overall project schedule
- Integration plans and procedures are being defined
- Design is mature enough to meet the 90% readiness requirement at CD-3 and to initiate the procurement of LLP items

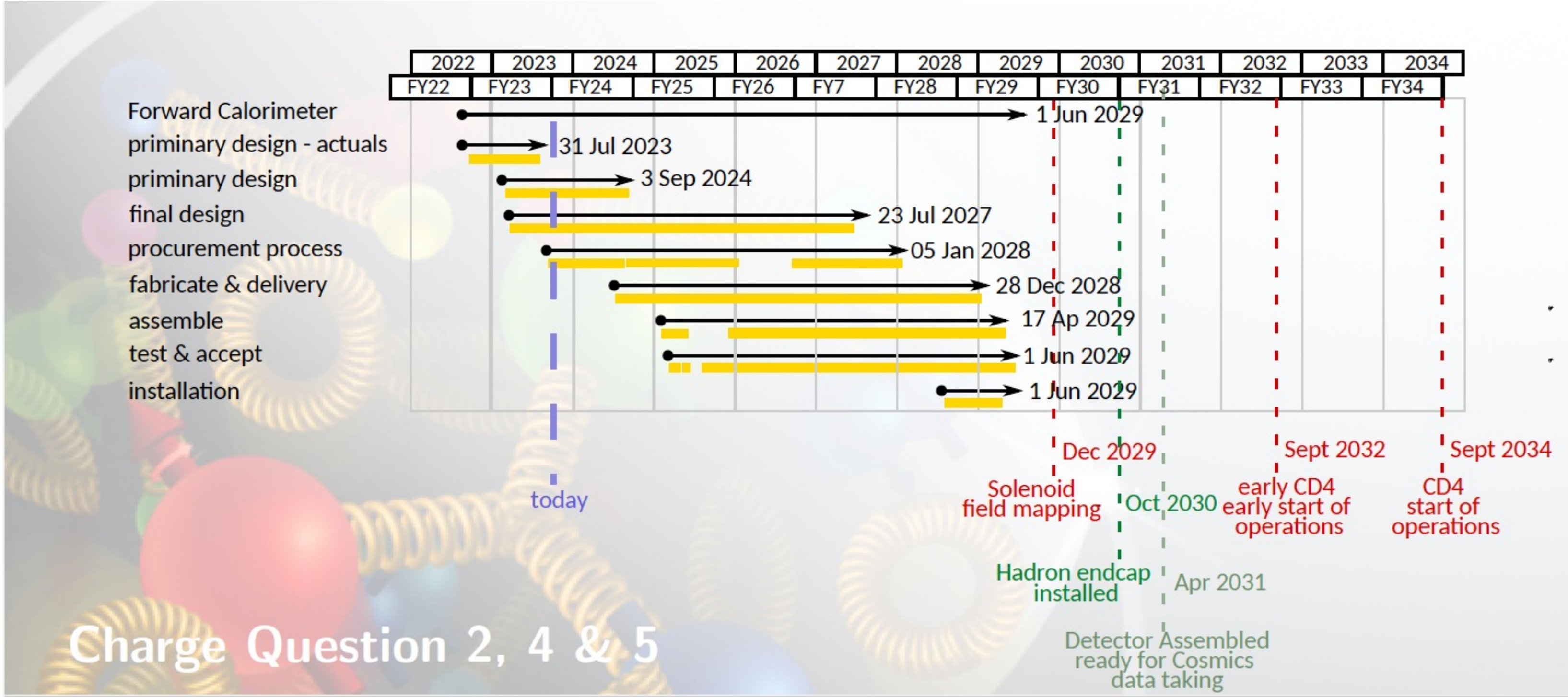
More details in the follow up talks

Backup

Schedule

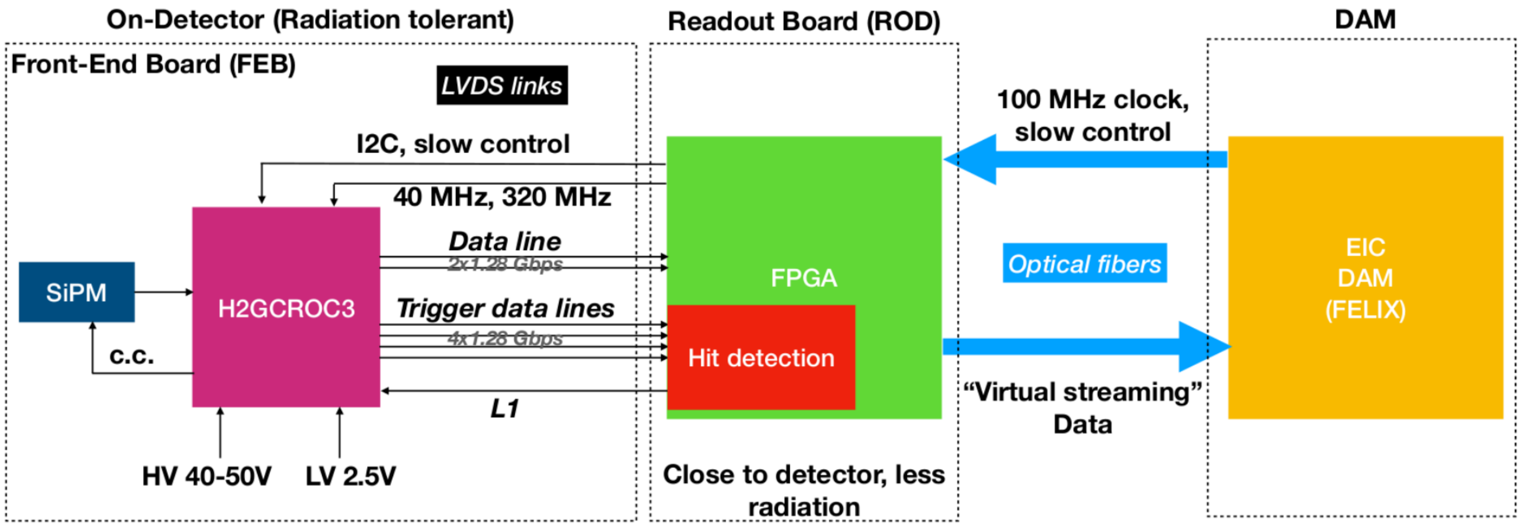
CD3A Baseline - Updated cartoon schedule – FHCal steel / tungsten

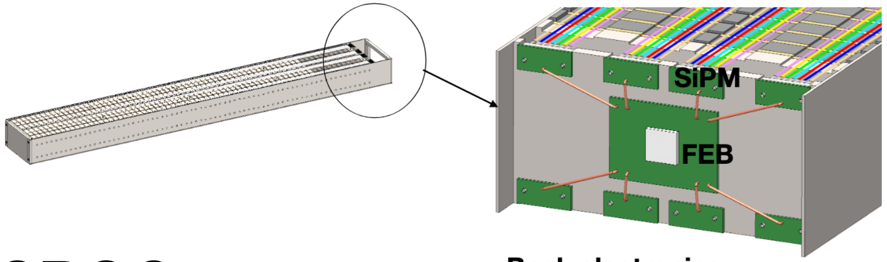
Template



2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034
FY22 FY23 FY24 FY25 FY26 FY7 FY28 FY29 FY30 FY31 FY32 FY33 FY34
Forward Calorimeter
priminary design - actuals
priminary design
final design
procurement process
fabricate & delivery
assemble
test & accept
installation
1 Jun 2029
31 Jul 2023
3 Sep 2024
23 Jul 2027
05 Jan 2028
28 Dec 2028
17 Ap 2029
1 Jun 2029
1 Jun 2029
today
Dec 2029
Solenoid field mapping
Oct 2030
Hadron endcap installed
Apr 2031
Detector Assembled ready for Cosmics data taking
Sept 2032
early CD4 early start of operations
Sept 2034
CD4 start of operations
Charge Question 2, 4 & 5

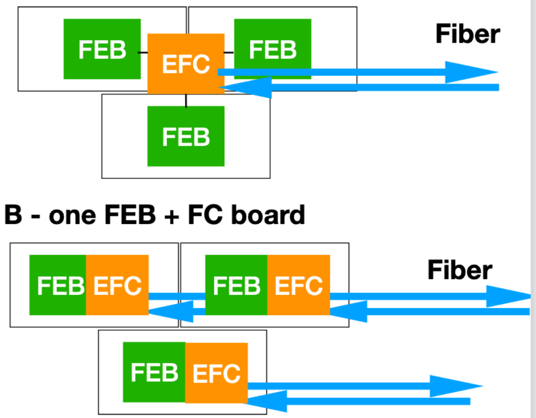
Electronics





Back electronics

Option A - multiple FEB served with FC



Option B - one FEB + FC board

- An adaptation of CMS H2GCROC
  - Will be used for all three ePIC HCal subsystems