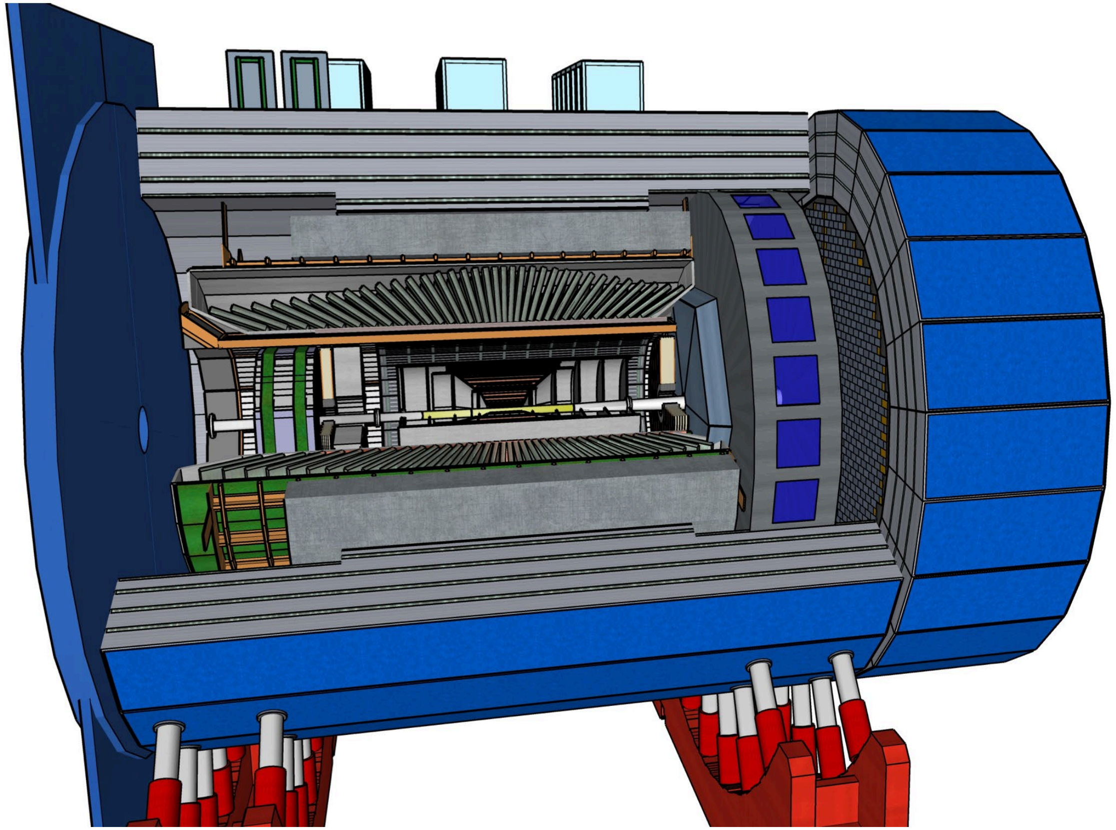
ECCE Design Overview



Or Hen, Tanja Horn, John Lajoie

EIC Detector-1 Global Detector Integration Group Meeting

16 May 2022

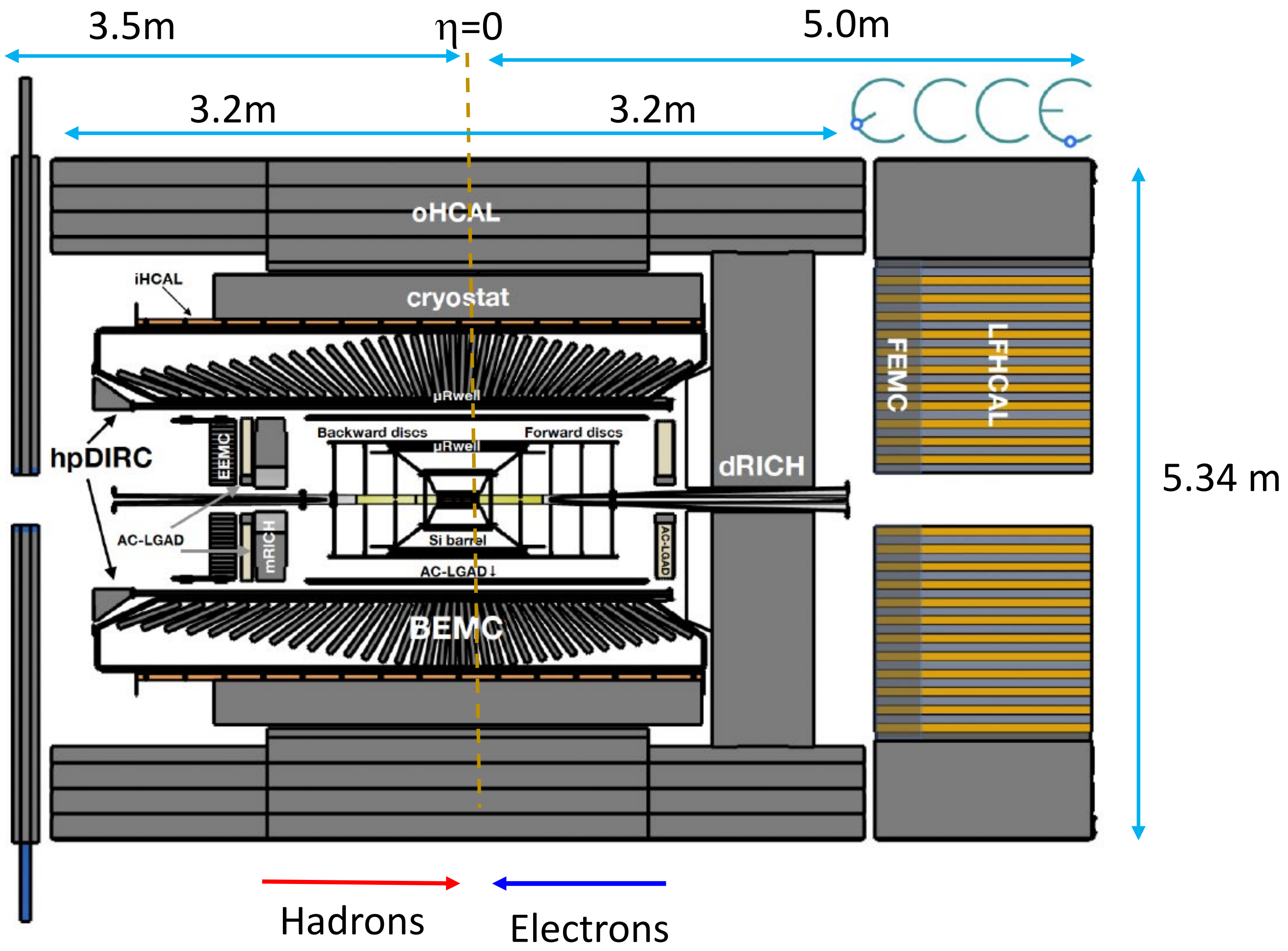
ECCE Design Introduction Overview

- The ECCE detector is a physics-driven balance of
  - the reuse of equipment
  - the use of mature detector technologies where possible, and
  - the use of detector technologies that are at the near-end of an extensive R&D effort and were judged absolutely essential for the EIC science.
- The ECCE detector is highly integrated with the interaction region
  - This led to several detector technologies with multi-purpose use, and use of AI to optimize detector choices, locations, and materials.
  - The vision to use streaming readout with multiple detector technologies and to be compatible with AI/ML led to integration of detector with electronics and computing.

The ECCE Reference Detector

The ECCE detector size is determined by the reuse of the BaBar magnet and sPHENIX HCAL, and further EIC detector needs:

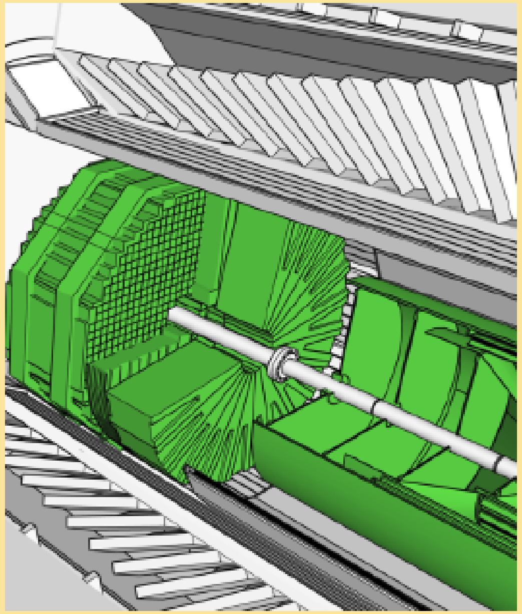
- Needs +5 m on proton/ion side.
- Needs less space (-3.5 m) on electron side.
- The detector radius is 2.7 meter, with the RCS beam at 3.35 meter.



- ❑ -4.5 /+5.0 m machine-element-free region available for central EIC detector
- ❑ 25 mrad crossing angle (IP6 design)
- ❑ Detector rotated by 8 mrad in horizontal plane to account for e-beam angle

The ECCE Reference Technologies

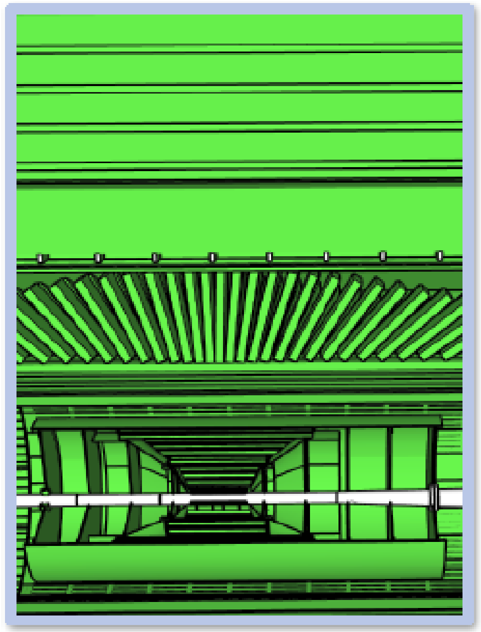
For additional technical details if desired please see the ECCE technical notes: https://www.ecce-eic.org/ecce-internal-notes (PW: ECCEprop)



Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)



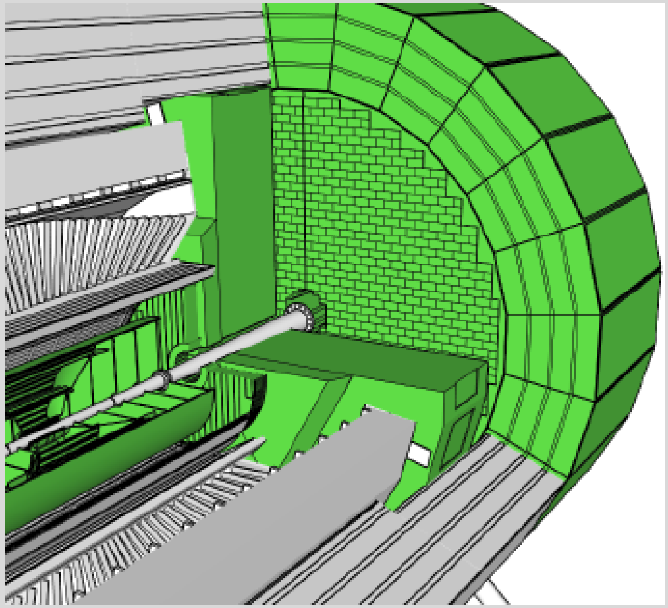
Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)



Forward Endcap

Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

PID:
- dRICH
- AC-LGAD TOF

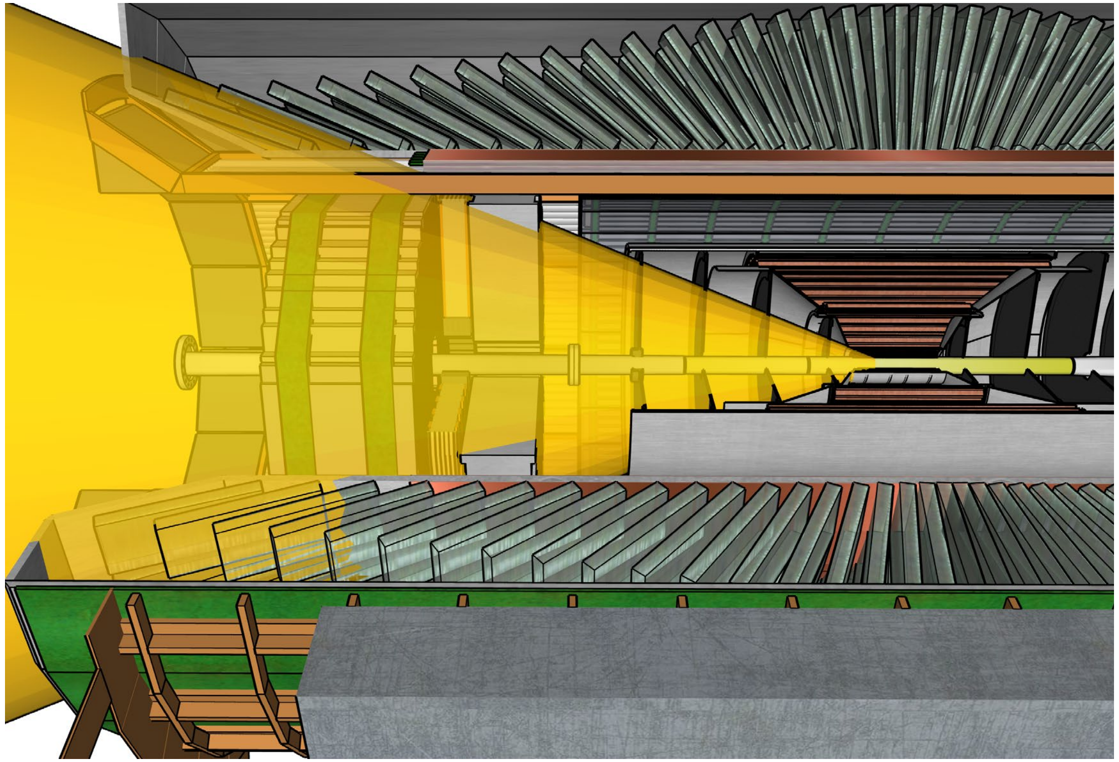
Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCAL)

Key Requirements Central Detector Overview

Topic	Challenge	ECCE solution	Comment
Hermetic e^- coverage	Leave no gaps in e^- EMcal coverage while also folding in PID/hpDIRC readout needs	hpDIRC readout in backward region; Moved EEMC inward as much as possible; Extend BEMC longitudinally	Good coverage for negative rapidity; performance verified with full simulations
Momentum resolution in forward/backward regions at high η	Achieve YR requirements with a realistic tracker including support materials in the BaBar solenoid	Five ITS3 Si disks forward and four disks backward; Additional AC-LGAD tracking before (after) dRICH (mRICH)	Used AI optimization. Upgrade option: AC-LGAD ring in forward region behind dRICH for $\eta = 3$–3.5
Backward Particle Identification	Constrained space to maximize EMCal coverage	AC-LGAD TOF for low-momentum; mRICH for hadron PID	mRICH is a space-efficient solution
Backward e^- PID, π^- suppression up to 10^{-4}	Highest precision EM calorimetry	Use all $PbWO_4$	Can separate out EMCal to reach beyond $\eta = -3.4$
Barrel PID – e/π separation up to 10^{-2}–10^{-4}, down to 0.2 GeV/c	Need good EMcal resolution; need additional e/π below 2 GeV/c	55 cm long SciGlass towers for high precision EMcal; hpDIRC for π veto down to $p = 0.3$ GeV/c; AC-LGAD TOF for $p \leq 0.4$ GeV.	Leave 4 cm for μRWELL between hpDIRC and EMCal to seed PID performance of hpDIRC and improve tacking resolution
Barrel PID – $\pi/K/p$ separation down to 0.2 GeV/c	hpDIRC only covers down to 0.6 GeV/c	AC-LGAD TOF for 0.2 $<$p $<$0.6 GeV/c	μRWELL directly after hpDIRC to increase performance.
Barrel Tracking resolution	Achieve YR requirements with a realistic tracker including support materials in the BaBar solenoid	Three ITS3 Si vertex and two Si sagitta layers followed by two μRWELL, AC-LGAD, and far outer μRWELL layer;	Used AI optimization of tracker and support system layout
Forward Hadronic calorimetry	Jet energy resolution $<50\%/\sqrt{E}$	Longitudinally separated calorimeter to meet needs in high-η region.	Upgrade Option: Dual Calorimeter (or only central in region of highest need)
Forward Particle Identification	Constrained space in forward region	AC-LGAD TOF for low- momentum; dRICH for high-momentum (C_4F_{10} based)	Seed dRICH ring finder with AC-LGAD before dRICH; Employ recirculation and gas recovery systems for environmentally unfriendly gas use.

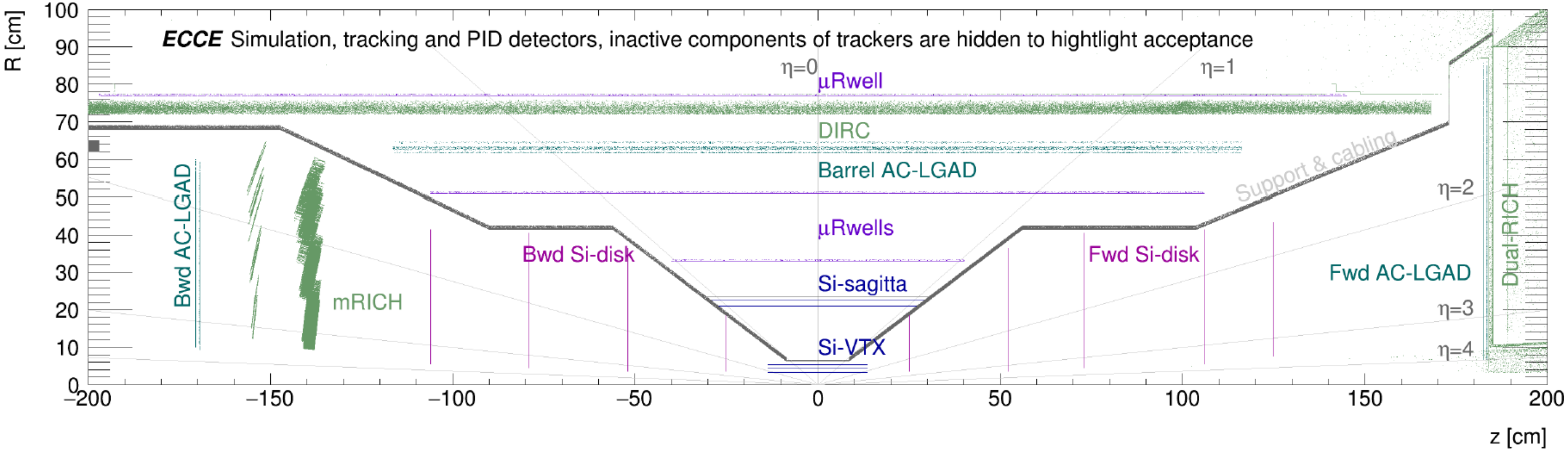
Hermetic electron coverage

- ❑ DIRC readout on electron side to avoid interference with PID and forward detectors
- ❑ Move eEMCAL inside the DIRC to optimize for continuous calorimeter coverage electron ID



- ❑ **After moving the eEMCAl inside the DIRC there is still a gap in sensitive area of the EMCals (barrel and endcap) – this gap needs to be reduced**
  - ❑ Extend barrel EMCAL backward
  - ❑ Reduce the cooling/support for the backward EMCal → save a few cm
  - ❑ Absorb a thin MPGD (for DIRC PID) into the DIRC frame → saves a few cm
  - ❑ Further reduce the gap by reducing the backward tracking by ~15cm to shift detector in along z towards the IP – no negative impact on tracking as checked in simulation

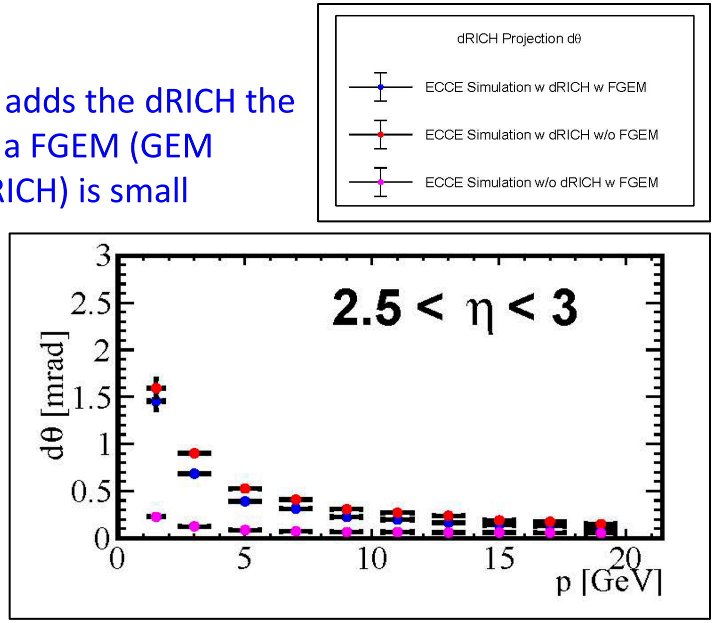
ECCE Tracking System



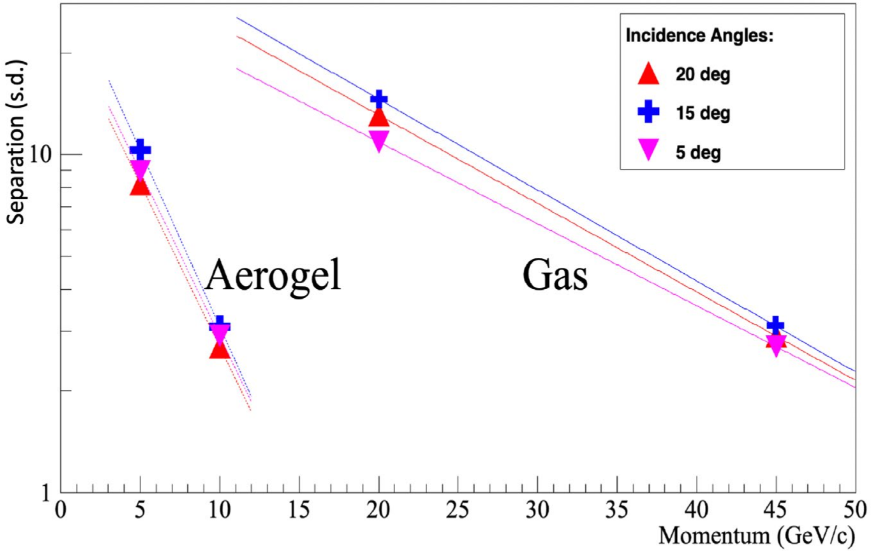
- ❑ Hybrid tracking detector design: Monolithic Active Pixel Sensor (**MAPS**) based silicon vertex/tracking subsystem, the **muRWELL** tracking subsystem and the **AC-LGAD** outer tracker, which also serves as the ToF detector. Ordering and resolution optimization were driven by AI.
  - ❑ MAPS 3-layer silicon vertex, 2-layer silicon sagitta layers, five disks in the hadron endcap, four disks in the electron endcap for primary and secondary vertex reconstruction
  - ❑ muRWell 2 layers in the barrel following silicon and cylindrical muRWell gas trackers at large radii providing a tracking layer after the DIRC – integrated with PID/DIRC performance
  - ❑ AC-LGAD ToF layer provides precision space-time measurement on each track – integrated with PID

Motivations behind the choices

Once one adds the dRICH the impact of a FGEM (GEM behind dRICH) is small



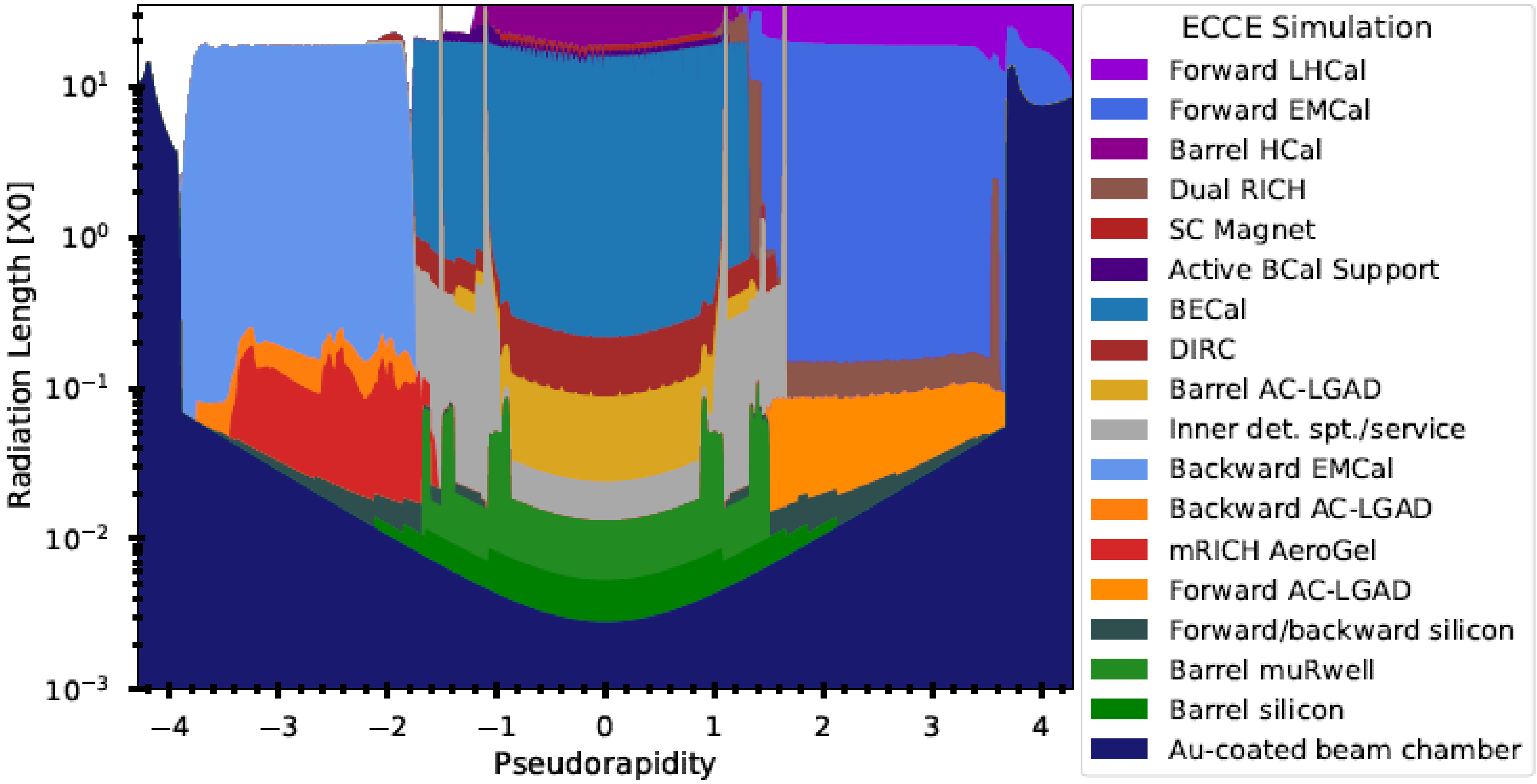
- ❑ Information provided by experts (EICSC, eRDxxx, E&D, ….)
    - ○ ITS3 for sagitta layer
    - ○ CAD model with estimates for services
- ❑ Several iterations of optimization of the design layout performed with AI-assistance
    - ○ Suggests MPGD behind PID in forward direction does not improve tracking performance (and not absolutely needed for PID)
    - ○ Material for readout and services has a large impact on tracking performance – investigated projective design
- ❑ All tracking elements were implemented in the mechanical model - barrel MPGD layer added last with limited time to check details on cm scale



Expected dRICH performance from ECCE Geant4 simulation. Desired 3 s.d. already reached without FGEM (GEM behind dRICH)

ECCE Material Budget

- Low material budget
  - Minimize bremsstrahlung and conversions for primary particles
  - Improve tracking performance at large |η| by minimizing multiple Coulomb scattering
  - Minimize the dead material in front of the high-resolution EM calorimeters

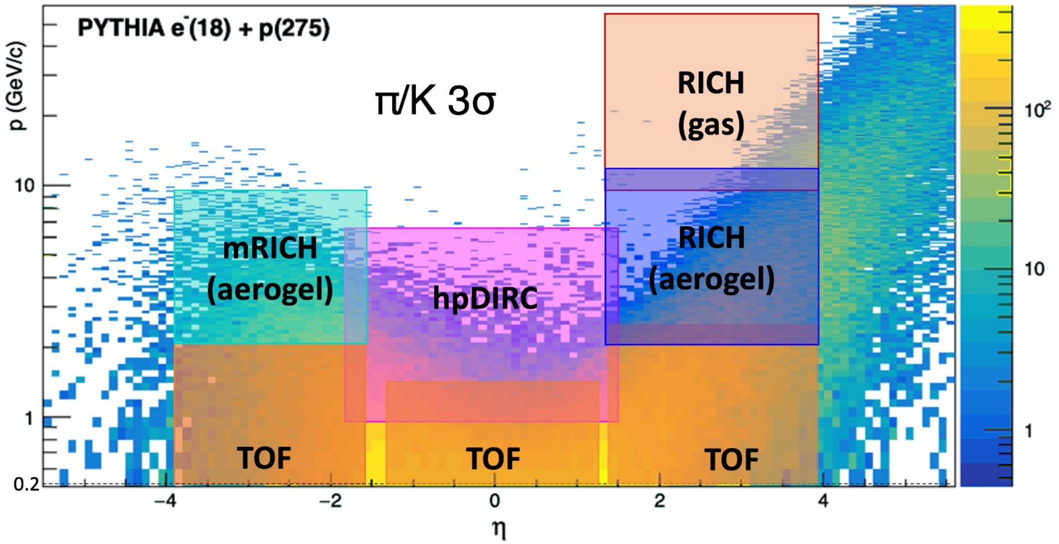


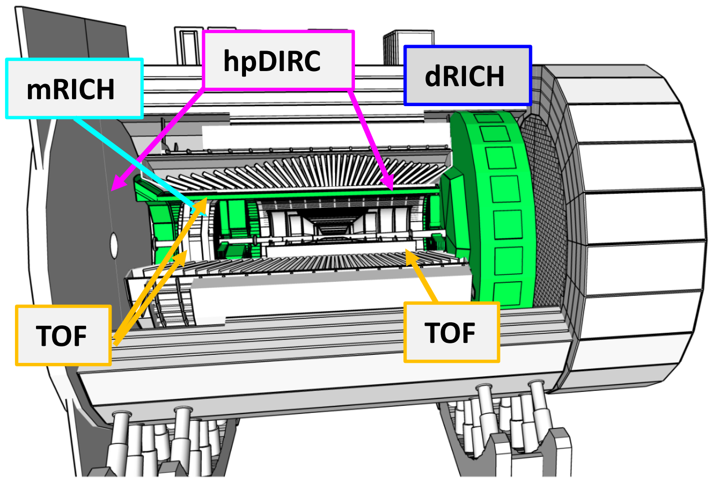
Charged Particle Identification

- **ECCE PID technologies are based on** the outcome of the **EIC generic R&D** (eRD14) and **in line with the reference EIC detector concept in the Yellow Report.**
  - Backward: Short, modular RICH **(mRICH)**
  - Barrel: Radially compact with flexible design high-performance DIRC **(hpDIRC)**
  - Forward: Double-radiator RICH **(dRICH)**
  - AC-LGAD based time-of-flight (TOF) system for hadronic PID in momentum range below the thresholds of the Cherenkov detectors

- **Geometries were optimized to fit the ECCE baseline design while maintaining the required performance** to assure wide momentum coverage across the full phase space.

Cherenkov detectors, complemented by other technologies at lower momenta





EIC hpDIRC

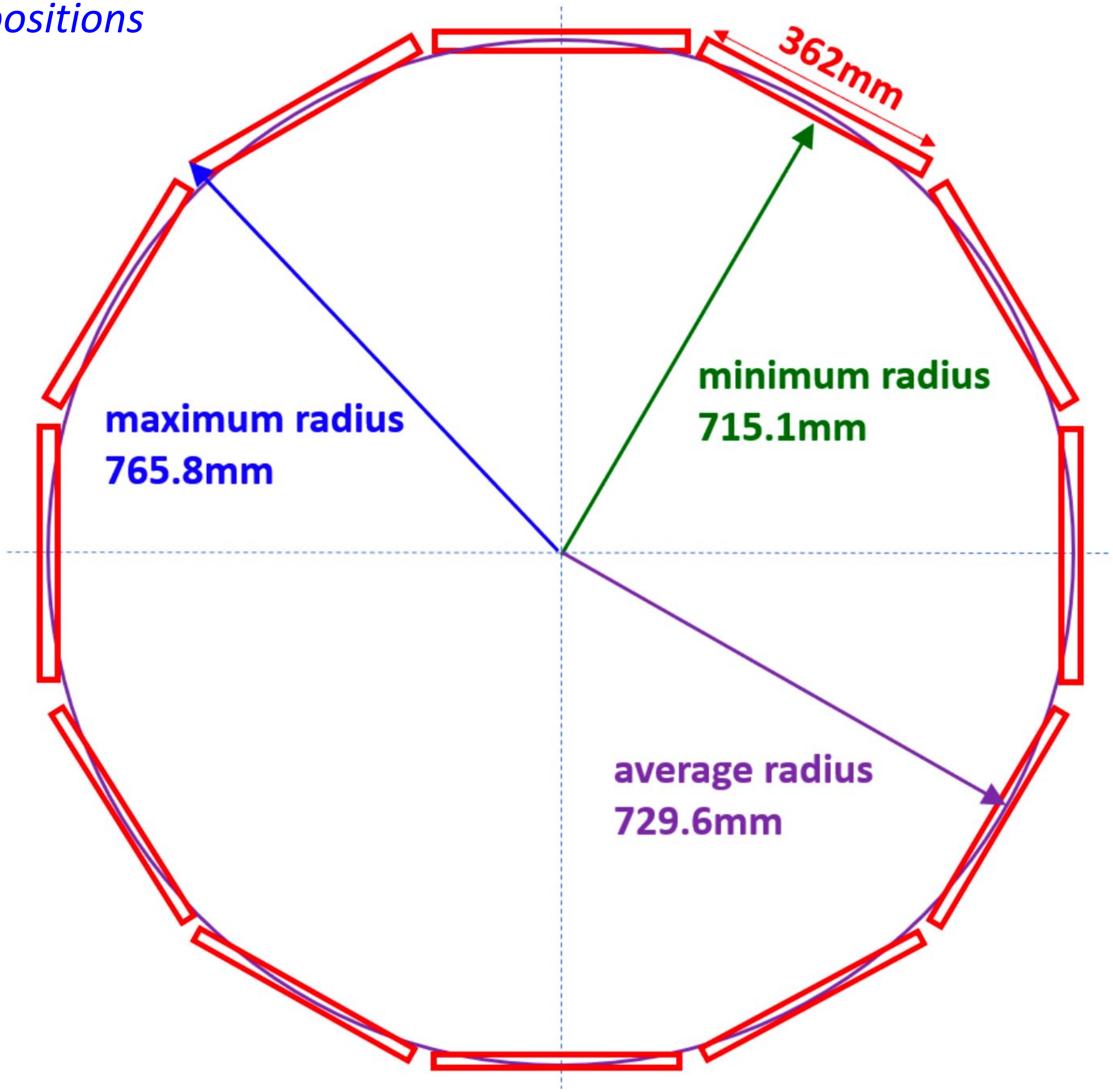
Numbers may further change with Order(cm) to resolve mismatch in global geometry database of frame position and detector positions

- **Barrel hpDIRC with 72cm radius**
- **Radiator bars:**
  - **420cm bar length** (works with both reused BaBar DIRC bars or new bars)
  - **12 bar boxes**, 10 long bars side-by-side in a bar box, 3 BaBar DIRC bars plus one half BaBar DIRC bar glued to form one long bar (or 3 BaBar DIRC bars plus one new short plate)
- **Focusing optics:**

  Radiation-hard 3-layer spherical lens
- **Expansion volume:**

  Solid fused silica prism: 24 x 36 x 30 cm^3 (H x W x L)
- **Readout:**

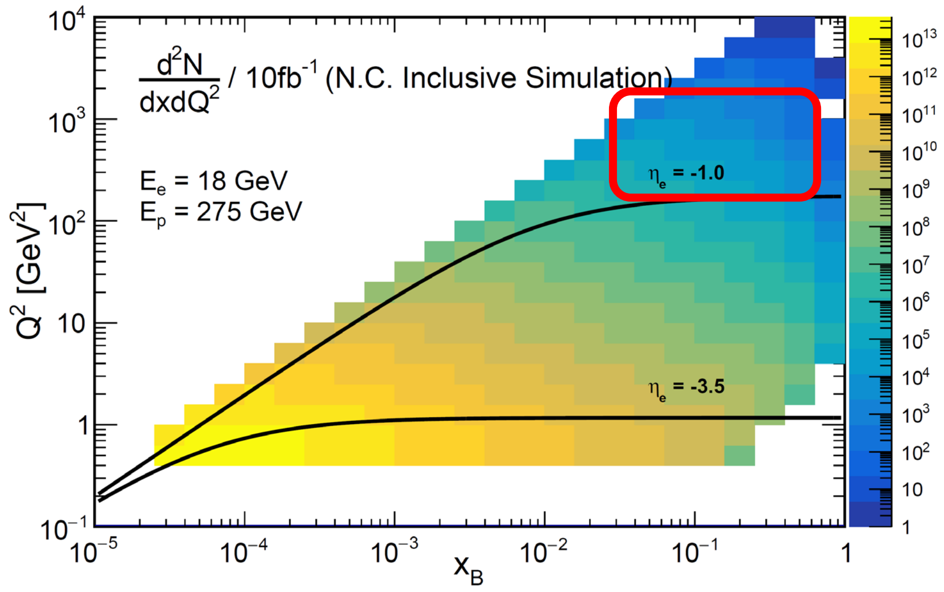
  PHOTONIS MCP-PMT Sensors + NALU's ASIC based Readout Electronics



Barrel PID – e/pi

Scattered electron kinematics measurement is essential at the EIC

- ❑ High precision, hermetic detection of the scattered electron is required over a broad range in η and over energy range from 0.1 to tens of GeV
  - ○ In the very backward direction high precision is required for electron kinematics measurement
  - ○ In backward and barrel region it is required for clean electron identification. In the barrel region, driven by high-x and high-Q^2 science drivers
- ❑ In ECCE we chose Sciglass in the barrel as this provides excellent e/h separation due to its good energy resolution, matched to the backward region need, and its cost effectiveness



η	[-4 .. -1.8]	[-1.7 .. 1.3]	[1.3 .. 4]
Material	$PbWO_4$	SciGlass	Pb/Sc
X_0 (mm)	8.9	24-28	16.4
R_M (mm)	19.6	35	35
Cell (mm)	20	40	40
X/X_0	22.5	17.5	19
Δz (mm)	60	56	48

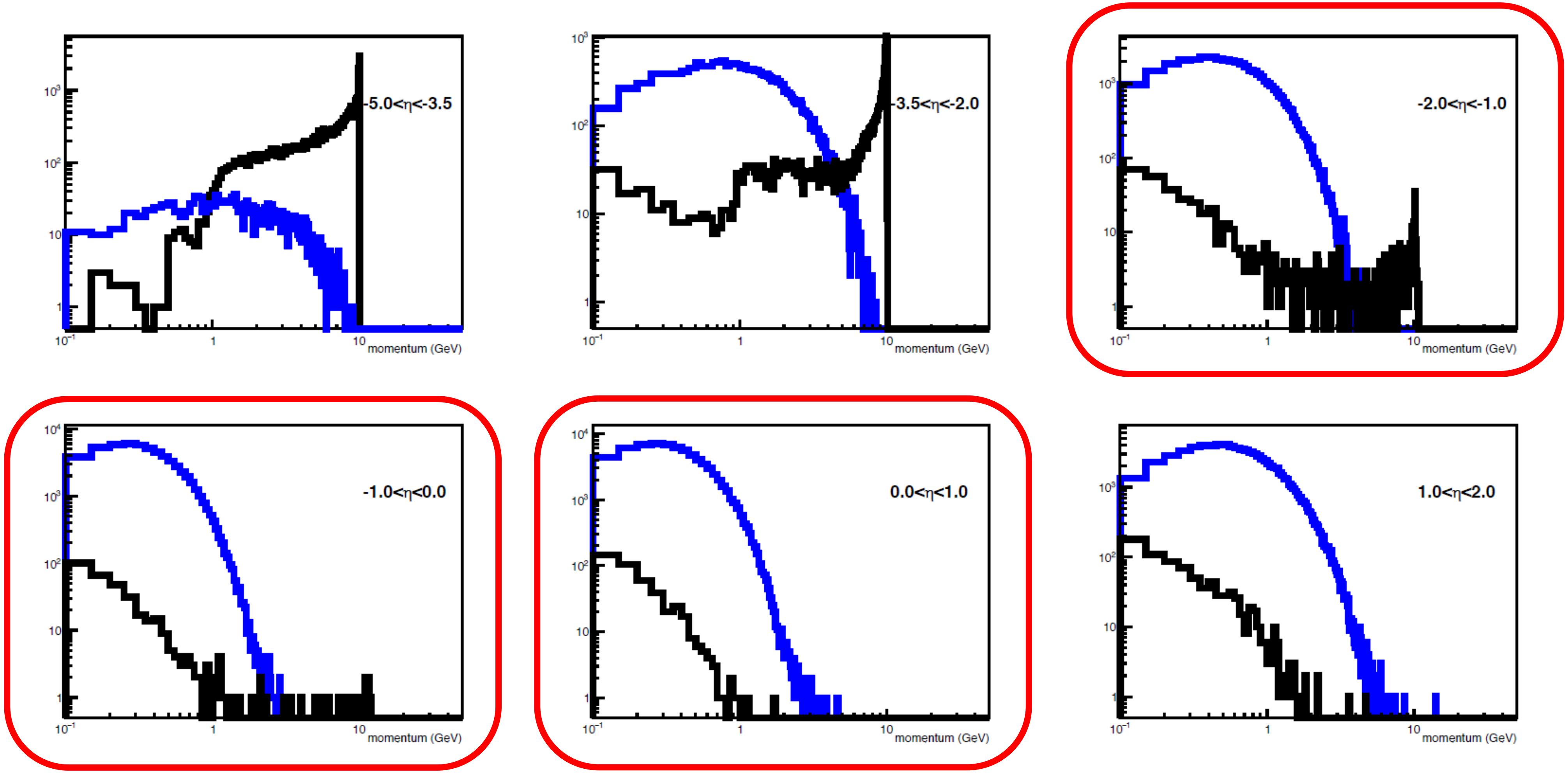
Requirements

- ❑ Good energy resolution
  - ○ e.g., region -2 < η < -1 requires ~7%/√E
- ❑ e/h separation up to 10^{-4}

e/π SEPARATION

NEEDS

ΔG needs pi/e 10^{-3} , A_{PV} needs pi/e 10^{-4} in η bins -2 to 1



10 x 100 GeV Pion/e- Ratio (Work by **Hanjie Liu**)

Homogeneous Design based on PANDA

PANDA

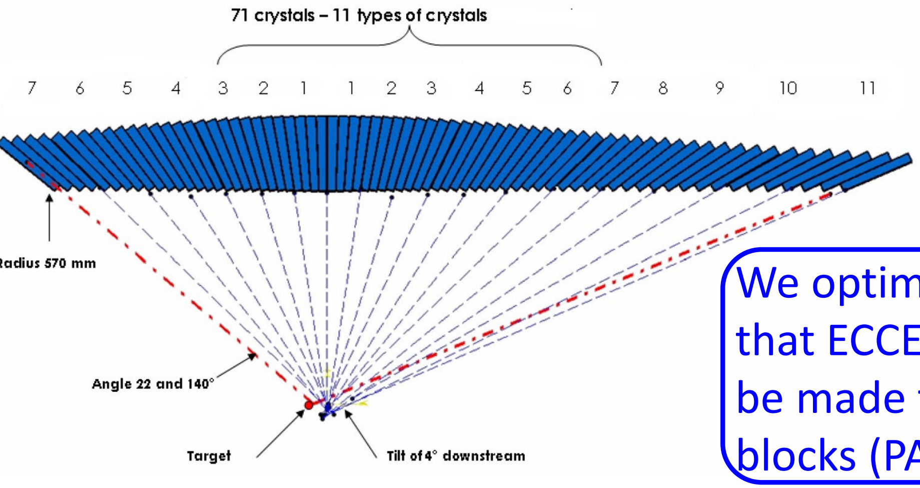


Figure 5.4: Crystal arrangement of the barrel along the beam axis. Positions of the different crystal types are indicated. Due to the mirror symmetry, 11 types are sufficient instead of 18.

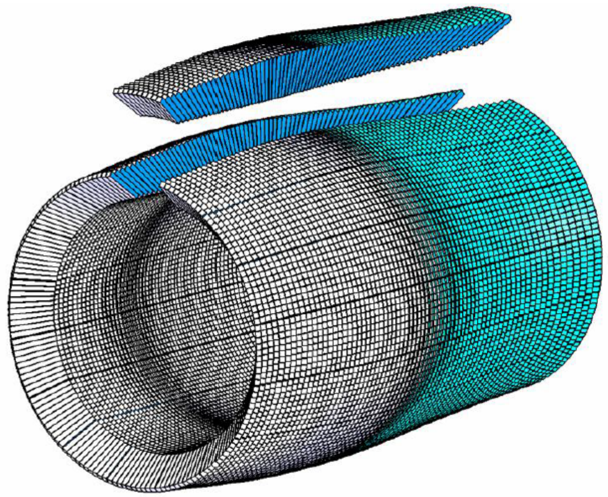
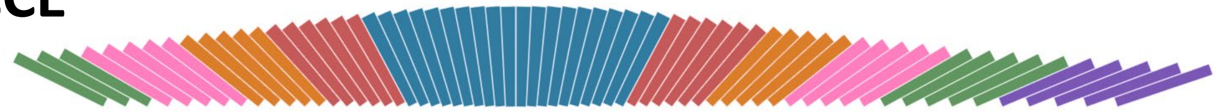


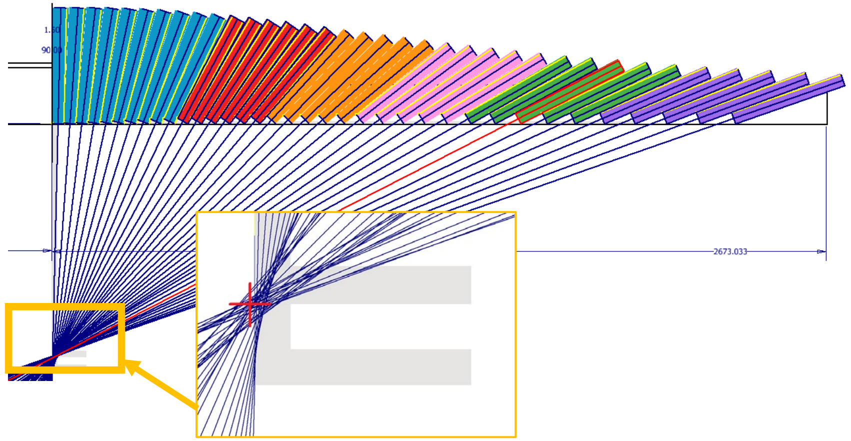
Figure 5.5: View of the total barrel volume with a separated single slice of 710 crystals. A slice covering 1/16 of the barrel volume.

ECCE

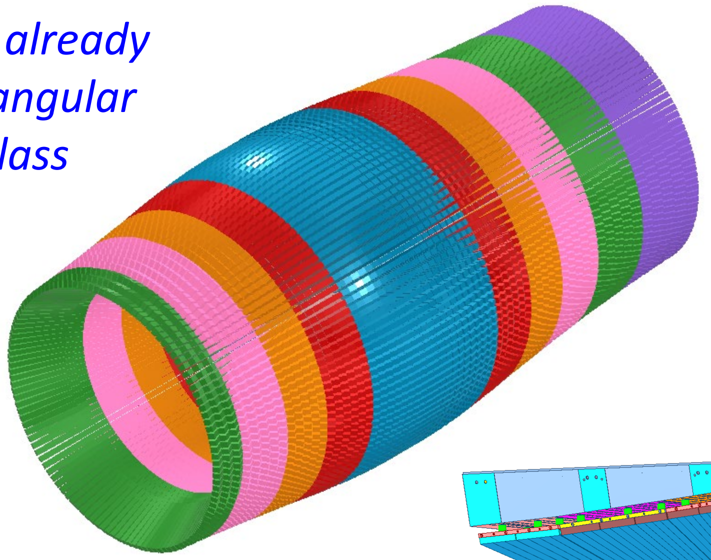
Based on realistic CAD design (CUA)

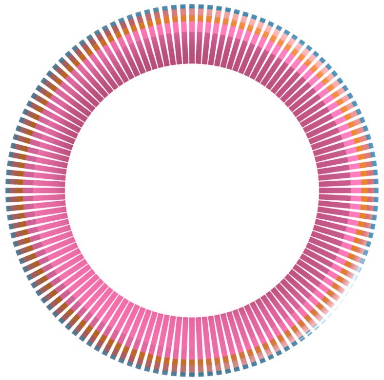


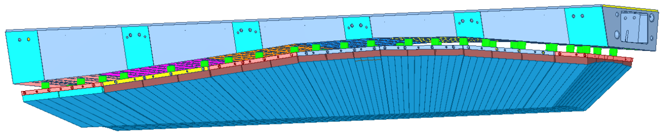
We optimized the geometry so that ECCE barrel calorimeter can be made from 6 families of blocks (PANDA has 11 families)



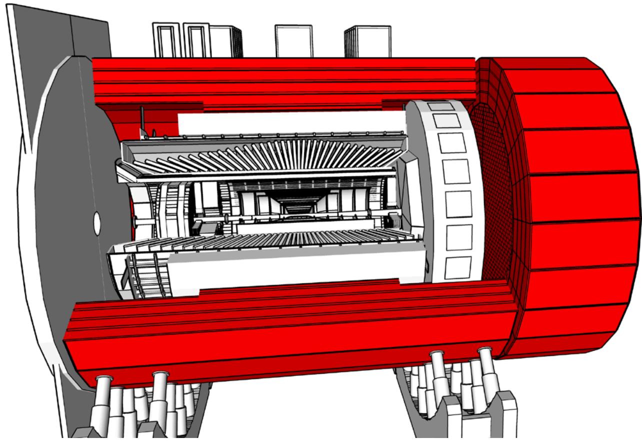
With these families we already reduced any gap both angular and radially between glass blocks to <5mm







Hadronic Calorimeters



- Main purpose: jet energy measurement
  - Particle Flow Algorithm usage anticipated (where HCal role is identification and energy measurements of the neutral hadrons, namely neutrons and K_L)

- **ECCE HCAL technologies are based on existing hadronic calorimeters** with **components optimized to fit the ECCE baseline design and providing the required performance and coverage**
- The barrel HCAL is a re-use of the hadronic calorimeter from sPHENIX – it has two components
  - Outer HCAL (OHCAL): uniform sampling in azimuth and also serves as barrel flux return. *Note that the Babar magnet material corresponds to only 0.36 nuclear interaction lengths.*
  - Inner HCAL (IHCAL): provides additional longitudinal segment and aids overall calibration of the calorimeter system
- The forward calorimeter is an integrated ECAL+HCAL with longitudinal segmentation and reducing dead material, it has a depth of more than 7 interaction lengths
- The ECCE reference detector includes a flux return in the electron endcap, as no NAS or White Paper EIC science process was found to benefit from a backward hadronic calorimeter within the first years of data taking.

η	[-1 .. 1]	[1 .. 4]
σ_E/E	~75%/√E + 15%*	~33%/√E + 1.4%
depth	~4-5 λ_I	~7-8 λ_I

*Based on prototype beam tests and earlier experiments

Later work showed that the IHCAL may be challenging to integrate with the EMCAL frame – work ongoing

Backward Hadronic Calorimeter

On average the energy in an eHCAL is quite low in DIS events, @ Q^2>1 GeV^2, W^2>10 GeV^2 , 0.01<y<0.95:

13% of DIS events have E_{eHCAL}>1.0 GeV
3% of DIS events have E_{eHCAL} >1.0 GeV from neutral hadrons

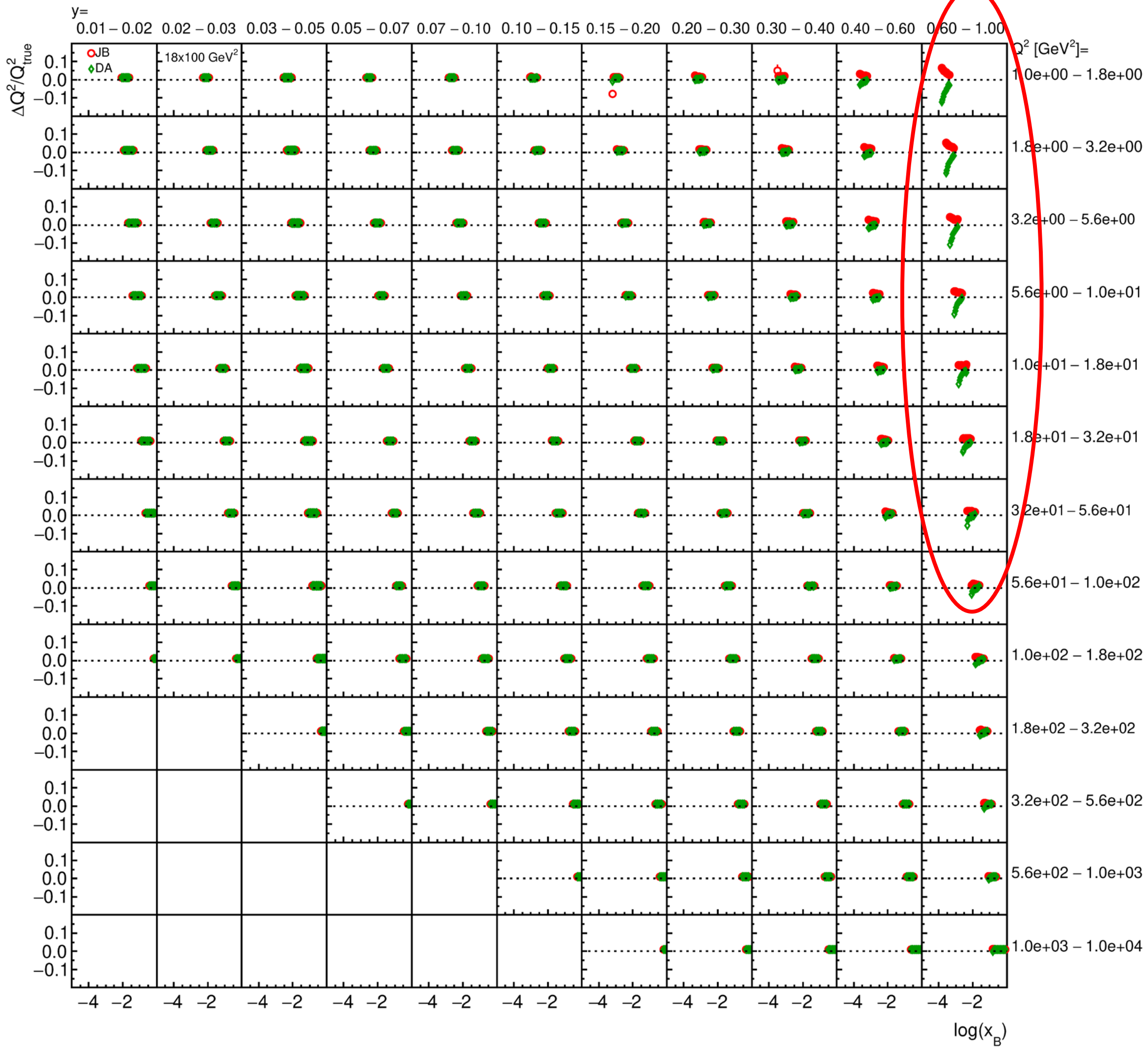
8% of DIS events have E_{eHCAL}>1.5 GeV
1.7% of DIS events have E_{eHCAL} >1.5 GeV from neutral hadrons

The eHCAL has an influence on the reconstruction of the DIS variables in the regions of low Q^2 and high y. *However, these are exactly the regions where the reconstruction of DIS variables using the scattered-lepton information is superior to the Jacquet-Blondel and double-angle method*.

Hence, from this point of view, an eHCAL is not needed.

Conversely, science interest in a low Q^2 and high y region for use of the J-B method or complementarity reasons may lead to an eHCAL upgrade. Could be based on the STAR FCS Fe/Sc with partial re-use

DIS Kinematics Reconstruction



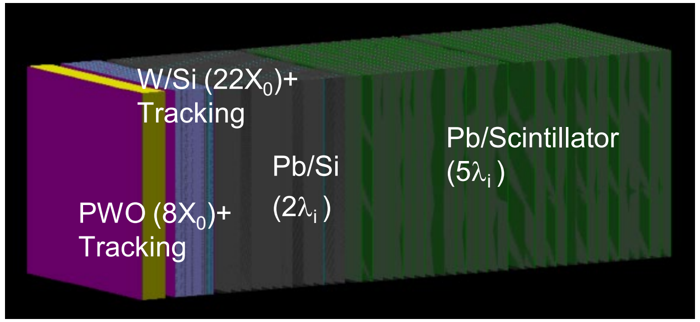
Key Requirements FF/FB Overview

Topic	Challenge	ECCE solution	Comment
Far-Backward – Low-Q^2 Tagger	Measure low-Q^2 photo-production with as minimal a Q^2-gap as possible.	Spectrometer with AC-LGAD tracking and $PbWO_4$ calorimetry	
Far-Backward – Luminosity Detector	e-ion collision luminosity to better than 1% and relative Luminosity for spin asymmetries to 10^{-4}	Zero Degree Calorimeter with x-ray absorber and e^+/e^- pair spectrometer with AC-LGAD tracking and $PbWO_4$ calorimetry	two complementary detection systems
Far-Forward – B0 Spectrometer	$\eta > 4$ charged particle tracking and γ measurement	Four Si trackers with 10 cm $PbWO_4$ calorimeter	
Far-Forward – Off-momentum Detectors	forward particles (Δ, Λ, Σ, etc) decay product measurement	AC-LGAD detectors	Sensors on one side detect p, on other side p^- from Λ decay; sensors outside beam pipe
Far-Forward – Roman Pots	Detect low-p_T forward-going particles	AC-LGAD detectors	fast timing ($\sim$35 ps) removes vertex smearing effects from crab rotation; 10σ from beam
Far-Forward – Zero-degree Calorimeter	Measure forward-going neutrons γ and heavy-ion fission product	FOCAL-type calorimeter with high-precision EM and Hadron Calorimetry	Upgrade option: AC-LGAD layer to capture very high rapidity charged tracks

Motivation behind the technology choices

Zero Degree Calorimeter

- ECCE ZDC has dimensions of 60cm x 60cm x 162cm for the needed acceptance (YR) and consists of $PbWO_4$ crystal, W/Si layer, Pb/Si, and Pb/Scintillator layers



- The "Cadillac" of ZDCs since interest expressed by EIC-Japan to provide it in-kind
- B0: add a **$PbWO_4$ (11.2 R.L.) calorimeter behind the 4th tracking layer to obtain 100% acceptance** for $\gamma+\gamma$ from π^0 to cleanly isolate u-channel DVCS
- Otherwise followed Yellow Report and expert guidance
- Backward detectors selected based on interest expressed by EIC-Israel and U. York

Backup

Global Detector Location Database

ECCE used similar, but this structure is hybrid of ATHENA/ECCE structures

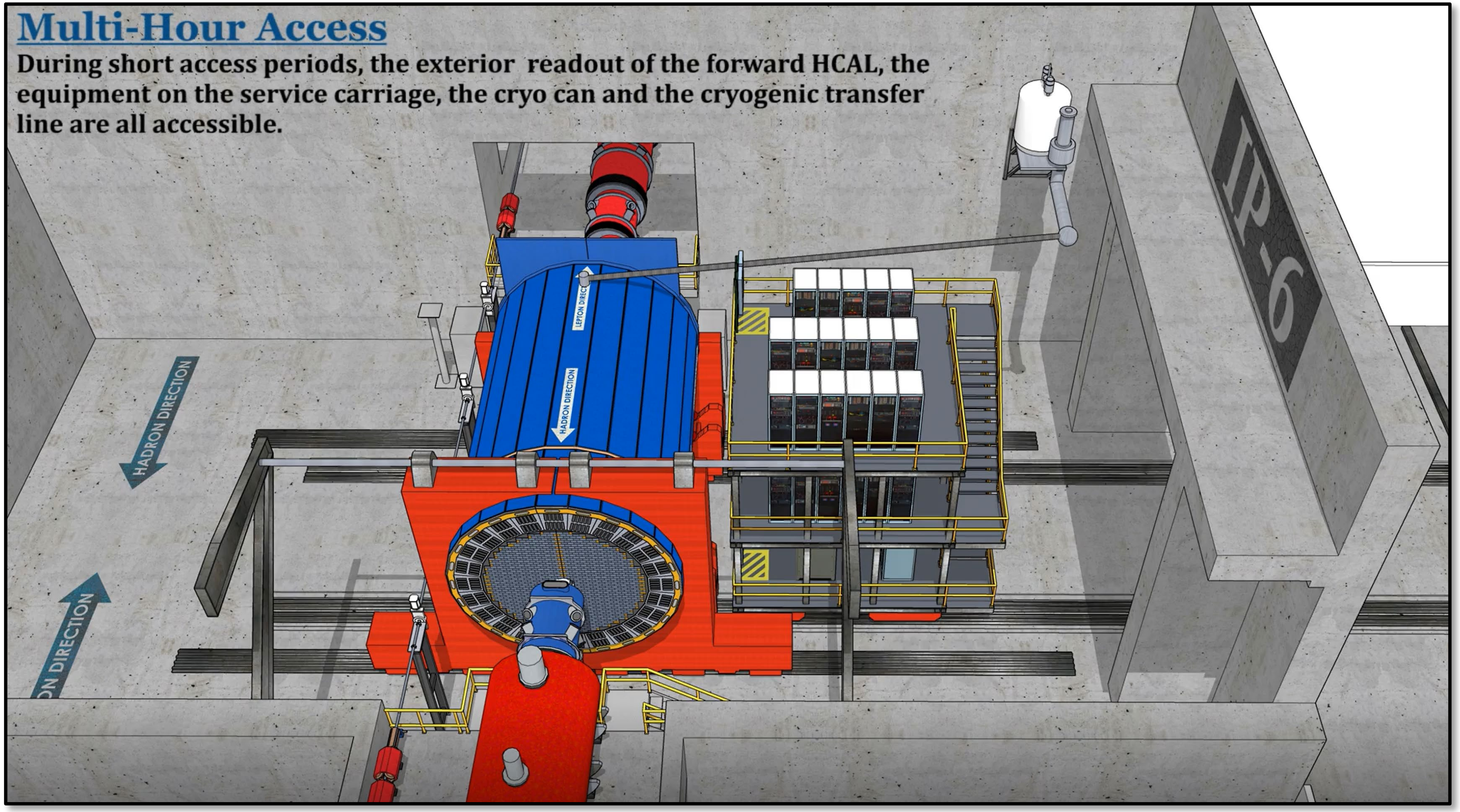
Region	Component	Sub-Component	WBS	Length (cm)	Inner Radius (cm)	Outer Radius (cm)	Offset from Center (cm)	Physical Start (cm)	Physical End (cm)	Volume (m³)	Weight (kg)	Technology	Notes
HADRON DIRECTION END CAP	**Hadron Calorimeter**		6.10.06	171	30	267	328	499	328	33.611645	215,210	FeSc, WSc last segment	Tower size: 5cm x 5cm x 140cm, 20cm readout Offset: measured from face nearest to interaction point Volume: calculated as cylindrical volume minus the volume of the embedded ECAL Weight: estimated as 79% iron and 21% plastic
	Electromagnetic Calorimeter		6.10.05	38	30	190	328	366	328	4.2021943	27,165	Pb/Sc	Tower size: 1cm (1.65cm) x 1cm(1.65cm) x 37.5cm, 5cm readout Offset: measured from face nearest to interaction point Weight: estimated as 85% lead glass and 15% steel
	Service Gap			8			320	328	320				Offset: measured from location nearest to interaction point
CENTRAL DETECTOR	**Barrel Hadron Calorimeter**		6.10.06	640		267	0	320	-320	72.60	464,834	FeSc	Offset: measured from center of detector Volume: calculated as sum of the sub-sections Weight: estimated as 79% iron and 21% plastic
		HD Section		*170*	*194*	*267*	*150*	*320*	*150*	*17.97*			*Offset: measured from face nearest to interaction point*
		Central Section		*300*	*180*	*267*	*0*	*150*	*-150*	*36.65*			*Offset: measured from center of detector*
		LD Section		*170*	*194*	*267*	*-150*	*-150*	*-320*	*17.97*			*Offset: measured from face nearest to interaction point*
	Dual RICH		6.10.04	100	10		180	280	180	10.29	1,911	Aerogel/Gas	Offset: measured from face nearest to interaction point Volume: calculated as sum of the sub-sections Weight: based on parametric estimate from CLAS LTCC
		Detector Section		*80*	*10*	*195*	*200*	*280*	*200*	*9.53*			*Offset: measured from face nearest to interaction point*
		Aerogel Section		*20*	*10*	*110*	*180*	*200*	*180*	*0.75*			*Offset: measured from face nearest to interaction point*
	Solenoid Magnet		6.10.07	384	142	177	0	192	-192	13.47	45,956	Solenoid	Weight: based on parametric estimate from CLEO II
	EMCal Outer Support			445	134	140	-30	192.5	-252.5	2.30	3,608	Steel, Instrumented	Weight: calculated as 20% of total volume as steel (balance is air)
	EMCal Electronics			480	125.5	134	-45	195	-285	3.33	1,938	Near eta=0	Weight: calculated as 25% silicon (balance is air)
	Barrel EMCal		6.10.05	480	80	125.5	-45	195	-285	14.10	49,463	Sci Glass	Weight: based on parametric estimate from CMS EMCal
	EMCal Inner Support			480	79.5	80	-45	195	-285	0.12	944	Steel	Weight: calculated as 100% steel
	Barrel Gem Tracker		6.10.03	340	77	79.5	-5	165	-175	0.42	84	muRWell (plane type)	Weight: based on parametric estimate from SBS Gem
	DIRC Support			455	65	77	-257	168	-287	2.60	1,019	Steel	Offset: measured from point where DIRC bar connects to the readout Volume: calculated as sum of sub-sections Weight: estimated as 5% of total volume as steel (balance is air & detector)
		Bar Support		*425*	*65*	*77*	*-257*	*168*	*-257*	*2.28*			
		Readout Support		*30*	*65*	*105*	*-257*	*-257*	*-287*	*0.32*			*Readout support is triangular frame, therefore volume is halved.*
	DIRC Detector		6.10.04		71.5	76.6	-257	168	-287	1.28	893	Fused silica bars	Detector is totally enclosed by DIRC Support. Weight: calculated as sum of sub-components
		DIRC Bar		*425*	*71.5*	*76.6*	*-257*	*168*	*-257*	*1.01*	*702*		*Weight: calculated as 30% quartz (balance is air & support system)*
		DIRC Readout		*30*	*71.5*	*104.4*	*-257*	*-257*	*-287*	*0.27*	*191*		*Readout is triangular, therefore volume is halved.* *Weight: Calculated as 30% silicon(balance is air & support system)*
	Barrel Time of Flight/Tracker		6.10.03	270	63	65	15	150	-120	0.22	43	AC/LGAD	Weight: based on parametric estimate from SBS Gem
	HD Time of Flight/Tracker		6.10.03	15	12	62	155.5	170.5	155.5	0.17	35	AC/LGAD	Offset: measured from face nearest to interaction point Weight: based on parametric estimate from SBS Gem
	Silicon Tracker		6.10.03	228	3	45.9	0	126	-102	1.50	227	MAPS	Weight: calculated as 3% aluminum and 3% silicon (balance is air)
	Modular RICH		6.10.04	25	10	64	-135	-135	-160	0.31	58	Aerogel	Offset: measured from face nearest to interaction point Weight: based on parametric estimate from CLAS LTCC
	LD Time of Flight/Tracker		6.10.03	10	12	64	-161	-161	-171	0.12	25	AC/LGAD	Offset: measured from face nearest to interaction point Weight: based on parametric estimate from SBS Gem
	LD EMCal		6.10.05	60	9	63	-175	-175	-235	0.73	4,738	PbWO4	Offset: measured from face nearest to interaction point Weight: estimated as 85% lead glass and 15% steel
	Service Gap			10			-320	-320	-330	0.00			Offset: measured from location nearest to interaction point
LEPTON DIRECTION ENDCAP	**Backward Field Return**		6.10.06	20.32			-330	-330	-350.32	5.18	40,649	Iron	Offset: measured from face nearest to interaction point Weight: calculated as 100% iron.
		Return Cylinder		*20.32*	*20*	*270*	*-330*	*-330*	*-350.32*	*4.63*			
		Support Panel		*7.62*	*454*	*664*	*-336.35*	*-336.35*	*-343.97*	*0.55*			*Height: specified in outer radius* *Width: specified in inner radius*

Detector-1 Reference Parameters

Parameter	Detector 1-Solenoid	Comments
Central Field (T)	1.5	Central field is ≈ 1.3 T for 4596 A operating current
Coil length (mm)	3512	This values ranges from 3503 to 3516 mm in various lterature not sure about the cold or warm length
Warm bore diameter (m)	2.84	
Polarity	Bipolar	
Lowest operating field (T)	0.5	
Flat Field area	± 100 cm around center 80 cm radius	Based on John Lajohe's email dated 04/27/2022
Field uniformity in Flat field Area (%)	8.5	Based on John Lajohe's email dated 04/27/2022
RICH area	From z=+180 cm to 280 cn	Based on John Lajohe's email dated 04/27/2022
Projectivity in RICH Area (mrad@30GeV/c) Projectivity in RICH Area (A/Tmm^2)	0.1 10	Based on John Lajohe's email dated 04/27/2022
Stray field requirement	<0.5 mT @ z=-5.3 m, @z=+7.4 m, and @R=3.4 m	
Cryostat length (m)	<3.85	
Cryostat outer diamter (m)	<3.54	
Charging voltage (V)	10	
Fast discharge voltage maximum (V)	500	
Quench hot spot temperature (K)	<150	
Temperature margin (K)	>1.5	
Current margin (%)	>30	
Charging time (hr)	2-3	
Cooldown time (weeks)	3-4	
Cooling scheme	Thermosiphon	
Conductor	Al Stabilized NbTi Rutherford Cable	
Operating Temperature	4.5	

O2: Central Detector Maintenance

Describe the accessibility of your detector systems and their electronics for urgent interventions and for annual maintenance. How long does urgent access to detector components and electronics require during beam operations? Are there any detectors or electronics that are not accessible even during annual maintenance periods?



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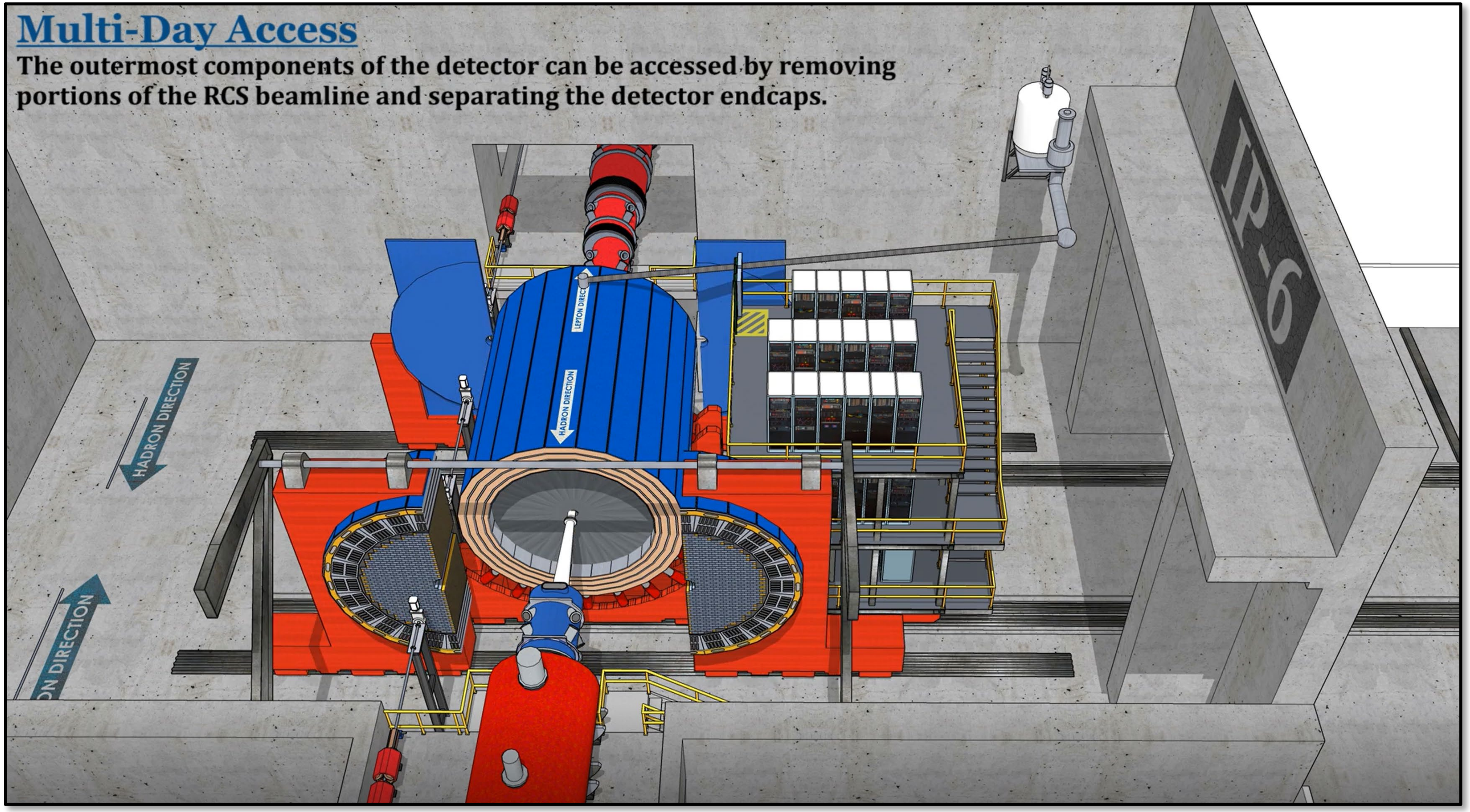

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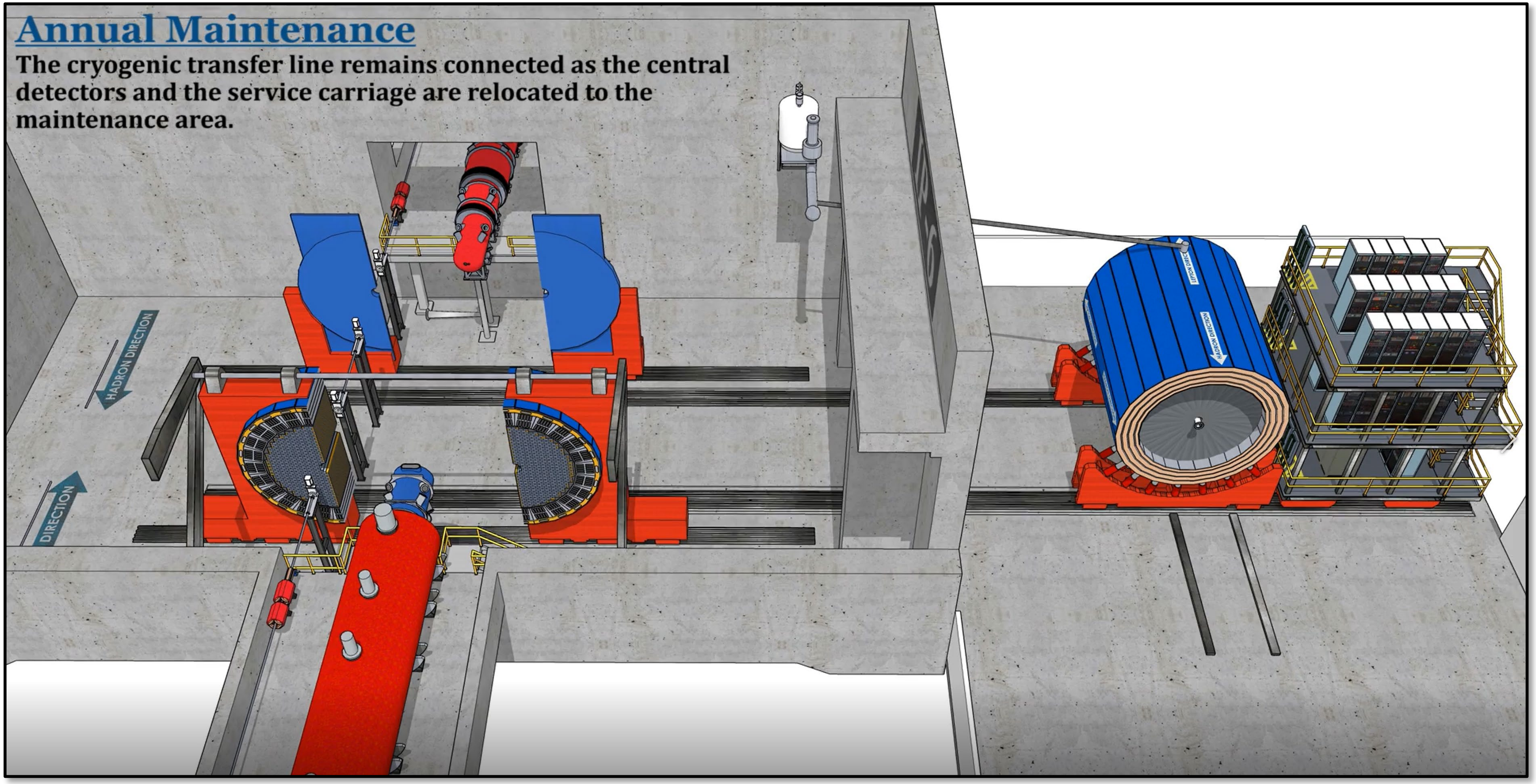

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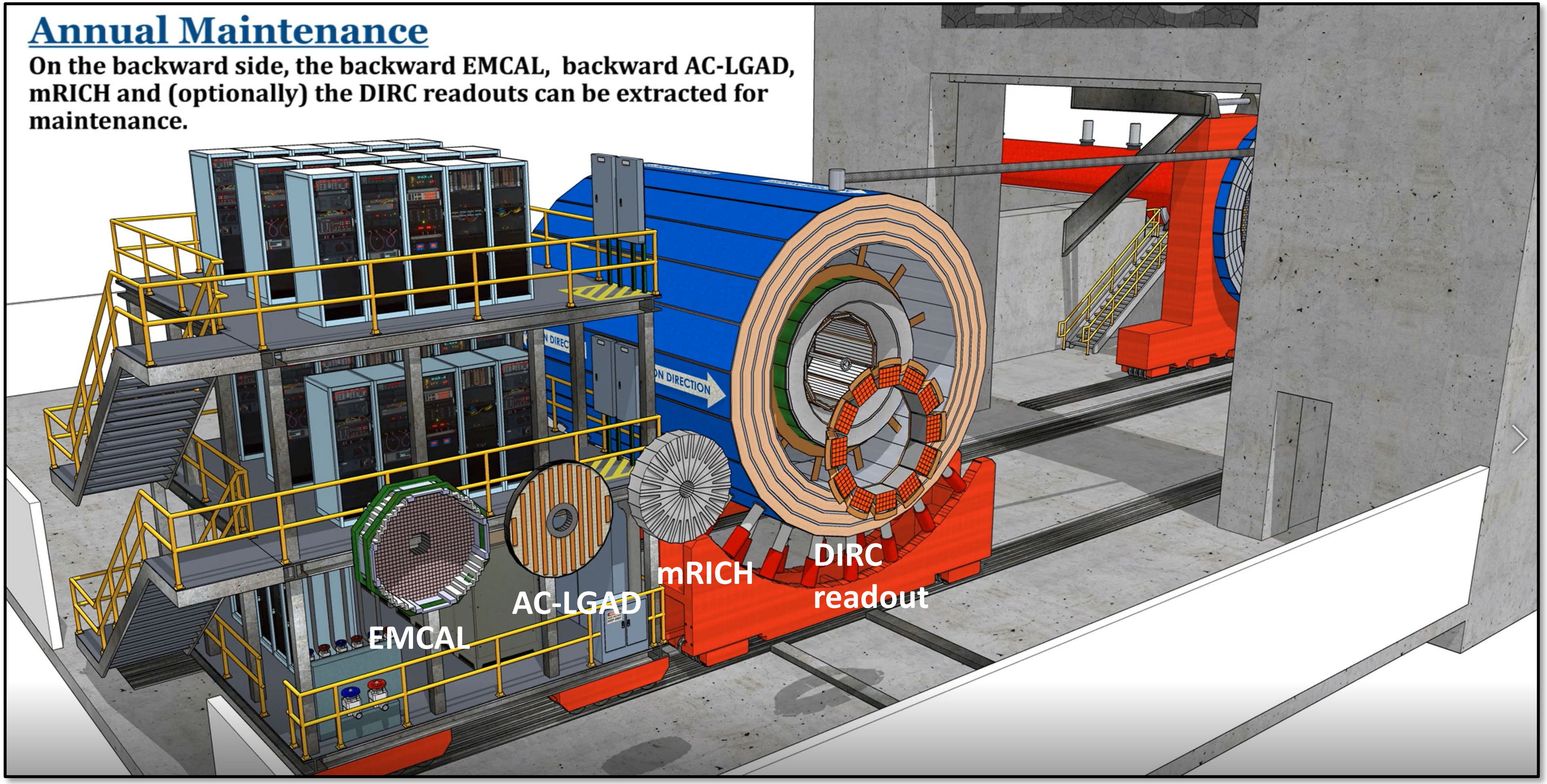

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