

Design of the ECCE Detector for the Electron Ion Collider

J. K. Adkins³⁶, Y. Akiba⁵³, A. Albataineh⁶⁹, M. Amaryan⁴⁷, I. C. Arsene⁷³, C. Ayerbe Gayoso³⁸, J. Bae⁶¹, X. Bai⁷⁸, M.D. Baker^{4,28}, M. Bashkanov⁸⁷, R. Bellwied⁶⁷, F. Benmokhtar¹⁴, V. Berdnikov¹², J. C. Bernauer^{55,56,57}, F. Bock⁴⁹, W. Boeglin¹⁶, M. Borysova⁸³, E. Brash¹⁰, P. Brindza²⁸, W. J. Briscoe²⁰, M. Brooks³², S. Bueltmann⁴⁷, M. H. S. Bukhari²⁷, A. Bylinkin⁶⁹, R. Capobianco⁶⁶, W.-C. Chang², Y. Cheon⁵⁹, K. Chen⁷, K.-F. Chen⁴⁶, K.-Y. Cheng⁴⁰, M. Chiu⁴, T. Chujo⁷⁶, Z. Citron¹, E. Cline^{55,56}, E. Cohen⁴⁴, T. Cormier⁴⁹, Y. Corrales Morales³², C. Cotton⁷⁸, J. Crafts¹², C. Crawford⁷⁰, S. Creekmore⁴⁹, C. Cuevas²⁸, J. Cunningham⁴⁹, G. David⁴, C. T. Dean³², M. Demarteau⁴⁹, S. Diehl⁶⁶, N. Doshita⁸⁵, R. Dupre²³, J. M. Durham³², R. Dzhygadlo¹⁹, R. Ehlers⁴⁹, L. El Fassi³⁸, A. Emmert⁷⁸, R. Ent²⁸, C. Fanelli³⁷, R. Fatemi⁷⁰, S. Fegan⁸⁷, M. Finger⁸, M. Finger Jr.⁸, J. Frantz⁴⁸, M. Friedman²², I. Friscic⁸⁸, D. Gangadharan⁶⁷, S. Gardner¹⁸, K. Gates¹⁸, F. Geurts⁵², R. Gilman⁵⁴, D. Glazier¹⁸, E. Glimos⁴⁹, Y. Goto⁵³, N. Grau³, S. V. Greene⁷⁹, A. Q. Guo²⁵, L. Guo¹⁶, S. K. Ha⁸⁶, J. Haggerty⁴, T. Hayward⁶⁶, X. He¹⁷, O. Hen³⁷, D. W. Higinbotham²⁸, M. Hoballah²³, T. Horn¹², A. Hognmrtsyan¹, P.-h. J. Hsu⁴⁵, J. Huang⁴, G. Huber⁷⁴, A. Hutson⁶⁷, K. Y. Hwang⁸⁷, C. Hyde⁴⁷, M. Inaba⁶⁴, T. Iwata⁸⁵, H.S. Jo³¹, K. Joo⁶⁶, N. Kalantarians⁸¹, G. Kalicy¹², K. Kawade⁶⁰, S. J. D. Kay⁷⁴, A. Kim⁶⁶, B. Kim⁶¹, C. Kim⁵¹, M. Kim⁵³, Y. Kim⁵¹, Y. Kim⁵⁹, E. Kistenev⁴, V. Klimenko⁶⁶, S. H. Ko⁵⁸, I. Korover³⁷, W. Korsch⁷⁰, G. Krintiras⁶⁹, S. Kuhn⁴⁷, C.-M. Kuo⁴⁰, T. Kutz³⁷, J. Lajoie²⁶, D. Lawrence²⁸, S. Lebedev²⁶, H. Lee⁶¹, J. S. H. Lee⁷⁵, S. W. Lee³¹, Y.-J. Lee³⁷, W. Li⁵², W. Li^{55,56,84}, X. Li⁹, X. Li³², Y. T. Liang²⁵, S. Lim⁵¹, C.-h. Lin², D. X. Lin²⁵, K. Liu³², M. X. Liu³², K. Livingston¹⁸, N. Liyanage⁷⁸, W.J. Llope⁸², C. Loizides⁴⁹, E. Long⁷², R.-S. Lu⁴⁶, Z. Lu⁹, W. Lynch⁸⁷, D. Marchand²³, M. Marcisovsky¹³, P. Markowitz¹⁶, H. Marukyan¹, P. McGaughey³², M. Mihovilovic⁷¹, R. G. Milner³⁷, A. Milov⁸³, Y. Miyachi⁸⁵, A. Mkrtchyan¹, P. Monaghan¹⁰, R. Montgomery¹⁸, D. Morrison⁴, A. Movsisyan¹, H. Mkrtchyan¹, A. Mkrtchyan¹, C. Munoz Camacho²³, M. Murray⁶⁹, K. Nagai³², J. Nagle⁶⁵, I. Nakagawa⁵³, C. Natrass⁷⁷, D. Nguyen²⁸, S. Niccolai²³, R. Nouicer⁴, G. Nukazuka⁵³, M. Nycz⁷⁸, V. A. Okorokov⁴³, S. Orešić⁷⁴, J.D. Osborn⁴⁹, C. O'Shaughnessy³², S. Paganis⁴⁶, Z. Papandreou⁷⁴, S. F. Pate⁴², M. Patel²⁶, C. Paus³⁷, G. Penman¹⁸, M. G. Perdekamp⁶⁸, D. V. Perepelitsa⁶⁵, H. Periera da Costa³², K. Peters¹⁹, W. Phelps¹⁰, E. Piasezky⁶², C. Pinkenburg⁴, I. Prochazka⁸, T. Protzman³⁴, M. L. Purschke⁴, J. Putschke⁸², J. R. Pybus³⁷, R. Rajput-Ghoshal²⁸, J. Rason⁴⁹, B. Raue¹⁶, K. Read⁴⁹, K. Røed⁷³, R. Reed³⁴, J. Reinhold¹⁶, E. L. Renner³², J. Richards⁶⁶, C. Riedl⁶⁸, T. Rinn⁴, J. Roche⁴⁸, G. M. Roland³⁷, G. Ron²², M. Rosati²⁶, C. Royon⁶⁹, J. Ryu⁵¹, S. Salur⁵⁴, N. Santiesteban³⁷, R. Santos⁶⁶, M. Sarsour¹⁷, J. Schambach⁴⁹, A. Schmidt²⁰, N. Schmidt⁴⁹, C. Schwarz¹⁹, J. Schwiening¹⁹, R. Seidl⁵³, A. Sickles⁶⁸, P. Simmerling⁶⁶, S. Sirca⁷¹, D. Sharma¹⁷, Z. Shi³², T.-A. Shibata⁴¹, C.-W. Shih⁴⁰, S. Shimizu⁵³, U. Shrestha⁶⁶, K. Slifer⁷², K. Smith³², D. Sokhan^{18,24}, R. Soltz³⁵, W. Sondheim³², J. Song⁹, J. Song⁵¹, I. I. Strakovsky²⁰, P. Steinberg⁴, P. Stepanov¹², J. Stevens⁸⁴, J. Strube⁵⁰, P. Sun⁹, X. Sun⁷, K. Suresh⁷⁴, V. Tadevosyan¹, W.-C. Tang⁴⁰, S. Tapia Araya²⁶, S. Tarafdar⁷⁹, L. Teodorescu⁵, A. Timmins⁶⁷, L. Tomasek¹³, N. Trotta⁶⁶, R. Trotta¹², T. S. Tveter⁷³, E. Umaka²⁶, A. Usman⁷⁴, H. W. van Hecke³², C. Van Hulse²³, J. Velkovska⁷⁹, E. Voutier²³, P.K. Wang²³, Q. Wang⁶⁹, Y. Wang⁷, Y. Wang⁶³, D. P. Watts⁸⁷, N. Wickramaarachchi¹², L. Weinstein⁴⁷, M. Williams³⁷, C.-P. Wong³², L. Wood⁵⁰, M. H. Wood⁶, C. Woody⁴, B. Wyslouch³⁷, Z. Xiao⁶³, Y. Yamazaki³⁰, Y. Yang³⁹, Z. Ye⁶³, H. D. Yoo⁸⁷, M. Yurov³², N. Zachariou⁸⁷, W.A. Zajc¹¹, J. Zhang⁷⁸, Y. Zhang⁶³, Y. X. Zhao²⁵, X. Zheng⁷⁸, P. Zhuang⁶³

¹A. Alikhanyan National Laboratory, Yerevan, Armenia

²Institute of Physics, Academia Sinica, Taipei, Taiwan

³Augustana University, Sioux Falls, , SD, USA

⁴Brookhaven National Laboratory, Upton, 11973, NY, USA

⁵Brunel University London, Uxbridge, , UK

⁶Canisius College, 2001 Main St., Buffalo, 14208, NY, USA

⁷Central China Normal University, Wuhan, China

⁸Charles University, Prague, Czech Republic

⁹China Institute of Atomic Energy, Fangshan, Beijing, China

¹⁰Christopher Newport University, Newport News, , VA, USA

¹¹Columbia University, New York, , NY, USA

¹²Catholic University of America, 620 Michigan Ave. NE, Washington DC, 20064, USA

¹³Czech Technical University, Prague, Czech Republic

¹⁴Duquesne University, Pittsburgh, , PA, USA

¹⁵Duke University, , , NC, USA

¹⁶Florida International University, Miami, , FL, USA

¹⁷Georgia State University, Atlanta, , GA, USA

¹⁸University of Glasgow, Glasgow, , UK

¹⁹GSF Helmholtzzentrum fuer Schwerionenforschung, Planckstrasse 1, Darmstadt, 64291, Germany

²⁰The George Washington University, Washington, DC, 20052, USA

²¹Hampton University, Hampton, , VA, USA

²²Hebrew University, Jerusalem, , Isreal

²³Universite Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France

²⁴IRFU, CEA, Universite Paris-Saclay, Gif-sur-Yvette France

²⁵Chinese Academy of Sciences, Lanzhou, , , China

- ²⁶Iowa State University, , IA, USA
- ²⁷Jazan University, Jazan, Sadui Arabia
- ²⁸Thomas Jefferson National Accelerator Facility, 12000 Jefferson Ave., Newport News, 24450, VA, USA
- ²⁹James Madison University, , VA, USA
- ³⁰Kobe University, Kobe, Japan
- ³¹Kyungpook National University, Daegu, Republic of Korea
- ³²Los Alamos National Laboratory, , NM, USA
- ³³Lawrence Berkeley National Lab, Berkeley, , USA
- ³⁴Lehigh University, Bethlehem, , PA, USA
- ³⁵Lawrence Livermore National Laboratory, Livermore, , CA, USA
- ³⁶Morehead State University, Morehead, , KY,
- ³⁷Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, 02139, MA, USA
- ³⁸Mississippi State University, Mississippi State, , MS, USA
- ³⁹National Cheng Kung University, Tainan, , Taiwan
- ⁴⁰National Central University, Chungli, Taiwan
- ⁴¹Nihon University, Tokyo, Japan
- ⁴²New Mexico State University, Physics Department, Las Cruces, NM, 88003, USA
- ⁴³National Research Nuclear University MEPhI, Moscow, 115409, Russian Federation
- ⁴⁴Nuclear Research Center - Negev, Beer-Sheva, Isreal
- ⁴⁵National Tsing Hua University, Hsinchu, Taiwan
- ⁴⁶National Taiwan University, Taipei, Taiwan
- ⁴⁷Old Dominion University, Norfolk, , VA, USA
- ⁴⁸Ohio University, Athens, 45701, OH, USA
- ⁴⁹Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, 37831, TN, USA
- ⁵⁰Pacific Northwest National Laboratory, Richland, , WA, USA
- ⁵¹Pusan National University, Busan, Republic of Korea
- ⁵²Rice University, P.O. Box 1892, Houston, 77251, TX, USA
- ⁵³RIKEN Nishina Center, Wako, Saitama, Japan
- ⁵⁴The State University of New Jersey, Piscataway, , NJ, USA
- ⁵⁵Center for Frontiers in Nuclear Science, Stony Brook, 11794, NY, USA
- ⁵⁶Stony Brook University, 100 Nicolls Rd., Stony Brook, 11794, NY, USA
- ⁵⁷RIKEN BNL Research Center, Upton, 11973, NY, USA
- ⁵⁸Seoul National University, Seoul, Republic of Korea
- ⁵⁹Sejong University, Seoul, Republic of Korea
- ⁶⁰Shinshu University, Matsumoto, Nagano, Japan
- ⁶¹Sungkyunkwan University, Suwon, Republic of Korea
- ⁶²Tel Aviv University, P.O. Box 39040, Tel Aviv, 6997801, Israel
- ⁶³Tsinghua University, Beijing, China
- ⁶⁴Tsukuba University of Technology, Tsukuba, Ibaraki, Japan
- ⁶⁵University of Colorado Boulder, Boulder, 80309, CO, USA
- ⁶⁶University of Connecticut, Storrs, , CT, USA
- ⁶⁷University of Houston, Houston, , TX, USA
- ⁶⁸University of Illinois, Urbana, , IL, USA
- ⁶⁹University of Kansas, 1450 Jayhawk Blvd., Lawrence, 66045, KS, USA
- ⁷⁰University of Kentucky, Lexington, 40506, KY, USA
- ⁷¹University of Ljubljana, Ljubljana, Slovenia, Ljubljana, , , Slovenia
- ⁷²University of New Hampshire, Durham, , NH, USA
- ⁷³University of Oslo, Oslo, Norway
- ⁷⁴University of Regina, Regina, , SK, Canada
- ⁷⁵University of Seoul, Seoul, Republic of Korea
- ⁷⁶University of Tsukuba, Tsukuba, Japan
- ⁷⁷University of Tennessee, Knoxville, 37996, TN, USA
- ⁷⁸University of Virginia, Charlottesville, , VA, USA
- ⁷⁹Vanderbilt University, PMB 401807,2301 Vanderbilt Place, Nashville, 37235, TN, USA
- ⁸⁰Virginia Tech, Blacksburg, , VA, USA
- ⁸¹Virginia Union University, Richmond, , VA, USA
- ⁸²Wayne State University, 666 W. Hancock St., Detroit, 48230, MI, USA
- ⁸³Weizmann Institute of Science, Rehovot, Israel
- ⁸⁴The College of William and Mary, Williamsburg, VA, USA
- ⁸⁵Yamagata University, Yamagata, Japan
- ⁸⁶Yarmouk University, Irbid, Jordan
- ⁸⁷Yonsei University, Seoul, Republic of Korea
- ⁸⁸University of York, York, UK
- ⁸⁹University of Zagreb, Zagreb, Croatia

The EIC Comprehensive QCD Experiment (ECCE) detector has been designed to address the full scope of the proposed Electron Ion Collider (EIC) physics program as presented in the EIC white paper and the National Academy of Science report. ECCE is a detector designed to be built within the budget envelope set out by the EIC project while simultaneously managing cost and schedule risks. This detector concept has been selected to be the basis for the project detector.

Keywords: ECCE, Electron Ion Collider, Tracking, Calorimetry, PID

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17	1. Introduction	35	
18	The physics program at the Electron-Ion Collider (EIC) –	36	
19	planned for construction at Brookhaven National Laboratory	37	
20	(BNL), in close partnership with the Thomas Jefferson National	38	
21	Accelerator Facility (TJNAF) – will be the culmination	39	
22	of decades of research into the quark and gluon substructure of	40	
23	hadrons and nuclei, and provide scientific opportunities well	41	
24	into the next three decades. The EIC will address a broad	42	
25	set of questions, described in a 2018 report by the National	43	
26	Academies of Science (NAS) [1]:	44	
27		45	
28	• While the longitudinal momenta of quarks and gluons in	46	
29	nucleons and nuclei have been measured with great precision	47	
30	at previous facilities – most notably CEBAF at JLab and the	48	
31	HERA collider at DESY – the full three-dimensional momentum	49	
32	and spatial structure of even a proton has yet to be fully	50	
33	elucidated, particularly including spin, which requires the	51	
34	separation of the intrinsic spin of the constituent particles	52	
	from their orbital motion.	53	
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- These studies will also provide insight into how the mutual interactions of quarks and gluons generate the nucleon mass and the masses of other hadrons. The nucleon mass is one of the single most important scales in all of physics, as it is the basis for nuclear masses, and thus the mass of essentially all of visible matter.

- The density of quarks and gluons which carry the smallest x , the fraction of the nuclear momentum (or that of its constituent nucleons), can grow so large that their mutual interactions enter a non-linear regime in which elegant, universal features emerge in what may be a new, distinct state of matter characterized by a “saturation momentum scale”. Probing this state requires high energy beams and large nuclear size (A), and will answer longstanding questions raised by the heavy ion programs at RHIC and the LHC.

To carry out this ambitious physics program, the EIC requires a comprehensive experimental program carefully designed to extract all of the physics from the scattering of electrons off of hadrons and nuclei. An ideal EIC detector must measure nearly every particle emerging from the interaction point, including its direction, its momentum, as well as its identity. Each of these aspects of the EIC physics program, and how a single comprehensive detector system could address them, was studied by the EIC scientific community and led to the community-authored “Yellow Report” [2]. The report also identified a set of detector performance requirements that flow down from the physics requirements of the EIC science program articulated in the NAS report:

- The outgoing electron must be distinguished from other produced particles in the event, with a pion rejection of 10^3 — 10^4 even at large angles, in order to characterize the kinematic properties of the initial scattering process. These include the momentum fraction of the struck target constituent (x) and the squared momentum transfer (Q^2).

- A large-acceptance magnetic spectrometer is needed to measure the scattered electron momentum, as well as those of the other charged hadrons and leptons. The magnet dimensions and field strength should be matched to the scientific program and the medium-energy scale of the EIC. This requires a nearly 4π angular aperture, and the ability to make precisely measurements of the sagitta of its curved trajectory, to measure its momentum down to low- p_t , and its point of origin, to distinguish particles from charm and bottom hadron decays.

- A high-purity hadron particle identification (PID) system, able to provide continuous (e/π) and (K/π) discrimination

out to the highest momentum (60 GeV), is important for identifying particles containing different light quark flavors.

- A hermetic electromagnetic calorimeter system, with matching hadronic sections, is required to measure neutral particles (particularly photons and neutrons) and, in tandem with the spectrometer, to reconstruct hadronic jets which carry kinematic information about the struck quark or gluon, as well as its radiative properties via its substructure.
- Far-forward detector systems, in the direction of incoming hadron, are needed in order to perform measurements of deeply-virtual Compton scattering and diffractive processes, e.g. by measuring the small deflections of the incoming proton and suppress incoherent interactions with nuclei.
- Far-backward detectors in the direction of the incoming electron are needed to reach the very lowest values of Q^2 , and to measure luminosity for both absolute cross-section extractions as well as precision spin dependent asymmetries.

As a response to the joint BNL/JLab call for detector proposals, this document presents the EIC Comprehensive QCD Experiment (ECCE), which has been designed, simulated and extensively studied by the 96 institutes in the newly-formed ECCE proto-collaboration. The ECCE detector has been designed to address the full scope of the EIC physics program as presented in the EIC white paper [3] and the NAS report. The specific requirements that each of the ECCE detector systems has to meet flow down, in turn, from the more general detector requirements described in the Yellow Report. Through judicious use of select articles of existing equipment, ECCE can be built within the budget envelope set out by the EIC project while simultaneously managing cost and schedule risks.

The ECCE concept reuses the BaBar superconducting solenoid as well as the sPHENIX barrel flux return and hadronic calorimeter. These two pieces of equipment are currently being installed in RHIC Interaction Region 8 (IR8) as part of the sPHENIX detector. Engineering studies have confirmed that these two components can be relocated to IR6, the IR where the EIC project currently plans to site the on-project detector. At the same time, should the EIC project change its plans, ECCE can be installed in IR8. Additional details concerning ECCE subsystems, performance, and selected physics objectives are provided in separate articles within this same collection.

2. ECCE detector overview

The ECCE detector consists of three major components: the central detector, the far-forward system, and the far-backward region. The ECCE central detector has a cylindrical geometry based on the BaBar/sPHENIX superconducting solenoid, and has three primary subdivisions: the barrel, the forward endcap

and the backward endcap (Fig. 2). Henceforth “forward” is defined as the hadron/nuclear beam direction and backwards the electron beam direction. We will use electron or backward, and hadron or forward interchangeably when describing the endcaps.

Table 1 lists the physics requirements in the ECCE central detector, the technical challenges associated with its realization, and the ECCE solutions that achieves the stated goals. Comments about future upgrade paths are also provided.

Table 2 presents similar information for the far-forward and far-backwards regions. These requirements, which guide our detector design, stem from the needs of the EIC science program presented in the EIC white paper and NAS report, and studied further in the EIC Yellow Report and CDR.

Figure 2 shows the ECCE central detector and lists its key components and the technology selected for each sub-system. Here, we provide general technical details on these detector technologies and their implementation:

Magnet ECCE intends to reuse the BaBar superconducting solenoid that is currently planned for use in the sPHENIX experiment and will be available after its conclusion. Its reuse for the EIC was the subject of an engineering study and risk analysis in 2020 [12] whose main conclusion was that the “magnet should be suitable for prolonged use as part of the detector system for the EIC project.” Additional performance assessment will be conducted during an sPHENIX long-duration high field test (at 1.4 T) planned in 2022. This test, followed by the first full duration run of sPHENIX in early 2023, will validate the feasibility of its reuse in ECCE. Preparing the solenoid for reuse will involve proactive maintenance and several minor modifications. We also plan to carry through a replacement magnet engineering and design assessment as risk mitigation, as described in Section 11.

Electron endcap The ECCE electron endcap region comprises four subsystems:

Tracker The silicon electron endcap detector consists of four disks, which provide precise measurements of charged tracks (especially electron tracks) in the backward pseudorapidity region. The technology for the silicon disk assembly is the ITS-3 silicon sensor with pixel pitch at $10\ \mu\text{m}$. The detector mechanical structure design will be informed by the EIC eRD111 studies. In addition, the AC-LGAD TOF detectors described below will provide an additional high-precision tracking point after the disks at large distance from the interaction point.

mRICH The design goal of the modular RICH (mRICH) is to achieve 3σ K/p separation in the momentum range from 3 to 10 GeV/c, within the physical constraints of the ECCE detector. It also provides excellent e/p separation for momenta below 2 GeV/c. In addition, the RICH detectors contribute to e/π identification. e.g., when combined with an EM calorimeter, the mRICH and hpDIRC will provide excel-

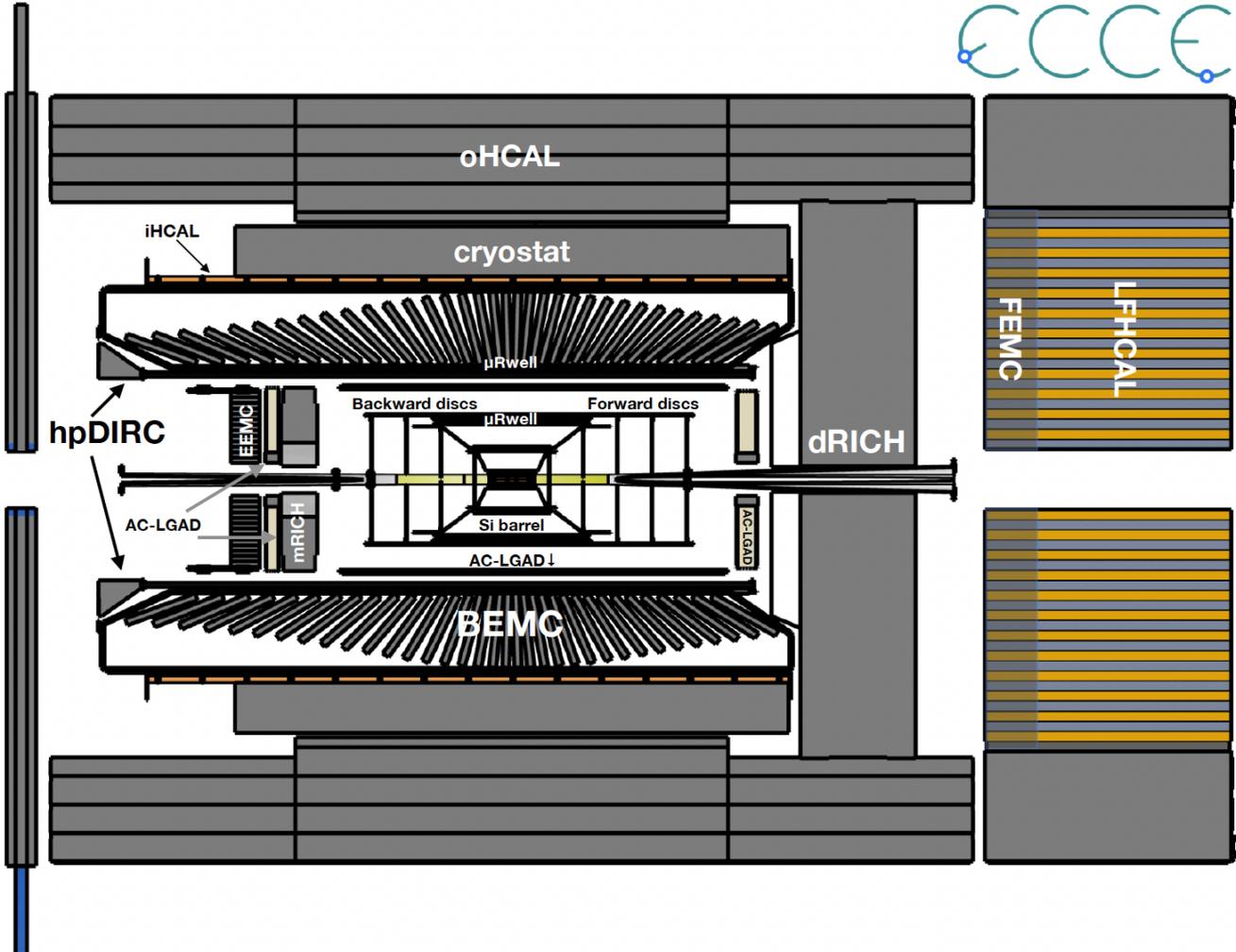


Figure 1: Side view of the full ECCE detector system, oriented with the hadron beam arriving from the left and the electron beam arriving from the right.

189 lent suppression of the low-momentum charged-pion²⁰⁹
 190 backgrounds, which limits the ability to measure the²¹⁰
 191 scattered electron in kinematics where it loses most²¹¹
 192 of its energy. 212

193 **AC-LGAD TOF** TOF measurement using AC-LGAD²¹³
 194 technology will be used for PID in the momen-²¹⁴
 195 tum range below the Cherenkov detectors thresholds.²¹⁵
 196 These detectors also provide a high-precision track-
 197 ing point. 216

198 **EEMC** The Electron Endcap EM Calorimeter (EEMC)²¹⁷
 199 is a high-resolution electromagnetic calorimeter that²¹⁸
 200 is capable of providing precision scattered electron²¹⁹
 201 and final-state photon detection in the region $-3.7 <^{220}$
 202 $\eta < -1.5$, required by the EIC science program. The²²¹
 203 choice of technology is 2 cm x 2 cm x 20 cm PbWO₄²²²
 204 providing 22 radiation lengths and the overall design²²³
 205 concept is the same as in the EIC YR. 224

206 **Fe flux return** We will use a passive flux return as we de-²²⁵
 207 termined there is no substantial benefits to our sci-²²⁶
 208 entific program by having an active an electron end-²²⁷

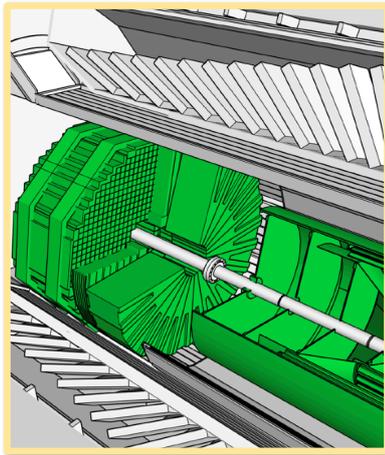
cap hadron calorimeter. We note that adequate space
 was left as a possible upgrade path towards high-
 luminosity running where one might want to mea-
 sure the jet distribution in the low- x , high- Q^2 region
 if the physics case would be made.

Central barrel The ECCE central barrel region comprises six
 subsystems:

Silicon Tracker The silicon barrel detector consists of
 five layers: three vertex layers close to the beam pipe
 and two middle layers providing the central track
 sagitta measurements. All layers use the ITS-3 sen-
 sors with pixel pitch at 10 μm with an average materi-
 al budget of 0.05% X_0 per layer.

μRwell Tracker The Si tracker is supplemented by two
 μRwell layers between the Si sagitta layer and the
 hpDIRC, and a single outer barrel μRwell layer be-
 tween the DIRC and BECAL.

AC-LGAD TOF is placed just before the hpDIRC to pro-
 vide a precise TOF measurement as well as an addi-



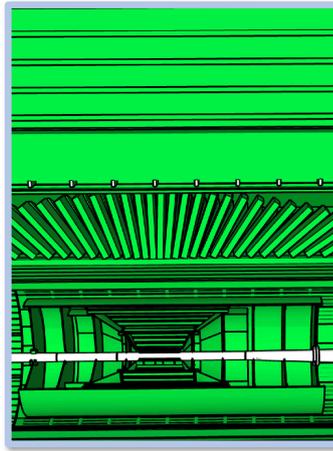
Backward Endcap

Tracking:

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

PID:

- mRICH
- AC-LGAD TOF
- PbWO₄ EM Calorimeter (EEMC)



Barrel

Tracking:

- ITS3 MAPS Si (vertex x3; sagitta x2)
- μ RWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μ RWell (after hpDIRC)

h-PID:

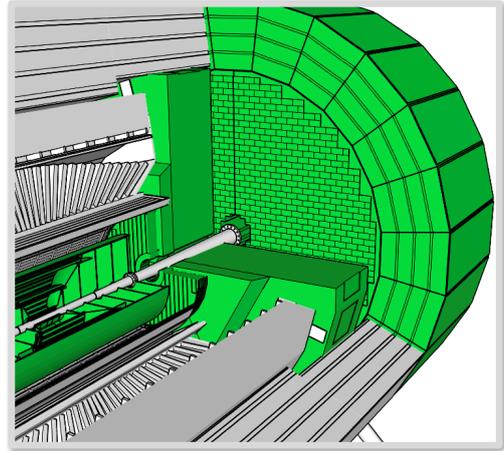
- AC-LGAD TOF
- hpDIRC

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)



Figure 2: Principal components of the ECCE central detector: backward/electron endcap (left), barrel (center), and forward/hadron endcap (right).

228 tional tracking point. See electron endcap discussion²⁴⁸
 229 for details. ²⁴⁹

230 **hpDIRC** The high-performance DIRC provides particle²⁵⁰
 231 identification with three standard deviations (s.d.) or²⁵¹
 232 more separation for π/K up to 6 GeV/c, e/π up to²⁵²
 233 1.2 GeV/c, and K/p up to 12 GeV/c. ²⁵³

234 **BECAL** The barrel ECAL (BECAL) is a homogeneous²⁵⁵
 235 projective electromagnetic calorimeter built out of²⁵⁶
 236 9088 clear scintillating glass (SciGlass) towers, ar-²⁵⁷
 237 ranged in 71 rings in the η direction, with 128 towers²⁵⁸
 238 per ring along ϕ . The SciGlass towers have a front²⁵⁹
 239 face of 4 cm \times 4 cm and are 55 cm deep including²⁶⁰
 240 \sim 10cm readout, providing 17 radiation lengths and²⁶¹
 241 better than 4%/ \sqrt{E} + (1–2)% resolution. This res-
 242 olution surpasses the EIC YR requirement to com-²⁶²
 243 plement the tracking system and ease electron iden-²⁶³
 244 tification and π/e rejection, with an eye to the future²⁶⁴
 245 high-luminosity EIC science needs. Their shape is²⁶⁵
 246 slightly tapered to be nearly projective to the interac-²⁶⁶
 247 tion point. ²⁶⁷

iHCAL/OHCAL The ECCE outer barrel hadronic calorimeter (oHCAL) is integrated into the barrel flux return for the ECCE solenoid magnet. and is a reuse from the sPHENIX experiment. Its design consists of 32 sectors of 1020 magnet steel, with an inner and outer radii of 1.9 m and 2.6 m respectively. Each sector is 6.3 m long and weighs 14 tons. The barrel inner HCAL (iHCAL) is a hadronic calorimeter that is integrated into the BECAL support frame. Its design consists of 32 sectors of stainless steel, with an inner radius of 135 cm and an outer radius of 138.5 cm.

Hadron endcap The ECCE hadron endcap region comprises five subsystems:

Tracker The silicon hadron endcap detector consists of five disks, which provide precisely measured space points for charged particle tracking in the forward pseudorapidity region. This detector will enhance the capability to determine the decay vertex of long decayed particles and measure the majority of

Table 1: Key detector requirements for ECCE central detector, with associated challenges, and a brief description of the ECCE approach to address each issue.

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 μ RWELL between hpDIRC and EMCal to seed PID performance of hpDIRC and improve tracking 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	μ RWELL 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 μ RWELL, AC-LGAD, and far outer μ RWELL 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.

charged particles in the asymmetric $e + p$ and $e + A_{291}$ collisions. The technology for the silicon disk as-²⁹²sembly is ITS-3 silicon sensor with pixel pitch of²⁹³ 10 μm . The detector mechanical structure design will²⁹⁴ be informed by the EIC eRD111 studies. An AC-²⁹⁵LGAD TOF detector placed in front of the dRICH²⁹⁶ will provide an additional high-precision tracking²⁹⁷ point.²⁹⁸

AC-LGAD TOF See electron endcap for details.²⁹⁹

dRICH The dual-radiator Ring Imaging Cherenkov³⁰⁰ (dRICH) detector is designed to provide continu-³⁰¹ous hadron identification in the (outgoing) ion-side³⁰² with 3 s.d. or more for π/K from ~ 0.7 GeV/c to³⁰³ ~ 50 GeV/c, and for e/π from a few hundred MeV/c³⁰⁴ up to ~ 15 GeV/c.³⁰⁵

FEMC The forward ECal (FEMC) will be a Pb-³⁰⁶Scintillator shashlik calorimeter. Its towers have³⁰⁷ an active depth of 37.5cm with an additional 5cm³⁰⁸ readout space. Each tower consists out of 66 lay-³⁰⁹ers of alternating 1 cm \times 1 cm \times 0.16 cm Pb and³¹⁰ 1 cm \times 1 cm \times 0.4 cm Scintillator material.³¹¹

LFHCAL The forward HCal (LFHCAL) is a steel-³¹²scintillator calorimeter. Its towers have an active³¹³

depth of 1.4 m with an additional space for the read-³¹⁴out of about 20-30 cm depending on their radial po-³¹⁵sition. Each tower consists out of 140 layers of al-³¹⁶ternating 5cm x 5cm x 1.6cm steel and 5cm x 5cm x³¹⁷ 0.4cm scintillator material. In each scintillator a loop³¹⁸ of wavelength shifting fiber is embedded. 10 consec-³¹⁹utive fibers in a tower are read out together by 1 Sili-³²⁰con photo multiplier, leading to 7 samples per tower.

Far-forward detectors The auxiliary detectors consist of a set³²¹ of trackers and calorimeters that are, in general, closely³²² integrated with the beam elements. The systems are de-³²³signed to measure very forward and backward particles to³²⁴ high precision with a high rejection of beam related back-³²⁵ground. The far forward and far backward detection sys-³²⁶tem consists of the following components:

B0 spectrometer The B0 spectrometer measures charged³²⁷ particles and photons at forward ($\eta > 3$) angles³²⁸ to facilitate studies if exclusive processes and gen-³²⁹eral process characterization. This subsystem is de-³³⁰signed for reconstructing charged particles with an-³³¹gles $5.5 < \theta < 20.0$ mrad, and also large angle pro-³³²tons from nuclear breakup. The B0 detector is em-³³³bedded in the first dipole magnet after the interaction

Table 2: ECCE Detector Far-Forward/Far-Backward requirements

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 (~ 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

point (B0pf). It consists of four layers of AC-LGAD tracking planes followed by an array of PbWO₄ crystals for the photon detection. The PbWO₄ array consists of 250 crystals, each 10 cm long with a surface area of 2x2 cm² to enable measurement of processes such as u-channel DVCS.

Zero-Degree Calorimeter The ZDC consists of four different calorimeters.

- PbWO₄ Crystal calorimeter: For good measurement of low energy photons. In front of the crystal layer, a silicon pixel layer is attached.
- W/Si sampling calorimeter: This is an ALICE FoCal-E style calorimeter and consists of alternating tungsten plates and silicon sensor planes. It is meant to measure the residual photon energy escaping the PbWO₄ Crystals and the shower development of photons and neutrons.
- Pb/Si sampling calorimeter: This is a calorimeter with 3 cm-thick lead plane absorbers and active silicon pad layers, where the pad-layer design is as in the W/Si calorimeter.
- Pb/Sci. sampling calorimeter: This is to measure hadron shower energy and uses 3 cm thick lead plane absorbers with 2 mm-thick scintillator planes as active materials. The calorimeter is segmented as 10 cm x 10 cm on a plane and 15 layers of scintillator planes will be read together, making a tower.

Far-backward detectors The auxiliary far-backward detectors consist of a set of trackers and calorimeters.

Low- Q^2 tagger Two detection systems located at different distances from the beam, each including two AC-

LGAD tracking layers followed by a high-resolution PbWO₄ calorimeter.

Luminosity monitor Forward PbWO₄ calorimeter with a passive x-ray absorber and a two-arm e^+/e^- pair spectrometer. Each includes with AC-LGAD tracking layers and a high-resolution PbWO₄ calorimeter.

Electronics/DAQ The ECCE DAQ is a fully streaming readout (SRO) design capable of supporting high bandwidth to the Event Buffer and Data Compressor (EBDC) computers as well as high bandwidth to the data storage. A key component of this design is the Data Aggregation Module (DAM), the model for which we take as the current ATLAS FELIX board that will be used by sPHENIX in their hybrid streaming DAQ. We assume the development of a specific iteration of a FELIX-like board [13] as the DAM board for ECCE (also referred to as "EIC-FELIX" in the text that follows) that will serve as a common interface for all the subsystems. The use of a common interface reduces the number of electronics designs that needs to be verified and supported throughout the lifetime of the experiment.

The general design of the ECCE data acquisition builds on the sPHENIX DAQ system, which already incorporates and demonstrates almost all concepts of the envisioned ECCE DAQ system. However, while sPHENIX had to be a hybrid of triggered and streaming readout components, the ECCE DAQ will be built around a trigger-less Streaming Readout (SRO) concept from the start, similar to many of the JLab streaming readout systems currently under test.

Computing ECCE computing will be based on a distributed model with multiple sites for calibration, storage and computing. The model calls for disk space sufficient for holding up to 3 weeks of data so calibrations can be generated

379 and reconstruction done in near-time. Tape storage will
 380 be used for backup, but will not be part of the primary
 381 pipeline for analysis.

382 **Infrastructure** The detector infrastructure consists of the con-
 383 ventional mechanical and electrical facilities necessary to
 384 construct and operate the detector. Specific components
 385 to ECCE are: specialized carriage and structural compo-
 386 nents, specialized installation engineering and compo-
 387 nents.

388 Figure 3 shows the material distribution of the ECCE central
 389 detector via a radiation length scan of the detailed ECCE
 390 GEANT4 model. The large acceptance and low mass inner
 391 tracker (green) is hermetically enclosed by the PID de-
 392 tectors (red and yellow) and EM calorimetry (blue). Hadronic
 393 calorimeters further cover $\eta > -1.1$.

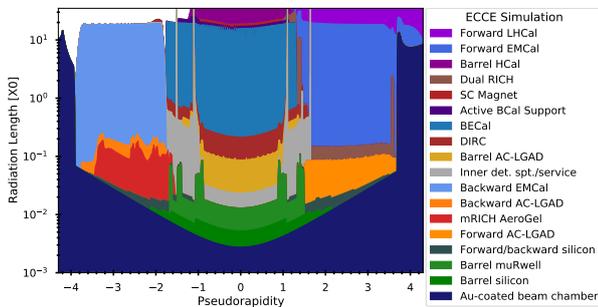


Figure 3: The stacked plot of material distribution in the ECCE detector subsystems, which is quantified as the radiation length that photons from the central interaction point observe and is averaged over azimuth.

394 3. Magnet

395 The BaBar superconducting solenoid will be repurposed for
 396 the ECCE experiment. It was previously moved from SLAC
 397 to BNL for use in the sPHENIX experiment at RHIC. ECCE
 398 plans to reuse the BaBar/sPHENIX solenoid and the surround-
 399 ing combined hadronic calorimetry and flux containment sys-
 400 tem for the magnet.

401 The magnet for the BaBar experiment at PEP-II at SLAC was
 402 manufactured by Ansaldo in 1997 and commissioned in 1998.
 403 It was transferred to BNL in 2015 for use in the sPHENIX ex-
 404 periment and passed an initial high-field test (up to 1.3 T) in
 405 2018. Its main design parameters are listed in Table 3. For an
 406 EIC detector the region covered by the barrel detectors should
 407 span a pseudo-rapidity $-1 < \eta < 1$, corresponding to an angle
 408 of ~ 40 degrees. This corresponds well with the BaBar solenoid,
 409 which has a warm bore diameter of 2.84 meters and a coil length
 410 of 3.512 meters, corresponding to a 39 degree angle.

411 The reuse of the BaBar solenoid for the EIC was the subject
 412 of an engineering study and risk analysis in 2020 [12]. The
 413 main conclusion of the assessment was that the “magnet should
 414 be suitable for prolonged use as part of the detector system
 415 for the EIC project.” The report also suggested the implemen-
 416 tation of several maintenance and improvement modifications,



Figure 4: The BaBar solenoid in late February 2022, during installation in the sPHENIX experiment. The solenoid is surrounded by the barrel outer hadronic calorimeter and flux return. The barrel flux return (outer hadronic calorimeter) and BaBar solenoid are items planned to be reused by the ECCE experiment. The experimental cradle may also be reused.

417 including new protection circuits such as voltage taps, inspec-
 418 tion and, as needed, reinforcement of the internal mechanical
 419 support, including new strain gauges, and replacement of control
 instrumentation sensors. The implementation of some of these
 suggestions would involve opening the magnet cryostat, which
 would create additional risk of magnet failure. In 2021 JLab
 engineers revisited the risk analysis and, following extensive
 discussions, decided that any modifications or refurbishment
 that require opening the BaBar solenoid cryostat would not
 be worth the additional risk [14]. They further noted that no
 such actions will be necessary if the magnet continues to oper-
 ate well throughout a high-field magnet test with the sPHENIX
 experiment flux return (which will also be re-used for ECCE)
 in mid-2022 and subsequent initial sPHENIX experimental
 operations starting in 2023 (until 2025).

Further magnet engineering studies of the ECCE detector
 magnet indicate that the unbalanced forces on the magnet are
 small, a net force of 4kN or less than 1000 lbs, because the
 magnetic field at the locations of the ECCE forward and back-
 ward calorimeters are small and most of the magnetic flux is
 returned through the barrel. These small forces should not
 present a substantial engineering difficulty in the proposed
 ECCE configuration.

The scope of the reuse of the BaBar solenoid in ECCE
 includes a review by a panel of experts (following initial

Table 3: Design parameters of the BaBar superconducting solenoid.

Central Induction	1.5 T* (1.4 T in ECCE flux return)
Conductor Peak Field	2.3 T
Winding structure	Two layers, graded current densit
Uniformity in tracking region	$\pm 3\%$
Winding Length	3512 mm <i>at R.T.</i>
Winding mean radius	1530 mm <i>at R.T.</i>
Operating Current	4596 A (4650 A*)
Inductance	2.57 H (2.56 H*)
Stored Energy	27 MJ
Total Turns	1067
Total Length of Conductor	10,300 m

* Design Value

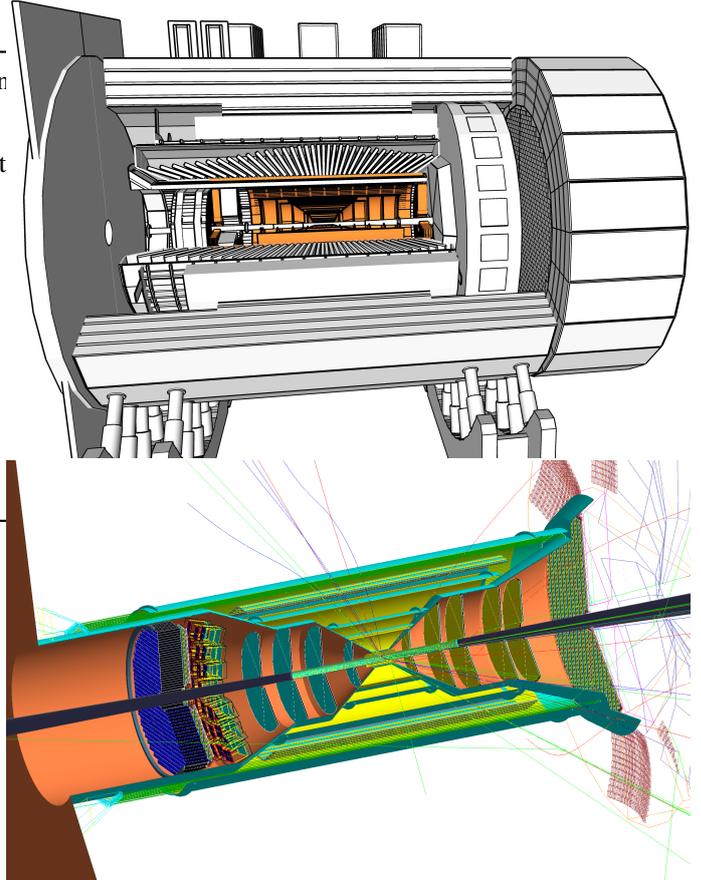


Figure 5: Tracking system of ECCE in mechanical model (top) and GEANT4 simulation (bottom). The tracking system is tightly integrated with the PID detectors which is also shown on the right. Support and cabling for these detectors was implemented (copper-colored cylinder-cone) to count for its material and acceptance effects.

442 sPHENIX running), the disconnect of the magnet in IP-8 and
 443 move to IP-6, a new valve box, and assembly and magnet map-
 444 ping in IP-6. The risk mitigation strategy associated with the re-
 445 use of the BaBar solenoid, including the design of a potential
 446 replacement magnet, are discussed in Section 11.

447 4. Tracking

448 ECCE features a hybrid tracking detector design (Figure 5)
 449 using three state-of-the-art technologies to achieve high pre-
 450 cision primary and decay vertex determination, fine tracking
 451 momentum and distance of closest approach resolution in the
 452 $|\eta| \leq 3.5$ region with full azimuth coverage [15]. The ECCE
 453 tracking detector consists of the Monolithic Active Pixel Sensor
 454 (MAPS) based silicon vertex/tracking subsystem, the μ RWELL
 455 tracking subsystem and the AC-LGAD outer tracker, which also
 456 serves as the ToF detector. The ECCE tracking design has been
 457 optimized assisted by Artificial Intelligence (AI) as further dis-
 458 cussed below taking into account BaBar magnet coverage, in-
 459 tegration with the other detector subsystems, and cost.

460 The detector geometry is shown in schematic form in Fig. 6
 461 which displays the detector in the $R - z$ plane. The barrel layers
 462 centered at $z = 0$ have a cylindrical geometry, while the end-
 463 cap layers centered at $R = 0$ are disks oriented around the z
 464 axis. The MAPS silicon detector contains 3-layer silicon ver-
 465 tex layers, 2-layer silicon sagitta layers, five disks in the hadron
 466 endcap and four disks in the electron endcap region. This sil-
 467 icon vertex/tracking detector provides the desired primary ver-
 468 tex and displaced vertex reconstruction also documented in the
 469 EIC yellow report [16] and the essential tracking momentum
 470 and DCA_{2D} resolutions (see Fig. 8 and Fig. 9) for heavy fla-
 471 vor measurements. For the barrel at large radii, which have the
 472 largest surface area, cylindrical μ RWELL gas trackers are used
 473 to optimize performance at reduced overall cost. These are in-
 474 troduced both right outside the Si tracker and in front of the bar-
 475 rel EM calorimeter. In addition, an AC-LGAD based ToF layer
 476 in each section provides a precision space-time measurement

on each track. The tracking system is thus tightly integrated
 with the PID detectors.

4.1. MAPS

The silicon vertex and sagitta layers utilize Monolithic Ac-
 tive Pixel Sensor (MAPS) technology, as implemented in
 high-precision ($10 \mu\text{m}$ pixel pitch) low-material (0.05%/layer)
 ALICE-ITS-3-type sensors [17, 18], used in both cylindrical
 and disk configurations.

The MAPS detector systems have been costed using the Tow-
 erJazz 65nm production line. This technology is in the pro-
 totype sensor design and characterization stage. Recent R&D

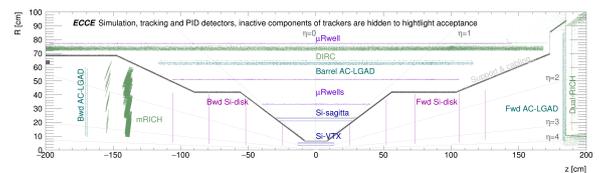


Figure 6: Schematic view of the ECCE tracker, including silicon, μ RWELL, AC-LGAD, DIRC, mRICH and dRICH detector systems. **Need better version of this image.**

488 on the ITS-3 has delivered a 32 by 32 pixel matrix prototype⁵³⁰
 489 sensor using the 65nm production line that is undergoing beam⁵³¹
 490 test studies at CERN. Validation of the curved ALPIDE (ITS-⁵³²
 491 3) sensor performance has obtained by early beam test results.⁵³³
 492 The mechanical design for the silicon tracking detector, espe-⁵³⁴
 493 cially for the stave and disk layout and assembly, is led by the⁵³⁵
 494 ongoing EIC R&D project eRD111. Reduction of the mate-⁵³⁶
 495 rial budgets for the EIC silicon tracking detector service parts⁵³⁷
 496 is also being studied as part of the EIC eRD104 project. Alter-⁵³⁸
 497 native silicon technologies have been explored such as the De-⁵³⁹
 498 pleted MAPS (DMAPS), and progress in the MALTA DMAPS
 499 technology has been reported in [19]. All these R&D activities⁵⁴⁰
 500 align with other major project upgrades or construction projects⁵⁴¹
 501 such as the ALICE ITS-3 upgrade. The required sensor R&D⁵⁴²
 502 is included in the ECCE detector R&D plan.

503 4.2. μ RWELL

504 The μ RWELL technology is a single-stage amplification Mi-⁵⁴⁷
 505 cro Pattern Gaseous Detector (MPGD) that is a derivative of the⁵⁴⁸
 506 Gas Electron Multiplier (GEM) technology. It features a single⁵⁴⁹
 507 kapton foil with GEM-like conical holes that are closed off at⁵⁵⁰
 508 the bottom by gluing the kapton foil to a readout structure to⁵⁵¹
 509 form a microscopic *well* structure. The technology shares simi-⁵⁵²
 510 lar performances with a GEM detector in term of rate capability,⁵⁵³
 511 while providing a better spatial resolution than GEM. Further-⁵⁵⁴
 512 more, compared to GEMs, μ RWELL presents the advantages⁵⁵⁵
 513 of flexibility, more convenient fabrication and lower production⁵⁵⁶
 514 cost that makes it the ideal candidate for large detectors. Large⁵⁵⁷
 515 area μ RWELL foils have already been developed and manufac-⁵⁵⁸
 516 tured at CERN. In ECCE μ RWELL layers will form three barrel⁵⁵⁹
 517 tracking layers further out from the beam-pipe than the silicon⁵⁶⁰
 518 layers. The barrel gas tracker layers include two inner barrel⁵⁶¹
 519 μ RWELL layers, as well as a single outer barrel μ RWELL. All⁵⁶²
 520 μ RWELL detectors will have 2D strip based readout. The strip⁵⁶³
 521 pitch for all three layers will be 400 μ m. Figure 7 shows the⁵⁶⁴
 522 resolution results from a μ RWELL prototype detector in test⁵⁶⁵
 523 beam at Fermilab (June-July 2018) as part of the EIC eRD-6⁵⁶⁶
 524 activities. The measurements were done using a beam hitting⁵⁶⁷
 525 the detector perpendicularly, and using detailed MC simulations⁵⁶⁸
 526 we estimate a 55 μ m resolution for a curved geometry where the⁵⁶⁹
 527 particle hits the detector at an angle. Funding was recently se-⁵⁷⁰
 528 cured, and work is underway by ECCE collaborators to build⁵⁷¹
 529 and test large area cylindrical μ RWELL detectors.

The Korean institutions in the ECCE collaboration will man-
 ufacture the μ RWELL foils for the ECCE μ RWELL detectors.
 Specifically, a Korean manufacturer (Mecaro) has demonstrated
 that they can produce high quality large MPGD foils for the
 CMS detector at the LHC, working in conjunction with mem-
 ber institutions of the Korean ECCE collaboration. In addition,
 Chinese institutions in the ECCE collaboration have experience
 with the DLC resistive coating required for μ RWELL detectors.
 We are confident that the foreseen arrangement will be success-
 ful.

543 4.3. AI optimization

544 A detailed study of the detector design with AI has been ac-
 545 complished during the ECCE detector proposal development
 and a framework for Multi-Objective Optimization (MOO) has
 been incorporated in the ECCE detector design simulation. AI
 has played a crucial role in choosing the combination of tech-
 546 nologies for the inner tracker. The choice of having ITS-3 and
 the μ RWELL gas tracking layers, as well as the disk mini-
 mum radii were supported by AI. This has been an iterative
 process that evolved over time and required interplay between
 the ECCE teams working on Physics, Detector and Computing.

Our approach deals with a complex optimization in a mul-
 tidimensional design space driven by multiple objectives that
 encode the detector performance, while satisfying several me-
 chanical constraints. This framework has been developed for
 the optimization of the inner tracker of ECCE and can in prin-
 ciple be extended to another sub-detector or to a system of
 sub-detectors, provided a viable parametrization of the detec-
 tor simulation can be produced. Different parametrizations of
 the inner tracker design have been explored and most of our
 studies have been characterized by at least 11 parameters in the
 design space characterizing the location of the tracking layers
 in the central region and the disks in the two endcaps. The
 parametrization has been extended to include the support struc-
 ture in the design optimization process and more recently to
 the outer tracking layers. The different designs have been opti-
 mized with particle gun samples of pions and then studied and
 validated with independent data samples and physics analyses.
 At least three objective functions have been optimized simulta-
 neously. In particular, for a 3-objective problem we utilized the
 momentum resolution, the polar angular resolution along with
 the Kalman filter efficiency of π tracks. This problem has been
 tackled with evolutionary algorithms to assist the design dur-
 ing the detector proposal. A recently developed framework for
 MOO, PYMOO [20], has been implemented which supports algo-
 rithms like NSGA-II and NSGA-III [21] and distributed evalua-
 tion with task scheduler like Dask [22].

577 This approach accommodated both mechanical and geomet-
 578 rical constraints during the optimization process. In our studies
 we included at least 5 constraints (*e.g.*, the outermost location
 as well as the difference between the outer and inner radius of
 a disk, or the radius of the outermost layer in the inner tracker).
 Overlaps in the design are excluded by a combination of con-
 581 straints, ranges for the exploration of the parameters and in-
 582 ternal checks done before and during the entire optimization
 process. Further details can be found in [23].

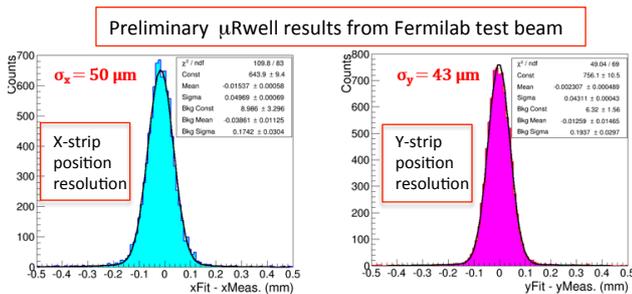


Figure 7: Preliminary results of spatial resolution performances of the
 μ RWELL prototype with 2D X-Y strip readout layer.

The AI-assisted design has been used as input to multiple iterations of the ECCE tracker design, which led to the current tracker layout [15] (Fig. 5 and 6), and is also contributing to the ongoing project R&D to reduce the impact of readout and services on the tracking resolution as discussed in Section 4.6.

4.4. Expected backgrounds

Vacuum and background estimates were done in joint working group meetings across proto-collaborations. A detailed simulation study was carried out to assess the collision signal and background from beam gaps and Synchrotron radiation on tracking detectors in BaBar magnetic field [24]. Although the beam gas background was found to be small, the Synchrotron radiation on the MAPS-based silicon trackers can be very significant and its uncertainty is large at this stage of the EIC design. A high-Z coating in the Be-section of the beam pipe (e.g. $2\ \mu\text{m}$ Au coating) was shown to reduce the Synchrotron hit rate in the silicon vertex tracker by four orders of magnitude resulting in a manageable hit rate [24, 25]. Therefore, all ECCE studies adopted such Synchrotron shielding coating which introduces $0.06\% X_0$ (at $\eta = 0$) of additional material to the beam pipe ($\sim 30\%$ relative increase).

4.5. Tracking performance

The performance of the ECCE reference tracker design has been studied using single pions propagated through the GEANT4 simulation framework. The momentum resolution is presented in Fig. 8 with the YR requirement indicated as dash lines. In the region ($-1 < \eta < 3.0$) the ECCE momentum resolution is consistent with YR physics requirements for all bins. We note that between $1 < \eta < 1.5$ we do see a substantial deviation that is not obvious in Figure 8. This difference is expected, as ECCE simulations take into account material for readout and services (copper-colored structure in right of Figure 5), whose impact is largest in this region. Further AI-assisted optimization in this region is on-going as discussed in Section 4.6. In the backward region $\eta < -1.0$ and in the most forward bin the ECCE momentum resolution provided by tracking is larger than what is required by the YR requirements. However, ECCE is an integrated detector and in this region the physics performance, and in particular for $\eta < -2.5$ is achieved through excellent EM calorimetry. Due to the limited time since the call for proposals to produce and analyze complete GEANT4 simulations for physics performance, many of the physics studies used a tracking alone without the improvements that calorimetry can provide. Nevertheless, these studies all show excellent performance for EIC physics. The addition of the calorimetry information will only improve these results, as shown for key physics topics. We further note the dominant YR requirement for the momentum resolution in the backward region is driven by coherent J/ψ production on the nuclei, and in particular the t -reconstruction from the forward particles. Nonetheless, the ECCE physics studies have shown that for both 1.4 T and 3.0 T field strengths the t -reconstruction resolution is dominated by the calorimeter.

The resolution of measurements of distance-of-closest-approach (DCA_{2D}), which is critical for heavy flavor measurements, is provided in Fig. 9 and also compared with YR requirement. The ECCE DCA resolution is consistent with YR requirements, and delivers robust physics programs in heavy flavor measurements and beyond standard model search.

4.6. Ongoing R&D for support structure optimization

Given the importance of the service structure in the tracking detector, the reduction of the impact of readout and services on tracking resolution is subject of ongoing R&D and ECCE has made tremendous progress on this front using AI. The AI investigation in the ECCE framework focused on optimizing the tracker design with a projective support cone structure that reduces the amount of material a particle traverses. The design concept is illustrated in the Tracking Tech Note [15] and more details on the AI based studies can be found in [23]. The momentum resolutions resulting from this investigation are shown in Fig. 10. The largest impact is in the region between central barrel and endcaps ($1 < \eta < 1.5$ and $-1.5 < \eta < -1$) while the tracking momentum resolution in the central barrel as well as at large pseudo-rapidities ($|\eta| > 1.5$) is largely unaffected.

5. Particle Identification

The ability to identify hadrons in the final state is a key requirement for the physics program of the EIC. Being able to tag the flavor of the struck quark in semi-inclusive DIS can, for instance, provides valuable information about the transverse momentum distributions (and potentially orbital angular momentum) of the strange sea, while open charm (with subsequent decays into kaons) is important for probing the distribution of gluons in protons and nuclei.

The choice of ECCE PID detector technologies was based on the outcome of the EIC generic R&D program (eRD14 EIC PID Consortium and eRD29 on TOF with the LGADs technology), started in 2015, and in line with the baseline EIC detector concept in the Yellow Report (YR) [16]. The longitudinally compact, modular RICH (mRICH), the radially thin high-performance DIRC (hpDIRC), the dual-radiator RICH (dRICH), and AC-LGADs based TOF, provide excellent PID over a wide momentum range for the full final state phase space [26]. The geometries of all PID detectors were optimized to fit the ECCE baseline design while maintaining the required performance. Figure 11 (left) shows the four PID systems in a 3D model of the ECCE detector and (right) their π/K separation coverage as a function of momentum and pseudo-rapidity for a sample of physics events. Compared to the YR reference detector, a number of key design features of the PID systems were optimized for ECCE.

The expected PID performance of the three ECCE Cherenkov detectors was obtained from standalone GEANT4 simulation and analytical calculations, parametrized and used as input into the ECCE physics studies. Figure 12 shows the parametrized π/K separation power in units of the number of

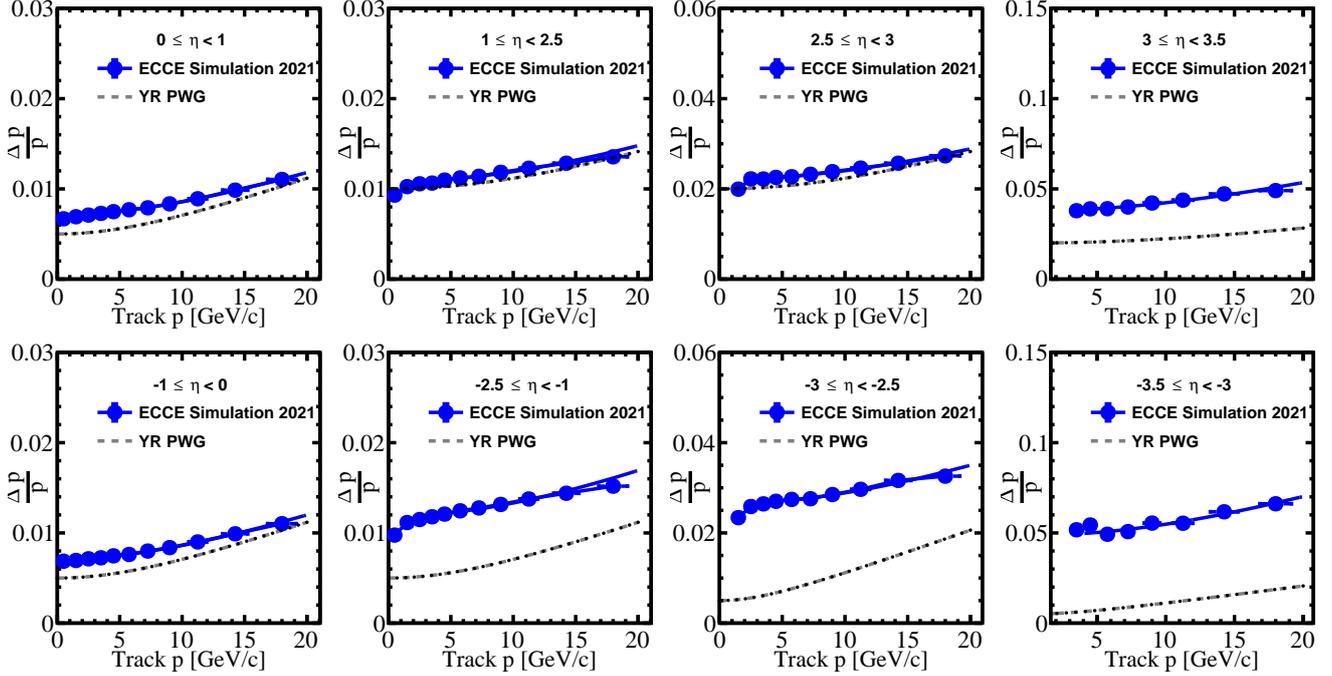


Figure 8: ECCE pion track momentum resolution (data points) with the EIC YR PWG requirements for the tracker indicated by the dashed lines. Note that the ECCE performance simulations take into account materials for readout and services. The impact of these can be observed most clearly in the bins covering the barrel/barrel endcap transition regions. As an integrated EIC detector with all subsystems operating in a complementary way, ECCE achieves the EIC physics goals.

standard deviations as a function of pseudo-rapidity and momentum for conservative assumptions for the tracking angular-resolution.

Note that subsequent tuning of the PID detector geometries and reconstruction algorithms resulted in further improvement of the PID performance, which are not reflected in the shown parametrization. The resulting momentum coverage for the separation of e/π , π/K , and K/p with three standard deviations or more is summarized in Table 4 for the three Cherenkov systems. The Cherenkov system performance is further separated into the nominal “Ring Imaging” mode of operation, which provides positive ID of the particle type, and the so-called “threshold mode” or “veto mode”, which uses the number of Cherenkov photons in excess of the expected background to differentiate between particle types above or below the threshold for Cherenkov light emission. The combined performance of the ECCE Cherenkov detectors meets or exceeds the ECCE PID requirements.

Table 4: Summary of the PID performance of the ECCE Cherenkov systems (momentum coverage in GeV/c).

PID	Mode	mRICH	hpDIRC	dRICH	
				aerogel	gas
π/K	Ring Imaging	2 – 9	1 – 7	2 – 13	12 – 50
	Threshold	0.6 – 2	0.3 – 1	0.7 – 2	3.5 – 12
e/π	Ring Imaging	0.6 – 2.5	< 1.2	0.6 – 13	3.5 – 15
	Threshold	< 0.6	–	< 0.6	< 3.5

The Cherenkov systems provide, in addition to hadron PID,

a significant contribution to the e/π identification. When combined with the EM calorimeter, the mRICH and hpDIRC will provide excellent suppression of the low-momentum charged-pion backgrounds, which otherwise limit the ability of the EM-Cal to measure the scattered electron in kinematics where it loses most of its energy. The time-of-flight (TOF) system, using the AC-LGAD technology, will provide hadronic PID and electron identification in the momentum range below the thresholds of the Cherenkov detectors and provide a time resolution of 25 ps and a position resolution of about 30 μm over a 4 π coverage.

Figure 13 shows the realistic ECCE magnetic field with highlighted PID detectors envelopes. In the region of the hpDIRC detector plane, where the MCP-PMTs will be located, the magnetic field is at a level of 0.3–0.4 T, which provides a large safety margin in terms of the MCP-PMT field tolerance. Both RICH detectors in ECCE assume SiPM, which are insensitive to magnetic fields of this strength, as their baseline photosensor. Bending of the charged particle tracks in RICH detectors can have an impact on the performance, but no significant sensitivity was observed in the ECCE simulation studies so far.

5.1. mRICH

The novel design of the mRICH modules consists of four components. A block of aerogel serves as the Cherenkov radiator, immediately followed by an acrylic Fresnel lens, which focuses the ring image and acts as a UV filter. A pixelated optical sensor is located in the image plane, and flat mirrors form the sides of each mRICH module.

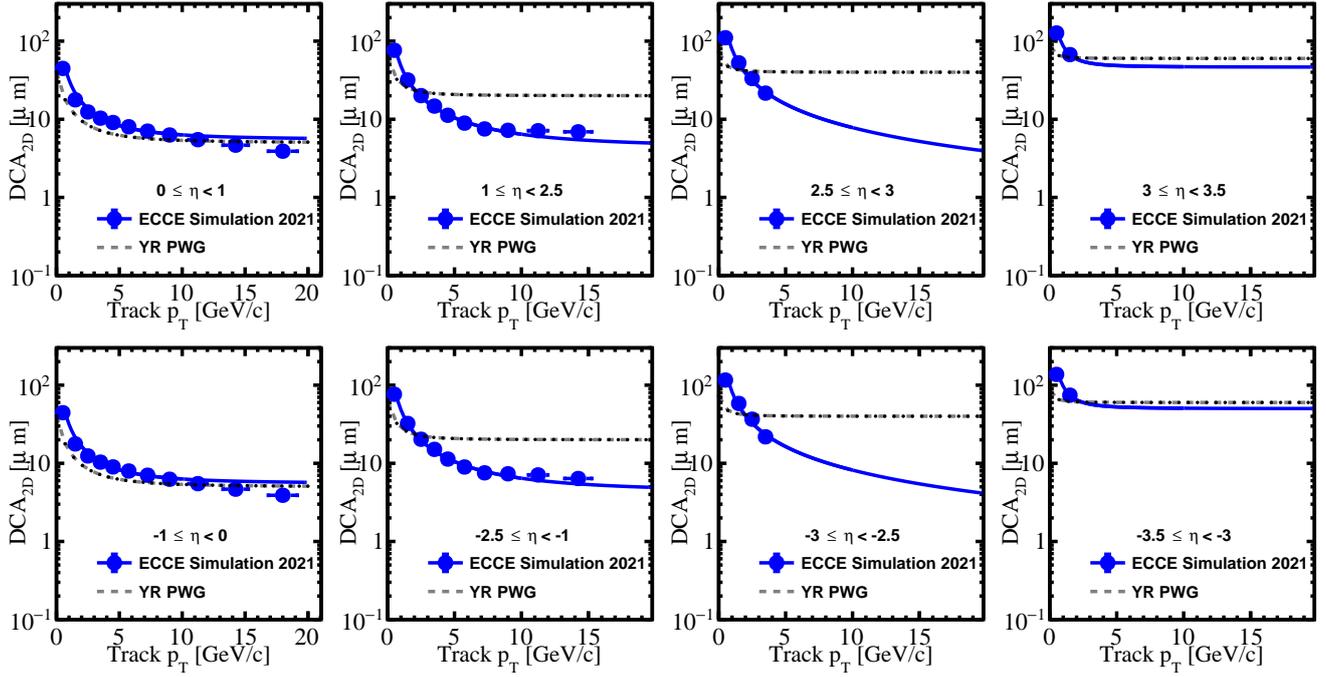


Figure 9: Pion DCA_{2D} resolutions (data points), which is compared to the EIC YR PWG requirement (dashed lines). The ECCE DCA resolution is consistent with YR requirements.

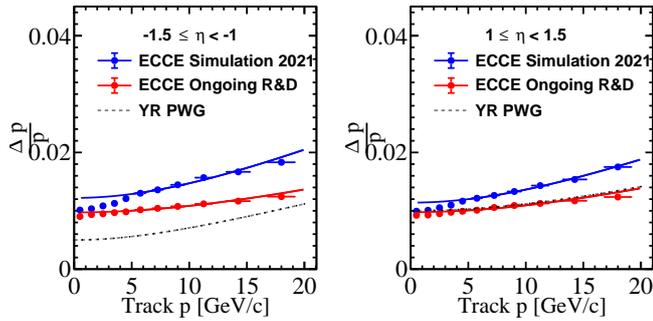


Figure 10: The momentum dependence of the tracker momentum resolution for the ECCE reference tracker design (ECCE Simulation, blue solid circles) and for the projective mechanical support design of the ECCE ongoing project R&D that will continue after the proposal (red solid circles). The latter shows a reduction of the impact of readout and services on the tracking resolution. Note that the backward region (left panel) relies on the EM calorimeter, and thus a resolution larger than the EIC YR PWG requirement is acceptable.

738 Several optimizations of the ECCE mRICH design were
 739 made compared to the YR reference detector: (1) the projective
 740 array design was optimized maximizing the acceptance, removing
 741 the polar-angle dependence, and reducing the material budget;
 742 (2) the dead region between the mRICH modules is minimized
 743 using optimized thin module walls and mirrors (shorter as well)
 744 (3) an integrated mRICH array mechanical design was designed,
 745 consistent with the simulated array configuration in GEANT4.

746 To study the performance of mRICH setup in ECCE, a set of
 747 tracks from the most demanding parts of the phase space were
 748 used, where the performance is expected to deteriorate, setting
 749 a lower limit on the performance and comparing it to what we
 750 see from the parametrizations. The study specifically focuses
 751 on the cases where the particles are incident at the surface of
 752 the aerogel closer to the outer edges with an outward angles
 753 and tracking angular resolution of 2.5 mrad. Fig. 14 shows the
 754 results for the e/π and π/K separation. The dips in the π/K
 755 separation at 2 and 3.8 GeV/c are due to the Cherenkov thresholds
 756 for kaons and protons in the aerogel. The obtained results show
 757 better performance than that used in the parametrization, shown
 758 in Fig. 12a, which indicates a better momentum reach once the
 759 mRICH reconstruction is further optimized.

761 5.2. hpDIRC

762 The radially-compact hpDIRC is based on a fast focusing
 763 DIRC design. Thin rectangular bars, made of synthetic fused
 764 silica, serve as Cherenkov radiators and guide the photons to the
 765 readout section where they are focused by a lens and recorded

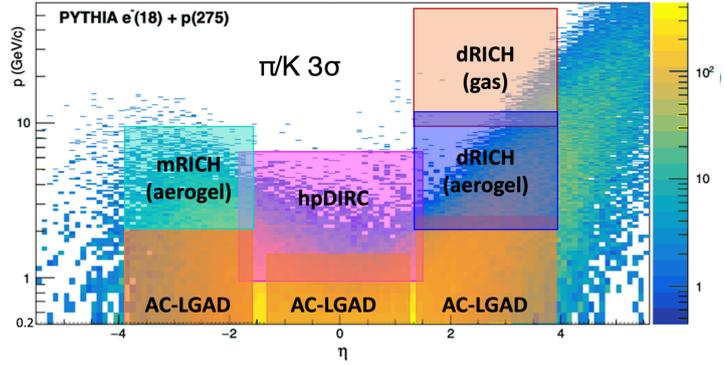
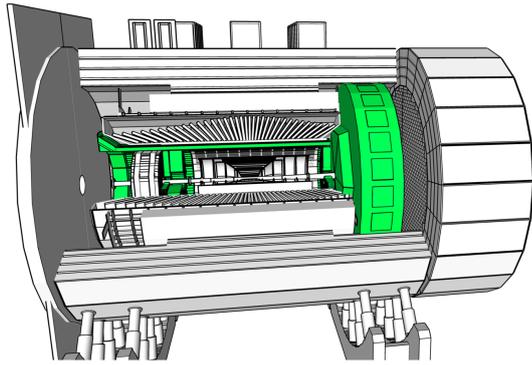


Figure 11: Left: 3D model of the ECCE detector with the PID systems highlighted. Right: Expected 3 s.d. π/K separation coverage for the ECCE PID systems as a function of the particle momentum and pseudo-rapidity. Full coverage is achieved by making use of the veto mode of the Cherenkov detectors, complementing the TOF PID in the low momentum region.

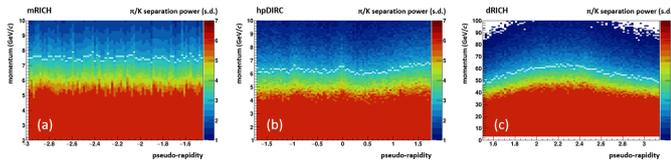


Figure 12: Parametrized π/K separation power in ECCE as a function of particle momentum and pseudo-rapidity for mRICH (a), hpDIRC (b), and dRICH (c) based on standalone full GEANT4 simulation and analytical calculation. The white symbol marks the maximum momentum for 3 s.d. π/K separation in each pseudo-rapidity bin. **Need as column of figures instead of a row OR double wide.**

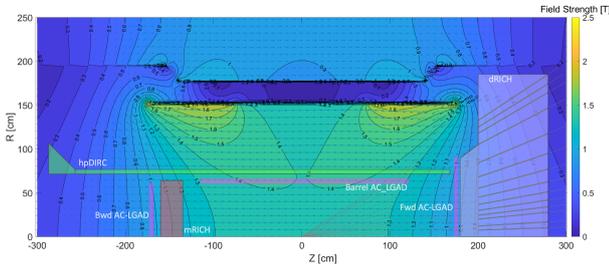
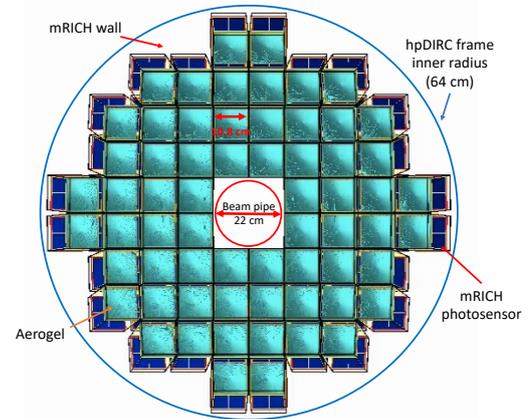


Figure 13: ECCE magnetic field map with the PID detector envelopes overlaid. **Need double wide figure or square with larger fonts.**

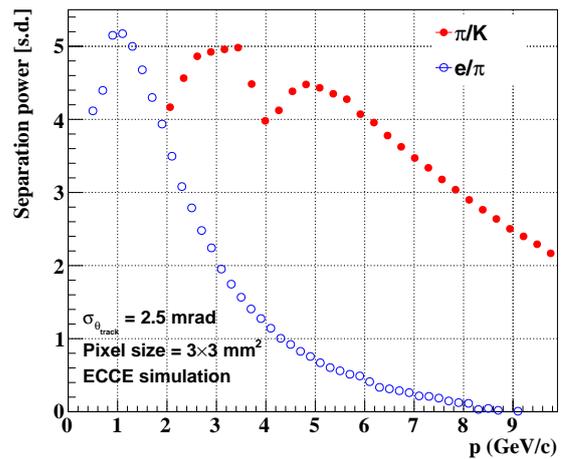


Figure 14: Left: Front view of mRICH module array in the allocated space projected towards the IP. Right: The separation power of the mRICH in units of number of standard deviations (s.d.) as function of particle momentum from ECCE simulation.

by an array of pixelated photon sensors, placed on the back surface of a fused silica prism expansion volume. Key features of the hpDIRC include three-layer spherical lenses, photosensors with small (3 mm×3 mm) pixels, and fast readout electronics.

Compared to the YR reference detector, several design aspects were optimized for ECCE. The expansion volume and readout were moved from the hadron side to the electron side for better detector integration and to minimize gaps in the EM calorimeter coverage. The bar box radius was decreased to match the EM calorimeter barrel size and the number of bar boxes, as well as the number of bars per bar box, were tuned to optimize the azimuthal coverage of the hpDIRC and to be consistent with the reuse of the BaBar DIRC bars. None of these changes had a significant impact on the performance of the hpDIRC.

Figure 15 shows the hpDIRC geometry as well as the expected performance of the hpDIRC from the standalone GEANT4 simulation studies for two particular cases. The black points show the separation power for charged pions and kaons as a function of the polar angle at a momentum of 6 GeV/c while the red points show the same quantity for charged pions and electrons at 1.2 GeV/c. The expected particle identification performance of the hpDIRC exceeds the ECCE PID goal of three standard deviation (s.d.) separation power for e/π up to 1.2 GeV/c and π/K up to 6 GeV/c for the entire polar angle range.

5.3. dRICH

The dual-radiator Ring Imaging Cherenkov (dRICH) detector configuration for ECCE consists of 6 identical, transversely open sectors. Each contains two radiators (aerogel and C₂F₆ gas), sharing the same outward focusing mirror and readout planes, which are instrumented with highly segmented photosensors (3 mm×3 mm pixels), located outside of charged particle acceptance. The photosensor tiles are arranged on a curved surface to compensate for aberrations. Photons from a Cherenkov cone may split over two or more sectors thanks to the open geometry of the dRICH sectors.

In comparison to the YR reference detector the ECCE dRICH radial size was scaled down by 25% to fit into the envelope limited by the HCAL and moved about 40 cm closer towards the IP to maintain the original acceptance.

Figure 16 shows the preliminary results of the dRICH K/π separation power for three incidence angles and selected momenta. The results are obtained from the full ECCE simulation framework with the realistic magnetic field map and the conservative tracking resolution. Note that the simulated design uses a simplified flat detector plane and that the mirror curvature is not fully optimized yet. The results are in good agreement with expectations and already reach the desired 3 s.d. or more over almost the full required momentum range. Further improvement of the dRICH performance is expected once the planned AI-based geometry optimization is completed.

5.4. AC-LGAD-based TOF

The AC-LGAD TOF system is based on a simple p-n diode concept, where the diode is fabricated on a thin high-resistivity

p-type silicon substrate. A highly-doped p-layer (the “gain” layer) is implanted under the n-type cathode. Application of a reverse bias voltage creates an intense electric field in this superficial region of the sensor to start an avalanche multiplication for the electrons. The drift of the multiplied carriers through the thin substrate generates a fast signal with a time resolution of ~20–30 ps.

The TOF layers were placed in each section of ECCE detector and their positions were optimized to best compliment the Cherenkov detectors to cover the lowest possible particle momenta with a nearly 4π coverage, and maximize the time (25 ps) and position (pixel granularity of 0.5×2.6 mm²) resolution. We further plan to use the DIRC timing measurement to supplement the AC-LGAD TOF measurement. This is especially useful for the $\eta \approx -1.5$ region where a gap exists in the AC-LGAD coverage and the DIRC offers excellent TOF resolution. Figure 17 (left) shows a visualization of the AC-LGAD geometry from the full GEANT4 simulation. Figure 17 (right) summarizes the performance of the TOF layers in each sector of the ECCE detector for π/K , e/π , and K/p separation.

The PID performance in terms of $1/\beta$ vs. p for the central barrel, as a benchmark, is shown in Fig. 18 (left) for an expected timing precision of 25 ps. The long dashed lines indicate the $\pm 3\sigma$ range around mean $1/\beta$ values for each particle species. As shown, the $\pm 3\sigma$ bands for pions and kaons are well separated over a momentum range of $0.1 < p < 1.3$ GeV/c, while proton identification is further extended to around 2.2 GeV/c. For electrons, clean separation from pions is achieved for $p < 0.45$ GeV/c by at least 3σ . Similar performance studies are also carried out for endcap TOFs.

The resolution of the start time, t_0 , self-determined by the scattered electron and final-state hadrons via an iterative fitting procedure, was included in all performance studies and is shown in Fig. 18 (right). In addition to providing hadronic PID, the excellent position resolution of AC-LGADs TOF significantly improves the momentum resolution of high momentum particles in the very forward region.

6. Electromagnetic and Hadronic Calorimetry

The ECCE electromagnetic calorimeter system[27] consists of three components which allow high precision electron detection and hadron suppression in the backward, barrel, and forward directions. Hadronic calorimetry is essential for the barrel and forward endcap regions for hadron and jet reconstruction performance. Jet yields in the backward region were found to be sufficiently infrequent that hadronic calorimetry would provide little to no scientific benefit. The details for all six calorimeters envisioned for ECCE can be found in Tab. 5.

6.1. Electron Endcap EM Calorimeter (EEMC)

The EEMC is a high-resolution electromagnetic calorimeter designed for precision measurements of the energy of scattered electrons and final-state photons in the electron-going region. Its required energy resolution is driven by the need for a precise measurement of the scattered electron’s energy and direction to determine the event kinematics in inclusive DIS events.

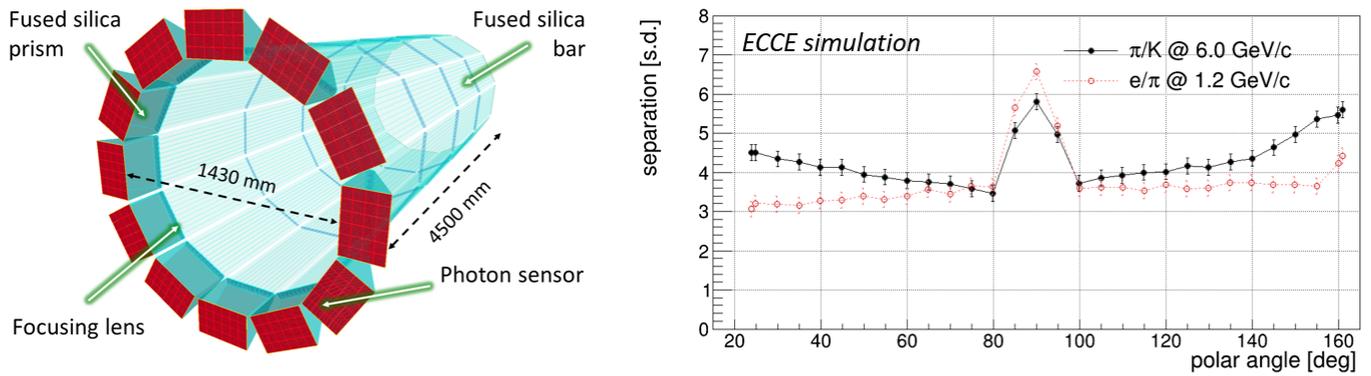


Figure 15: hpDIRC geometry (left) and expected PID performance (right) from the GEANT4 standalone simulation. The e/π and π/K separation power is shown in units of number of standard deviations (s.d.) as a function of the particle polar angle for e/π at 1.2 GeV/c and π/K up to 6 GeV/c.

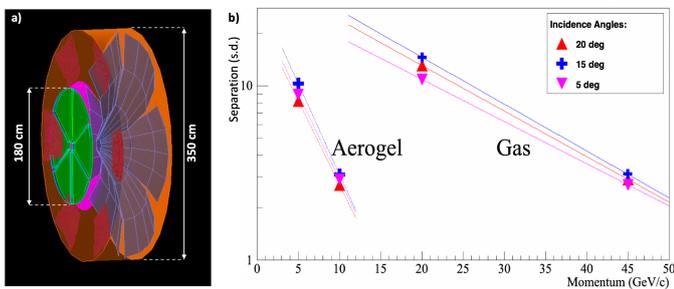


Figure 16: dRICH geometry (a) and expected performance (b) from the ECCE GEANT4 simulation. The K/π separation power is shown as a function of momentum for a simplified dRICH geometry (flat detector plane).

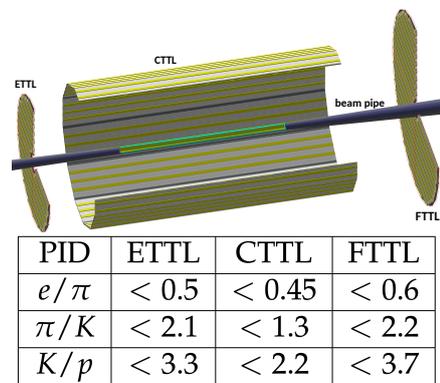


Figure 17: (left) A schematic view of the timing and tracking layers (TTLs) in ECCE as simulated with GEANT4. The different subdetectors are called ETTL (electron endcap), CTTL (barrel) and FTTL (hadron endcap). (right) Right: Momentum coverage in GeV/c of the ECCE Time-of-Flight detector in corresponding regions

874 The design of the EEMC is based on an array of approxi-
 875 mately 3000 lead tungsten crystals (PbWO_4) of size $2 \times 2 \times$
 876 20 cm^3 ($\sim 22X_0$) and transverse size equal to its Moliere
 877 radius [32, 33] readout by SiPMs yielding an expected energy
 878 resolution of $2\%/\sqrt{E} + 1\%$, based on prototype beam test mea-
 879 surements by the EEMCAL consortium and documented in
 880 the Yellow Report [16]. Fig. 20 shows the EEMC performance
 881 in the full ECCE detector simulations, consistent with the mea-
 882 surements. The corresponding particle identification power is
 883 shown in Fig. 21 for distinguishing electrons and pions (left) as
 884 well separating the two photons from a neutral pion decay. 904

885 The choice of technology and overall design concept is com-
 886 mon for all three proto-collaborations, with additional details of
 887 the development of this detector by the EEMCAL consortium
 888 summarized in the expression of interest [34]. The ECCE de-
 889 sign only includes the PbWO_4 crystals due to the overall small
 890 detector radius. The EEMCAL Consortium is planning to
 891 support one or more EIC detectors as needed and is therefore
 892 part of multiple detector proposals. 912

893 The EEMC is located inside the inner universal frame and
 894 allows to reconstruct particles with $-3.4 < \eta < -1.8$. This goes
 895 back to the difference between mechanical space and detector
 896 performance that is also documented in the Yellow Report. The
 897 material budget almost reaches $\eta = -4$, but slopes rapidly down
 898 at $\eta = -3.7$. This is because of the beam crossing and asym- 918

metric beam pipe (see the EEMCAL Consortium report [35]).
 Then the performance is only good to one crystal away which
 is $\eta = -3.4$ unless one squeezes to the beam pipe with a small
 inner calorimeter. To extend the reach of the backward EEMC
 to a pseudorapidity of -3.7 one can thus envision a small in-
 ner calorimeter of 208 crystals and an outer calorimeter just
 behind it. There is sufficient longitudinal space accommodate
 this, but moving the outer calorimeter back could impact the
 acceptance in the transition region between the EEMC and the
 central barrel. If possible, this arrangement would allow the
 outer calorimeter to be removed over the beam pipe flange for
 maintenance, and separate removal of the small inner calori-
 meter in two halves. We intend to pursue this improvement to
 the baseline design as a part of a detailed, integrated mechanical
 engineering design of the ECCE detector.

The EEMCAL team has begun to organize activi-
 ties into mechanical design, scintillator, readout, and soft-
 ware/simulation among the collaborating institutions. Design
 activities of the mechanical support structure commenced in
 2021. The design is based on models of existing detectors that

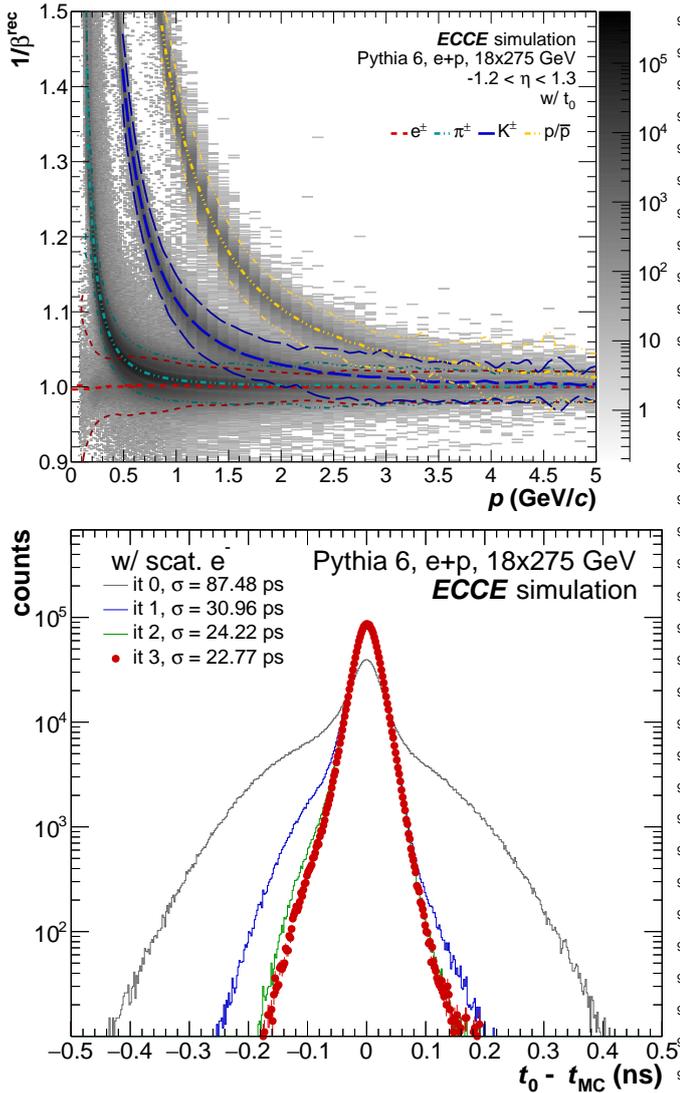


Figure 18: (left) Expected $1/\beta$ performance of the AC-LGADs TOF in the barrel as a function of particle momentum, assuming 25 ps time resolutions from full simulations including the start time estimates. (right) Expected start time (t_0) resolution as a function of iteration, for events where the scattered electron could be identified.

the team has recently constructed, in particular the Neutral Particle Spectrometer at Jefferson Lab [32]. As such, it is maturing rapidly and a document on mechanical design and integration has been completed [35].

6.2. Barrel EM Calorimeter (BEMC)

The barrel electromagnetic calorimeter (BEMC) is a projective homogeneous calorimeter based on an inorganic scintillator material that produces the shower due to high Z components. This allows for a cost-effective solution that provides excellent energy resolution and sufficient e/π rejection to achieve the EIC physics, which can be seen in Fig. 21. Further improvements are expected by determining exactly the Birk's constant and using shower shape criteria to distinguish elongated hadronic and rounder electromagnetic showers. The reference design of the BEMC is based on an array of approximately 9000 Scintillating

Glass (SciGlass) blocks of size $4 \times 4 \times 45.5$ cm³, plus an additional 10cm of radial readout space. SciGlass has an expected energy resolution of $2.5\%/\sqrt{E} + 1.6\%$ based on earlier measurements [28, 29], comparable to PbWO₄ for a significantly lower cost. The energy resolution of the BEMC is shown in red in Fig. 20 (left) in its optimal acceptance ($-1.4 < \eta < 1.1$).

The development of SciGlass started with the generic detector R&D [36]. During this phase the team worked in close contact with producers of SciGlass to establish robust QA protocols at all stages of production to ensure the quality needed for the EIC. The validation of large-scale SciGlass production is now continued in the ongoing project R&D (eRD105). An initial 40 cm SciGlass bar of high quality has been produced this Fall (see Fig. 22 bottom right), and a prototype with nine 20-cm long SciGlass bars recently saw a successful beam test at Jefferson Lab, confirming the expected energy resolution. It is expected that multiple 45-cm long SciGlass bars will be produced in the next few months.

Just as for the EEMC, the BEMC attaches to the outer universal frame. Adapting the geometry of the homogeneous barrel EM calorimeter at PANDA [37], the BEMC towers are organized in 128 blocks by ϕ slice and 70 blocks in η , which will be assembled in super modules stretching the full length in η and 8 towers in ϕ for installation in the universal frame. Figure 22 (top) shows a sketch of the BEMC illustrating the at least six different families of glass blocks needed to achieve the required projectivity in η . For comparison, PANDA uses 11 different crystal types for their barrel. The optimal number of families still has to be determined, optimizing for efficient production as well as minimal leakage between towers. Also indicated is a schematic of the support box (modeled after the PANDA barrel calorimeter) for readout and other services that mounts to the outer universal frame.

The BEMC has been designed with projectivity in η and ϕ . This requires that the tower angular deflection depends on its location in the calorimeter. Additionally, the towers have a stronger inclination at higher absolute pseudorapidities, leading to an asymmetric tapered shape of the glass blocks, which increases with $|\eta|$. Their front face is tilted such that it is facing the interaction point shifted by $z = -10$ cm and tilted 10° in the azimuthal direction, to avoid channeling between the towers. Such a projective design delivers a more uniform performance, mainly aimed at the transition regions between the barrel and forward and backward regions, as defined by the length to bore ratio of the magnet. All the towers have the same length, 45.5 cm (not including ~ 10 cm readout), and inner size 4×4 cm in the present simulation. However, the upper area sections vary from 5 to 6.6 cm in each side depending on their location.

6.3. Barrel Hadron Calorimeters: oHCAL and iHCAL

The energy resolution of reconstructed jets in the central barrel will be dominated by the track momentum resolution, as the jets in this region are relatively low momentum and the measurement of the energy in the hadronic calorimeter does not improve knowledge of the track momentum. For jet reconstruction, the primary use for a hadronic calorimeter in the central

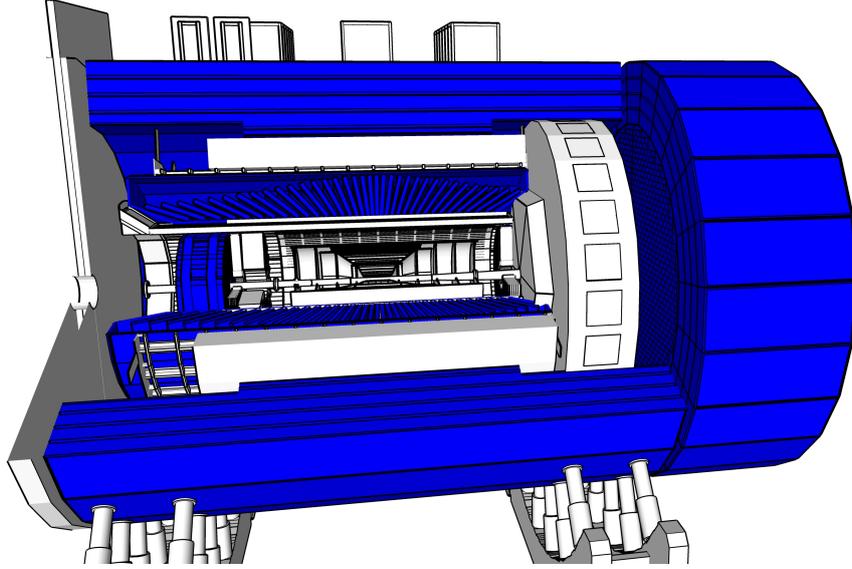


Figure 19: The electromagnetic and hadronic calorimeters in ECCE

Table 5: Specifications and properties for the electromagnetic and hadronic calorimeters from the Geant simulation. Note that d_{act} does not include readout. The acceptance of the EEMC can be achieved with a small inner calorimeter as discussed in the text. The energy resolutions for EEMC, BEMC and oHCAL are those expected from prototype tests or experiments [16, 28, 29, 30]. Further details can be found in the ECCE Tech Note [31].

	EEMC	BEMC	FEMC	IHCAL	oHCAL	LFHCAL
tower size	$2 \times 2 \times 20 \text{ cm}^3$	$4 \times 4 \times 45.5 \text{ cm}^3$	in: $1 \times 1 \times 37.5 \text{ cm}^3$ out: $1.6 \times 1.6 \times 37.5 \text{ cm}^3$	$\Delta\eta \sim 0.1$ $\Delta\phi \sim 0.1$ $l \sim 4.5 \text{ cm}$	$\Delta\eta \sim 0.1$ $\Delta\phi \sim 0.1$ $l \sim 88 \text{ cm}$	$5 \times 5 \times 140 \text{ cm}^3$
material	PbWO ₄	projective SciGlass	Pb/Scintillator	Steel/ Scintillator	Steel/ Scintillator	Steel/W/ Scintillator
d_{abs}	-	-	1.6 mm	13 mm	in: 10.2 mm out: 14.7 mm	16 mm
d_{act}	20 cm	45.5 cm	4 mm	7 mm	7 mm	4 mm
N_{layers}	1	1	66	4	5	70
$N_{towers(channel)}$	2876	8960	19200/34416	1728	1536	9040(63280)
X/X_0	~ 22	~ 17	~ 19	~ 2	36 – 48	65 – 72
R_M	2.73 cm	3.58 cm	5.18 cm	2.48 cm	14.40 cm	21.11 cm
f_{sampl}	0.914	0.970	0.220	0.059	0.035	0.040
λ/λ_0	~ 0.9	~ 1.6	~ 0.9	~ 0.2	$\sim 4 - 5$	7.6 – 8.2
η acceptance	$-3.7 < \eta < -1.8$	$-1.7 < \eta < 1.3$	$1.3 < \eta < 4$	$1.1 < \eta < 1.1$	$1.1 < \eta < 1.1$	$1.1 < \eta < 4$
resolution						
- energy	$2/\sqrt{E} \oplus 1$	$2.5/\sqrt{E} \oplus 1.6$	$7.1/\sqrt{E} \oplus 0.3$		$75/\sqrt{E} \oplus 14.5$	$33.2/\sqrt{E} \oplus 1.4$
- φ	~ 0.03	~ 0.05	~ 0.04		~ 0.1	~ 0.25
- η	~ 0.015	~ 0.018	~ 0.02		~ 0.06	~ 0.08

989 barrel will be to collect neutral hadronic energy and thus im¹⁰⁰⁴
990 prove the overall knowledge of the Jet Energy Scale (JES). For
991 this purpose, the Yellow Report indicates that a resolution of¹⁰⁰⁵
992 $(80 - 100)\%/\sqrt{E} \oplus (7 - 10)\%$ will be adequate. Therefore,¹⁰⁰⁶
993 we decided to reuse the sPHENIX Outer Hadronic Calorime¹⁰⁰⁷
994 ter (oHCAL), which instruments the barrel flux return steel of¹⁰⁰⁸
995 the BaBar solenoid to provide hadronic calorimetry with an¹⁰⁰⁹
996 energy resolution of $75\%/\sqrt{E} \oplus 14.5\%$, as measured in test¹⁰¹⁰
997 beam. We also plan to instrument the support for the barrel¹⁰¹¹
998 electromagnetic calorimeter to provide an additional longitudi¹⁰¹²
999 nal segment of hadronic calorimetry. This will provide an Inner¹⁰¹³
1000 Hadronic Calorimeter (IHCAL) very similar in design to the¹⁰¹⁴
1001 sPHENIX inner HCAL. The inner HCAL is useful to moni¹⁰¹⁵
1002 tor shower leakage from the barrel electromagnetic calorimeter¹⁰¹⁶
1003 as well as improve the calibration of the combined calorimeter¹⁰¹⁷

system.

The basic calorimeter concept for the iHCAL/oHCAL is a sampling calorimeter with absorber plates tilted from the radial direction. This design provides more uniform sampling in azimuth and gives some information about the longitudinal shower development. The outer HCAL uses tapered 1020 magnet steel plates which maintain a uniform gap size for the scintillating tiles. The inner HCAL will be made from stainless steel, as it sits inside the magnetic field. The Inner HCAL will not require tapered plates as studies have that tapering the shorter inner HCAL plates is not necessary, and tapering them substantially increases the machining cost. Extruded tiles of plastic scintillator with an embedded wavelength shifting fiber are interspersed between the absorber plates and read out at the outer radius with silicon photomultipliers (SiPMs). A 12 degree

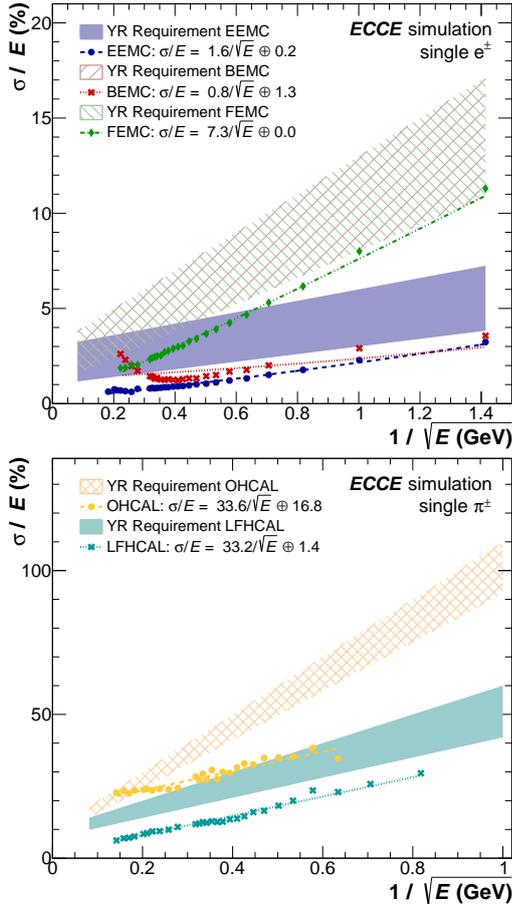


Figure 20: The electron (left) and pion (right) energy resolution of the electromagnetic and hadronic calorimeters, respectively, compared to the Yellow Report requirement (shaded/hashed area).

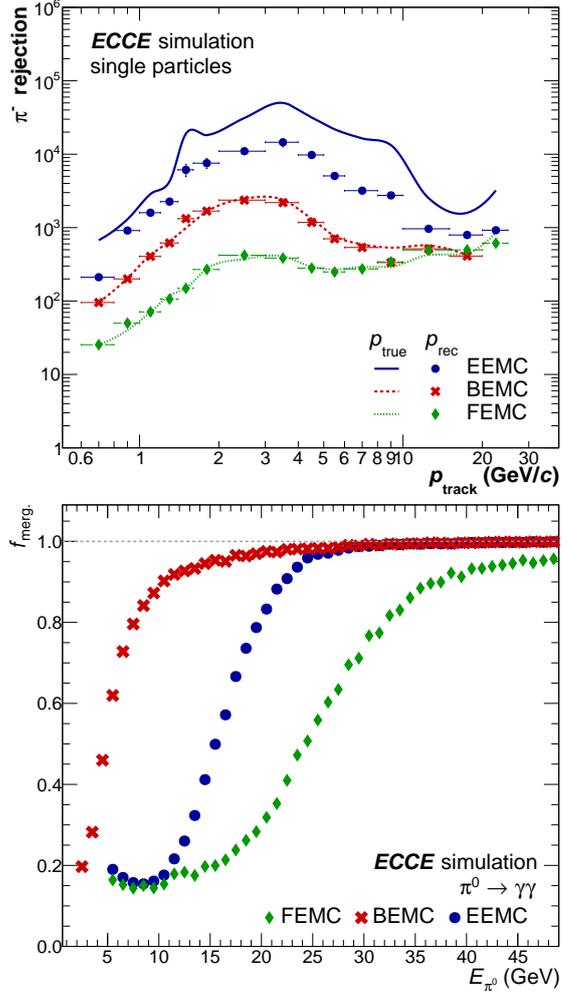


Figure 21: (left) Pion rejection factor for the different ECals with $E/p > 1 - 1.6\sigma_E/E$ and shower shape cuts applied as a function of true and reconstructed momentum. (right) Fraction of neutral pions for which the showers from their decay photons are merged into a single cluster and can not be reconstructed using an invariant-mass-based approach for the different electromagnetic calorimeters.

1019 tilt angle relative to the radius is chosen in the outer HCAL so
 1020 that a radial track from the center of the interaction region tra-
 1021 verses at least four scintillator tiles. The inner HCAL is tilted
 1022 at 36 degrees, in the opposite direction compared to the outer
 1023 HCAL. Each tile has a single SiPM, and the analog signal from
 1024 each tile in a tower (five for the Outer HCAL, four for the Inner
 1025 HCAL) are ganged to a single preamplifier channel to form a
 1026 calorimeter tower. Tiles are divided in slices of pseudorapidity
 1027 so that the overall segmentation is $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$. The
 1028 Outer HCAL is longitudinally symmetric around the interaction
 1029 point and requires 24 tiles along the η direction. The design
 1030 thus requires 12 different shapes for tiles for each longitudinal
 1031 segment. The inner HCAL is extended along the backwards
 1032 direction, and is comprised of 12 tiles in η in the forward direc-
 1033 tion and 15 tiles in η in the backwards direction. There are 1536
 1034 readout channels (towers) in the oHCAL and 1728 channels for
 1035 the inner HCAL.

1036 6.4. Hadron Endcap Electromagnetic (FEMC) and Hadronic 1037 Calorimeter (LFHCAL)

1038 The desired performance in the forward region is governed
 1039 by the jet energy resolution requirements, as well as very
 1040 good energy resolution ($35\%/\sqrt{E}$ to reach the desired resolu-

tion in δx) for the physics processes connected to the origin of mass. Additionally, an excellent position resolution in particular within the ECal is required for PID within the jet. Within this region a higher particle density is expected than in the central barrel, supporting the need for excellent position an energy resolution in both calorimeters. Both detector systems need to be able to handle the expected energies of incoming particles up to 150 GeV. Due to the asymmetric collision system, these calorimeters are therefore focused strongly on high energetic particle shower containment while still providing good energy resolution at low energies.

We envision the forward calorimeter system as an integrated ECal and HCal, where the installation units, where appropriate, are constructed in a common casing. These so-called modules will consist of an electro-magnetic calorimeter segment in the front which is part of the forward EMCAL (FEMC) followed by a hadronic calorimeter segment which is part of the longitudinally separated HCal (LFHCAL). In between these segments a

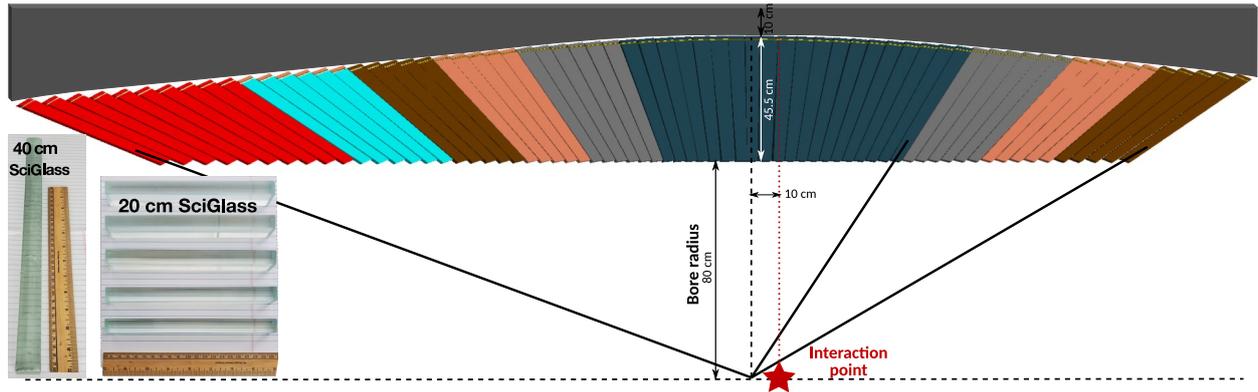


Figure 22: Side cut view of the barrel assembly from Geant4 illustrating the six different families of glass block sizes needed to achieve the needed projectivity. Also shown is a schematic of the support box (grey) based on the PANDA design that holds readout, cooling, and other services and mounts to the outer universal frame.

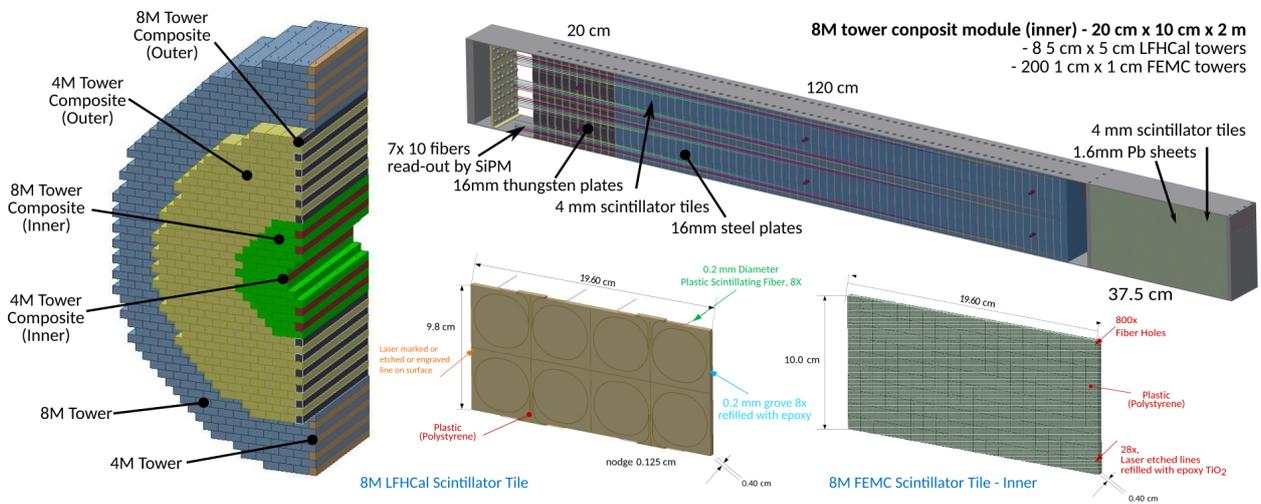


Figure 23: Details of the combined FEMC and LFHCAL design, indicating a fully assembled half disk, the 8-tower module design and the individual scintillator tile designs for the an LFHCAL-FEMC 8M tower inner module.

1059 read-out section is foreseen for the ECal. The modules of up¹⁰⁷⁹
 1060 to four different sizes will be installed in half shells surround¹⁰⁸⁰
 1061 ing the beam pipe, which are movable on steel trolleys to giv¹⁰⁸¹
 1062 access to the inner detectors in the barrel in the hadron going¹⁰⁸²
 1063 direction. This integrated E- and HCal design reduces the dead¹⁰⁸³
 1064 material in the detector acceptance and allows for an easier in¹⁰⁸⁴
 1065 stallation in the experimental hall. ¹⁰⁸⁵

1066 The forward ECal (FEMC) will be a Pb-Scintillator shashlik¹⁰⁸⁶
 1067 calorimeter. It is placed after the tracking and particle ident¹⁰⁸⁷
 1068 tification detectors and made up of two half disks with a ra¹⁰⁸⁸
 1069 dius of about 1.83m. The calorimeter is based on the lead¹⁰⁸⁹
 1070 scintillator "shashlik" calorimeter designs already utilized for¹⁰⁹⁰
 1071 ALICE, STAR and PHENIX. However, it employs more mod¹⁰⁹¹
 1072 ern techniques for the readout as well as scintillation tile sepa¹⁰⁹²
 1073 ration. The towers were designed to be smaller than the Moliere¹⁰⁹³
 1074 radius in order to allow for a further shower separation at high¹⁰⁹⁴
 1075 rapidity. ¹⁰⁹⁵

1076 The towers have an active depth of 37.5 cm with and consist¹⁰⁹⁶
 1077 out of 66 layer of 0.16 cm Pb sheets and 0.4 cm scintillator ma¹⁰⁹⁷
 1078 terial, as can be seen in Tab. 5. Due to the high occupancy of ¹⁰⁹⁸

the detector at large pseudorapities and the collimation of the particles in this area in physical space, the tower size will vary depending on its radial position with respect to the beam axis. Towers which are close to the beam pipe ($R < 0.8$ m) will have a active tower size of 1 cm×1 cm×37.5 cm. For the outer radii this granularity is not necessary and thus the size is increased to 1.65 cm×1.65 cm×37.5 cm. In order to collect the light produced in the scintillator tiles, each scintillator and Pb-plate is pierced by four 0.2 mm-wavelength shifting fibers. These fibers are used to collect the light generated in the scintillators across all 66 layers. All four fibers are read out together by one silicon photomultiplier (SiPM). The FEMC is constructed with modules size of at least 5 cm×5 cm×37.5 cm (1M module) up to 10 cm×20 cm×37.5 cm (8M modules) aligning with the module sizes of the hadronic calorimeter. In order to separate the light produced in different segments of the 8M-tile a gap between the 1 cm×1 cm tower tiles is created by edging into the scintillator using a laser. These 0.37 mm deep gaps are then refilled with a mixture of epoxy and titanium-oxide in order to reduce the light cross talk among different towers. Depending

on their radial position this leads to either 72 or 200 read-out towers in one 8M modules.

The longitudinally segmented forward HCal (LFHCAL) is a Steel-Tungsten-Scintillator calorimeter adapted from the PSD calorimeter for the NA61/SHINE experiment [38], but it has been severely modified to meet the desired physics performance laid out in the Yellow Report. It is made up of two half disks with a radius of about 2.6 m.

The LFHCAL towers have an active depth of 1.4 m with an additional space for the readout of about 20–30 cm depending on their radial position, as seen in Table 5. Each tower consists out of 70 layers of 1.6 cm absorber and 0.4 cm scintillator material. For the first 60 layers the absorber material is steel, while the last 10 layers serve as tail catcher and are thus made out of tungsten to maximize the interaction length within the available space. The front face of the tower is 5 cm×5 cm.

In each scintillator a loop of wavelength shifting fiber is embedded, as can be seen in Fig. 23 (middle). Ten consecutive fibers in a tower are read out together by one Silicon photo multiplier, leading to seven samples per tower. The towers are constructed in units of 8-, 4-, 2- and 1-tower modules to ease the construction and reduce the dead space between the towers and the active detection area. Similar as for the FEMC the scintillator tiles in the larger modules are made out of one piece and then separated by a gaps refilled with epoxy and titanium oxide to reduce light cross-talk among the different readout towers. For the same purpose the wavelength shifting fibers running on the sides of the towers are grouped early on according to their readout unit and separated by thin plastic pieces over the full length. They terminate in one common light collector which is directly attached to a SiPM. The entire detector will consist of 63280 readout channels grouped in 9040 read-out towers.

The majority of the calorimeter will be built out of 8-tower modules (~1091) which are stacked in the support frame using a lego-like system for alignment and internal stability, as can be seen in Fig. 23 (left). The remaining module sizes are necessary to fill the gaps at the edges and around the beam pipe to allow for maximum coverage. The absorber plates in the modules are held to their frame by four screws each. To leave space for the read-out fibers, the steel and scintillator plates are not entirely square but equipped with 1.25 mm grooves, creating the fiber channels on the sides. These fiber channels are covered by 0.5 mm thin steel plates for protection after module installation and testing, in order to protect the fragile fibers. For internal alignment we rely on the usage of 1–2 cm steel or tungsten absorber plates. Afterwards the modules will be self-supporting within the outer support frame. The steel in the LFHCAL serves as flux return for the BaBar magnet, thus a significant force is exerted on the calorimeter, which needs to be compensated for by the frame and internal support structure. The achieved energy resolution according to the simulations for both calorimeters can be found in Fig. 20. The required resolutions can be met in both cases and further improvements can be expected using machine learning for the clusterization which proves challenging in this direction. The excellent position resolution in the FEMC should in addition allow the effective sep-

aration of electrons and pions as well neutral pion decays, as seen in Fig. 21. The projected performance meets the physics requirements by the $e - \text{Adiffractional } J/\psi$ production and the u -Channel DVCS, as well as meson (pion/kaon) structure function measurements through the Sullivan process.

7. Far-Forward/Far-Backward Detectors

A schematic of the far-forward detectors is shown in Figure 24 and include the B0 spectrometer, off-momentum trackers, Roman Pots and ZDC (see Table 6 for position and dimensions). The far-backward region consists of two detector systems (low- Q^2 tagger and luminosity monitor). All far-forward/far-backward detectors are required for the EIC physics as described in the Yellow Report. The following describes their setup and performance. For further details, see Ref. [39].

7.1. B0 Detector

The B0 spectrometer is located inside B0pf dipole magnet. Its main use is to measure forward going hadrons and photons for exclusive reactions. The B0 acceptance is defined by the B0pf magnet. Its design is challenging due to the two beam pipes (electron and hadron) that it needs to accommodate and the fact that they are not parallel to each other due to the 0.025 mrad IP6 crossing angle. Moreover, the service access to the detectors inside of the dipole is only possible from the IP side, where the distance between the beam pipes is narrowest. Following these limitations the B0 detector require using compact and efficient detection technologies.

Our design uses four AC-LGAD tracker layers with 30 cm spacing between each layer. They will provide charged particle detection for $6 < \theta < 22.5$ mrad. The use of AC-LGAD sensors will allow good position and timing resolutions. The AC-LGAD sensor will have a 3.2x3.2 cm² area, with four dedicated ASIC units on each sensor. In addition, a PbWO₄ calorimeter will be positioned behind the fourth tracking layer at 683 cm from the IP. Using the PbWO₄ in the B0 calorimeter will increase the detection fraction of the two decayed γ s from the u -Channel π_0 production from 40% to 100%, and enable measurements of u -Channel DVCS events which without it will be swamped by the π^0 events with single γ detected. The calorimeter is constructed from 10 cm long 2x2 cm² PbWO₄ crystals and positioned to leave 7 cm for the readout system. Both trackers and Calorimeter has oval holes in the center to accommodate the hadron beam pipe, and a cutaway in the side to accommodate the electron beam and allow installation and service of the detector system (see Fig. 24).

Figure 25 (left) shows the simulated momentum and its resolution $\sigma[\Delta p/p]$ as a function of truth momentum. It is below 5% for the studied kinematic region. The effect of the presence of dead material (2mm of Cu after each Si plane) layers on the momentum resolution is also shown and estimated to degrade the resolution by 2% uniformly as a function of p . The photon energy reconstructed in the B0 calorimeter and its resolution are shown in Fig 25 (right) for photons originating in the

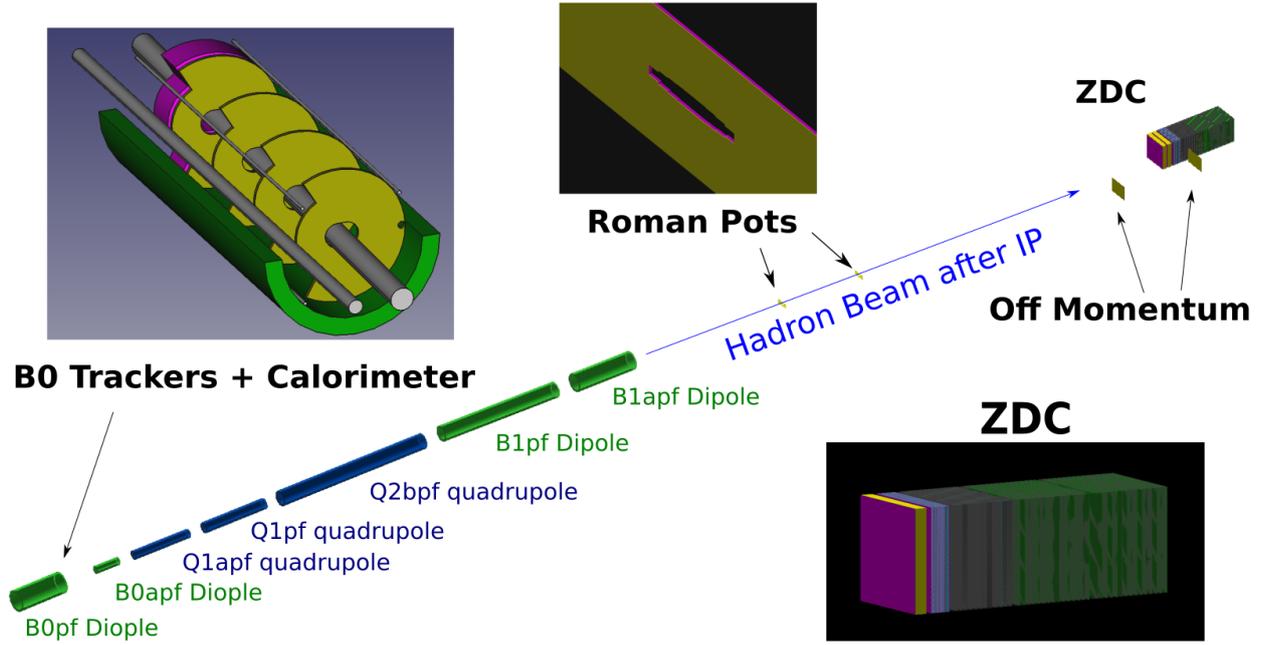


Figure 24: The layout of the EIC Far-Forward region.

Table 6: Summary of far-forward detector locations and angular acceptances for charged hadrons, neutrons, photons, and light nuclei or nuclear fragments. In some cases, the angular acceptance is not uniform in ϕ , as noted in the table. For the three silicon detectors (Roman Pots, Off-Momentum Detectors, and B0 spectrometer) a depth is not given, just the 2D size of the silicon plane. For the Roman Pots and Off-Momentum Detectors, the simulations have two silicon planes spaced 2m apart, while the B0 detectors have four silicon planes evenly spaced along the first 1.0 m length of the B0pf dipole magnet bore. The planes have a "hole" for the passage of the hadron beam pipe that has a radius of 3.2 cm.

Detector	(x,z) Position [m]	Dimensions	θ [mrad]	Notes
ZDC	(-0.96, 37.5)	(60cm, 60cm, 1.62m)	$\theta < 5.5$	~ 4.0 mrad at $\phi = \pi$
Roman Pots (2 stations)	(-0.83, 26.0) (-0.92, 28.0)	(30cm, 10cm)	$0.0 < \theta < 5.5$	10σ cut.
Off-Momentum Detector	(-1.62, 34.5), (-1.71, 36.5)	(50cm, 35cm)	$0.0 < \theta < 5.0$	$0.4 < x_L < 0.6$
B0 Trackers and Calorimeter	(x = -0.15, $5.8 < z < 7.0$)	(32cm, 38m)	$6.0 < \theta < 22.5$	~ 20 mrad at $\phi=0$

1209 interaction vertex with pseudorapidity $4 < \eta < 6$ and energy $0 < E_\gamma < 60$ GeV. It is found to be below 7% for the studied kinematic region. In general about 60% of the energy is reconstructed within a 2×2 crystal grid with some dips in efficiency at low E_γ and high η .

1214 7.2. Roman Pots

1215 Diffractive processes such as deeply virtual Compton scattering will produce protons with high energy and small p_T with only a small separation from the hadron beam. The Roman Pots are designed to detect such particles. They will consist of two double-layer 25×12 cm² AC-LGAD stations, located inside the beam line 26 and 28 m downstream the interaction point and 10σ from the main beam. This technology will provide the necessary position and timing resolution for a precise measurement with minimized background.

1224 The vacuum environment will require special cooling. We

will use heat sinks made of metal foam through which compressed air will flow. Such cooling systems are already in use at the LHC.

1228 7.3. Off-momentum Detectors

1229 Off-momentum detectors complement the Roman Pots by measuring charged particles that have a smaller magnetic rigidity than the main hadron beam. Such particles will be bent outside the beam pipe. The detectors consist of tracking planes based on AC-LGAD sensors.

1230 Good timing resolution on the order of 10s facilitates the rejection of pileup and beam related background, since particles that do not come directly from the interaction point will have a different flight path than the particles of interest. Such techniques have been used extensively by the CMS Precision Proton Spectrometer and the ATLAS Forward Proton Group at the LHC.

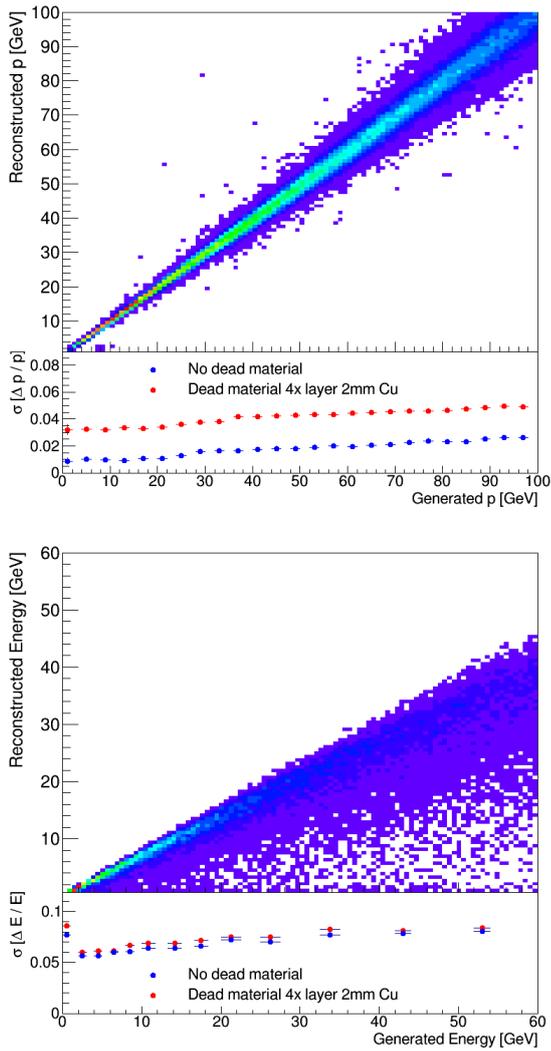


Figure 25: (left) Reconstructed momentum and its resolution for μ^- tracks found in the B0 tracker; (right) reconstructed energy of photons and its resolution in the B0 calorimeter.

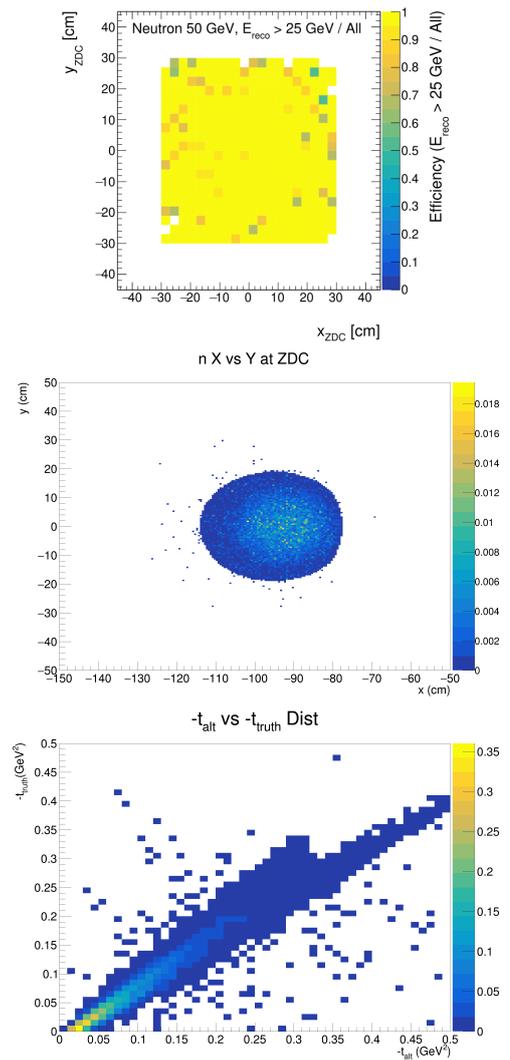


Figure 26: (left) ZDC detection efficiency for neutrons in its local coordinate system. (middle) Detection distribution of neutron hits in the ZDC for meson structure function processes without the beam pipe blocking contribution. z -axis reflects the normalized yield. (right) Reconstructed t versus true t , where t is reconstructed as from the baryon information, $t_{alt} = (p_p - p_n)^2$, which is reliable with a resolution of $< 0.025 \text{ GeV}^2$.

7.4. Zero Degree Calorimeter (ZDC)

The size of the ECCE ZDC is $60 \text{ cm} \times 60 \text{ cm} \times 162 \text{ cm}$, and the weight is greater than 6t. As shown in Fig. 24, the ZDC consists of PbWO_4 crystal layer, W/Si layer, Pb/Si layer and Pb/Scintillator layer.

The estimated energy resolution for high energy photons is well below the required value. For the low energy photons estimated resolution for 100 MeV photons using 5% smearing reaches 20%, which is still acceptable. The neutron energy resolution is consistent with and even smaller than the Report required value of $50\% / \sqrt{E} + 5\%$. For 40 GeV and GeV photons, the position resolution is estimated as 1.1 mm and 1.5 mm respectively. On the crystal layer, the cluster finding efficiency is $> 95\%$ for both 20 GeV photons and 100 MeV photons with the seed energy requirement of 15 MeV for clustering.

While the ZDC is used for a variety of measurements in ECCE, we evaluate its performance here using simulations of

meson structure function measurements that represent a key performance driver for this detector. In these reactions, neutrons from the Sullivan process carry 80-98% of the proton beam momentum and are detected at far-forward angles in the ZDC. The detection fraction for neutrons (t resolution) is 59% (0.019 GeV^2) at the lowest, 5 on 41, and 100% ($0.005\text{-}0.007 \text{ GeV}^2$) at the higher energy combinations. Due to the large size and high inherent ZDC detection efficiency (Fig. 26 (left)), the ECCE detection efficiency for these events is quite high, $\sim 80\%$, and nearly independent of Q^2 . A density plot of event distribution is shown in the left panel of Fig. 26. The detection efficiency is highest for events with small $-t < 0.15 \text{ GeV}^2$, which are needed for measurements such as the pion form factor, and decreases rapidly with $-t$. The t -range of optimal acceptance is dictated by the size of the ZDC, as the energetic

neutrons from higher $-t$ events are emitted at an angle larger than the ZDC acceptance.

We further find the ZDC to offer excellent reconstruction of t . Compared with the t reconstruction from the measurement of the π^+ and e' tracks, the ZDC's baryon measurement is significantly more reliable, in agreement with EIC YR studies. Due to the excellent position resolution of the ZDC, the neutron momentum is reconstructed to within 1% of the "true" momentum. With this information, t is reconstructed from the neutron track in a manner that reproduces the true value very closely see Fig. 26 (right). Such a reliable reconstruction of t is essential for many processes such as the pion form factor measurement, where the rapid fall off of the cross section needs to be measured to confirm the dominance of the Sullivan mechanism. The high quality ZDC proposed by ECCE is clearly of paramount importance to the feasibility of such measurements.

7.5. Low- Q^2 Tagger

The low Q^2 -tagger will facilitate measurement of reactions with small cross sections, e.g. timelike Compton scattering. Measuring the scattered electron will allow the s dependence to be measured as well as giving some measure of the production four momentum transfer, or t . When coupled with proton detection in the far forward region there will be the possibility of applying exclusivity cuts.

The low- Q^2 Tagger consists of two stations, located 24 m and 37 m from the interaction point. Each station includes a double layered AC-LGAD tracker, followed by a PbWO₄ electromagnetic calorimeter. The detectors surface areas are 40.5 cm×40.5 cm at 24 m and 30 cm×21 cm at 37 m and their calorimeters both use 20 cm long 2 cm×2 cm PbWO₄ crystals.

The tracking planes enable the determination of the electron scattering angle, that in turn facilitate a precise determination of Q^2 . The calorimeter provides an energy measurement to complement the tracking and provide additional shower shape information to confirm that the particle really is an electron.

7.6. Luminosity Monitors

For the luminosity measurements, an accuracy of the order of 1% is required, or relative luminosity determination exceeding 10⁻⁴ precision. The latter is driven by the size of the asymmetries we want to measure. This requirement drives the utilization of several complementary approaches for both relative and absolute measurements of the luminosity, allowing us to understand and constraint the beam-size effects, synchrotron radiation, as well as systematic uncertainties. The approach we will follow is based on existing experience from HERA. The absolute luminosity is determined by correlating the total energy in the calorimeter with the number of photons. The low- Q^2 tagger can also provide key information on the relative luminosities and thus impose further constraints on the luminosity determination.

The luminosity monitor will be located along the photon zero-degree line in the far backward region and will measure bremsstrahlung photons. It uses both a dedicated calorimeter to measure direct photons, and two spectrometer arms to measure

e^+e^- pairs from conversions. The direct photon calorimeter will have a size of 16 cm×16 cm and will use 20cm long 2x2 cm² PbWO₄ crystals. The e^+ and e^- from photon conversions will be deflected above and below the main photon beam by a small dipole magnet before entering the spectrometer arms. Each arm includes two 8×16 cm² AC-LGAD tracking layers followed by a PbWO₄ calorimeter with a matching surface area (also made of 20cm long 2x2 cm² crystals). The tracking planes in the e^+/e^- arms will allow reconstructing the gamma spot to help understand and constraint beam-size effects.

8. Electronics and Data Acquisition

The general design of the ECCE data acquisition builds on the sPHENIX DAQ system and many of the JLAB streaming readout systems under test [39]. These systems already incorporate and demonstrate almost all concepts of the envisioned ECCE DAQ system. The ECCE DAQ system will be built around a trigger-less Streaming Readout (SRO) concept from the start.

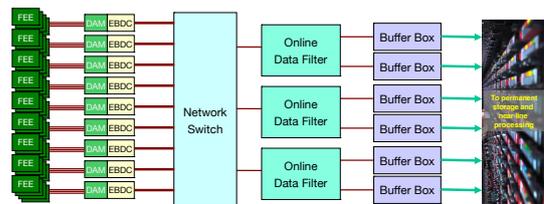


Figure 27: The schematic view of the ECCE Data Acquisition system. With the detector systems connecting to FEE cards from the left, the digitized data are sent to "Data Aggregation Modules" (DAM) that filter and package the data. The "Event Buffer and Data Compressor" (EBDC) nodes perform another filter, noise suppression, and clustering step on the scope of the connected detector channels, and align the hits by timing value. The data are then sent to processing nodes that perform a filtering/trigging step on the entire detector view. Data from selected crossings then get stored temporarily on large file servers ("Buffer Boxes") before being sent to long-term storage at the computing center.

As detailed in the Yellow Report [2], the Streaming Readout concept has proven superior to a classic triggered scheme in several ways. Modern readout technologies often do not follow a strict "event" paradigm in the sense that data from collider crossing n are already arriving from one front-end, while other parts can still be transmitting data from trigger $n-1$, $n-2$, or earlier crossings. In streaming mode, there is no need to wait for the completion of the data transmission from a given crossing, as the data parts are later re-assembled by their embedded clock information. This usually leads to a higher data throughput in streaming mode.

The other advantage is that classic trigger setups are always limited in their selection power because the amount of data they can sample to arrive at a trigger decision is generally much more restricted than in streaming mode, where the software- or firmware-based selection algorithms have, at least in principle, access to the data from all detector components. The processing power to increase the quality of the event selection has become cheaper every year, and this trend is expected to continue.

In a trigger-less data acquisition scheme, each channel with a signal exceeding a threshold is transferred after being labeled with a time-stamp, irregardless of the status of the other channels. The resulting data is often a waveform, or a list of fired pixel-type detector elements, or some combination of both. Subsequent processing layers reduce the amount of information by categorizing the information by time, so that eventually the detector information of one bunch crossing is together in one place. While traversing the various processing layers, data is filtered and packaged, and waveform processing and clustering algorithms are applied that further reduce the amount of data to a few key properties.

The progression of processing layers is schematically shown in Fig. 27. With the connections from the detector, typically fibers, coming from the left, detector-specific Front-End Electronics (FEE) cards digitize the signals, and send digital data on to the “Data Aggregation Module” (DAM). An current example of such a DAM is the ATLAS FELIX card [13].

The DAM plays a central role as it provides a common detector interface for the expected large variety of detector readout technologies that are found upstream of the DAM. While the DAM still needs to run detector-specific firmware to receive and package the data, it provides common hardware and common APIs for the subsequent data handling, and greatly reduces the software development efforts.

The “Event Buffer and Data Compressor” (EBDC) nodes, the offline data filter, and the file servers (“Buffer Boxes”) shown in Fig 27 are Linux PCs that form the next layers of the processing chain.

The Front End Electronics including ASICs will need to be compatible with the streaming readout DAQ system plan. FEEs will need to support continuous sampling modes and not require an external trigger to convert detector signals because this will introduce large unwanted DAQ deadtime. Full waveform sampling for high occupancy detectors with zero suppression and feature extraction (time & charge) will be needed for a flexible streaming readout system.

ASIC devices have been carefully evaluated for each of the ECCE experiment detector systems and are listed for the PID detectors in Table 7. High channel counts for the hpDIRC and mRICH detectors have based their readout on the High Density System-on-a-Chip (HDSoc) ASIC that is commercially produced by Nalu Scientific. The HDSoc has 64 channels and a very high bandwidth sampling ADC for waveform capture and feature extraction modes. This ASIC will support the streaming readout model. The dRICH detector is planning to use the MAROC3 ASIC which is a 64-channel device that interfaces directly to a 64 pixel maPMT device. Supporting electronics to configure the MAROC3 and provide streaming data has been in use at Jefferson Lab for the CLAS12 RICH detector for several years and is a mature technology and the MAROC3 device is now commercially available. The 64-channel SAMPA amplifier and digitizer ASIC is strongly considered for the μ RWELL tracking detectors and is a very good example of an ASIC that will operate within the requirements of a streaming readout front end.

AC-Low Gain Avalanche Diodes (AC-LGAD) sensors

planned for the Time-Of-Flight PID detector system, where the channel counts are very dense, as well as the far-forward detectors. Development of front-end electronics, particularly ASIC chips, for AC-LGAD readout is part of the eRD112 project for targeted EIC detector R&D. The strategy is to base designs on the ATLAS ALTIROC (130 nm) and CMS ETROC (65 nm) designs as a starting point, and reduce the pixel granularity and timing jitter to meet the EIC requirements. Specifically, the IJCLab (Orsay)/ OMEGA (IN2P3-École Polytechnique) group on the eRD112 team is a main developer of the ATLAS ALTIROC, and will play the lead role at the initial stage of ASIC development. A preliminary 130 nm ASIC design with a pitch size of 0.5 mm \times 0.5 mm has been achieved as a stepping stone, that meets the requirements set by the EIC Roman Pot, B0 detector, and Off-Momentum detector. Future development will focus on further improving the timing jitter and scaling up to meet the requirements of the large-scale TOF system.

The calorimeter readout in ECCE will make use of a common digitizer design for all calorimeter systems. The development will start with the existing 64-channel, 14-bit ADCs running at six times the RHIC bunch crossing frequency of just below 10 MHz, at about 60 MHz designed for the sPHENIX calorimeters. ECCE will have a common digitizer design for all calorimeters, although the form factors may differ depending on the detector implementation. It is likely that the sampling frequency will be higher based on the detector requirements. The ECCE calorimeter subsystem includes a very high channel count, however no custom ASIC development is considered because the existing sPHENIX 64-channel 14-bit ADC design is proven and reduces the number of separate electronics designs that need to be developed, verified, and maintained throughout the lifetime of the experiment.

9. Computing plan

The ECCE consortium plans to deploy a federated computing model for the EIC, where multiple facilities are used. A similar strategy has been successfully deployed by the LHC in the form of the Worldwide LHC Computing Grid (WLCG) [40]. ECCE has developed a tiered “Butterfly” model for EIC computing as shown in Figure 28 [41]. In this model, both compute and storage resources are distributed with data storage focused at the Echelon 1 sites. This means access to data by users will be performed by connecting Echelon 3 sites directly to Echelon 1 sites. The Echelon 1 sites will themselves provide significant compute capability, but will also farm out large campaigns to Echelon 2 sites, taking advantage of the diverse computing resources available at collaborating institutions.

We have adopted a fixed-latency offline computing model where both the final calibration and reconstruction of raw data occur within 2-3 weeks of acquisition [41] with resource requirements shown in Table 8. During this period, raw data will be buffered on disk at all of the Echelon 1 sites, along with permanent archival copies on tapes. Final calibration will be performed semi-automatically including accumulating sufficient data for tracker alignment and energy scale calibration of the calorimeters. The ECCE computing team is also pioneering

Table 7: PID Detector ASICs and channel counts.

PID WBS Name	Detector	ASIC	Channels
Barrel PID	hpDIRC	High Density SoC	69,632
	TOF	eRD112 development	8,600,000
Electron Endcap	mRICH	High Density SoC	65,536
	TOF	eRD112 development	920,000
Hadron Endcap	dRICH	MAROC3	5,376
	TOF	eRD112 development	1,840,000
Far-Forward Detectors	Roman Pots	eRD112 development	524,288
	B0 Detector	eRD112 development	2.6M
	Off-Momentum Detectors	eRD112 development	1.8M
Far-Backward Detectors	Low- Q^2 Tagger	eRD112 development	4.6M
	Luminosity Monitor	eRD112 development	268,441

1477 the application of state-of-the-art AI/ML algorithms in detector
1478 optimization [42, 23], simulation, and PID [43], as well as
1479 real-time reconstruction in streaming readout [44, 45], data
1480 reduction [46], and signal processing [47]. AI/ML will continue
1481 to play an integral and essential role in the ECCE online and
1482 offline computing. After calibration, data processing will be re-
1483 leased to multiple sites including HTC facilities at both Echelon
1484 1 and 2 sites as in Fig. 28. We expect that the produced simulation
1485 sample will focus on 10% of the EIC collision cross-section that
1486 is directly relevant for the signal and background of the core
1487 ECCE physics program. These events will be simulated to
1488 $O(10)$ times the statistics in real data to constrain systematic un-
1489 certainty from the simulated sample to be much smaller than the
1490 data statistical uncertainty. The projected simulation resources
1491 are equivalent to the needs shown in the data reconstruction as
1492 in Table 8.

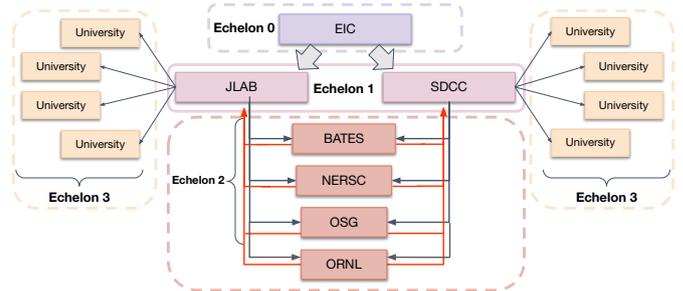


Figure 28: EIC Butterfly model of federated offsite computing [41]. In this model, nearly all storage is contained in echelon 1 while large portions of the raw data processing is delegated to multiple HTC/HPC facilities.

1493 During the development of this proposal, a detailed detec-
1494 tor model was simulated and reconstructed taking advantage of
1495 years of ongoing development and validation with the Fun4All
1496 EIC/sPHENIX software [24, 48]. Fun4All was determined to
1497 be the best software stack for the ECCE proposal studies, for
1498 expediency, reliability and its familiarity within the software
1499 team. Software is constantly evolving and choices will be re-
1500 evaluated in the coming months to ensure that over the next
1501 decade the ECCE software will incorporate the most advanced
1502 framework and packages with the aim of delivering a high per-
1503 formance, user-friendly, and reliable software stack. For ex-
1504 ample, the inclusion of AI as a tool to optimize detector de-
1505 sign [42] has been utilized within the ECCE software stack as
1506 described in Ref. [23]. Another example includes the integra-
1507 tion of A Common Tracking Software (ACTS) package [49] as
1508 highlighted in Ref. [50], and used in preliminary ECCE track-
1509 ing pattern recognition and efficiency studies.

10. Infrastructure/Integration

The interaction region has an overall length of 9.5m. The ECCE detector extends from -4.5m to 5.0m around the origin. A total of half a meter of space between the end caps and the first interaction region magnets is reserved for vacuum pumps, valves, etc. The ECCE detector has an outer radius of 2.67 meters, which fits into the constraint given by the Rapid Cycling Synchrotron (RCS) located at 3.35m. To achieve the necessary alignment of the magnet with the electron direction the detector is rotated by 8 mrad in the horizontal plane.

The central detector features service gaps for routing out cables and services. For example, service gaps between the central barrel and the forward calorimeter assembly and the backward flux return are envisioned, as indicated in the Sketchup mechanical model on the cover page. Additional space between the inner detectors and hpDIRC, and barrel EMCal and cryostat allow for routing cables out towards the service gaps. The beam

Table 8: Estimate of raw data storage and compute needs for first three years of ECCE, assuming ramp up to full luminosity by year 3 [41]

	ECCE Runs		
	year-1	year-2	year-3
Luminosity	$10^{33}\text{cm}^{-2}\text{s}^{-1}$	$2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$
Weeks of Running	10	20	30
Operational efficiency	40%	50%	60%
Disk (temporary)	1.2 PB	3.0 PB	18.1 PB
Disk (permanent)	0.4 PB	2.4 PB	20.6 PB
Data Rate to Storage	6.7 Gbps	16.7 Gbps	100 Gbps
Raw Data Storage (no duplicates)	4 PB	20 PB	181 PB
Recon process time/core	5.4 s/ev	5.4 s/ev	5.4 s/ev
Streaming-unpacked event size	33kB	33kB	33kB
Number of events produced	121 billion	605 billion	5,443 billion
Recon Storage	0.4 PB	2 PB	18 PB
CPU-core hours (recon+calib)	191M core-hours	953M core-hours	8,573M core-hours
2020-cores needed to process in 30 weeks	38k	189k	1,701k

1527 pipe diameter increases in radius from the interaction point to 1554
 1528 the end caps¹, and thus includes several sections divided by 1555
 1529 flanges. This has to be taken into account for detector instal+1556
 1530 lation and servicing. For example, the diameter of the beam 1557
 1531 pipe flange at the location of the EEMC determines the con+1558
 1532 figuration of the first layer of PbWO₄. The beam pipe would 1559
 1533 need to be disassembled for the EEMC to be inserted/extracted 1560
 1534 from its nominal position. To maximize the EEMC acceptance 1561
 1535 and allowing for easy access the ECCE detector includes an 1562
 1536 option to separate out the inner EEMC. Taking into account the 1563
 1537 beam pipe diameter, the outer endcap detectors like the forward 1564
 1538 calorimeter assembly are foreseen to follow a clam shell design 1565

1539 11. Technology Selection, Risk and R&D 1566

1540 While the ECCE detector design seeks to minimize risk 1567
 1541 through strategic re-use and the selection of mature, yet state- 1570
 1542 of-the-art detector technologies, there are nevertheless risks as- 1571
 1543 sociated with some ECCE detector technology choices. Our 1572
 1544 strategy has been to clearly identify these risks and develop an 1573
 1545 appropriate mitigation strategy, either through developing alter- 1574
 1546 natives should the risks be realized or eliminating risk through 1575
 1547 an aggressive R&D program. We have developed an extensive 1576
 1548 risk registry for the ECCE proposal that includes risk impact, 1577
 1549 likelihood and mitigation strategy for a wide array of technical 1578
 1550 and cost & schedule risks. This risk registry is available as part 1579
 1551 of the ECCE supplemental materials [51]. 1580

1552 A list of specific risks related to the ECCE technology selec- 1581
 1553 tion includes: 1582

- **BaBar Solenoid:** As a mitigation against the schedule risk posed by a potential problem with the BaBar solenoid developing during sPHENIX running, we plan to proceed with the initial engineering and design for a replacement magnet. A final decision to proceed with the BaBar solenoid or produce a new magnet will be taken in mid-2023 after the performance of the BaBar solenoid during the first year of sPHENIX running is reviewed by a panel of experts. The risk-mitigation decision tree is shown in Figure 29. Assuming a five-year construction for a new magnet, consistent with the duration of new SC magnets recently built as part of the Jefferson Lab 12-GeV Upgrade project, the ECCE schedule for detector construction and assembly would remain consistent with an early CD-4A date if procurement of a replacement magnet is determined to be necessary. 1583

- **SciGlass Calorimetry:** The use of SciGlass for electromagnetic calorimetry in the ECCE barrel offers a low-cost solution to large area electromagnetic calorimetry with excellent energy resolution. The performance of SciGlass has been demonstrated in short (20 cm) bars. The performance validation of longer blocks is part of the ongoing EIC project R&D (eRD105) and the demonstration of large scale commercial production with high quality and uniformity is part of an ongoing Phase2 SBIR/STTR. The ECCE strategy to address the risk associated with SciGlass, if it is realized, is two-fold: if SciGlass cannot be produced on-schedule in sufficient quantities for ECCE needs, one option would be to refurbish half of the existing sPHENIX W/SciFi calorimeter to cover half of the ECCE acceptance, reducing the overall need for SciGlass. The refurbished sPHENIX calorimeter could meet 1584

¹this is necessary to allow the cone of proton/neutron and nuclear breakup particles to pass through 1585

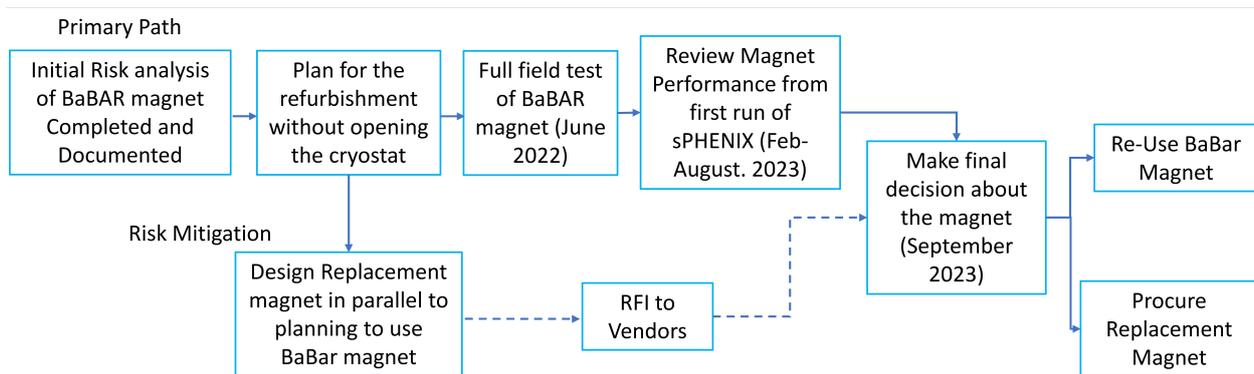


Figure 29: Decision tree for the risk mitigation strategy associated with the reuse of the BaBar solenoid.

required energy resolution in the forward ($\eta > 0$) acceptance, albeit with lower performance compared with SciGlass. SciGlass would still be used at the backwards direction ($\eta < 0$) where optimal energy resolution is required. If SciGlass were unavailable in sufficient quantity for the backwards region as well, the remaining half of the ECCE acceptance could be covered with PbGl towers at additional expense.

- Cylindrical μ RWell Tracking:** The ECCE experiment utilizes μ RWell tracking layers in the central barrel as a low-mass, cost-effective means to provide the additional tracking points required to achieve the required momentum resolution. While cylindrical μ RWell detector should be technically possible, it remains to be demonstrated that they can provide stable operation at the required $55\mu\text{m}$ resolution in a magnetic field. ECCE plans an aggressive R&D program, working with our international partners, to demonstrate the performance of cylindrical μ RWell detectors and address any technical challenges that may arise.
- AC-LGADs:** ECCE plans AC-LGAD sensors for TOF not only in the forward and backwards region but in the central barrel as well. Cylindrical detectors based on LGAD sensors have not been previously demonstrated, and AC-LGAD sensors require additional R&D to demonstrate and characterize their performance and suitability for use in both the TOF and Roman Pot detectors in ECCE. To mitigate this risk, ECCE plans a comprehensive R&D for AC-LGAD sensor and readout development, characterization and readout.
- B0 Detector:** The current design of the B0 detector calls for a crystal calorimeter to be installed after the tracking stations in the B0 warm bore to enable studies of physics processes that require γ energy measurement such as u-channel DVCS. The installation, integration and maintenance of this detector present severe mechanical challenges due to the tight constraints in the magnet bore that will require detailed mechanical designs. If it is determined

that installation of a crystal calorimeter is not feasible we will be forced to accept the loss of scope and install only the tracking planes.

In addition to detailing risks in the ECCE risk registry, we also document potential risk opportunities. We list a few representative examples here, additional information is available in the ECCE risk registry and opportunity log, both of which are available in the ECCE supplemental material.

- Reduction of the number of hpDIRC sensors:** R&D performed for the PANDA DIRC suggests that the sensor coverage can be reduced by up to 30% without significant impact on the PID performance. A positive outcome of the simulation study and validation in test beam would allow ECCE to take advantage of this opportunity.
- Improved ITS3 sensor yields:** Si tracker costs could be reduced if ITS3 sensor yield is higher than anticipated. We intend to take advantage of knowledge gained from ALICE ITS3 production, as well as with the foundry to optimize sensor yields.
- hpDIRC lightguide shape:** Currently three options are being considered for the lightguide section of the bar box, which couples the narrow radiator bars to the lenses and prism. Use of one wide plate per bar box would be the most cost efficient. We intend to perform a simulation study and a test experiment with particle beams to validate this potentially cost-saving and performance-enhancing hpDIRC option for ECCE.

12. Detector vs. Machine Project Scope

Prior to the start of the detector proposal process, several decisions were made by the project to distinguish the scope of the detector project from that of the EIC machine project:

- The accelerator/cryogenics scope will provide a cryogenic distribution can in the experimental Hall at IP6. The remaining scope in the Hall is included in the detector magnet.

- The IR and vacuum (IR magnets, beam pipes, pumps, valves, windows, etc.) are part of the accelerator/IR scope.
- The luminosity detector is included in this detector proposal and includes anything that comes behind the version/exit window. Up to that is assumed as accelerator scope.
- The polarimetry scope is not included in this detector proposal as it is handled external to the proposals through the across proto-collaborations polarimetry working group.
- Any required IP-6 de-installation costs are assumed to be covered as regular laboratory operations costs.
- The infrastructure scope includes items that are directly related to the ECCE specific detector proposal (support structures, cradle, specific gas handling systems, etc.).

13. Upgrades

The ECCE baseline detector can be augmented with additional upgrades that either enhance or expand the existing physics reach:

- **Dual-Readout Calorimetry:** The addition of a dual-readout calorimeter, replacing the FEMC and LFHCAL in the forward region would provide a significant improvement in energy resolution for hadrons in the forward region. Because the tracking momentum resolution worsens with increasing momentum while the calorimeter energy resolution improves with increasing energy, the association of tracks with high-resolution clusters in the forward calorimeters can be used to improve the knowledge of high momentum tracks (the so-called "particle-flow" approach). With a dual-readout calorimeter, the cross-over point between the tracking and calorimeter resolution would be pushed lower, enabling this improvement for a larger fraction of the tracks detected in the forward arm. Adding such improved capabilities to ECCE would improve measurements of SIDIS hadrons, TMD measurements with jets, and the ability to reconstruct event kinematics using the hadronic remnants. The Korean HEP community is very interested in deploying dual-readout calorimetry in ECCE as they develop the technology for future high-energy facilities.
- **Muon Chambers:** The addition of muon chambers to the ECCE baseline would enable the improved detection and tagging of semi-leptonic decays of heavy flavor. ECCE collaborators in Israel have expressed an interest in providing this upgrade as an in-kind contribution to ECCE. The ability to use muons for such processes as DVCS and DVMP removes an ambiguity between the produced leptons in the electron channel and the scattered electron. Such an upgrade can enhance the ability of ECCE to produce the science in the EIC white paper and NAS report.

- **Hadron Arm High-Rapidity Tracking Layer:** The addition of a small, high rapidity AC-LGAD layer ($3.0 < \eta < 3.5$) in front of the forward electromagnetic calorimeter could improve track momentum resolution for very high momentum ($p_T > 20$ GeV/c) charged tracks. It would also allow the detection of hadrons that enter the forward calorimeters from outside the acceptance of the inner tracker. This would be very beneficial for the deconvolution of overlapping clusters in the forward calorimeters as a necessary component to implementing a particle flow algorithm for the reconstruction of forward jets.
- **Backwards Hadronic Calorimeter:** While the ECCE baseline does not include a backwards hadronic calorimeter in the electron-going region, the addition of such a calorimeter could contribute to the reconstruction of event kinematics by the double-angle of Jacquet-Blondel methods at high-y, and contribute to electron identification in the backwards region. Such a calorimeter could be based on the STAR FCS Fe/Sc hadronic calorimeter, with partial re-use of the existing STAR additional modules and new modules constructed to complete the acceptance. We have studied this extensively within ECCE, and a hadronic calorimeter in the backwards region is not required to pursue the science program in the EIC white paper or NAS report and therefore does not justify the substantial expense required at this time. However, it is possible as the EIC program matures and the EIC luminosity increases we may revisit this with a simple upgrade.

14. Summary

In summary, the ECCE detector has been designed to address the full scope of the EIC physics program as presented in the EIC white paper [3] and the NAS report. ECCE can be built within the budget envelope set out by the EIC project while simultaneously managing cost and schedule risks. This detector proposal has been reviewed and has been selected to be the basis for the project detector for the future collider.

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