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An overview of the imaging layers of the Barrel Imaging Calorimeter for ePIC at the Electron Ion Collider

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Barrel Imaging Calorimeter (BIC) is a hybrid detector for the electron-Proton/Ion Collider (ePIC) experiment at the Electron-Ion Collider (EIC). BIC is a high-performance sampling calorimeter with inexpensive, low-power HV-CMOS sensors for shower profiling. The state-of-the-art hybrid concept comprises 6 layers of HV-CMOS sensors interleaved with the first 5 Pb/ScFi layers, followed by a large volume filled with the Pb/ScFi layers. The detector design meets the stringent ECAL requirements in the barrel region as outlined in the EIC yellow report. Some of the important requirements are 10^4 π suppression at low momenta, decent energy resolution for photon energy reconstruction, fine granularity for good $\pi^0 - \gamma$ separation up to 10 GeV, and the measurement of low-energy photons down to 100 MeV with a range exceeding 10 GeV.

This report presents an overview of the Barrel Imaging Calorimeter design, with a focus on the imaging layers. BIC with the coverage of (-1.71 < η < 1.31), consists of 48 trapezoidal sectors built of layers of scintillating fibers embedded in lead and 6 slots for imaging layers. The imaging layers are composed of AstroPix, an HV-CMOS monolithic silicon sensor inspired by ATLASPix3 and MuPix, designed using a 180 nm CMOS process for future gamma-ray astrophysics missions. The imaging layers consist of Trays holding the AstroPix Staves that are built out of Modules. BIC will incorporate a total of 140 m^2 of AstroPix sensor area in the barrel imaging region. The AstroPix sensors offer the advantages of a fully monolithic structure, low manufacturing cost, and a low material budget, along with fast charge collection, high radiation tolerance, and low-power operation. They feature large sensitive areas, low noise, a wide dynamic range, and good energy/spatial resolution. The report will include a brief discussion on AstroPix performance.

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1. Introduction

The Electron-Ion Collider (EIC) is designed to address some of the most fundamental questions in nuclear physics, including the origin of nucleon spin and mass, the partonic structure of nucleons and nuclei, and the behavior of dense gluonic matter [1]. The EIC physics program depends on precise four-momentum reconstruction of the scattered electron. The Barrel Electromagnetic Calorimeter (Barrel ECAL) must deliver precision measurements of energy and shower profile to distinguish electrons from background pions in Deep Inelastic Scattering (DIS) processes. Additionally, the calorimeter must precisely measure photon energies and positions from Deeply Virtual Compton Scattering (DVCS) and resolve photon pairs from $\pi^0 \to \gamma\gamma$ decays, as shown in Fig. 1.

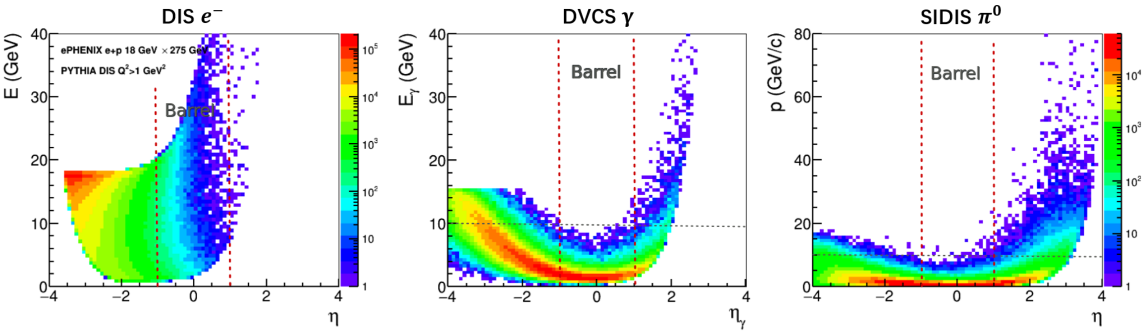
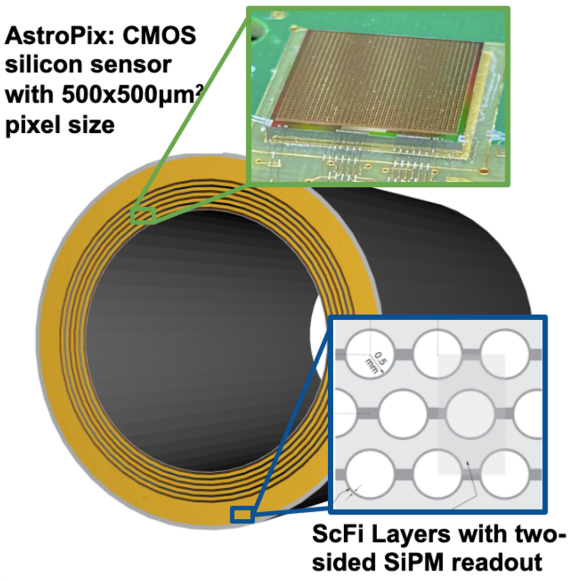


Figure 1: Simulated momentum of particles in e+p collisions at beam energies of 18×275 GeV/c [1]. The η-range covering central barrel region of electromagnetic calorimeter is highlighted with red dashed lines. Left: DIS e^- from PYTHIA [2]; Middle: DVCS γ from MILOU [3]; and Right: π^0 from PYTHIA.

The Barrel ECAL serves as the principal subsystem for electron identification and separation from pions within the ePIC detector. To meet physics objectives, the Barrel ECAL must provide: (1) robust electron identification with a pion suppression factor of $\sim 10^4$ at low momenta ($p < 4$ GeV/c), (2) energy resolution better than $10\%/\sqrt{E} \oplus (2\text{–}3)\%$, (3) photon detection from 50 MeV to 10 GeV with γ/π^0 separation up to 10 GeV, and (4) reliable particle identification (PID) for charged hadrons and low-energy muons. The design must also comply with tight spatial constraints within the solenoid while maintaining the necessary performance to fulfill the comprehensive physics goals.

1.1 Barrel Electromagnetic Calorimeter Concept

The ePIC Barrel Imaging Calorimeter (BIC) integrates two complementary detector technologies to meet the stringent physics performance requirements. It combines a lead-scintillating fiber (Pb/ScFi) sampling calorimeter, with a high-granularity silicon pixel tracker based on *AstroPix* sensors [4–8]. The Pb/ScFi subsystem, derived from the proven GlueX Barrel Calorimeter design [9], provides a robust, radiation-tolerant, and cost-effective method for high-resolution electromagnetic energy measurement through efficient scintillation light collection. The *AstroPix* sensor originally developed for NASA's space mission [4], offer low power consumption, high radiation tolerance, scalability, and excellent spatial precision. This hybrid architecture achieves outstanding spatial and energy resolution, providing precise position reconstruction and advanced shower profile characterization, which are critical for reliable e^-/π and π^0/γ discrimination in the barrel region.



(a) The Barrel Imaging Calorimeter (BIC).

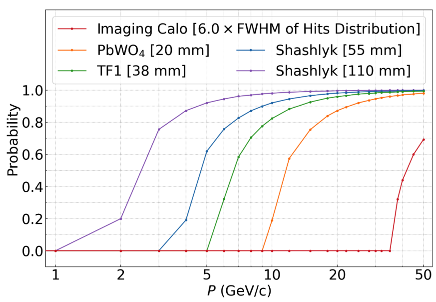
(b) 6 layers of HV-CMOS MAPS, AstroPix.

(c) Pb/ScFi calorimeter with superior energy resolution.

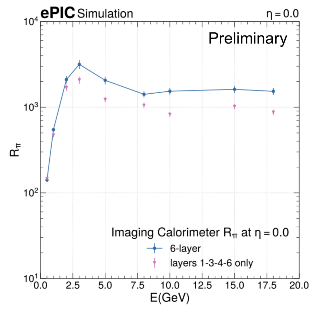
Figure 2: The Barrel Imaging Calorimeter (BIC) at the ePIC detector integrates a high-performance Pb/ScFi sampling calorimeter with AstroPix silicon tracking layer for detailed shower profiling.

1.2 BIC Performance

The performance of the BIC design has been studied in through comprehensive simulations to evaluate its capability to meet the key physics requirements of the EIC, as outlined in the Yellow Report [1]. For the simulation, six layers of *AstroPix* sensors were implemented, interleaved with Pb/ScFi layers featuring the same plastic scintillating fiber dimensions as the GlueX design [9].



(a)



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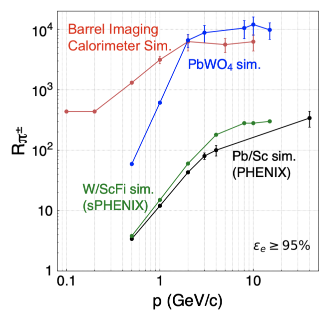


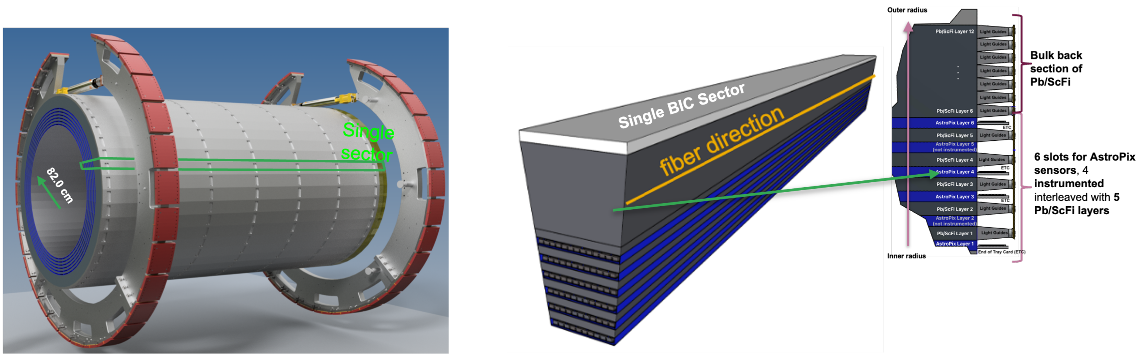
(c)

Figure 3: (a) The cluster merging at $\eta = 0$ for two γs from π^0 decay at particular π^0 momentum, P [10]. (b) The charged pion suppression factor for 95% e^- efficiency at $\eta = 0$ demonstrates superior performance for both the full 6-layer and the baseline 4-layer imaging tracker. (c) The pion rejection power of the BIC (red solid line) compared with other technologies listed in the EIC Yellow Report [1, 10].

The proposed design meets and exceeds the Barrel ECAL requirements specified in the Yellow Report for the central region [11]. Simulations of the Pb/ScFi calorimeter indicate an energy resolution of $\sigma_E/E = (5.3 \pm 0.1)\%/\sqrt{E} \oplus (0.73 \pm 0.05)\%$ for photons at normal incidence, with testbeam performance reported in [12]. The imaging layers provide excellent spatial resolution, enabling full 3D shower reconstruction, efficient separation of $\pi^0 \to \gamma\gamma$ decays from single photons at energies above 20 GeV, and precise photon impact position measurement. Fig. 3(a) shows the probability of merging two γ showers at $r = 103$ cm. Fig. 3(b) shows the charged pion suppression factor at $\eta = 0$ for 95% electron efficiency for 6-layer and 4-layer tracker, demonstrating rejection exceeding 10^3 at low to mid energies. As shown in Fig. 3(c), AI-based classification using 3D cluster profiles achieves superior e–π discrimination for $p \leq 4$ GeV/c, while maintaining performance comparable to crystal calorimeters at higher momenta at significantly lower cost.

2. BIC Design

The BIC is located in the barrel region of the ePIC detector, spanning 435 cm in length with an inner radius of 82.5 cm, covering the pseudorapidity range $-1.71 \lesssim \eta \lesssim 1.31$. Fig. 4(a) shows its layout: 48 trapezoidal sectors form a cylindrical assembly with a total thickness of 17.1 X_0 at $\eta = 0$. Each sector contains six imaging layers, separated by $\sim$ 1.43 X_0 of Pb/ScFi, housing AstroPix sensors that enable full 3D electromagnetic-shower reconstruction with $\sim$ 144 μm spatial precision. In the baseline design, four layers (slots 1, 3, 4, and 6) are instrumented, with the remaining two reserved for upgrades. The innermost layer also provides a tracking point behind the DIRC.



(a) (b)

Figure 4: (a) 3D rendering of the BIC. (b) The structure of a single sector, featuring interleaved Pb/ScFi and imaging layers, followed by the Pb/ScFi bulk section. On the right, the side view of the Sector is shown.

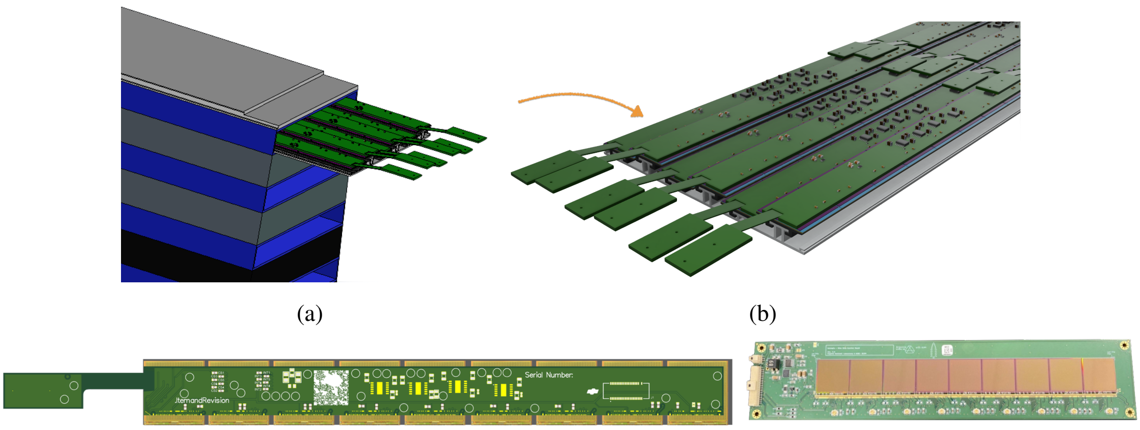
The Pb/ScFi matrix is read out via End-of-Sector Boxes (ESBs) at both ends of Sector, which also house system services. ESB contains light guides, SiPMs, and the CALOROC front-end board for Pb/ScFi readout, while AstroPix layers are read out via End-of-Tray Cards (ETCs) located in the same region. Fig. 4(b) shows a side view of a Sector, illustrating the six imaging layers interleaved with Pb/ScFi and the mechanical envelope containing the ESB, light guides, SiPMs, and ETCs.

2.1 Pb/ScFi

The Pb/ScFi section of the BIC uses 1 mm scintillating fibers embedded in a lead matrix, aligned along the z-axis and read out on both ends to provide simultaneous energy measurement and longitudinal position determination. Light from the fibers is routed through light guides that split the signal into 12 rows by 5 columns at each sector end, coupled to SiPMs via silicon optical interfaces ("optical cookies"). The SiPMs have a 50 μm pixel pitch, balancing dynamic range and photon detection efficiency. CALOROC ASIC-based front-end electronics process the SiPM outputs, achieving the timing precision needed to reconstruct the hit z-coordinate with ~ 1 cm$/\sqrt{E}$ resolution while maintaining low noise and high radiation tolerance.

2.2 AstroPix Imaging Layers

The imaging layers of the BIC use AstroPix sensors, monolithic HV-CMOS MAPS with a 500 μm pixel pitch, placed between Pb/ScFi layers for fine 3D shower reconstruction and particle identification. Fig. 5(a) shows an AstroPix tray in the innermost imaging layer. Each Module, the basic building block, consists of nine 2 cm $\times$ 2 cm AstroPix chips, daisy-chained, mounted on an aluminum baseplate, and read out via a flexible PCB (Fig. 5(c)). Twelve Modules form a stave, and each radial layer in a Sector has trays containing six or seven staves depending on radius (Fig. 5(b)). Each tray spans half a Sector and is read out by an End-of-Tray Card (ETC), which handles chip configuration, signal conditioning, data formatting, and communication, interfacing directly with all Modules to ensure efficient readout.



(a) (b) (c) (d)

Figure 5: (a) CAD model of the innermost imaging layer positioned within the Sector envelope. (b) The first imaging layer has neighboring staves arranged with an overlap to ensure complete coverage. (c) AstroPix module CAD with (d) test article of the Module, 9-chip PCB test board. Results listed in [13]

The BIC detector consists of 48 Sectors, each equipped with eight AstroPix trays. In the innermost layer, each half-sector contains six staves, while the other three instrumented layers have trays with seven staves each, totaling 54 staves per Sector and 648 AstroPix Modules. Across all 48 Sectors, this corresponds to about 31,104 Modules, or roughly 279,936 AstroPix sensors.

3. AstroPix - an HVCMOS MAPS

The AstroPix sensor is a 180 nm HV-CMOS monolithic active pixel sensor (MAPS) based on the ATLASPix architecture [14–16]. Adapted for gamma-ray astrophysics, AstroPix provides the digital energy resolution required for Compton-scattering and pair-production event reconstruction. Its key performance targets; wide dynamic range, timing, low power consumption, and energy resolution, are summarized in Table 1. Each pixel integrates an amplifier followed by a low-pass filter, suppressing noise while maintaining the required energy performance.. Versions 3 and 4 are currently under evaluation, with their carrier boards shown in Fig. 6.

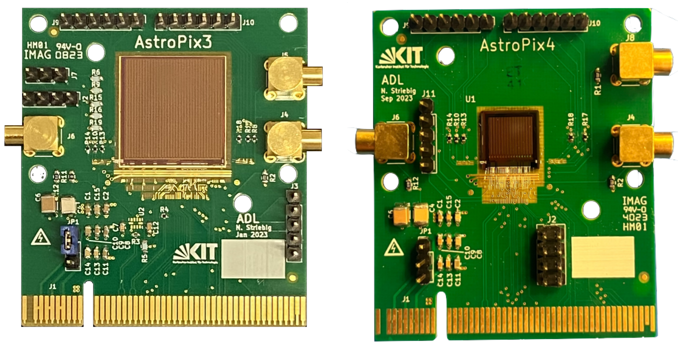
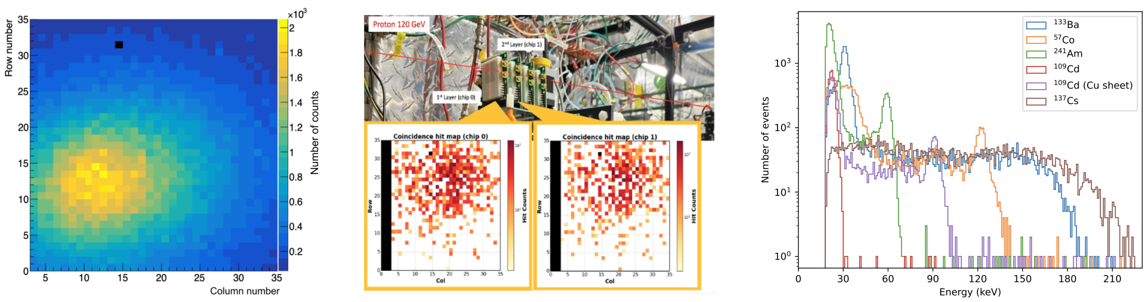


Figure 6: AstroPix v3 (left) and v4 (right) carrier boards.

Pixel size	0.5×0.5 mm^2
Chip size	2×2 cm^2
Power usage	< 2 mW/cm^2
Dynamic range	25-700 keV
Energy resolution	10%@60 keV
Time resolution	15-20 ns
Passive material	< 5% on chip
Si Thickness	500 μm

Table 1: AstroPix sensor specifications for BIC.

AstroPix version 3: The AstroPix sensor design evolved through several iterations, culminating in the first full-scale flight-prototype chip: AstroPix v3. This version uses the full $\sim 18.7 \times 19.58$ mm^2 reticle with a 35×35 pixel matrix at 500×500 μm^2 pitch. Signals are read out via a daisy-chained row–column architecture to the digital periphery. Fig. 7(a) shows a beam hit map from a 120 GeV proton test, confirming that over 98% of pixels functioned as expected. A multilayer telescope of AstroPix v3 chips was also tested, with coincidence events from the first two layers shown in Fig. 7(b). Individual pixels were energy-calibrated on the bench with radioactive sources (Fig. 7(c)), and noisy pixels were masked prior to testing. At high hit rates, the daisy-chained readout produced ghost hits, a known architectural effect.



(a) (b) (c)

Figure 7: (a) Beam spot recorded with AstroPix v3 in the 120 GeV proton testbeam at FTBF, Fermilab. Black colored pixels are masked. (b) Hit map for coincident events from the double-layered AstroPix telescope (picture on top) at FTBF. (c) Energy calibration response from a single pixel of an AstroPix v3 chip [8].

AstroPix version 4: AstroPix v4, produced in a multi-project wafer run, features a smaller 10 mm× 10 mm die with a 16×13 array of 500×500 μm^2 pixels, each equipped with an individual pixel-level readout and hit buffer, resolving the ghost-hit issue observed in the daisy-chained architecture of earlier versions. It incorporates three timestamps: 2.5 MHz coarse, 20 MHz fine, and a 16-bit flash TDC, providing a ToT and timestamp clock granularity of ~ 3.125 ns and an expected overall timing of 15–20 ns (to be measured). AstroPix v4 also introduces TuneDACs for pixel-by-pixel threshold tuning and masking. Fig. 8 shows the energy calibration of all pixels (left) and the spectroscopic Time-over-Threshold (ToT) distributions obtained for several radiation sources on right.

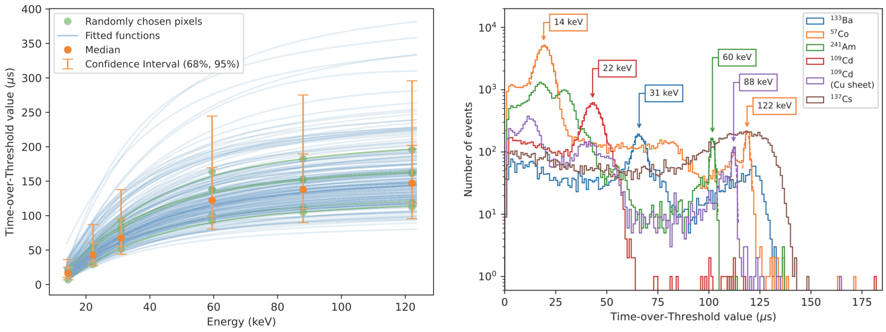


Figure 8: (Left) Energy calibration for all calibrated pixels. Green points and fits illustrate mean ToT for few pixels. (Right) Calibrated energy responses from a single pixel of an AstroPix_v4 chip. Plots from [6].

The AstroPix v3 and v4 sensors have been evaluated extensively through laboratory bench testing and dedicated test beam campaigns, with their performance results documented in several publications [5–8].

AstroPix version 5: AstroPix version 5 is the latest full-size design iteration of the sensor, with a chip area of approximately 18.7 mm $\times$ 19.58 mm and a 36×34 pixel matrix. The pixel size remains unchanged from previous versions, retaining the 500 μm pitch optimized for the BIC imaging layers. AstroPix v5 represents the final design architecture for the BIC detector, while the production chip (AstroPix v6) will be a scaled variant with a final die size of 20 mm$\times$20 mm. Version 5 incorporates several final requirements and corrections identified in v4, including redesigned comparator columns to satisfy updated foundry process rules, improved synchronization of the flash-TDC, and an enhanced in-pixel amplifier with dynamic feedback to increase the dynamic range. AstroPix v5 has been submitted for fabrication, with delivery expected in spring 2026.

4. Summary

This paper presents an overview of the Barrel Imaging Calorimeter (BIC) developed for the ePIC experiment at the future Electron–Ion Collider, a hybrid electromagnetic calorimeter that integrates a Pb/scintillating-fiber sampling calorimeter with multiple layers of high-granularity HV-CMOS silicon sensors (AstroPix) to achieve precise energy and spatial measurements. The detector comprises 48 trapezoidal sectors with six imaging layers, four instrumented in the baseline design providing detailed 3D shower profiling that enables robust electron identification, photon reconstruction, and efficient $\pi^0 - \gamma$ separation up to high energies. The Pb/ScFi subsystem delivers excellent energy resolution, while the AstroPix layers supply fine spatial granularity using low-power, radiation-tolerant monolithic sensors originally developed for gamma-ray astrophysics. Prototype evaluations of successive AstroPix versions (v3–v5) demonstrate high pixel efficiency, good timing and energy performance, and architectural improvements toward the final full-scale implementation of the BIC within the ePIC detector.

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