Chapter 2

Detector Requirements

2.1 Experimental Equipment Requirements Summary and Physics Motivation

The performance requirements for the ePIC detector evolved from the community ”Yellow Report” [23] initiative led by the EIC User Group (EICUG) in 2020-2021. The purpose of this process was to advance the state and detail of previous physics and detector studies and document the requirements for a general purpose EIC detectors, which are conceived to match the whole EIC physics scope as defined in 2018 in the National Academy of Sciences, Engineering, and Medicine report evaluating the EIC project [194]. Following the Yellow Report process, an open call for detector proposals from the EIC project led to two candidates - the ATHENA [33] and ECCE [36] detector proposals. The development of the detector proposals was supported by additional studies that further refined the detector requirements and the available detector technologies to address them. Following the selection of the ECCE proposal as the reference design for the EIC detector, the ATHENA and ECCE collaborations merged in the ePIC Collaboration and underwent a year-long consolidation process where the best approaches from both proposals were combined to form the ePIC detector. The detector optimization continued within the ePIC Collaboration resulting in the present detector baseline, which is presented in this preTDR document. The ePIC detector is detailed in Chapter 3 with an overall introductory description in Sec. 3.1.

The experimental program at the Electron-Ion Collider (EIC) demands a versatile detector system capable of reconstructing final-state particles with high precision over a wide kinematic range. This is obtained with the combination of a Central Detector (Figure 3.2 in Chapter 3) sitting at the interaction region and covering the pseudorapidity range (-3.5 , 3.5) [NOTE: in the Project Requirement table the range is -4 - 4.] and Far Detectors (Figure 3.4 in Chapter 3) situated along the outgoing beam lines giving access to the pseudorapidity domain that cannot be covered in the Central Detector. Figure 3.1 in Chapter 3 shows how the scattered electron for different x - Q^2 and hadrons are distributed over the detector rapidity coverage. Three areas can be identified in the Central Detector: the barrel region indicatively corresponding to the pseudorapidity range (-1.5 , 1.5) and the endcaps, the backward one covering the pseudorapidity range (-3.5 , -1.5) the and the forward one in the pseudorapidity range (1.5 , 3.5). The design of the collider Storage Ring and Interaction Region (Chapter 5) imposes important constraints to both the Central Detector and the Far Detectors. The Central Detector cannot exceed a length of 9.5 m and adequate clearance must be provided for the beam pipe resulting from the merging in the Interaction Region of the electron and ion pipes. The beamline elements realizing the Interaction Region set constraints to the acceptance of the Far Detectors.

The performance requirements for the ePIC detector are summarized in Figure 2.1, which specifies performance requirements for tracking, calorimetry, and particle identification across different pseudorapidity (η) regions. In this section we describe these requirements and connect them to their underlying physics motivations from which these requirements were derived as well as the selection of detector technologies enabling these requirements.

In chapter 3 we will describe in detail the technology selection, design, integration and performance of the ePIC detector, including detector resources as power, cooling, cryogens accompany the subsystem description. The global detector integration providing efficient operation, maintenance capability and the pathway for services, communication and resources is described in Sec. 3.3. In the same Section also infrastructure capabilities to support operations and maintenance are presented.

We will demonstrate by presenting the subsystem performance that the detector design meets the requirements and that a detector that meets these requirements can meet the physics goals of the EIC. The detailed link between the requirements and the performance in reconstructing particles in the event final state are provided in Sec. 4.2. The global detector performance as resulting from requirement matching is demonstrated by the studies of challenging physics measurement provided in Sec. 4.4.

The experimental system includes polarimetry and luminosity detectors, which shall measure the electron and proton beam polarization and monitor the instantaneous collision luminosities. They are detailed in Secs. 3.2.9 and 3.2.8.1 respectively.

η	Nomenclature			Tracking and Solenoid				Electromagnetic Calorimetry			Hadron PID: $\pi/K/p$		Hadronic Calorimetry	
				Resolution σ_p, p [GeV/c]	max X/X_0	min p_T	transverse pointing $dca(xy)$, p_T[GeV/c]	Resolution σ_E, E [GeV]	PID	$E_{\min}$	Momentum range	Separation	Resolution σ_E, E [GeV]	$E_{\min}$
<-4.6	↓ p/A	Far Backward Detectors	low-Q^2 tagger	$< 5\%$				$10\%/\sqrt{E}$ $\oplus 3\%$						
-4.6 to -4.0				Not Accessible										
-4.0 to -3.5				Reduced Performance										
-3.5 to -3.0		Central Detector	Backward Detector	$0.1\% * p$ $\oplus 2\%$	$< 5\%$	$100\,\mathrm{MeV/c}$ (pions) $130\,\mathrm{MeV/c}$ (kaons)	$30\,\mu\mathrm{m}/p_T$ $\oplus 40\,\mu\mathrm{m}$	$< (2-3)\%/\sqrt{E}$ $\oplus (1-2)\%$	π supp. up to 10^4	100 MeV	1 - 7 GeV/c	$> 3\sigma$	$100\%/\sqrt{E}$ $\oplus 10\%$	500 MeV
-3.0 to -2.5														
-2.5 to -2.0				$0.05\% * p$ $\oplus 1\%$			$30\,\mu\mathrm{m}/p_T$ $\oplus 20\,\mu\mathrm{m}$							
-2.0 to -1.5								$< 10\%/\sqrt{E}$ $\oplus (2-3)\%$	π supp. up to $10^3 - 10^2$	100 MeV	0.2 - 6 GeV/c			
-1.5 to -1.0														
-1.0 to -0.5			Barrel	$0.05\% * p$ $\oplus 0.5\%$			$20\,\mu\mathrm{m}/p_T$ $\oplus 5\,\mu\mathrm{m}$		π supp. up to 10^2				$100\%/\sqrt{E}$ $\oplus 10\%$	
-0.5 to 0.0														
0.0 to 0.5														
0.5 to 1.0														
1.0 to 1.5			Forward Detector	$0.05\% * p$ $\oplus 1\%$			$30\,\mu\mathrm{m}/p_T$ $\oplus 20\,\mu\mathrm{m}$	$< (10-12)\%/\sqrt{E}$ $\oplus (2-3)\%$	3σ e/π up to $15\,\mathrm{GeV/c}$	100 MeV	0.2 - 50 GeV/c		$50\%/\sqrt{E}$ $\oplus 10\%$	
1.5 to 2.0														
2.0 to 2.5														
2.5 to 3.0				$0.10\% * p$ $\oplus 2\%$			$30\,\mu\mathrm{m}/p_T$ $\oplus 40\,\mu\mathrm{m}$							
3.0 to 3.5														
3.5 to 4.0				Reduced Performance										
4.0 to 4.6				Not Accessible										
>4.6		Far Forward Detectors	B0 Spectrometer	$< 7\%$ $p_T > 1\,\mathrm{GeV}$	$< 5\%$			$< 20\%/\sqrt{E}$ $\oplus 3\%$		100 MeV				
			Off Momentum Spectrometer	$< 10\%$ $p_T > 1\,\mathrm{GeV}$										
			Roman Pots	$< 5\%$ $p_T > 0.5\,\mathrm{GeV}$										
	↑ e		Zero Degree Neutral Detection					$< 20\%/\sqrt{E}$ $\oplus 5\%$		100 MeV			$< 50\%/\sqrt{E}$ $\oplus 5\%$	

Figure 2.1: Table presenting the Experimental Equipment Requirements Summary for the ePIC detector.

2.1.1 Requirements of Tracking Resolution and Momentum Measurement in the Central Detector

Precise momentum and vertex reconstruction are essential across the full acceptance with the following most relevant requirements:

- In the most central region ($-1.0 < \eta < 1.0$), a resolution of $\sigma_p/p \simeq 0.05\% \cdot p \oplus 0.5\%$ and vertex impact parameter resolution better than $20\ \mu\mathrm{m}/p_T \oplus 5\ \mu\mathrm{m}$ is required (p and p_T in GeV/c).
- Forward in the η-range (1.0 , 2.5) and backward in the η-range ($-2.5\ -\ -1.0$) regions demand $\sigma_p/p \simeq 0.05\% \cdot p \oplus 1\%$ to enable kinematic reconstruction at high x and to identify scattered hadrons at low Q^2 (p in GeV/c).
- The above requirements are relaxed for the further regions defined as forward in the η-range (2.5 , 3.5) and backward in the η-range (-3.5 , -2.5) resulting in $\sigma_p/p \simeq 0.1\% \cdot p \oplus 2\%$ (p in GeV/c).

An additional requirement is posed by the usage of the hpDIRC in the barrel region: a 0.5 mrad tracking resolution is needed as input to reach its peak performance.

Physics Motivation: These requirements stem from the need to precisely reconstruct deep-inelastic scattering (DIS) kinematics and hadronic final states. Momentum resolution and vertexing are crucial for semi-inclusive and exclusive processes, such as measurements of transverse-momentum dependent distributions (TMDs), generalized parton distributions (GPDs), and heavy-flavor tagging. In particular, good vertex resolution enables charm and beauty hadron identification, essential for studies of gluon dynamics in the nucleon and nuclei [23,27]. How these requirements enable the physics performance is described in Sections 4.4.1.1,4.4.2 and 4.4.3.

The technologies chosen by ePIC to achieve these requirements represent a balance between resolution and material budget in the detector, as well as a balance between technology maturity and risk. The extremely low material budget requirement is dictated by the need of accurate scattered electron reconstruction needed for the large majority of the measurements within the EIC physics scope.

Enabling Technologies:

- *Magnetic field:* A superconducting 1.7 T solenoid magnet in the central detector bends charged particle trajectories to provide a momentum measurement. It has a bore radius of 1420 mm. The large bore is a crucial parameter for the overall detector design. In fact, in the central region all detector systems apart the hadronic calorimeter are internal to the solenoid, an arrangement made possible by the bore size. The solenoidal field enhances the momentum resolution in the barrel region, in spite of the limited lever arm of the tracking system in the transversal direction. In the central detector endcaps the momentum resolution is limited by the field configuration, therefore requiring the synergistic complement of the tracking measurements with information from other detector systems. The design of this novel superconducting solenoid is presented in Section 3.2.2.
- *Silicon pixel vertex detector:* Based on ITS3/MOSAIX MAPS (Monolithic Active Pixel Sensor) technology [46] with low material budget ($< 0.05\%\ X/X_0$ per layer in the first three layers), providing excellent spatial precision ($\sim 20\ \mu$m pixel size), which enables charm and bottom tagging near the interaction point and precise determination of the event vertex. Additional layers of Si sensors based on an evolution of the ITS3 technology, the EIC Large Area Sensors, provide the sagitta measurement used in determination of the particle momentum. Disc

trackers by MOSAIX-based sensors provide tracking coverage in the forward and backward directions. The adopted ITS3 technology results in a long integration time O(μs), therefore requiring the complement of trackers with fine time resolution. The Silicon Vertex Tracker (SVT) subsystem is described in Section 3.2.3.1.

- *Gaseous tracking detectors:* MicroPattern Gaseous Detectors (MPGD) complete the tracking system in the Central Detector by enriching the measured coordinates per track. They also provide fine time resolution O($\sim$10 ns), a precious feature for complementing the SVT sensors. The central barrel is supplemented by cylindrical Micromegas and hybrid μRWELL-GEM detectors, offering continuous tracking and low multiple scattering. μRWELL-GEM discs provide additional tracking in the forward/backward directions. ePIC MPGDs are discussed in Section 3.2.3.2.

2.1.2 Electromagnetic Calorimetry in the Central Detector

Resolution requirements can be summarized as:

- Barrel region extended to $\eta = -2$: $\sigma_E/E \approx (10)\%/\sqrt{E} \oplus (2-3)\%$ (E in GeV).
- Backward region (electron-going direction) for η lower than -2.0: superior resolution $\sigma_E/E \approx 2\%/\sqrt{E} \oplus (1-2)\%$ (E in GeV).
- Forward region: $\sigma_E/E \approx (10-12)\%/\sqrt{E} \oplus (2-3)\%$ (E in GeV).
- All electromagnetic calorimeters in the central detector shall allow for separation of single-photons from neutral-pion decay into two photons, for energies up to 10 GeV.

Another fundamental requirement is the electron identification by suppressing the the pion contamination in the reconstructed electron sample. The requested suppression factor is up to 10^4, a requirement for the backward region. The electron/pion separation provided by the electromagnetic calorimeters will be complemented by the separation power provided by the PID devices, offering this capability together with their hadron identification power. **Physics Motivation:** Accurate reconstruction of the scattered electron energy is the back- bone of DIS kinematics in inclusive and semi-inclusive measurements. In the backward region, high precision is mandatory for accessing the low-x regime key for the complete access of unpolarized and polarized structure functions and quark and gluon parton distribution functions (Sec.s 4.4.1 and 4.4.2). Central and forward calorimetry ensures robust e/π separation, π^0 reconstruction and supports jet, photon and electromagnetically decaying mesons measurements needed for studies of nucleon mass generation and quark-gluon dynamics as well as the identification of DVCS photons in exclusive measurements [23,27] (Sec.s 4.4.1, 4.4.2, 4.4.3 and 4.4.4).

Enabling Technologies:

- *Backward (electron-going) calorimeter:* A homogeneous crystal calorimeter ($PbWO_4$) with a fine granularity geometry coupled to SiPM readout has been selected. The radiator material offers small Moliere radius, and when coupled with the selected photosensors provides high light yield and fast response. Therefore, the extremely fine energy resolution required in the backward region can be obtained. The fine granularity also provides tracking information, therefore supporting the backward tracking system. The technology is also compatible with the compact design adopted in ePIC (Section 3.2.5.1).

- *Central calorimeter:* A sampling calorimeter using scintillating fibers embedded in Pb absorber following the GlueX design provides a uniform response and good linearity over wide energy range. This is supplemented by an integrated preshower detector based on AstroPix MAPS sensors to improve e/π separation and clustering, while also providing e/γ separation capabilities (Section 3.2.5.2).
- *Forward calorimeter:* A W–SciFi sampling calorimeter optimized for compact size and a large dynamic range provides forward coverage for electromagnetic calorimetry. The technology was proposed and developed for application at the EIC and it has already been validated by usage in the sPHENIX experiment [42]. It consists of scintillating fiber matrices embedding in epoxy heavy loaded with tungstate powder, offering good granularity and extended homogeneity together with an easily affortable construction procedure. (Section 3.2.5.3).

In addition to specific detector technologies, integration between the electromagnetic calorimetry and the tracking systems improves e/π discrimination and supports PID-driven particle flow algorithms.

2.1.3 Hadronic Calorimetry in the Central Detector

Hadronic calorimetry complements and supplements tracking for full jet energy reconstruction also through inclusion of hadronic neutral energy. For the study of physics channels with single jet the central hadronic calorimeters plays a major role. Di-jet channels are supported by forward and backward hadron calorimetry and high energy capabilities are needed in the forward domain. These requirements results in the following

- Resolution target: $\sigma_E/E \approx 50\%/\sqrt{E} \oplus 10\%$ in the forward region; relaxed to $100\%/\sqrt{E} \oplus 10\%$ in the central and backward regions (E in GeV).

Physics Motivation: Hadronic calorimetry complements and supplements tracking for full jet energy reconstruction through inclusion of hadronic neutral energy, needed to study hadronization in cold nuclear matter, parton energy loss, and jet correlations in $e+A$ collisions (Sec. 4.4.4). Forward calorimetry in particular supports the search for gluon saturation phenomena by reconstructing diffractive and dihadron correlations [23, 27] (Sec. 4.4.3).

Enabling Technologies:

- *Technological commonalities of the ePIC hadronic calorimeters*: these sampling calorimeters all use steel radiators and scintillating elements as active components; the selected sensors are SiPMs.
- *Steel-scintillator sampling calorimetry* in the central barrel provides coverage for full jet reconstruction through the re-use of a modified sPHENIX hadronic calorimeter (Section 3.2.6.2).
- *Longitudinally segmented high-resolution calorimetry* in the forward region, using ”SiPM-on-tile” technology, to enable the separation of hadronic showers in high occupancy environment. The technology concept was introduced by the CALICE Collaboration [173] for application at ILC and it has been evolved to satisfy ePIC requirements and to develop a design enabling an effective construction and assembly. The Longitudinally-segmented Forward Hadronic Calorimeter (LFHCAL) is described in Section 3.2.6.3.
- *A tail-catcher for hadronic neutrals* in the backwards region where hadronic particle energies are low. The design of the backwards hadronic calorimeter takes advantages of synergies with the design for the forward HCAL (Section 3.2.6.1).

2.1.4 Particle Identification (PID) in the Central Detector

- $\pi/K/p$ separation up to $p \lesssim 6$ GeV/c in the barrel region, $p \lesssim 10$ GeV/c in the backward region, and $p \lesssim 50$ GeV/c in the forward region.
- Electron/pion separation across all regions to supplement electromagnetic calorimetry separation power particularly at low energies.

Physics Motivation: PID is vital for semi-inclusive DIS (Sec. 4.4.2), where identified hadrons provide flavor sensitivity to quark TMDs and fragmentation functions. Forward PID enables separation of kaons and protons at high momentum, essential for accessing the strange quark and gluon Sivers functions. Backward PID is required for neutron-rich targets, e.g. deuteron and ^{3}He beams, used to disentangle flavor-separated polarization [23,27]. Hadron PID supports the reconstruction of heavy flavor particles by the identification of the decay products, a powerful approach for the rejection of the combinatorial background. PID subsystems increase the electron/pion separation capability of the ePIC detector. As already recalled, high level pion rejection in the electron sample is required for the identification of the scattered electron and the measurement of parity violating asymmetries.

Enabling Technologies: Cherenkov imaging approaches are adopted in the central and endcap regions, complemented by Time-of-Flight (ToF) systems to extend the separation capabilities to the low momentum range.

- *Barrel region:* The severe space limitations of the central region impose to adopt a technology where only a thin radiator is present in the acceptance volume, while Cherenkov photons are transported and detected outside the acceptance domain. Therefore, the DIRC (Detection of Internally Reflected Cherenkov) principle is adopted with long fused-silica radiator bars also acting as light guides by total internal reflection. The original approach first adopted in BaBar [31] is evolved by the introduction of focusing elements at the end of the bars and by using fine time resolution MCP-PMT sensors in order to increase the resolution and, therefore, the separation domain resulting in the high performance DIRC (Section 3.2.4.3).
- *Forward region:* A dual-radiator focusing RICH (dRICH) combining aerogel and gas radiators (C_2F_6) for $\pi/K/p$ separation in a wide momentum range up to 50 GeV/c is adopted. The space constrains impose an off-center optics carefully designed to minimize the optical aberration. The selected photosensor are SiPMs, which can operate in a region of non-neglibile magnetic field with field line orientation incompatible with vacuum-based photosensors. The dRICH is presented in details in Section 3.2.4.4.
- *Backward region:* A proximity-focused RICH with extended proximity gap to increase the resolution using an aerogel radiator and read-out based on HRPPDs, novel large-size MCP-PMTs. The fast signal from a charged track crossing the sensor plane also produced Cherenkov photons in the fused-silica HRPPD window thus providing a high-resolution ToF measurement, extending PID capabilities at low momentum. This detector is described in Section 3.2.4.2.
- *Extending PID capability at low momentum in the central and forward region* is provided by AC-LGAD-based timing layers with $\sigma_t \sim 30$ ps [107]. AC-LGAD layers also provide fine resolution space information supplementing the detector tracking system. (Section 3.2.4.1).

2.1.5 Far-Forward and Far-Backward Detectors

Six far detector subsystems complement the central detector. They are distributed along the beam line within ±50 m. B0 system, Off-Momentum Detectors, Roman Pots and Zero Degree Calorimeter, globally referred to as far forward detectors, are positioned along the outgoing ion beam line at increasing distances from the interaction point. B0 system, Off-Momentum Detectors and Roman Pots provide tracking of hadrons scattered at smaller and smaller angles, while the B0 system offers also electromagnetic calorimeter capabilities at small scattering angle. The Zero Degree Calorimeter is dedicated to neutrals in the very forward region. The far backward detectors, namely the Luminosity system and the low-Q^2 taggers are situated along the outgoing electron beam line.

- All far detectors must have the capability to resolve the 10 ns beam crossing frequency at maximum luminosity.
- All trackers in the far forward detectors must have a time resolution $\lesssim$ 35 ps.
- The B0 system includes tracker and electromagnetic calorimetry covering the angular range $(5.5\ mrad, 20\ mrad)$; transverse momentum resolution better than 7% for transverse momenta larger than 1 GeV/c and energy resolution $\sigma_E/E \lesssim 20\%/\sqrt{E} \oplus 3\%$ are requested. High granularity layout is needed to offer two-shower resolution capability.
- Off-Momentum spectrometers and Roman Pots, which cover very small angles below 10 $mrad$ and 5 $mrad$ respectively, have to provide transverse momentum resolution at the 10% level for transverse momentum exceeding 1 GeV/c and 5% level for transverse momenta exceeding 0.5 GeV/c, respectively.
- Zero-degree calorimeters detect neutral particles with $\sigma_E/E \lesssim 20\%/\sqrt{E} \oplus 5\%$ for photons and $\sigma_E/E \lesssim 50\%/\sqrt{E} \oplus 5\%$ for neutrons.
- Low Q^2 taggers designed for $Q^2 < 0.1\ GeV^2$ include tracking and electromagnetic calorimetry to provide $\sigma_p/p < 5\%$ and $\sigma_E/E \lesssim 10\%/\sqrt{E} \oplus 3\%$. They have to face the challenge of very high rates and, therefore, they will be able to measure the momentum of more than 10 electrons per bunch crossing and they will provide timing resolution sufficient to resolve the 10 ns beam crossing repetition rate at high luminosity.
- The luminosity system must provide precise determination of the absolute luminosity at 1% level and precise determination of relative luminosity at 10^{-4} level sorted by spin states. This implies resolving the single bunches as spin state be alternated in consecutive bunches.

Physics Motivation: Far-forward detectors enable measurement of recoil protons in exclusive processes (DVCS, vector meson production, diffractive scattering) (Sec. 4.4.3), which are central to imaging the spatial distribution of partons through GPDs and support origin-of-the-mass studies. The far-backward detectors provide low-Q^2 tagging and neutron detection, important for nuclear structure studies and for reconstructing kinematics in charged-current DIS [23,27] (Sec. 4.4.3).

Enabling Technologies:

- *Integrated B0 magnet spectrometer:* A charged particle tracker by AC-LGAD technology and a crystal electromagnetic calorimeter integrated into the bore of the B0 magnet. This challenging and highly integrated detector is described in Section 3.2.7.2.
- *Off-momentum spectrometers:* Precision AC-LGAD tracking stations for separating off-momentum charged fragments, see Section 3.2.7.1.
- *Roman Pot spectrometers:* AC-LGAD pixel detectors in movable vessels close to the beamline, for detecting forward protons scattered at milliradian angles, as described in Section 3.2.7.1.
- *Zero-degree calorimeters (ZDC):* A compact ”SiPM-on-tile” sampling scintillator design optimized for high granularity and radiation tolerance, see Section 3.2.7.3.

- *Low-Q^2 taggers:* Sampling calorimeters and tracking stations based on TimePix4 readout located near the beam pipe in the backward region for detecting electrons at angles below 5°, as described in Section 3.2.8.2.

- *High-rate, high-precision calorimetry for luminosity determination:* The measurement is based on the detection of Bremsstrahlung photons generated by the colliding beams. A high-rate calorimeter by the same SciFi-W technology adopted for the forward electromagnetic calorimeter of the CD provides fast monitoring interaction by interaction. High accuracy measurement is provided by a couple of pair spectrometers detecting the e^+ e^- pair from the conversion of the Bremsstrahlung photons. The pair spectrometers are equipped with tracking elements by AC-LGAD technology and calorimeters by SciFi-W technology. The luminosity system is discussed in Sec. 3.2.8.1.

In summary, the performance requirements of the EIC detector directly reflect the needs of the scientific goals of the program: uncovering the spin and mass structure of the nucleon, mapping its 3D momentum and spatial distributions, and exploring the gluon-dominated regime in nuclei. The requirements in tracking, calorimetry, PID, and far-forward instrumentation are all tailored to ensure precise and comprehensive coverage of the broad EIC physics program.