Enabling future detector technology within ePIC at the EIC

Contact persons: S. Dalla Torre[*], D. Elia[†], P.G. Jones[‡], J. Lajoie[§] and C. Munoz Camacho[¶]

On behalf of **the ePIC Collaboration**

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Abstract

The ePIC experiment at the EIC incorporates a wide variety of detector technologies. The different technological approaches are imposed by the broad EIC physics scope and by the nature of the collider, which is asymmetric in energy and beam particles, and by the wide variety of ion species that will collide with electrons. Major parts of the experiment use novel technologies, developed for application in ePIC and with applications at major coming experiments and facilities, worldwide. The ePIC detector is, therefore, both a stimulus toward innovative detector approaches and a testbench for the implementation of novel technologies in collider experiments.

This document is to underline the value of the ePIC detector in terms of technological developments and the options for collaborative efforts that can be beneficial to fundamental studies at high energies.

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[*] INFN Sezione di Trieste, Trieste, Italy

[†] INFN Sezione di Bari, Bari, Italy

[‡] University of Birmingham, Birmingham, United Kingdom

[§] Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

[¶] Universitè Paris-Saclay, CNRS - IJCLab, Orsay, France

1 Introduction

The **ePIC detector [1] at the Electron Ion Collider (EIC) [2] is a unique environment for enabling future detector technologies**, which are also needed for other major worldwide facilities, in a synergistic approach towards progressing in the technological field. In fact, the timelines of CERN facilities and ePIC timelines (Sec. 2) suggest a virtuous scenario for R&D: there is reciprocal benefit between ePIC R&D and construction and the so-called LHC upgrade phase "2b", which involves LHCb and ALICE in LS4, thanks to consistent timelines. Then, during the '30s, not considering LHC experiments, the experiment at EIC, namely ePIC and a potential experiment at the second EIC interaction, will be the largest particle collider experiments worldwide running and probably the only ones in operation between the end of LHC and the start of FCC. Therefore the experimental effort at EIC should be identified as an ideal companion for detector R&D synergies by the EPPSU.

The variety and richness of the detector technologies in ePIC originate from the pecularities of the EIC accelerator. The ePIC detector is part of the United Stated Department of Energy EIC project, marked by a specific international character calling for worldwide contributions in the science and detector areas, is dedicated to the ultimate understanding of **Quantum ChromoDynamics (QCD)**. It is, therefore, a flagship project in the context of **physics pursued with lepton-hadron collisions** [3]. The broad physics scope clusters around key scientific questions synthetically summarized as the origin of the nucleon mass and spin, nucleon tomography, the interaction of quarks and gluons in the nuclear medium, quark confinement and the properties of high-density gluon states. This ambitious goal requires an ambitious collider (high luminosity, variety of ion beams from H to U, beam polarization and tunable center-of-mass energy) and a detector capable of coping with the global physics scope by inclusive and semi-inclusive Deep Inelastic Scattering (DIS) and selected exclusive channels: the ePIC detector. The variety of measurements, the asymmetry of the colliding beams and the modulation of the phase-space in the laboratory frame with the variation of the energies and the ion species require the adoption of a variety of detector technologies, including established and novel ones. This synergy is shown by a series of detector-technology meetings with the CERN community and the ongoing ALICE-ePIC collaboration towards the development of novel detectors incorporating silicon Monolithic Active Pixel Sensors (MAPS).

In this input document to the EPPSU 2025 process, the ePIC detector is briefly summarized, in order to provide a frame to the main focus: the novel detector technologies enabled via their adoption in ePIC. The application in ePIC supports and facilitates their development.

2 The ePIC detector

The detector is realized, in collaboration with the EIC project, by the **ePIC Collaboration**, at present more than 1000 members from 177 Institutions in 25 countries distributed in 4 world regions. While the US community in ePIC is the largest one with 492 members (48%), European and Asian institutions are very numerous. In particular, 299 collaboration members (29%) are from European counties. The wide interest of the European community for the EIC facility and science scope is also indicated by considering the composition of the EIC User Group [4], where both experimentalists and theorists are present. The members from European countries are more then 400 over the 1549 scientists forming the User Group, indicating an interest beyond the participation in ePIC and including a large representative of European theorists.

The detector consists of a Central Detector (CD), 9.5 m long, situated at the interaction point and a set of far detectors along the outgoing beam lines, which complete the small-angle acceptance. Among the far detectors, the luminosity system provides measurements and monitoring of the collider luminosity.

Figure 1 presents a schematic view of the CD. The tracking subsystem is formed by light-weighted, high space resolution silicon MAPS arranged in cylindrical and disk geometries and complemented by a set of more external MPGDs also in cylindrical or pseudo-cylindrical and disk layers. The particle momenta are measured thanks to tracking and a new superconducting solenoid with 1.7 T reference magnetic field, which can opearte up to 2 T. Particle IDentification (PID) devices are by Cherenkov imaging counters for momenta above a few GeV/c and Time-Of-Flight (TOF) layers at lower momenta. A proximity focusing RICH with aerogel radiator equips the backward endcap, a high performance DIRC by fused silica bars provides PID in the barrel, and a dual-radiator RICH making use of aerogel and gas is used in the forward endcap. AC-LGAD layers measure the timing in the barrel and the forward region, while the same photosensors of the backward RICH, which are sitting in the acceptance, also provide time measurement. All calorimeters make use of SiPMs as sensors.

Electromagnetic calorimetry is by fine granularity lead tungstate crystals in the backward direction, a hybrid calorimetry with imaging layers and sampling by lead and scintillating fibers in the barrel and sampling by lead and tungsten powder in epoxy in the forward direction. Hadronic calorimetry is by iron and scintillator elements. In the forward, the new approach of SiPM-on-tile is adopted, with a fine granularity insert in the most inner region.

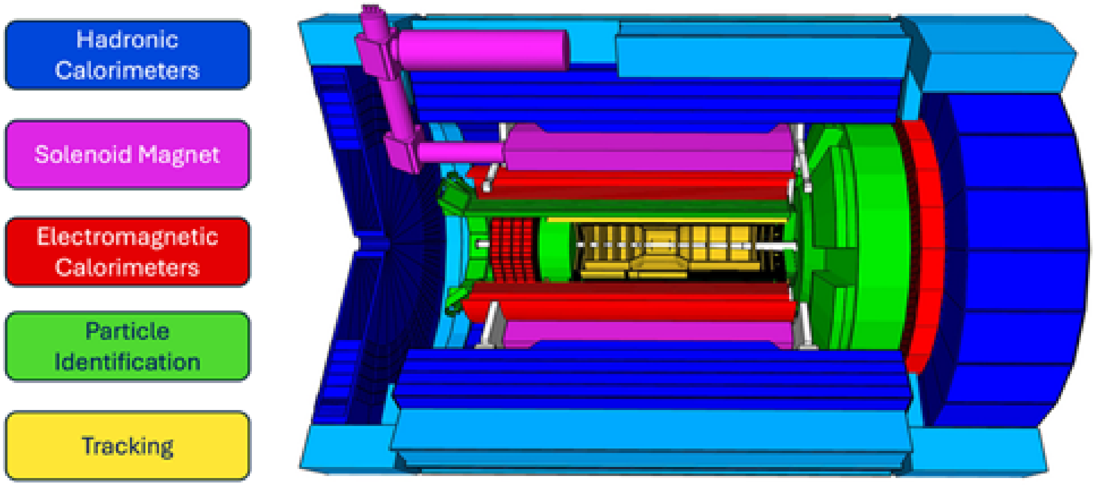

Figure 1: Schematic view of the ePIC central detector.

The far forward detectors and the luminosity system make use of AC-LGADs for tracking and lead-tungsten calorimetry; the same technology of the insert of the forward hadronic calorimeter is adopted for the zero-degree-calorimeter (ZDC). The far backward low Q^2-taggers, which sit in a very high-rate region, adopt the Timepix4 technology.

Unbiased data acquisition, data selection flexibility and the parallel acquisition of data for a variety of physics studies is ensured by a triggerless streaming read-out, acquisition and event reconstruction system, where timing information is the key parameter for the correct association of the event information.

The ePIC detector will be completed and installed by 2030 and the early physics phase will start in the first half of the 2030s.

The similarities between the requirements characterizing the detectors at the future circular Higgs, electroweak, and top FCC-ee facility (a recent overview can be found in [5]) and those of the ePIC detector are remarkable, as it clearly results from the description provided here, even if in brief format. Therefore, the comparison of the EIC and ePIC timelines and the possible FCC-ee timelines suggests that the detector technologies that will be realized and operated on a large scale in ePIC can be regarded as precursors for the needs of the detectors at the large electron-positron collider. These precursors will be in operation ten or more years in advance.

3 Novel detector technologies and implementations, techniques and methods in ePIC

We present a selection of novel technologies and implementations, techniques and methods adopted for the ePIC detector, underlining the synergy of these developments with other major coming facilities and experiments in the worldwide panorama. The aggressive timelines of the EIC project and of the ePIC detector realization make the technological development for ePIC both a stimulus towards novel detector technologies and a test-bench for several among them, which will be implemented on a large scale. The following examples of future applications of the novel technologies adopted in ePIC are directly extracted from "The 2021 ECFA Detector Research and Development Roadmap" [6].

ePIC solenoid - A superconducting detector magnet is one of the key components for particle physics experiments to analyze the momentum and polarity of charged particles. It is required to have a large warm bore to install many types of particle detectors, and a large solid angle to maximize the detection efficiency of particles. It has been discussed in [7, 8] that there has not been built a large bore, high field superconducting solenoid for a collider experiment since 2010. At present the main concern for the detector solenoid development is the gradual loss of the key technologies and experiences, because large-scale detector magnets with Al-stabilized conductor have not been fabricated after the success of CMS and ATLAS-Central Solenoid in LHC in the 1990s –2000s. To fully realize the EIC scientific promise, the ePIC Experiment is building a new 2T superconducting solenoid, with a 3.5 m long coil and a 2.84 m diameter room temperature bore. The operating temperature will be 4.5 K utilizing a Thermosiphon cooling scheme. The conductor used for the magnet will be a Cu stabilized NbTi Rutherford cable, 22 strands of 0.847 mm diameter NbTi superconductor will be used to make the Rutherford cable of 8.85 mm x 1.49 mm size. The overall size of the copper cladded conductor is 11.4 mm x 4.6 mm. Unfortunately, in the time frame of the design phase of the EIC and ePIC we could not locate worldwide a vendor capability and willingness to develop an Al-stabilized conductor. There are several design constraints to the magnet:

1. To optimize the tracking performance closest to the electron-ion interaction point the field is kept flat over a region of 200 cm in z and 80 cm in radius;

2. To maximize the RICH performance based on the gas radiator it is critical to minimize the bending of the tracks in the volume of the gas radiator -for this one needs to shape the field that is parallel to the different scattering angles ($1.5 < \eta < 3.5$) of particles covered by the RICH;

3. The fringe field requirements at the nearby interaction region magnets is 10 G, which together with the fact that the magnet center is shifted by 10 cm with respect to the center of the detector barrel and its endcaps, requires extreme care to balance the forces on the coils and optimize the layout of the flux return.

The MARCO solenoid is made of three modules with three identical superconducting coils. This design is to limit the size of the superconducting cable folding in vendor input. For each module, 6 single layers of superconductor are wound internally to a mandrel, for a total number of turns per layer varying between 92 and 93, according to the conductor exits. The total number of turns per module is 556. Each layer is separated by an inter-layer fiber glass insulation of 2 layers of 0.2 mm to achieve a good electrical insulation after winding and to prevent the conductor damages. At the ultimate working field (B0) of 2.0 T, the magnet has a stored magnetic energy of 45 MJ and an inductance of 5.847 H. The inductance is constant at every current value up to the nominal current of 3924 A. At nominal position, the magnet is well balanced within the yoke. The maximum axial force (Fz) along the axis of the magnet is 32.2 kN pointing towards the lepton endcap. Even if the ePIC solenoid does not use the Al stabilized conductor as desired for future particle physics experiments, building the similar Cu stabilized conductor and a new large-scale superconducting solenoid for a collider experiment > 15 years after the CMS solenoid was built will provide critical lessons learned for the experimental community.

A lightweight, MAPS based, Silicon Vertex Tracker - Silicon Monolithic Active Pixel Sensors (MAPS) are ideally suited to meet the stringent charged-particle tracking and vertex resolution requirements at the EIC because of their high point resolution, low power dissipation, and the possibility to integrate them in a low-mass instrument. The STAR experiment pioneered their use in a collider experiment and the ALICE experiment presents the current state-of-the-art.

The ePIC Silicon Vertex Tracker (SVT) will use MAPS sensors developed in a 65 nm CMOS imaging process based upon the ALICE ITS3 development. This technology enables a high granularity and low power consumption design, and offers stitching on 300 mm wafers for the development of large area sensors.

The three inner barrel layers of the SVT will use the ALICE ITS3 wafer-scale sensor, which is called MOSAIX. MOSAIX is composed of up to twelve Repeated Sensor Units (RSUs), stitched along the length of the sensor, giving a maximum active length of approximately 27 cm. Sensors with a width of three, four, and five RSUs will be used to construct the SVT inner barrel layers, L0, L1 and L2, with radii of ≈ 36, 48, and 120 mm, respectively. The sensors will be thinned to below 50 μm and bent to form a nearly self-supporting structure inspired by the ALICE ITS3 development, adapted to the larger EIC beampipe radius and with suitably adapted services.

The SVT outer barrel and endcap disks will cover a large active area of approximately 8 m^2. Considerations based on yield, cost, integration, and coverage require the use of a sensor with a smaller size than the wafer-scale sensor used in the inner barrel. These regions will use the MOSAIX sensor with modifications to reduce the size. This sensor would still be large in traditional terms and is therefore referred to as the EIC Large

Area Sensor (EIC-LAS). The EIC-LAS will be one RSU wide and either 5 or 6 RSUs long. In addition to the reduction in size, the EIC-LAS will have a lower number of data links than MOSAIX to match the lower SVT data rate, reduce material associated with services, and ease integration aspects. EIC-LAS sensors will be powered in series by a constant current and a dedicated communication protocol will be used to reduce the number of slow control links from the counting room to the sensor. These functions, together with the negative sensor bias voltage, will be provided by a supporting ancillary ASIC which is under development in a 110 nm SOI process.

Supporting aspects of the SVT system, i.e. mechanical support, cooling and service integration must match the performance enabled by the sensor technology, demanding state-of-the art technologies to achieve the goals of position stability, ultra-low material budget and thermally stable and safe operation. In particular, the ePIC SVT aspires to implement air cooling on a scale unprecedented in particle physics, to reduce the amount of material on the detector required for cooling, an approach that will be central to tracking systems in future lepton colliders. The ePIC SVT will make use of modern composite fabrication techniques, including the co-curing of electrical services into the structures, to develop the mechanical support structures.

The SVT outer barrel layers will be segmented in staves. The staves are composite structures using carbon-composite skins, a central carbon-composite I-beam spar and cross-ribs made of heat conducting carbon foam. The side walls will be formed by low mass Flexible Printed Circuit (FPC) tapes incorporating aluminum conductors. The SVT disks feature a two-sided design with a corrugated carbon composite core. The barrel and disk structures can be used to flow air for cooling internal to the structures. The staves and disks will be supported by carbon-composite global supports.

The SVT will have an overall length approximately 2.4 m and an outer radius of approximately 0.4 m. The development of the MOSAIX sensor, driven by the ALICE collaboration, is advanced and its timeline is compatible with those of the EIC. The SVT development has synergies with those for the future high energy electron-positron facilities, the Super Tau-Charm Facility, and the muon collider.

Hybrid MPGD: µRWELL with GEM preamplification - Micro-Pattern Gaseous Detector (MPGD) technologies have been chosen to complement the silicon-based tracking layers in MAPS technology of the ePIC detector (Fig. 1), thanks to their capacity to cover large area at lower cost, while providing space point measurements with submillimetric resolution and good timing resolution ∼10-20 ns. The gaseous trackers are based on two MPGD technologies: cylindrical Micromegas for the barrel inner tracker and hybrid GEM-μRWELL technology for the barrel outer tracker and the outermost layers of both the electron and hadron endcap trackers.

The hybrid GEM-µRWELL detectors are a new concept. A GEM foil acts as a pre-amplification layer for the ionization charges produced in the drift region, while the µRWELL layer provides a second amplification stage. This architecture results in high gain, which offers relevant advantages.

This double amplification scheme requires only moderate bias voltage across each of the amplification stage to achieve a high enough gain for the detector to operate at full efficiency (≥97-98%) and in a safe and stable condition, also in two-dimensional strip (2D-strip) readout detectors, as it is the case in ePIC. In fact, high gain capability is particularly important when using 2D-strip readout structures, where the signal is split between the two planes of the readout layer.

Another major advantage offered by the high-gain capability is the preservation of the fine spacial resolution for inclined particle trajectories and in non-uniform magnetic field. This is pursued at ePIC by two different approaches.

1. **Thin drift layer for the barrel outer tracker** - The gap of the ionization drift volume in standard MPGDs is typically 3 or 4 mm thick. This geometry results in a significant deterioration of both the hit point resolution and the timing resolution when the impinging particle crosses the detector at an angle larger than 15°. This is due to the negative impact of both the large ionization trail left by the incoming particle in the ionization volume and the Lorentz (E × B) effect. In the thin-gap MPGD detector concept, the thickness of the gas volume in the drift region is reduced to around 1 mm. The concept has been developed to recover the position and timing resolution performance. The hybrid GEM-µRWELL with double amplification is an essential ingredient of the thin-gap MPGD detector concept that compensates for the reduced ionization charge produced in the thin drift region. The thin-gap hybrid GEM-µRWELL is the technology adopted for the outer tracker in the barrel region of ePIC detector.

2. ***μ*****TPC readout mode for the gaseous detectors in the endcaps** - The reduction of the detector drift gap below 3 mm is not necessary for the disks covering pseudo-rapidity regions with $|\eta| > 2$, where most of the tracks impinge the detector at angles lower than 20°. The particle tracks may, however, be affected by the non-uniformity of the solenoidal field at the locations of the disks. This requires additional technical solutions, such as the longitudinal reconstruction of the track in μTPC mode, to retain the position resolution necessary for reliable tracking performances. The μTPC mode also implies stringent requirements on the signal timing for each read-out strip, which are presently under study.

The R&D studies to establish the hybrid GEM-μRWELL technology both with thin-gap geometry and μTPC read-out mode are well advanced, while the performance needs confirmation when the novel technologies are coupled to the SALSA front-end ASIC under development. The approach can be applied wherever large surfaces have to be instrumented with gaseous detectors preserving space and time performance for a wide variety of trajectory phacespace and in presence of non-homogeneous magnetic field. These needs are required, for instance, for the large muon systems at the HL-LHC and FCC-hh.

Innovative applications of SiPMs in calorimetry

Silicon Photo Multipliers (SiPM), introduced towards the end of the 20th century for application in fundamental research, are nowadays largely used in a much wider domain including applications of social interest. The trend suggests that SiPMs are going to dominate the worldwide panorama of photodetectors in fundamental research and beyond. Their development is fast and remarkable. In particular, the rate of dark noise has largely decreased in the most advanced devices. Nowadays, a variety of sensors with different characteristics are available, while R&D for SiPMs with improved performance is actively pursued. In this context, ePIC has selected SiPMs as sensors for all its calorimeters. The combination of these sensors and novel calorimeter concepts results in the innovative technologies introduced in the following.

SiPMs as sensors for a crystal electromagnetic calorimeter - The EIC physics program requires high-precision detection and identification of the scattered electrons emitted in the electron-going direction, as well as final-state photons. The highest resolution in electromagnetic calorimeters can be provided by homogeneous materials. The preferred material radiator for the backward ECal of ePIC is lead tungstate ($PbWO_4$), an extremely fast, compact, and radiation-hard scintillator providing sufficient luminescence yield (15 - 25 photoelectrons/MeV) to achieve good energy resolution. The active area consists of roughly 3000 $PbWO_4$ crystals extending 20 cm in the longitudinal dimension and with transverse block dimensions of 2.05 cm×2.05 cm matched to its Molière radius. Due to the high magnetic field in the detector area, scintillating light will be read out by Silicon Photomultipliers (SiPMs). SiPMs are very attractive as a readout solution for scintillating crystals. Several challenges have prevented their use for high-resolution homogeneous calorimeters in the past. Firstly, their present size is relatively small compared to the radiator size, which does not allow the collection of most of the scintillation light. Secondly, the sensors need to be capable of covering a large dynamic range over more than 3 orders of magnitude when the electromagnetic shower is laterally deposited over a large number of detector modules. Therefore, the active area of the SiPM has to be composed of a sufficient number of pixels to avoid saturation. Finally, additional challenging aspects of SiPMs are their relatively high rate of dark noise, the dependence of their performance on temperature, as well as their modest radiation hardness. Recently developed sensors with very high density of pixels (10– and 15–μm pitch) have been shown to provide a good linearity over several orders of magnitude. In order to compensate for the small sensor size, each $PbWO_4$ crystal in ePIC will be read by several (4 or 16) independent sensors. Linearity measurements show 2% linearity up to 3500 photoelectrons. The effect of radiation in these SiPMs and ways to anneal its effects are currently under study.

SiPMs coupled to $PbWO_4$ crystal in ePIC will pave the way to the future use of high-resolution calorimeters required in all future high energy electron-positron collider and for the muon collider.

W/SciFi electromagnetic calorimeter - Fiber calorimeters have been in use in high-energy and nuclear physics experiments for nearly 40 years, standing out as some of the finest sampling calorimeters in operation. They offer excellent energy resolution, granularity, hermeticity, and homogeneity, along with precise timing and position resolution—all achievable within highly compact designs. This technology is particularly well-suited to leverage advancements in compact photodetectors such as avalanche photodiodes and SiPMs. These qualities make fiber calorimeters an attractive choice for the ePIC central detector.

However, traditional construction techniques for such calorimeters have been labor-intensive and somewhat limiting, especially when building compact calorimeters with good energy resolution. These designs require managing large quantities of thin scintillating fibers, finely spaced within absorber materials. To address these challenges, a new technology utilizing tungsten (W) powder as an absorber was developed through the generic detector R&D program for the EIC. This innovation simplifies the construction processes and it was specifically designed for easily adoption by university groups: in fact, it does not require significant infrastructure investment.

The W/ScFi technology, pioneered at UCLA, has proven to be remarkably straightforward, enabling its rapid adoption across US universities, as well as institutions in China, Europe, and India among the ePIC collaborators. Notably, the sPHENIX barrel EMCal, consisting of approximately 25,000 readout towers, was recently constructed using this technique and is now operational at RHIC.

For the ePIC detector, this technology will be deployed in the hadron endcap, maximizing all its advantageous properties. Featuring SiPM readout, the calorimeter achieves about 23 radiation lengths within only 27 cm of integration space along the beamline. It is expected to be one of the most compact sampling calorimeters characterized by such parameters ever constructed. As it is the case for other calorimetry technologies pioneered for application at the EIC, the W/SciFi electromagnetic calorimeter approach will contribute in advancing detector technologies for future experiments at all high-energy electron-positron colliders and at the muon collider.

SiPM-on-tile hadronic calorimeter - The The SiPM-on-tile calorimeter technology allows to construct hadronic calorimeters with high granularity in all three spatial dimensions, which enables the ideal application of particle flow jet reconstruction techniques. Potentialities to reconstruct also the time development of the jet are also available. Particle flow jet reconstruction aims to combine measurements from tracking systems, electromagnetic and hadronic calorimeters into reconstructing the full jet energy and its direction, which requires an efficient association of measured charge particle tracks to their corresponding calorimeter clusters, to isolate calorimeter depositions stemming from neutral particles.

High granularity calorimeters have been developed for almost two decades by the CALICE collaboration in the context of detector for a future Higgs-factory linear collider experiment. Out of this extensive R&D program, the SiPM-on-tile technology has emerged as mature and cost effective option to realize hadronic calorimeters out of plastic scintillator tiles with tens of cm^2 area which are directly coupled to one individual Silicon Photomultiplier (SiPM) per tile. Large area active layers can be constructed out of arbitrary numbers and arrangements of such tiles. Active layers of these tiles are inserted between absorber plate materials (usually steel or tungsten). Since each tile can be read out individually, a full three dimensional imaging of individual particle showers within jets can be obtained. Using injection molded plastic scintillating materials for the tiles yields a low overall cost per channel and large simplifies the construction procedure, enabling an unprecedented spatial granularity.

SiPM-on-tile calorimeters are planned for several sub-systems of the ePIC detector, including the backwards (electron-side) hadronic calorimeter, the forward (hadron-side) hadronic calorimeter (including a very high granularity insert in the highest rapidity region) and the very forward zero degree calorimeter (ZDC). In particular, the the forward hadronic calorimeter is a major realization with 18320 towers of transverse size of $2.5{\times}2.5\ \text{cm}^2$ and a total interaction length ranging between 5.8 and 6.7 λ_0. First prototypes showcasing small longitudinal segments of the whole system have been constructed and tested in beam test campaigns at CERN. A prototype of the ZDC has been operated as part of the STAR detector in the 2024 physics run of RHIC. In 2025, a 4000 channel prototype of 8 modules (roughly 1% of the whole installation) of the ePIC forward hadronic calorimeter will be tested at CERN. The existing ZDC prototype will be extended and operated in the final RHIC physics run in 2025.

The ongoing work focuses on scaling the production, assembly and quality assurance procedures of these systems up to the full size of the ePIC detector. In addition, the development of readout electronics that compliant with the full streaming operation envisioned for ePIC is in progress.

Hybrid Si/PbSciFi electromagnetic calorimeter - Electromagnetic calorimetry in the barrel region of ePIC poses significant challenges due to stringent physics requirements. These include achieving electron-pion separation with a rejection factor of 10^3–10^4 at low momenta, energy resolution better than $10\%/\sqrt{E} \oplus 1-2\%$ for photon reconstruction, and π^0-γ separation up to 10 GeV. Additionally, the system must measure low-energy photons down to 100 MeV while operating within the constrained space inside the solenoid.

Traditional approaches, such as PbWO_4 crystals or Shashlyk calorimeters, cannot meet these demands due to limitations in material availability, cost, or inadequate electron-pion separation, particularly given the radial space constraints. To overcome these challenges, ePIC uses a hybrid barrel electromagnetic calorimeter, the Barrel Imaging Calorimeter (BIC), that combines scintillating fiber and lead (Pb/ScFi) sampling layers, based on the GlueX BCAL design pioneered at KLOE, with layers of highly-granular AstroPix silicon sensors.

AstroPix is a low-power monolithic active pixel sensor (HV-MAPS) with a 500 μm pixel pitch, derived from ATLASPix and developed by Karlsruhe Institute of Technology in collaboration with NASA-GSFC and Argonne National Laboratory for space-based applications (as part of the NASA AMEGO-X program). This sensor is an ideal fit for the barrel electromagnetic calorimeter, providing the necessary spatial granularity and excellent energy resolution, along with sufficient time resolution for 3D shower imaging.

The hybrid design enables the detector to meet all of the EIC's stringent requirements, including achieving an energy resolution of approximately $5.2\%/\sqrt{E} \oplus 1.0\%$. The BIC represents one of the largest silicon detectors ever constructed and marks the first large-scale application of HV-CMOS technology for particle detection. Key challenges include scaling production to cover and test over 100 m^2 of silicon sensors and reconstructing the volumes of data generated by the granular hybrid system to fully utilize their multidimensional character. Recent beam and bench tests have demonstrated the calorimeter's readiness to meet the demands of the EIC physics program while advancing detector technologies for future experiments at all high-energy electron-positron colliders and at the muon collider.

AC-LGADs - The AC-LGAD (AC-coupled Low Gain Avalanche Detector/Diode) is a new type of semiconductor detector that incorporates an AC-coupled electrode into a conventional LGAD structure, thereby achieving high spatial resolution and reduced dead area in addition to excellent timing performance. LGADs feature a strong internal electric-field multiplication region, which efficiently amplifies charges and provides time resolutions on the order of tens of picoseconds. However, conventional LGADs suffer from limited spatial resolution and dead zones because each pixel requires a separate readout electrode. Overcoming this "acceptance hole" typically necessitates a multilayer design, which increases both the material budget and the required installation space. AC-LGADs address these challenges by coupling the readout electrode to the signal layer through an insulating layer. This design effectively eliminates acceptance holes by removing the gaps between electrodes. This architecture also enables charge sharing among adjacent electrodes, significantly improving spatial resolution. As a result, a single-layer configuration becomes feasible, reducing the total material and creating a more compact detector with improved performance. These advantages make AC-LGADs an attractive choice for tracking and timing layers in future large collider experiments, offering high time and spatial resolution with minimal interference for other detectors, even when the experimental space is limited.

In recent years, the ePIC collaboration has been actively developing this new technology for practical applications. The collaboration plans to employ it for particle identification in the low-p_{T} region. The collaboration is exploring various electrode designs, such as strip and pixel types, to accommodate different particle multiplicities. Specifically, strip detectors will cover the mid-rapidity region, while pixel detectors will be used in the forward-rapidity region. Time resolutions below 35 ps and spatial resolutions better than 30 μm have already been achieved. Going forward, the ePIC collaboration will continue to enhance the sensor performance and move toward an engineered design, aiming to deploy this technology as a fully operational detector.

The ongoing research and development of AC-LGAD-based sensors will play an essential role in advancing particle physics experiments. This technology, when fully mature, will complete the ePIC detector and it can contribute to particle identification in the HI-LHC era at ALICE and LHCb, while also supporting the tracking systems of these experiments.

Photosensors for Cherenkov imaging counters

ePIC is paving the way to novel approaches in single photon detection for Cherenkov imaging technologies by exploiting the application of sensors so far never used in experiments.

High Rate Picosecond Photodetectors (HRPPD) - Vacuum-based photodetectors are since the early days of Cherenkov detectors a privileged choice for the sensors thanks to the use of efficient photoconverters in the visible range, where radiator chromatic effects are moderate, and to the low dark count rate. The increasing need to operate in magnetic field limits the usage of traditional PhotoMultiplier Tubes (PMTs), while opening the way to MicroChannel Plate (MCP) PMTs, more tolerant to magnetic field. So far, they have been adopted only in the TOP counter of the BELLE II experiment. Commercial MCP-PMTs, produced by a few companies, are small size ones, never overcoming the 2 in^2 maximum surface area. Novel large-size sensors by Incom Inc[1] offer a unique opportunity to overcome the current limitations. The development and engineering of these detectors is by a cooperative academia-industry effort. In recent year, ePIC has played a major role in contributing to this development. HRPPDs are characterized by a sensitive area of 10.4×10.4 cm^2, a limited dead-area of 25%, a quantum efficiency equivalent to high-quality PMTs, excellent timing resolution better than 15 ps for single photoelectron signals and expected life of a few C/cm^2. The dark count rate is low (∼1 kHz/cm^2). HRPPDs are pixelized with DC coupling to front-end electronics. HRPPDs represent a concrete option for Cherenkov imaging counters. In ePIC, they will be used in the backward proximity focusing RICH and are considered as sensors for the high performance DIRC. The extended usage in ePIC will provide consolidated confidence in the industrial process and in the sensor reliability. The required R& D needed to develop HRPPDs is completed and the engineering phase is advanced. A major challenge for further applications is preserving the industrial interest beyond the dedicated production series for ePIC.

SiPMs - In ePIC, SiPMs extensively used in calorimetry, are also selected for the dRICH. Their application as single photon sensors in Cherenkov imaging devices has been considered for 20 years and never adopted due to the dark count rate, where background signals are intrinsically indistinguishable from single photon signals. These rates substantially increase by radiation damage. An extended and robust R&D program, conducted within ePIC for the application of SiPMs in the dual RICH, has proven that thermal annealing cycles can, to a large extend, recover the damage, also in repeated cycles of irradiation/annealing and that thermal annealing is conceivable in place applying reversed bias to the sensors. This approach, combined with low temperature operation and hit selection by fine timestamp, qualifies SiPMs for the application in Cherenkov imaging counters. The usage in ePIC dual RICH will prove the validity of the approach and it will open the way to further progress related to the expected advancement and novel development in the field of SiPMs. The R&D for the usage of SiPMs as single photon detectors is completed and the engineering phase is advanced. Applying these concepts to novel SiPMs technologies as the 3-D SiPMs is being considered as a potential path forward in the approach.

Novel or upgraded RICH detectors are foreseen for ALICE3, LHCb, BELLE II, the fix-target program at CERN and considered as an option for FCC-ee. When completely established as single photon sensors, HRPPDs and SiPMs can be selected for a large number of these programs. Therefore, by qualifying these technologies for ePIC RICHes, the ePIC collaboration is paving the way towards the approach to single photon detection for the next generation of Cherenkov imaging devices.

New frontend ASICs with triggerless architecture -

A new generation of frontend ASICs are being developed for ePIC. They support the specific requirements of the different sensor technologies, while designed so to satisfy the prescriptions for triggerless operation and streaming readout. To this end all these frontend ASICs, apart ALCOR, include output links with rate capability greater than 1 Gbps. In ALCOR, the requirement of high throughput bandwidth is met with a different strategy, namely multiple links of 788 Mbps. The ASICs are briefly described in the following.

EICROC – The EICROC is designed for the readout of the AC-LGAD pixels, arranged in a 32x32 matrix and implemented in a wafer-bumped, 130 nm CMOS technology node and featuring radiation tolerance. Preamp, discriminator, TDC and ADC are included for sensors with capacitance of up to 5 pF. The target is to achieve a time resolution better than 30 ps and a power dissipation of less than 2 mW per channel. Also, EICROC needs to be sensitive to very low charge (∼2 fC) to be able to exploit AC-LGAD charge sharing capability, which will provide a spatial resolution better than 50 μm, when using pixel-size of 500x500 μm^2.

CALOROC – The CALOROC is applicable to the readout of SiPMs in calorimeters. It consists of 64 channels implemented in a BGA-packaged, 130 nm CMOS technology node and it is radiation tolerant. In addition, to facilitate the bias trimming of the SiPM channels, it includes ADCs, TOTs and TOAs for sensor with capacities up to 10 nF and dynamic range up to 12 nC. Power dissipation is lower than 10 mW per channel.

FCFD – The FCFD will be coupled to the AC-LGAD strips with 128 channels. It will be used also for HRPPD readout. It is implemented in a 65 nm CMOS technology node for wire-bonding to sensors and it is radiation tolerant. It includes constant fraction discriminators, TDCs and ADCs and supports sensors with capacitance up to 15 pF. The timing precision is better than 30 ps.

SALSA – The 64-channel SALSA ASIC is designed to readout MPGDs. It is implemented in a BGA-packaged, 65 nm CMOS technology node and it is radiation tolerant. In addition to extensive facilities for

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[1] Incom Inc., 294 Southbridge Rd, Charlton, Massachusetts, 01507, United States

data processing, it supports readout from detector with capacitance up to 200 pF and offers a dynamic range up to 250 fC, multiple selectable shaping parameters down to signals as short as 50 ns, dual polarity and 12-bit ADCs. The power dissipation is less than 15 mW per channel.

ALCOR - The ALCOR ASIC is designed for the readout of SiPMs where sensitivity to single photoelectron is required, and specific for the dRICH detector in ePIC. It consists of 64 channels implemented in a BGA-packaged, 110 nm CMOS technology node and it is radiation tolerant. In addition to facilities for bias trimming of SiPM channels, it includes amplification, conditioning, TDCs, inhibit and digitization for single-photon tagging or selection based on time and charge. The timing precision is better than 150 ps. The inhibit functions acts as a fast shutter to decrease the impact of SiPM dark rates. The power dissipation is less than 12 mW per channel.

These ASICs are at various stages of development with IP blocks being tested making use of Multiple Project Wafer (MPW) runs. The final designs will be submitted for fabrication by 2027 and following the final design reviews.

The development of five new frontend chips suited to modern triggerless read-out and data acquisition chains, designed for different detector families, namely tracking by MPGDs, calorimetry read-out by SiPMs, timing and tracking with AC-LGADS with pixel and strip arrangements, and the novel application of SiPMs for single photon detection in Cherenkov imaging devices, offers to the whole community dedicated to fundamental research in particle and nuclear physics a rich contribution of up-to-date building blocks to design the readout in the next generation of experiment upgrades and new experimental efforts.

Innovative Compute-Detector Integration Using Streaming Readout - The ePIC detector is characterized by high channel counts ($16{\cdot}10^9$ pixels, and $8{\cdot}10^6$ digitized channels), high rates (500 kHz), and low occupancy. The development of streaming ASICs coupled with high-rate fiber and network resources offers the possibility of reading all hit data into commercially available computing. While there are significant custom electronics remaining in the system in the readout, aggregation, and data transfer stages of the DAQ, this approach bypasses the need for the complexity and expense of a traditional hardware based trigger system. Moving processing tasks from custom electronics to computing decreases cost and increases flexibility as regards programming tools, algorithms, and hardware.

The streaming design allows the minimization of selection bias in analysis by ensuring that the event selection can be performed using the full detector readout. It operates with no global dead-time, and offers unprecedented characterization of background and noise.

Streaming designs require a larger bandwidth from the front end than triggered systems in order to accommodate backgrounds and detector noise. Meeting these requirements will require an accurate evaluation of beam backgrounds during the design phase, as well as the implementation of high-level filters that can be applied both during data aggregation by accelerators such as FPGAs and within streaming computing facilities using CPU and GPU algorithms. The latter approach enables the use of consistent algorithms for both streaming data and potential offline reprocessing, while providing a more robust framework for managing systematic biases and uncertainties.

The streaming DAQ is integrated with the streaming computing for a seamless data processing from the detector readout to the physics analysis.

Streaming computing serves two key purposes. First, it maximizes scientific output by processing all signals from the detector, minimizing selection bias and related systematic uncertainties, while enabling precise measurement of background and noise, which provides unprecedented control over these factors in the analysis.

Second, it accelerates scientific progress by enabling a rapid turnaround of recorded data to physics analysis, with a goal of achieving this within two weeks, a timescale determined by the time required for autonomous alignment and calibration of the detector. This time period accounts for the specific requirements of eA physics, where high-statistics features for straightforward detector signal calibration are lacking, and accommodates the multi-iteration calibration process needed for the diverse set of detector subsystems in ePIC. Additionally, a portion of the data will be processed in near real-time to provide prompt feedback to accelerator and detector operations.

ePIC will drive innovations in streaming readout and the processing of streaming data using AI and heterogeneous computing. The algorithms developed for autonomous experimentation, control, and the selection of physics events within the continuous stream of collision data will have broad relevance for other experiments, such as those planned for the FCC. Data management and processing at ePIC will be distributed immediately after the streaming DAQ, which sends the data to the compute facilities at BNL and Jefferson Lab and from there to global processing and storage. The unique streaming case and requirement for autonomous calibrations of a large-scale detector system with high channel count will contribute to advancements in distributed computing within HEP and related fields. Notably, the orchestration of streaming data processing across the distributed computing fabric planned for the EIC will benefit all experiments involving time-sensitive patterns and will ensure that the detector experts at the various ePIC institutions have rapid access to the required resources for aligning, calibrating, and validating the detector.

The work on streaming data will provide unprecedented access to detector information across all running conditions of the experiment. Combined with ongoing efforts on a data model and adherence to FAIR principles, these data assets will serve as a catalyst for AI applications at ePIC. This will foster collaboration with other large-scale experiments in NP, HEP, and related disciplines.

Novel approaches to synchrotron radiation simulation - Synchrotron radiation (SR) is an intrinsic consequence of charged particle acceleration in magnetic fields, playing a dual role in colliders. While essential for beam diagnostics, it presents significant challenges, particularly in high-luminosity machines like the EIC. The intense SR emitted by beams can generate secondary particles, elevate background levels in detectors, and cause localized heating and damage to machine components, including vacuum chambers and magnets. These effects pose a critical barrier to achieving the precise measurements required for the ePIC experiment's exploration of QCD and hadronic structure.

To address these challenges, SynradG4 [9] has been developed recently at BNL, a novel simulation framework built on Geant4, tailored for comprehensive modeling of SR. SynradG4 integrates advanced photon transport and interaction models with high-resolution beam dynamics inputs, enabling precise predictions of SR-induced particle showers and their effects on both the detector and the machine. By leveraging detailed beam optics to track charged particles through the machine lattice accurately, SynradG4 provides a unique platform to evaluate and mitigate SR's detrimental impacts.

The framework incorporates several novel elements, including enhanced modeling of photon-material interactions and a high-precision approach to simulating the generation and transport of SR photons using the Geant4 libraries [10–12]. These innovations allow for a more accurate representation of the spatial and temporal characteristics of SR effects within the interaction region. SynradG4 is validated against alternative, experimentally verified simulation tools, offering confidence in its predictive capabilities.

Despite its readiness, applying SynradG4 simulations to the the full complexity of the EIC lattice and integrating machine-specific phenomena like SR masking and radiation shielding remains an active area of development. Close collaboration between machine and detector experts will be essential to address these challenges, ensuring SynradG4 fulfills its role in safeguarding machine components and optimizing detector performance. This effort positions SynradG4 as a critical tool for enabling precision physics in the next generation of colliders, with particular reference to electron-positron colliders.

4 Conclusions

A wide set of novel technologies and implementations, techniques and methods are being adopted for the ePIC detector at the EIC. They are largely synergistic with the requirements of other major coming facilities and experiments. The timelines of the ePIC detector realization provide an opportunity to gain experience with large-scale deployments of new technologies as well as a stimulus to continued development.

The technologies considered in this document include the ePIC solenoid, the novel light-weight flexible Si tracker, μRWELL with GEM preamplification, the usage of SiPMS as sensors in homogeneous electromagnetic calorimetry, a hybrid electromagnetic calorimeter with imaging layers and sampling by lead and scintillating fibers, the approach to electromagnetic calorimetry by tungstan powder and scintillating fibers, hadronic calorimetry by SiPM-on-tile approach, the extended usage of AC-LGADs, two novel approaches for photosensors in Cherenkov imaging devices, a set of five novel front-end ASICs, the homogenous approach in streaming read-out/DAQ/data analysis and computing and novel tools for synchrotron radiation simulation.

Synergies with the experiments at the FCC, the HL-LHC, the muon collider and the future fixed-target program at CERN are self-evident and have been specifically underlined, technology by technology. These synergies are remarkable abundant with experiments at FCC-ee. It has been underlined that the timelines of the EIC project and those possible for FCC-ee qualify the usage of novel ePIC technologies and methods as precursors of those needed at the FCC-ee: they will be in operation in operation at least ten years earlier. A common effort towards the further development and validation of these technologies and methods is mutually beneficial to these experimental programs and to ePIC. Therefore, ePIC represents an opportunity for worldwide technological progress in fundamental research at high energy.

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