PROCEEDINGS OF SCIENCE

EIC vertex and tracking detector

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The Electron-Ion Collider facility at Brookhaven National Laboratory will enable a rich science programme with its high luminosity, high energy collisions of electrons with protons and ions. ePIC is the first detector being developed for this new facility. It is to be ready for data taking in the 2030s. The ePIC detector will utilise an innermost, high resolution Silicon Vertex Tracker, able to precisely measure primary and secondary vertices as well as particle momentum with wide acceptance. This paper will give an overview of the ePIC Silicon Vertex Tracker geometry, projected performance, development of ultra-thin detector layers with large area coverage.

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1. The Electron-Ion Collider

The Electron-Ion Collider (EIC) is a new particle accelerator under construction at Brookhaven National Laboratory (BNL). It is extending the capabilities of the current Relativistic Heavy Ion Collider (RHIC) facility with the addition of an electron storage ring. It will continue the exploration of strongly interacting matter via Deep Inelastic Scattering (DIS), with the aim to answer two overarching science questions; how does the mass and spin of the nucleon arise from its constituents, and what are the emergent properties of dense systems of gluons. This is to be achieved by colliding high energy electrons with high energy proton and ion beams over a large range of centre of mass energies (20 to 140 GeV), at luminosities up to 10^{34} cm^{-2} s^{-1} [1]. Additionally, the EIC will be a globally unique facility as the world's first accelerator, colliding beams of highly polarised (70 %) electrons with highly polarised (70 %) protons/light-ions, as well as the world's first collider of highly polarised electrons with heavy-ions (such as gold, lead, or uranium). The EIC is an approved U.S. Department of Energy project and data taking is planned to start within 10 years of the closure of RHIC, scheduled for the end of 2025. The EIC Project covers the development of the accelerator facility and one detector, known as the Electron-Proton/Ion Collider (ePIC). This paper will briefly introduce the ePIC detector and then discuss the development of its Silicon Vertex Tracker (SVT) system.

2. The Electron-Proton/Ion Collider

The requirements of ePIC are derived from the need for precise measurements of physics observables in key DIS processes; inclusive, semi-inclusive, and exclusive. All these DIS processes will be studied at the EIC. To achieve these requirements, ePIC needs to provide; high performance electron identification and reconstruction, tracking and hadronic calorimetry, heavy flavours identification from vertexing, light flavours from dedicated particle identification (PID) detectors, efficient proton tagging, and coverage of the full acceptance range.

These requirements will be satisfied with a compact central detector (Figure 1) and extensive beamline instrumentation integral to the science programme. The central detector will have a radius of 2.67 m and a length of 9.5 m. It combines tracking and vertexing, PID, and EM and hadronic calorimetry. There will be different electron and hadron endcaps to account for the asymmetric beam energies. It will sit within a 1.7 T magnetic field and accommodate a streaming readout approach.

3. Tracking requirements for ePIC

Tracking and vertexing within the ePIC detector comprises a silicon detector (close to the interaction point), complemented by gaseous trackers further out. The requirement for precise tracking of low momentum particles has been one of the most challenging. This has driven a need for a very high pointing resolution and an ultra-low material budget. These requirements were first quantified in the EIC Yellow Report [1]. These have dictated a system needing to utilise high granularity, low powered active elements, while keeping all service materials (mechanics, cooling, powering and data distribution) to a minimum. The total material budget of the ePIC tracker has to be $\leq 5\%$ x/X_0 (inclusive of all active and inactive material) [1].

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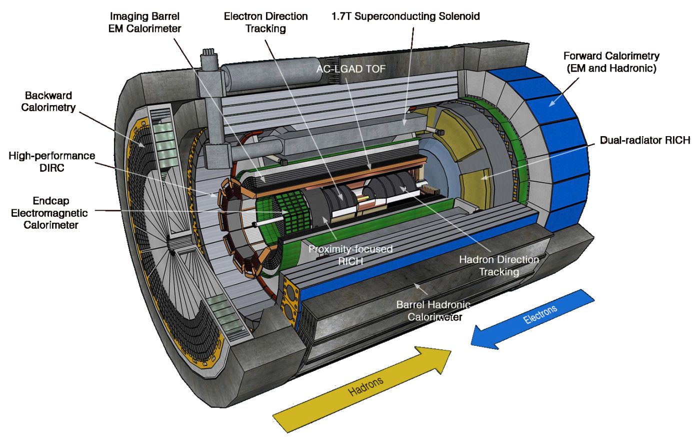


Figure 1: The ePIC detector configuration, showing the many sub-detector elements of the central detector.

Although the operational environment does impose requirements, these are less challenging to meet. Total rates are to be of the order of GHz [2, 3]. These include DIS $e{+}p$ events up to 500 kHz, for collisions between 10 GeV electrons and 275 GeV protons, at 10^{34} cm^{-2} s^{-1} (the highest luminosity runs), and background particles rates, including hadron beam gas, electron beam gas and synchrotron radiation. The hadron and electron beam gases are estimated to be in the order of tens of kHz and a few MHz respectively. The synchrotron radiation can be reduced by two orders of magnitude with a 5 µm gold coating to the beam pipe.

Radiation levels within ePIC have also been considered for the highest luminosity beam conditions (10^{34} cm^{-2} s^{-1}, for 10×275 GeV $e{+}p$ DIS events). These are low to moderate, with the Total Ionizing Dose (TID) below 1 Mrad and neutron fluence below 1×10^{10} n_{eq}cm^{-2} [4]. There are also integration constraints that need to be accounted for. Firstly, there is a large, ~ 33 mm, beam pipe diameter, at the Interaction Point (IP), limiting the closest position for vertex reconstruction (and therefore limiting the precision achievable). Secondly, the beam pipes diverge as they moves away from the IP. This complicates the design of the mechanical supports and the integration procedures within the SVT. Because of this, the SVT will be designed in two halves (the split runs parallel to the detector hall floor) and will be clamped around the beam pipe. Beam pipe bake-out will occur with the detector in situ. This leads to additional demands on cooling requirements, especially when trying to maximise the vertexing capability and keeping acceptance at the large η, all while keeping within the material budget requirement.

4. The ePIC Silicon Vertex Tracker

The SVT within ePIC will be a well integrated detector, with a large acceptance range and enabling high precision measurements. It is to be built with large area, low power Monolithic Active Pixel Sensor (MAPS), based on a 65 nm commercial, Complementary Metal-Oxide-Semiconductor (CMOS) imaging process by Tower Partners Semiconductor Company (TPSCo). The SVT is designed to cover a total active area of approximately 8.5 m^2, over four regions (Figure 2); the Inner Barrel (IB) (3 layers), Outer Barrel (OB) (2 layers), Electron Encap (EE) (5 layers), and Hadron Endcap (HE) (5 layers).

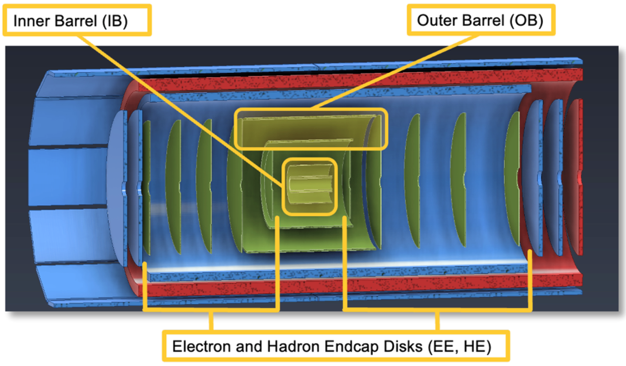


Figure 2: Layout of the ePIC SVT (green), consisting of 5 barrel layers (3 IB and 2 OB) and endcap regions with 5 layers in both the hadron and electron going directions. The SVT is surrounded by Micro-Pattern Gas Detector (MPGD) layers (blue) and the Time of Flight (ToF) PID detector (red).

In order to meet the stringent requirements of vertex and tracking at the EIC, the SVT is designed to reach a spatial resolution of ≤ 5 µm through a combination of high granularity (~ 20 µm pixel pitch), low power (≤ 40 mW cm^{-2}) sensor design coupled with lightweight support structures, cooling and electrical services. The specified material budget of all three IB layers (L0-2) is 0.05% x/X_0 per layer, the inner OB layer (L3) and all EE and HE disks (E/HD0-4) is 0.25% x/X_0 each, while the outer OB layer (L4) is 0.55% x/X_0. The sensor technology has been developed for the Inner Tracker System 3 (ITS3) upgrade of the A Large Ion Collider Experiment (ALICE) experiment [5]. All sensors in the SVT will utilise the same building blocks of the ITS3 MOnolithic Stitched Active pIXel (MOSAIX) segment [6]. These building blocks are the Left EndCap (LEC), Repeated Sensor Unit (RSU), and Right EndCap (REC) and can be seen in Figure 3. The LEC contains all the readout and powering connections for the segment (measuring 4.5×19.56 mm^2), the RSU contains the active pixel array (measuring 21.67×19.56 mm^2, with a pixel pitch of 22.8×20.8 µm^2), and the REC contains additional powering connections (measuring 1.5×19.56 mm^2). MOSAIX sensors are diced from a wafer as multiple segments (3, 4, or 5), depending on the layer.

The SVT IB will utilise the same MOSAIX sensor, with L0, L1 and L2 utilising sensors of three, four and five segments, respectively (which equate to diced widths of 58.7, 78.3 and 97.8 mm respectively, all with a length of 266 mm). These sensors will be thin, wafer-scale, silicon bent around the beam pipe with minimal mechanical support, air cooling and no services in the active area. The layers are positioned to optimise the transverse pointing resolution, within operational constraints. For L0-1 these constraints are the beam pipe diameter, a 5 mm clearance for the beam pipe bake-out and the available sensor widths (4 sensors are utilised for both L0 and L1). L2 is designed as a dual purpose vertexing and sagitta layer, but without any increase to the material (8 sensors are required for the entirety of L2).

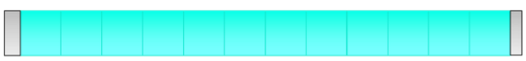


Figure 3: Basic structure of an ITS3 MOSAIX [6] segment, consisting (from left to right) of 1 LEC, 12 RSUs, and 1 REC.

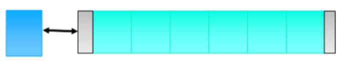


Figure 4: Basic structure of an EIC-LAS (built from the same LEC, RSUs, and REC as MOSAIX [6]) with an AncASIC (left of image).

The OB and endcaps will use an EIC specific version of these segments, optimised for high yield, low cost and large area coverage, referred to as EIC - Large Area Sensor (EIC-LAS). The optimisations planned for EIC-LAS are to shorten the chip (to prevent the need for power connections at both ends), and reduce the data links from eight to one (as the hit rate within ePIC will be significantly lower than in ITS3). Further, service minimisation, optimisations will be achieved with the development of an Ancillary Application Specific Integrated Circuit (AncASIC), which will enable serial powering and multiplexed slow controls, to reduce the service material.

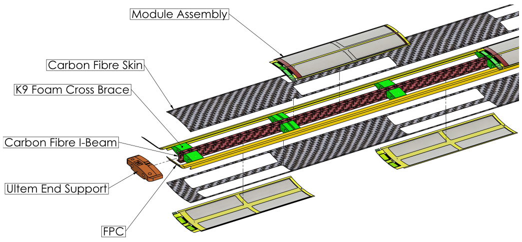


Figure 5: Exploded CAD model of the OB stave structure.

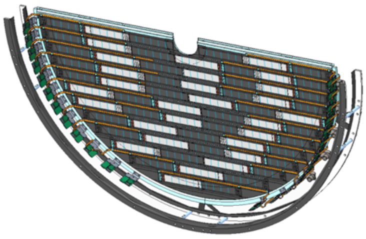
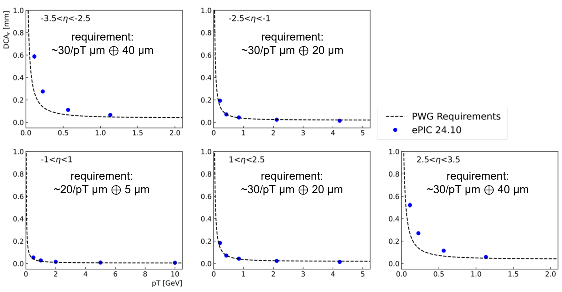
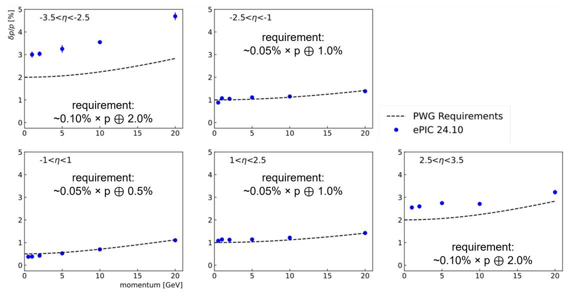


Figure 6: CAD model of an endcap half disk structure.

The combination of an AncASIC and EIC-LAS will form a module, that will populate support structures. The OB will be formed of staves, with a central spine, longerons, heat spreading carbon foam (in the regions of the AncASIC and LEC), carbon fibre face sheets and completed with (2 EIC-LAS wide) slight curved, modules on both stave sides, alternated to overlap the inactive regions and optimising coverage (Figure 5). The endcap disks are built (as half disks) around a corrugated carbon fibre core with back-to-back modules (again, overlapping the inactive regions) on a carbon fibre face sheet, to cover the corrugation opening on both the front and back disk sides (Figure 6). Both the staves and disks are to run at room temperature and be air cooled. These support structures are designed to provide the needed air channels. They also integrate electrical interfaces, in the form of aluminium-based Flexible Printed Circuit (FPC)s, which connect the modules to the stave ends (and disk edges), where electrical to optical conversion (of the high-speed data) occurs via the CERN developed Versatile link (Transceiver) plus (VTRx+). A dedicated set of boards will distribute power, control signals and high-speed data between the ePIC control room and the SVT.



(a) Radial Distance of Closest Approach (DCA)



(b) Momentum resolution

Figure 7: Simulated transverse pointing resolution, given as the radial DCA (a) and relative momentum resolution (b) for the ePIC SVT in different regions of pseudorapidity, as a function of momentum. Based on the October 2024 simulation campaign.

Figure 7 shows the simulated transverse pointing (7a) and relative momentum (7b) resolutions of the SVT's tracking performance. The target resolutions, from the EIC Yellow Report [1], are also included (dashed lines) in the plots. Requirements on transverse pointing resolution are met in the barrel region and at mid-pseudorapidity, with good agreement at large η ($|\eta| \geq 2.5$). Requirements on relative momentum resolution are met in the barrel region and mid-pseudorapidity, but remain a challenge at large η (especially for the e-going side, $\eta \leq -2.5$) with the available 1.7 T magnetic field.

5. Ongoing activities

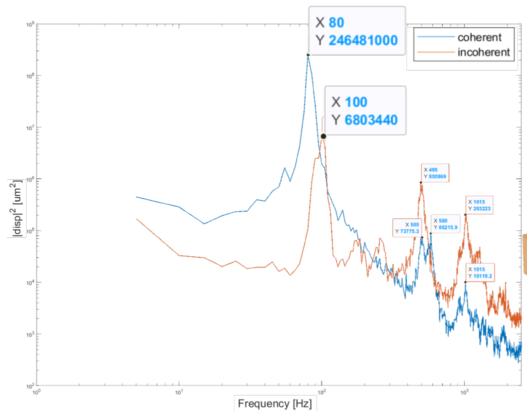
Developments within the SVT are targeting low mass technology solutions to satisfy the physics requirements and achieve the tight integration of all SVT regions. This includes (but is not limited to) the production of engineering samples to demonstrate the bending of silicon to the required IB radii, studies on vibration and temperature related to air cooling for both the OB and endcaps, procedures to replicate material maps from Computer Aided Deisign (CAD) models in the simulation framework, and service reductions.

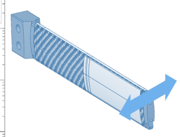
The IB of the SVT, like ITS3, intends to use thinned silicon sensors bent around the beam pipe. Where ITS3 are bending a single silicon sensor (per half layer) to a (minimum) radius of 19 mm, the SVT IB only needs to bend to a (minimum) radius of 38 mm, but needs multiple sensors, connected together (to produce each half layer). L0&1 require two connected sensors per half layer, and L2 requires four sensors per half layer. Initial trials have successfully been performed on joining two dummy L0 silicon pieces and bending them to the required minimum radius (Figure 8).

Figure 8: Initial engineering structure of two dummy silicon sensors connected and bend to a radius of 38 mm.

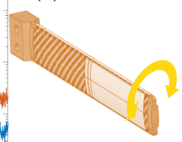
The SVT will operate with an estimated total sensor power of approximately 10 kW (including overheads related to powering and data transmission). The base-line cooling solution for the entire SVT is air cooling. Within the OB, studies are ongoing with air flow through the stave core. These studies have been based on a quarter-length, L4 stave, test structure. Vibration of the test structure, due to the air flow, has been the initial focus. Both coherent and incoherent vibrations have been studied, with the first modal frequency around 100 Hz for the incoherent and around 80 Hz for the coherent vibrations. These are both close to or meeting the targeted 100 Hz minimum frequency.

For the endcap disks, initial test structures have been developed for ongoing mechanical and thermal tests. Thermal measurements have been made with overlapping heater structures, to represent the overlapping areas on the disks (Figure 10a). They allow the observation of the temperature profile along an air channels. Results show that the hottest area of the silicon (LEC)





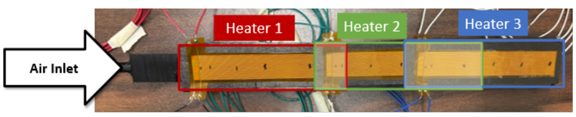
(a) Coherent



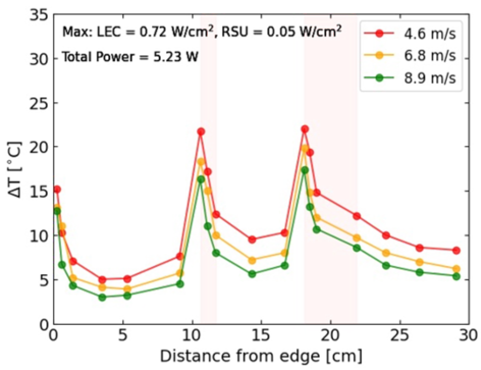
(b) Incoherent

Figure 9: Plot of a test, quarter length OB stave structure vibration due to the air flow, showing both coherent (blue, a) and incoherent (orange, b) vibration.

can be around 20 °C above the ambient temperature, with 4.6 m s^{-1} of air, with the RSU around 10 °C above ambient (Figure 10b). The RSU can be maintained around 5 °C above ambient with 8.9 m s^{-1} of air (over the scale of the test structure). This shows that manageable air speeds can be used to ensure RSU temperatures do not exceed a maximum of 40 °C.



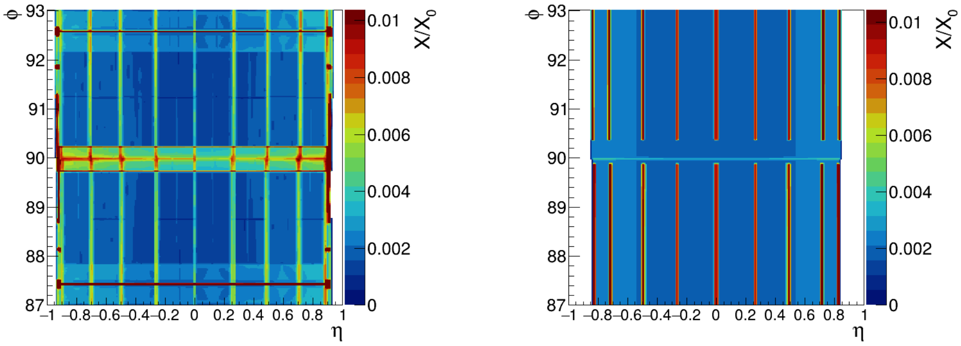
(a) Single air channel of the endcap disk corrugation, with three heater structures to emulate the LEC and RSU thermal loads (with overlapping heater regions).



(b) Thermal camera data of the structure in (a).

Figure 10: Endcap disk thermal test structure (a) and its measured temperature profile along the three heater structures with three air velocities (b).

Scripts have been developed to convert CAD models to a geometry compatible with the simulation framework. This has been used as a cross-checking tool to compare with the standard simulation geometry (the CAD-based geometry is not suitable as the main simulation geometry as the number of vertices are much higher and simulations are much slower), as material values and locations can be verified against that in the CAD models. The complex stave structure (Figure 11a) makes achieving accurate material coverage challenging without this cross-check. This has already been used to generate simplified simulation geometries that follow the non-uniform material structure of the OB stave (Figure 11b).



(a) Material of the CAD-based geometry. **(b)** Material of a simplified simulation geometry.

Figure 11: Material scans to compare the material of single L4 staves. (a) based on a CAD model and (b) based on a simplified simulation geometry.

6. Conclusion

The EIC will be a world's unique facility to continue the exploration of strongly interacting matter using DIS. It will commence operations in the 2030s. The ePIC SVT is a large, thin, MAPS-based detector, with very demanding requirements for precision measurements and integration. There are synergies with the ALICE ITS3 developments, but also a large programme of dedicated development on a low-mass detector with integrated mechanical and cooling structures. A number of services reductions have been implemented to keep the total material budget of the detector to a minimum.

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