PROCEEDINGS OF SCIENCE

Development of a Silicon Vertex and Tracking Detector for the Electron-Ion Collider

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The Electron-Ion Collider being built at the Brookhaven National Laboratory will further the study of Quantum Chromodynamics via a rich science programme enabled by high luminosity, high energy collisions of electrons with protons and ions. The ePIC detector is being developed to be the first EIC experiment, ready for data taking in the early/mid 2030s. The innermost element of the ePIC detector is a high resolution Silicon Vertex Tracker able to provide precise measurements of primary and secondary vertices and of particles momentum. This paper will present the ePIC Silicon Vertex Tracker geometry and its performance evaluated in simulations, and will give a brief overview of the ongoing R&D towards high granularity and ultra thin detector layers.

The 32nd International Workshop on Vertex Detectors (VERTEX2023)
16-20 October 2023
Sestri Levante, Genova, Italy

[*] Speaker

PoS(VERTEX2023)038

1. The Electron Ion Collider

The Electron-Ion Collider is a new particle accelerator under construction at the Brookhaven National Laboratory (BNL) designed to continue exploration of strongly interacting matter using Deep Inelastic Scattering (DIS). The EIC will collide high energy electrons with high energy proton and ion beams over a large range of center of mass energy (28 to 140 GeV), at luminosities up to 10^{34} cm^{-2} s^{-1} [1]. The EIC machine will be capable of delivering highly polarised (70%) beams of electrons, protons and light ions. It will provide ions from deuterons to heavy nuclei such as gold, lead, or uranium. The EIC science case covers a broad physics programme, at the core of which are four fundamental themes: nucleon spin, nucleon imaging, gluon saturation, and hadronization [2]. The EIC is an approved US Department of Energy project and data taking is scheduled to start in the early/mid 2030s. The EIC Project covers the development of the accelerator facility and one detector, known as the EIC Project Detector. This paper will briefly introduce the EIC Project Detector and then discuss the development of its Silicon Vertex and Tracking (SVT) system.

2. The EIC Project Detector: ePIC

The requirements for an EIC detector are derived from the need of precision measurements of the physics observables in the key DIS processes under study at the EIC: inclusive, semi-inclusive, exclusive/diffractive. An EIC detector needs to provide high performance electron identification and reconstruction, heavy flavors identification from vertexing, light flavour separation via particle identification (PID), efficient proton tagging, full acceptance range coverage.

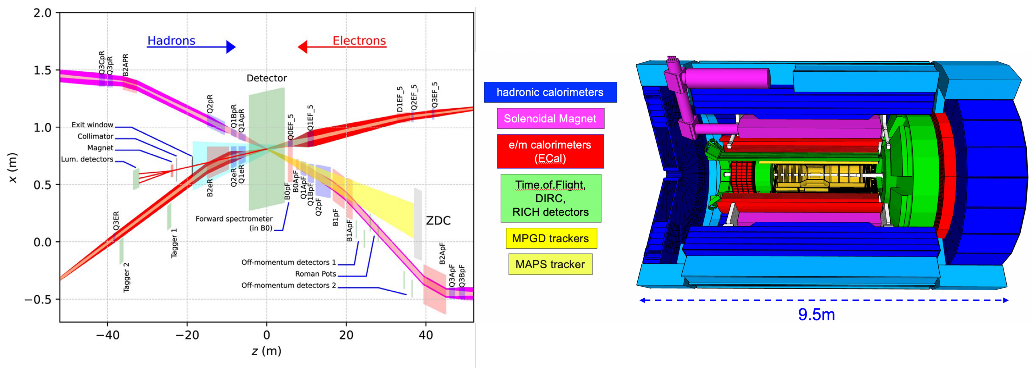

Figure 1: Left: Overview of the EIC interaction region with the central detector around the collision point and ancillary detectors along the beam line. Right: ePIC detector configuration.

The ePIC experiment aims at satisfying these requirements with a compact central detector combined with extensive beam line instrumentation integral to the science programme (figure 1). The central detector covers an area of approximately 9.5 m × 5.5 m, with a number of detector sub-systems providing vertexing and tracking, particle identification, electromagnetic and hadronic calorimetry. It features an asymmetric design, reflecting the asymmetry in the energy of the colliding beams, to best measure collision products in the electron and hadron going direction. A magnetic field of 1.7 T surrounds the tracking system. A streaming readout system is chosen for the ePIC detector, integrating all the sub-detector components.

3. Vertex and tracking measurements at ePIC

The ePIC vertex and tracking detector is composed of silicon detectors close to the interaction point, complemented by gaseous trackers at larger radii. The most challenging requirements for this system are dictated by the need of precise low momentum particles tracking, primary and secondary vertices reconstruction. These requirements are quantified in the EIC Yellow Report [3] and reproduced in table 1. To achieve the required momentum and transverse pointing resolution the ePIC vertex and tracking detector will need very high granularity and ultra-low material budget. The latter constraint is possibly the most stringent, demanding aggressive developments of low power active elements and lightweight mechanics, cooling and electrical services to reach well below 1% x/X_0 per layer, and at most 5% in total.

Tracking requirements from PWGs						
			Momentum res.	Material budget	Minimum pT	Transverse pointing res.
η						
-3.5 to -3.0	Central Detector	Backward Detector	σp/p ~ 0.1%×p ⊕ 0.5%	~5% X0 or less	100-150 MeV/c	
-3.0 to -2.5					100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 40 µm
-2.5 to -2.0			σp/p ~ 0.05%×p ⊕ 0.5%		100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 20 µm
-2.0 to -1.5					100-150 MeV/c	
-1.5 to -1.0					100-150 MeV/c	
-1.0 to -0.5		Barrel	σp/p ~ 0.05%×p ⊕ 0.5%		100-150 MeV/c	dca(xy) ~ 20/pT µm ⊕ 5 µm
-0.5 to 0						
0 to 0.5						
0.5 to 1.0						
1.0 to 1.5		Forward Detector	σp/p ~ 0.05%×p ⊕ 1%		100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 20 µm
1.5 to 2.0					100-150 MeV/c	
2.0 to 2.5					100-150 MeV/c	
2.5 to 3.0			σp/p ~ 0.1%×p ⊕ 2%		100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 40 µm
3.0 to 3.5					100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 60 µm

Table 1: Physics derived requirements for the ePIC vertex and tracking system, including silicon and gaseous detectors [3].

The operational environment poses less severe challenges. Particle rates are estimated to be at most a few MHz, including DIS *ep* collisions and sources of background [4]. In particular, the particle rate from DIS *ep* collisions is estimated at 500 kHz for the highest luminosity runs. These would see collisions of 10 GeV electrons and 275 GeV protons at 10^{34} cm^{-2} s^{-1}. Particle rates from background events consist of electron and hadron beam gas interactions, estimated to be up to a few MHz and a few hundred kHz respectively, and synchrotron radiation. The latter is reduced from 1 MHz to 10 kHz by coating of the beam pipe with a 5 μm layer of gold.

Radiation levels have been estimated for the beam configuration with the highest luminosity, including contributions from hadron and electron beam gas interactions. In order to obtain a worst-case estimate, fluence and dose have been estimated assuming 10 years of running at top luminosity, with six months of operation each year during which detector and accelerator would be 100% efficient. Even under these assumptions, the radiation levels in the SVT will be low to moderate (figure 2). The majority of the SVT will see fluence levels well below 10^{11} n_{eq} cm^{-2}. Innermost central layers and layers in the hadron going direction will experience slightly higher fluence between 10^{11} and 10^{12} n_{eq} cm^{-2}, with some small regions reaching above 10^{12} n_{eq} cm^{-2}. The dose rate map indicates that areas close to the beam pipe will experience a total ionising dose between ten and a few hundred krad, while the rest of the SVT remains below 10 krad.

Constraints coming from integration aspects will also need to be taken into account during the development of the SVT. The large beam pipe diameter of 31.8 mm at the interaction point works

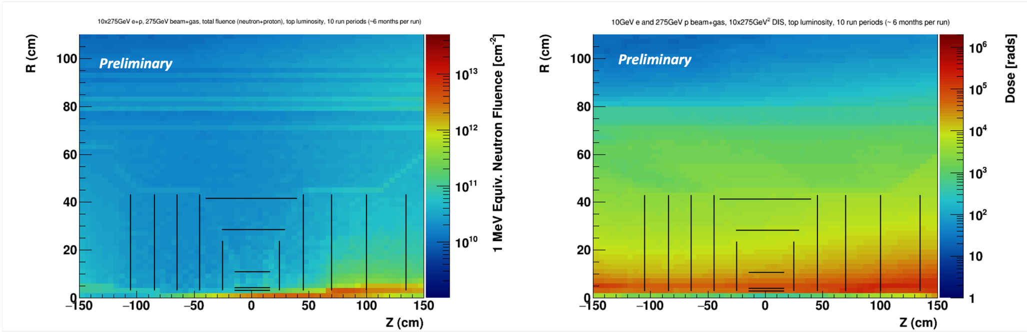

Figure 2: Maps of fluence (left) and total ionising dose (right) over the ePIC tracking envelop. This is a worst-case estimate assuming 10 years of running at top luminosity with 100% efficient accelerator and detector. The black lines indicate the approximate location of the ePIC SVT detector layers. Worked based off inputs from [4].

against the requirement of high precision vertex reconstruction. The beam pipe diameter increases away from the interaction point, already within the SVT envelop, complicating the design of the mechanical supports and the integration procedures of the SVT. This detector will be designed in two halves and assembled around the beam pipe, before insertion into the ePIC detector. Beam pipe bake-out will happen with the detector in situ, leading to demanding cooling requirements to maximise vertexing capability and acceptance at large pseudorapidity with layers as close as possible to the beam pipe, within the material budget.

4. The ePIC Silicon Vertex Tracker

The ePIC Silicon Vertex Tracker detector is designed to provide high precision measurements over a large acceptance range. It consists of four well-integrated regions, covering a total active area of approximately 8.5 m^2, as shown in figure 3: the Inner Barrel (IB) and Outer Barrel (OB) in the central area, made of three and two detecting layers respectively, surrounded by two endcaps with five detecting layers each. These are called the Electron Endcap (EE) and Hadron Endcap (HE) based on their location on either side of the collision point; the EE is positioned in the direction of the electron beam and has acceptance for a large fraction of the scattered electrons, while the HE provides acceptance for many of the hadrons produced in the collisions. This SVT configuration provides acceptance over the pseudorapidity range between $-3.5 \leq \eta \leq +3.5$.

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 sensor design (≤ 40 mW cm^{-2}), and lightweight support structures, cooling, and electrical services. The SVT development aims at reaching 0.05% x/X_0 in the IB, 0.25% x/X_0 in the innermost OB layer and in the disks, and 0.55% x/X_0 in the outermost OB layer. The sensors technology selected to meet these requirements is a new generation, large area Monolithic Active Pixel Sensor (MAPS) in a commercial 65 nm CMOS imaging process, developed for the ITS3 upgrade of the ALICE experiment at CERN [5].

The main task of the IB is to provide precise vertex reconstruction, while also contributing to momentum measurement. The large beam pipe diameter, together with constraints from beam

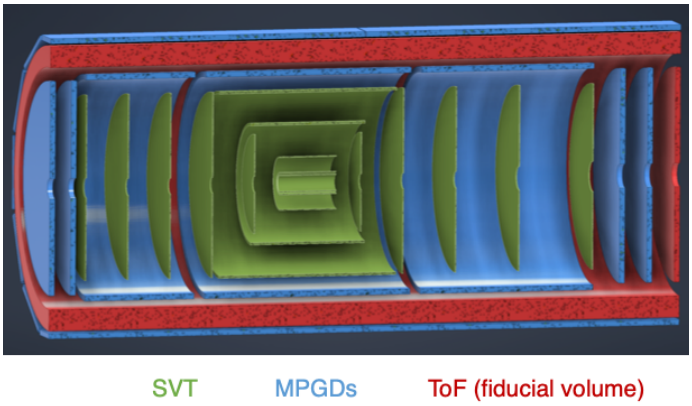

Figure 3: Layout of the ePIC SVT showing the barrel region made of five layers and the endcap regions made of five layers each. The figure also includes the Micro Pattern Gas Detector (MPGD) layers and the envelop of the Time of Flight PID detector.

pipe bake-out, pushes the first layer away from the interaction point. Under these conditions, the specified transverse pointing resolution can be reached only with very thin IB layers at optimised radii, with pixel pitch not contributing significantly in the range considered (between 20 and 25 μm). To reach the target material budget, the IB will adopt the ALICE ITS3 wafer scale sensor and ultra-thin detector concept, adapted to the large EIC beam pipe diameter. It will consist of three layers of silicon sensors thinned below 50 μm and bent around the beam pipe, with minimal mechanical support, air cooling, and no electrical services in active area. The position of the first layer is constrained to a radius 36 mm, based on ongoing studies of temperature profile during bake-out (see section 5). The second layer is positioned at a distance from the first layer chosen to maximise vertex resolution, with a radius of 48 mm. The third layer aims at maintaining the very low material budget at a radius of 120 mm, and serves both vertexing and sagitta measurements.

The OB, EE and HE will be equipped with the EIC Large Area Sensor (LAS) optimised for high yield, low cost, large area coverage. This sensor will be a modified version of the ITS3 sensor: it will be stitched but not wafer-scale, and it will have a reduced the number of data links. These sensors will be mounted on lightweight support structures, in the form of staves for the OB and disks for the endcaps, with integrated cooling and electrical interfaces for power, data and slow control. The OB layers and the endcap disks are positioned to provide high precision measurements over a large level arm to improve momentum resolution and optimise acceptance at large pseudorapidity. The OB layers are placed at radii of 270 mm and 420 mm. Disks span an area from 250 mm from the interaction point, to 1350 mm in the hadron going direction and 1050 mm in the electron going direction. The inner opening of the disks needs to accommodate beam pipe bake-out constraints as well as beam pipe divergence. These translate into six different inner opening geometries over ten disks.

Figures 4 and 5 show the simulated tracking performance of the SVT in terms of transverse pointing resolution and relative momentum resolution. The target resolution, as stated in the Yellow Report (table 1), is also shown in the plots. Requirements on transverse pointing resolution are met in the barrel region and at mid-pseudorapidity, with good agreement at $|\eta| \geq 2.5$. Requirements on relative momentum resolution are met in the barrel and most of the hadron going direction, but remain challenging in the electron going direction with the available magnetic field.

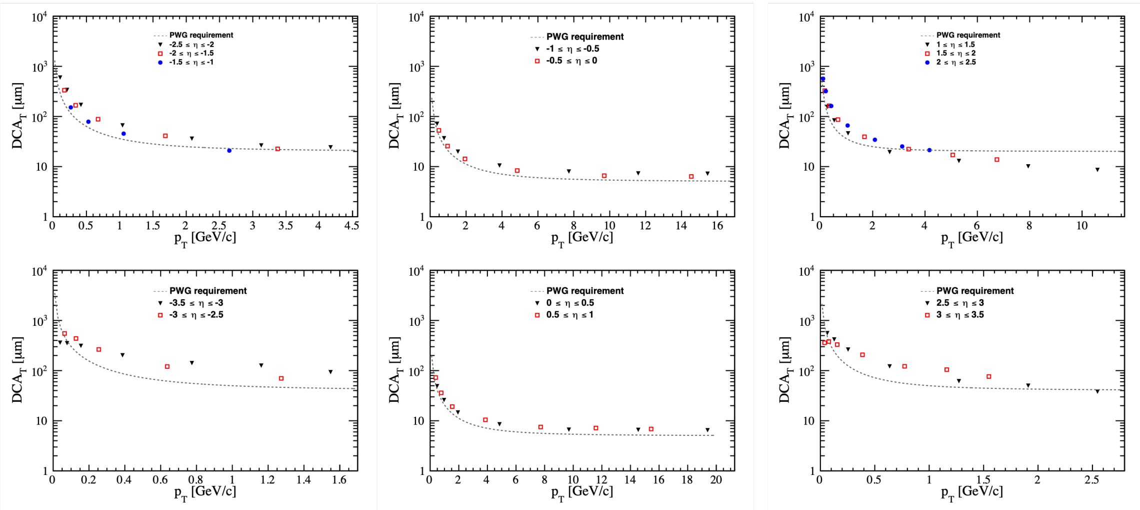

Figure 4: Simulated transverse point resolution for the ePIC SVT in different regions of pseudorapidity, given as the transverse distance of closest approach, as a function of momentum.

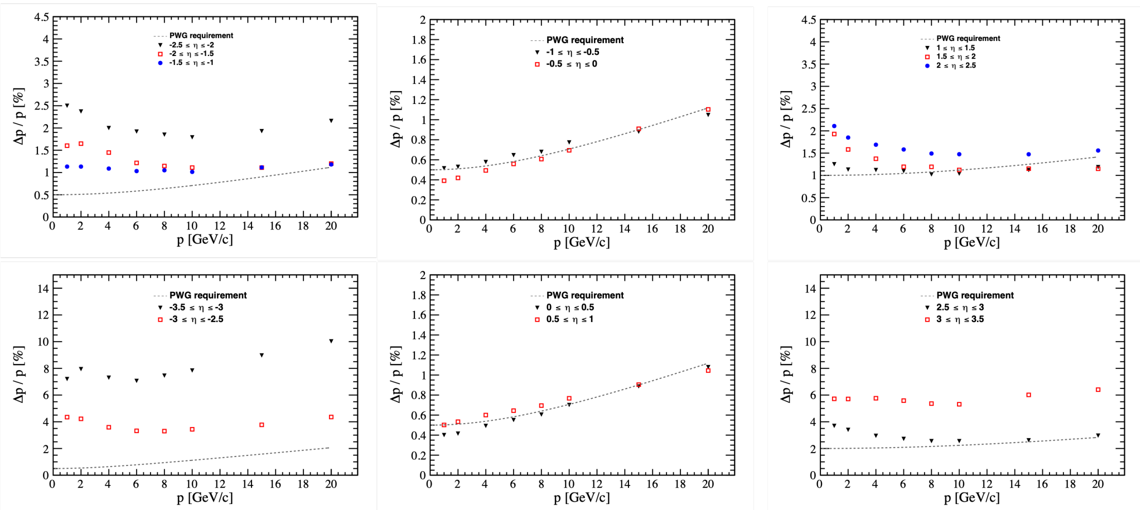

Figure 5: Simulated relative momentum resolution for the ePIC SVT in different regions of pseudorapidity as a function of momentum.

Hit rates have been estimated in the SVT for the case of 10 GeV electrons colliding with 100 GeV protons with 4.48×10^{34} cm^{-2} s^{-1} luminosity and 184 kHz particle rate, including electron and hadron beam gas interactions and synchrotron radiation. The study assumes 20.8 x 22.8 μm^2 pixels and 2 μs frame rate. As shown in figure 6, hit rates in the SVT are dominated by hits from background particles. Rates of a few MHz are measured in the IB, EE and HE, while the OB sees less than 1 Mhz. These translate into an average hit occupancy of a few 10^{-9} hits per pixel per readout frame in the disks, and between 10^{-8} and 10^{-10} hits per pixel per readout frame in the barrel layers.

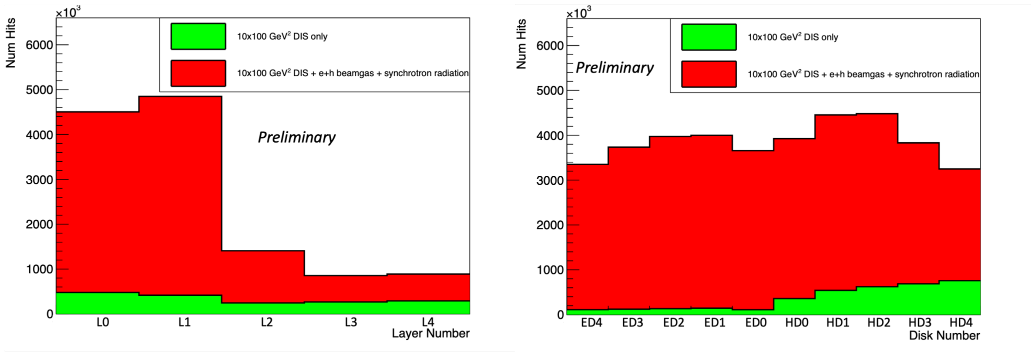

Figure 6: Hit rates in the ePIC detector for 10 GeV electrons on 100 GeV protons, at 4.48×10^{34} cm^{-2} s^{-1} luminosity and 184 kHz particle rate, including electron and hadron beam gas interactions and synchrotron radiation. Cluster size and fake hit rate in the sensor are not accounted for. Barrel layers (L), EE and HE disks (ED, HD) are numbered 0 to 4 moving away from the interaction point.

5. Ongoing R&D activities

The R&D programme underway for the development of the ePIC SVT targets the development of low mass technological solutions to satisfy the physics derived requirements and achieve tight integration of the different SVT regions. Sensor development is ongoing in collaboration with the ALICE ITS3 project. Conceptual design of lightweight OB and endcaps progresses including studies of air cooling through the support structure, development of serial powering regulator and architecture, and data transmission on optical fibers. Interplay between beam pipe bake-out and SVT cooling is under study in collaboration with the EIC project.

The SVT will operate at room temperature with an estimated total sensor power consumption of ~4 kW. The preferred cooling solution for this detector is air cooling, baselined for the IB and under study for OB and endcaps. For the latter, air flow internal to the support structure is studied in two scenarios. Research is starting into the design and construction of corrugated support structures for the disks that would provide built-in channels for air flow. Tests of air cooling through carbon foam have started on small stave structures of different foam types and thicknesses. The tests use heat loads to simulate different power densities expected in different areas of the sensors, and room temperature air at a speed between 1 – 8 m/s. The temperature difference along the length of a 10 cm stave made of 4 mm thick CVD foam has been measured showing that the set target of less than 10° C difference along the stave is reached for power densities up to 0.5 W cm^{-2}. Similar tests conducted on a 50 cm long, 6 mm thick RVC foam achieve Δ T < 10° C for power densities < 0.1 W cm^{-2}. Based on these encouraging preliminary results, tests are planned to continue on SVT size staves currently under fabrication.

Air cooling for the IB need to consider requirements during beam pipe bake-out when a large temperature gradient will need to be accommodated over a short distance. During bake-out, hot gas will be pumped through the beam pipe to achieve a temperature of 100° C. The target IB temperature during bake-out is currently set at 30° C. Initial simulations show that a clearance of approximately 5 mm between beam pipe and first IB layer would achieve this target, with an air flow of 5 m/s and air temperature of ≤ 20° C. This would however lead to cooling of the beam pipe inner surface to around 70° C, if a 100° C gas is used. Simulations will continue to investigate the minimum hot gas temperature to keep the inner surface of the beam pipe at 100° C and its effect on the innermost barrel layer.

A serial powering scheme is being designed for the OB, EE, HE based-off the concept developed for the upgraded ATLAS and CMS detectors at the HL-LHC [6, 7]. A constant current flowing between groups of four EIC-LAS will be converted into the voltages needed by these sensors by the Shunt-LDO regulator [8]. The design of the latter is ongoing to match the EIC-LAS specifications. To reduce material associated with power distribution further, current will be distributed over aluminium flex cables on the staves and disks. The same flex cables will also be used to route sensor slow control and data lines. The possibility of transmitting data off staves and disks via optical fibers directly is being investigated, exploiting the low radiation levels in the SVT.

6. Conclusion

The EIC will be a worldwide unique facility to continue exploration of strongly interacting matter using DIS, commencing operation in the early/mid 2030s. At the heart of the first EIC experiment, ePIC, is a large acceptance, highly granular, thin, MAPS based Silicon Vertex Tracker, designed to meet very demanding requirements for precision measurements and integration. The development of this detector is ongoing exploiting synergies with ALICE ITS3 developments in combination with a programme of dedicated R&D on lightweight, integrated mechanics, cooling and electrical services.

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PoS(VERTEX2023)038