Precision Central Silicon Tracking & Vertexing for the EIC

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Abstract

We propose to develop a detailed concept for a central silicon pixel detector for an Electron-Ion Collider at BNL or JLab, exploring the advantages of using HV-CMOS or HR-CMOS MAPS technologies. The sensor development will exploit the newly created Birmingham Instrumentation Laboratory for Particle Physics and its Applications and will be closely coupled with simulations to optimise the basic layout, location and sensor/pixel dimensions. The design will be tested in full detector simulations to evaluate its performance with respect to the identification and precision measurement of heavy flavour processes and scattered electrons at high Q^2. A detailed evaluation of expected EIC performance for these processes will therefore be a key deliverable.

Introduction

Lepton-hadron interactions in general and Deep Inelastic Scattering in particular have had a long heritage of discovery in the US and Europe. The HERA electron-proton facility at DESY, Hamburg, Germany is the only realisation to date in colliding beam mode. As well as giving a transformational change in centre-of-mass energy, it also showed the vital importance of central tracking, both for the identification and measurement of the scattered beam electron at large Q^2 and for a wide range of hadronic final state studies [1]. Notable among these was the power of central tracking to unlock heavy flavour signatures, either through direct reconstruction of charmed or beauty hadrons, notably $D^*(2010)^{\pm}$ [2], or through the study of variables sensitive to the presence of secondary vertices [3]. Through the processes $\gamma^* g \to c\bar{c}$ and $\gamma^* g \to b\bar{b}$, heavy flavour production is directly sensitive to the gluon density at lowest order as well as probing a wide range of issues in perturbative QCD. By combining two (H1) or three (ZEUS) inner barrel layers of silicon detectors with drift chambers at larger radii, the HERA collaborations were able to make high quality measurements of the charm and beauty contributions to the proton structure function and a wide range of other observables.

Among the aims of future DIS facilities [4], possibly the most compelling are the extensions to colliding beam kinematics for the first time in the cases of nuclear (e+A) and polarised proton targets. These topics are very well addressed by the Electron Ion Collider [5]. The focus of the physics programme on the role of gluons within the structure of hadrons places an enhanced importance on heavy flavour observables. The successful use of heavy flavours as hard probes in relativistic heavy ion (A+A) collisions adds further motivation to the study of such processes in the e+A case, where they may provide

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a vital baseline in which the signature particles do not pass through hot dense nuclear matter. Open charm production in polarised $e+p$ scattering has also provided insights into the role of gluons in the spin structure of the proton, for example at the COMPASS experiment [6]. Whilst these issues are fully recognised within the EIC white paper and have been followed up since, there have been no detailed studies to date which look closely at the optimisation of the central silicon tracker layout for an EIC, the most suitable detector technologies or the possibility of developing bespoke sensors for the particular needs of the environment.

The Birmingham membership of the EIC user group combines world-leading expertise in previous and future lepton-hadron scattering experiments (Newman), previous and present heavy ion collision experiments (Jones) and silicon detector development and production (Allport, Gonella). The University of Birmingham has recently invested heavily in a new silicon detector laboratory (The Birmingham Instrumentation Laboratory for Particle Physics and its Applications, or BILPA), a 200 m^2 set of clean rooms that is scheduled to begin operation in July 2016, and four new associated faculty appointments. Early BILPA projects include the production of silicon strip modules for the ATLAS ITK detector in the High Luminosity phase of the LHC (HL-LHC) and R&D into radiation-hard reconfigurable Monolithic Active Pixel Sensors (MAPS) for long-term deployment in outer tracking, digital calorimetry and medical applications (hadron therapy). There is substantial capacity and a strong commitment to broaden this range of activities as well as the target user-base in terms of applications in collider physics and beyond. The Birmingham physics department also hosts an MC40 cyclotron, which is the UK's only AIDA-2020 Transnational Access facility. The particle physics group has been using the MC40 for several years to irradiate detector and electronics components in order to characterise their radiation tolerance.

In the following, we propose to develop a technology and detector concept for a silicon pixel tracker in the central region of an EIC detector, through a set of simulation studies of detector layout and physics capability evaluation, closely linked to a detector R&D programme focusing on sensor and readout solutions. We aim to take advantage of the progress towards technologies offering ever-smaller feature sizes to achieve optimal spatial resolution and signal-to-noise ratio.

As a basic technology solution, we propose to explore the advantages of new developments in MAPS technologies (HV/HR-CMOS sensors). High resistivity substrates and novel structures offer the possibility of charge collection through drift, which results in much faster signals than collection by diffusion (as used in conventional CMOS imaging sensors) as well as much less charge spreading at the collection electrodes and better signal-to-noise. Through the CERN RD50 collaboration and AIDA-2020, we are participating in R&D studies on such detectors for possible applications at the HL-LHC, where the faster charge collection has also been shown to greatly reduce radiation-induced charge trapping. We have also secured UK R&D funding to develop concepts (based on previous work towards digital calorimetry for CLIC/ILC within CALICE) to explore the use of radiation-hard MAPS with HV/HR-CMOS technologies for the much more demanding environments at future hadron colliders. This latter project builds on prior collaboration with the Rutherford Appleton Laboratory (RAL) Technology Department using the TowerJazz (now TowerJazz Panasonic Co. Ltd, TPSCo) foundry, which helped establish the links with that company now being exploited for the ALICE ITS upgrade. Concepts developed at RAL with TPSCo are also being explored that allow efficient charge collection with minimal capacitance seen by the circuit connected to the collecting electrode, which is expected to significantly reduce the electronic noise and power consumption in the device. For the EIC, we would build on our expertise in silicon detectors for vertexing and tracking, as well as in deep sub-micron CMOS microelectronics for High Energy Physics experiments [7–11].

Proposed Programme of Work

The proposed programme naturally breaks down into three inter-connected work packages, which run in parallel, but with changing emphasis as time progresses. Work Package 1 (WP1) is concerned with the sensor development and testing. Work Package 2 (WP2) deals with basic simulations of the detector layout. Finally, Work Package 3 (WP3) involves a physics performance evaluation focussing on the detection of open heavy flavour decays. These work packages are described in more detail below.

WP1: Sensor Development (Gonella, Allport)

In recent years developments of CMOS technologies for particle physics experiments have shown great potential towards thin detectors with high spatial resolution, low material, and low power consumption. Our goal is to improve the achievable spatial resolution as foundries move to finer lithography processes by exploiting charge collection by means of an electric field through the sensitive volume of the detector. Charge collection by drift has the benefit of reducing the charge collected by diffusion, and thus the extent of the collected charge cloud, which will become increasingly important as pixel sizes become smaller. Coupled with targeting the minimal thickness possible, this would allow good in-pixel signal-to-noise ratios, and hence high efficiency, to be retained. The optimal pixel size and electrode configuration for the best possible spatial resolution will be investigated with TCAD simulations. This very powerful process and device simulation tool has previously been used by Gonella, but is not yet implemented in Birmingham.

One technology we propose to start with is the HR-CMOS variant of the TPSCo 180 nm process used for the state-of-the-art ALPIDE MAPS detectors being developed by ALICE. We are currently working with TPSCo together with colleagues from RAL and Sussex University on the design of radiation-hard, reconfigurable MAPS detectors for outer tracking and digital electromagnetic calorimeters. Within this activity we plan the submission of a multi-project manufacturing run to produce arrays of different pixel flavours with separated collection electrode and electronics, which we will characterise with the aim of achieving low noise and low power through a reduced sensor capacitance. In particular, we will purse a novel development fro RAL, in collaboration with TPSCo, with the diode junction on the backside of the sensor. This can allow full depletion while potentially achieving lower input capacitance with respect to the ALPIDE chip design that is used by ALICE.

One benefit of using TPSCo is that their portfolio of technologies already includes a 65 nm node and due to their scale, further reductions in feature size should be anticipated, allowing reduced pixel size, potentially lower power consumption and more in-pixel functionality. Moving to this smaller technology node would become part of the project at a later stage, beyond the first year.

In addition to the TPSCo technology we have access through our membership of the CERN RD50 collaboration to the L-Foundry 150 nm technology process [12], including design capability. The L-Foundry technology is currently being actively pursued as a candidate for a monolithic pixel sensor for the outer layers of the ATLAS pixel detector at the HL-LHC. This technology offers advantages in terms of design options, and comes at a lower cost with respect to alternative technologies investigated for particle physics experiments. For instance, it allows structures to be designed with large collection electrodes containing the electronics, which is not possible with the TPSCo process. While this configuration has an increased input capacitance with respect to that implemented in the TPSCo process, it has the benefit of larger collected charge and, thus, larger signal. The high resistivity substrate (~ 2 kΩcm) coupled with the possibility of applying bias voltage up to ~ 100 V allows development of depleted MAPS where charge is collected by drift in a large depleted volume. The RD50 collaboration is organising a multilayer mask submission in the second half of 2016. Should the funding be available for us to include arrays of suitable designs with different pixel flavours and dimensions in this submission, it would allow us to obtain test structures and MAPS prototypes targeting EIC specifications.

When devices become available, initial characterisation of the structures will take place within the BILPA facility and results compared with TCAD simulations. Beyond the first year, prototypes from both technologies would also be tested to assess charge collection efficiency for minimum ionising particles using our ^{90}Sr β source set-up. In particular, we propose to assess the relative benefits of either low noise, achieved via small input capacitance, or large collected signal, achieved with a large depletion volume, by measuring the resultant signal-to-noise ratio. Tests would also be carried out before and after irradiation at the Birmingham MC40 cyclotron. Studies performed elsewhere [13] have placed the total maximum irradiation fluence at EIC at the level of 10^{10} 1 MeV neutron equivalents per cm^2 per year. Whilst sensor performance degradation is not expected to be significant at the EIC due to the low fluence predicted by simulation, particular emphasis will be placed on the total ionising dose (TID) and its effect on the electronic circuits within the MAPS. This has been shown to be important at relatively low TID values (below a few Mrad) [14], long before bulk damage effects become an issue. TID effects have been observed with the ATLAS Insertable B Layer, which resulted in significant changes in transistor currents leading to increased power consumption. Such an effect potentially requires additional material to achieve adequate cooling. Since cooling, supports and electrical services tend to dominate the material budget and hence multiple scattering limitations, understanding these effects will be key to an optimal vertex detector design for the EIC.

Finally, to fully exploit the potential of CMOS technologies for thin pixel detectors with high spatial resolution, we also propose to work on the conceptual development of a low mass powering scheme. Based on serial powering expertise available within the group [15], we will look into a current based powering scheme, similar to that now proposed as the baseline for the vertex detectors of ATLAS and CMS at the HL-LHC.

WP2: Silicon Detector Layout Investigations (Jones, Newman)

Work package 2 consists of a basic evaluation of the optimisation of the requirements for a central silicon detector at an EIC, by developing the Geant4 simulations of the detector in both the eRHIC and MEIC contexts.

In the Geant4 model of the BeAST detector concept for the EIC, the central silicon detector is based upon the ALICE ITS [13]. Being a MAPS based detector, already optimised to the requirements of a collider environment, this is an excellent starting point. However, the requirements of the EIC are likely to differ due to the different physics programme, in particular the lower overall multiplicity of tracks per event and the need for a greater emphasis on detecting and measuring single isolated tracks at large transverse momentum, corresponding for example to the scattered electron in high Q^2 neutral current events. The programme of work in WP2 will include investigating the sensitivity of the tracker response and performance in the EIC physics context to changes in the pixel dimensions ($28 \times 28\ \mu$m^2 in the ALICE ITS), signal-to-noise, or reductions in the material budget ($0.3X_0$ per layer in the ITS).

In all cases, the question to be addressed is what is the optimal balance between detector specification and resource requirements, in light of single particle performance and heavy flavour identification, informed by the physics studies described in WP3 and the technology issues of WP1. Compatibility with the outer tracking detector capability is clearly a key issue in this context. The figures of merit on which to judge the performance include the single hit resolution, the isolated charged particle p_T resolution for scattered electrons and the resolution on the distance of closest approach (DCA) to the primary vertex of secondary tracks from heavy flavour decays in hadronic jets seeded by charm and beauty quarks. The specific questions to be addressed in the initial stages of the project include the following.

- How many layers should there be and at what radii?
- What is the optimal layout of the pixels on modules and modules on the detector?
- At what point does multiple scattering in dead material, rather than the pixel sensitive volume, limit the precision.

These questions will be answered to a large extent by 'single particle gun' simulations over a suitable range of polar angles and energies with variations in the basic detector design as implemented in Geant4. For isolated tracks, this is straightforward. For secondary vertexing studies, an interface to jets fragmented and hadronised using PYTHIA will be required.

A further important question is what fluence to expect the detectors to be exposed to during their lifetimes and to what extent radiation hardness considerations are important for the detector and readout questions in WP1. This is not expected to pose any serious problems with the proposed detector technologies, though the effect of the total ionising dose on the embedded electronics may be more of an issue. Since these questions require a different set of simulations, there are no plans to approach them in the first year.

WP3: Physics Performance Evaluation (Newman, Jones)

First studies of the charm production capabilities of an EIC have been made [5, 16]. These give indications of the kinematic range over which the charm cross section can be measured and show that statistical limitations are not a major concern assuming anticipated luminosities and run times. However, to date, there have been no detailed evaluations of the performance of the EIC for heavy flavour production at the level of full simulations of a detector, with corresponding systematics. The situation is similar for inclusive neutral current measurements at large Q^2.

The programme of Work Package 3 consists of a more detailed investigation of the performance of EIC central tracking, including the silicon detector model being developed in WP2. We propose to concentrate initially on the $e+$A programme, though a further set of investigations of polarised $e+p$ could be included later. The physics observables to be studied include:

- Cross sections for identified charmed mesons D^0, $D^\pm$ and $D^{*\pm}$ in photoproduction and DIS
- Beauty and charm cross sections at $Q^2 \to 0$ from secondary vertex studies in samples of photoproduced jets, including separation of light quark backgrounds.
- Extractions of the beauty ($F_2^{b\bar{b}}$) and charm ($F_2^{c\bar{c}}$) contributions to the generalised structure function F_2 for nuclei and corresponding nuclear modification ratio from inclusive secondary vertex distributions in DIS.
- Inclusive neutral current DIS at large Q^2 and corresponding nuclear modification ratio.

Suitable event generators with which to approach the study include PYTHIA for heavy flavour photoproduction, RAPGAP for heavy flavour electroproduction and DJANGOH or RAPGAP for inclusive high Q^2

DIS simulations. All of these generators have been used extensively in similar studies at HERA. Whilst not all are yet interfaced to nuclear PDFs, initial studies can be performed in $e+p$ mode, since the final states produced in the central region in hard scattering processes are very similar in $e+p$ and $e+$A and cross sections scale with $e+$A to first approximation. In the later stages of the programme, where the focus is on nuclear modification factors, work may have to be invested in interfacing the generators to the nuclear PDFs which are currently on the market [17, 18].

Once benchmarked, the generators will be interfaced to the Geant4 detector simulations discussed in the context of WP2 in order to study the EIC capabilities with realistic simulations of systematic effects. Where possible (more likely to be the case for the isolated high Q^2 scattered electrons than the heavy flavour studies), the EIC-SMEAR fast-simulation may be sufficient and would save substantially on CPU time. This fast simulation may also be a necessary ingredient of the secondary vertexing studies in order to obtain adequate statistics on the light quark component for realistic background estimates.

The full long-term aim of the studies in WP3 consist of the following.

- Compare truth particle level outputs from different generators and decide on one or more to take forward per process.
- Interface to Geant4 EIC simulations and EIC-SMEAR where possible, and generate simulated data samples.
- Use standard analysis tools, similar to those employed at HERA, to obtain pseudodata on the proposed physics observables.
- Use standard (QCD DGLAP) fitting tools with the pseudodata as input in order to evaluate the corresponding sensitivity to the nuclear gluon density.

All of the above would be iterated in combination with the ongoing programme in WP2. Whilst this represents a programme extending beyond an initial one year study, it factorises sufficiently into smaller tasks for valuable results to be obtained within one year. Initial target results will be the expected resolutions on basic quantities such as the width of the D^* and D meson peaks obtained from direct reconstruction, as well as the efficiency and background rejection power of secondary vertex selections as a function of the choice of DCA cut.

Synergies

This proposal has a strong synergy with the ongoing R&D project investigating the possible use of MAPS for forward and backward tracking (eRD16) and with ongoing investigations of the sensitivity of heavy flavour observables to the nuclear gluon density at relatively large Bjorken-x (LDRD Project LD1601). This work will also benefit from, and contribute to, the Geant4 detector simulations that currently exist for the two detector concepts. We look forward to the possibility of collaborating with existing R&D efforts and simulation efforts and sharing our resources wherever possible.

Timeline and Deliverables

Foundry runs are already planned or anticipated for submission during the second half of 2016. Some thought is being given to the type of structures that might be most relevant for an initial EIC sensor study.

These first structures are expected to be available for testing from mid-2017. Initial testing of these first prototype sensors will begin in the second half of 2017, starting with electrical characterisation using the probe-station facilities within BILPA. We will perform TCAD simulations to predict the expected performance of the sensors in advance of their initial characterisation. In the first half of 2017 we will develop a readout system for the sensors to subsequently allow measurements of signal-to-noise with minimum ionising particles. Based on the predicted position resolution that could be achievable, we will modify the existing Geant4 detector models to begin an optimisation study of the tracker itself, exploring the number of layers, layer radii and ladder length. Setting up the basic software environments required for WP2 and WP3 can begin from the start of the project.

In an initial 1 year programme, we anticipate that the relative emphasis will be on WP1 (45%), WP2 (35%) and WP3 (20%). Should follow-on funding become available, either through the current scheme, or by leveraging resources from other funding streams, our plan will be to fully characterise the sensor properties, before and after irradiation, together with developing an increasingly mature concept for the central tracker, including support materials and services.

To summarise, the key deliverables in the first year of R&D are as follows:

- WP1: Specification and submission of prototypes and test structures in TPSCo and L-Foundry
- WP1: TCAD simulations to optimise pixel geometry and aspect ratio
- WP1: Initial characterisation of the sensor properties and associated electronics
- WP2: Study of track momentum resolution and impact parameter resolution with different assumptions on spatial resolution of the pixel hits and number of tracking layers.
- WP3: Benchmark $e+p$ or $e+$A Monte Carlo models for heavy flavour processes and interface to EIC simulations for first studies of D^* and secondary vertex signatures.

Personnel

The proponents combine a wide range of skills and experience in silicon detector technology, detector simulations, nuclear physics and deep inelastic scattering, which is very well matched to the requirements of the proposed programme.

Prof Phil Allport joined the University of Birmingham in 2014 to take up the post of director of the newly created Birmingham Instrumentation Laboratory for Particle Physics and its Applications. He previously ran a similar laboratory in Liverpool, as well as being the ATLAS Upgrade Coordinator 2011-15. He leads the Birmingham RD50 group and is the AIDA-2020 Transnational Access contact for the MC40 cyclotron.

Dr Laura Gonella is a lecturer in silicon detector technologies, with particular expertise in CMOS pixel sensors. She joined the University of Birmingham in 2015, having previously been assistant professor in Bonn. She currently co-leads the ATLAS ITK Strip Tracker Upgrade ASICs group.

Prof Peter Jones is the leader of the Birmingham Nuclear Physics Research Group. He has extensive experience of experiments involving relativistic heavy ion collisions as a member of the STAR collaboration (Strangeness Working Group Convenor 1996-2001) and ALICE collaborations (Editorial Board member 2015-present).

Prof Paul Newman is the leader of the Birmingham Particle Physics Research Group. He has extensive experience of experiments in Deep Inelastic Scattering as a member of the H1 Collaboration (Physics Coordinator 2001-4) and the LHeC Study Group (Coordination Group and Low-x Working Group Convener).

Request for Resources

Wherever possible, existing Birmingham resources will be devoted to the project. These include computing resources, consumables and access to the MC40 cyclotron for early-stage irradiation work. It also includes access to test structures from an already planned TPSCo foundry run. Furthermore, the University of Birmingham School of Physics has committed to devote a PhD studentship to the project with a start date in the financial year 2016-17. The proponents will also devote a certain fraction of their time without charge to the project (Allport (0.05 FTE), Gonella (0.2 FTE), Jones (0.1 FTE) and Newman (0.1 FTE)). To carry out the work contained in this proposal we are requesting the support of a full-time postdoc (1 FTE). The postdoc will be involved primarily in WP1 and WP2, sharing their time equally between carrying out sensor tests and layout simulations. The requested funding therefore amounts to the following:

- One full-time postdoc, approximately £103k, including overheads.
- Travel to and from UK partners (RAL) £1k.
- Travel to and from the US to attend EIC meetings £6k.
- Licenses for TCAD (two plus maintenance) £1k.
- Contribution to 2016 RD50 L-Foundry run £4k.

In total the 2016-17 requirement is thus approximately £115k, or equivalently $163k at current exchange rates.

References

[1] P. Newman and M. Wing, Rev. Mod. Phys. **86** (2014) no.3, 1037 doi:10.1103/RevModPhys.86.1037 [arXiv:1308.3368 [hep-ex]].

[2] H. Abramowicz *et al.* [H1 and ZEUS Collaborations], JHEP **1509** (2015) 149 doi:10.1007/JHEP09(2015)149 [arXiv:1503.06042 [hep-ex]].

[3] F. D. Aaron *et al.* [H1 Collaboration], Eur. Phys. J. C **65** (2010) 89 doi:10.1140/epjc/s10052-009-1190-0 [arXiv:0907.2643 [hep-ex]].

[4] P. Newman and A. Stasto, Nature Physics **9** (2013) 448.

[5] A. Accardi *et al.*, arXiv:1212.1701 [nucl-ex].

[6] C. Adolph *et al.* [COMPASS Collaboration], Phys. Rev. D **87** (2013) no.5, 052018 doi:10.1103/PhysRevD.87.052018 [arXiv:1211.6849 [hep-ex]].

[7] P.P Allport *et al.*, "Results with p-type pixel sensors with different geometries for the HL-LHC", Nucl.Instrum.Meth. A731 (2013) 216-218, DOI: 10.1016/j.nima.2013.03.034

[8] P.P Allport *et al.*, "Performance of P-type micro-strip detectors after irradiation to 7.5 x 10^{15} p cm^{-2} ", IEEE Trans. Nucl. Sci. 52 (2005) 1903-1906, DOI: 10.1109/TNS.2005.856747

[9] R. Turchetta *et al.*, "Monolithic active pixel sensors (MAPS) in a VLSI CMOS technology" Nucl. Instrum. Meth. A501 (2003) 251-259 DOI: 10.1016/S0168-9002(02)02043-0

[10] M. Barbero, *et al.*, "The FE-I4 pixel readout chip and the IBL module, Proceedings of Science", PoS (Vertex 2011), 038

[11] M. Backhaus on behalf of the ATLAS CMOS pixel collaboration, "Radiation-hard active CMOS pixel sensors for the HL-LHC detector upgrades", 2015 JINST 10 C02031

[12] P. Rymaszewski *et al.*, JINST **11** (2016) no.02, C02045 doi:10.1088/1748-0221/11/02/C02045 [arXiv:1601.00459 [physics.ins-det]].

[13] A. Kiselev, "BeAST Detector (Brookhaven eA Solenoidal Tracker)", Presentation at the EIC User Group Meeting, Berkeley, January 2016.

[14] L. Gonella *et al.*, Nucl. Instrum. Meth. A **582** (2007) 750. doi:10.1016/j.nima.2007.07.068

[15] L. Gonella, “Low mass hybrid pixel detectors for the high luminosity LHC upgrade”, PhD thesis, Universitäts- und Landesbibliothek Bonn, November 2013.

[16] Christian Weiss *et al.*, Wiki of JLab LDRD Project LD1601 "Nuclear gluons with charm at EIC".

[17] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP **0904** (2009) 065 doi:10.1088/1126-6708/2009/04/065 [arXiv:0902.4154 [hep-ph]].

[18] K. Kovarik *et al.*, Phys. Rev. D **93** (2016) no.8, 085037 doi:10.1103/PhysRevD.93.085037 [arXiv:1509.00792 [hep-ph]].