Forward/Backward Tracking at EIC using MAPS Detectors

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Abstract:

We propose to develop a concept for a backward (electron-going direction) tracking station near the collision vertex. We focus on detection of the scattered electron, as the precision of this measurement defines the kinematics of the collision. Disks of thinned-silicon sensors (MAPS) detectors will be laid out, including conceptual design for the arrangement of services, including cooling, power, and readout. We will perform simulations to specify layout and sensors optimized for high priority early physics measurements, and eventually determine whether a copy of the same tracker should be used in the hadron-going direction. We will also perform R&D on low-mass cabling utilizing aluminum traces.

I. Introduction

The US Nuclear physics program plans to build an Electron Ion Collider to study the gluonic structure of nucleons and nuclei. The facility will be built at Brookhaven National Laboratory as an upgrade to the Relativistic Heavy Ion Collider accelerator or at the Thomas Jefferson National Accelerator Laboratory as an upgrade to the CEBAF facility. The Electron Ion Collider is scheduled to be online in the 2025 to 2030 time frame and the Relativistic Nuclear Collisions program (RNC) at LBL is preparing to take a leading role in doing the science at this facility. In this proposal, we propose to develop key instrumentation for an EIC detector and we are requesting seed money to initiate the program. In particular, we propose to build upon our past experience in constructing Silicon vertex trackers for RHIC and the LHC and we will design the next generation Si tracker for use at forward, and backward angles at the EIC.

We focus on detection of the scattered electron, as the precision of this measurement sets the precision with which the kinematics of the collision can be determined for all physics observables. Disks of thinned Monolithic Active Pixel Sensors (MAPS) are an attractive technology, providing excellent position resolution while minimizing multiple scattering. We consider the proposed research below to be a first step in developing silicon detectors for an EIC experiment. Subsequent studies will determine whether an identical silicon tracker is appropriate for the hadron-going direction and optimize a barrel microvertex tracker for heavy flavor measurements at central rapidity. We envision future production of prototype sensor modules and beam tests with candidate readout electronics.

Several concepts for an EIC detector exist at this time. There are three designs [1-3] for eRHIC detectors, and one for MEIC. We will initially focus on the eRHIC detectors in this proposal, as the larger $\sqrt{s}$ implies more stringent tracking requirements for the scattered electron. The eRHIC detector concepts envision solenoidal magnetic fields in the range of 0.5 to 3 T. These utilize three possible magnets: the STAR solenoid with a field of 0.5T, the BaBar solenoid with a field of 1.5T, and a new solenoid with a field of 3T. Consequently, the tracking requirements differ, and indeed the concepts currently rely upon different technologies for forward/backward tracking.

As the precision of measuring the scattered electron is key for determining the event kinematics, high tracking precision is necessary, so we propose to develop conceptual designs using multiple layers of silicon pixel sensors. As multiple scattering and bremsstrahlung limit the precision with which the electron's momentum and direction can be measured, thinned silicon is of great interest.

LBNL has experience with the design, construction, and operation of a monolithic active pixel (MAPS) based silicon tracker, having recently completed the Heavy Flavor Tracker (HFT) for STAR. Data analysis is underway to characterize the detector performance and produce physics results this year. Thus, the LBNL Relativistic Nuclear Collisions (RNC) group is well-equipped to consider such a tracker for the EIC. Furthermore, we have just undertaken R&D for the ALICE inner tracker upgrade. We will construct the middle layers of this detector at

LBNL beginning in FY16; this activity involves design of the mechanics, cooling, cabling, as well as assembly and testing. Thus we very interested in – and have the relevant expertise for - designing a subsequent generation detector.

It should be noted that both the STAR and ALICE trackers utilize thinned silicon sensors designed at Strasbourg and CERN, respectively. Both trackers are barrel trackers covering pseudorapidity of approximately $-1 < \eta < 1$. Consequently, those designs are not directly applicable to a forward tracker with a disk geometry. The ALICE Muon Forward Tracker consists of MAPS disks[4]. However this design is not optimized for the EIC detector. Furthermore, it includes a significant amount of material in the cooling plate, and it should be possible to optimize it for electron measurements. Since the technology is rapidly advancing, the EIC detector should take advantage of anticipated improvements in sensor architecture, robustness against radiation damage, and readout speed.

Physics Observables and resulting requirements on tracking the scattered electron

The 2012 EIC whitepaper [5] identifies in its executive summary "the most intellectually pressing questions that an EIC will address that relate to our detailed and fundamental understanding of QCD in this frontier environment" as:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?
- Where does the saturation of gluon densities set in? Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

The whitepaper then continues to describe key inclusive, semi-inclusive, and exclusive differential cross-section (asymmetry) measurements over broad kinematic ranges to address these questions.

Measurement of the inclusive differential deep-inelastic scattering cross-sections, for example, relies crucially on the determination of the inelasticity y and of the Bjorken-x and Q^2 invariants in the corresponding inclusive structure functions $F_2(x,Q^2)$, $F_L(x,Q^2)$, and $g_1(x,Q^2)$. Precision insights in the nuclear gluon distributions and the helicity distribution of gluons in the polarized nucleon is obtained through perturbative QCD analyses, which rely on data over a broad kinematic range in (x, Q^2) and, in particular, a range of scales, Q^2, at any given Bjorken-x.

Bjorken-x and Q^2 in deep-inelastic scattering processes can be reconstructed by measurement of the scattered electron, by measurement of the struck quark after hadronization (current jet), or by a combination of the leptonic and hadronic observables [6]. By (HERA) convention, the scattering angles are expressed with respect to direction of the *hadron* beam.

The scattering region along the direction of the *electron* beam, that is, *large*-angle electron scattering in the above convention, is of particular scientific interest. Specifically, this region gives access to the gluon-dense environment at small-x, through leptonic and hadronic observables with energies below the *electron* beam-energy. Tracking in this region serves both leptonic and hadronic momentum measurement and imposes significant challenges in the solenoidal fields that are under consideration. The momentum measurement, together with the energy measurement with electromagnetic calorimetry, is key to the identification of the scattered electron through measurement of E/p. Unobserved losses of the scattered electron's energy, e.g. bremsstrahlung, introduce a bias in Bjorken-x, typically towards smaller values. The above combined point to a need to develop a well-integrated, low-mass tracker.

The scattering region along the direction of the *hadron* beam is of considerable scientific interest as well. Here, new insights are anticipated for example in the partonic energy-loss mechanism(s) in cold nuclear matter. The observation of identified charmed hadrons in semi-inclusive processes would be qualitatively new and is likely to require topological reconstruction with a precision tracker.

Position and momentum resolution for the scattered electron

For inclusive and semi-inclusive deep inelastic scattering, we need collisions of at least $\sqrt{s} = 50$ GeV in order to reach x down to 10^{-3}, where gluons and sea quarks dominate the parton distributions. The same is true for measurement of azimuthal asymmetries and exclusive properties.

The scattered lepton must be measured in a wide rapidity range of up to $|\eta| < 4$. The silicon disk trackers must therefore cover a region of large (absolute) η. The scattered lepton must be measured with high survival probability and be separated from hadrons and photons with high purity in each x-Q^2 bin. Electron identification is a second driver of the resolution required.

Of the eRHIC detectors, the current BeAST concept incorporates (idealized) silicon tracking in both the central and forward regions. The momentum resolution specified from simulations by the BEAST experiment using the 3 T solenoid is $\delta p/p = 1\%$ for electrons up to momenta of 10 GeV/c and $-2 < \eta < -1$, with the resolution requirement relaxing to approximately 2% as η approaches -3 [3,7]. Semi-inclusive DIS measurements require a momentum resolution for the hadrons better than 3% at $1 < \eta < 3$. We will adopt these as baseline specifications and will investigate implications for realistic silicon disk trackers also with the alternative fields and geometries of the other design concepts.

The detector concept based upon the BaBar magnet includes tracking over the range $-3 < \eta < 4$. That concept envisions an $r\Delta\phi$ resolution of 50 μm for $-3 < \eta < -2$, based upon GEM trackers [2], yielding momentum resolution $\Delta p/p < 5\%$ for tracks of $p < 4$ GeV/c and $-3 < \eta < -1$. Precision measurement of the electron using calorimetric measurement of the scattered electron polar angle is envisioned. We will study what is achievable with a realistic silicon disk tracker and the BaBar magnetic field, and evaluate how the physics goals and EMCal specifications would be affected.

The goals of e-A collisions also require precise measurement of the scattered electron to fix the kinematics. While there are many theoretical papers laying out the physics case for e-A, the experimental requirements are less well developed. We will initially utilize the requirements for e-p to specify the sensor and readout. However, we will also conduct further research into requirements for e-A observables.

The LBNL group is interested in coherent vector meson electro-production in e-A collisions $e+A \rightarrow e + V + A$, where V is a ρ, ρ' ω, ϕ J/ψ or other vector meson. These collisions can be used to probe the gluonic structure of nuclei, by measuring the form factors of the nuclear targets at small or moderate momentum transfers where saturation effects may be expected. Since the vector meson final state is typically two charged particles (i.e. $\phi \rightarrow K^+K^-$), the final state reconstruction is rather straightforward. The main tracking challenge is to maximize the acceptance to cover the widest possible range in Q^2 and y. For low Q^2 (i.e. photoproduction), y effectively gives the photon energy.

The challenge comes at low y and Q^2, where the electron loses relatively little energy, and is only slightly deflected. This region is of particular interest because it includes the transition between high energies, where vector meson electro- and photo-production are dominated by Pomeron exchange to the lower-energy regime where meson exchange dominates. The crossover is clearly identifiable because it corresponds to a minimum in the cross-section, occurring around (for nearly-real photons) photon energies of 10 GeV in the target frame.

The kinematics of the process determines the tracking system requirements. Here, we focus on the low-energy photon emission. For photoproduction, $Q^2 \sim 0$, at eRHIC with 20 GeV electron beams on 100 GeV/nucleon gold beams, an electron can emit a photon with a lab frame energy of 100 MeV (0.5% of its energy). This is equivalent to a 20 GeV photon in the ion rest frame, i.e. a bit above the Jlab energy range. Such a process produces a J/ψ at a rapidity of -1.2, well within the acceptance of any planned detector. The challenge is to determine the Q^2 of the photon. A key goal of this proposal is to determine how far in the forward region we can track these electrons, and then to determine the range of coverage in y and Q^2.

II. R&D Goals for this Proposal

Sensor specifications

Developing a concept for the electron-going direction forward silicon tracker requires translating the physics requirements into sensor specifications. We will do this by building upon the existing simulation studies, using simulation tools which were developed at BNL.

The ALICE ITS upgrade is expected to use the next generation of MAPS sensors developed at CERN, namely the ALPIDE sensor [4]. This defines the starting point for the following generation of MAPS sensors; the first step in this project will be to determine the extent to which the ALPIDE sensor already addresses the EIC needs.

The ALPIDE sensors have the following characteristics:

Pixel pitch	28μm x 28μm
Integration time	8-10 μs
Power consumption	39mW/cm^2
Dead area	1.1mm x 30mm
Dimensions	15mm x 30mm

The above represents the current state-of-the-art for MAPS sensor design. The ALPIDE sensors will be thinned to 50μm thickness and combined into ladder structures (9 sensors in length) that have a radiation length X/X_0 = 0.3% for ALICE.

The detailed tracking requirements for the pointing resolution required for physics using forward angle discs at an EIC detector will be determined from the resolution requirements summarized above and GEANT simulations of the ALPIDE response. Should the ALPIDE sensors prove not to meet the necessary requirements, we will specify the areas for sensor design improvement and develop a plan for achieving the necessary sensor modifications.

An initial study was already made in [7], for a 3T solenoid of 2m length and 1.2 m radius. These simulated hadron tracking, and showed that with a 30 micron pixel size, $\delta p/p$ = 2 - 5% for sub 1 GeV/c to 50 GeV/c pions. We will study this further, for a realistic array of current-generation ALPIDE sensors, to determine whether the momentum resolution is sufficient or whether a different pixel granularity will be required. Higher granularity would imply increased data rate, while any change drives a new sensor design. For the scattered electron, the required tracking resolution depends on the magnetic field but also the resolution of the electromagnetic calorimeter behind the tracker. We aim to provide several specifications based on simulations with the two magnets and reasonable expectations for electromagnetic calorimetry in the EIC era. It is quite possible that initial running may utilize an existing EMCAL, so it is crucial that the tracking be optimized for such a possibility.

As the BaBar magnet-based concept current assumes GEM tracking, the first step is to evaluate the performance with the current-generation ALPIDE pixel geometry and the forward field from the 1.5T solenoid. This will inform possible tradeoffs between pixel size, disk location, and EMCAL requirements.

Readout rate

We will use the anticipated EIC luminosities envisioned for first generation colliders eRHIC and eLIC to evaluate the tracker readout speed required. For example, simulations with PYTHIA 6 show that e-p collisions at 10 x 250 GeV produce approximately 0.3 charged particle per event per unit rapidity at mid-rapidity [7]. The multiplicity is just below 1 particle per unit rapidity one at $\eta \sim 3$ (the hadron-going direction). At negative rapidity, in the electron beam direction, the multiplicities are lower. Increasing the electron beam energy to 20 GeV increases the multiplicity by less than a factor of two at mid-rapidity. Clearly, the particle multiplicity per event does not drive detector granularity in such collisions. For collisions of electrons with heavy nuclei, such as Pb or Au, studies show a multiplicity increase by a factor of approximately 2 [7]. Even if the increase is larger than that, the sensor specifications are also not multiplicity driven in e-A collisions.

A luminosity of 10^{33} cm^{-2} s^{-1} translates to particle rates of 8 x 10^3 and 2.5 x 10^4 per unit η and ϕ per second, at η = 0 and 3, respectively for 10 x 250 GeV e-p collisions. The total photon-proton cross section is ~0.1mb, nearly independent of $\sqrt{s}$ in the EIC range. At an instantaneous luminosity of 10^{33} cm^{-2} s^{-1} this implies a total interaction rate of 100kHz. Acceptance reduces this by a factor that will need to be quantified. However, as the EIC detector is envisioned to have a large acceptance, and there will be a variety of triggers, the readout rate for the tracker will not be low. We will evaluate the capabilities of current sensors and readout schemes and define developments that will be required for the EIC.

Conceptual design of forward tracking disks and services

The necessary infrastructure for making the ALPIDE silicon sensors into a complete detector system is already under development by ALICE. A complete readout system employing continuous readout of the sensors will be ready to deploy in the 2018 timeframe. Similarly, a liquid based cooling system and low mass mechanics are also under development. This work leads to a complete set of infrastructure for low mass linear arrays of sensors to be read out, cooled and positioned with stability and accuracy. With these building blocks, a disk tracker system involving potentially overlapping linear arrays of sensors in a low mass mechanical structure can be envisioned. Such structures need to be simulated and optimized for the EIC environment. We propose to initiate this work.

The deliverable in one year will be a conceptual design of a forward tracker, based upon simulations with two different magnetic field and central barrel configurations.

Development of low mass cables

An integral part of low radiation length detectors is the use of aluminum conductors in the infrastructure for the readout of signals and the delivery of power. Whilst it is highly desirable to use aluminum conductor technology, the fabrication of aluminum printed circuit board technology is not readily available in industry. The use of aluminum conductor in flex PCBs is not part of the standard PCB process. Thus, the highly optimized processes for the etching of traces and the electrochemical metallization of vias that is employed for copper based PCBs is unavailable for aluminum conductor. There is no commercial purpose for industry to spend

the effort and money to develop and refine these processes, as the customer base would likely be limited to specialty uses such as high energy and nuclear physics experiments. At this point we are aware of only two moderately reliable sources of such PCBs. One is the CERN PCB shop and the other is Kharkov in Ukraine. While both offer the technology, their capabilities are different and production capacity is limited. There is a strong need in the community for another source of aluminum conductor flex PCBs.

We propose to undertake a collaboration with industry, specifically Hughes Corporation, and attempt to develop a commercial option for aluminum conductor flex PCBs to supplement the CERN and Kharkov options. The development will concentrate on the two main issues with using aluminum as a conductor: the development of electrochemically plated through vias (CERN uses primarily vacuum deposition to metalize the vias) and the refinement of the etching process to allow for fine pitch traces. We have had some initial successes with Hughes in the STAR Pixel detector development and believe that pursuing this collaboration will potentially be beneficial for the EIC detectors as well as for the community at large.

The development process will be iterative. We will define sample flex PCB designs to demonstrate capability, and work with the vendor(s) to establish processes for progress toward meeting the design requirements. This will require procurement of test parts from the vendor. The cost, given the new processes to be developed, will be significantly higher than copper based PCBs. It is estimated that approximately $5k/PCB run can be expected and that we would need of order 4 PCB fabrication runs to demonstrate progress. This leads to a request of $20k.

Simulations

The proposed simulations studies will build upon the extensive work documented in [7] and the simulation results described in presentations by Alexander Kiselev, among others. We plan to utilize the existing simulation tools from BNL to evaluate the performance of realistic forward/backward tracker stations, including the cabling and other infrastructure layout. This will involve learning the toolkit, modeling the sensor and electronics response and simulating the multiple scattering in all detector materials. The LBNL group has considerable experience in such modeling, including handling multiple collisions recorded within the read-out period of the sensors. We will build upon the very successful HFT simulation software.

We envision performing several simulations with one (or more, if one size doesn't fit all) trackers in order to respect the boundary conditions set by the different magnet, barrel, and endcap detector concepts. We expect our studies to primarily utilize PYTHIA, but we will also investigate the extension of the Starlight event generator for e-A collisions in order to study performance for coherent vector meson production.

Lastly, it will be important to investigate to what extent the forward/backward tracker concept interacts with IR design. Though it is not clear whether we will be able to do that as part of the initial R&D work, we will keep in mind the need to make relevant information accessible to the machine designers.

III. Funding request

0.5 postdoc FTE; to work on R&D for sensor, services layout, and low-mass cable
0.25 postdoc FTE; to work on simulations
$20K for cable prototyping
5 trips at $1200/trip; to enable postdocs to attend workshops and learn how to use the EIC simulation tools developed at BNL

cost, including LBNL overheads:

75% postdoc (for 1 year)	$126,850
M&S	$25,844
Travel	$7,803
Total	$160,497

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