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J. H. Lee

T. Sako

K. Tanida

M. Murray

Q. Wang

See next page for additional authors

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Authors

J. H. Lee, T. Sako, K. Tanida, M. Murray, Q. Wang, N. Nickel, Y. Yamazaki, Y. Itow, H. Menjo, T. Shibata, C. E. Hyde, V. Baturin, Y. Goto, I. Nakagawa, R. Seidl, K. Kawade, A. Deshpande, B. Schmookler, K. Nakano, T. Chujo, and Y. Miyachi

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J. H. Lee
Brookhaven National Laboratory, Upton, NY 11973, USA
T. Sako
Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan
K. Tanida
Japan Atomic Energy Agency, Tokai-mura, Ibaraki 319-1195, Japan
M. Murray, Q. Wang, and N. Nickel
University of Kansas, Lawrence, KS 66045, USA
Y. Yamazaki
Kobe University, Kobe, Hyogo, Japan
Y. Itow, and H. Menjo
Nagoya University, Nagoya, Aichi, Japan
T. Shibata
Nihon University, Tokyo, Japan
C. E. Hyde, V. Baturin*
Old Dominion University, Norfolk, VA 23529, USA
Y. Goto, I. Nakagawa, and R. Seidl
RIKEN Nishina Center, Hirosawa, Wako, Saitama 351-0198, Japan
K. Kawade
Shinshu University, Nagano, Japan
A. Deshpande†,*, and B. Schmookler*
Stony Brook University, SUNY, Stony Brook, New York 11794-3800, USA
K. Nakano
Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
T. Chujo
Tsukuba University, Tsukuba, Ibaraki 305, Japan
Y. Miyachi
Yamagata University, Yamagata, Japan

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* also *Center for Frontiers in Nuclear Science, SUNY, Stony Brook NY 11794*

† also *Brookhaven National Laboratory, Upton, NY 11973, USA*

Principal Investigators: Yuji Goto and Michael Murray

Contact Persons: Yuji Goto and Michael Murray

Abstract

The Electron Ion Collider offers the opportunity to make un-paralleled multidimensional measurements of the spin structure of the proton and nuclei, as well as a study of the onset of partonic saturation at small Bjorken-x [1]. An important requirement of the physics program is the tagging of spectator neutrons and the identification of forward photons. We propose to design and build a Zero Degree Calorimeter, or ZDC, to measure photons and neutrons with excellent energy & position resolution.

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1 Motivation for the research

We propose to design a high-resolution position-sensitive Zero Degree Calorimeter, ZDC, to measure neutrons and photons at the EIC. The ZDCs will serve critical roles for a number of important physics topics, such as distinguishing between coherent diffractive scattering in which the nucleus remains intact and incoherent scattering in which the nucleus breaks up; measuring geometry of $e + A$ collisions, spectator tagging in $e + d/^{3}He$, asymmetries of leading baryons, and spectroscopy. These physics goals require that the ZDCs have

- high efficiency for neutrons and for low-energy photons
- excellent energy, p_T and position resolution
- large acceptance
- sufficient radiation hardness

1.1 Layout of the Forward Region

Figure 1 shows the forward detectors on the hadron going side of the interaction region. An active transverse space of 60 cm square, with a depth of ≥ 2 m is available for the ZDC, with additional transverse space for shower containment. This depth should allow about six to ten interaction lengths of tungsten calorimetry to be installed which will provide excellent longitudinal containment of the showers from incoming neutrons. We will develop ZDCs that along with the B0 tracker, Roman Pots, & the Off Energy Detectors, OED, form an integrated forward system for characterizing electron ion collisions.

Much of the infrastructure for design and simulation has already been developed by Jefferson Lab and BNL personnel [2].This framework, along with basic parametrizations of estimated detector performance is currently being used for preparing the EIC Yellow Report. This proposal seeks to develop a realistic detector configuration that can actually deliver the performance needed for the EIC physics goals.

1.2 Technologies

1.2.1 Review of Calorimetry

There are several possible approaches to achieve high energy and position resolution in an electromagnetic calorimeter. As an example, the ALICE FoCal [3], is silicon-tungsten (Si+W) sampling calorimeter with longitudinal segmentation. Low granularity layers are used for the energy measurement while higher granularity layers provide accurate position information. A schematic of FoCal is shown in Fig. 2.

From simulations the photon energy resolution for FoCal is estimated to be $\sigma_E = \frac{25\%}{\sqrt{E}} \oplus 2\%$. This is comparable to that expected for the sPHENIX W/SciFi calorimeter. Other technologies that would provide suitable resolution include crystals ($PbWO_4$, LYSO, GSO, LSO), DSB:Ce glass, and W/SciFi. $PbWO_4$ crystals and DSB:Ce glass have been developed

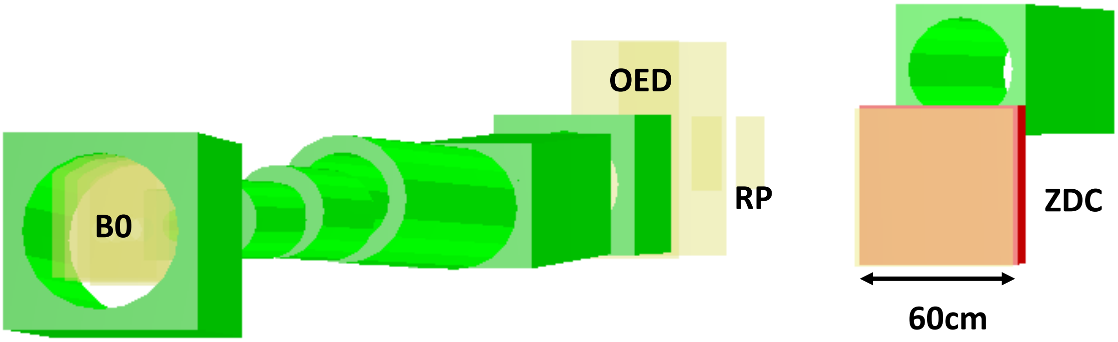

Figure 1: Schematic view of the far forward region of the EIC Magnets are shown in green while detectors are in orange and the beam pipes are hidden. The B0 serves as the first tracking station. Protons and other ions (in order of increasing rigidity) in the B0 tracker, the Off Energy Detectors (OED) and the Roman Pots (RP). The ZDC measures both photons and neutrons.

and characterized by the eRD1 Consortium and the Neutral Particle Spectrometer project at Jefferson Lab. Tests have shown energy resolutions of $\sim 2\%/\sqrt{E}$ for photon energies ~ 4 GeV [4]. The orbiting Fermi Gamma Ray Telescope uses a CsI crystal array and tracker to achieve very high spatial and energy resolution [5].

The hadronic part of the ZDC is needed for neutron identification. An energy resolution of $\sigma_E < 50\%/\sqrt{E}$ with an angular resolution of at least 3 mrad$/\sqrt{E}$ is desired, especially for tagging spectator neutrons from light nuclei. Cerenkov calorimeters, which measure only the high energy component of the showers, give excellent position resolution and tight containment but are non-compensating and so somewhat non-linear. Sampling all charged particles produced gives better energy resolution at the cost of worse lateral containment. This proposal seeks to exploit both techniques to maximize both the energy and position resolution of the ZDC. This could be done by using the quartz fibers developed for the LHC ZDCs, [6], with traditional scintillators.

1.2.2 Event reconstruction

Since there is no tracking for the forward neutrons it will not be possible to use current particle flow algorithms [7] for event reconstruction. However CALICE collaboration has shown that high granularity calorimetry allows shower by shower reconstruction and significant improvement in resolution. [7]. Recently machine learning approaches has been applied

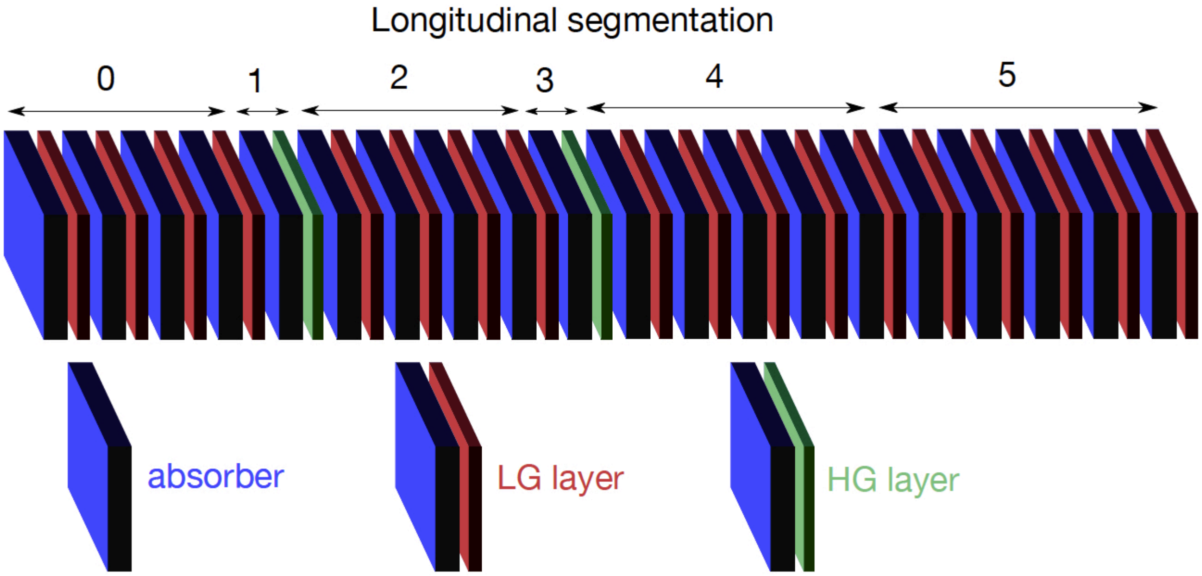

Figure 2: Schematic of the FoCal electromagnetic calorimeter. The blue absorber is tungsten, the red low grantularity silcon layers are used for energy measurement while the green high granularity layers give precise position information [3].

to the reconstruction of physics objects and seems to hold great promise [8, 9, 10]. We seek to exploit these developments by building a ZDC that is finely segmented in 3 dimensions. Part of the development task will be to see what level of segmentation is required for the physics goals outlined above.

1.3 Physics

1.3.1 $e + A$ collision geometry

Exclusive vector meson production in diffractive process is one of the key measurements at the EIC [1]. For the coherent process where the nucleus remains intact, the momentum-transfer (t) dependent cross-section can be translated to the transverse spatial distribution of gluons in the nucleus. In addition to contributing to our understanding of nuclear binding in the shadowing and anti-shadowing regions of x from roughly 0.01 to 0.2, the nuclear gluon distribution at ultra-low x are considered to be directly sensitive to gluon saturation as a function of Q^2. Exclusive incoherent vector meson production in $e + A \rightarrow e + V + X$ occurs when the nucleus breaks up from its interaction with the vector meson. The probe can be used to characterize spatial density fluctuations in nuclei [11], and so it will be important to identify these events. This requires accurate determination of the exclusivity of the reaction, which must be determined by identifying break-up of the excited nucleus [12]. It is a strenuous measurement since the incoherent cross-section is expected to be much larger than the coherent cross-section in the moderate and high-t ranges of the coherent process where a precision to extract the spatial distribution is required. Evaporated neutrons from the break-up in the diffraction process can be used to separate the incoherence/coherence most probably ($> 90\%$). At the highest ion energy of (275 GeV)Z, a nucleon in a heavy nucleus such as ^{208}Pb has a typical momentum of ~ 110 GeV/c. Evaporation neutrons are easily contained within the 4 mrad line-of-sight acceptance of the downstream quadrupoles. Even "balistic" neutrons, emitted incoherently from Fermi-sea are largely within the ZDC acceptance. This leads to a requirement to measure neutrons and photons at near zero degree precisely to complete the coverage of coherence tagging in a wide t range. The latest study [12] shows that photons from de-excitation of the exited nucleus and also evaporated protons signal incoherence in absence of evaporated neutrons.

Collision geometry is an important measure of high energy nucleus-nucleus collisions. On the other hand, event-by-event characterization of collision geometry has rarely been discussed in deep-inelastic scattering experiments off nuclei. It has been proposed that collision geometries can be tagged through forward neutron multiplicities emitted near at zero degree [13]. Constraining geometry, such as the "propagation length" of the struck parton inside the nucleus can be extremely beneficial in constraining nuclear effects for the electron-nucleus collisions at EIC. In particular, a tag on long propagation-length events should significantly enhance any signal for gluon saturation in inclusive or semi-inclusive DIS. The geometry tag consists in counting the number of neutrons and selecting the top 1 to 2% of events with the highest multiplicity. This neutron number distribution can be inferred from the total hadronic energy deposition in the ZDC. For example, an event with 10 neutrons would deposit over 1 TeV in the ZDC. Even with a constant term of order 5%, the multiplicity resolution would be $\leq \pm 1$.

Energy deposition in the ZDC can be used as a good measure of propagation length length d, whereas the impact parameter b is not as well controlled. However, it is precisely the length d that is most important for nuclear effects, including both hadronization and gluon saturation.

1.3.2 Spectator tagging in $e + d/^{3}$He

The EIC offers the exciting potential to directly probe the quark-gluon content of nuclear binding, especially in light nuclei such as the deuteron and ^{3}He. This is achieved by tagging one or more "spectator nucleons" in the final state of both inclusive $e + A$ and exclusive (e.g. $e + d \to epnV$) reactions. Identifying spectators in these processes constrains the kinematics of the"targe" nucleon. The spectator is characterized by a lightcone momentum $\alpha P_A^+/A$ and a transverse momentum $\mathbf{p}_T$. Viewed in the nuclear rest-frame, the spectator 3-momentum is $\mathbf{p}_{\text{Rest}} \approx [\mathbf{p}_T, (\alpha - 1)M_N,]$. Tagging events with spectator kinematics $\alpha \to 1$ and $\mathbf{p}_T \to 0$ corresponds to putting the active nucleon almost on its' mass shell. Thus tagging spectator protons enables the measurement of inclusive and exclusive reactions on a nearly on-shell neutron. The ZDC enables tagging of a nearly on-shell proton in $d(e, e'n_S)X$ reactions. This is a vital calibration of the theory of a "nearly on-shell nucleon", since the genuine on-shell proton is measured in $e + p$. Conversely, spectator tagging of large p_T and/or large $|\alpha - 1|$ probes the quark-gluon content of high-momentum nucleons, related to

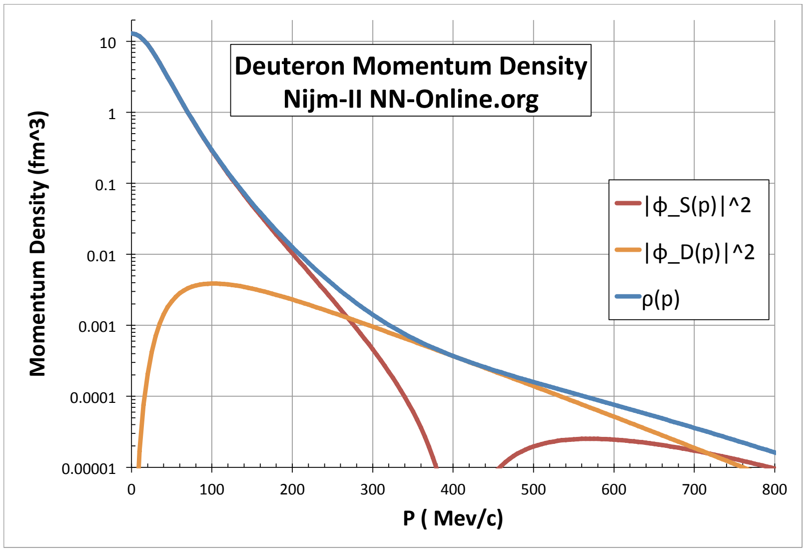

Figure 3: Nucleon momentum distribution in the deuteron.

short-range-correlations (SRC) and the EMC effect [14].

The SRC is a nucleon-nucleon interaction at very short distance which shows high momentum nucleon in the nucleus rest frame. It shows how nucleons form a nucleus, and has a deep connection to the EMC effect. Experiments have shown it is universal that ∼20% of nucleons are in SRC pairs. These SRC pairs have high momentum and are spatially very close to each other. If the nucleon PDF is significantly modified for these pairs, but not modified for other nucleons, SRC is the cause of the EMC effect. Almost all of these SRC pairs are found to be similar to a quasi-deuteron at its high momentum tail. In addition to the SRC study in $e+A$ collisions, we will be able to understand the deuteron as a baseline of SRC pair in $e+d$ collisions by measuring $e+d \to e+X+n$ at zero degree. In this reaction we measure the structure functions of a proton with the SRC effect on top. Pure SRC effect between a proton and neutron can be extracted by comparing this to the structure function measurement of a proton from ep collisions. Since the EMC effect may be a strong function of Bjorken-x and expected to be also significant at high-x, the neutron-tagged data should be collected also during the high-luminosity operation in order to access as high-x as possible.

Spectator neutron tagging of a nearly on-shell proton in the deuteron places stringent demands on the ZDC energy resolution. A $50\%/\sqrt{E}$ single neutron resolution of a 100 GeV/c neutron corresponds to a 5% relative energy measurement, equivalently $\sigma(\alpha) \approx 0.05$ or $\sigma(p_n) = 50$ MeV/c in the deuteron rest frame. The implied sensitivity to the deuteron momentum distribution is illustrated in Fig. 3. By spectator neutron tagging in the ZDC, the nearly on-shell active proton can be studied in three bins of $\pm\sigma(p_n)$, spanning three orders of magnitude in the momentum density.

The measured SRC effect allows us high precision determination of the structure functions of a neutron without "the EMC effect", though $e+d \to e+X+p$, i.e. spectator proton tagged ed scattering. Furthermore, the isospin component of the partonic structure of nucleons can be extracted if we also measure the charged-current (CC) cross sections for both protons and neutrons. Since only u and $\bar{d}$ quarks couple to the electron in e^-p CC reactions, the information on d and $\bar{u}$ quarks can only be obtained if we measure the CC cross sections of neutrons and assume isospin symmetry of the proton and the neutron. Therefore, the proton tagging should be collected with as much integrated luminosity as possible since the CC cross section is small and the precision of the measurement will be limited by statistics. An alternative data with $e +^3$ He with neutron tagging may supplement the proton-tagged CC $e + d$ measurements. Again the presence of forward instruments is highly desired for full luminosity $e + p$ and $e + d/^3$He operation.

Double and triple spectator/recoil tagging $e + d \to e'pnX$ and $e +^3$ He $\to e'ppnX$ can provide detailed study of diffractive DIS on both the proton and neutron, allowing the separation of vaccuum exchange (Pomeron) and non-vacuum exchange (Reggeon).

The parton density extraction at high-x may have a strong impact on the current and future high-energy collider experiment such as high-luminosity operation of the LHC (HL-LHC) and the Future Circular Collider (FCC), where the sensitivities of many BSM search analyses are limited by the knowledge of parton-density functions of the proton. As the luminosity increases at the LHC, the collision events from high-x partons become accessible and this extend the search to high-mass regions. Also important for these searches is to know the gluon structure at high-x since some of the models can be accessed only via gluon-intiated processes.

The structure function measurements at various collision energies at the EIC allows to precisely extract the gluons through QCD analysis of the cross section data from much wider kinematic coverage in (x, Q^2). This, in combination with the flavour decomposition of nucleon structure and QCD analysis with HERA and the LHC Drell-Yan, direct photon and jet data opens new era in understanding the partonic structure of nucleons and also boosts the search potential of the current and next-generation hadron colliders.

1.3.3 Meson structure

EIC enables a quantitative understanding of the structure of hadrons, such as the nucleon, pion and kaon, in terms of quarks and gluons. It will address four central questions:

- How do hadron masses and radii emerge for lightquark systems from QCD?
- What is the origin and role of dynamical chiral symmetry breaking (DCSB)?
- What is the interplay of the strong and Higgs-driven mass generation mechanisms?
- What are the basic mechanisms that determine the distribution of mass, momentum, charge, spin, etc. within hadrons?

Five key measurements are:

Hadron masses in light quark systems Pion and kaon parton distribution functions (PDFs) and pion generalized parton distributions (GPDs)

Gluon (binding) energy in NG modes Open charm production from pion and kaon

Mass acquisition from DCSB Pion and kaon form factors

Strong versus Higgs-driven mass generating mechanisms Valence quark distributions in pion and kaon at large momentum fraction x

Timelike analog of mass acquisition Fragmentation of a quark into pions or kaons

Further details can be found in Ref. [15].

Pion and kaon structure will be measured using the Sullivan process, the electron deep-inelastic-scattering (DIS) off the meson cloud of a nucleon target. Theoretically, the Sullivan process can provide reliable access to a meson target as t becomes space-like, if the pole associated with the ground-state meson remains the dominant feature of the process and the structure of the related correlation evolves slowly and smoothly with virtuality. To check whether these conditions are satisfied empirically, one can take data covering a range in t, particularly low $|t|$, and compare with phenomenological and theoretical expectations.

In the case of a proton-to-neutron Sullivan process, used to tag a virtual pion target, the final state neutron moves forward with a large part of the initial beam energy. For an EIC with proton beam energy $E_b = 100$ GeV, this means detecting near to 100 GeV neutrons in a zero-degree calorimeter (ZDC). The ZDC must reconstruct the energy and position well enough to help constrain both the scattering kinematics and the 4-momentum of the pion. A 60 cm × 60 cm ZDC allows for high detection efficiency for a wide range of energies as shown in Fig. 4. Lower energies (5 on 41, 5 on 100) require at least 60 cm × 60 cm size. All energies need good ZDC angular resolution for the required $|t|$ resolution. In particular higher energies (10 on 100, 10 on 135, 18 on 275) require a resolution of better than 1 cm.

In the case of a proton-to-Λ Sullivan process, used to tag a virtual kaon target, the final state Λ moves forward with a large part of the initial beam energy and also decays via two primary modes: $\Lambda \to n + \pi^0$ or $\Lambda \to p + \pi^-$. To detect these decay products, the ZDC should have the same features as for the forward neutron detection, including additional high resolution and high granularity EMCal before ZDC for the neutral channel ($\Lambda \to n + \pi^0$), and the additional B0, OED, and RP for the charged channel decay.

1.3.4 Leading baryons and very forward asymmetries

Leading proton and neutron production in DIS were measured and their production mechanisms were studied at HERA by comparing with fragmentation process and one pion exchange (OPE) process. The results support that the OPE process dominates the production, but there are still tension in detailed understanding of the mechanism and comparison between ZEUS and H1 data. It is also important to compare the data from $e+p$ collisions and $p+p$ collisions where also some tension exists. In addition to the production cross section measurement, the asymmetry measurement will give us useful additional input for the study

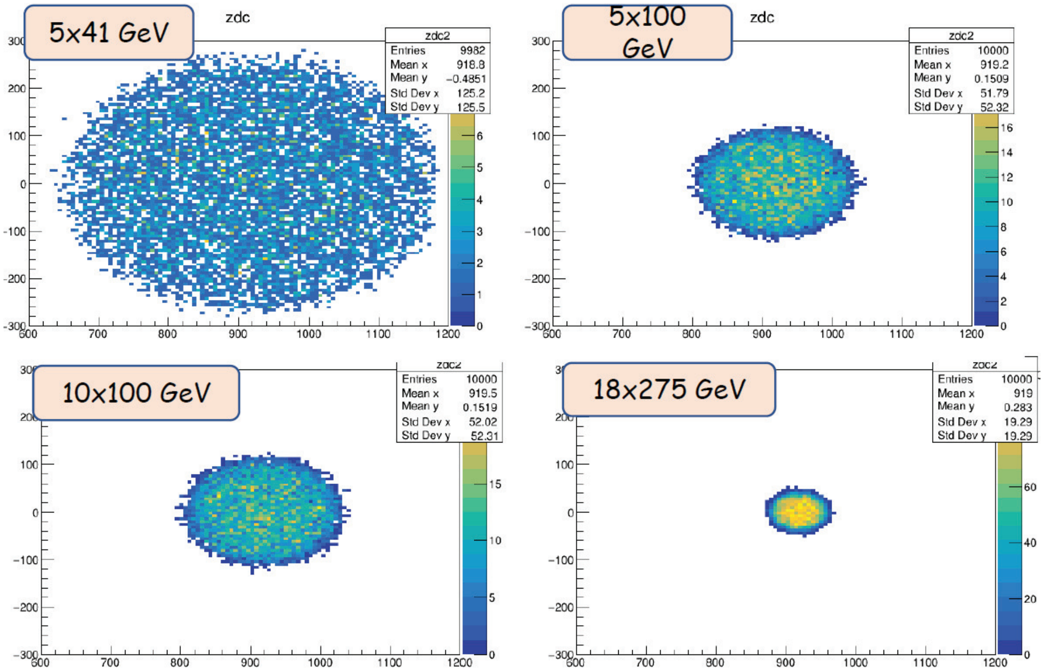

Figure 4: Detection of forward neutrons with 60 cm × 60 cm ZDC.

of the production mechanism. The very forward inclusive neutron production is known to show a large left-right asymmetry. The spin asymmetry measurement of the leading baryons in e+p collisions will give us useful additional information, too. In order to study them systematically, it is very important to have wide aperture effectively to cover wide x_F ($0.1 < x_F < 1$) and p_T (> 1 GeV/c).

Not only leading baryons, it is also important to measure production of photon and various hadrons in the very forward region. The data will be used to understand energy flow and development of event generator, and applied for understanding air shower evolution of high-energy cosmic ray and neutrino interaction.

1.3.5 Spectroscopy

The recently observed charmonium-like X, Y, Z resonances are likely exotic candidates in heavy the quark sector [16]. They have provoked much interest experimentally and theoretically recently with an expectation of the states being clear multi-quark candidates. With the proposed energy and luminosity of EIC, the X, Y, Z states can potentially be discovered through meson photoproduction. There are opportunities of studying exotics in hadronic spectroscopy at the EIC, especially the heavy quark (c, b) sector in photoproduction with the extended energy lever arm of EIC. Examples include charged charmonium-like states $Z_c^+(3900)$, $Z_c^+(4430)$ which can be excited by the process $\gamma + p \to Z_c^+ n$ [17, 18]. For tagging and kinematically constrain the forward neutrons in these processes, it requires energy and position resolutions sufficient to constrain these processes kinematically.

1.3.6 Other topics

We're discussing nuclear fragments and isotope tagging as an important topic for the very forward apparatus. The Luminosity monitor and polarimetry are also important as application.

2 Performance requirements and resources requested

Detector R&D	Physics	Performance requirements	Resource requested	Support & collaboration
Soft photon detection	e+A nuclear breakup veto	$E_\gamma \leq 300$ MeV	detector simulation	This proposal Calorimeter consortium
		acceptance	acceptance simulation	This proposal BeAGLE group
		detector technology	detector R&D	N/A in FY21
EM + hadron calorimeter	e+A collision geometry	neutron multiplicity	high resolution not necessary	BeAGLE group
	spectator tagging	energy & position resolution	detector simulation	This proposal
	meson structure	neutron & Λ acceptance	detector simulation	This proposal Meson structure WG
		detector technology	FoCal R&D	RIKEN
			LHC-ZDC R&D	Kansas Univ.
		calibration scheme	design & simulation	This proposal
			system test	N/A in FY21
Radiation hardness		radiation dose	simulation study	This proposal Kobe Univ.
		detector technology	radiation test	This proposal Calorimeter consortium

Table 1: Table of performance requirements.

2.1 Soft photon detection

Detection capability of photons decayed from nuclear excitation is necessary to identify bound nuclear excitation as a hint of the coherence of the collision. In general, the photon decay chain of a heavy nucleus is dominated by photons of energy of order 10 KeV. These photons may be indistinguishable from background. However, for a special nucleus such as ^{208}Pb, every bound-state decay sequence has at least one photon of at least 2.6 MeV. After accounting for the boost of the nucleus with momentum Z(275 GeV/c, 20% of these decay photons (with minimum energy 455 MeV) are detectable in the ZDC aperture of ~ 4.5 mrad. In order to detect photons from nuclear excitation requires a large (as large as possible) aperture. It is possible that a 2nd IR design will allow a larger ZDC acceptance. Resolving nuclear decay photons from background will require a full absorption EM calorimeter with excellent energy resolution, e.g. made with crystal scintillator (LYSO, PWO, ...).

2.2 EM and hadron calorimeter

The ZDC detectors were installed to each collision points in RHIC primarily as the luminosity monitor by the neutron counting from collision point providing real time feedback to the accelerator operation. On the other hand, the ZDC detector was also used to determine the event plane, centrality determination, and so in heavy ion collisions. Further more, the ZDC itself played central role to discover unexpectedly large transverse single spin asymmetries at almost zero degree in polarized proton + proton[19] and proton + nucleus [20] collisions.

The ZDC detectors [21, 22] implemented for RHIC are designed to detect neutrons at zero degree ± 18 meters downstream of collision points and have coarse position resolution with a Shower-Max Detector (SMD). The ZDC demonstrated performance of about position resolution of approximately 1 cm and energy resolution of $\Delta E/E \sim 30$ % at $E = 100$ GeV for neutron detection. The ZDCs demonstrated radiation hardness and have been operated in physics stores. Unfortunately, the ZDC implemented for RHIC doesn't satisfy the performance requirement of the ZDC for EIC. Here we propose R&D for the new ZDC detector dedicated for the EIC.

The number of spectator neutrons is predicted to have somewhat correlation with the collision geometry. The required performance of the detector to identify the coherence of the collision is under development in other proposal[12] using the BeAGLE simulation.

Some of performance parameters are under ongoing study. Therefore the optimization of the performance requirements is also included in the scope of this proposal. In this proposal, the detector development is proposed based on the requirements known as of now as listed below.

2.2.1 Acceptance

A large acceptance (e.g. 60×60 cm^2) to establish good identification efficiency between coherent and incoherent collisions is necessary for vetoing spectator neutrons from nuclear breakup. This large acceptance is also required to determine the collision geometry[23] . For studying very forward production and asymmetry of hadrons and photons, a large acceptance is also important. The eRHIC aperture of ±4 mrad gives $p_T < 1\text{GeV}/c$ coverage for 275 GeV hadrons and photons, which covers the transition from elastic/diffraction to incoherent regime; for low-energy hadron beam the acceptance in terms of p_T is more limited e.g. $p_T < 0.4\text{GeV}/c$ coverage for 100 GeV beam.

2.2.2 Energy, position, and p_T resolutions

Due to the strong β squeeze < 1 meter for the high luminosity, a beam spread of ∼20 MeV and ∼1 cm of the hadron beam angular divergence is induced. Thus the position resolution of neutron in sub cm won't help. 1cm position resolution provides 300 μrad angular resolution, which can be translated to transverse momentum resolution $p_\mathrm{T} \sim 30$ MeV/c of 100 GeV spectator neutron.

The minimum energy resolution $\Delta E/E \sim 50\%/\sqrt{E(GeV)}$ to distinguish number of spectator neutrons from 20 to 30 for collision geometry determination. In order to accommodate a single MIP track to 30 spectator neutrons, wide dynamic energy range in the readout electronics is required.

It is anticipated to be a sampling type calorimeter with a sufficient longitudinal size of ∼10 interaction length[23]. It is also required to have a sufficient transverse size of ∼2 interaction length to avoid transverse leakage of the hadron shower and to achieve good hadron energy resolution.

2.3 Radiation hardness

From the DIS cross section, 60μb, and $10^{34}\text{cm}^{-2}\text{s}^{-1}$ luminosity, the event rate is evaluated to be 600 kHz. The beam-gas rate is evaluated to be 10 MHz by assuming 10^{-7}Pa vacuum pressure, which is 14 times larger than the event rate.

100 GeV dose/event $\sim 1.6 \times 10^{-8}$ Joule/event, and $e + p$ event rate 600 kHz gives 0.01 Joule/s. From LHCf simulation (with about $1\lambda_I$), 1/3 of dose is given in 1 kg material, 30 Gy/nb for $p + p$. For $e + p$ at EIC, this corresponds to 0.003 Gy/s which corresponds to 30 kGy/year with $10^{34}\text{cm}^{-2}\text{s}^{-1}$ luminosity. For 14 times larger beam-gas rate, this corresponds to 500 kGy/year. So, we evaluate the radiation dose to be $\sim O(100\text{k - 1MGy})$ or $n_{eq} \sim 10^{14-15}$ for 1-year operation of $e + p$ collisions, i.e. 10^{15-16} for lifetime.

Silicon and crystal scintillator (LYSO, PWO, ...) would stand for the expected dose. Some plastic scintillators like PEN may stand for > 0.1 MGy radiation. The plastic scintillator is still an atractive option since it shows good e/h ratio, thus better resolution for hadrons.

In such harsh radiation environment, however, the imperfect calibration may contribute more to the resolution of the ZDC. The expected stochastic term at 275 GeV for $50\%/\sqrt{E}$ calorimetry is about 3%. This could easily be spoiled by the channel-by-channel variation of detector response, which may change rapidly by radiation damage. It is, therefore, important to balance the bare performance of the calorimeter and the robustness against radiation damage.

If we construct a calorimeter with non-compensating material, it is necessary to weight the energy according to local shower energy profile to achieve the energy resolution of $50\%/\sqrt{E}$. This requires fine segmentation (e.g. $3 \times 3\,\mathrm{cm}$ or finer cells in the hadronic part of the calorimeter). It is also necessary to develop calibration scheme for such many channels.

Total dose should also be better estimated using dedicated simulation for the EIC IR, using realistic profile of the vacuum near the IR. It is, however, very difficult to predict the beam-gas rate since it depends on the accelerator running condition as well the aging effect, since the electron beam cleans up the beam pipe wall slowly throughout the beam operation. A possibility of switching detectors depending on the luminosity and background condition may also be a solution.

2.4 Simulations studies

We have begun simulation studies using the G4E framework. Figure 5 shows a schematic layout of the hadronic forward region of the EIC.To begin the process we have assumed a crystal electromagnetic section, currently 20cm of PbW04, backed up by a FOCAL like hadronic section with 1.0 cm tungsten plates separated by planes of silicon. We are planning on augmenting this setup with an array of fused silica Cerenkov fibers running longitudinally in order to identify the high energy core of the neutrons showers.

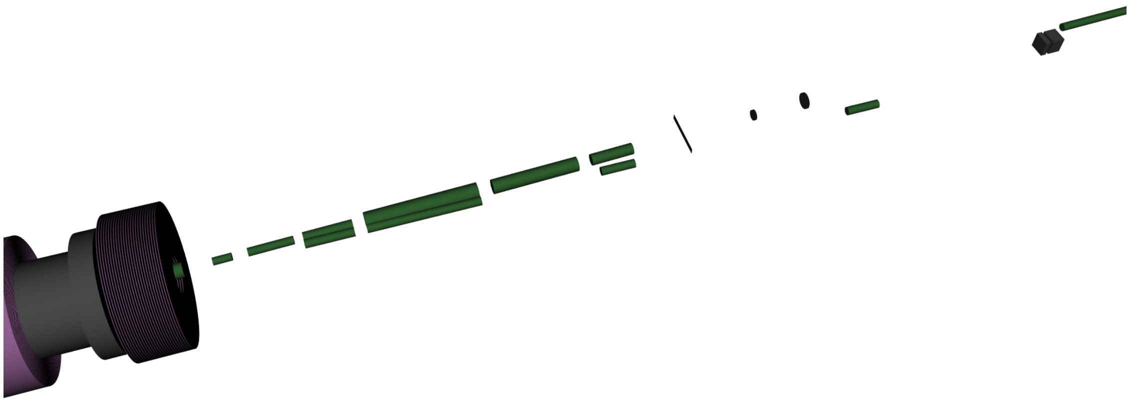

Figure 5: Schematic view of the forward region of the EIC showing the central detector, magnets, the off momentum detectors, Roman Pots and the ZDC.

Figure 6 shows events display for a 20 GeV neutron and a 500 MeV photon impinging upon the ZDC. During FY21 we will integrate BEAGLE into the simulation and focus on the developing the optimum detector configuration for simultaneous detector of soft photons $\approx$ 300 MeV and beam energy neutrons. This will be done by varying type and configuration of the crystals in the EM section and the segmentation and depth of the hadronic section. In addition we will also seek to optimize the p_T resolution of the photons by precisely identifying the core of the showers with both the silicon and quartz fibers. By the end of FY21 we hope to

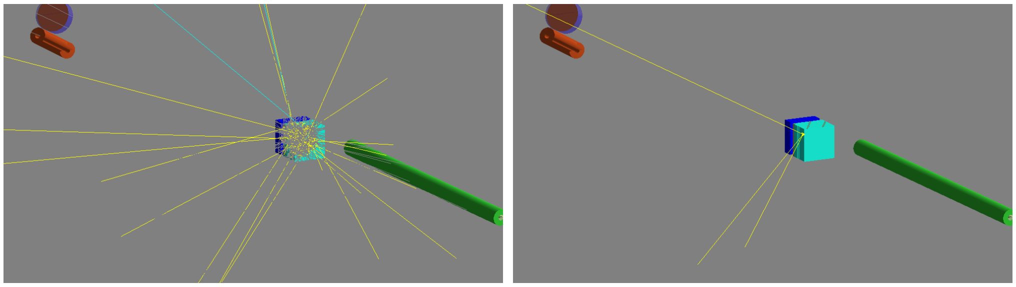

Figure 6: Event displays for (Left) a 20 GeV neutron and (Right) a 500 MeV photon impinging upon the ZDC

have a feasible conceptual design for a detector that could reach the physics goals highlighted above. Once this is done we will have the necessary tools to develop a calibration scheme and to realize a practical design of a detector that could actually be built.

Apart from the physics simulations it is also important to consider the radiation environment in which the ZDC will operate. We will profit from work already being done within the context of eRD21 on beam-gas interactions and by the JZCapa group on fused-silica fibers.

3 Deliverables and budget

The timeline, for the project is laid out in Table 2.

Table 2: Schedule for ZDC development

Period	Task	Group
10/2020 - 12/2020	Integration of simulation tools	KU
1/2021 - 3/2021	Test against physics requirements	KU/SBU
	Acceptance, σ_E, σ_{p_T}	KU
3/2021 - 5/2021	Comparison of different crystals	KU
3/2021 - 9/2021	Optimize neutron reconstruction	KU
6/2021 - 9/2021	Background studies	ODU
10/2020 - 12/2020	Radiation dose estimate	Japan
1/2021 - 7/2021	Test of Focal prototype	Japan
1/2021 - 7/2021	Test of CMS prototype	KU
7/2021 - 9/2021	Prepare publication	All

The KU group already has basic simulations in place. For physics simulations we will use BEAGLE as a benchmark but will also investigate the potential of other codes to simulated nuclear breakup and photon emission. The Japanese groups have considerable expertise with crystals that will be leveraged for this project. The KU group is also working with UIUC, Maryland and Ben Gurion on a joint ATLAS/CMS project to build new ZDCs for run 4 of the LHC. In FY21 this will involve reactor tests of fused silica fibers and beam tests at FNAL or CERN that will provide valuable input to this project.

The ODU group has deep experience at JLab and is already working on background studies for the EIC. Thus they are well placed to estimate how serious a problem background will be for the ZDC and how it can be mitigated.

As an institutional effort of RIKEN, the Japanese groups, will collaborate with ALICE-FoCal consortium on R&D and a prototype beam test. Note that Tsukuba University is one of the leading group of ALICE-FoCal project. In FY21 The Japanese groups will work on the silicon pad readout and trigger development. The silicon pad prototype sensor will be produce in Japan (Hamamatsu). They also will have a test beam in Japan. Both the sensor and beam test work will be very useful for the EIC ZDC.

The SBU/CFNS group has great expertise in the physics requirements for the EIC. They are well placed to ensure any conceptual design really satisfies the full physics requirements of the EIC.

The work outlined above will allow us to produce an idealized detector by the end of FY21 that meets the physics requirements. In FY22 we will work on the physical design of such a system, including photo-detection, electronics, mechanics, calibration and monitoring. This would allow us to start building prototype detectors in FY22. It is possible the Covid restrictions will make it difficult for group to meet in BNL. If this is the case we will meet either at SBU or Kansas.

Table 3 outlines the budget request for FY21. These costs are based on estimates from the various groups and include fringe benefits and overhead. As noted above if travel to BNL is not possible because of Covid we will meet at either SBU or Kansas.

Table 3: Budget for ZDC in FY21

Item	Institute	Cost
Postdoc 1/3 FTE	Kansas	$ 40K
Travel to BNL 3 people	Riken	$ 10k
US Travel	Old Dominion	$ 2k
Grad student summer	Old Dominion	$ 10.5k
Total		$ 62.5k

4 Summary

Zero Degree Calorimeters are an essential componant of any EIC experiment. The EIC imposes more stringent requirements energy and position resolution than either the RHIC or LHC programs. The group assembled for this project have significant and diverse expertise in calorimeter design. Support this year from the EIC R&D program will allow significant progress to be made on such a detector in a tinely manner.

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