Development of Position Sensitive Zero Degree Calorimeter for EIC

Y. Goto, I. Nakagawa, and R. Seidl
Nishina Center, RIKEN, Hirosawa, Wako, 351-0198, Saitama, Japan

J. H.Lee
Brookhaven National Laboratory, Upton, NY 11973, USA

Y. Yamazaki
Kobe University, Kobe, Hyogo, Japan

Y. Itow, and H. Menjo
Nagoya University, Nagoya, Aichi, Japan

T. Sako
ICRR, University of Tokyo, Kashiwa, Chiba, Japan

T. Chujo
Tsukuba University, Tsukuba, Ibaraki 305, Japan

K. Nakano
Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan

T. Shibata
Nihon University, Tokyo, Japan

Y. Miyachi
Yamagata University, Yamagata, Japan

K. Tanida
Japan Atomic Energy Agency, Tokai-mura, Ibaraki 319-1195, Japan

M. Murray, Q. Wang, and R. Chudasama
University of Kansas, Lawrence, KS 66045, USA

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Abstract

The development of position sensitive calorimeter to be implemented at zero degree is proposed.

1 Introduction

In this Letter of Intent, we propose development of zero-degree apparatus in the EIC experiment. Zero-degree detectors serve critical roles for a number of important physics topics at EIC. We will study requirements and technologies of zero-degree detectors, and mainly develop a position-sensitive zero-degree calorimeter.

One of the most important physics topics is identification of nuclear breakup in the exclusive processes on nuclei to distinguish between coherent (nucleus intact) and incoherent (nucleus decays) diffractive scattering. It requires to detector photons, too, so we will develop a system including:

- full absorption low-energy photon detector
- electromagnetic (EM) and hadron calorimeters with position measurement

with good enough energy, position, and p_T resolution, aperture and radiation hardness. Physics topics to be discussed in this Letter of Intent are $e + A$ collision geometry, spectator tagging in $e + d/^3He$, leading baryons and very forward asymmetries, spectroscopy, and so on.

Development items of the calorimeters include their energy/position/p_T resolutions, aperture (acceptance) and rad-hardness. We will also study tracking systems such as Roman Pots and particle-ID detectors in collaboration with other eRD groups, and optimum IR design in collaboration with accelerator groups. We'd like to maximize physics capability by studying detector design, development and simulation.

2 Physics

2.1 $e + A$ 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, thus 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, 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 [2]. 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%). The latest study [2] shows that photons from de-excitation of the exited nucleus and also evaporated protons signals incoherence in absence of evaporated neutrons.

This leads to a requirement measure neutrons and photons at near zero degree precisely to complete the coverage of coherence tagging in a wide t range.

Collision geometry is an important measure in collisions with nucleus, while the measurement for an event-by-event characterization is rarely discussed in the prior deep-inelastic scattering experiments off a nucleus. It has been proposed that collision geometries can be tagged through forward neutron multiplicities emitted near at zero degree [3]. This type of geometry gauge, if achieved, can be extremely beneficial in constraining nuclear effects for the electron-nucleus collisions at EIC. This neutron number distribution can be measured with a calorimeter at zero degree in the ion-going direction. Constraining collision geometry quantities like "traveling length" of struck parton in nucleus, which is correlated with the impact parameter of the collision, is very meaningful in the studies of nuclear medium effects. Energy deposition in the ZDC can be used as a good measure of traveling length d while the impact parameter b is not as well controlled. Even though the resolution of the traveling length is likely dominated by its intrinsic correlation with the number of emitted neutrons during the evaporation process, it's beneficial to keep the energy resolution for counting neutrons not to be further smeared by the measurement. With the determination of collision geometry in these measurements, our understanding of nuclear structure can be constrained with higher precision.

2.2 Spectator tagging in $e + d/^3He$

Other physics programs at EIC those require tagging forward neutrons are collisions with light ions, like in d and ^3He [4]. Identifying spectators in these processes for identifying that "target" nucleon and constraining kinematics for studies of the Short-Range Correlations (SRC) [5].

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 nuclei, 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 spatially very close each other. If the nucleon PDF could be 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 $e + d \rightarrow e + X + n$ at zero degree.

2.3 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 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.

2.4 Spectroscopy

The charmonium-like X, Y, Z resonances[6] recently observed are likely exotic candidates in heavy quark sector. They have been provoking 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 EIC especially heavy quark (c, b) sector in photoproduction with an extended energy lever arm of EIC. such as charged charmonium-like state $Z_c^+(3900)$, $Z_c^+(4430)$ by the process $\gamma + p \rightarrow Z_c^+ n$ [7, 8]. For tagging and kinematically constrain the forward neutrons in these processes, it requires energy and position resolutions sufficient to constrain these processes kinematically.

2.5 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.

3 Detector Performance Requirement

3.1 Photon detection

Detection capability of not only neutrons but also photons are required to identify the nuclear excitation states. Detection capability of photons decayed from nuclear excitation to identify the nuclear excitation states as the hint of the coherence of the collision. In order to detect photons from nuclear excitation requires a large (as large as possible) aperture. JLEIC aperture of ±10 mrad gives much better photon detection efficiency than eRHIC aperture of ±4 mrad. The energy of photon can be as low as below 300MeV. It will require a full absorption calorimeter with a good energy resolution, e.g. made with crystal scintillator (LYSO, PWO, ...).

3.2 Zero-Degree Calorimeter (ZDC)

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[11] and proton + nucleus [12] collisions.

The ZDC detectors [10] implemented for RHIC is designed to detect neutrons at zero degree $\pm$ 18 meters downstream of collision points and have coarse position resolution with a Shower-Max Detector (SMD). ZDC is composed of copper-tungsten alloy absorbers with optical fibers and each module has 1.7 interaction length (λ_I). A photomultiplier collects Cherenkov lights via the optical fibers in each module. Three ZDCs are located in series (5.1 (λ_I) in total) within the small acceptance, covering 10 cm in the transverse plane. SMD consists of x-y scintillator strip hodoscopes and is inserted between the first and second ZDC modules at the position of maximum hadronic shower approximately. The x-coordinate (horizontal) is sampled by 7 scintillator strips of 15 mm width, while the y-coordinate (vertical) is sampled by 8 strips of 20 mm width, tilted by 45 degrees. The ZDC demonstrated performance of about position resolution of approximately 1cm and energy resolution of $\Delta E/E \sim 30$ % at $E = 100$ GeV. 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[2] 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.

3.2.1 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[9] . For studying very forward production and asymmetry of hadrons and photons, a large acceptance is also important. JLEIC aperture of $\pm$10 mrad gives $p_T < 1\text{GeV}/c$ coverage for 100 GeV hadrons and photons, though eRHIC aperture of $\pm$4 mrad gives $p_T < 0.4\text{GeV}/c$ coverage.

3.2.2 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[9]. It is also required to have a sufficient transverse size of ∼2 interaction length to avoid transverse leakage of the hadron shower and to have a good enough hadron energy resolution.

3.3 Radiation hardness

From the DIS cross section, 60μb, and 10^{34}cm$-$2s^{-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}cm^{-2}s^{-1} luminosity. For 14 times larger beam-gas rate, this corresponds to 500 kGy/year. So, we evaluate the radiation dose to be $\sim O$(100k - 1MGy) or $n_{eq} \sim 3 \times 10^{12-13}$ for 1-year operation of $e + p$ collisions, i.e. 10^{14-15} for lifetime.

In this radiation dose, Silicon and crystal scintillator (LYSO, PWO, ...) should be OK. Some plastic scintillators like PEN stands for > 0.1 MGy radiation.

4 Detector technology of ZDC

Sampling type calorimeters are possible technology choices as the basic concept of the ZDC detector for EIC to be investigated in this proposal.

We will select one or two detector technologies, and study energy/position/p_T resolutions, aperture (acceptance) and rad-hardness of calorimeters. Table 1 shows comparison of technologies for the position layers. We'd like to maximize physics capability by studying detector design, development and simulation. We have two existing technology choice:

1. RHICf/LHCf detector
2. FoCal detector for ALICE

Table 1: Comparison of technologies for the position layers.

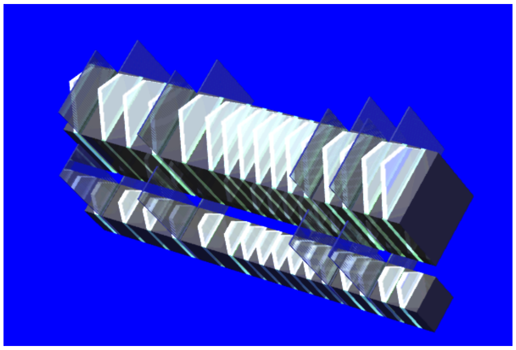
	Plastic fiber	Crystal bar	Quartz fiber	Silicon
Source	Scintillation		Cherenkov	
Signal	good	good	weak	good
Rad hardness	poor	OK	excellent	OK
Cost	$	$$	$$	$$$
Position resolution	good	good	poor	best
Large acceptance	OK	position dependent	OK	OK

While RHICf employs scintillators, FoCal employs silicon sensors. As a baseline of the technology choice, we'd like to perform prototype studies of these technologies. Other detector technologies besides above two base choices are also to be investigated.

4.1 RHICf

The RHICf detector was originally developed for the cosmic ray physics pursued at LHC and was operated at STAR in Run17. The detector was installed just in front of STAR West ZDC and operated in dedicated large β^* beam condition. Since it has been always operated under reduced luminosity, the radiation hardness of the detector need to be proven to apply the technology for the continuous operation during physics data taking in EIC. The development of the radiation hard scintillator is the part of the scope of this proposal. According to the back of the envelope calculation, the assumed radiation dose is 100 kGy for the integrated luminosity of 100/fb.

The RHICf detector, previously used as the LHCf Arm1 detector, consisted of a pair of compact electromagnetic sampling calorimeters. There were two diamond-shaped calorimeters, Small (2×2 cm) and Large (4×4 cm) calorimeters, stacked vertically in the detector. Each of the calorimeter has 16 layers of GSO scintillators of 1 mm thickness interleaved with tungsten plates of 2 radiation lengths for the first 11 layers and of 2 radiation lengths for the rest of layers. Total radiation lengths is 44. There were four layers of position sensitive detectors made with 1mm square GSO X-Y hodo-scopes in order to reconstruct the position of the incident particles. Consequently, rapidity or transverse momentum of the incident particles or invariant mass of two incident particles can be reconstructed. The energy resolution is expressed as $\sigma/E = 31.3/\sqrt{E}$ (GeV) + 2.8 % for electro-magnetic showers. Though the calorimeter had only 1.6 interaction lengths, the energy resolution is about 40 % at E = 100 GeV for hadron showers. The position resolutions are typically 170 μm and 2.5 mm for electro-magnetic and hadronic showers, respectively.



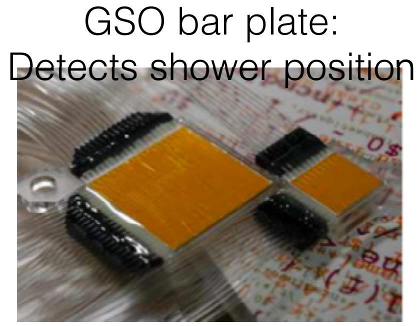


Figure 1: (Left) Longitudinal structure of the RHICf detector. (Right) Shower max GSO bar plate.

4.2 FoCal

On the other hand, the silicon based sampling calorimeter as FoCal can achieve higher granularity in general at higher cost compared the scintillator based one. The optimization is to be studied based on the balance between required performance and the cost such as possible hybrid between the scintillator as basic layers and the silicon as the shower max layers.

The FoCal detector is under development for ALICE forward upgrade. The detector consists of 24 layers made of pure tungsten absorbers, silicon sensors, printed circuit boards (PCB) and glue. The total thickness of a single layer is 4 mm, 3 mm of which consist of tungsten. The resulting radiation thickness of one layer is 0.97 X_0. The shower max layers are to be built with Monolithic Active Pixel Sensors (MAPS) as the active elements. With a pixel size of 30 μm it allows digital calorimetry, i.e. the particle ' s energy is determined by counting pixels, not by measuring the energy deposited. The use of MAPS allows the sensor part of the layer, including the PCB responsible for readout, to be kept as thin as 1 mm, which leads to a very small Moliere radius, calculated to be $R_{\mathrm{M}} \sim 11$ mm.

5 Development menu

We will configure groups to study following development menu.

Photon detector study We will evaluate performance of several crystal scintillators, e.g. LYSO, PWO, especially at low energy < 300 MeV. Energy resolution, speed, radiation hardness, etc. will be compared.

Prototype study of ZDC (EM + Hadron) with position sensitivity We're considering prototype study of FoCal and/or RHICf technology. We will study performance of energy and position resolutions with test beam and simulation. It is important to study e/h for hadron energy resolution.

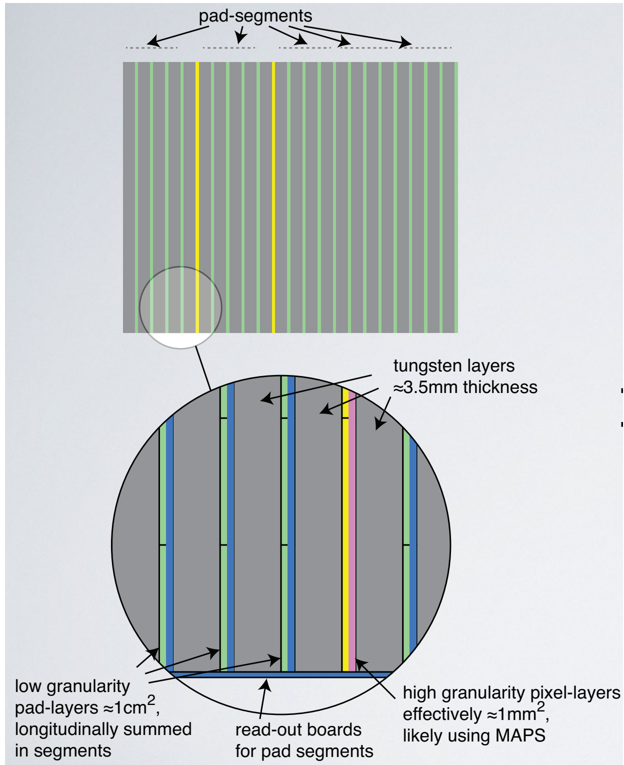


Figure 2: (Left) Longitudinal structure of the FoCal detector.

Radiation hardness study for new technology We will test radiation hardness of several types of plastic scintillators, e.g. PEN.

References

[1] A. Accardi *et. al* Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all arXiv:1212.1701

[2] E.C. Aschenauer, M.D. Baker, J.H. Lee, L. Zheng, EIC R&D Project eRD17 Progress Report

[3] L. Zheng, E.C. Aschenauer, J.H. Lee, Determination of electron-nucleus collision geometry with forward neutrons, Eur. Phys. J. A (2014) 50: 189

[4] Talks at *Polarized light ion physics with EIC*, Feb. 2018, Ghent University, Belgium

[5] Talks at *Short-range nuclear correlations at an Electron-Ion Collider*, Sep. 2018, CFNS Brookhaven National Laboratory

[6] R. Faccini, A. Pilloni, A.D. Polosa, Mod. Phys. Lett. A 27 1230025 (2012)

[7] Q. Lin, X. Liu, H Xu, PRD 88 (2013) 114009

[8] Talks at *The spectroscopy program at EIC and future accelerators*, Dec. 2018, Trento, Italy

[9] Electron-Ion Collider Detector Requirements and R&D Handbook (version 1.1)

[10] C. Adler, A. Denisov, E. Garcia, M. J. Murray, H. Strobele, and S. N. White, Nucl. Instrum. Methods Phys. Res., A 470, 488 (2001).

[11] A. Adare, et al., Phys. Rev. **D88**, 032006 (2013).

[12] C. Aidala, et al., Phys. Rev. Lett **120**, 022001 (2018).