Position Sensitive ZDC

1st EIC Yellow Report Workshop
at Temple University (remote only)
March 19th, 2020
Yuji Goto (RIKEN)
EIC R&D of ZDC

• Full-absorption photon detector
  • Crystal scintillators

• Prototype study of ZDC with position sensitivity
  • EM + Hadron calorimeters
  • ALICE-FoCal / ATLAS & CMS ZDC / ...

• Radiation hardness study for new technology
  • Plastic scintillators

• We presented a Letter of Intent at the EIC R&D meeting in January, 2020
  • “The committee urges the group to put forward a proposal focused on the most important technical questions and what physics areas it will open”
Physics topics at EIC zero degree

• Diffractive process in e + A collisions
  • Breakup of the excited nucleus
    • Exclusive vector meson production
  • Event-by-event characterization of collision geometry
    • Study of nuclear medium effects

• Spectator tagging in e + d / \(^3\)He collisions
  • Neutron structure
    • Spin structure, S & D waves
  • Neutron interactions
    • Short-range correlation (SRC) and EMC effect at large x
    • Diffraction and shadowing at small x

• Leading baryons

• Asymmetries at zero degree

• Spectroscopy

• Isotope tagging for nuclear fragments

• Relation to cosmic-ray physics
  • Understanding hadronization
  • Cosmic-ray acceleration in blazars
**e + d/³He collision at zero degree**

- **Spectator tagging**
  - Neutron structure
    - Neutron spin structure, S & D waves
  - Nucleon interactions
    - Short-range correlation (SRC) and EMC effect at large $x$
    - Diffraction and shadowing at small $x$

- Requiring good enough $p_T$ resolution
  - Challenging to achieve 30MeV $p_T$ resolution
  - Need to study if 50MeV $p_T$ resolution acceptable

March 19, 2020
**Detector performance requirements**

- **Photon detection**
  - Required to identify diffractive process in e+A collisions
    - Rapidity gap & coherent (nucleus remains intact)
  - Requiring to identify the nuclear excitation states in addition to the neutron detection
  - Photon energy < 300 MeV
- **Full absorption calorimeter, e.g. crystal calorimeter**
  - PbWO$_4$
    - $X_0 = 8.9$ mm, $r_M = 2.2$ cm, $\tau = 25$ nsec
    - 5% resolution at 300 MeV
  - LYSO
    - $X_0 = 11.4$ mm, $r_M = 2.1$ cm, $\tau = 40$ nsec
    - 2.6% resolution at 300 MeV (SuperB prototype)
ZDC requirements

• Acceptance
  • 25 mrad crossing angle for EIC at BNL
  • Forward magnet aperture $\pm 4$ mrad opening angle for ZDC

• Sufficient transverse size to avoid transverse leakage
  • $\sim 2$ interaction length
  • e.g. 60cm x 60cm
ZDC requirements

- **Position resolution**
  - 1 cm position resolution $\rightarrow$ 300 $\mu$rad angular resolution
  - $\rightarrow$ 30 MeV $p_T$ resolution for 100 GeV spectator neutron

- **Energy resolution**
  - Minimum requirement $\Delta E/E = 50%/\sqrt{E}$ (GeV)
  - $\rightarrow$ 50 MeV $p_T$ resolution for 100 GeV spectator neutron

- **Position layers (or Shower Max Detector)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Plastic fiber</th>
<th>Crystal bar</th>
<th>Quartz fiber</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>good</td>
<td>good</td>
<td>weak</td>
<td>good</td>
</tr>
<tr>
<td>Rad Hardness</td>
<td>poor</td>
<td>OK</td>
<td>excellent</td>
<td>OK</td>
</tr>
<tr>
<td>Cost</td>
<td>$</td>
<td>$$</td>
<td>$$</td>
<td>$$$</td>
</tr>
<tr>
<td>Position Resolution</td>
<td>good</td>
<td>good</td>
<td>poor</td>
<td>best</td>
</tr>
<tr>
<td>Large acceptance</td>
<td>OK</td>
<td>position dependent</td>
<td>OK</td>
<td>OK</td>
</tr>
</tbody>
</table>
Detector performance requirements

• Radiation hardness
  • $\sim O(100k - 1MGy)$ or $n_{eq} = 3 \times 10^{12} - 10^{13}$ for 1-year operation
  • $n_{eq} > 10^{14}$ for lifetime

• Silicon and LYSO should be OK for the dose

• Plastic scintillators?
  • Very good resolution for hadrons
    • Good e/h
  • Some plastic like PEN stands for $> 0.1$ MGy radiation
The design of the detector:

- 20 layers: W (3.5mm ≈ 1 X₀) + Si-sensors (2 types):
  - low granularity (LG), Si-pads
  - high granularity (HG), pixels (e.g. CMOS-MAPS)
- Moliere radius ~ 1-2 cm

<table>
<thead>
<tr>
<th>Pixel/Pad Size</th>
<th>LG</th>
<th>HG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel/Pad Size</td>
<td>≈ 1 cm²</td>
<td>≈ 30x30 μm²</td>
</tr>
<tr>
<td>Total # of pixels/pads</td>
<td>≈ 2.5 x 10⁵</td>
<td>≈ 2.5 x 10⁹</td>
</tr>
</tbody>
</table>

The surface area of the detector will be about 1 m²
mini-FoCal at PS and SPS (2018)

ΔE/E = 3.6 %
@ 150 GeV/c, e⁻ (SPS)

Pads connected to flex PCB

“mini-FoCal” has been built in Tsukuba, and shipped to CERN for test beam and ALICE test in 2018 APV25 hybrid + SRS for readout

Module design approaching final geometry
3 PAD sensors, 8x8 pads each
mini-FoCal in ALICE (2018)

Goal: measure/verify backgrounds in situ with p+p @ $\sqrt{s} = 13$ TeV collisions in ALICE
- Calibration based on test beam
- Comparison to MC (cluster spectrum, slid lines)

Cluster multiplicity:
- full acceptance
- $3.7 < \eta < 3.9$
- $3.9 < \eta < 4.1$
- $4.1 < \eta < 4.3$
- $4.3 < \eta < 4.5$

N. Novitzky
ATLAS & CMS ZDC

- W-quartz sampling calorimeter

THE CURRENT ATLAS & CMS ZDCs

- ZDCs located in the TAN (140 m from IPs)
- W-quartz sampling calorimeters
- ATLAS: EM + 3 Hadronic modules
- CMS: EM + 4 Hadronic modules
JZCaP collaboration

- ATLAS + CMS joint R&D effort
  - Radiation-hard fused silica rods
  - Increasing $H_2$ concentration

**MOTIVATION - RADIATION DAMAGE**

- The LHC upgrade during LS3 requires a rearrangement of the beam line.
- Less space left for the ZDC (from TAN - 10 cm, to TAXN, 5 cm) —> Narrower ZDC modules for Run4.
- TAXN ~ 15 m closer to the interaction point compared to TAN.
- Radiation levels will further increase.

- Fused quartz with high level of impurities inadequate for any pp running and damaged during PbPb running.

- Hardening the detector for pp running allows flexibility in installation to accommodate special LHC runs (e.g. O+O, p+O in Run3) that take place in the middle of pp running.
• Japanese group
  • RIKEN, Nagoya Univ., ICRR, Kobe Univ., Tsukuba Univ., Tokyo Tech., Nihon Univ., Yamagata Univ., JAÉA

• US group
  • BNL, Univ. of Kansas

• Discussing with
  • Participants in Joint CFNS & RBRC workshop on “Physics and detector requirements at zero-degree of colliders”
  • Follow-up meeting to be held
Summary

• We presented a Letter of Intent at the EIC R&D meeting in January, 2020
  • “The committee urges the group to put forward a proposal focused on the most important technical questions and what physics areas it will open”

• We’re going to submit a propose for EIC R&D of ZDC
  • Full-absorption photon detector
    • Crystal scintillators
    • We will consider collaboration with the calorimeter consortium
  • Prototype study of ZDC with position sensitivity
    • EM + Hadron calorimeters
    • RIKEN group is considering collaboration with ALICE-FoCal
    • We will consider to study ATLAS & CMS ZDC technology
  • Radiation hardness study for new technology
    • Kobe U. group is studying plastic scintillators
Backup Slides
Gluon saturation at extreme density

- Diffractive process in $e + A$ collision
  - Rapidity gap & coherent (nucleus remains intact)

- Diffractive cross section
  - First evidence for gluon saturation

- Exclusive vector meson production
  - $e + Au \rightarrow e' + Au' + J/\psi, \phi, \rho$
Gluon saturation at extreme density

- Exclusive vector meson production
  - Momentum transfer $t$ dependence translated to the transverse spatial distribution of gluons in the nucleus
- Incoherent process (nucleus breaks up)
  - Spatial density fluctuation in nucleus
  - Much larger than the coherent process
- Coherent process (nucleus remains intact)
  - Sensitive to the gluon saturation
  - Identify & veto breakup of the excited nucleus

![Graphs showing exclusive vector meson production](image)
**e + A collision at zero degree**

- Breakup of the excited nucleus
  - Evaporated neutrons (& protons)
    - Separate the coherent process ~90%
  - Photons from de-excitation of the excited nucleus
  - Requirement to measure neutrons and photons at zero degree in a wide \( t \) range

- Event-by-event characterization of collision geometry
  - Tagged through forward neutron multiplicities at zero degree
  - \( b \): impact parameter
  - \( d \): path length of struck parton in nucleus
  - “centrality” (high \( d \)) & “skin” (low \( d \))
  - Study of nuclear medium effects

Intra-nuclear cascading increases with \( d \) (forward particle production)

Leads to evaporation of nucleons from excited nucleus (very forward)
Physics at zero degree of EIC

- Leading baryons
- Fragmentation
- One pion exchange (OPE)

LN in DIS

$p_T^2$ dependence in bins of $x_L$

\[
\frac{d^2\sigma}{dx_L dp_T^2} \text{ [nb/GeV}^2]\]

H1 Preliminary

\[
\begin{array}{c}
\text{H1 Data (Prel.)} \\
0.65-0.85 \text{ GeV}^2 \\
0.85-1.21 \text{ GeV}^2 \\
1.21-1.45 \text{ GeV}^2 \\
1.45-2.45 \text{ GeV}^2 \\
0.65-0.85 \text{ GeV}^2 \\
0.85-1.21 \text{ GeV}^2 \\
1.21-1.45 \text{ GeV}^2 \\
1.45-2.45 \text{ GeV}^2 \\
\end{array}
\]

Inconsistency @ HERA

Need more data to understand production mechanism

Slide by Ciesielski

\[
d\sigma_{\gamma^* p \rightarrow nX} = f_{\pi/p}(x_L, t) \times d\sigma_{\gamma^* \pi^+ \rightarrow X}.
\]

The distribution of $p_T$ is defined solely by the pion flux

Sensitivity to the pion flux
Other physics

• Asymmetries at zero degree
  • Leading baryons
• Spectroscopy
• Isotope tagging for nuclear fragments
• Relation to cosmic-ray physics
  • Understanding hadronization
  • Cosmic-ray acceleration in blazars
**RHICf detector**

- Two position-sensitive sampling calorimeters
  - TS (small tower): 20mm x 20mm
  - TL (large tower): 40mm x 40mm
  - Tungsten absorber (44 $X_0$, 1.6 $\lambda_{int}$)
  - 16 GSO sampling layers
  - 4 XY pairs of GSO-bar position layers (MAPMT readout)