June 8, 2022

2022 RHIC/AGS Annual Users' Meeting

Calorimetry
Session: EIC Detector

Detector 1 Calo WG conveners: Friederike Block, Carlos Muñoz Camacho, Oleg Tsai, Paul E Raimer

Maria ŻUREK, Argonne National Laboratory
NAS Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?
EIC Physics Case
Calorimetry Role

DIS event kinematics - scattered electron or final state particles (CC DIS, low $y$)

Neutral Current DIS
- Detection of scattered electron with high precision - event kinematics
- Excellent e/h separation needed

Charged Current DIS
- Event kinematics from the final state particles (Jacquet-Blondel method)
- Jet measurement capabilities

Semi-Inclusive DIS
- Precise detection of scattered electron in coincidence with at least 1 hadron
- Measurement of SIDIS $\pi^0$, decay electrons (e.g. HF)

Deep Exclusive Processes
- Detection of all particles in event
- Detection of DVCS $\gamma$, exclusive $\pi^0$, decay electrons (e.g. VM)
- Separation of $\gamma/\pi^0$ for DVCS

→ See talk by A. Jentsch about far-forward (exclusivity) and far-backward region (Low $Q^2$, luminosity)
EIC Calorimetry Requirements

EIC Community outlined physics, detector requirements, and evolving detector concepts in the EIC Yellow Report.

Main tasks of the ECAL

- Detect the scattered e and separate them from π.
- Improve the electron momentum resolution at backward rapidities.
- Detect neutral particles (photons, π⁰), and measure the energy and the coordinates of the impact.
- Separate secondary electrons and positrons from charged hadrons.
- Provide spatial resolution of two photons sufficient to identify decays π⁰ → γγ at high energies.

Challenges: e/π PID, γ/π⁰ discrimination, high energy resolution at large |η| and momentum, dynamic range of sensors, available space
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<table>
<thead>
<tr>
<th>-4 &lt; η &lt; -2</th>
<th>-2 &lt; η &lt; -1</th>
<th></th>
<th>1 &lt; η &lt; 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E resolution</strong></td>
<td>2%√ Emoji:E + (1-3)%</td>
<td>7%√ Emoji:E + (1-3)%</td>
<td>(10-2) %√ Emoji:E + (1-3)%</td>
</tr>
<tr>
<td><strong>e/π separation</strong></td>
<td>up to 10⁻⁴</td>
<td>up to 10⁻⁴</td>
<td>up to 10⁻⁴</td>
</tr>
<tr>
<td><strong>Min E [GeV]</strong></td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>
EIC Calorimetry Requirements

DIS electrons

DVCS photons

SIDIS $\pi^0$

e/$\pi$ separation:
- Depends on momentum and $\eta$
- Tightest constrain from parity violating asymmetries $10^{-4}$
- $\Delta G$ requires $\sim 10^{-3}$
EIC Calorimetry Requirements

Main tasks of HCAL

- Precise reconstruction of the jet energy
  - Detection and isolation of neutral hadrons, in combination with information from EMCals, tracking and PID detectors.
  - Neutral/charged cluster discrimination with help of tracking
  - Complementing tracking at high $\eta$

- Detection of all the final state hadrons (Jaquet-Blondel method)
  - Proton fragmentation products in the forward area ($n$ and $K_L$ only in HCal)

Challenges: available space, energy resolution at high $\eta$

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>EIC Specifications</th>
<th>Conservative option</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma / E, %$</td>
<td>$E_{\min}, \text{MeV}$</td>
</tr>
<tr>
<td>-3.5 to -1.0</td>
<td>$45/\sqrt{E} + 7$</td>
<td>500</td>
</tr>
<tr>
<td>-1.0 to +1.0</td>
<td>$85/\sqrt{E} + 7$</td>
<td>500</td>
</tr>
<tr>
<td>+1.0 to +3.5</td>
<td>$35/\sqrt{E}$</td>
<td>500</td>
</tr>
</tbody>
</table>
Detector I Calorimetry
Backward Calorimetry

**Backward EMCAL**
- Non-projective **PbWO calorimeter** (EEEMC-Consortium)
  - $2 \times 2 \times 20 \text{ cm}^3$ crystals
  - Length $\sim 20X/X_0$, transverse size $\sim$Molière radius
  - Located inside the inner DIRC frame
  - Preferred readout: SiPMs of pixel size $10\mu\text{m}$ or $15\mu\text{m}$
  - Cooling to keep temperature stable within $\pm 0.1 \degree\text{C}$
- Ongoing efforts advancing the design to increase coverage in $\eta$ ($-3.7 < \eta < -1.5$) with inlay around beampipe

**Backward HCAL** in consideration
- Possible upgrade path

→ See C. Muñoz Camacho for EEEMCal, [https://indico.bnl.gov/event/15493/](https://indico.bnl.gov/event/15493/)
→ See B. Page, [https://indico.bnl.gov/event/15686/](https://indico.bnl.gov/event/15686/)
Backward EM Calorimetry

ATHENA

Resolution of inner [crystal] and outer [sci-glass] nECal

ECCE

ECCE G4 simulation

ν in EEMC, w/ mat. infront

YR requirement EM
νE = (2-3)E / (1-3)

Energy resolution

2.6% ∆E ⊕ 1.1%/E ⊕ 0.5%

Compton calorimeter / NPS prototype beam test
- 12x12 PWO modules (SICCAS crystals)
- Tested in JLab Hall-D

→ V. Berdnikov, https://indico.bnl.gov/event/15615/
→ Nucl. Inst. Meth. A 1013 (2021) 165683
Barrel EM Calorimetry

Technology I

8000 homogeneous blocks of SciGlass
- 45.5 cm length ($18 X_0$)
- $+ \sim 10$ cm radial readout space, read by SiPMs
- Coverage: $-1.7 < \eta < 1.3$
- SciGlass
  - Ongoing R&D EEEMCAL consortium
    → See Talk by T. Horn
  - Alternative to high resolution (expensive) crystal EMCal
  - 3 x 3 20 cm ($\sim 7 X_0$) SciGlass prototype detector tested in beam

→ See T. Horn, https://indico.bnl.gov/event/15802/
Barrel EM Calorimetry

Technology I

- Energy resolution
- Pion rejection
- Electron efficiency
- Separation of γ/π

**Geant4 Simulations**
- Implemented with the active components and support structures
- Materials in front of the EM calorimeter considered
- 1.5 T Magnetic Field

→ See T. Horn, https://indico.bnl.gov/event/15802/
Barrel EM Calorimetry

Technology II

- **Hybrid concept**
  - Imaging calorimetry based on monolithic silicon sensors **AstroPix** (NASA’s AMEGO-X mission) - 500 μm x 500 μm pixels
  - Scintillating fibers in Pb (Similar to **GlueX** Barrel ECal, 2-side readout w/ SiPMs)

- 6 layers of imaging Si sensors interleaved with 5 Pb/ScFi layers and followed by a large chunk of Pb/ScFi section (can be extended to inner HCAL)

- Total radiation thickness for EMCAL of ~20 $X_0$

- Detector coverage: -1.7 < $\eta$ < 1.3 which overlaps with “electron-going” side endcap

**Energy resolution** - SciFi/Pb Layers: 5.3% /$\sqrt{E}$ + 1.0%

**Position resolution** - Imaging Layers (+ 2-side SciFi readout): with 1st layer hit information ~ pixel size
Barrel EM Calorimetry
Technology II

- **Standalone Calorimeter**
  (no material/no magnetic field)
  → for apple-to-apple comparison with technologies presented in YR

- 2 step method: E/p cut + NN based on 3D position and energy information from imaging layers

- **Impact of material and 3T field**
- The lowest $p$ point at 0.7 GeV/c significantly affected by the high magnetic field
  - The rejection factor will go up with lower field
Barrel EM Calorimetry
Technology II

Pion rejection

- Standalone Calorimeter (no material/no magnetic field) → for apple-to-apple comparison with technologies presented in YR
- 2 step method: E/p cut + NN based on 3D position and energy information from imaging layers
- Impact of material and 3T field
  - The lowest p point at 0.7 GeV/c significantly affected by the high magnetic field
  - The rejection factor will go up with lower field

Separation of γ/π⁰

- Used shower profile (6FWHM) Shower profile from ATHENA simulation w/ 3T field. First check at r = 80 cm.
Barrel Hadronic Calorimetry

Reuse of sPHENIX outer (outside of the Solenoid) HCal ≈ 3.5λ₁

- Steel and scintillating tiles with wavelength shifting fiber
- Δη x Δφ ≈ 0.1 x 0.1
  (1,536 readout channels, SiPMs)

- Necessity and feasibility of inner HCal under development, depends on EMCAL choice

Two mature sampling EMCal designs considered:

- **Pb-Scintillator Shashlik**: scintillating tiles; light transported through the WLS fibers
  - Single towers smaller than $R_M (~5.2 \text{ cm})$, use shower maxima to separate close particles
  - $X/X_0 = 18.5$ (37.5 cm + 5 cm readout)

- **W/SciFi**: scintillating fibers embedded in W/epoxy mix
  - Similar to sPHENIX W/SciFi
  - $X/X_0 = 23$ (17 cm + 10 cm readout), 2.5 x 2.5 cm towers ($R_M = ~2.3 \text{ cm}$)
  - Easier construction for WSciFi calorimeter
  - Compactness and higher EM-shower containment

R&D: Improvement of light collection eff. and uniformity

Simulations:
- Expected $E$ resolution $\sim 11%/\sqrt{E} \oplus 2\%$
- Can effectively separate $\gamma/\pi^0$ ($z = 3.5 \text{ m}$) with ML methods

→ See O. Tsai, https://indico.bnl.gov/event/15686/
Forward Hadronic Calorimetry

Two designs based on longitudinally separated steel and scintillator tiles

- **Inspired by STAR Forward Calorimeter**
  - Fe/Scint (20 mm / 3 mm) sandwich
  - 4 longitudinal segments (scintillation tiles with two different time constants)
  - $\lambda/\lambda_0 = 7$ (ECAL + HCAL)

- **Inspired by Projectile Spectator Detector (CBM)**
  - 60 layers of steel-sci plates + 10 layers of W-Sci plates (5 x 5 cm towers)
  - 7 signals per tower (from 10 plates)
  - $\lambda/\lambda_0 = 6.9$ (HCAL only, larger shower containment)

- Ongoing efforts to explore granular inlay around beampipe

→ See O. Tsai, https://indico.bnl.gov/event/15810/
Performance on energy resolution and matching
- Cluster finding and track matching efficiencies good in center of LFHCAL, losses towards edges (further ML optimization in progress)
- Small $\eta$ dependence for energy resolution (fulfills YR requirements)

In general, our MC requires validation
- Validation for high Z absorbers
  - J. Adam, A. Jentsch (BNL), studies with Pb/Sc hcal eRD1/STAR
  - Work in progress to tune MC for Fe absorber

→ See O. Tsai, https://indico.bnl.gov/event/15810/
Summary and Outlook

- Electron-Ion Collider physics case requires a detector with unique capabilities
  - Detector requirements summarized in the EIC Yellow Report (YR)

- This talk summarizes the needs and proposed technology choices to fulfill the YR requirements for the EIC Electromagnetic and Hadronic Calorimetry in the Central Detector
  - See the talk about the Far-Forward and Far-Backward regions by A. Jentsch

- Active R&D efforts for different technologies
  - See the talks in the next 2 sessions

- Final Detector I technology choices for calorimetry under evaluation
  - Ongoing performance, risk, and cost studies and integration evaluations