Calorimetry for the Electron Ion Collider

Craig Woody
Brookhaven National Lab
CPAD Instrumentation Frontier Workshop 2022
November 30, 2022
Overview

The Electron Ion Collider at BNL

- Calorimeter requirements for EIC.
- Calorimeter technologies being considered for the ePIC detector.
- Other calorimeter technologies for a possible 2nd EIC detector.
EIC Detector Conceptual Design

- Low $Q^2$ scattered electron
- Hadrons from nuclear breakup

EIC Detector Conceptual Design

High $Q^2$ region

- $\eta = -0.88$
- $\theta = 90^\circ$

- $\eta = 0$
- $\theta = 135^\circ$

- $\eta = 0.88$
- $\theta = 45^\circ$

- $\eta = -4$
- $\theta = 178^\circ$

- Central Detector
- Lepton Endcap
- Hadron Endcap

Asymmetric Collisions

$p/A$ beam

Electron beam
EMCAL

**Requirements from EIC Yellow Report**

<table>
<thead>
<tr>
<th>Region</th>
<th>Resolution $σ/E$</th>
<th>Min E (MeV)</th>
<th>Granularity ($Δθ$)</th>
<th>Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backward -4 &lt; $η$ &lt; -2</td>
<td>2%/VE $⊕$ (1-3)%</td>
<td>20</td>
<td>&lt; 0.02</td>
<td>$ΔZ$ = 60 cm</td>
</tr>
<tr>
<td>Backward -2 &lt; $η$ &lt; -1</td>
<td>7%/VE $⊕$ (1-3)%</td>
<td>50</td>
<td>&lt; 0.02</td>
<td>$ΔZ$ = 60 cm</td>
</tr>
<tr>
<td>Barrel -1 &lt; $η$ &lt; -1</td>
<td>(10-12)%/VE $⊕$ (1-3)%</td>
<td>100</td>
<td>&lt; 0.025</td>
<td>$ΔZ$ = 30 cm</td>
</tr>
<tr>
<td>Forward 1 &lt; $η$ &lt; 4</td>
<td>(10-12)%/VE $⊕$ (1-3)%</td>
<td>100</td>
<td>&lt; 0.01</td>
<td>$ΔZ$ = 40 cm</td>
</tr>
</tbody>
</table>

- Need to measure the scattered electron with good resolution and provide e/h separation
- Require low $E_{min}$ to measure decays
- $γ/π^0$, e/h discrimination ($\sim 10^{-3} – 10^{-4}$)

C.Woody, EIC Calorimetry, CPAD 2022, 11-30-22
### Requirements from EIC Yellow Report

<table>
<thead>
<tr>
<th></th>
<th>Backward Endcap -4 &lt; $\eta$ &lt; -1</th>
<th>Barrel -1 &lt; $\eta$ &lt; -1</th>
<th>Forward Endcap 1 &lt; $\eta$ &lt; 2.5</th>
<th>Forward Endcap 2.5 &lt; $\eta$ &lt; 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution $\sigma_E/E$</td>
<td>50%/VE 6%</td>
<td>85%/VE 7%</td>
<td>50%/VE 6%</td>
<td>35%/VE 5%</td>
</tr>
<tr>
<td>Min E (GeV)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Granularity (cm$^2$)</td>
<td>10 x 10</td>
<td>10 x 10</td>
<td>10 x 10</td>
<td>10 x 10</td>
</tr>
<tr>
<td>Space</td>
<td>$\Delta Z = 100$ cm</td>
<td>$\Delta Z = 120$ cm</td>
<td>$\Delta Z = 120$ cm</td>
<td>$\Delta Z = 120$ cm</td>
</tr>
</tbody>
</table>

- Jet energies typically < 50 GeV
- Particle multiplicity within a jet is typically ~ 10

Would benefit from better calorimeter resolution for $\eta > 2.5$ due to degradation of tracking resolution

Would like to measure all hadrons (including neutrals) to minimize bias for jets and for determining event kinematics using Jacquet-Blondel method

Separate charged from neutral

Including all services
The ePIC Detector

**ePIC Calorimeter Systems**

- **Electron End Cap EMCAL (EEMC)**
  - PWO

- **Barrel EMCAL (BEMC)**
  - Scintillating Glass (Option 1)
  - Pb/SciFi/Si “Imaging” (Option 2)
    (see talk by J.Kim)

- **Outer HCal (oHCAL)**
  - Fe/Scint tile (sPHENIX re-use)

- **Forward EMCAL (FEMC)**
  - W/SciFi (similar to sPHENIX)
    (see talk by Z.Ji)

- **Longitudinally Segmented Forward HCAL (LFHCAL)**
  - Fe/W/Scint tile
    (see talk by N.Novitzky)

---

C.Woody, EIC Calorimetry, CPAD 2022, 11-30-22
PWO Endcap Calorimeter

Similar in design to the PANDA Endcap

- Coverage: $-3.4 < \eta < -1.5$ (possibly extended to $\eta = -3.7$)
- Consists of ~3000 PWO crystals
- $2 \times 2 \times 20$ cm$^3$ (Rectangular non-projective)
- Read out with SiPMs (3x3 mm$^2$) (either 4 or 16 per crystal)
- Energy Resolution: $2%/\sqrt{E} \oplus (1-3)\%$
- Angular Resolution $< 1^\circ$

Must measure energy/momentum and angle of the scattered electron

$Q^2_e = 2E_eE'_e (1 + \cos \theta'_e) = 4E_eE'_e \cos^2 \left( \frac{\theta'_e}{2} \right)$

Measuring $E'_e$ and $\theta_e$ determine $Q^2$
Status of PWO Crystals

Crystals for EIC are expected to be supplied by Crytur (Czech Republic)

CRYTUR can currently produce up to ~ 60 crystals/month

Neutral Particle Spectrometer (NPS) detector in the Super High Momentum Spectrometer (SHMS) in Hall C at JLAB

~ 25 msr detector with 1080 PWO crystals

“Precursor” to EIC

T. Horn CUA/JLAB
Scintillating Glass Barrel EMCAL

- Coverage: (-1.7 < \(\eta\) < 1.3)
- Consists of \(~9000\) blocks of \textit{new} Scintillating Glass (SciGlass)
- \(2 \times 2\) cm\(^2\) inner area, \(5 \times 5\) cm\(^2\) \(\rightarrow\) \(6 \times 6\) cm\(^2\) outer, 45.5 cm long (17 X0)
- Projective in \(\eta\) and \(\phi\) (but not pointing to the vertex)
- Read out with SiPMs (3x3 mm\(^2\)) (4 or 16 per crystal)
- Expected energy Resolution : \(2.5%/\sqrt{E} \oplus 1.6\%\) (similar to PWO)
Status of Scintillating Glass

A new type of Scintillating Glass is being developed at Catholic University and the Vitreous State Laboratory

Info provided by T. Horn CUA/JLAB

- Light Yield comparable to PWO (> 100 $\gamma$/MeV)
- Lower density than PWO $\Rightarrow$ longer blocks (17 X0 > 45 cm)
Scaling up to Produce 45 cm Blocks for EIC
A Joint Collaboration was formed between Catholic University/Vitreous State Laboratory and a new startup company

- Significant improvement in the quality of 40 cm blocks was made from 2021 to 2022

- Scintilex is now able to routinely produce good quality 40 cm blocks.
- Plans to test 3x3 prototype of 40 cm blocks this fall at JLAB.
- Challenge is to scale up production in order to produce the ~ 9000 blocks that are needed for EIC.
Outer HCAL

Reuses the sPHENIX Outer Hadronic Barrel Calorimeter

- Steel plates + scintillating tiles with WLS fiber readout
- Plates oriented parallel to beam
- Iron serves as flux return
- Plates are tilted to avoid channeling
- Two longitudinal sections (~4.5 λ)
  - Inner HCAL inside magnet
  - Outer HCAL outside magnet
- $\Delta \eta \times \Delta \phi \approx 0.1 \times 0.1$
- $2 \times 24 \times 64 = 3072$ readout channels

Test Beam 2016

Hadronic resolution
$\sim 81%/\sqrt{E} \oplus 12\%$

Outer HCAL installed in sPHENIX outside the solenoid magnet in March 2022
W/SciFi Calorimetry

- The Forward EMCAL is based on the technology developed for the sPHENIX EMCAL.
- It is a W/SciFi SPACAL consisting of a matrix of tungsten powder and epoxy with embedded scintillating fibers.
  - 0.47 mm dia. fibers, spacing 1 mm, SF ~ 2%
  - Density ~ 9.0 g/cm³, X₀ = ~ 7 mm, ~ 20 X₀ total, Rₘ ~ 2.3 cm

- W/SciFi modules consist of 4 towers, each with its own light guide that is read out on the front with a 2x2 array of 3x3 mm² SiPMs.

Energy Resolution ~ (13-15)%/√E ± 3%
Large area (8x8 tower) prototype

6144 Modules (24,576 towers)
sPHENIX W/SciFi EMCAL

Designed for high luminosity heavy ion collisions

Divided into 64 Sectors

\[2(\pm \eta) \times 32 \ (\phi)\]

Sector consists of 96 modules (384 towers)

Blocks and Sectors are approximately projective and tilted in both \(\eta\) and \(\phi\)

EMCAL sectors installed on the Inner HCAL of sPHENIX

Assembly completed in April 2022
Installation completed 11/23/2022
Improvements of W/SciFi Calorimetry for EIC

- Improve uniformity of light collection with a compact SiPM readout (→ reduce constant term)
- Improve the light collection efficiency (→ improve energy response at low energy)

Uniformity of the sPHENIX EMCAL measured in the test beam

8x8 Tower Prototype

Improved fiber arrangement and better optical coupling

Will also use 6x6 mm² SiPMs

Following talk in this session by Z.Ji
Shashlik Calorimetry

- **Mature technology**
  - The energy resolution can be tuned by changing the sampling fraction and/or the sampling frequency.
  - The absorber can be chosen to optimize the desired properties of the calorimeter (e.g., cost, compactness, degree of compensation with HCAL,...).
  - Readout can be done on either end which allows for a variety of different geometrical configurations.
  - The availability of low cost SiPMs now allows the possibility of reading out each fiber individually and determining the shower position < 1 $R_M$.

- **Most shashlik calorimeters that have been built so far have use Pb as the absorber.** However, using W as an absorber has several advantages:
  - For the same total $X_0$, a W shashlik calorimeter will occupy less space.
  - The $R_M$ of W is much smaller than for Pb (9.3 mm vs 16.0 mm). The showers are therefore much smaller and have less overlap with neighboring showers which improves the $\gamma/\pi^0$ separation and e/h separation.

Using W as an absorber also has some disadvantages:
  - W is more expensive and harder to machine.
  - It is more difficult and costly to make a shashlik calorimeter projective.
EMCAL Shashlik Calorimetry – Pb vs W

Energy resolution vs sampling fraction
20 X0 total length (L ~ 30 cm w/readout)

In order to resolve $\gamma/\pi^0$ at high momentum
fine segmentation and a small $R_M$ is required

Non projective geometry

Note:
- Projective geometry will improve separation, particularly in the $\eta$ ~ 1-3 region
- Can also use a preshower detector to improve $\gamma/\pi^0$ separation

C.Woody, EIC Calorimetry, CPAD 2022, 11-30-22
Summary & Conclusions

- EIC requires nearly $4\pi$ calorimeter coverage with regions requiring high resolution EMCAL and HCAL performance. However, there are also severe space limitations, particularly along the beam direction.

- The most demanding requirements for the EMCAL are in the backward direction to measure the scattered electron.

- The most demanding requirements for the HCAL are in the forward direction where one would like to measure all hadrons and the tracking resolution deteriorates due to the axial magnetic field.

- There are a number of promising new technologies to meet these requirements (e.g., new scintillating glasses, W/SciFi, W/Shashlik and Imaging EMCAL technologies, and longitudinally segmented and tilted plate configurations for the HCAL).
Backup
sPHENIX EMCAL Under Construction (Completed April 2022)

Block Production at UIUC (also Fudan U – Shanghai)
- 20 Tons of W powder
- 2600 km of fiber
- 665 kg of epoxy
- 88 m² of screens

Module and Sector Production at BNL
- Sector Burn-in and Testing
- Modules being glued into sectors

Nuclear Physics Lab

High Bay in BNL Physics Dept

C.Woody, EIC Calorimetry, CPAD 2022, 11-30-22
Energy Resolution

Energy resolution after position dependent correction

Beam Test 2018

Beam covering a 2.5 x 2.5 cm² area centered on a tower

Beam covering a 1.0 x 0.5 cm² area centered on a tower

Resolution ~ (13-15)%/√E ⊕ 3%

Resolution ~ (12-13)%/√E ⊕ 2.5%
Increasing Photocathode Coverage of W/SciFi Blocks

- The uniformity of the light exiting the fibers is very good but the light guide provides poor mixing and the SiPMs cover only 23% of the readout area of the light guide (6.4% of the total readout area of the block).
- The light collection efficiency and uniformity can be greatly improved by increasing the photocathode area coverage on the readout end of the block.

**Maximum photocathode coverage using the sPHENIX blocks**

- Hamamatsu S13360 6x6 mm² SiPM with TSVs (50 µm pixels)
- Increased coverage using existing sPHENIX light guides
- 2x2 array of 6x6 mm² SiPMs

**Increased coverage using existing sPHENIX light guides**

- 3 SiPMs in series then 3 summed in parallel
- (C/3 x 3 = C)
- Short light guide covering entire block
- Hamamatsu S13360 6x6 mm² SiPM with TSVs (50 µm pixels)
Imaging Calorimetry

Pb/SciFi Barrel EMCAL similar to GlueX design with embedded Si sensor layer

- 6 layers of imaging Si sensors using AstroPix chip interleaved with 5 Pb/SciFi layers followed by additional Pb/SciFi layers
- ~ 0.5 mm spatial resolution (~ pixel size)
- Coverage -1.5 < \( \eta \) < 1.2
Forward HCAL

Longitudinally segmented Forward HCAL

- 60 layers of steel and 10 layers of W absorbers (160 mm plates) $\rightarrow \sim 7 \lambda_h$
- Scintillating tiles (4 mm) read out with WLS fibers
- Divided longitudinally into 7 segments
- SiPM readout (10 fibers/SiPM, 7/tower)
- Modules of different sizes arranged radially from beam pipe to maximize efficiency and ease of assembly.

Following talk in this session by N. Novitzky
A Prototype W/Shashlik EMCAL (eRD1)

Originally designed for the NA64 Experiment at CERN

- Absorber plates are a W(80%)/Cu(20%) alloy that is easily machinable
  \[ \rho = 17.2 \text{ g/cm}^3, \ X_0 = 4.2 \text{ mm}, \ 38 \times 38 \times 1.58 \text{ mm}^3 \]
- Scintillating tiles: 38 x 38 x 1.63 mm$^3$ injection molded polystyrene (Uniplast, Russia).
- 1 mm dia WLS fibers (Saint-Gobain BCF-91A)
- 80 sampling layers, 31 X0 (27 cm)
- Each fiber read out with 3x3 mm$^2$ SiPMs

WLS fibers pass through stack in a slight spiral pattern to improve light collection uniformity and reduce dead areas.

Each fiber coupled to small lucite light mixer.

Hamamatsu S14160-3015P

3x3 module prototype
W/Cu Shashlik – Position and Energy Resolution

Effect of light collection map

Non-uniformity of light collection efficiency map
- Improves the position measurement
- Slightly worsens the energy resolution

Z. Shi (LANL/MIT)